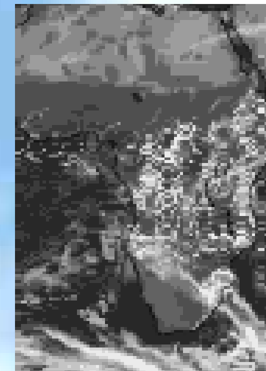
Tropical cloud feedbacks

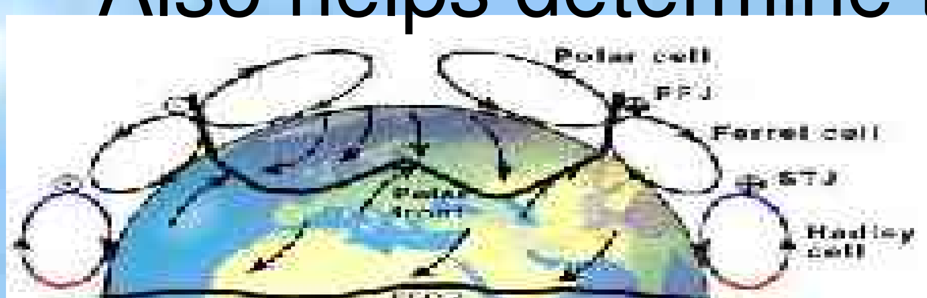
Richard Allan

University of Reading

Introduction



- Tropical cloudiness
  - Fundamental to global water cycle
  - Interface between atmospheric hydrological cycle and Earth’s radiative energy balance
- Product of tropical circulation
- Also helps determine this circulation

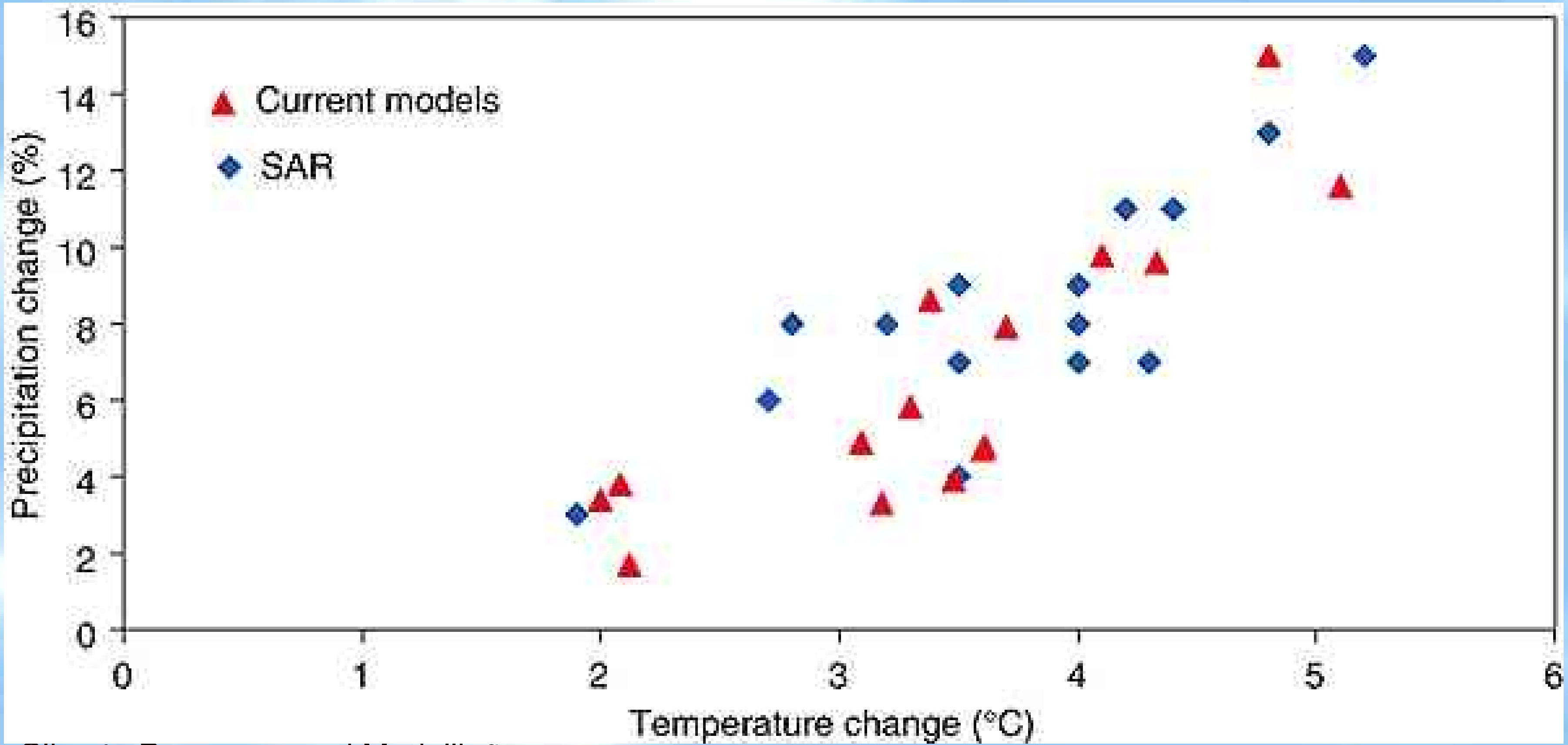


Importance of cloud feedbacks

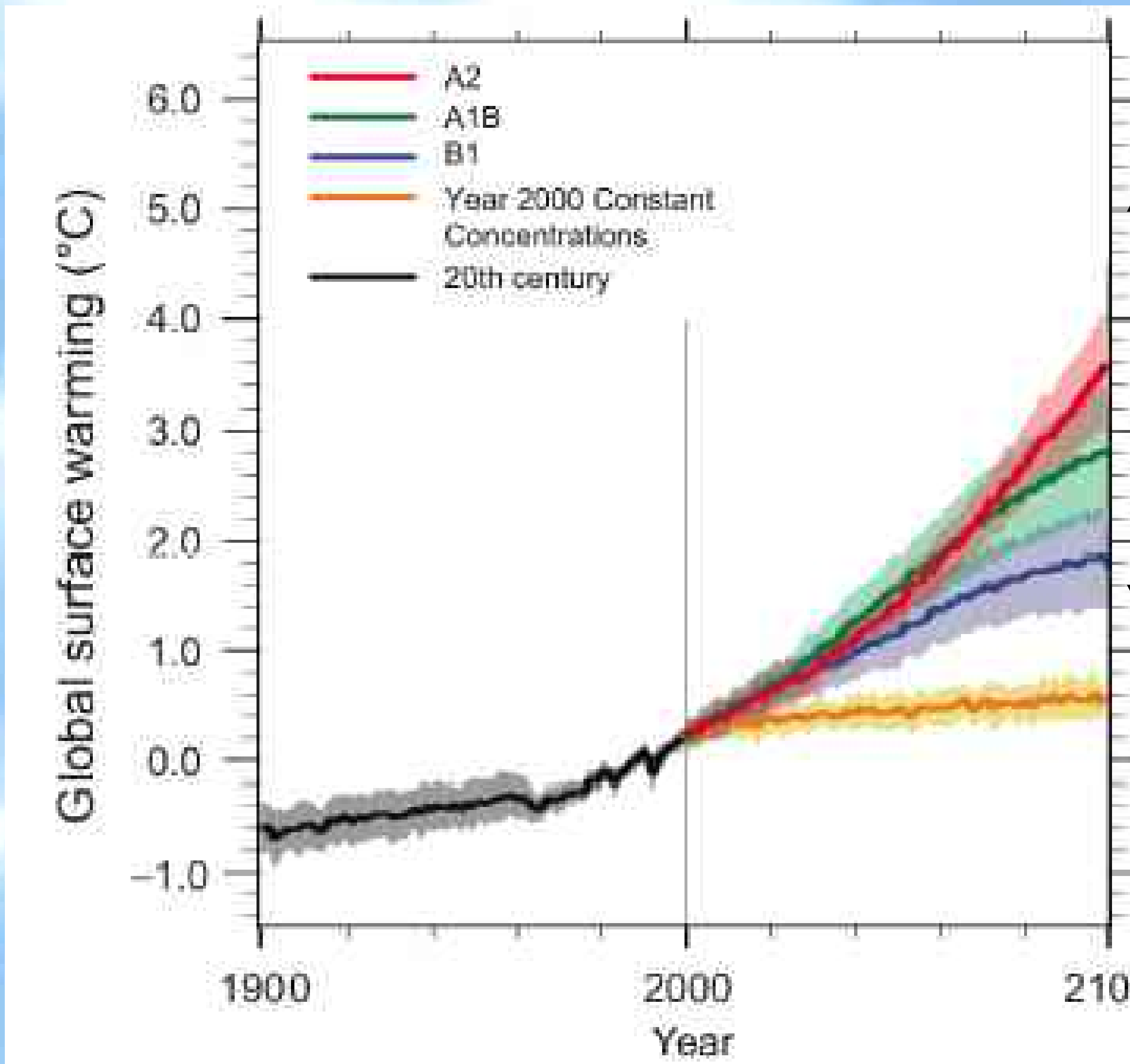
Climate Change

- Amount of warming
- Changes in water cycle

Precipitation responses to climate change



Warming due to range of IPCC future emissions



Likely range for A2, A1B, B1 scenarios:

1.1-5.4^{o}C

- Predicted magnitude of climate change has a very large range because of:
  - Uncertainty in future emissions
  - Uncertainty in climate feedbacks

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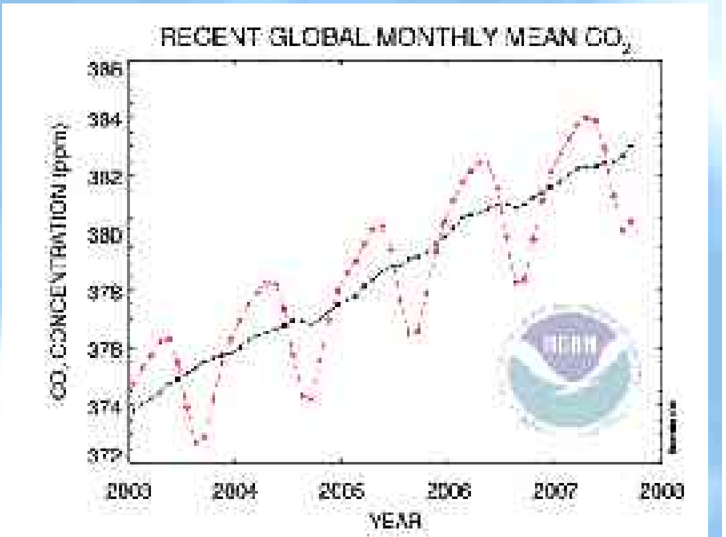
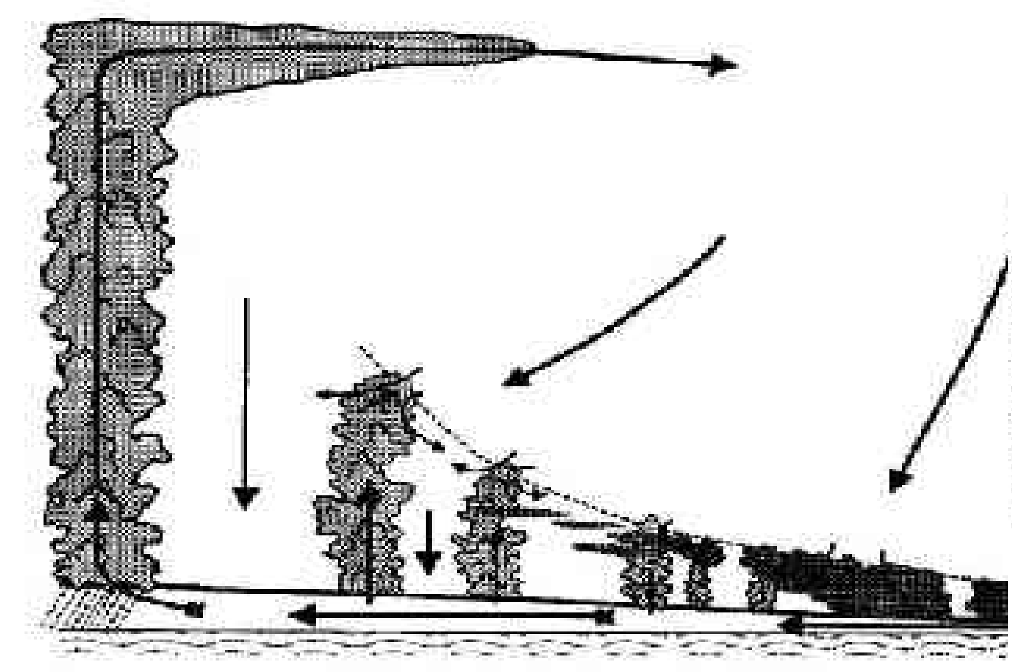
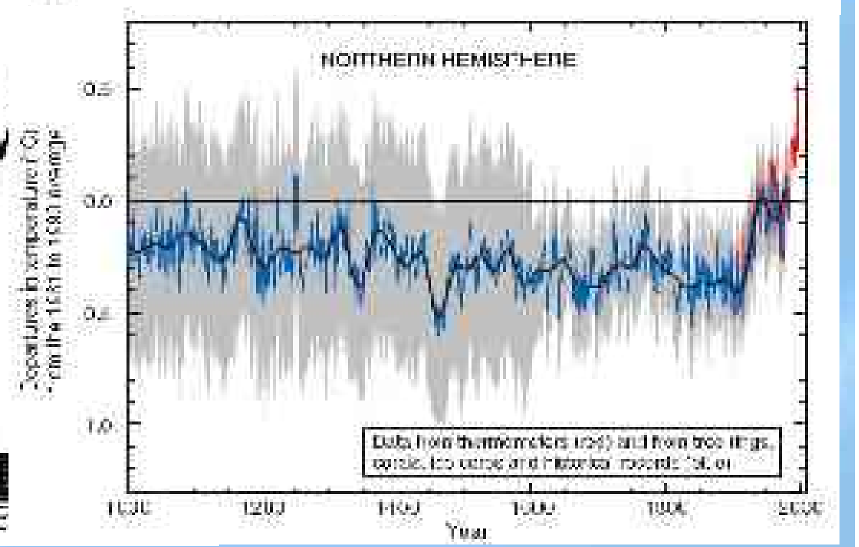
Uncertainty in Cloud Feedback

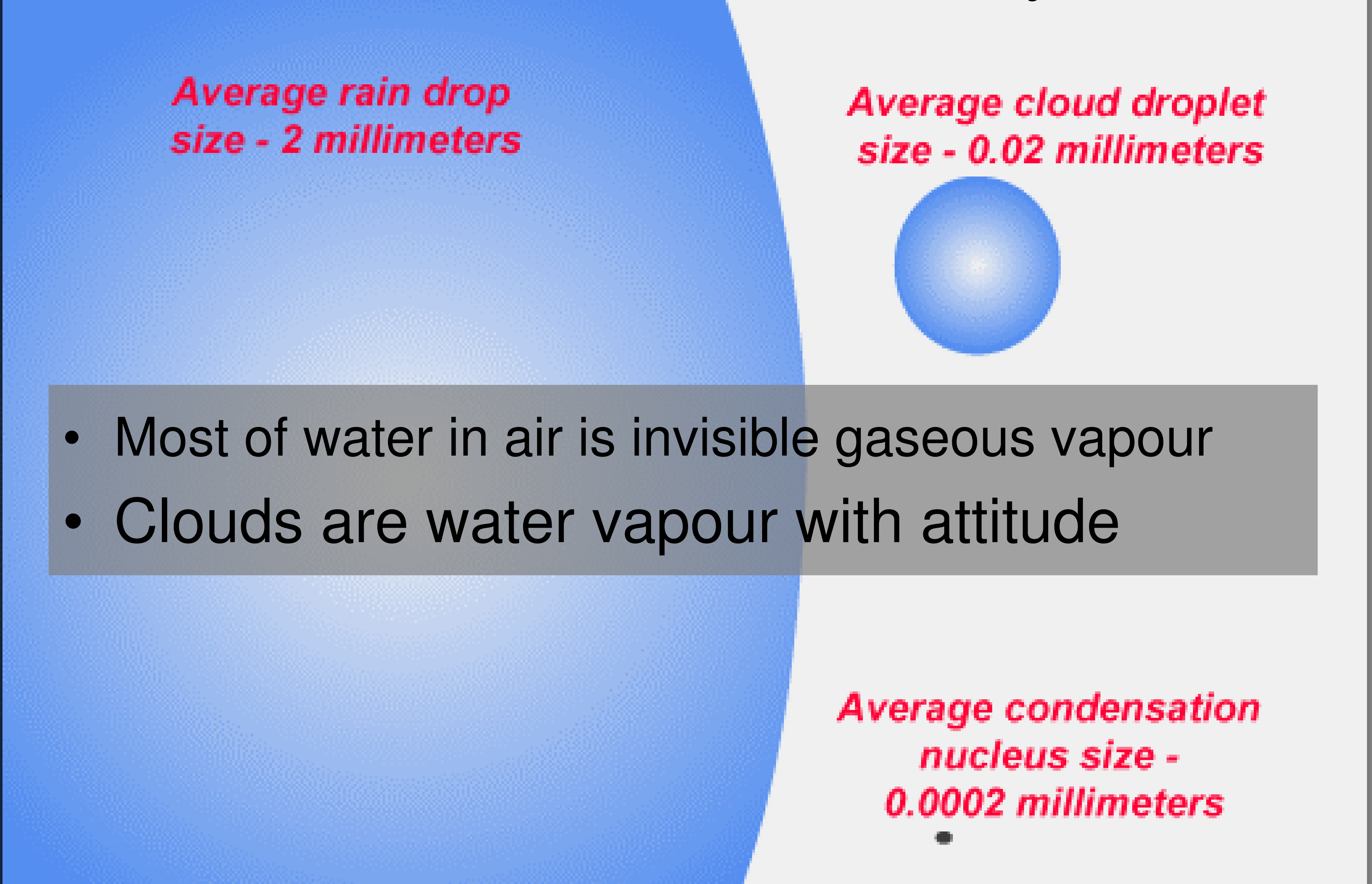
- How will clouds respond to anthropogenic climate change??





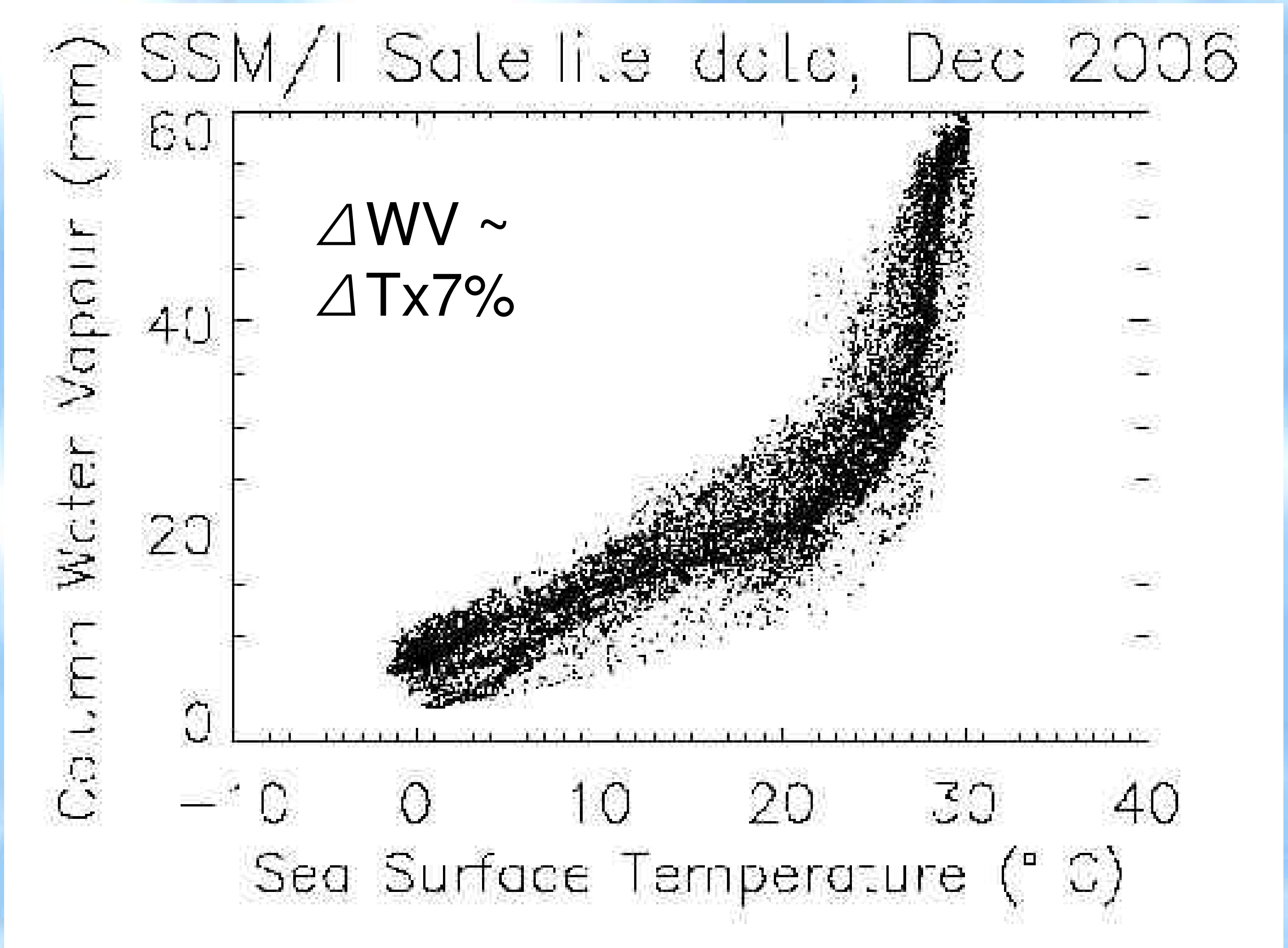


Clouds Revision: What, Why & How?



- Most of water in air is invisible gaseous vapour
- Clouds are water vapour with attitude

Warmer air can hold more water vapour

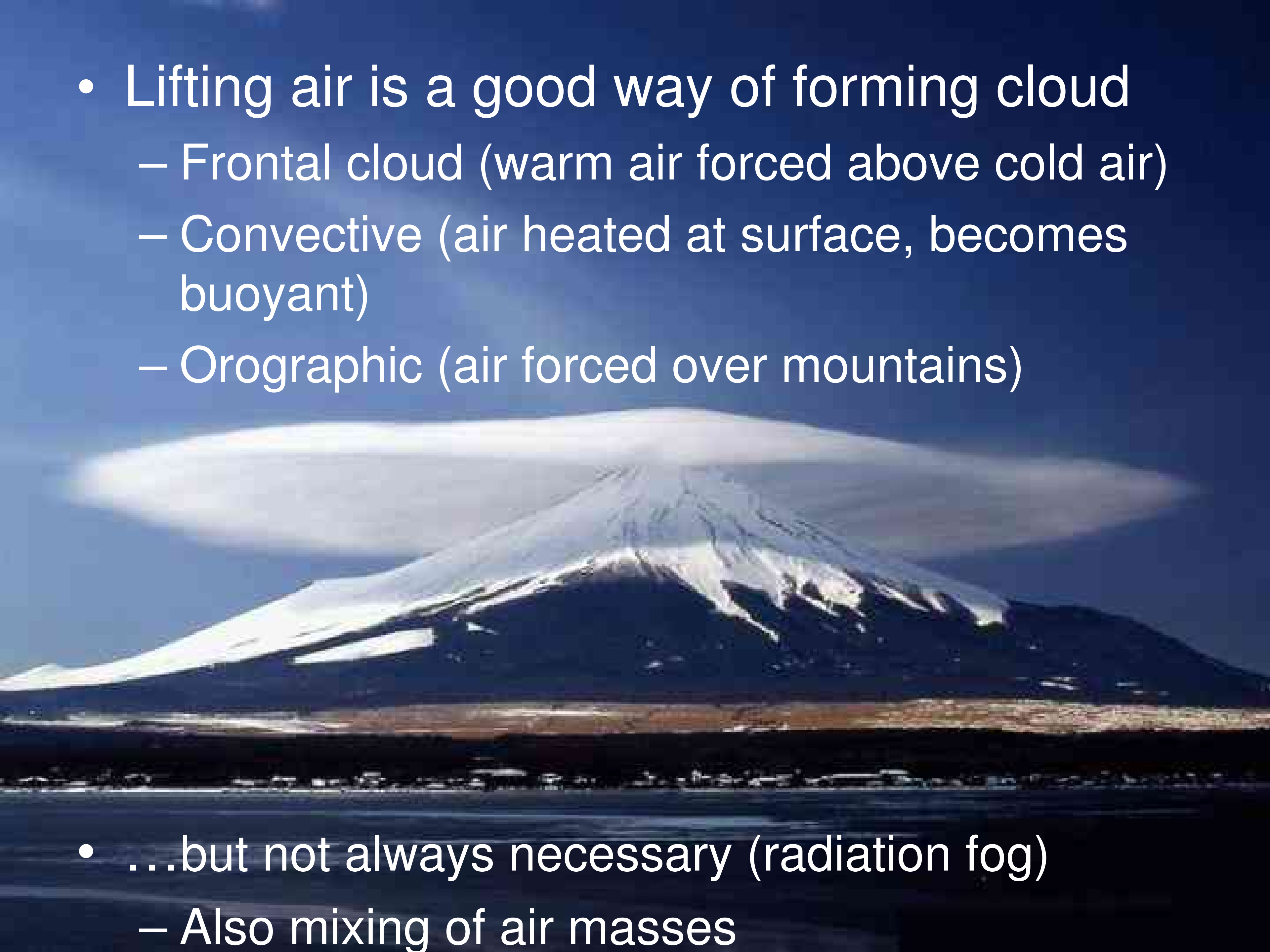


How do clouds form?

- For clouds to form, the water vapour amount in the air must surpass the saturation threshold (100% RH)
- This can be achieved by:
  - Adding more water vapour
  - Cooling the air

Cloud Formation

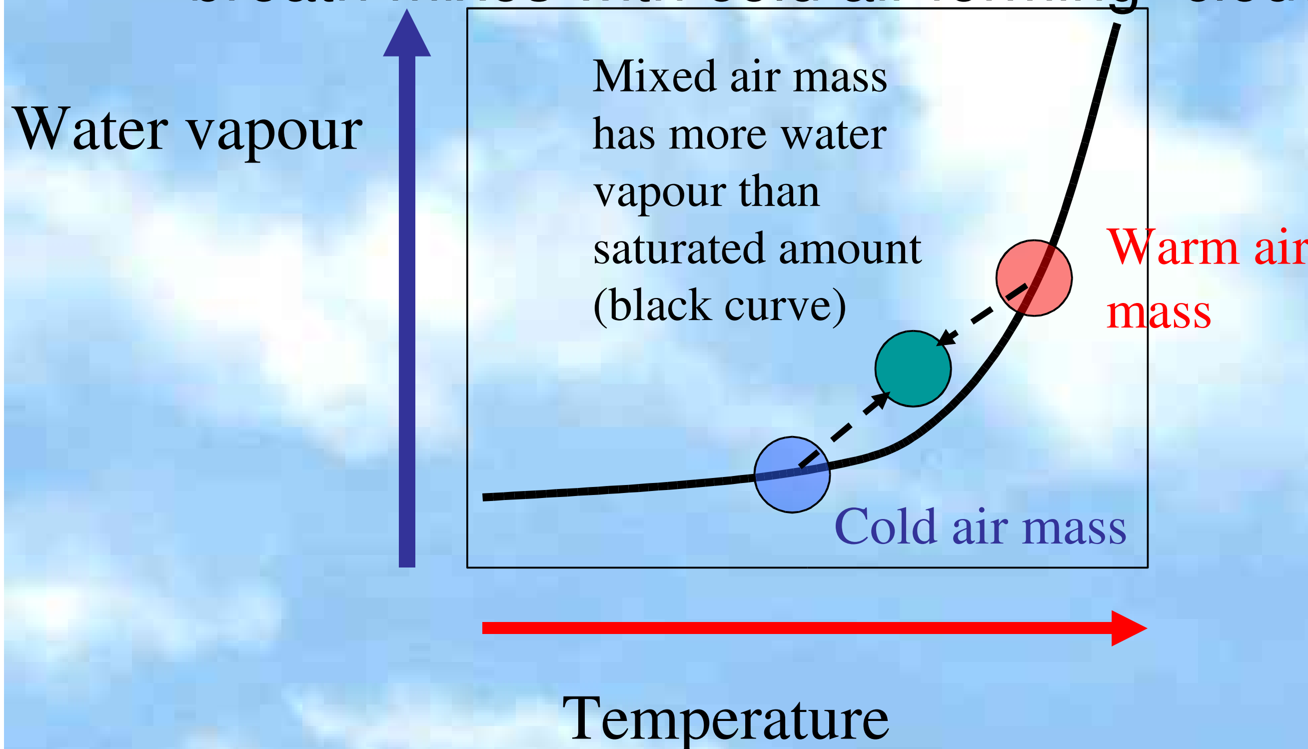
- Air that is lifted cools because the air pressure drops (adiabatic expansion)



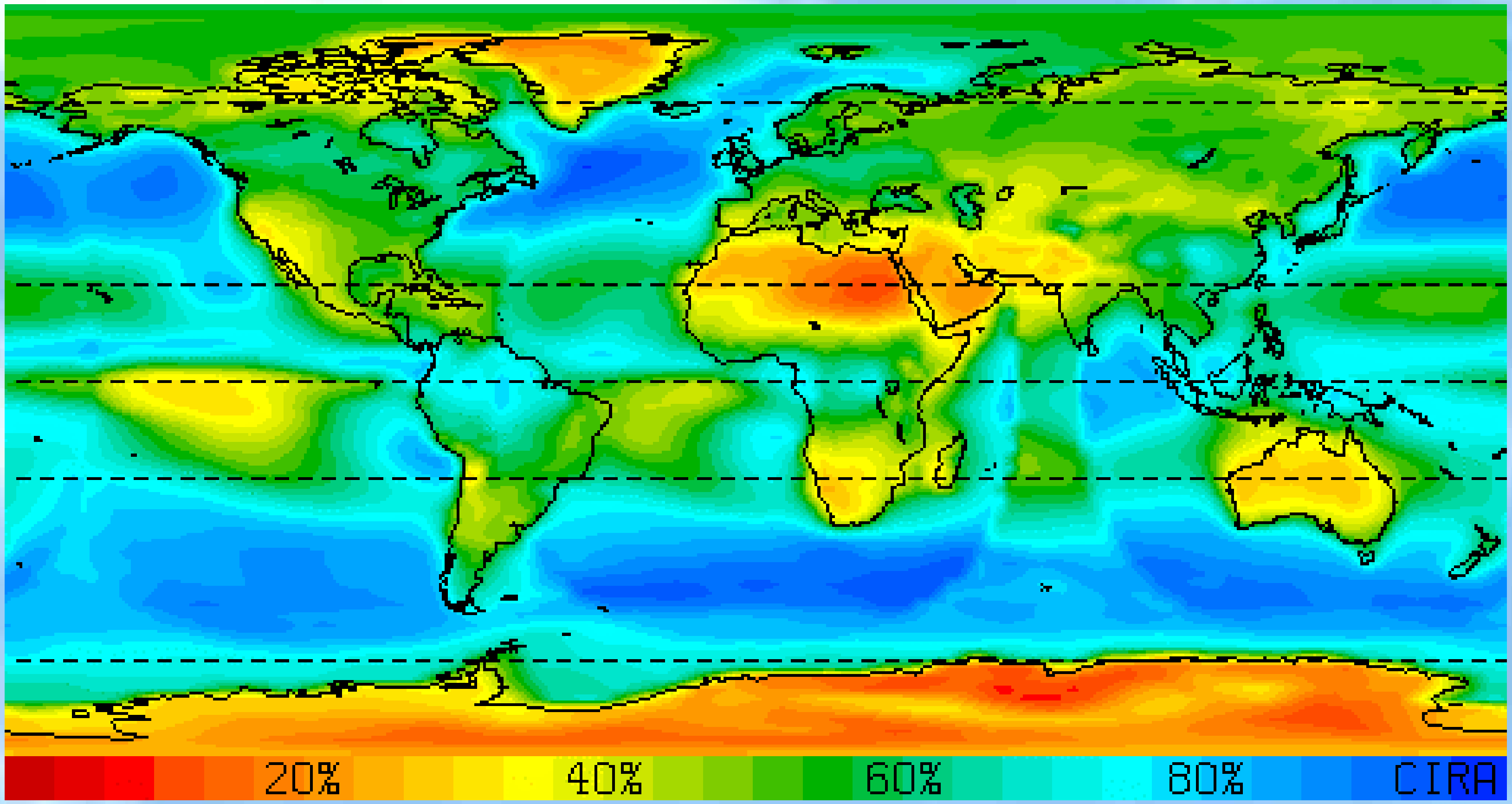
- Lifting air is a good way of forming cloud
  - Frontal cloud (warm air forced above cold air)
  - Convective (air heated at surface, becomes buoyant)
  - Orographic (air forced over mountains)
- …but not always necessary (radiation fog)
  - Also mixing of air masses

“Man-made clouds”

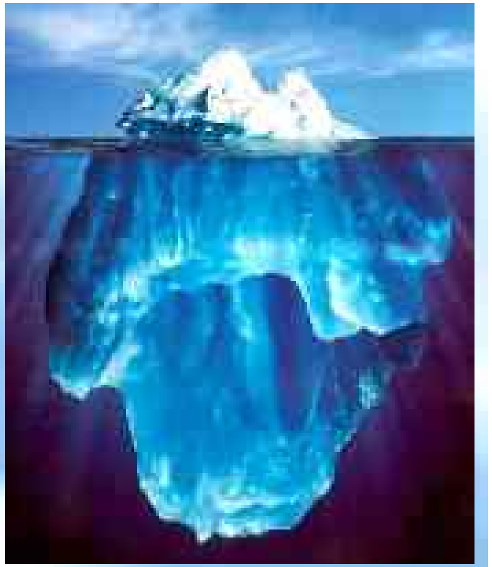
- Mixing air masses can increase humidity
  - e.g. when we breath out on a cold day, our warm moist breath mixes with cold air forming “cloud”



What is the global average cloud fraction?

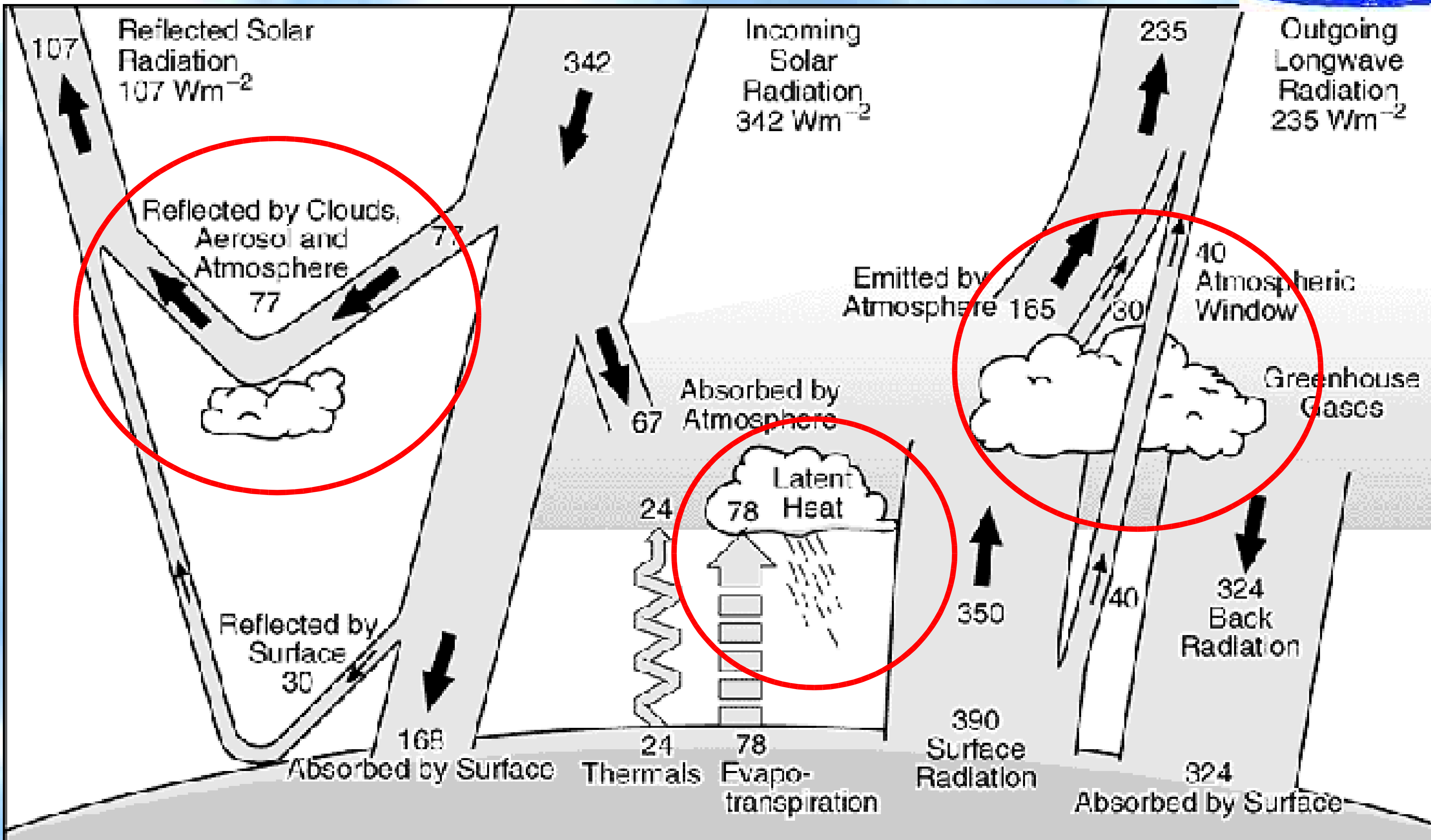


Radiative Impact of Cloud

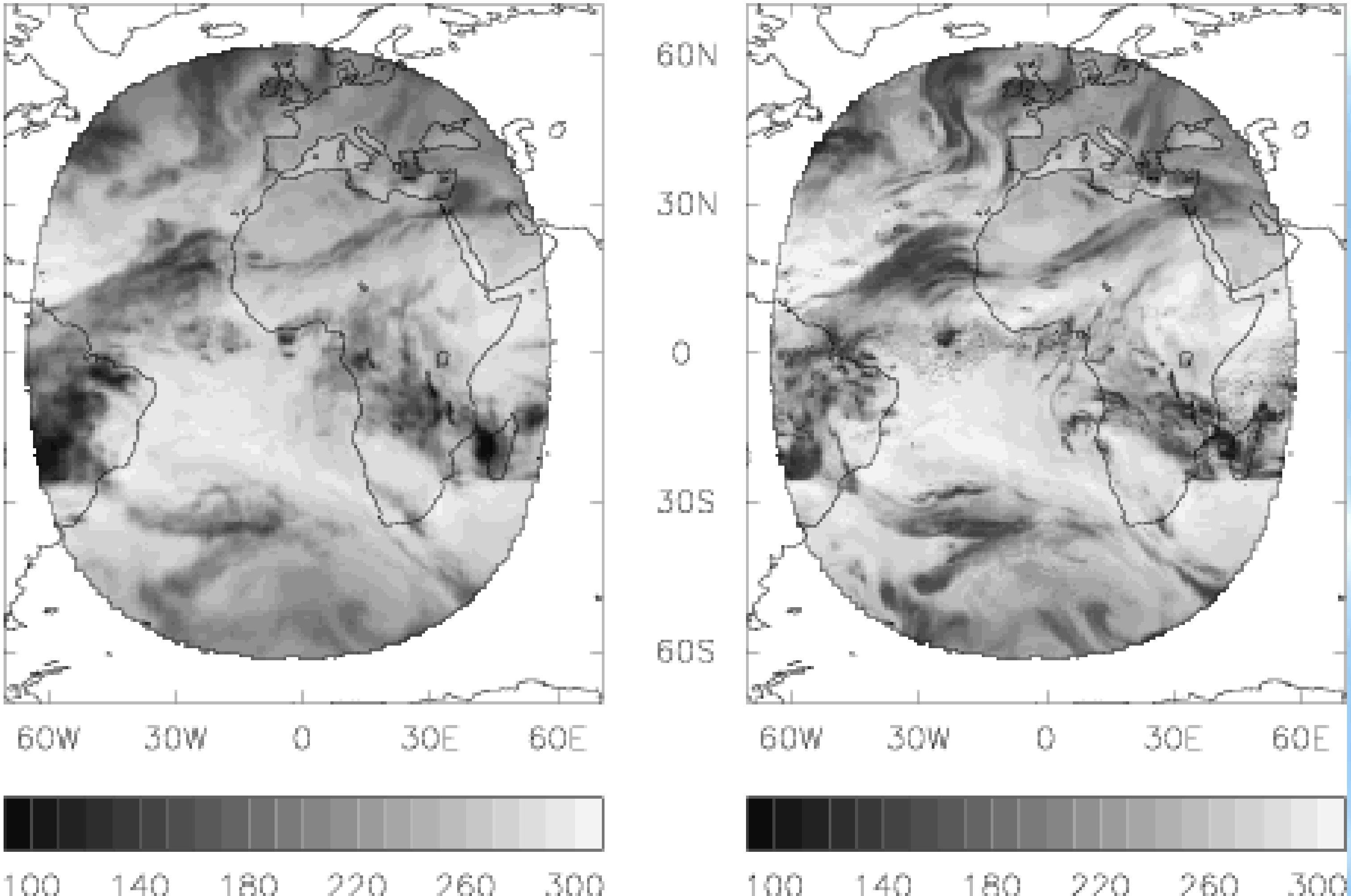


- Most of the water in the atmosphere is invisible vapour
  - Clouds are like the tip of the iceberg
- Clouds are water vapour with attitude
- Strong interaction with longwave and shortwave radiation (emission, absorption, scattering)

Global energy balance

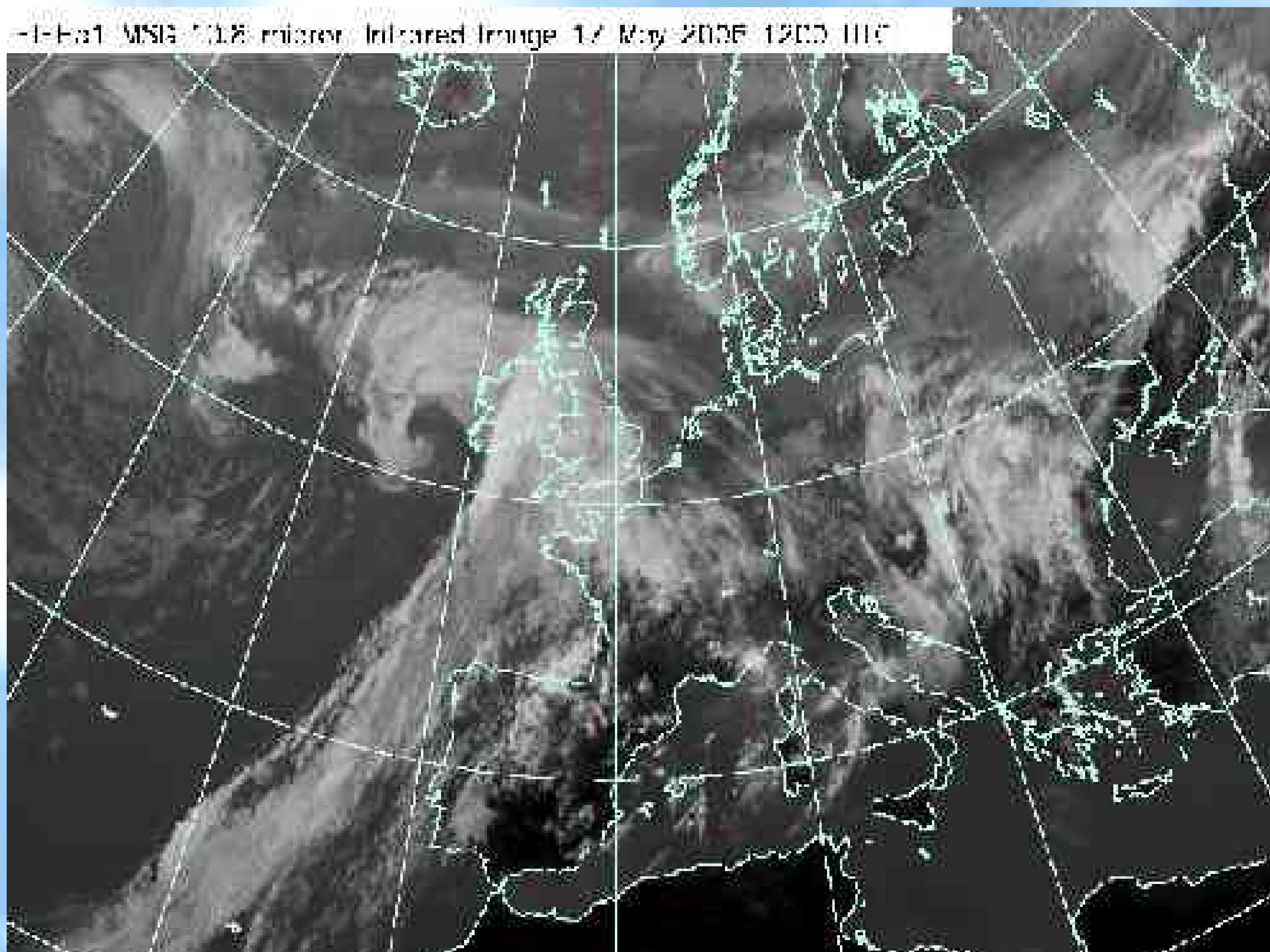


January 2008 OLR Animation

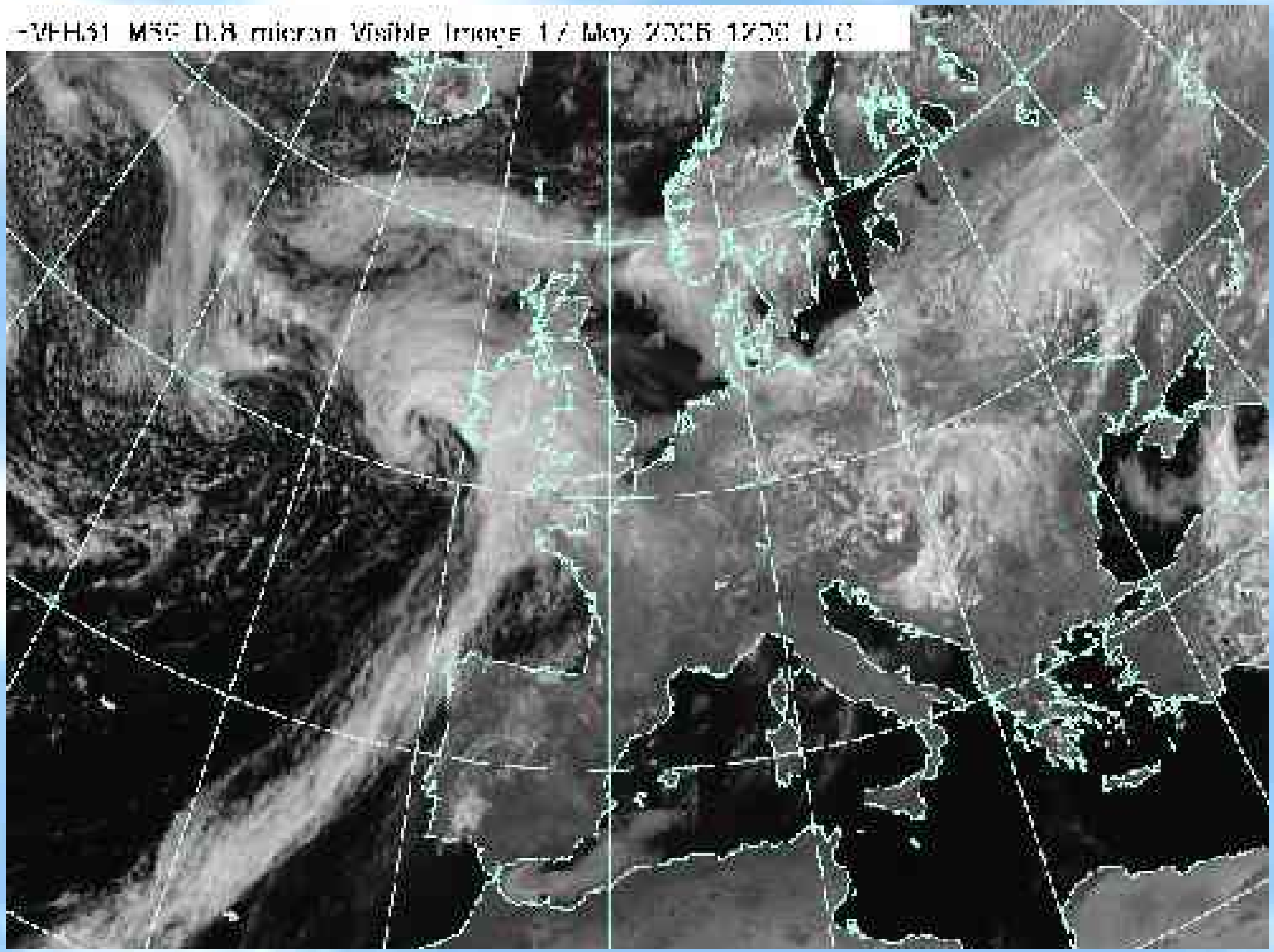


Outgoing thermal/longwave radiation to space

Infra-red/thermal radiation

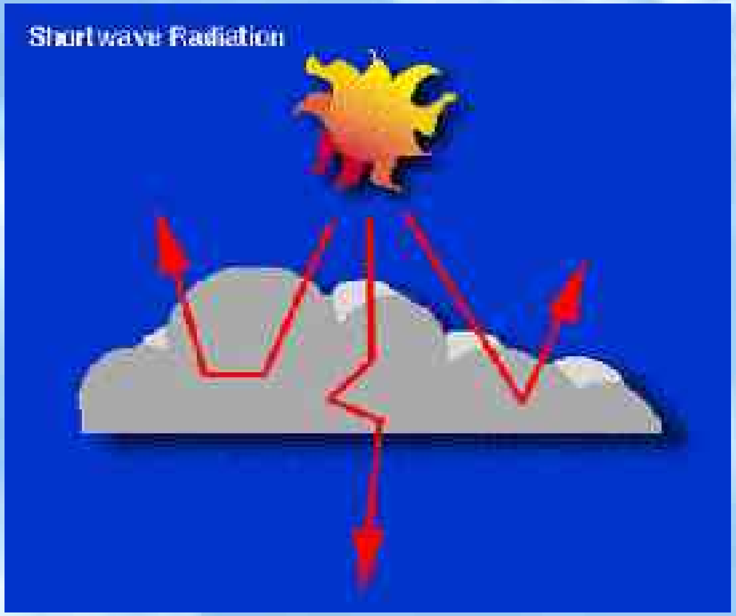


Visible/solar reflected radiation



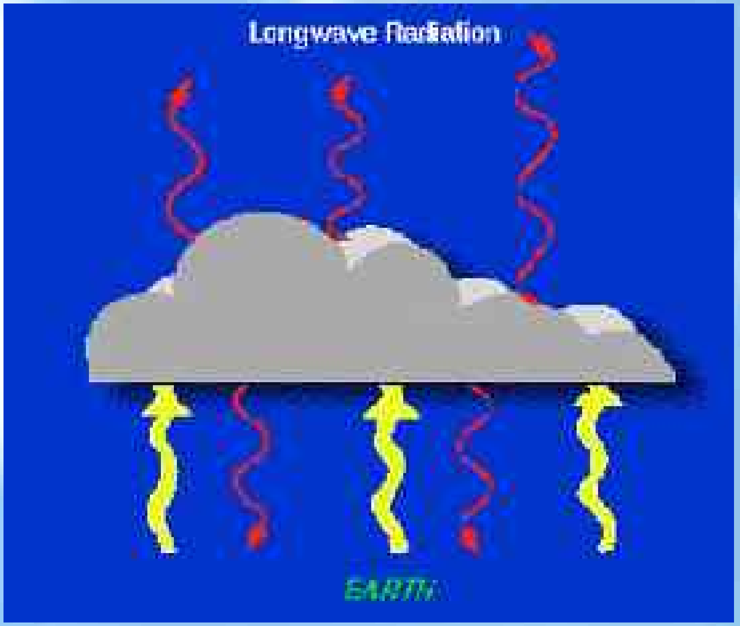
The two competing effects of clouds:

Cooling



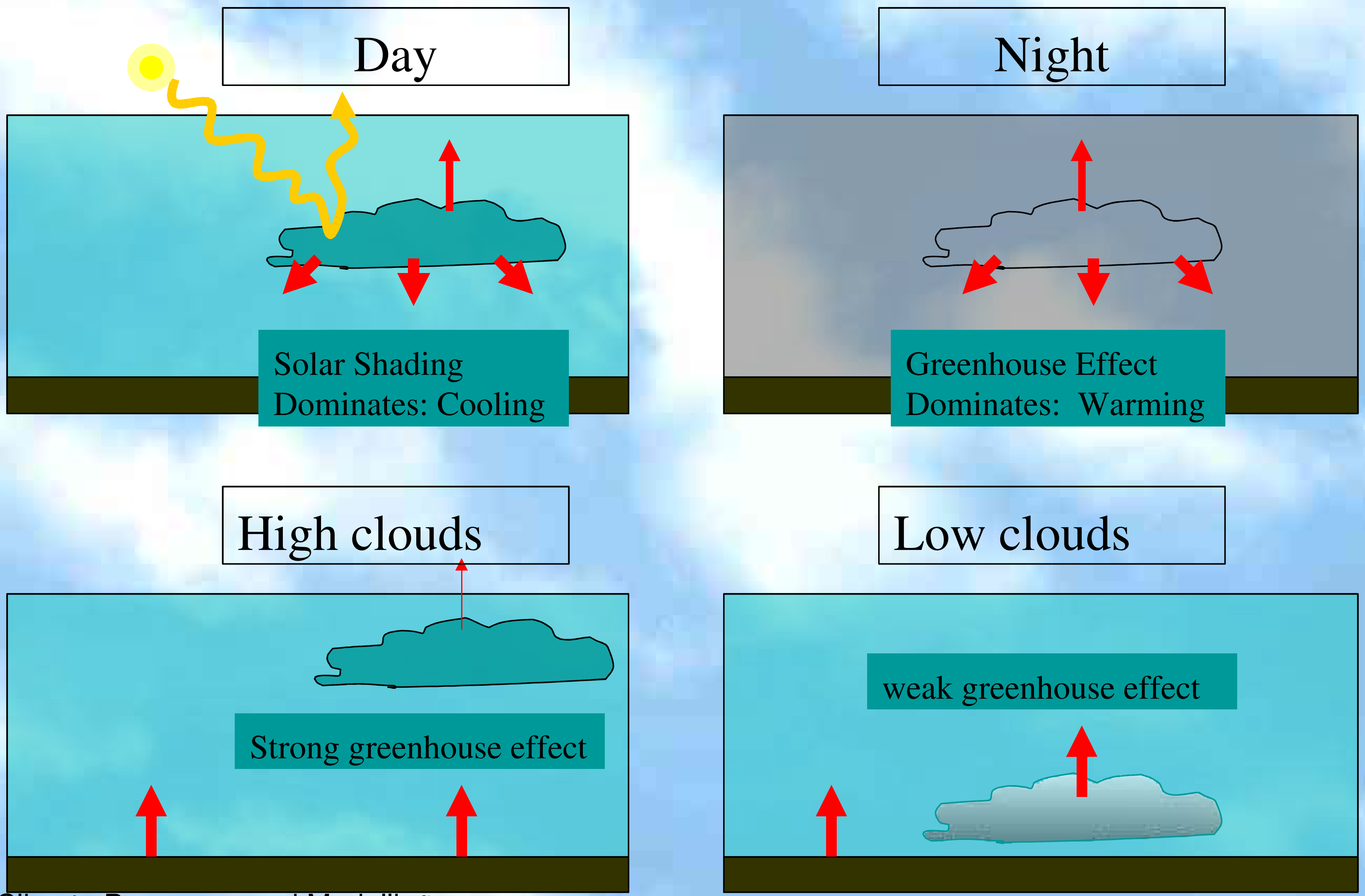
Cloud albedo effect

Warming

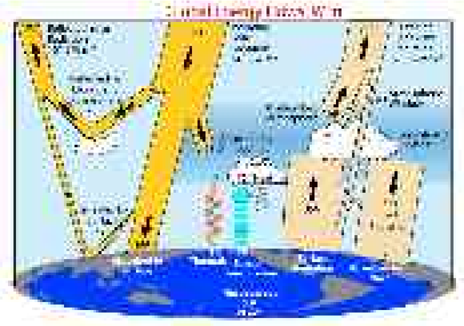


Cloud greenhouse forcing

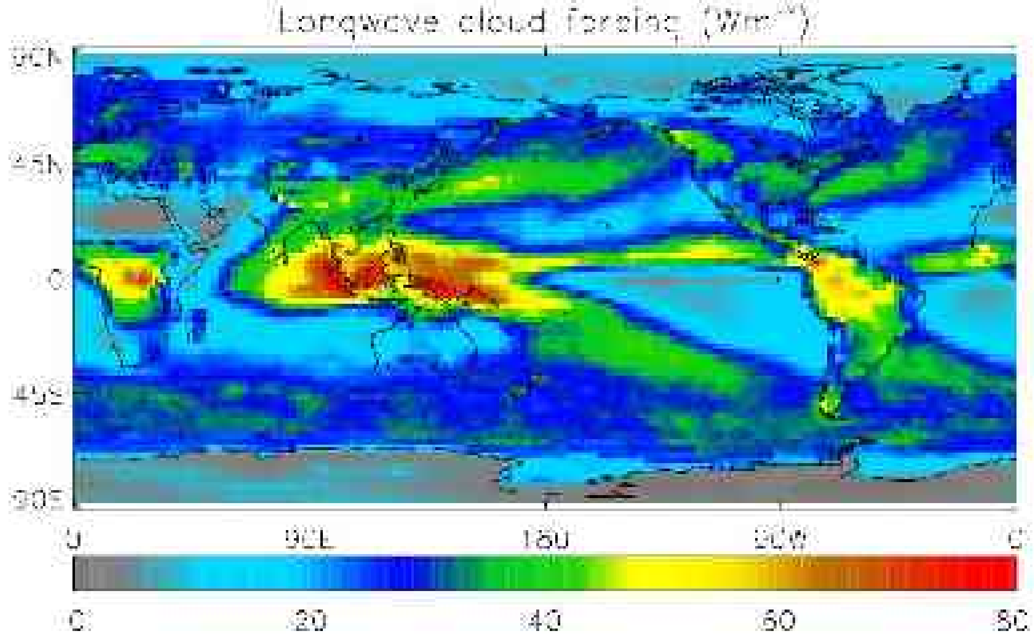
Radiative effect of clouds

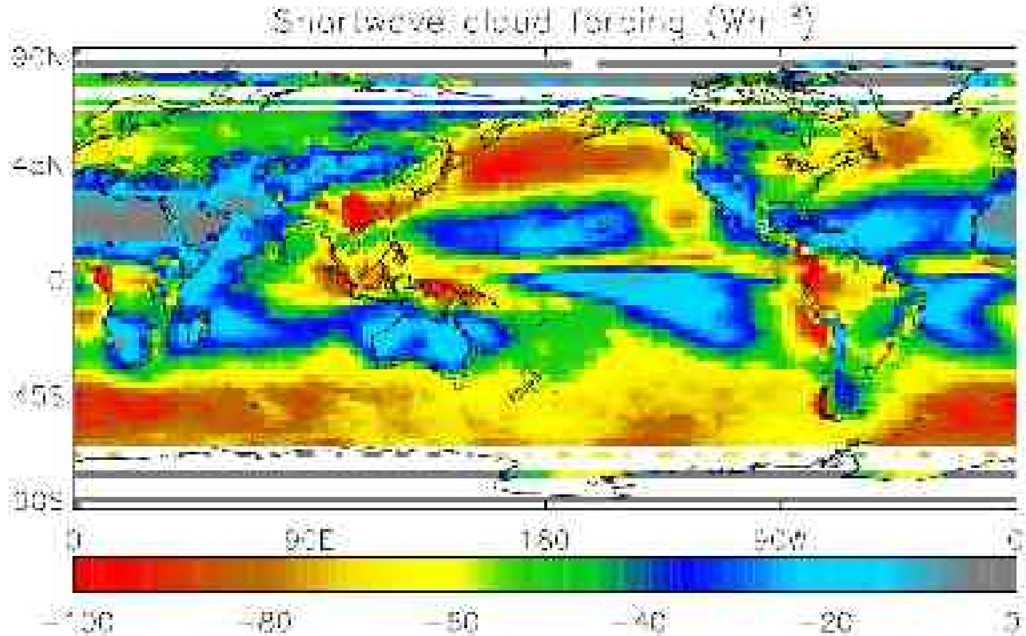


Global effect of clouds on radiation balance



- Satellite observations show that clouds exert a net cooling effect on the present climate (e.g. Ramanathan et al. 1989)
  - Calculated from differences between cloudy-sky and clear-sky radiative fluxes to space
  - thermal effect warms planet by ~30 Wm^{-2}
  - Solar shading cools planet by ~50 Wm^{-2}
  - Net cooling of ~20 Wm^{-2}
    - ~10% of clear-sky greenhouse effect





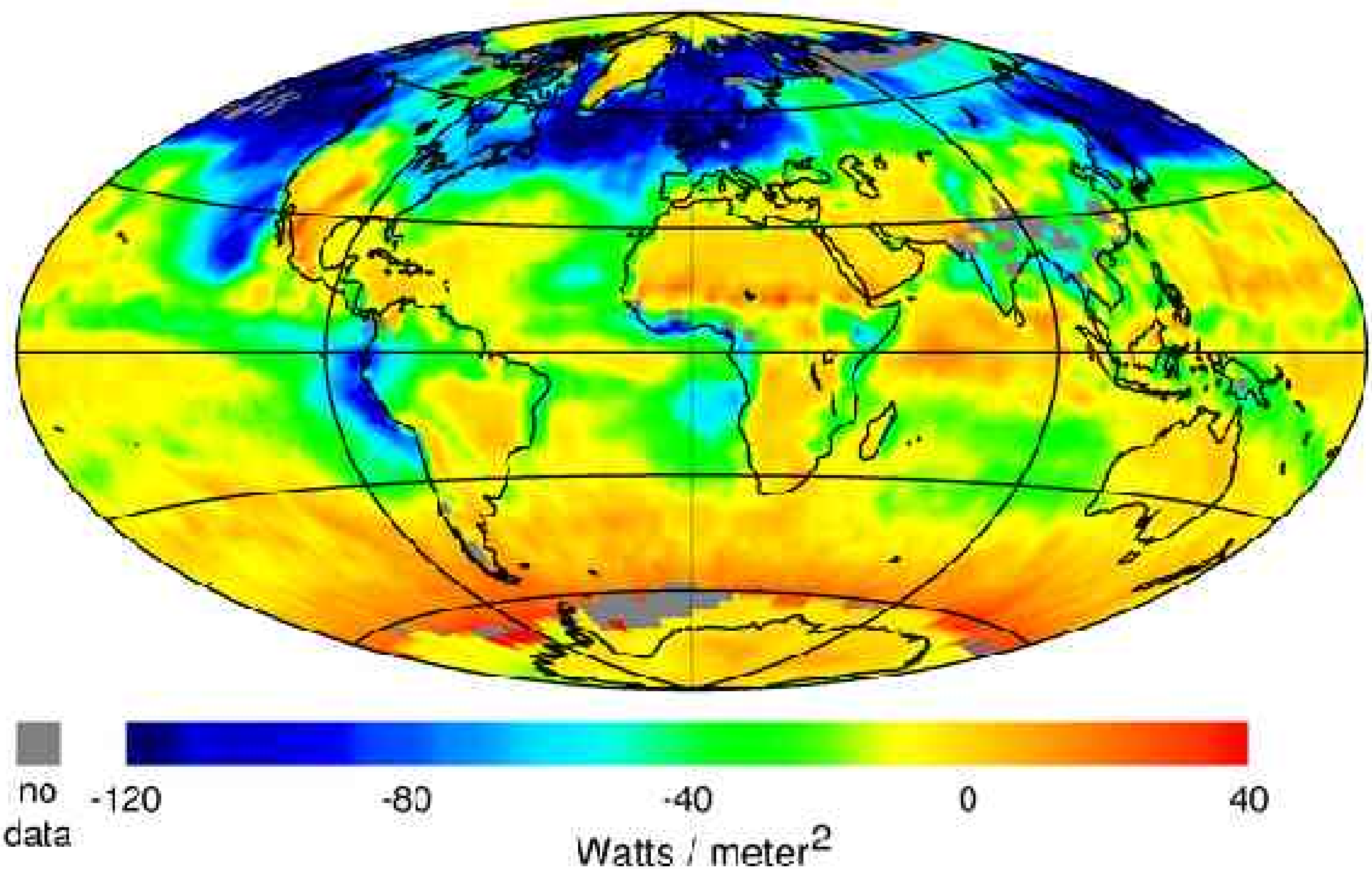
Recent CERES satellite data, 2001

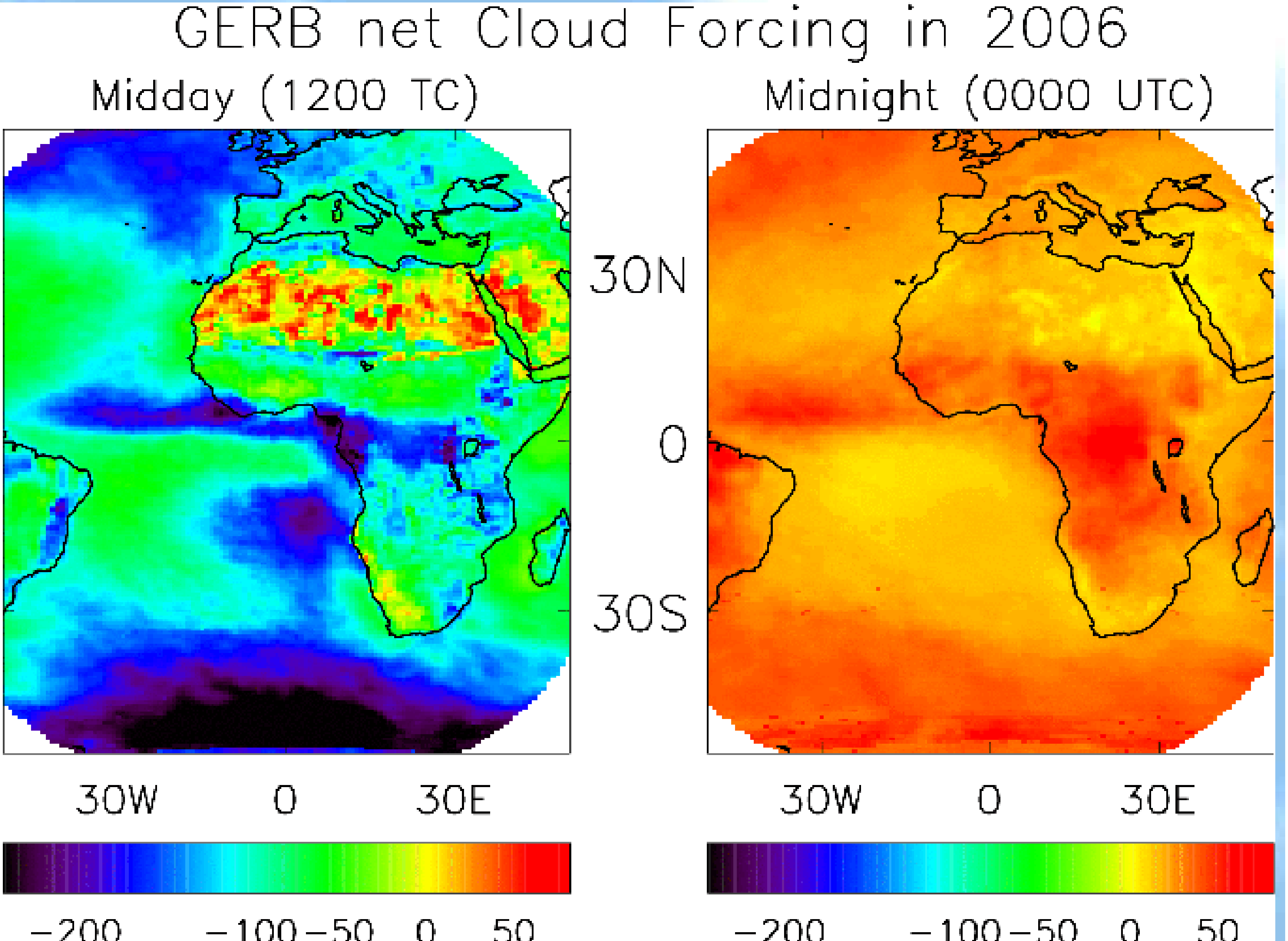
Thermal heating effect of clouds (top)

Solar cooling effect of clouds (bottom)

Reds signify strongest cloud effect while blues and greys signify a small cloud radiative effect

Net Cloud Forcing from CERES/Terra
July 2000





GERB net Cloud Forcing in 2006
Midday (1200 TC)
Midnight (0000 UTC)
30N
0
30S
30W
0
30E
30W
0
30E
−200
−100
−50
0
50
−200
−100
−50
0
50

Forcing and response: a natural experiment


29/3/06 11.05am
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29/3/06 12.26pm

- Clouds affect radiation fluxes

Radiation fluxes affect clouds

Revision: feedbacks

- Two primary requirements for cloud feedback

(1) Clouds respond to changes in temperature

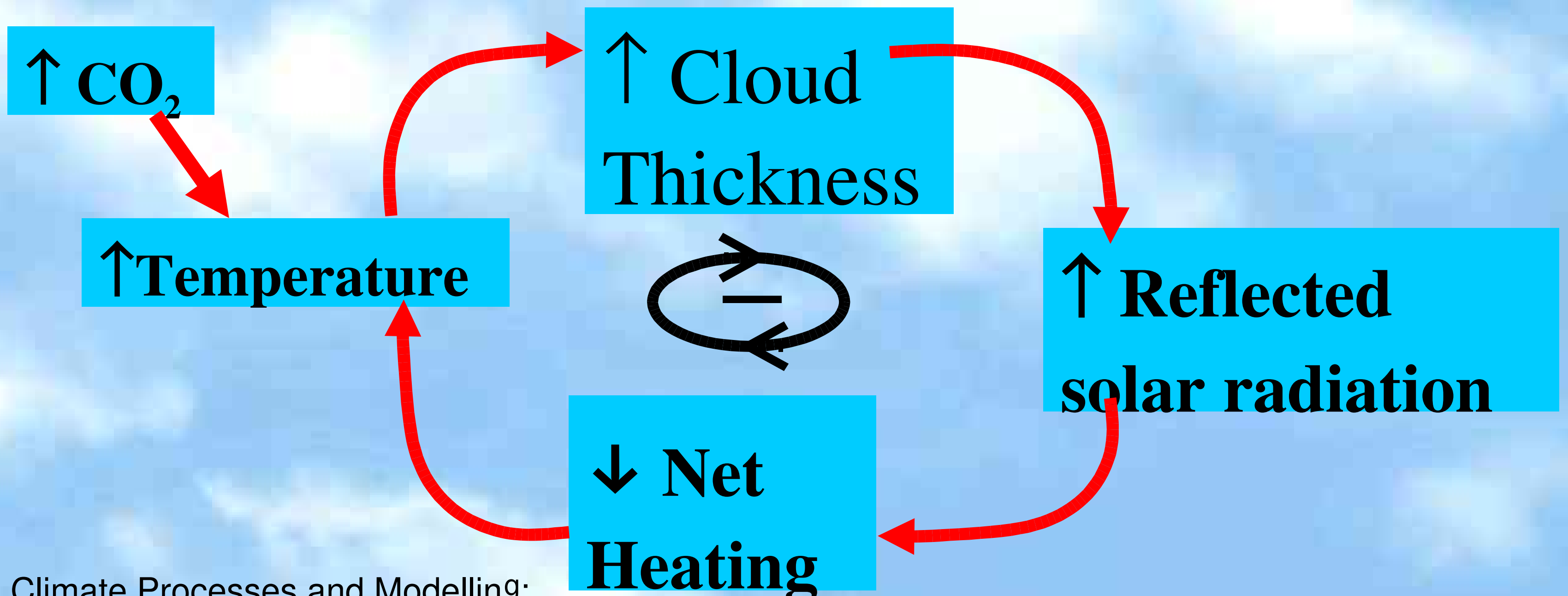
e.g. temperature rises in response to increased CO_2 cause an increase in cloud thickness

(2) Changes in cloud alter the radiative heating of the system

e.g. increased cloud thickness causes brightening of planet and hence cooling

Radiative Forcing and Feedbacks

- Increase in CO_2 → reduced OLR → heating
- Increased T to balance radiative forcing
- <u>Cloud feedback</u>: example…



Quantifying Feedbacks

$$\Delta R = \Delta Q + \lambda \Delta T_s$$

Net top of atmosphere radiation

Radiative forcing

Climate sensitivity

surface temperature

$$\Delta Q = -\lambda \Delta T_s$$

At equilibrium

Quantifying Feedbacks

Climate Sensitivity parameter

$$\lambda = \frac{\partial R}{\partial T_s} + \sum_x \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s} + \sum_x \sum_y \frac{\partial^2 R}{\partial x \partial y}\frac{\partial x \partial y}{\partial T_s^2} + \cdots$$

Black body feedback

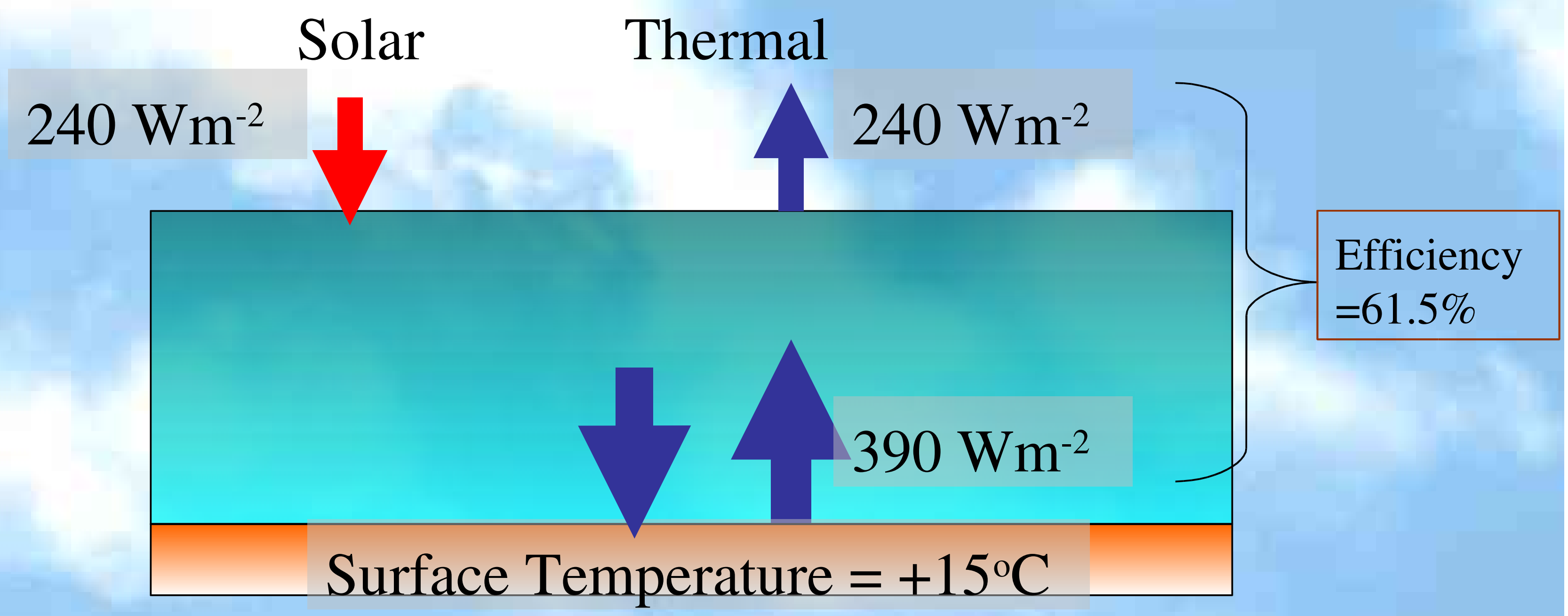
x denotes feedback variable, e.g. cloud, water vapour, ice-albedo, etc

$$\frac{\partial R}{\partial T_s} \approx -4\sigma T^3$$

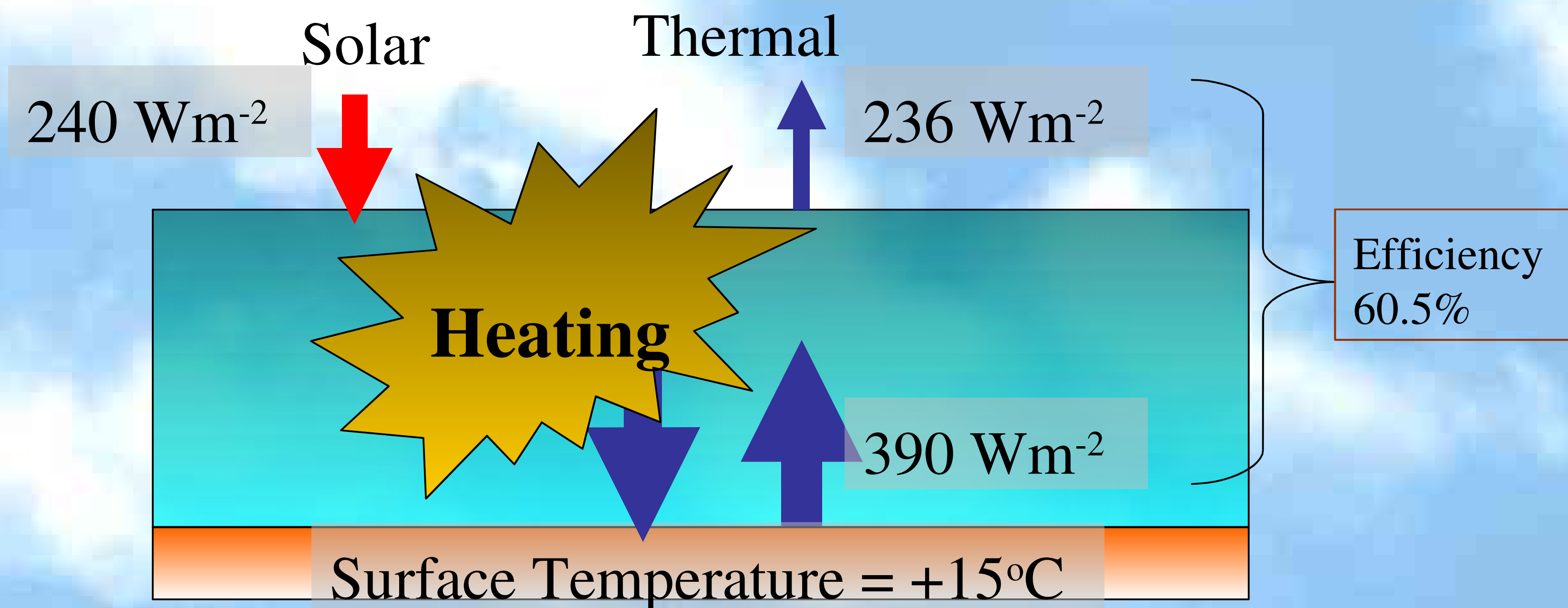
Black body feedback ~ -3.8 $Wm^{-2}K^{-1}$ assuming T=255 K

(using GCMs ~ -3.2 $Wm^{-2}K^{-1}$)

Earth's global average energy balance: present day



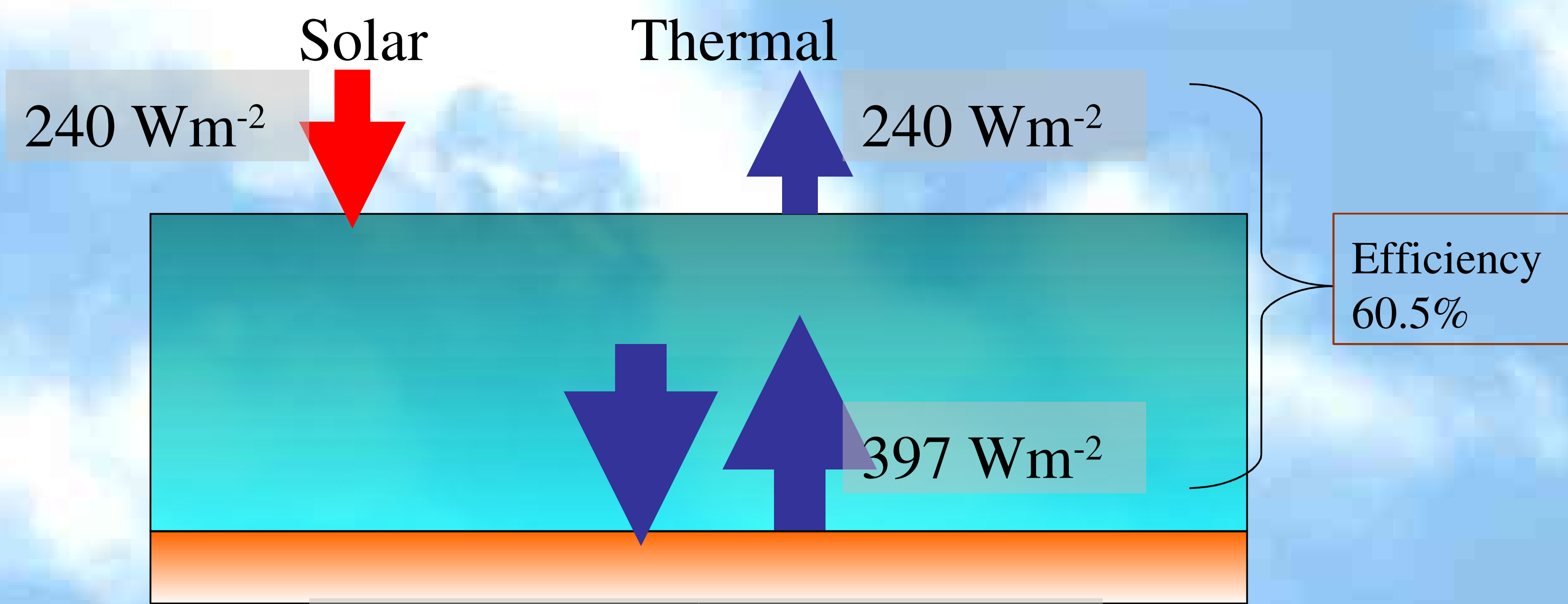
Earth's global average energy balance: present day, 2xCO_2



$\Delta Q_{CO2} \sim 5.35\ln(CO2/CO2\_base) = 5.35\ln(2)$

$\Delta Q_{CO2} \sim$ **3.7 Wm^{-2}**

Earth's global average energy balance: after warming (no feedbacks)



Surface Temperature = +16°C

$$\Delta Q = -\lambda \Delta T_s$$

$3.7 = -(-3.2)\,\Delta T$; $\mathbf{\Delta T \sim 1.2\ K}$

But, what happens with feedbacks?

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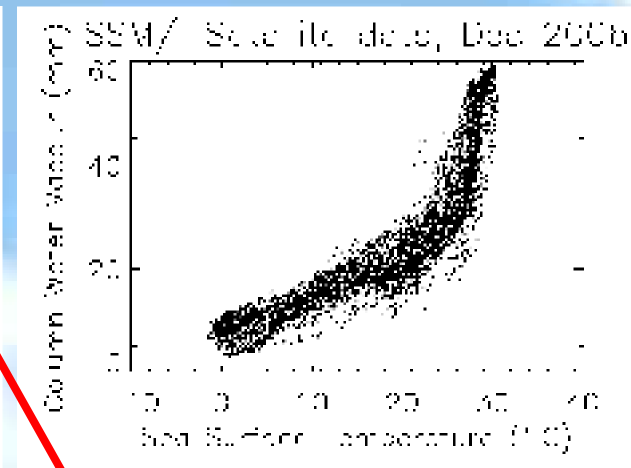
Example: Water vapour feedback

$$\frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s}$$



$0.2\ Wm^{-2}\%^{-1}$

$7\%K^{-1}$

$$\lambda_{WV} \sim (0.2)(7) = 1.4\ Wm^{-2}K^{-1}$$

$2xCO_2$ response + water vapour feedback

$$\Delta Q = -\lambda \Delta T_s$$

3.7 = – (-3.2+1.4) ΔT; **ΔT ~ 2 K**

So water vapour feedback approximately doubles no feedback temperature response to doubling of CO2

Including feedbacks from temperature lapse rate (negative), ice albedo (positive) and clouds (positive), models produce a best estimate **ΔT ~ 3 K**

Cloud feedback parameter

- In climate models, the "best" estimate cloud feedback parameter, $\lambda_{cld} \sim 0.7\ Wm^{-2}K^{-1}$
- But there is a big spread ($0.3\text{-}1.1\ Wm^{-2}K^{-1}$)
- This spread is the single largest contributor to uncertainty in climate sensitivity
- What is the real cloud feedback?

Cloud feedback: a more complex problem

$$\frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s}$$

- Depends on:
  - Type of cloud
  - Height of cloud
  - Time of day/year
  - Surface characteristics

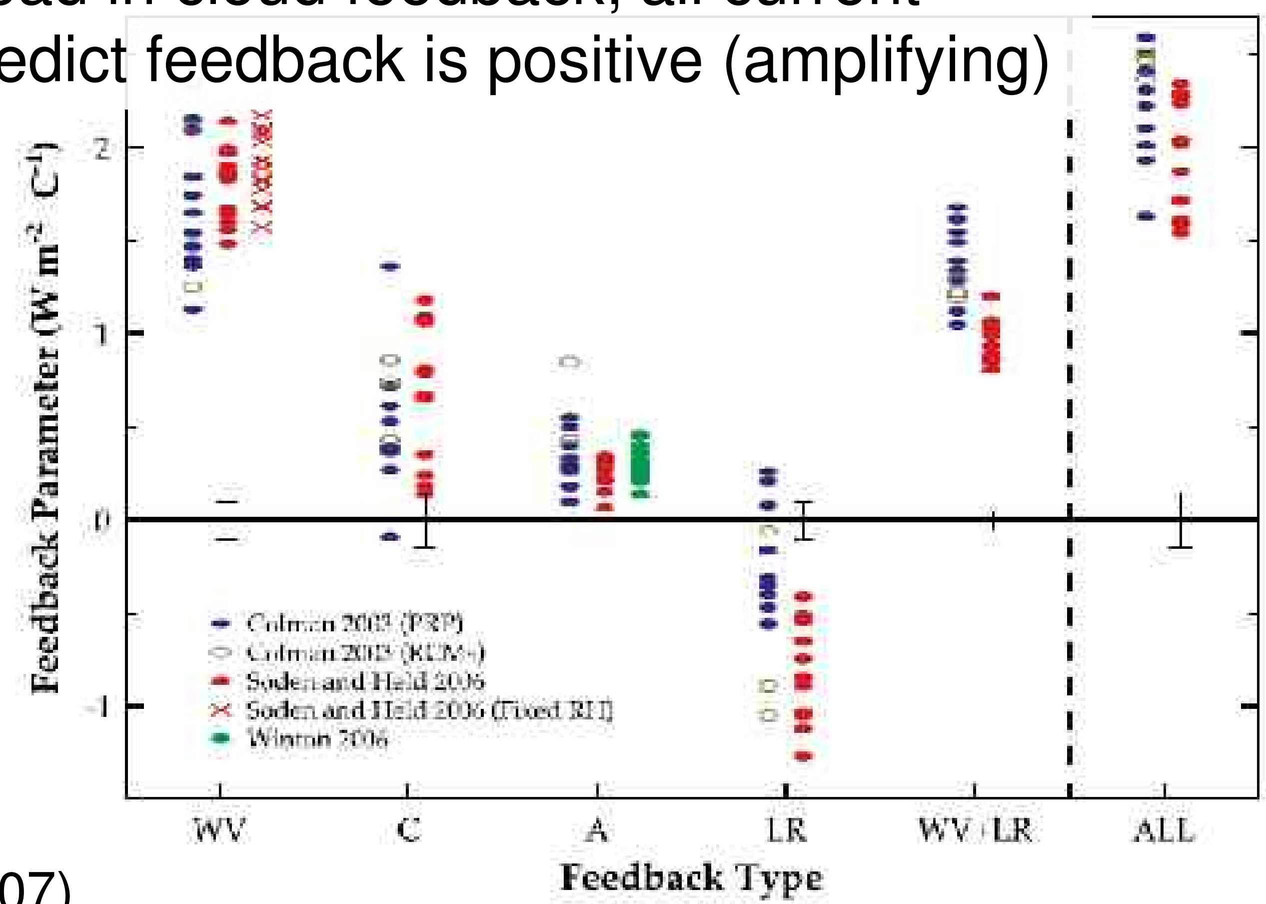
Non-trivial relationship between cloud and temperature

Response of cloud to warming is highly uncertain

What do the models tell us?

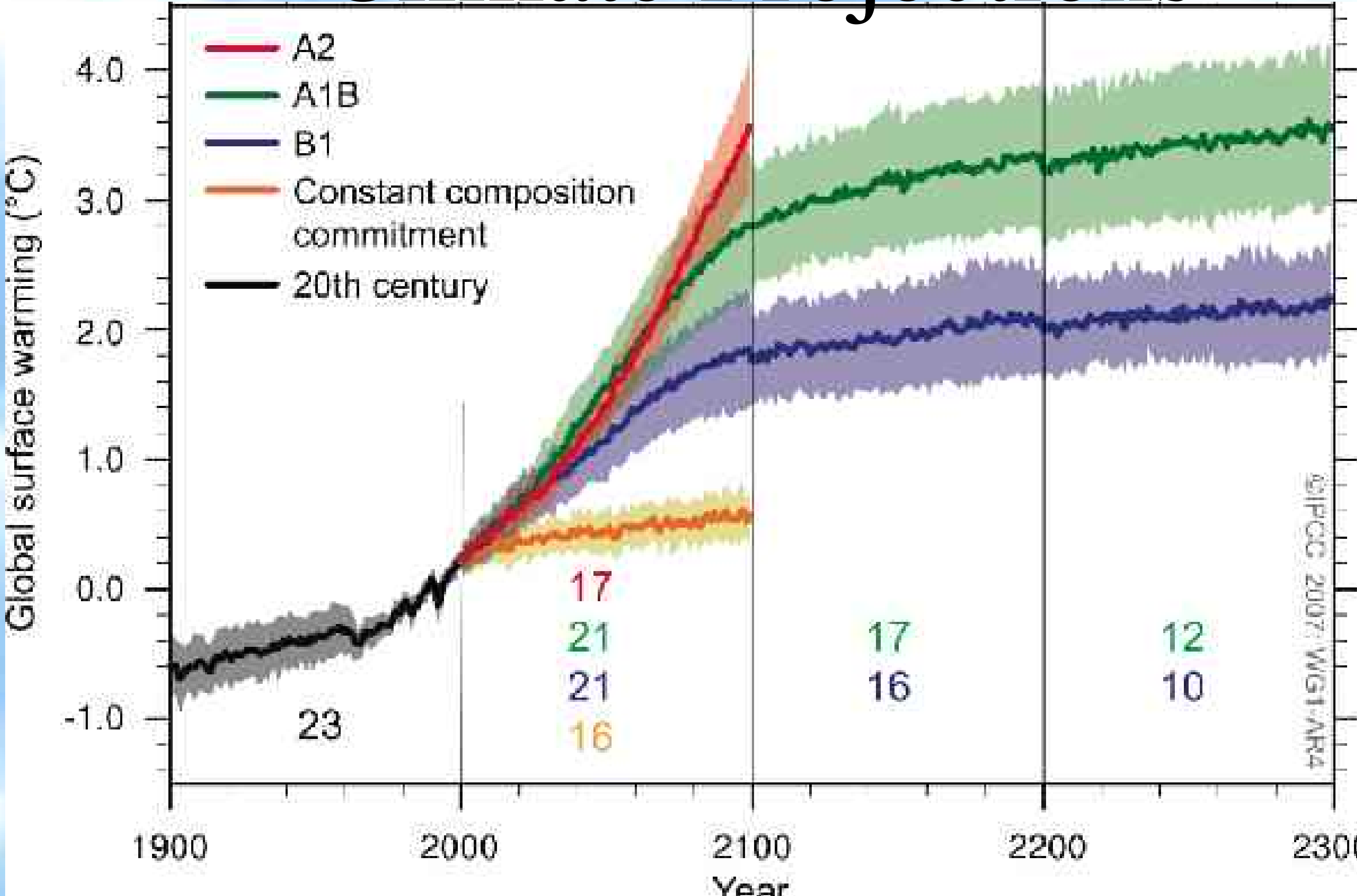
- Current climate models suggest that clouds generally enhance warming (positive feedback)
- But there is a large range in cloud feedback in the models, explaining much of the uncertainty in predictions of future warming
- …and we don’t know whether any model accurately represents cloud feedback

- Models agree on magnitude of positive feedbacks relating to ice-albedo and combined water vapour/temperature
- Large spread in cloud feedback; all current models predict feedback is positive (amplifying)



IPCC report (2007)

Climate Projections

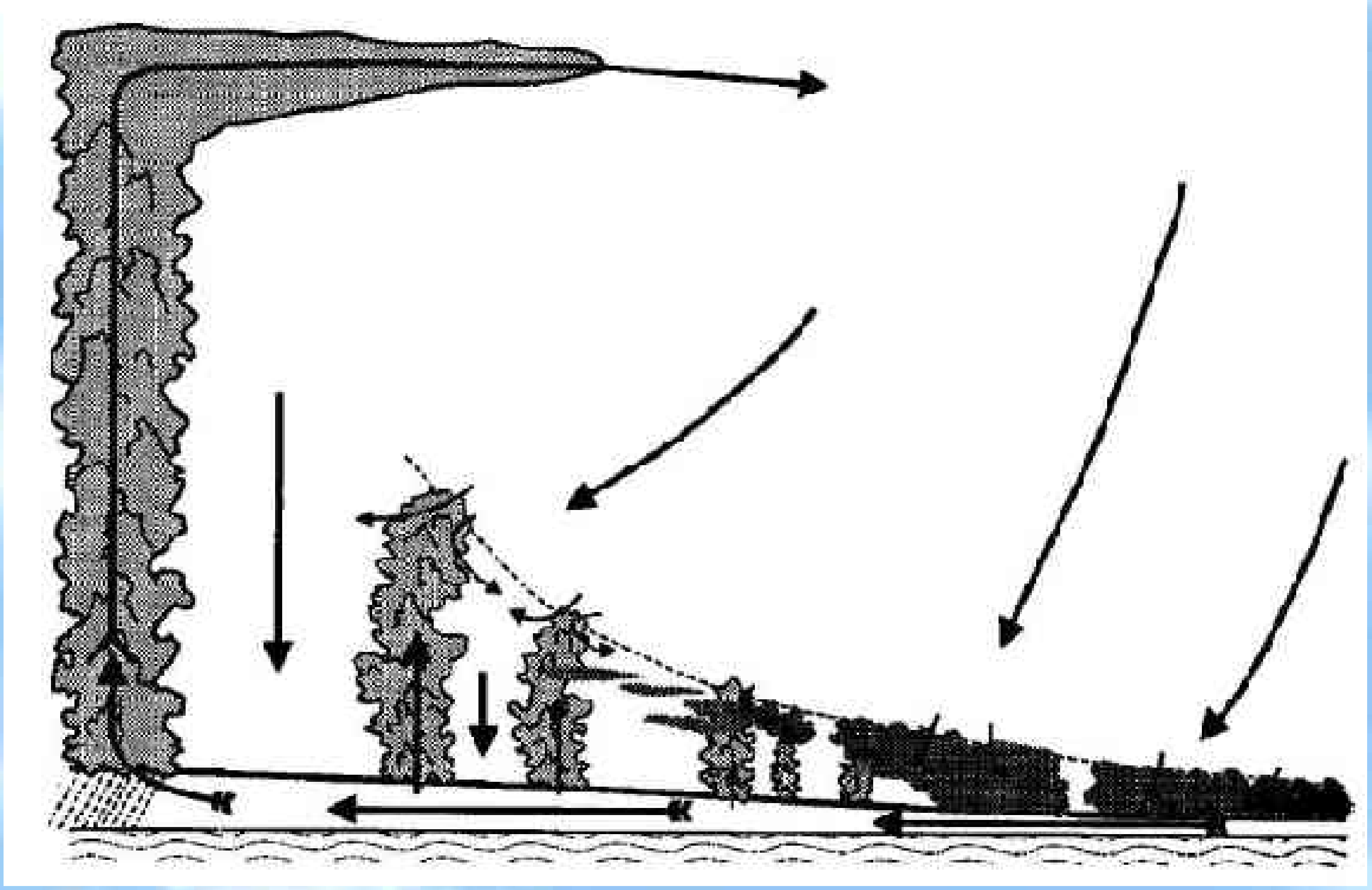


IPCC: www.ipcc.ch/ipccreports/ar4-wg1.htm

Tropical cloud feedbacks

- Deep convective and cirrus cloud
  - Small net cloud radiative effect
  - Large influence on surface/atmosphere energy and water budgets
- Boundary Layer Cloud
  - Large net cloud radiative effect
  - Extensive coverage
  - Sensitive to circulation and aerosol
- Mid-level and supercooled cloud
  - Ice to liquid phase crucial to radiative properties

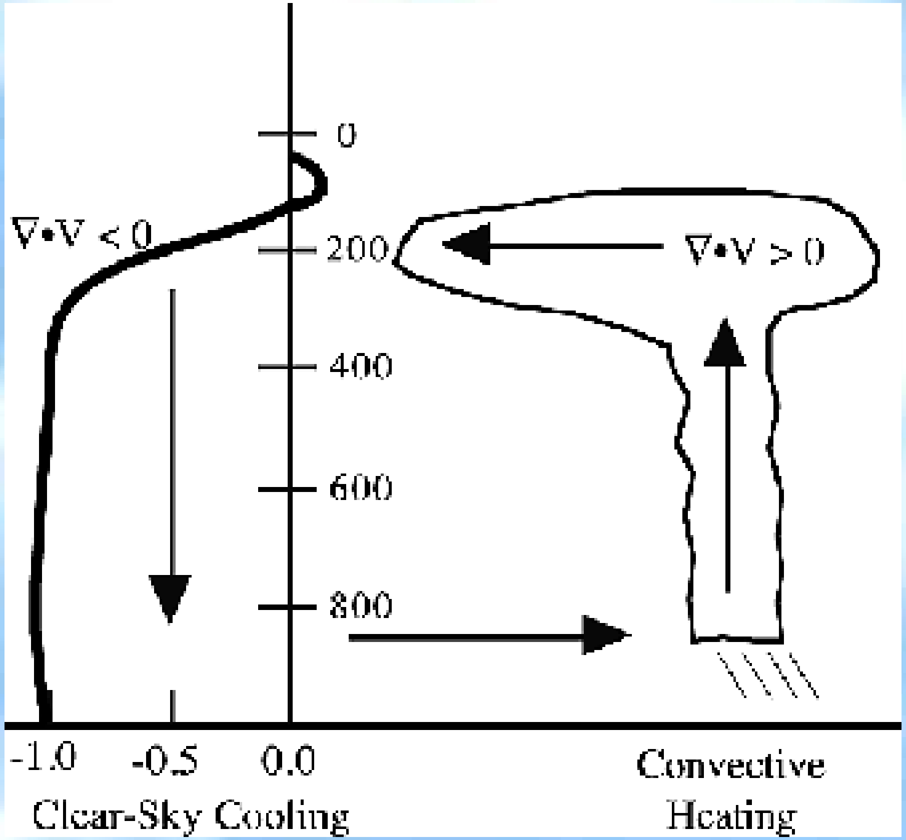
Schematic of tropical circulation



Hypothesis

- Distribution of tropical clouds relate to atmospheric circulation
- Increased warming everywhere will have only marginal effects on circulation
- Changes in cloud will be small
- Cloud feedback is zero

Tropical Anvil Feedback



Hartmann and Larson (2002) GRL

- Cirrus anvils detrain where clear-sky radiative cooling rapidly diminishes (H_2O)
- This is due to water vapour profile, determined by temperature through Clausius Clapeyron
- Above suggests as surface warms, temperature of detrainment level unchanged

→ positive cloud longwave radiatve feedback

Mid-level clouds

- Liquid-Ice transition (0 to -40^{o}C)
- Liquid droplets more reflective
  - e.g. Hogan et al. (2003) QJRMS **129** p.2089
- Warmer world → more liquid cloud?
  - e.g. Mitchell et al. (1989) Nature **341** p.132
- Climate models: crude representation
  - Underestimate in most models (e.g. Webb et al. 2001 Clim Dyn **17** p.905; Ringer and Allan 2004 Tellus **56A** p.308; Illingworth et al. 2007 BAMS **88** p.883)

Dynamic/thermodynamic components

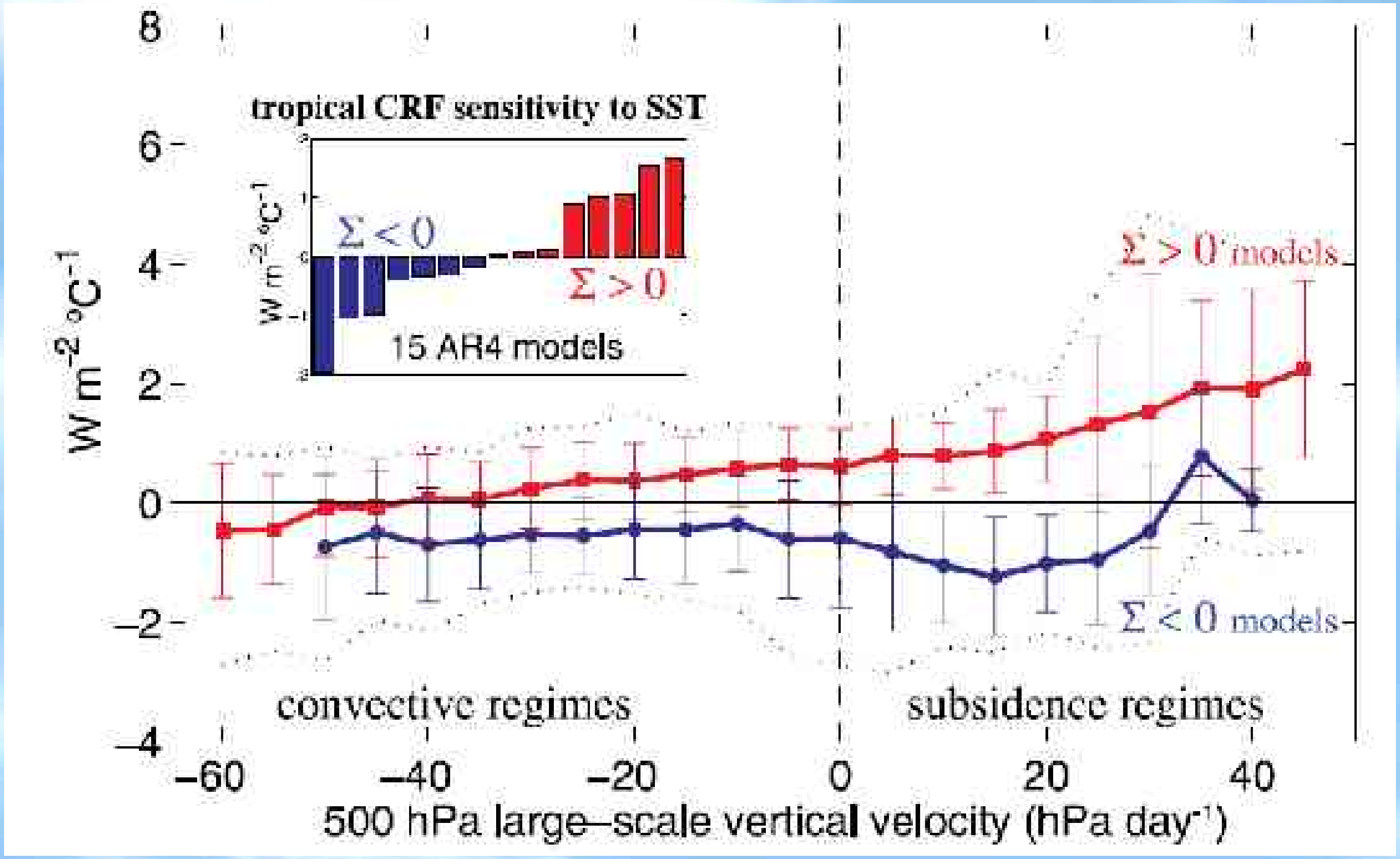
- In assessing cloud feedback, need to distinguish dynamical component
  - e.g. local change in cloud due to subtle shift in large scale circulation is not feedback

$$\overline{\delta c} = \int_{-\infty}^{+\infty} C_\omega \delta P_\omega \mathrm{d}\omega + \int_{-\infty}^{+\infty} P_\omega \delta C_\omega \mathrm{d}\omega + \int_{-\infty}^{+\infty} \delta P_\omega \delta C_\omega \mathrm{d}\omega$$

Change in cloud radiative effect due to:	Change in vertical motion locally	Change in cloud properties for given vertical motion bin	Co-variability (small)

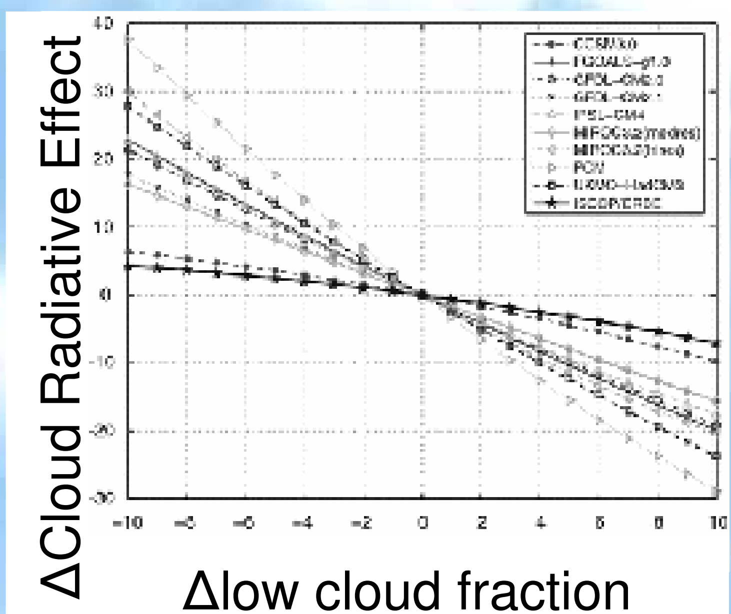
e.g. Bony et al. (2004) Climate Dynamics

Spread in cloud feedback in models appears to relate to **tropical low altitude clouds**

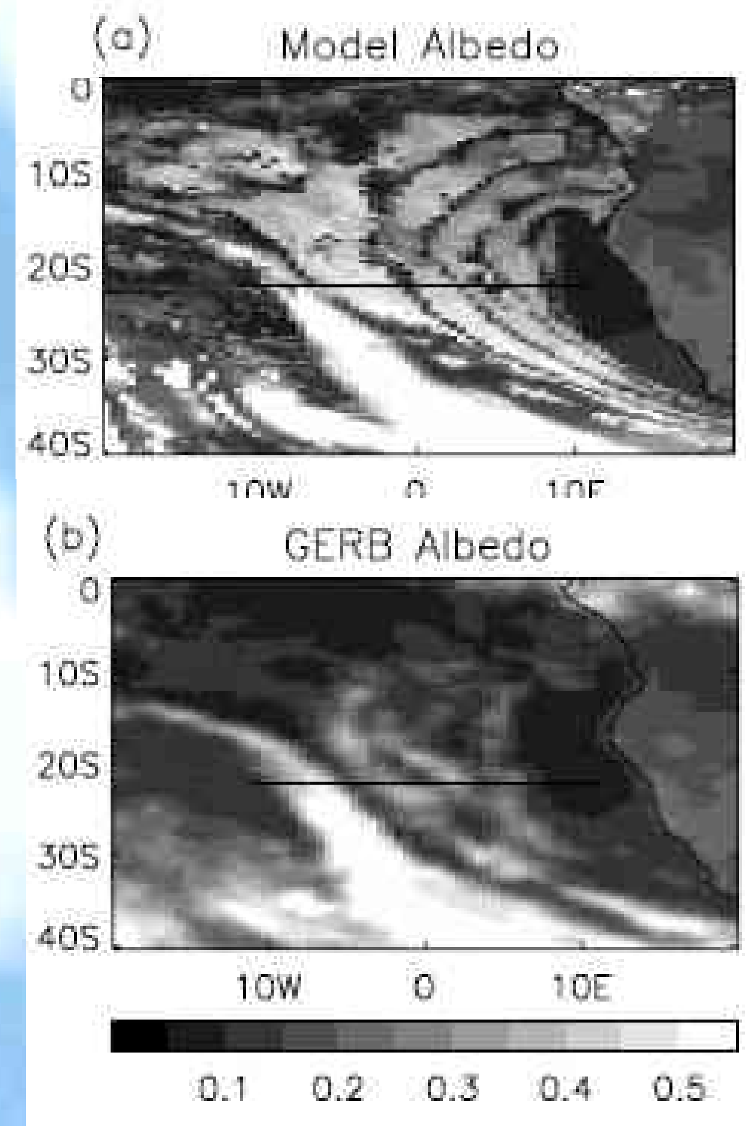


IPCC (2007), after Sandrine Bony and colleagues

Marine Low-level Clouds: too reflective in models?



Karlsson et al. (2007) Clim. Dyn



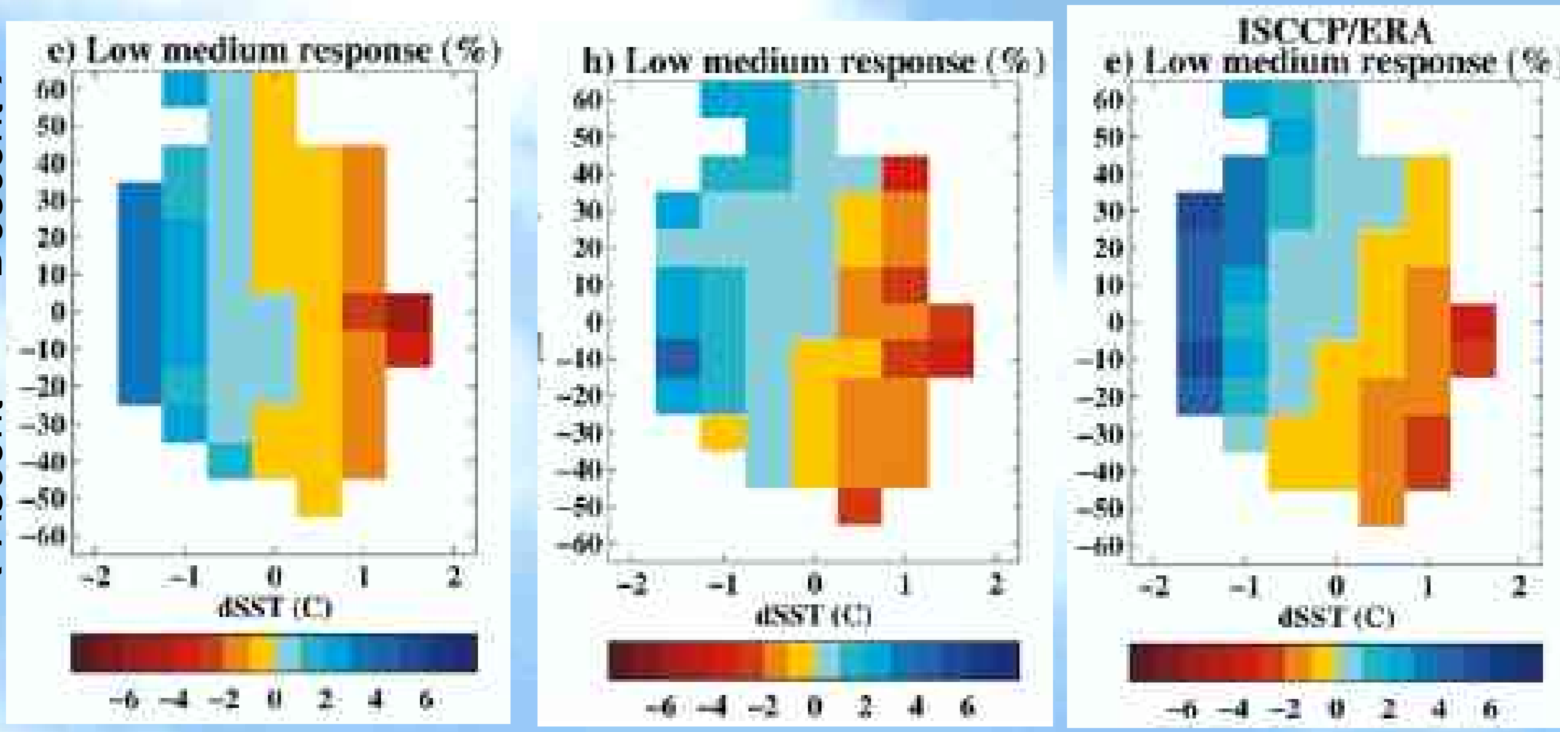
Allan et al. (2007) Q.J.R.M.S.

See also: Klein and Hartmann (1993) J.Clim; Wyant et al. (2006) Clim. Dyn.; Wood and Bretherton (2006) J. Clim, etc

Climate Model Evaluation

2xCO2 response	SST-forced response	Observed Response

Descent→ ←Ascent

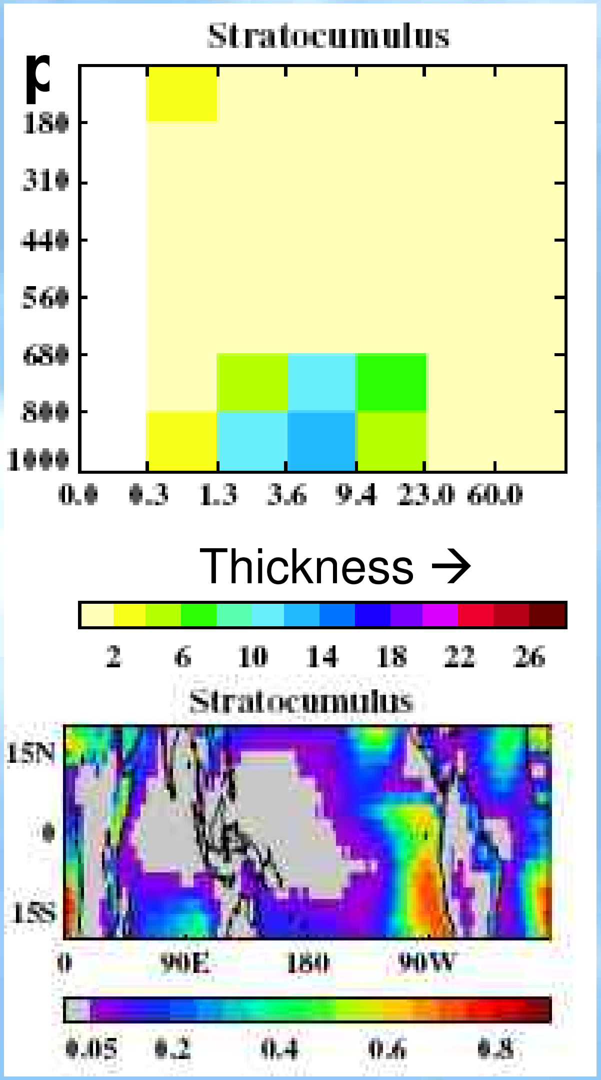


Descent→ ←Ascent

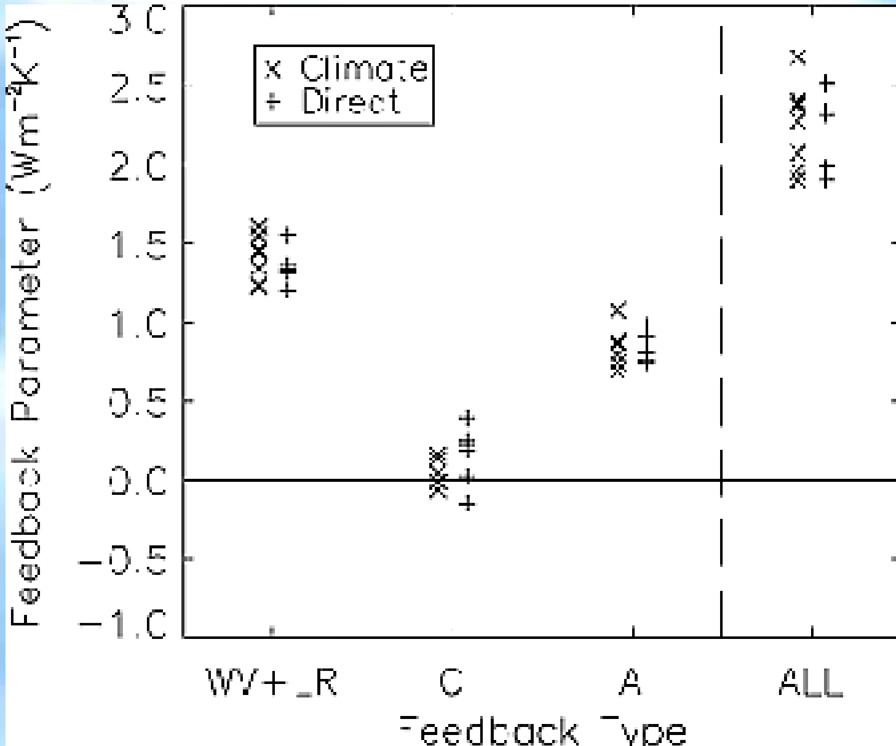
Williams et al. 2003 Clim. Dyn. **20** p.705

Clustering Techniques

- Identify "clusters" of common cloud types
  - Cloud height/thickness
  - e.g. marine stratocumulus
- Compare climatology and response between satellite data and observations
  - e.g. Williams & Tselioudis (2007) Clim Dyn. **29** p.231



Recent Advances

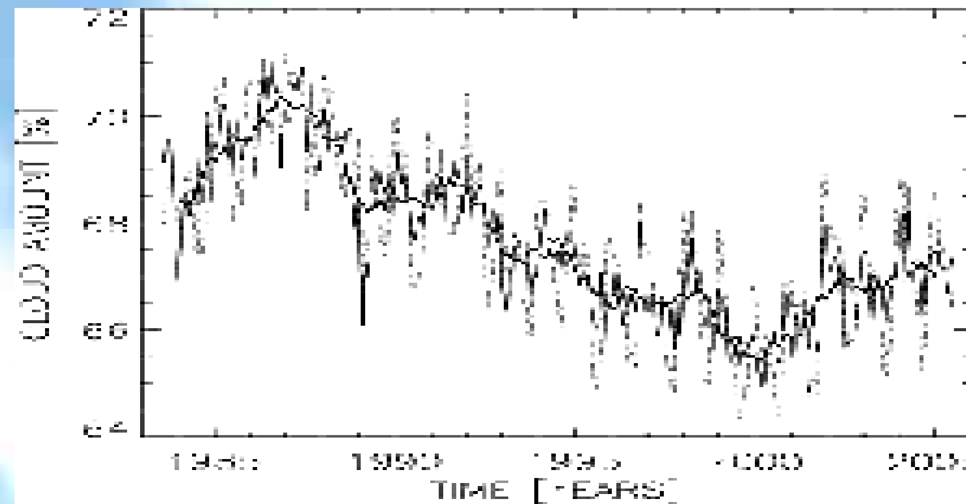


- Clouds respond to
  - direct forcing from CO_2
  - Climate response to ΔSST
- Cloud feedback uncertainty appears to stem from direct response rather than climate feedback resonse

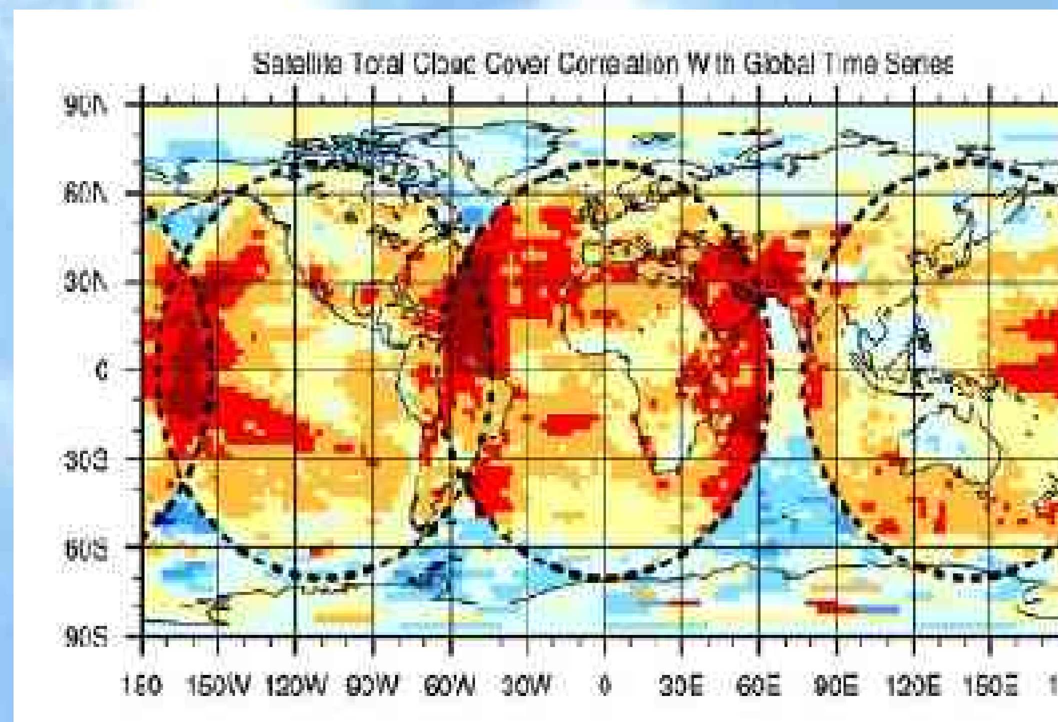
Andrews and Forster (2008) GRL (above); Gregory and Webb (2008) J Clim

Observations and cloud feedback

Changes in cloud from ISCCP



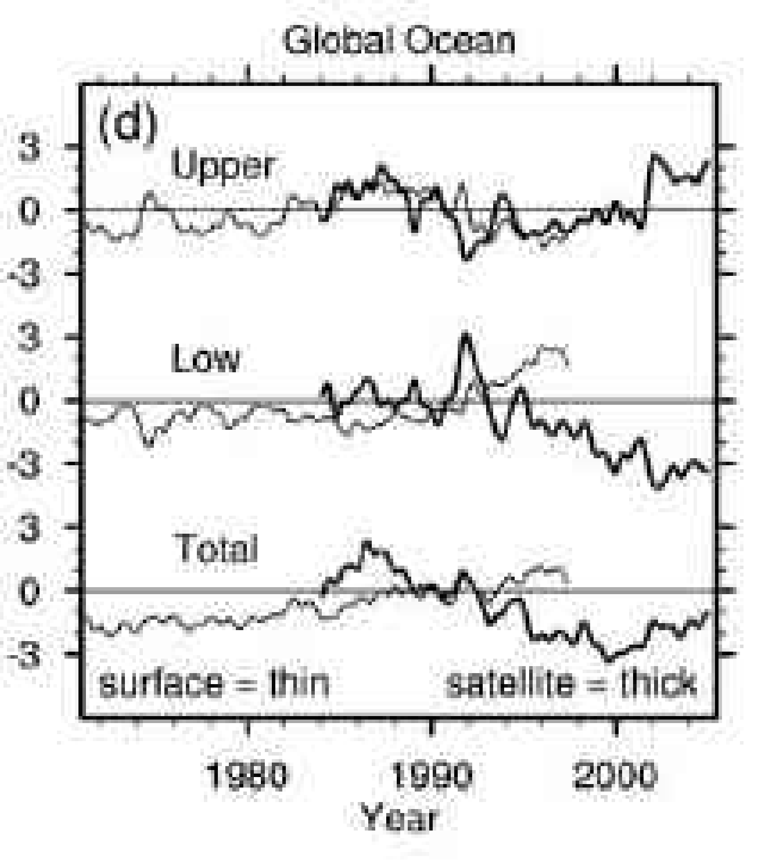
- Decadal changes in ISCCP cloud relate to viewing artifacts due to changes in geo-stationary satellite coverage
- Cloud thickness/cloud fraction compensation



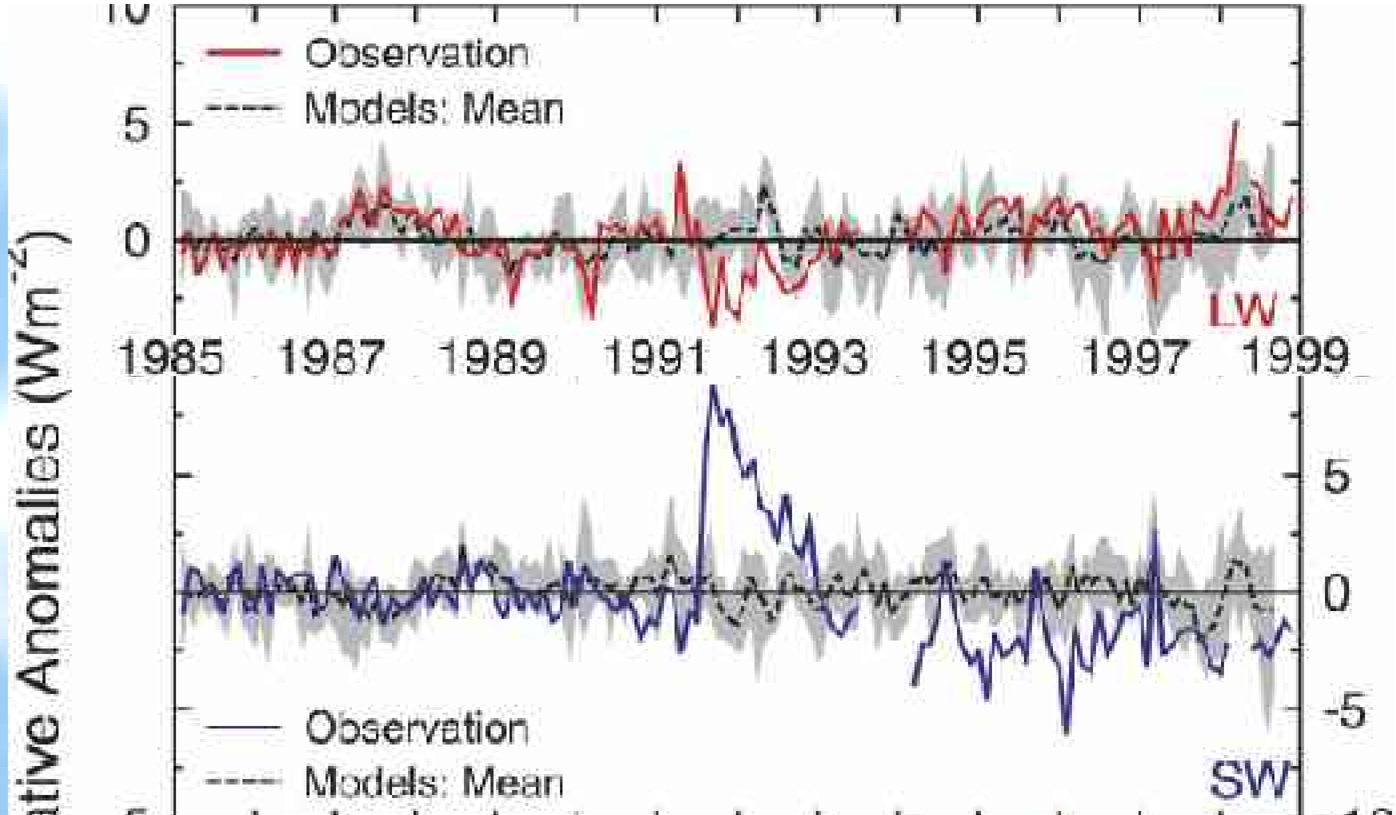
e.g. Norris (2005) JGR; Evan et al. (2007) GRL

Surface Observations

- Changes in low clouds: inconsistent between satellite measurements and surface observations
  - Norris (2005) J Geophys Res 110:D08206.



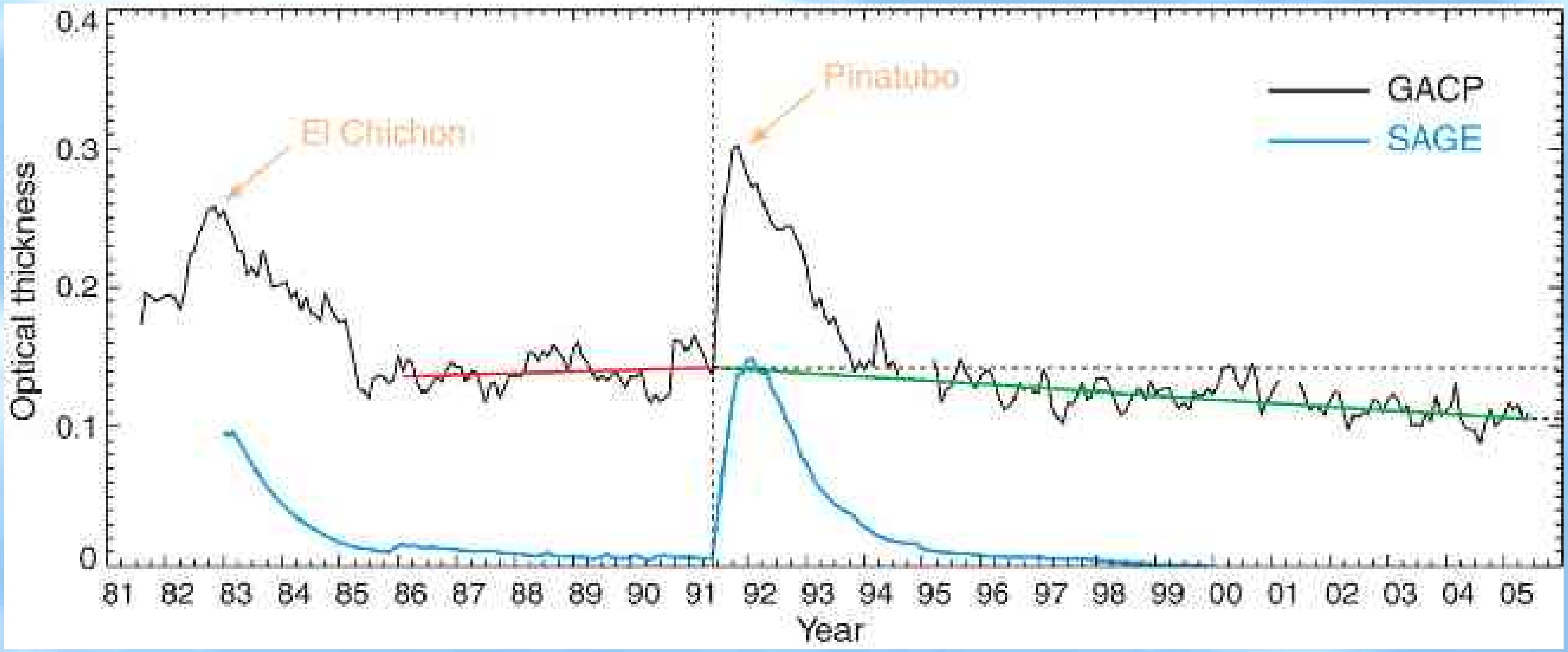
- Satellite reductions in cloud cover/albedo effect?
- Darkening of tropics from 1980s-90s
  - Aerosol, cloud, combination? Processes key to cloud feedback?



Wielicki et al. (2002) Science; Wong et al. (2006) J. Clim; Loeb et al. (2007) J. Clim

From Surface Dimming to Brightening?

(or the reverse from the top of atmosphere)



Mishchenko et al. (2007) Science; Wild et al. (2005) Science

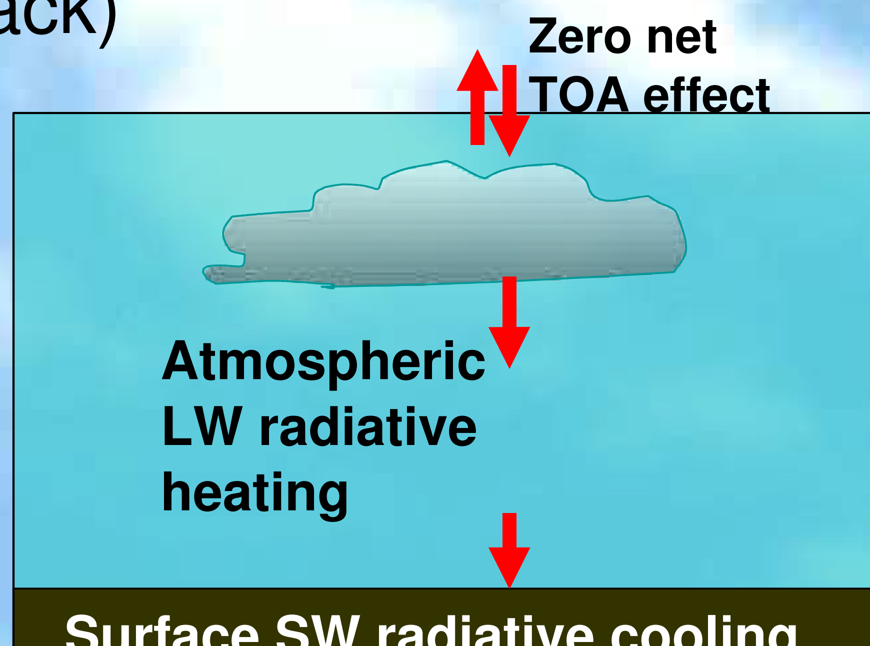
Other issues

- Lindzen hypothesis (negative cloud feedbacks)
- Clouds and Cosmic Rays
- Aerosol/cloud interactions

A final thought...

- Suppose there is an increase in high-level cloud which on average has a balancing shortwave (SW) and longwave (LW) radiative effect (ie no net radiative feedback)

- Increase in high cloud
  - → Increased atmospheric stability
  - → Reduced diurnal surface temperature range

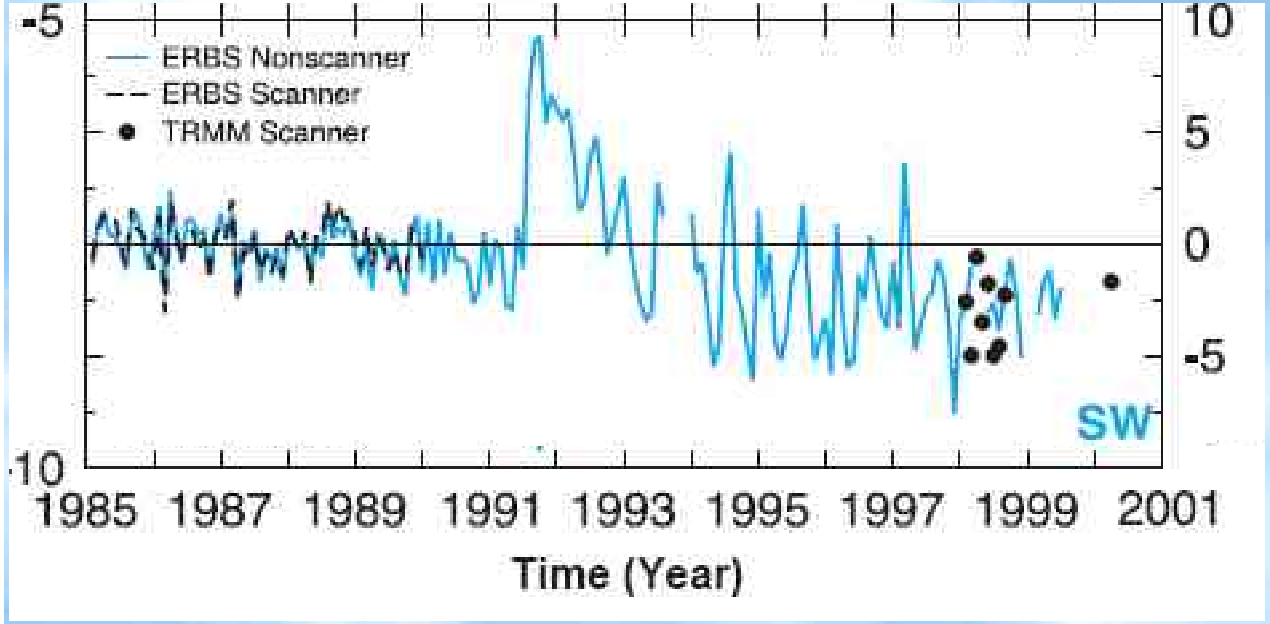


Conclusions

- Cloud feedback → uncertain climate prediction
- Model uncertainty appears to stem from
  - Low-altitude tropical ocean clouds
  - Direct response to CO_2 forcing
- Model cloud microphysics are relatively crude
- Can satellite observations constrain feedback?
  - Separating out effects from aerosol/CO_2 forcing, dynamical effects and SST feedback is a challenge
- Links to global water cycle crucial
  - How will precipitation respond to warming?

Extra Slides

Satellite reductions in cloud cover and cloud albedo effect?



Satellite data from Wielicki et al. (2002) suggests a reduction in the cloud albedo effect from the 1980s to the 1990s which is not captured by the models

Is the data reliable?

Unlikely to show feedback, but discrepancy with models may highlight missing process

Links to changes in aerosol rather than cloud?

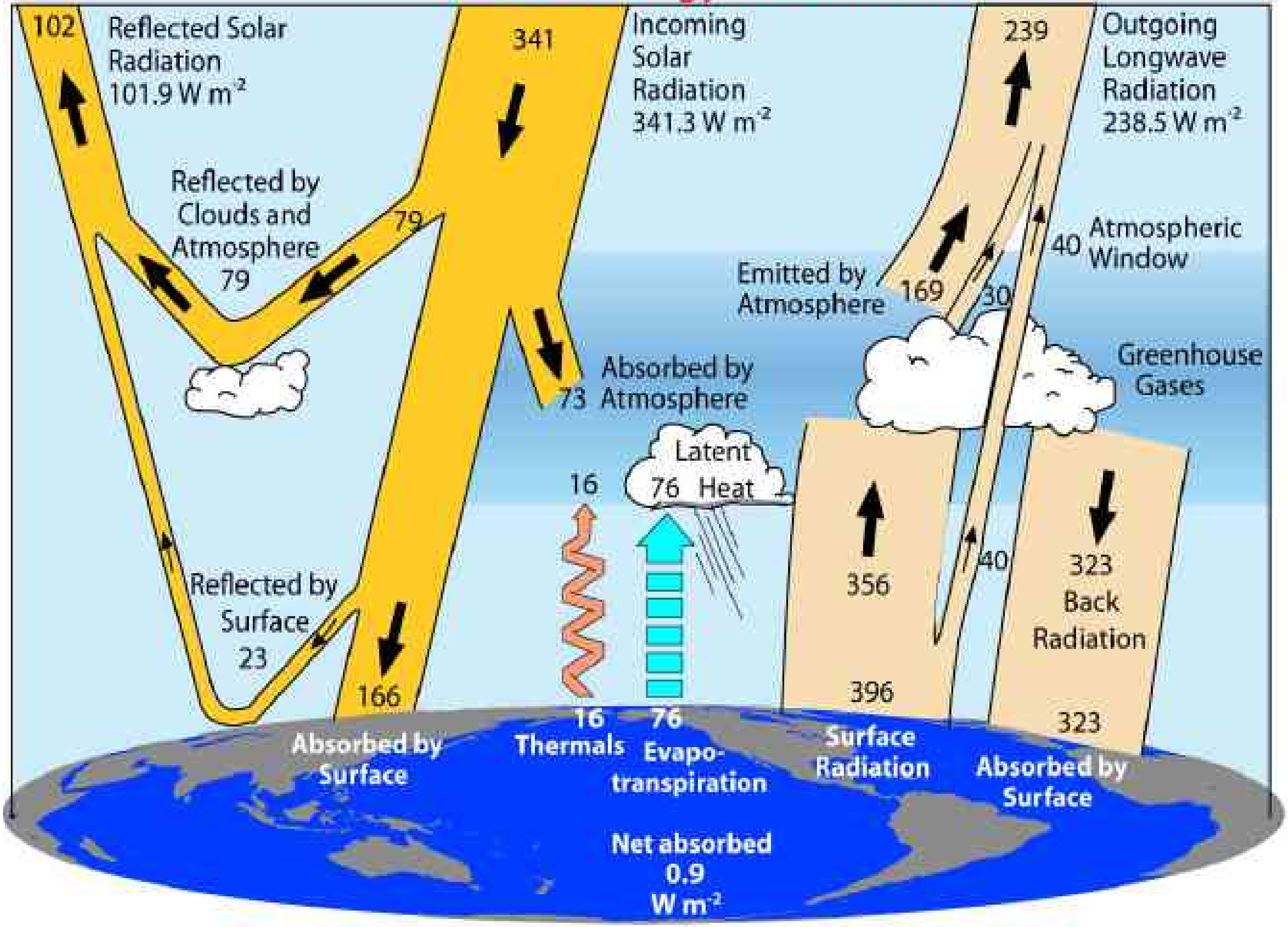
Recent Results

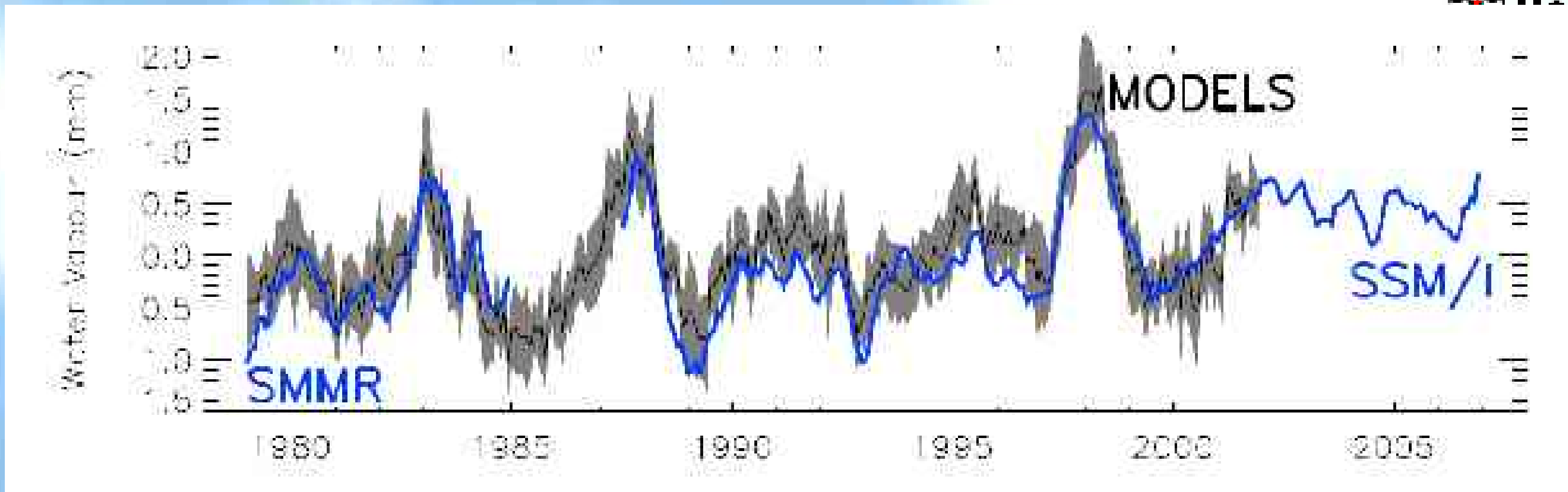
- Bony and Dufresne, Karlsson
- Wielicki, Loeb, Wild, etc
- Evan, Wyant, Ringer
- Cosmic Rays, Lindzen?

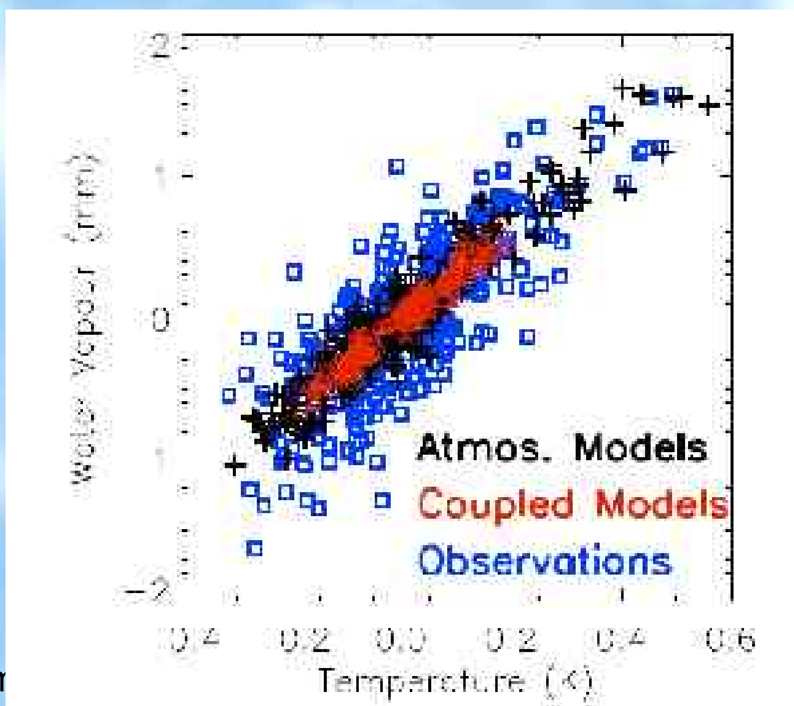
- Hartmann
- Gregory/Webb, Forster

- Wentz

Global Energy Flows W m^{-2}

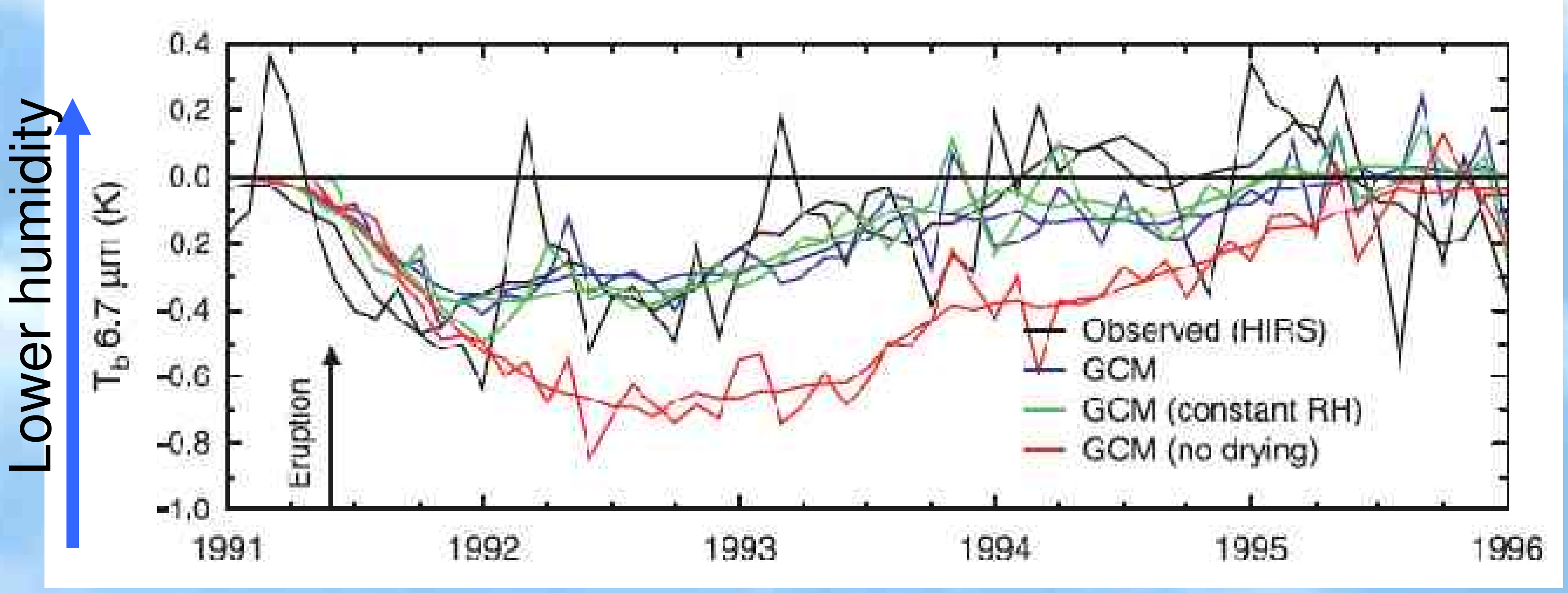






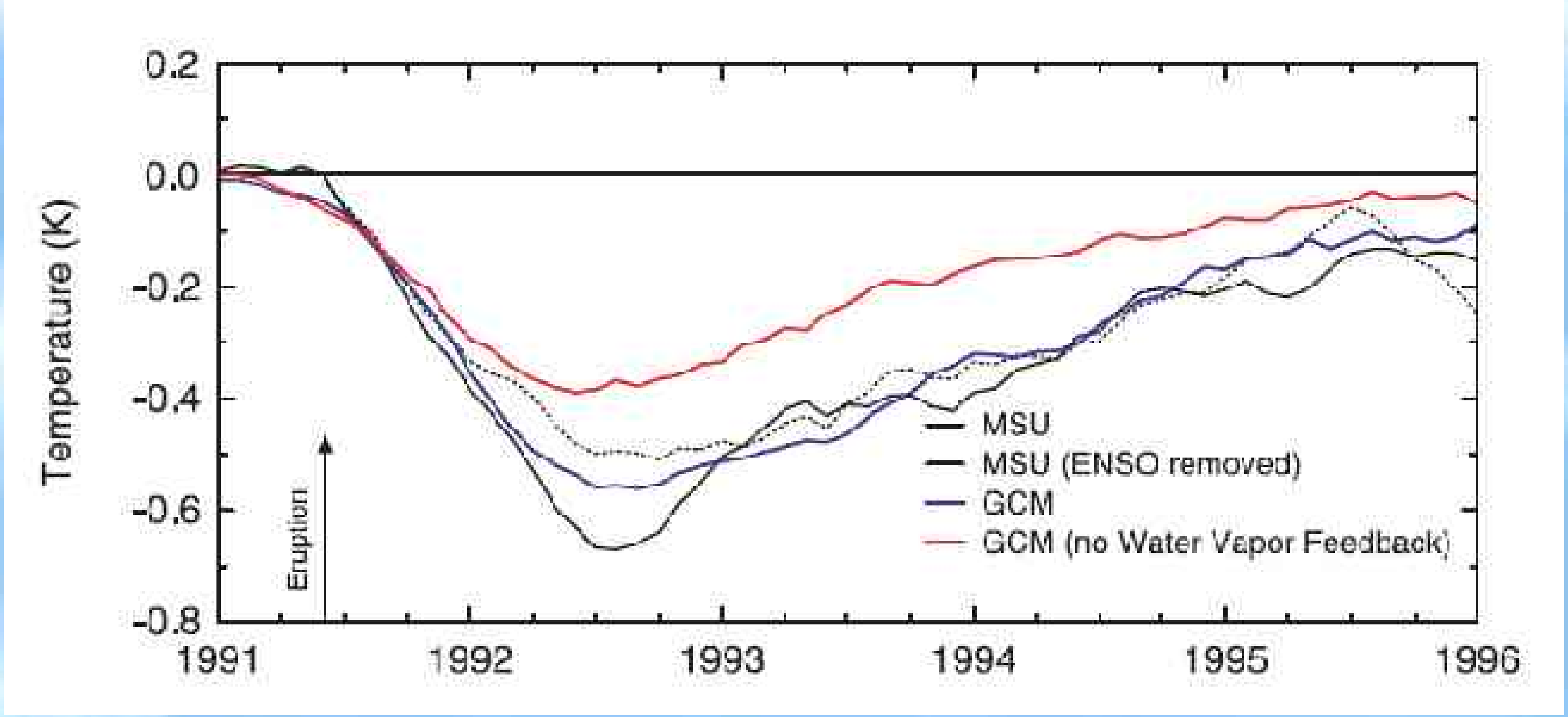
Models reproduce observed increases in total column water vapour

Model reproduces water vapour feedback response to cooling following Pinatubo eruption



Soden et al. (2002) *Science*

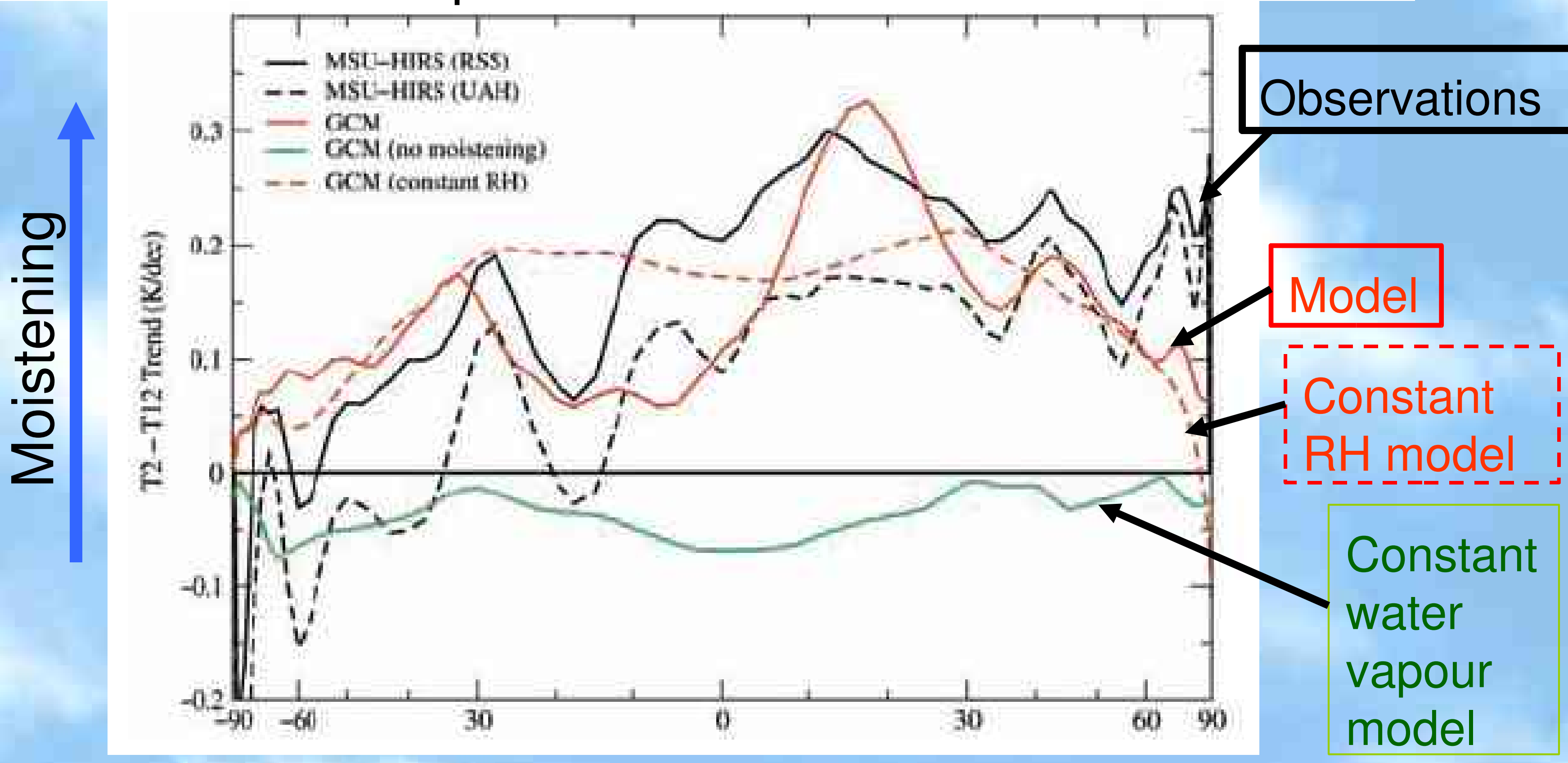
Model reproduces water vapour feedback response to Pinatubo eruption



Soden et al. (2002) *Science*

Upper tropospheric moistening consistent between models and satellite data

Trend in water vapour radiance channels: 1983-2004



Soden et al. (2005) *Science*