Atmospheric Water Vapour in the Climate System: Climate Models 2/3

Evaluating Climate Models and Feedbacks

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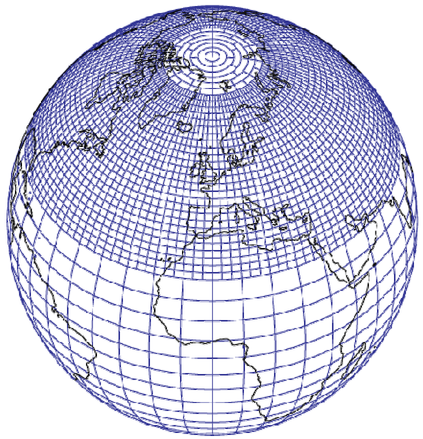
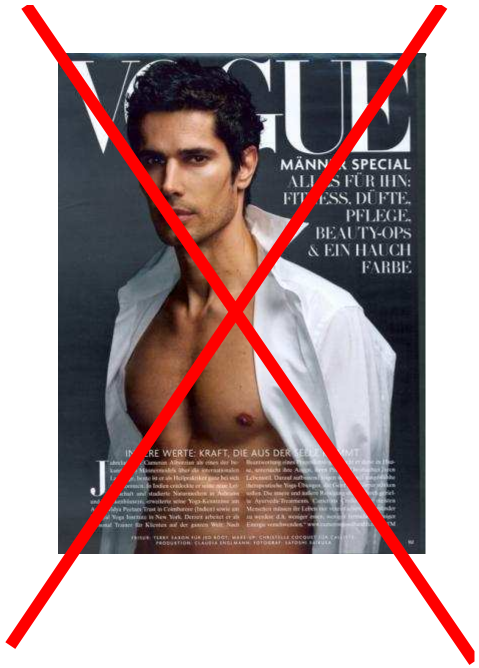
Atmospheric Water Vapour in the Climate System: Climate Models 2/3

- Recap
- Validating Climate Models
- Evaluating Feedbacks in Climate Models
- Climate model simulations
  - Radiative Forcing
  - Simulations of the 20th century
  - Projections and uncertainty
- Evaluating Climate Feedbacks
  - Water vapour feedback
  - Cloud feedback
  - Recent Advances
  - Implications for the water cycle

Recap



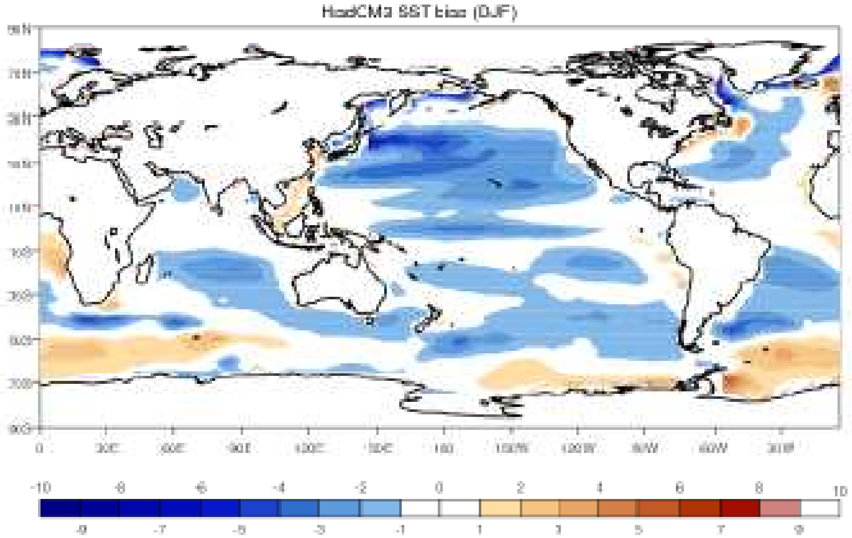


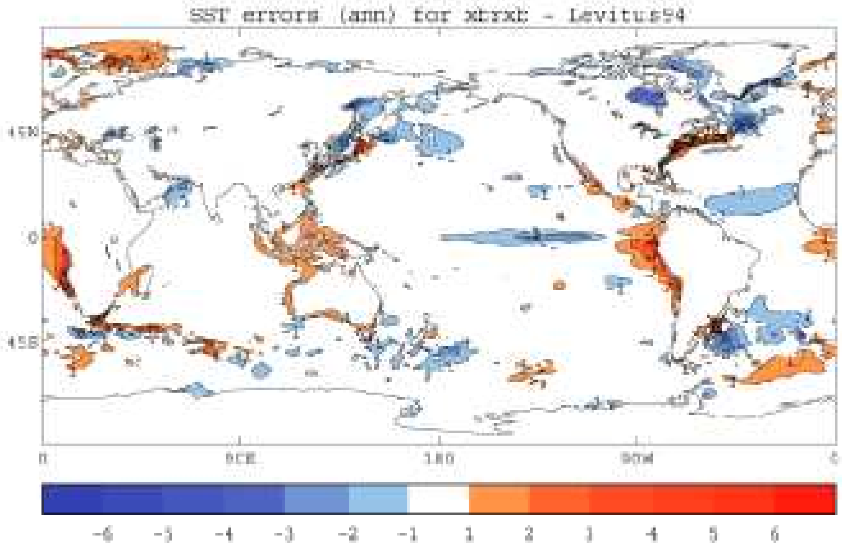
- Simple Models
  - Earth's energy balance
- Building Climate Models
  - Definitions (AGCM, RCM, AOGCM, Earth System Model, etc)
  - Parametrization
  - Development of Climate Models

Validating Climate Models

- A basic requirement is that models can reproduce the current climate given the current forcing
- If run for many years with current forcing, the climate should not “drift”
- The models should be able to reproduce recent changes in climate
- Can the models also reproduce past rapid climate changes from the palaeo record?

Sea surface temperature (SST)



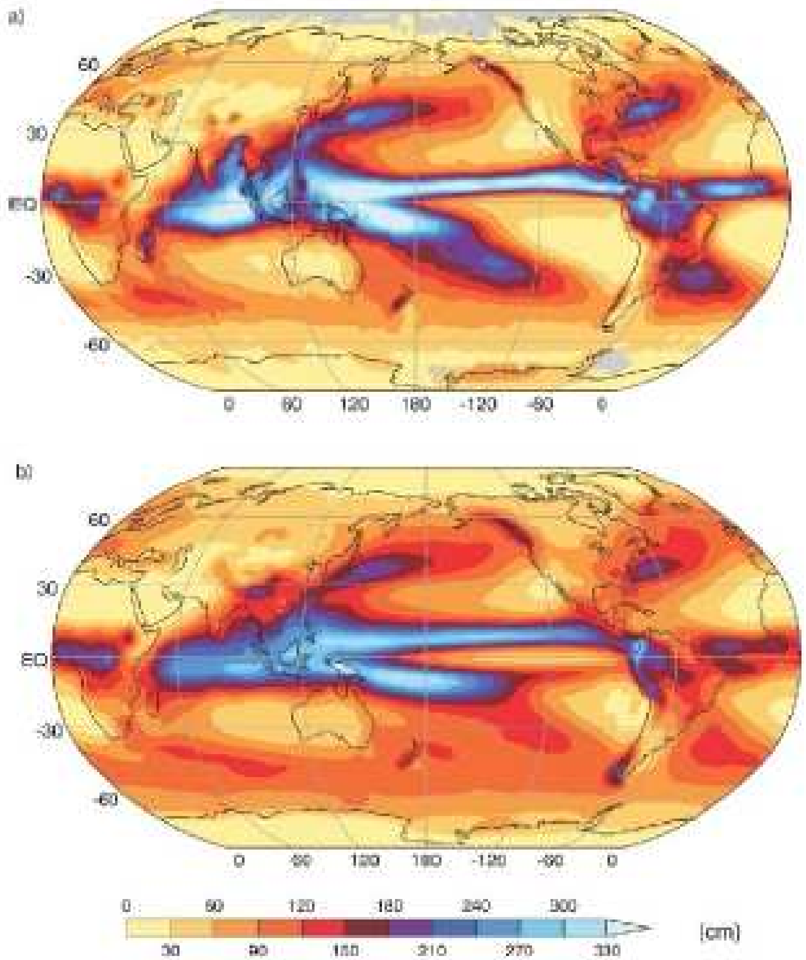


- The Sun's energy gets into the atmosphere via the Earth's surface
- Correct representation of SST is therefore an important element of climate simulation

Top panel shows the SST error (DJF) from a 1990's GCM

Lower panel shows the SST error (annual mean) in a 2007 GCM

Mean Climate - precipitation



- The present day rainfall distribution is important to simulate as correctly as possible

Top panel shows the observed annual average precipitation

Lower panel shows the average of 23 GCMs used in the 2007 IPCC report

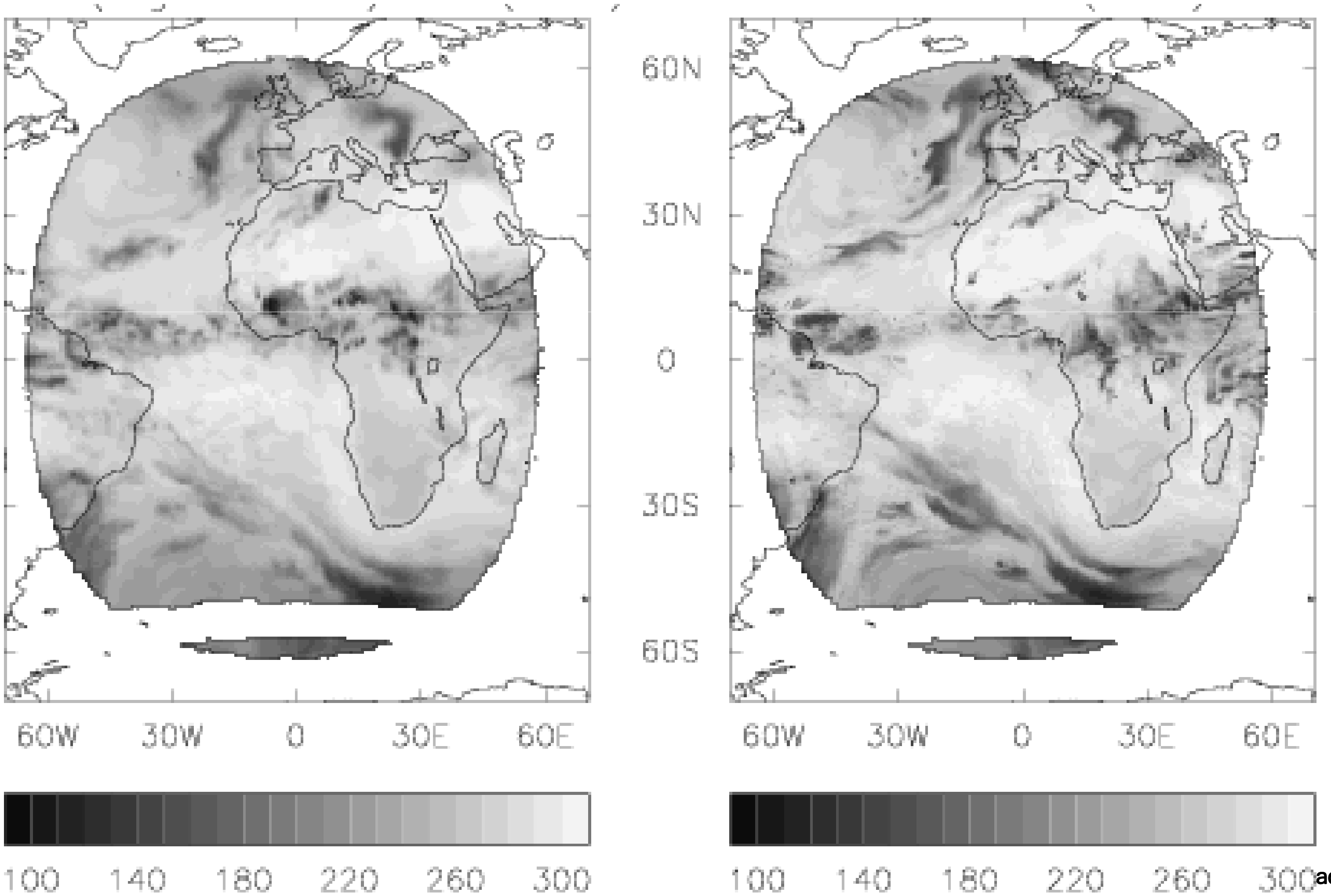
Figure from IPCC AR4. Chapter 8

Variability

- Simulating natural climate variability is also very important
- Natural cycles like ENSO (El Niño/Southern Oscillation) have a big impact on global weather patterns
- There are many other phenomena which cause climate variability on a wide range of time scales
- These are like building blocks of the mean climate pattern, so GCMs should reproduce them

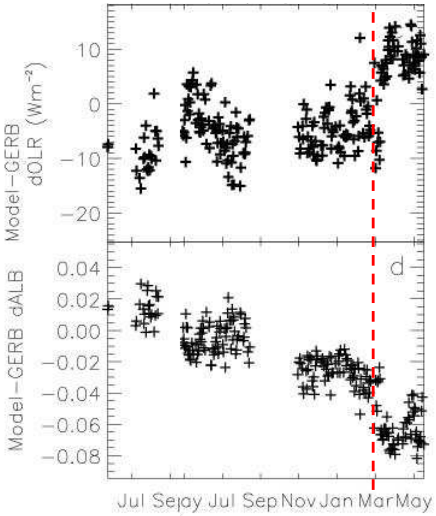
Using observations of past climate is a key test of the fidelity of climate model simulations…

Clouds and Radiation

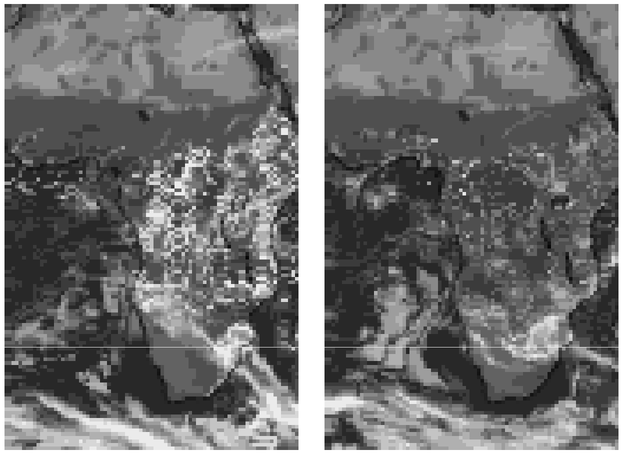


Continuous Monitoring of models and observations

1 Change in model minus GERB flux differences: relate to change in model physics implementation



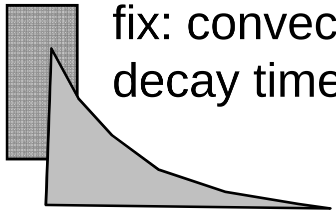
2005 2006



Model SW albedo

13th March | 14th March 2006

2 Identify problem and fix: convective cloud decay time-scale



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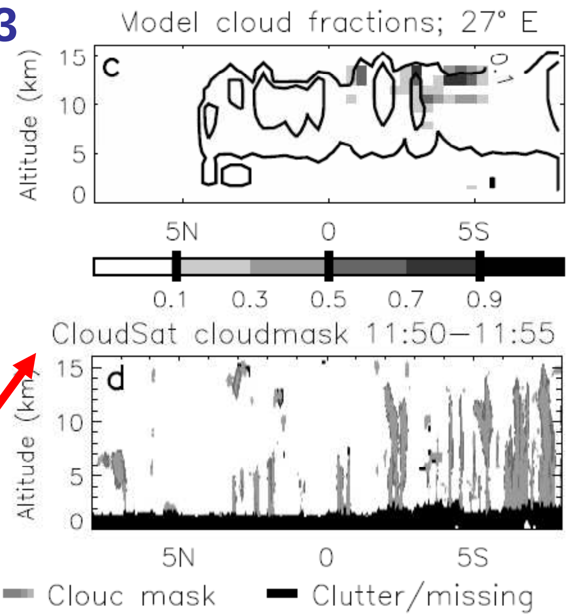
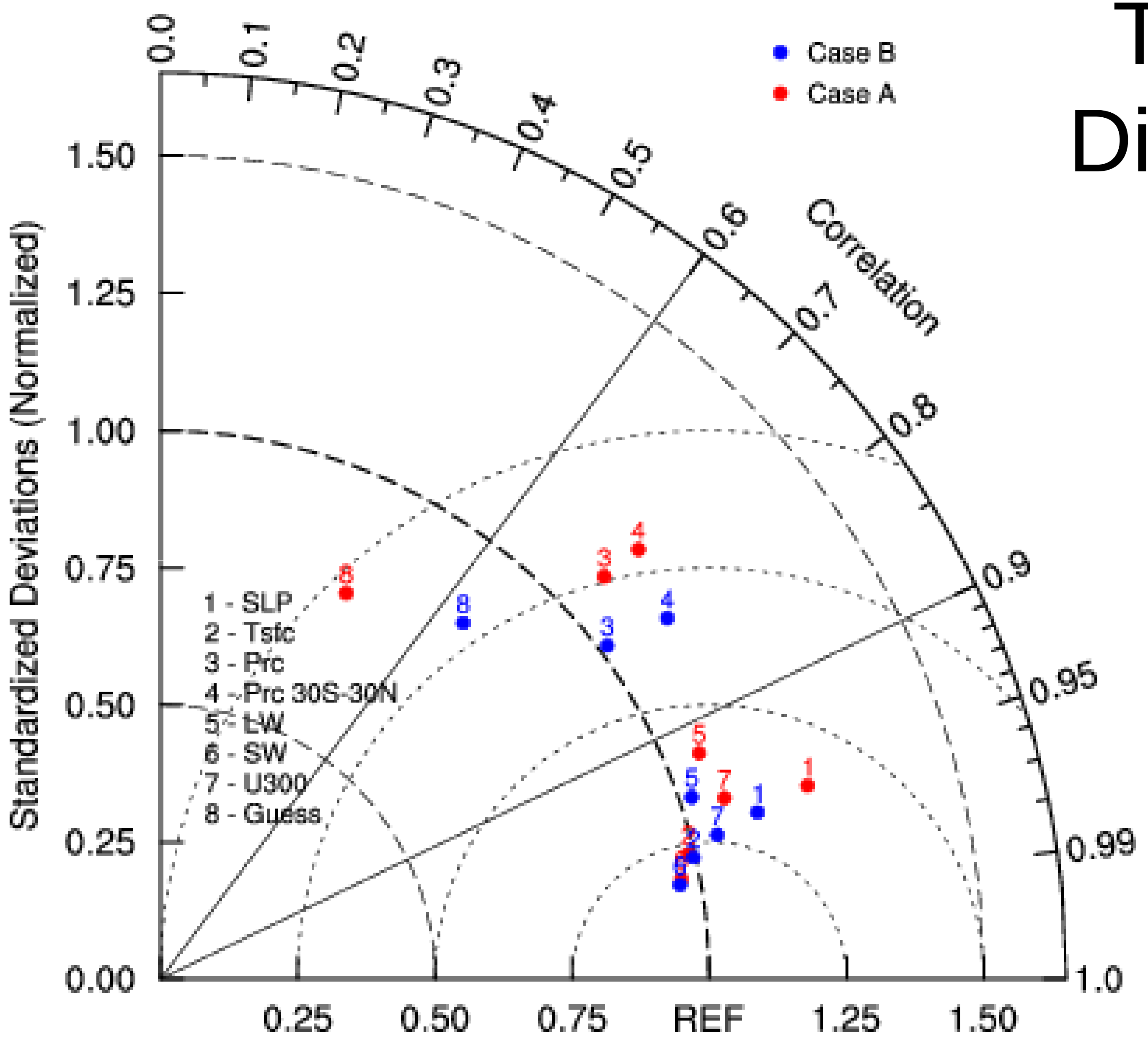


Allan et al. (2007) QJRMS

Monitor improvement using GERB/CloudSat

Taylor Diagram



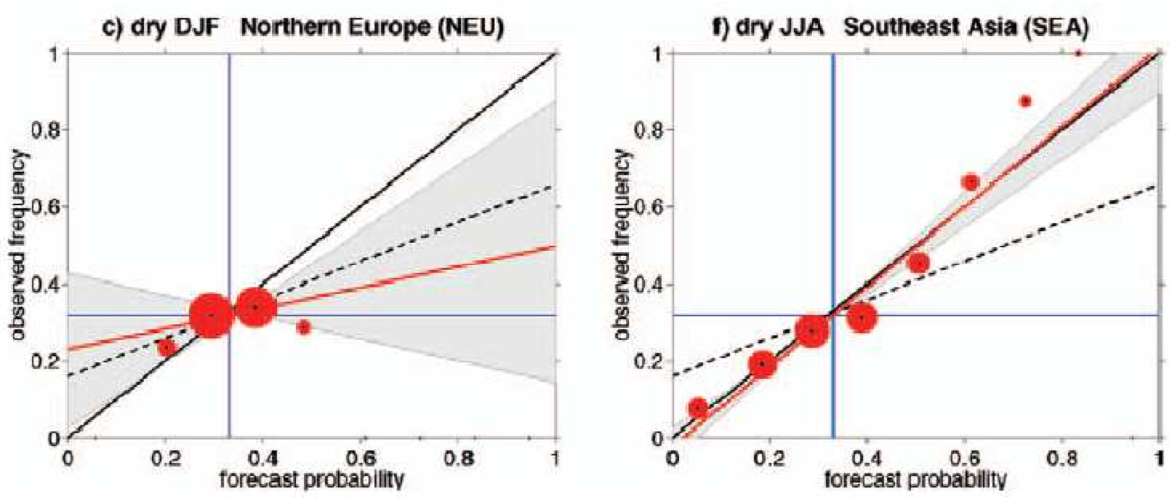
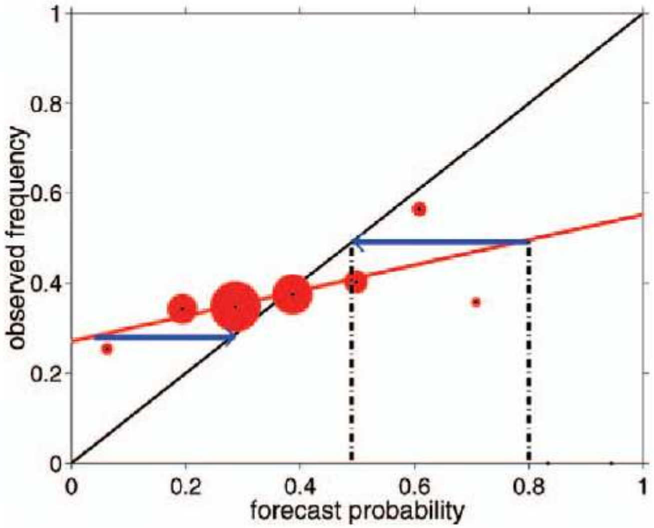


FIG. 4. Reliability diagrams for DEMETER multimodel seasonal forecasts for selected standard land regions. The data have been calculated over the forecast period 1980–2001 for $E_p^{\pm}(x)$ in DJF/JJA as indicated in the subpanel titles using 1-month lead ensembles started on 1 Nov/May for DJF/JJA. The area of the red solid circles is proportional to the bin population. The blue horizontal and vertical lines indicate the climatological frequency of the event in the observations and forecasts, respectively. The black dashed line separates skillful from unskillful regions in the diagram: points with forecast probabilities smaller (larger) than the climatological frequency, which fall below (above) this line, contribute to positive BSS; otherwise they contribute negatively to the BSS. Gray shaded areas indicate the uncertainty of the regression line (red) estimation based on a bootstrap resampling procedure, see text for details.

Palmer et al. (2009) BAMS "TOWARD SEAMLESS PREDICTION Calibration of Climate Change Projections Using Seasonal Forecasts"



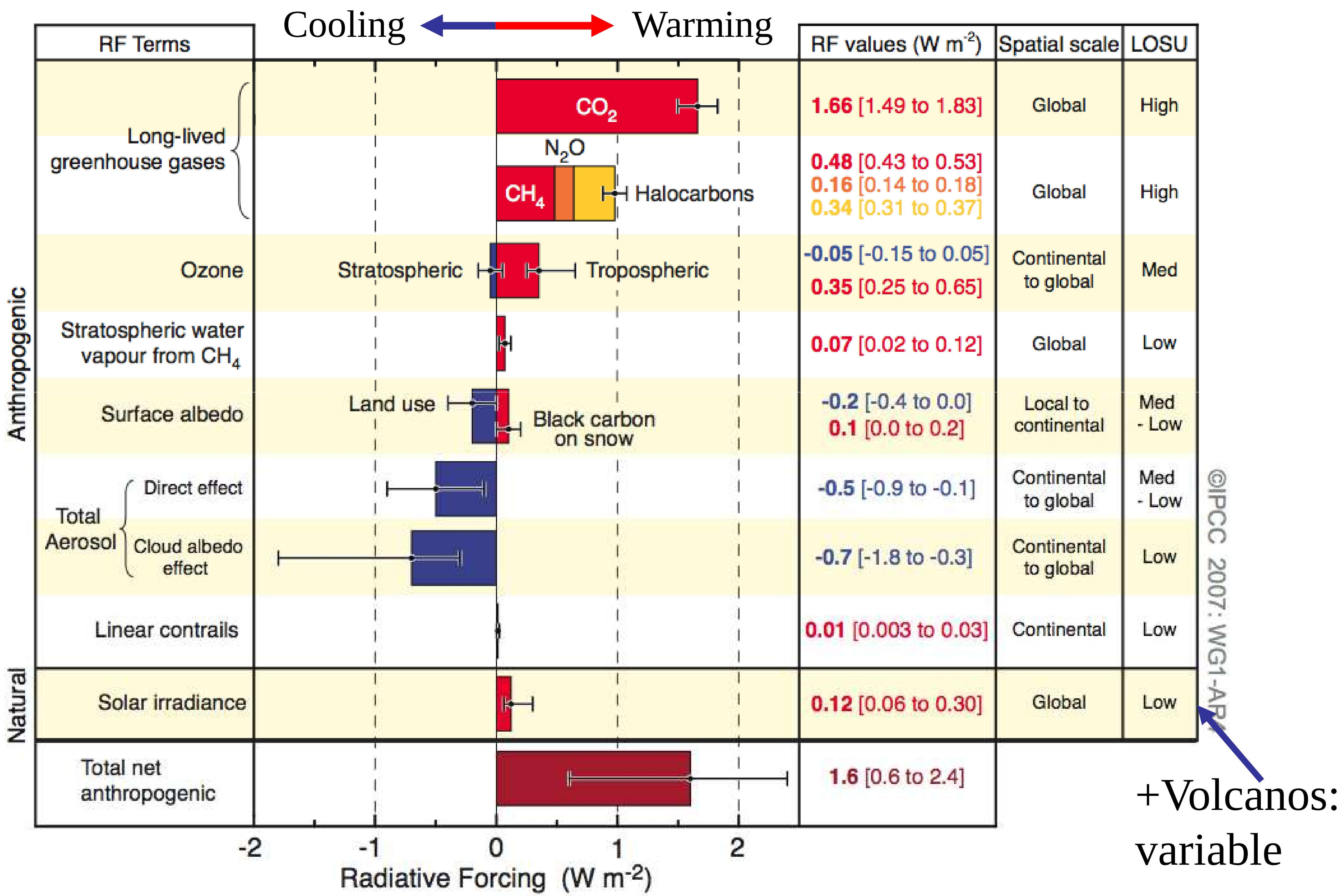
Water vapour and climate

Water vapour central in determining:
- Amount of warming
- Changes in water cycle

How do we predict climate change?

- Need to know what processes are important for determining the present day and past climate change
  - FORCINGS (e.g. solar output)
  - FEEDBACKS (e.g. ice-albedo)
- How will forcings change in the future?
- Will ocean/atmosphere processes amplify or retard this forcing of climate?

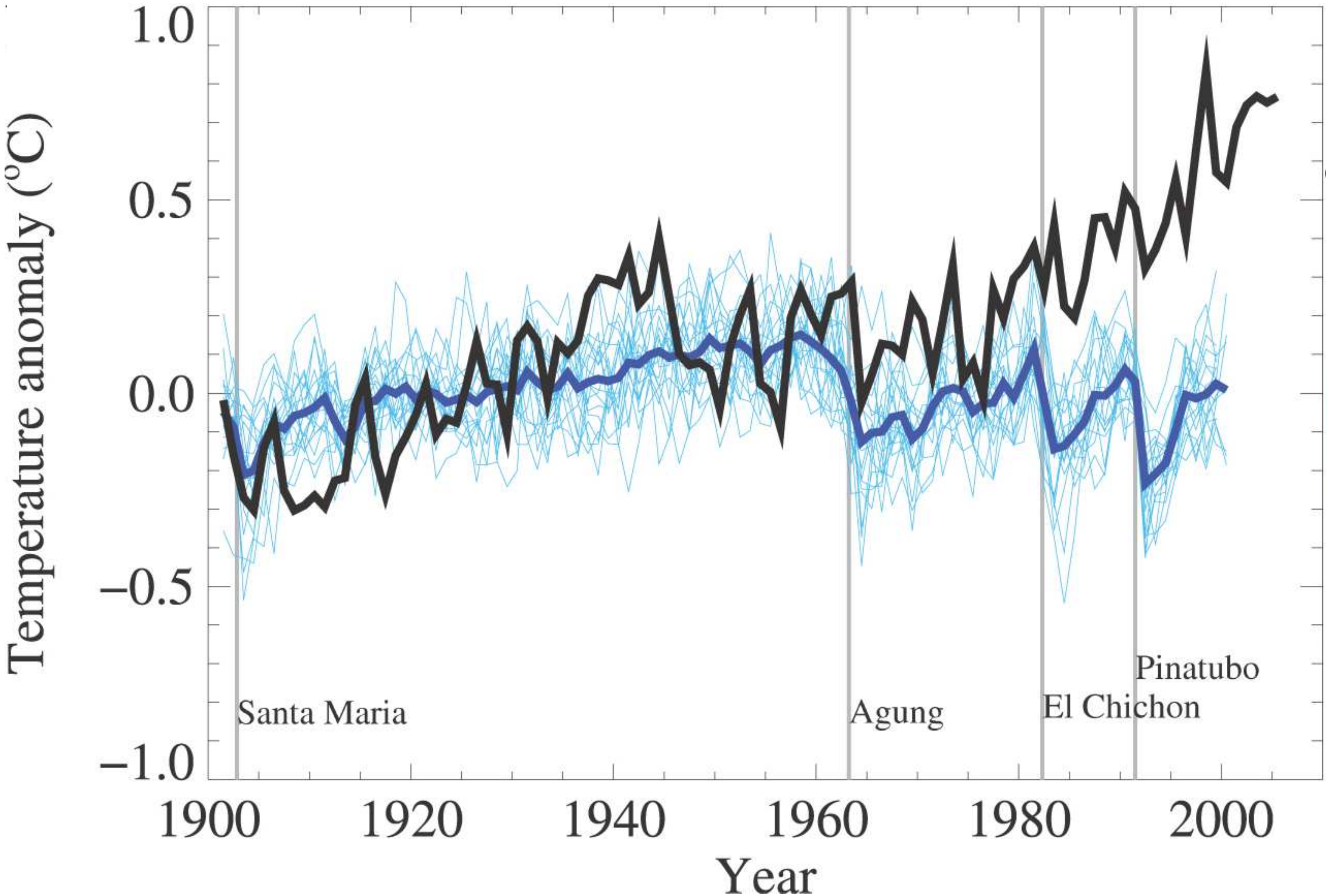
Factors influencing climate since 1750



Experiments with climate models

- How much of the recent warming can be explained by natural effects?
- To answer such questions, experiments can be performed with climate models

Natural factors can't explain recent warming



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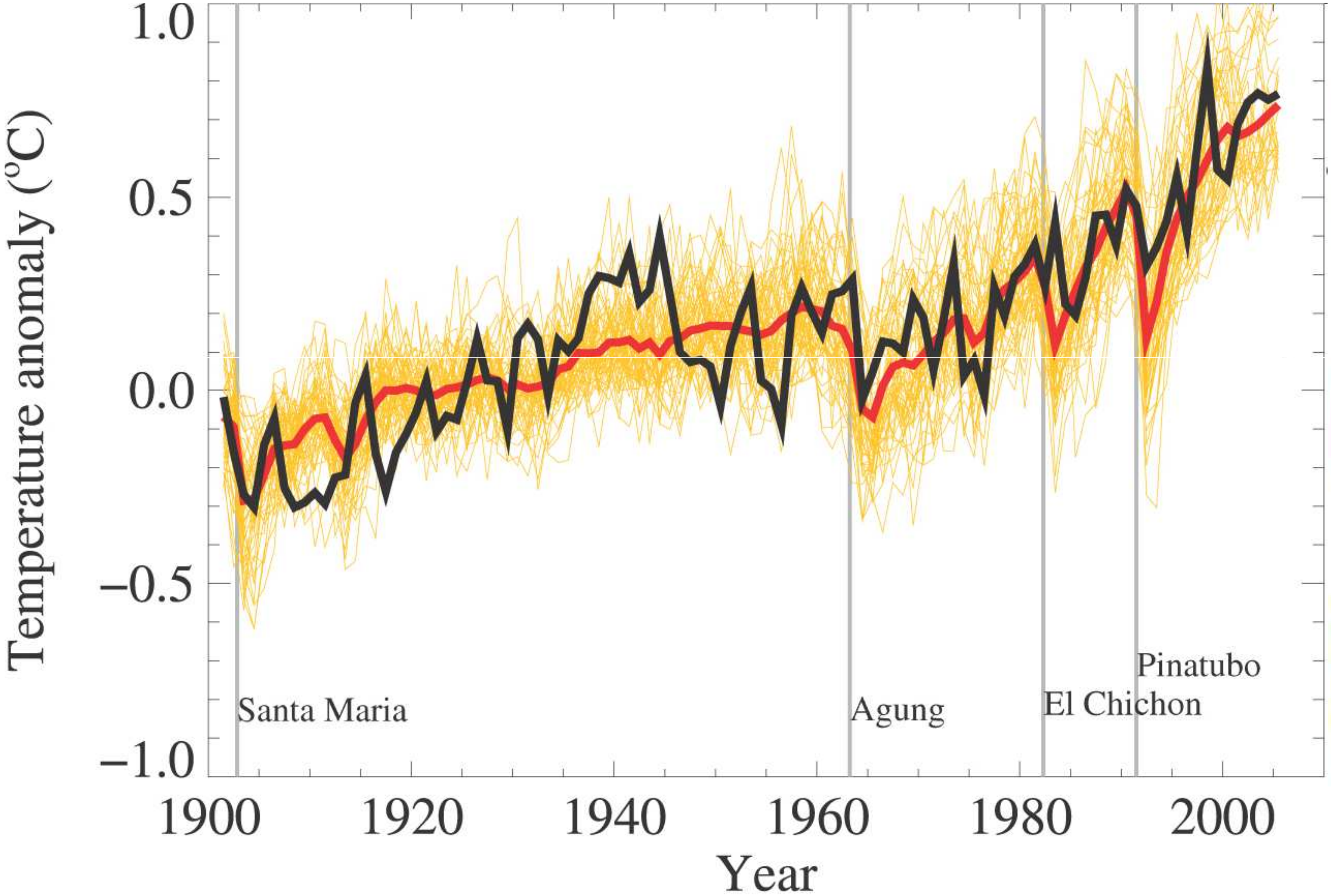
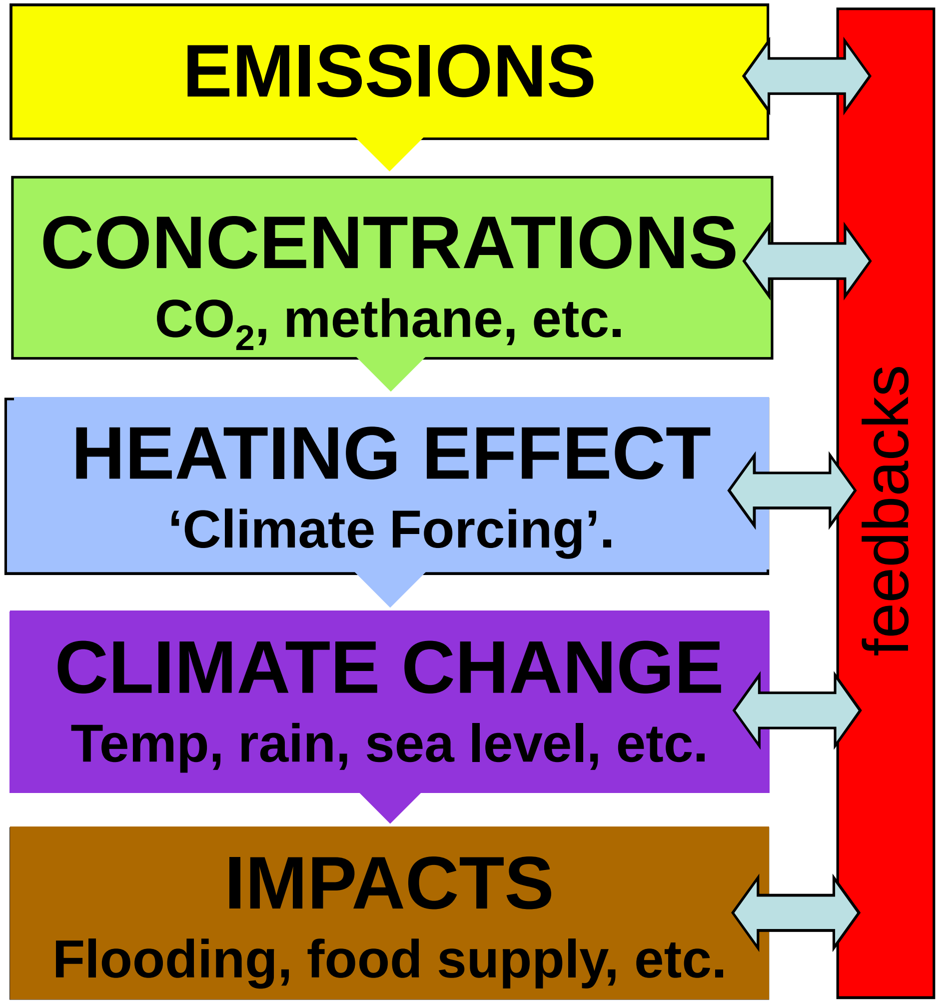
Recent warming can be simulated when man-made factors are included



Predicting future climate change



Scenarios from population, energy, economics models

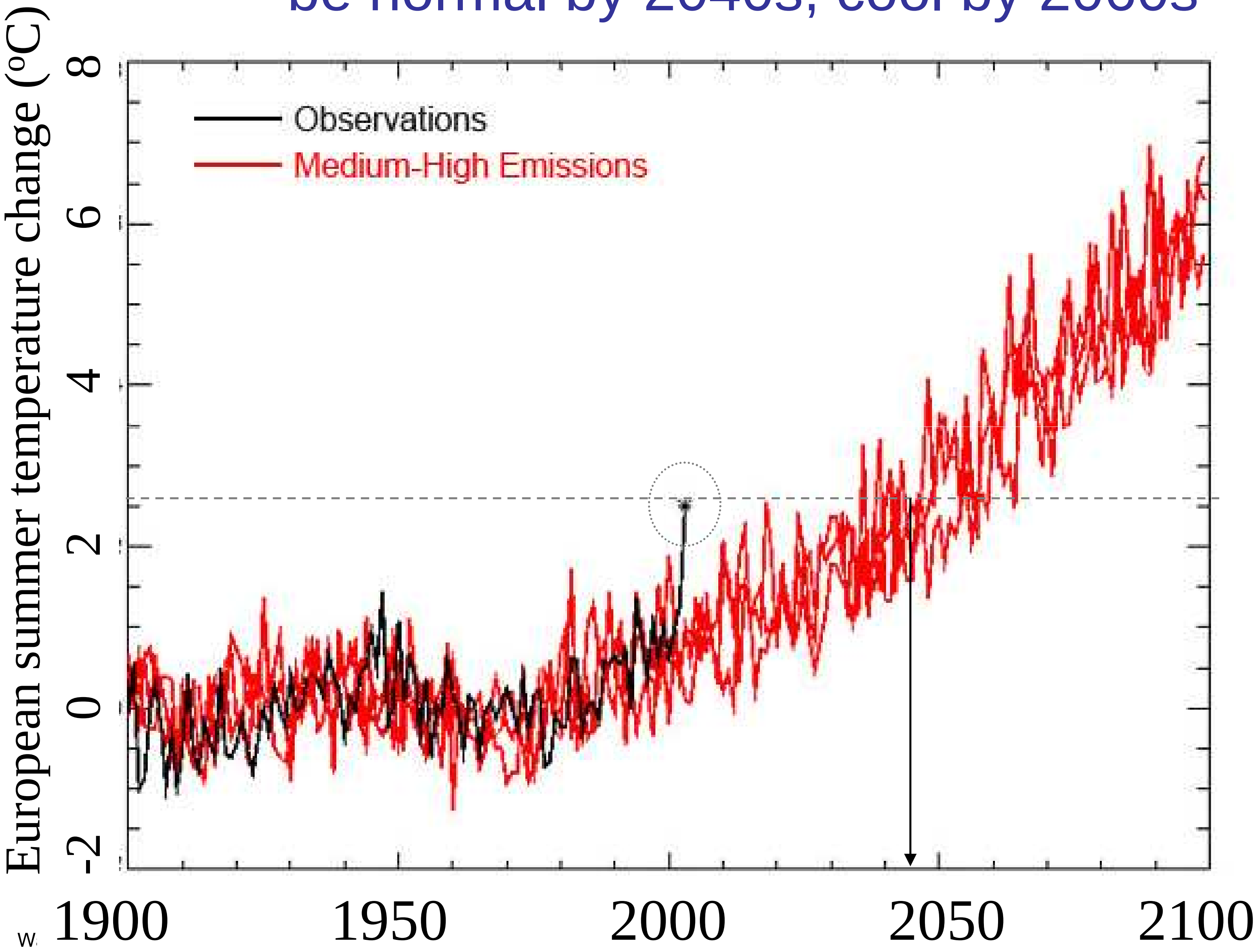
Carbon cycle and chemistry models

Gas properties

Coupled climate models

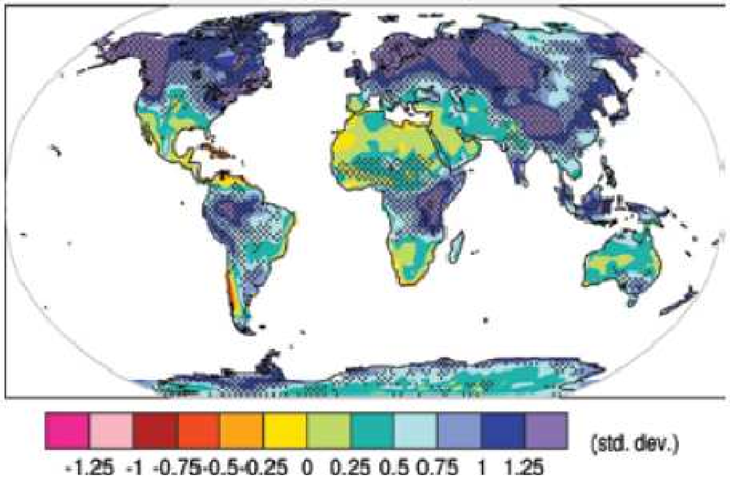
Impacts models

European 2003 summer temperatures could be normal by 2040s, cool by 2060s

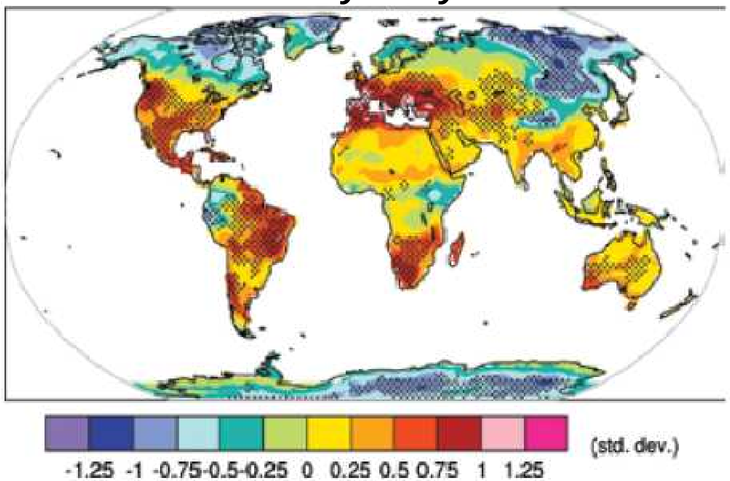


CLIMATE MODEL PROJECTIONS

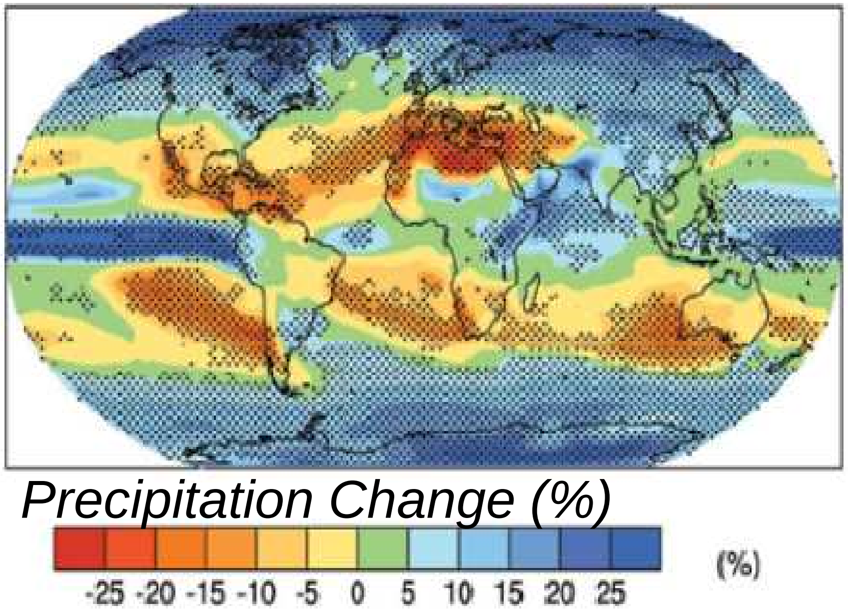
Precipitation Intensity



Dry Days

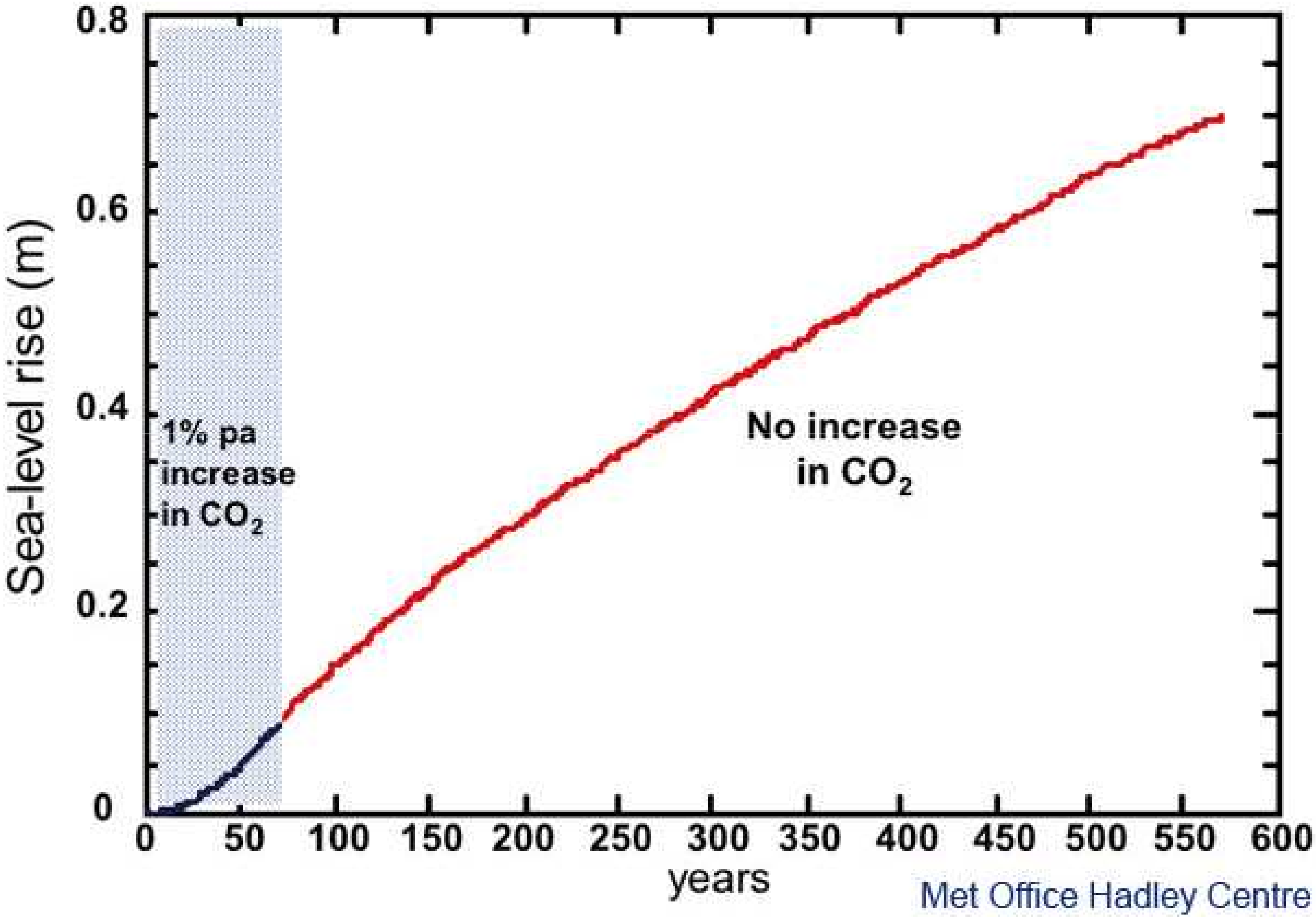


- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier

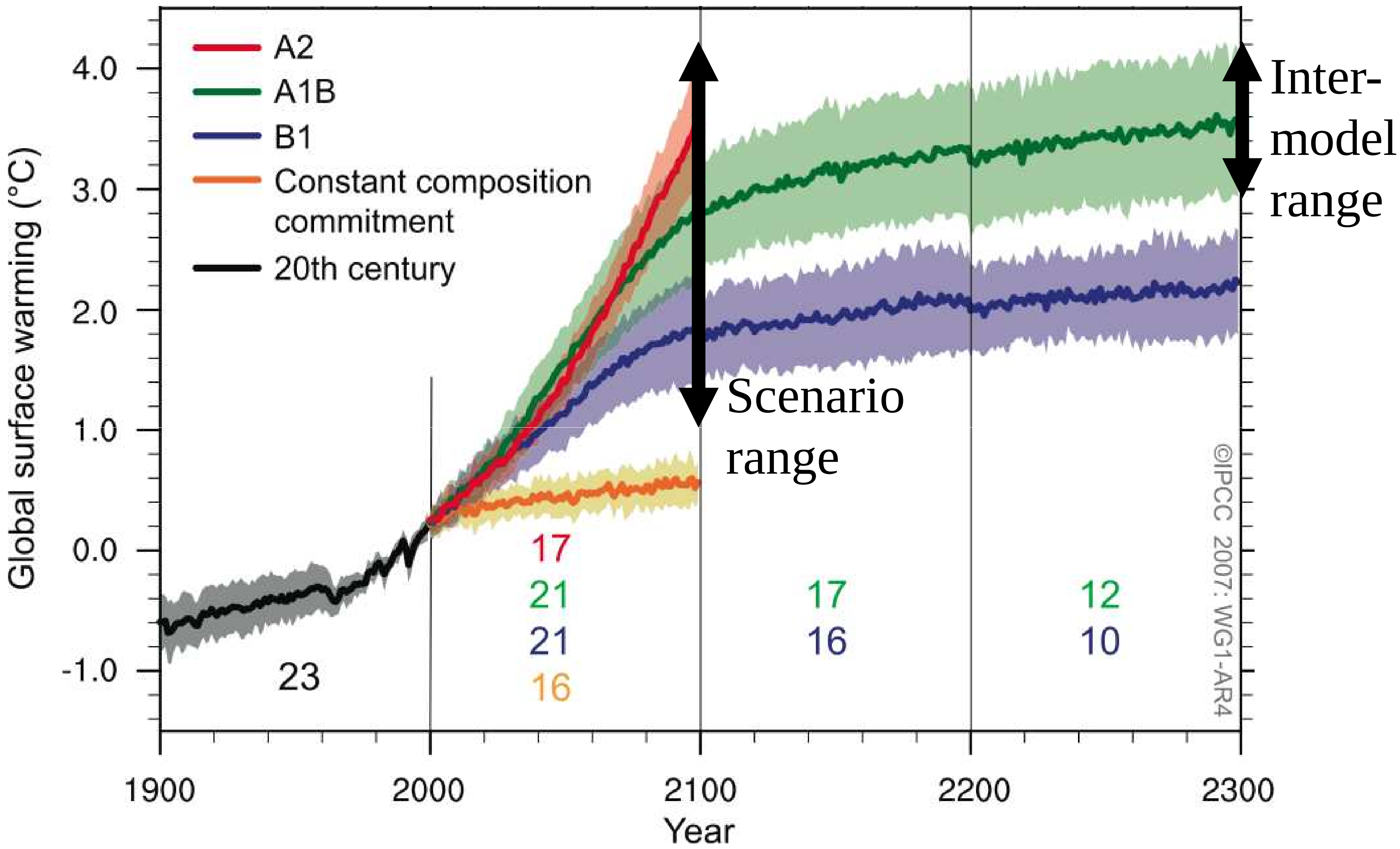


Intergovernmental Panel on Climate Change: www.ipcc.ch

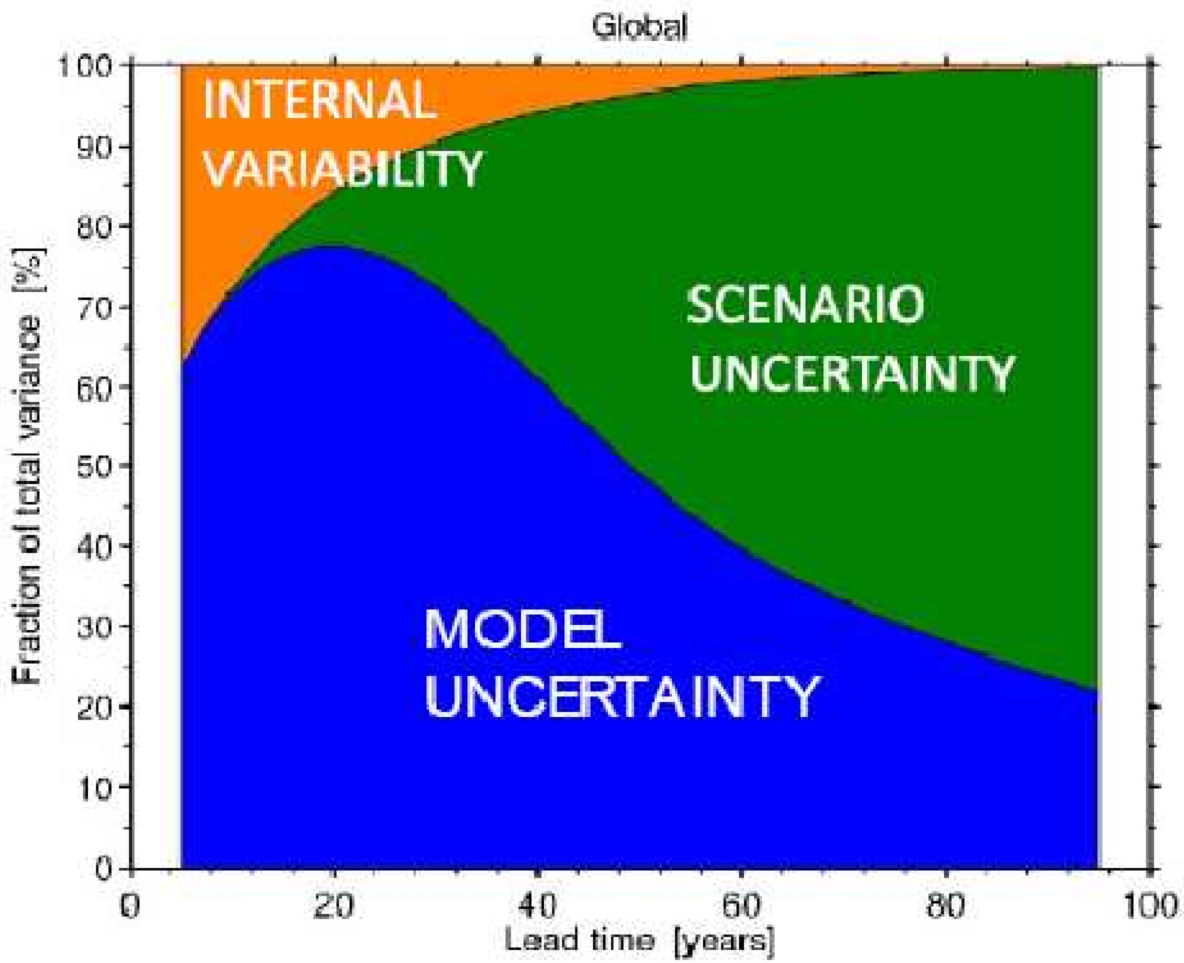
Long-term commitment to sea-level rise



What about future projections?



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



Global, decadal mean

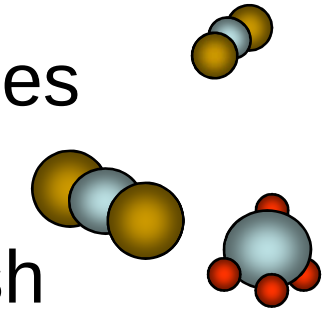
Relative sources of uncertainty in climate prediction for surface aire temperature [Hawkins and Sutton, 2009 BAMS]

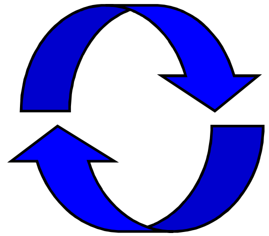
- Predicted magnitude of climate change has a very large range because of:
  - Uncertainty in future emissions
  - Uncertainty in climate feedbacks
  - *Uncertainty in initial conditions*

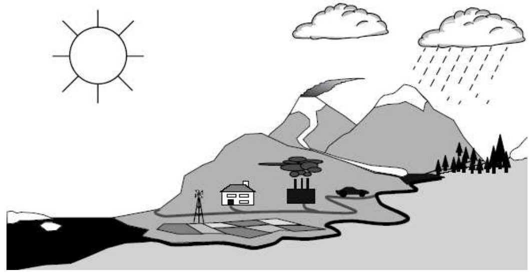
e.g. see Hawkins and Sutton (2009) BAMS

What are the projections of future climate?

- Increase in man-made greenhouse gases alone will not produce a *big* warming
- **Feedback loops** can amplify or diminish the warming from greenhouse gases
- Understanding these processes is crucial for accurate prediction of future climate







Forcing and response: a natural experiment


29/3/06 11.05am
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29/3/06 12.26pm
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Clouds affect radiation fluxes
Radiation fluxes affect clouds

Radiative Forcing and Feedbacks

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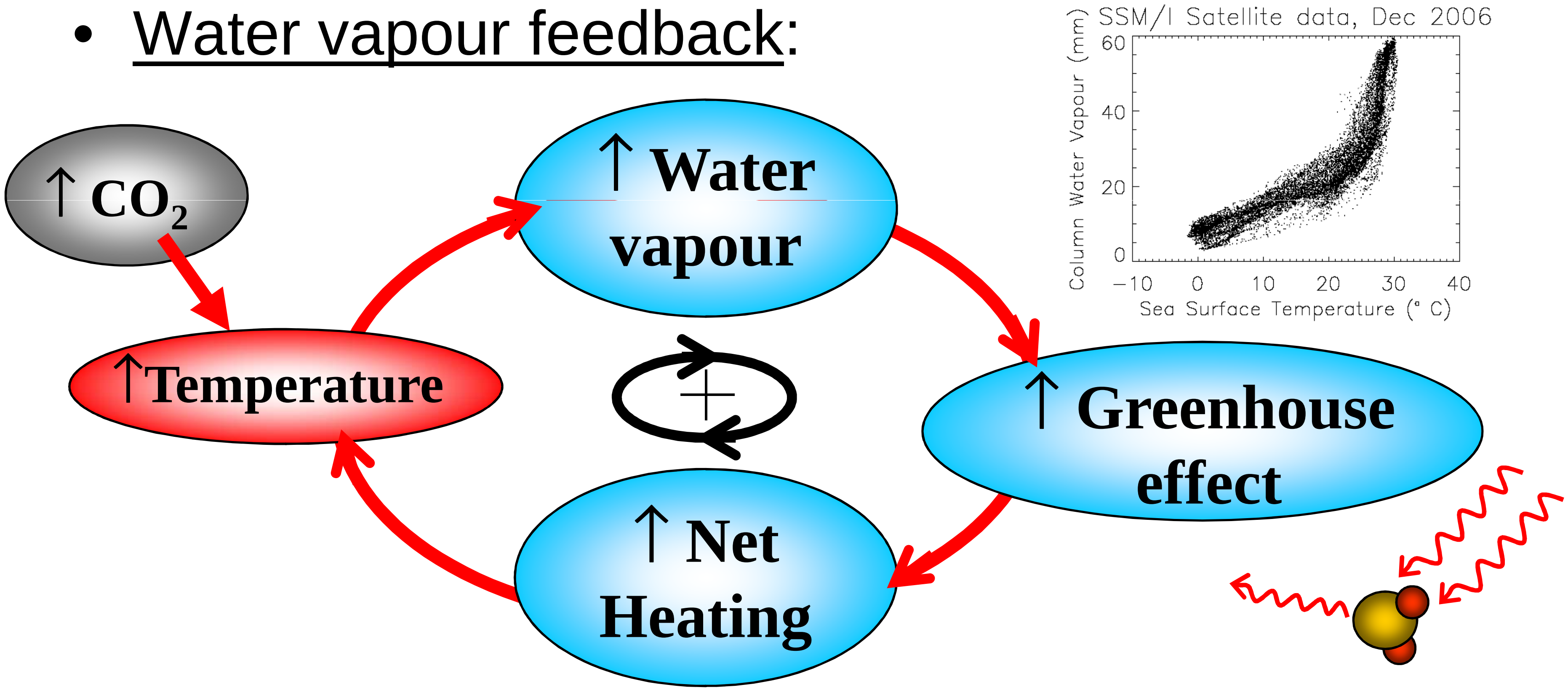
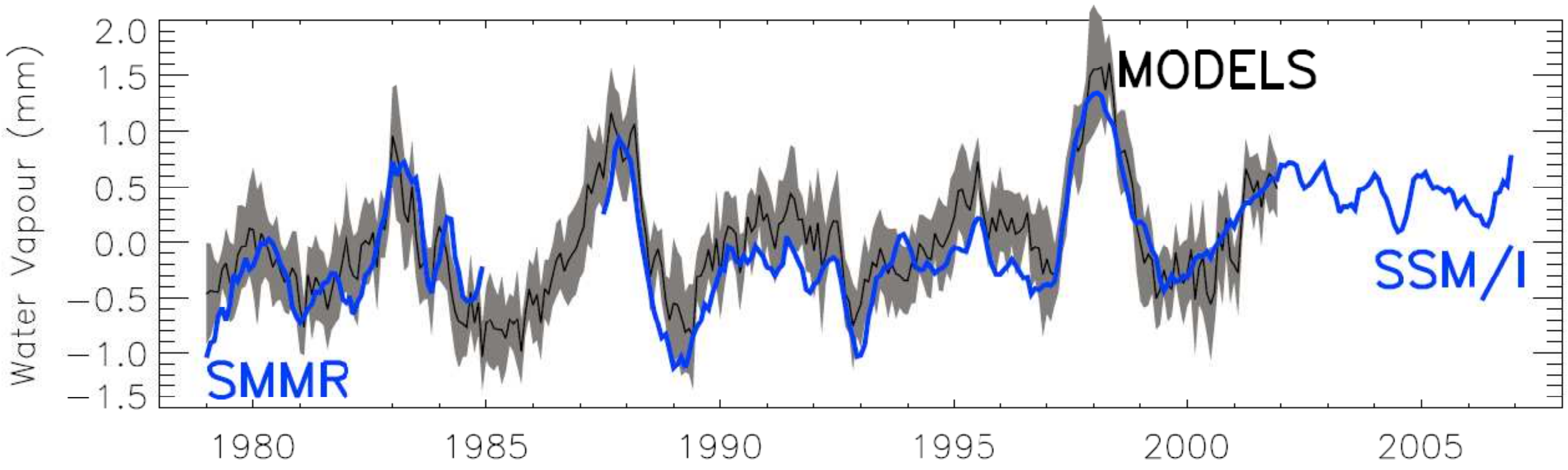
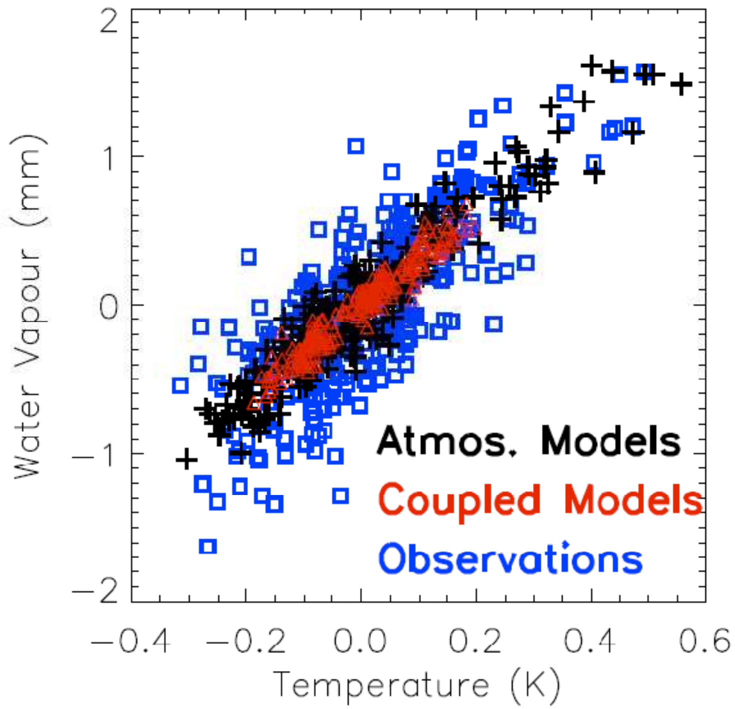
- Increase in CO_2 → reduced radiative cooling
- Increased Temperature to balance radiative forcing
- Water vapour feedback:





Atmospheric Moisture Rises with Warming in Climate Models and as detected by Satellite Observations



Quantifying Feedbacks

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

- ΔR: Net top of atmosphere radiation
- ΔQ: Radiative forcing
- λ: Climate sensitivity
- T_s: 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

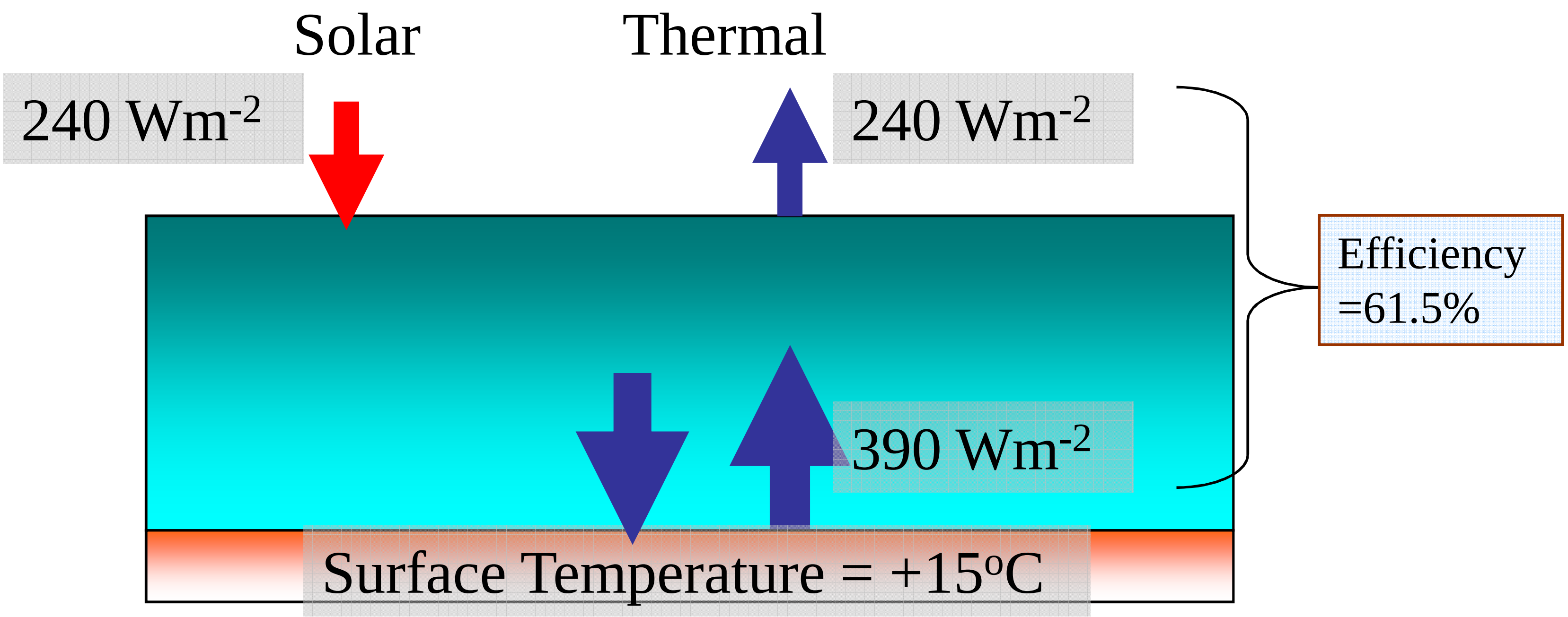
$$\frac{\partial R}{\partial T_s} \approx -4\sigma T^3$$

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

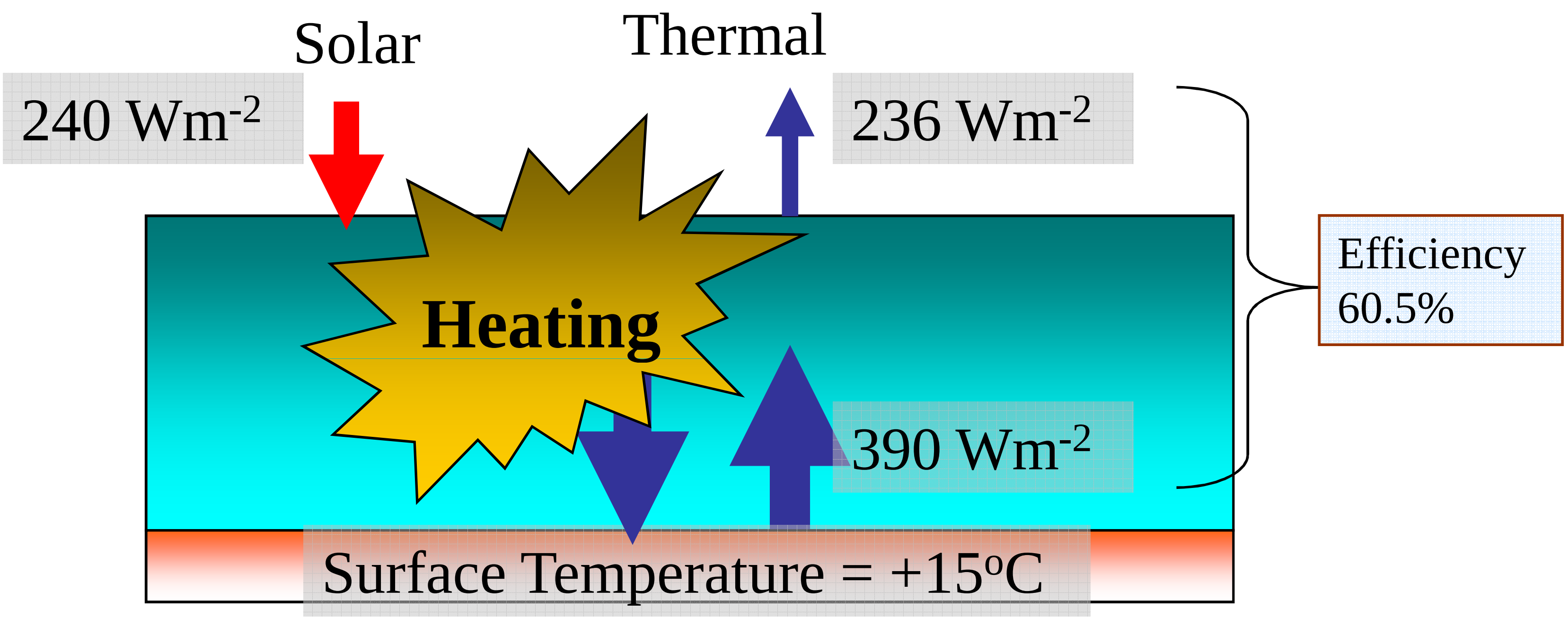
(using GCMs ~ -3.2 $Wm^{-2}K^{-1}$)

e.g. see Bony et al. (2006) J Clim

Earth's global average energy balance: present day



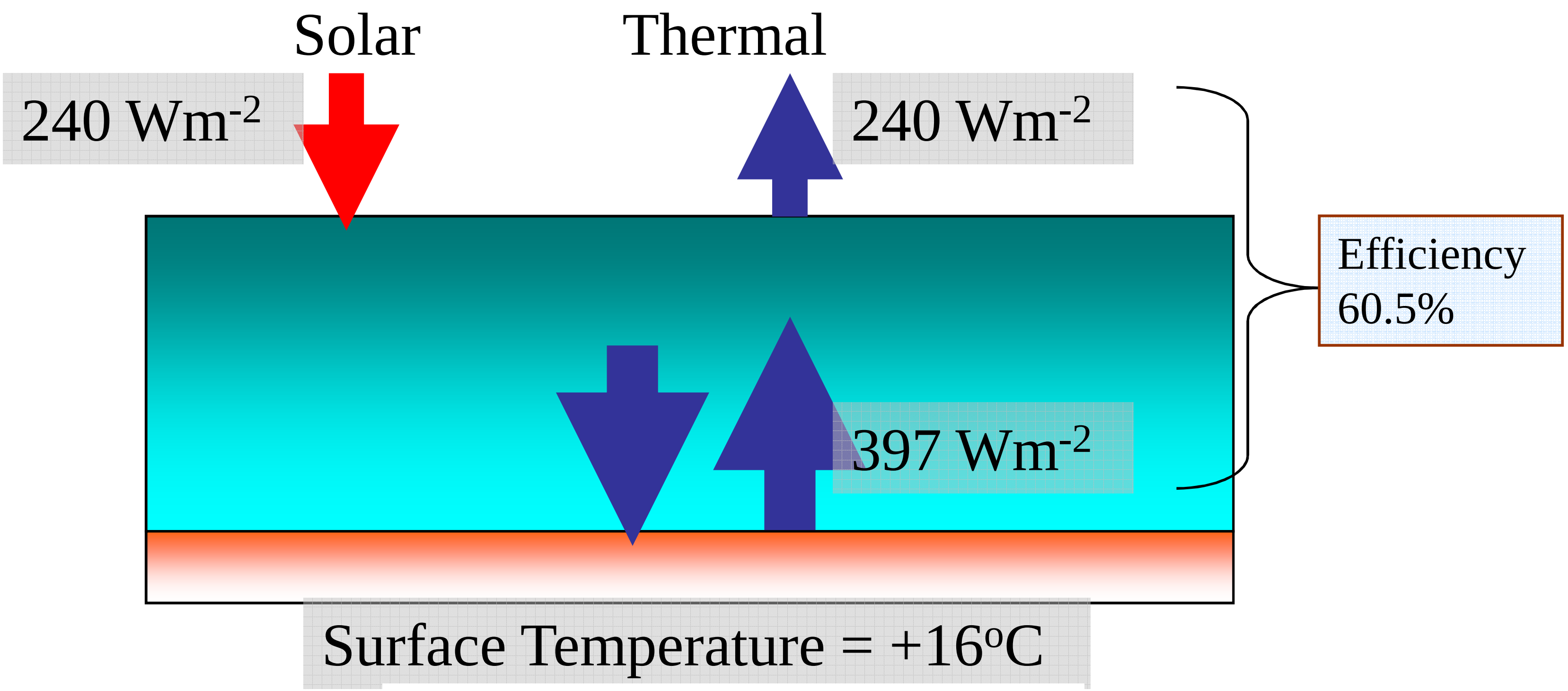
Earth's global average energy balance: present day, $2xCO_2$



ΔQ_{CO2} ~ 5.35ln(CO2/CO2_base) = 5.35ln(2)

ΔQ_{CO2} ~ **3.7 Wm^{-2}**

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

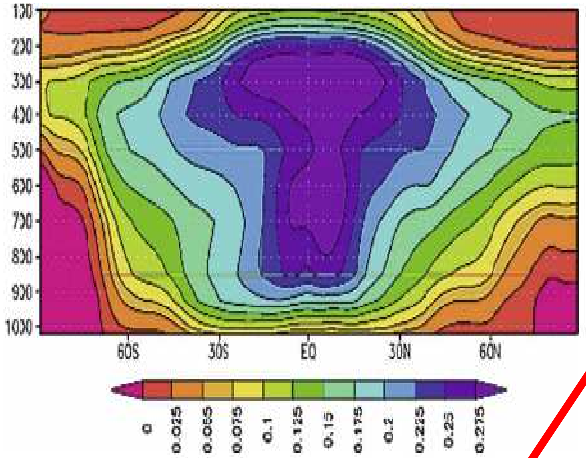


$$\Delta Q = -\lambda \Delta T_s$$

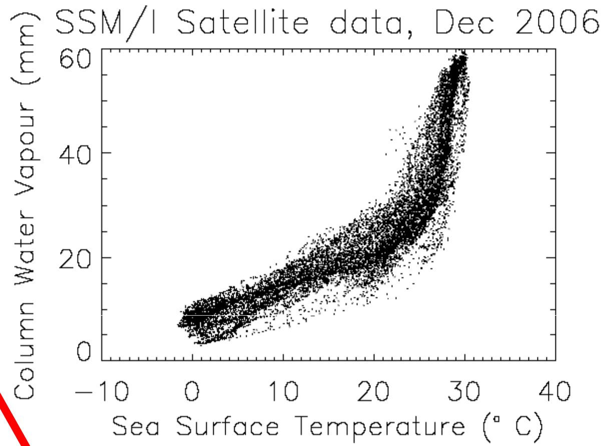
$$3.7 = -(-3.2)\,\Delta T; \quad \mathbf{\Delta T \sim 1.2\ K}$$

Climate sensitivity and water vapour feedback

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



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



~0.15 $Wm^{-2}\%^{-1}$

~10%K^{-1}

λ_{BB}=-3.2 $Wm^{-2}K^{-1}$ ~ $-4\sigma T^3$

λ_{WV}~(0.2)(7)=1.5 $Wm^{-2}K^{-1}$

$\lambda_{WV}+\lambda_{BB}$~1.5 - 3.2 = -1.7 $Wm^{-2}K^{-1}$

$2xCO_2$ Response + Water Vapour Feedback

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

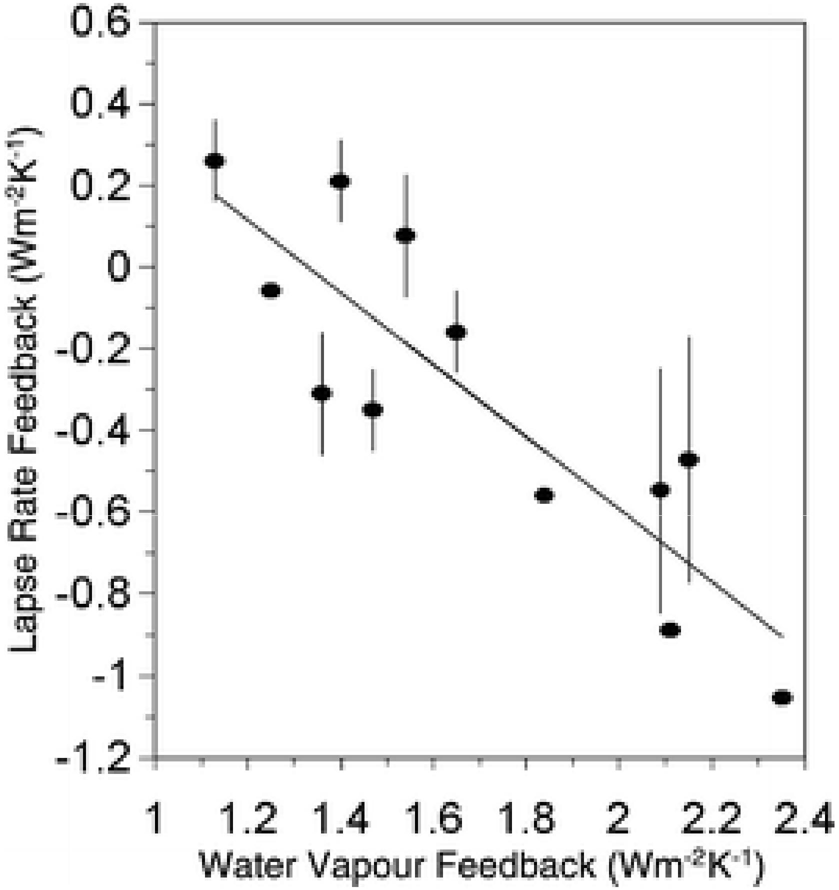
$$3.7 = -(-3.2+1.5)\,\Delta T; \quad \mathbf{\Delta T \sim 2\ K}$$

So water vapour feedback approximately doubles no feedback temperature response to doubling of CO_2

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

Evaluating Water Vapour Feedback in Models

Water vapour / T-lapse rate



- Compensation between water vapour and temperature lapse rate feedback in models

e.g. Colman (2003) Clim Dyn

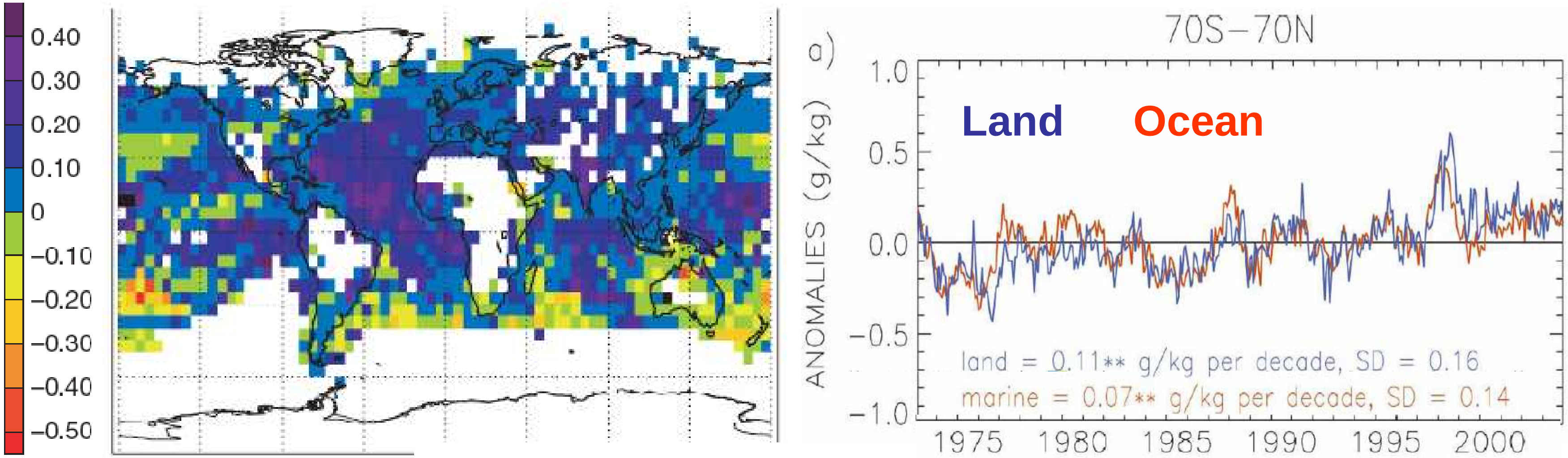
- Sensitivity to convective parametrizations?

e.g. Allan/Ramaswamy/Slingo (2002) JGR 107(D17)

$$\lambda_{WV+\Gamma}+\lambda_{BB} = \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s} \qquad x=T(z)_{\overline{RH}}$$

Does moisture rise at 7%/K over land surface?

Specific humidity trend correlation (left) and time series (right)

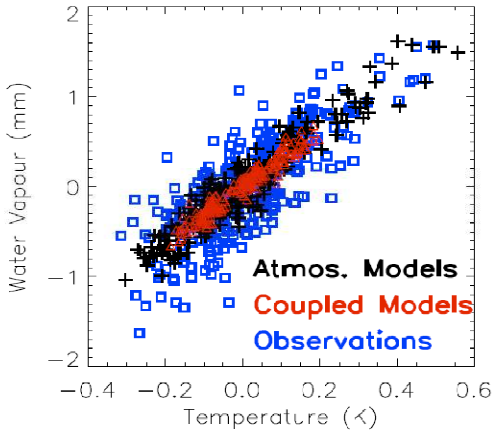


Willett et al. (2007) *Nature*; Willet et al. (2008) J Clim

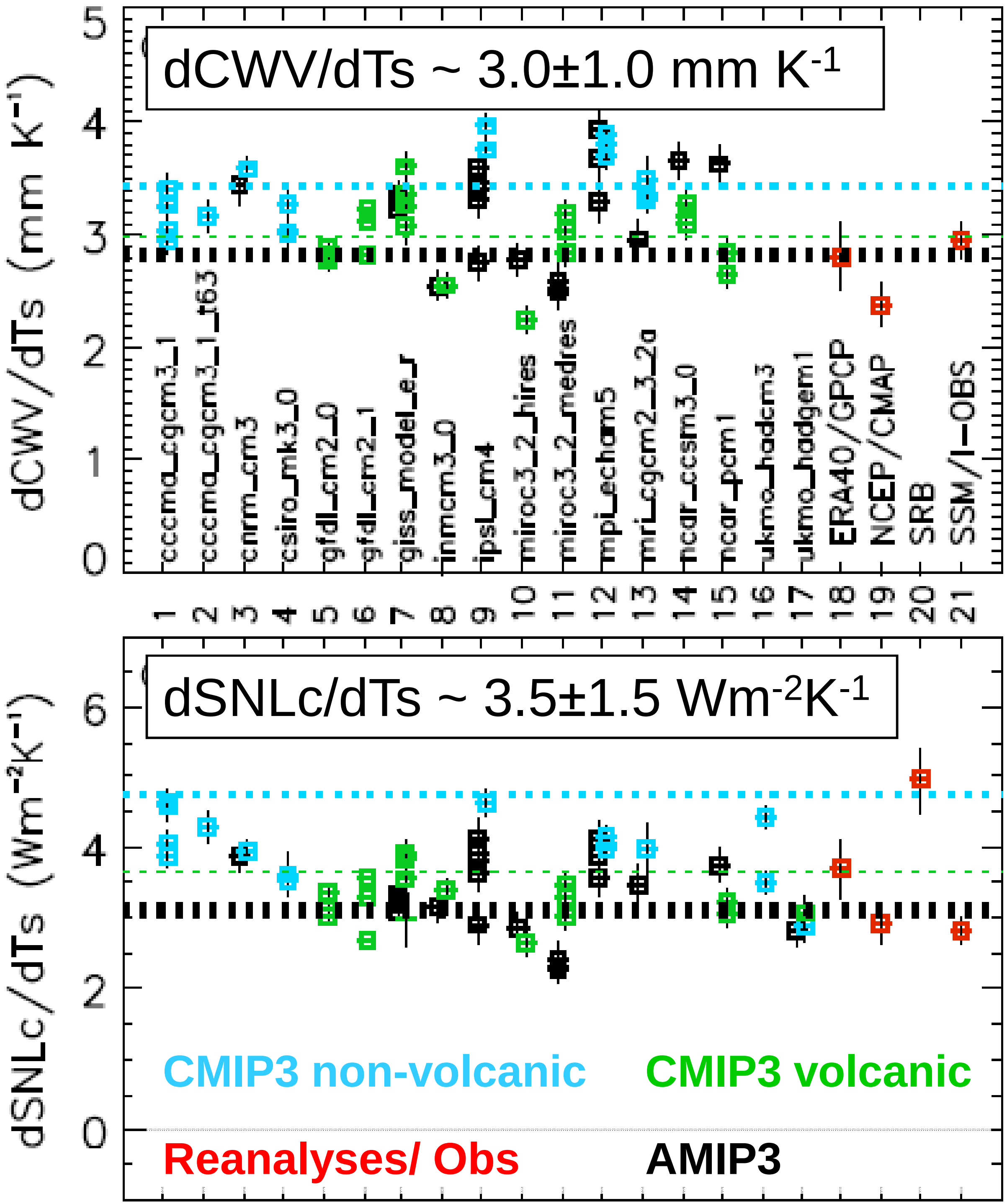
Moisture rises due to Clausius Clapeyron are higher for colder temperatures (e.g. higher latitudes or altitudes).

But some contradictory results (e.g., Wang et al. (2008) GRL)

Surface radiation



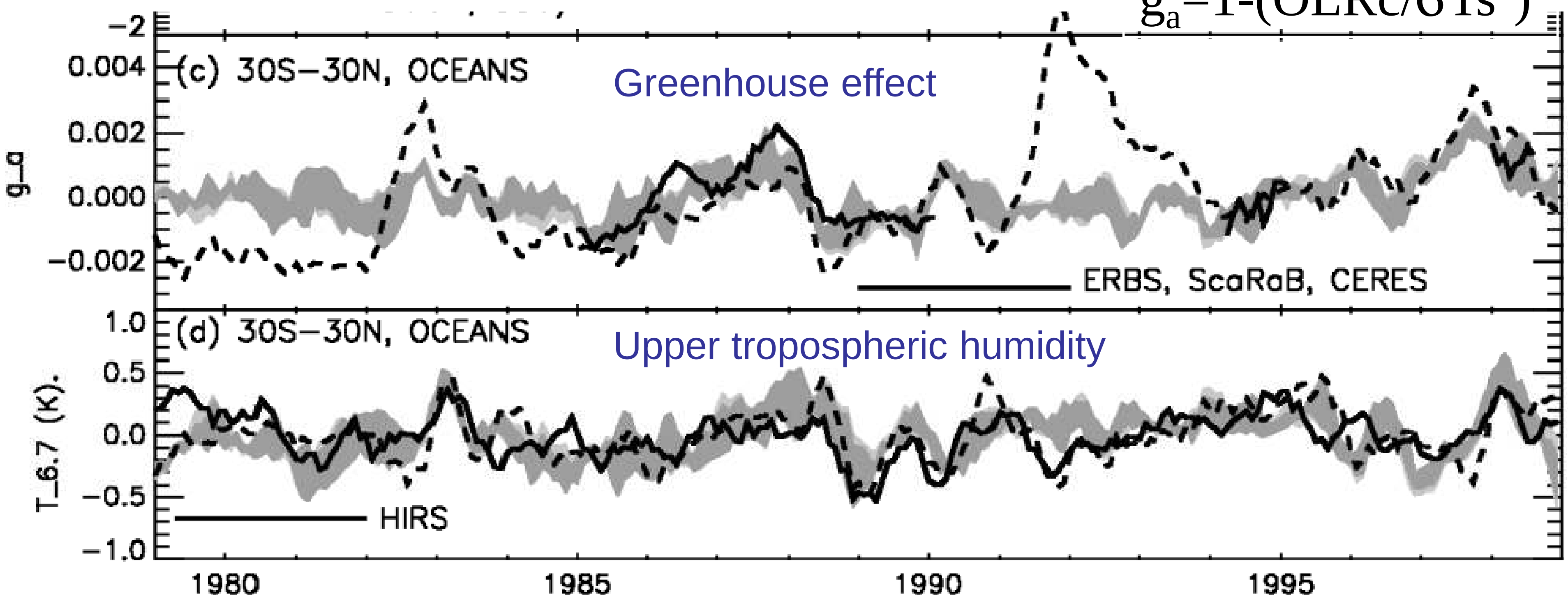
Models, reanalyses and observations show increased surface net downward longwave with warming due to increased water vapour



What about the upper troposphere?

Evaluating clear-sky longwave radiation and UTH

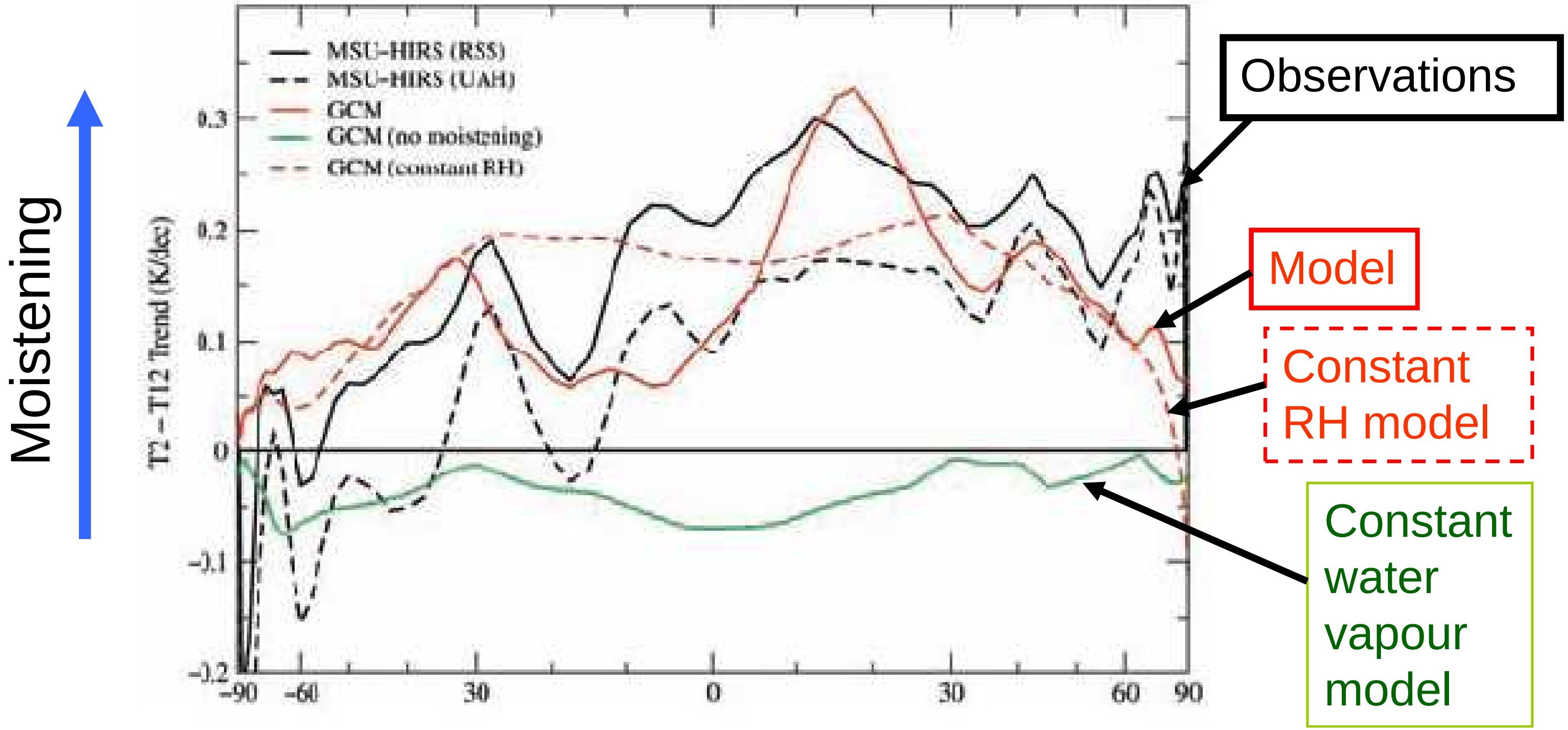
$g_a = 1 - (OLRc / \sigma Ts^4)$



(Allan et al. 2003, QJRMS, p.3371)

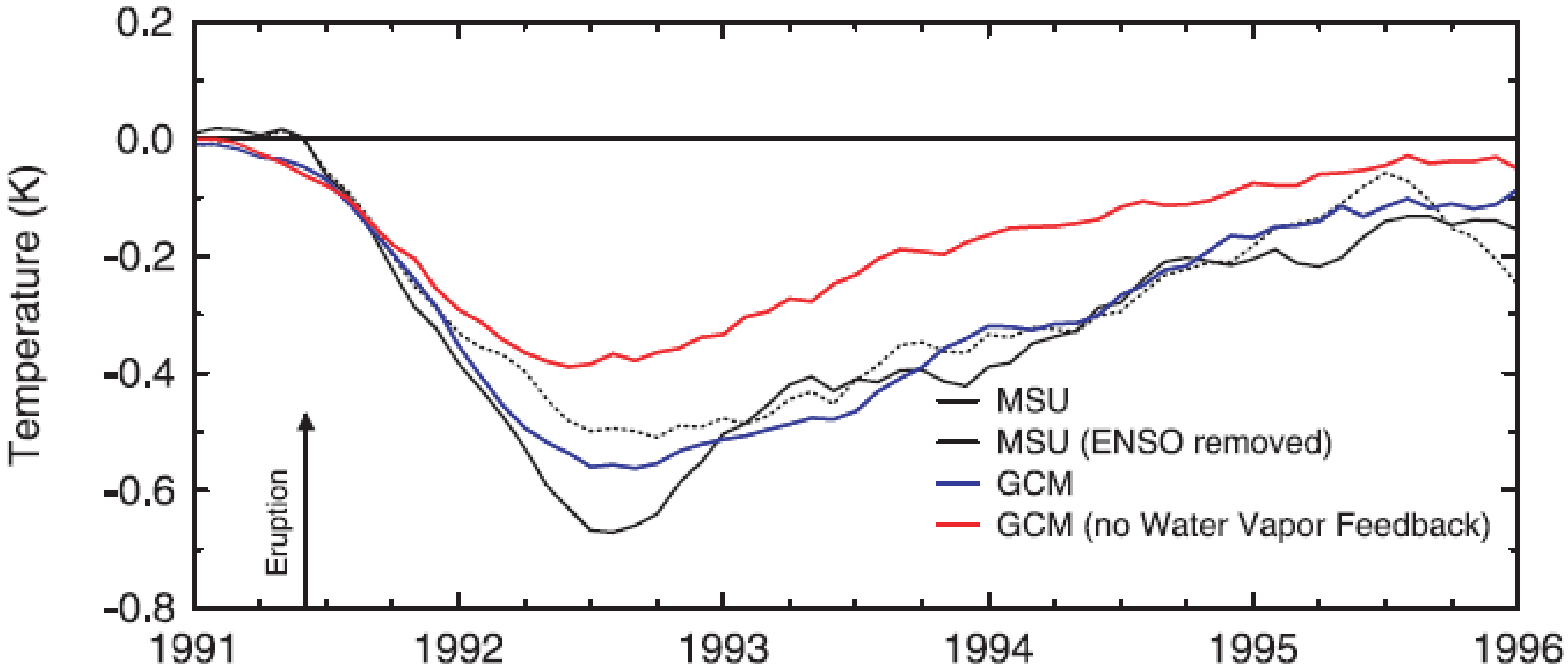
Upper tropospheric moistening consistent between models and satellite data

Trend in water vapour radiance channels: 1983-2004



Soden et al. (2005) *Science*

Model reproduces water vapour feedback response to Pinatubo eruption



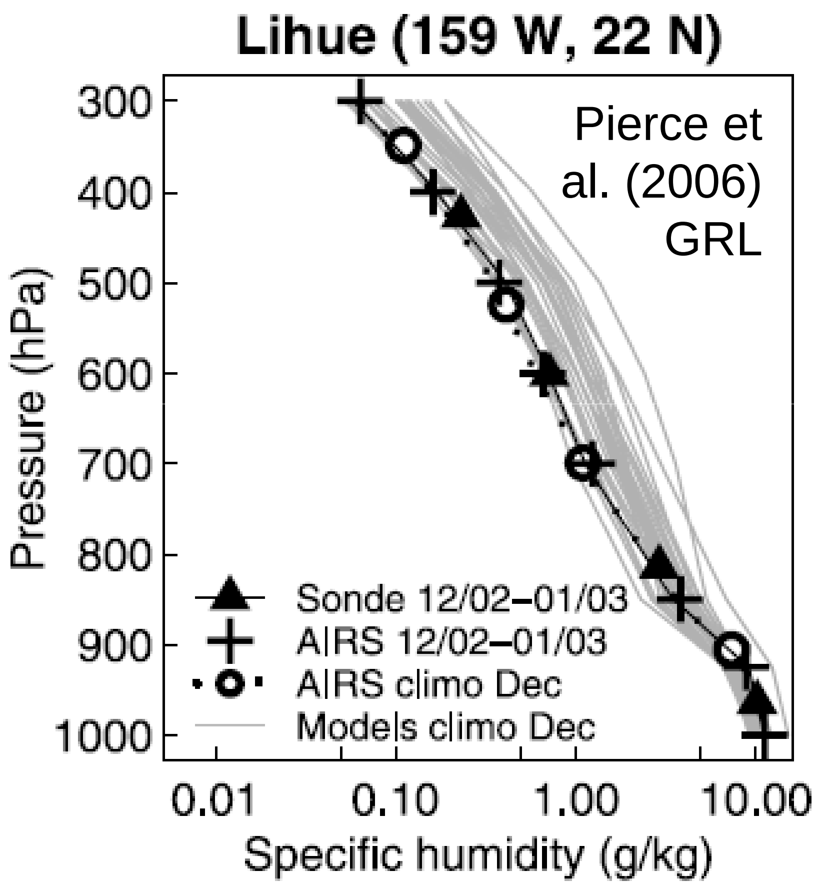
Soden et al. (2002) *Science*

Is the water vapour feedback issue solved?

- Why is RH conserved?
- Do feedbacks operate differently on different time-scales?
- Why does water vapour feedback/lapse rate feedback amplify climate sensitivity by nearly a factor of two?

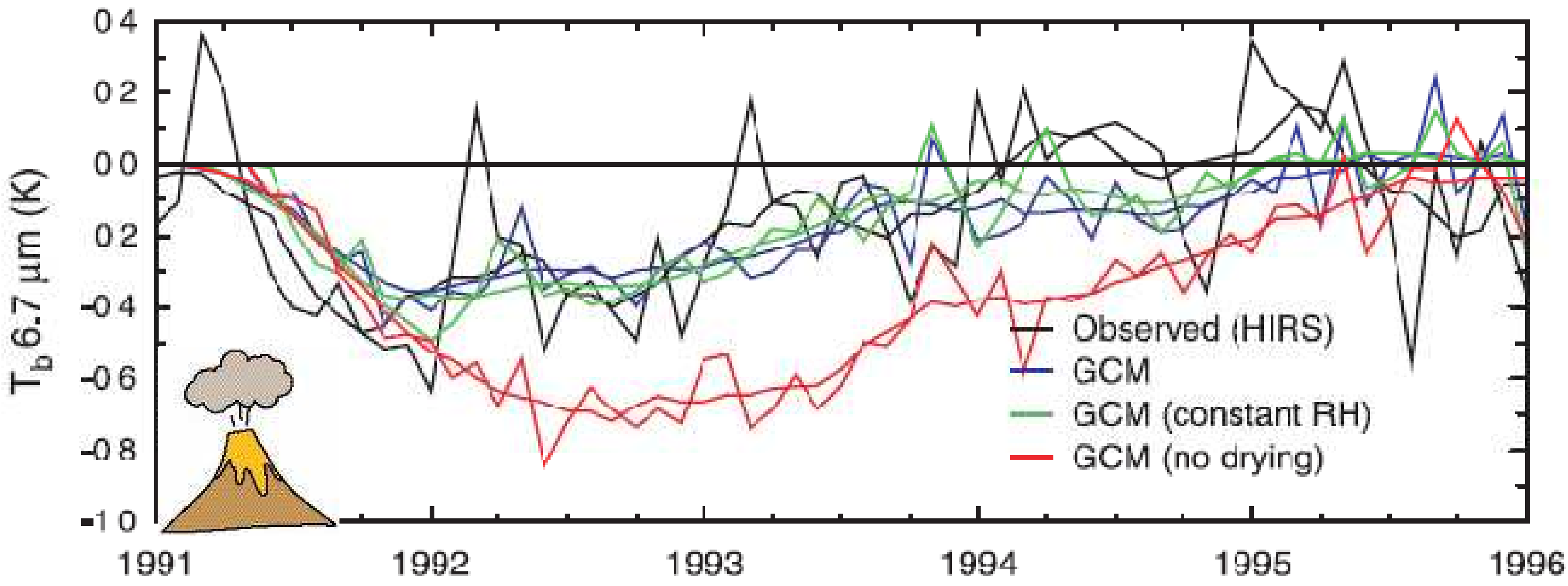
See: Bony et al. (2006) J Clim, Folkins et al. (2002) JGR; Sherwood and Meyer (2006) J Clim, Ingram (2009), also Simpson (1928) QJRMS

Is the mean state important?

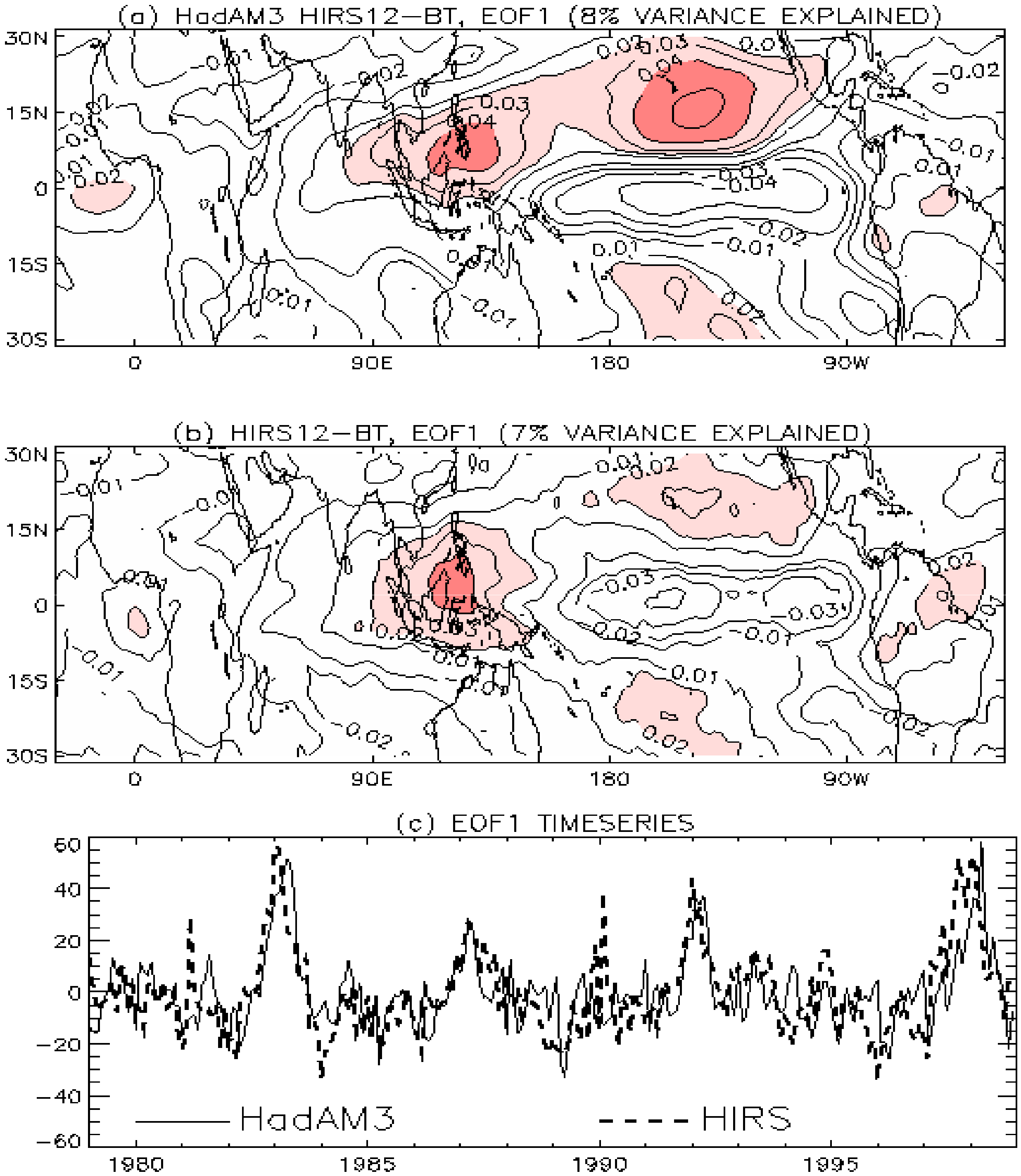


- Models appear to overestimate water vapour
  - Pierce et al. (2006) GRL; John and Soden (2006) GRL
  - But not for microwave data? [Brogniez and Pierrehumbert (2007) GRL]
- This does not appear to affect feedback strength
  - Held and Soden (2006), John and Soden (2006)
- What about the hydrological cycle?
  - Inaccurate mean state?

What time-scales do different processes operate on?



Soden et al. (2002) *Science*; Forster/Collins (2004) Clim Dyn; Harries and Futyan (2006) GRL



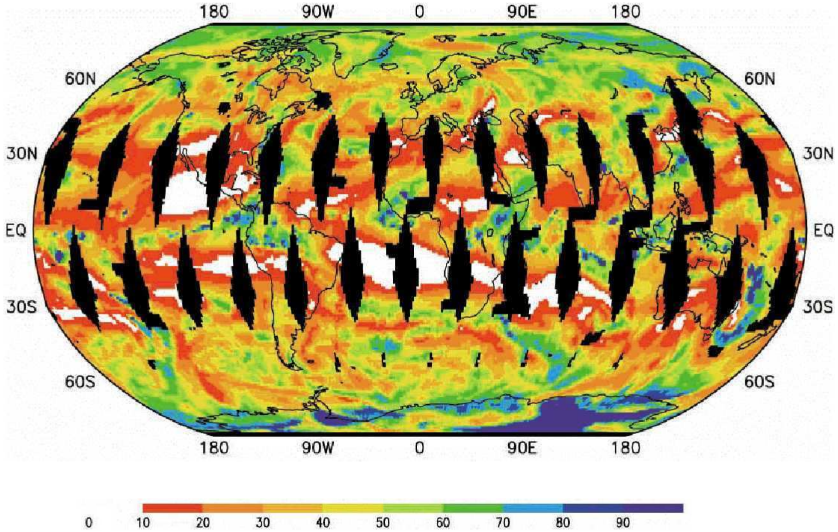
Do models represent the spatio-temporal variability in water vapour radiance?

Allan et al. 2003 QJRMS

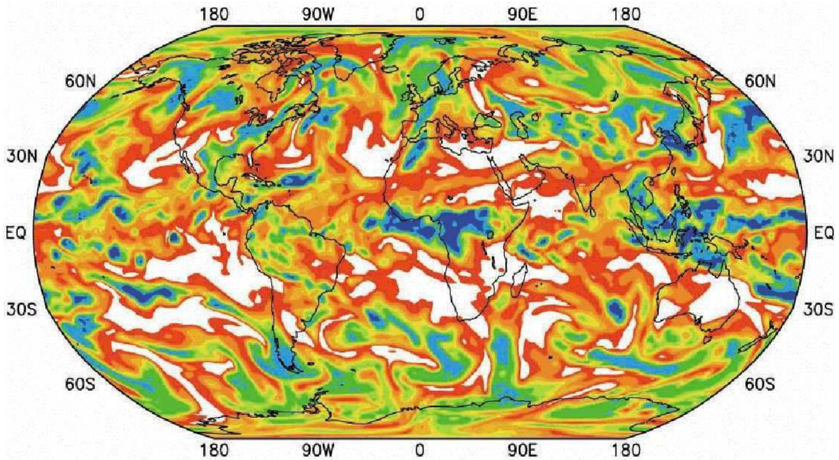
Distribution of upper tropospheric water vapour

(IPCC2001 Chapter 7)

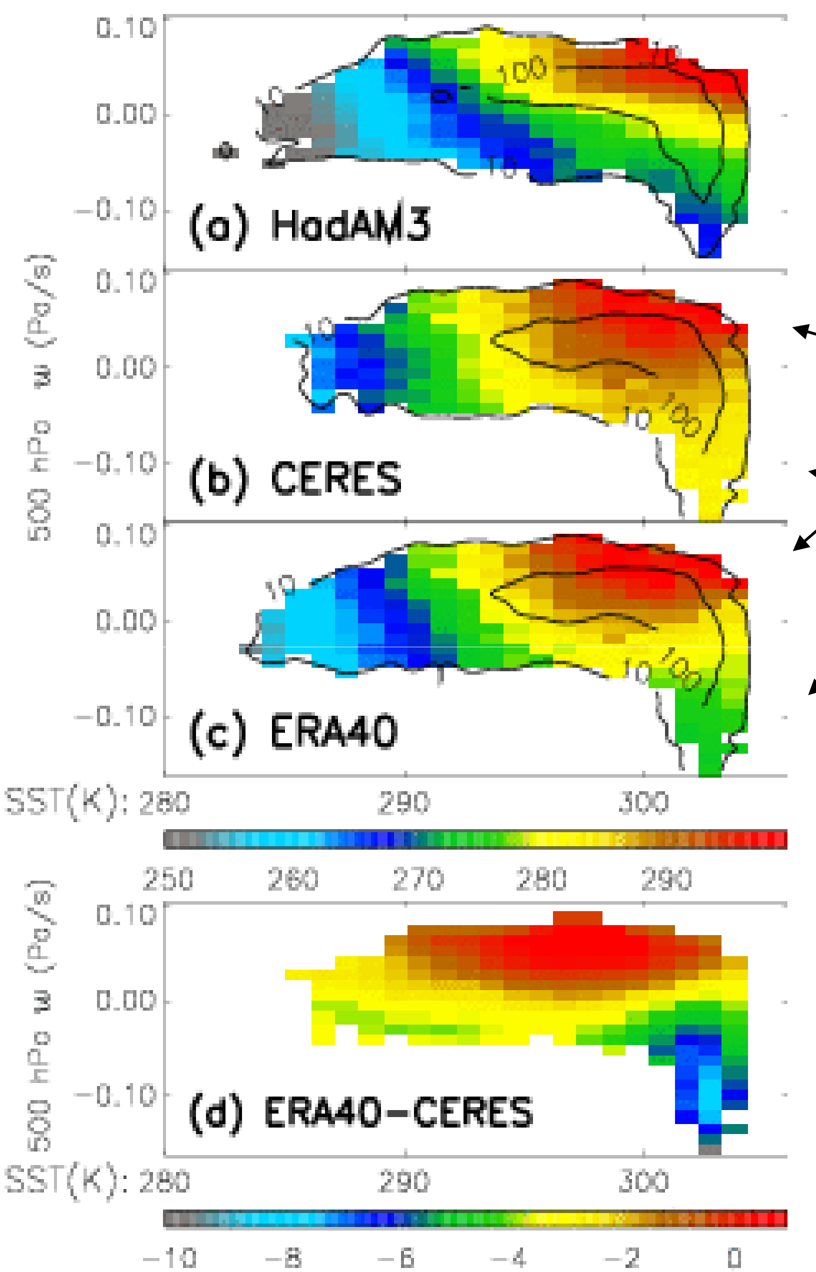
- **Relative humidity in 250-600 hPa layer from SSM/T-2 satellite retrievals (May 5 1998)**



- **Relative humidity at 400hPa simulated in a high resolution atmospheric model (ECHAM4 at T106 ~ 100km)**



Using dynamical regimes approach: clear-sky OLR



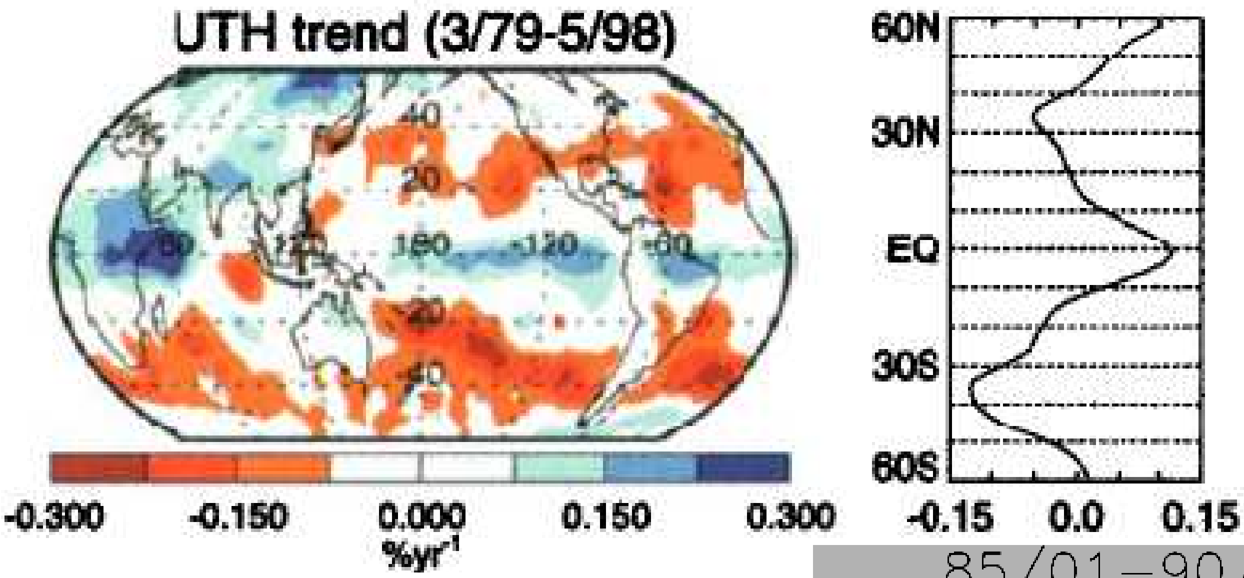
ERA40-CERES similar

ERA40 < CERES

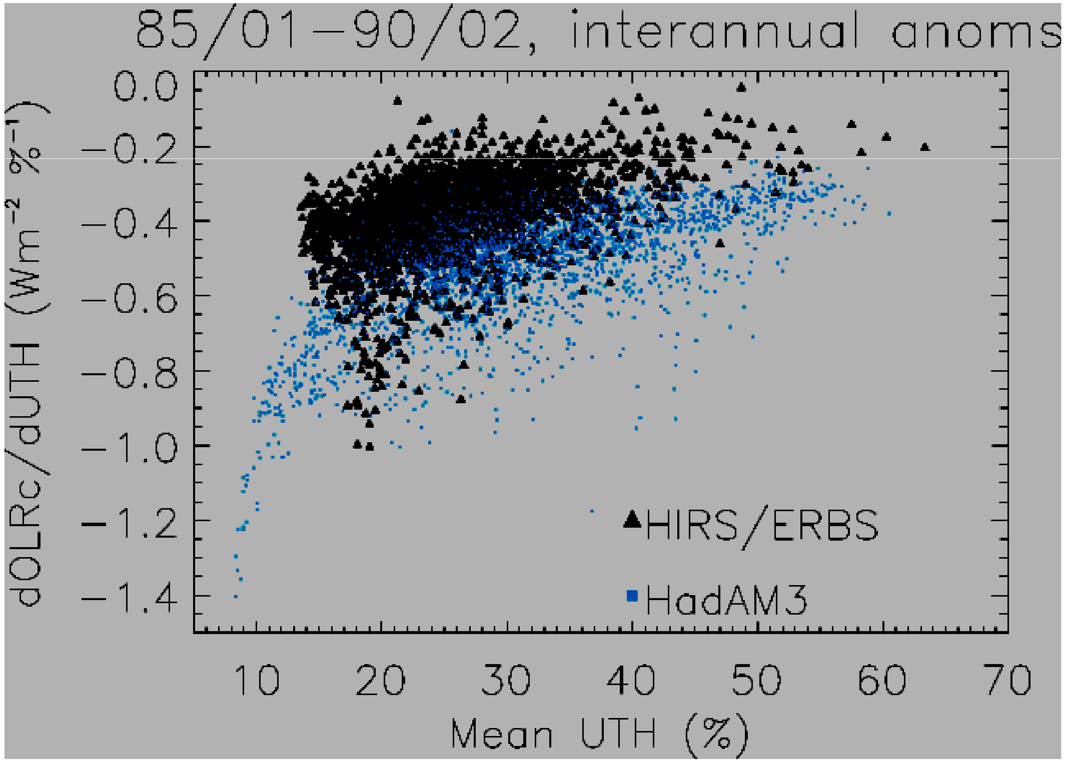
ERA40 minus CERES clear-sky OLR

(January-August 1998)

Allan and Ringer (2003) GRL



Bates and Jackson (2001) GRL



Trends in UTH (above)

Sensitivity of OLR to UTH (right)

Reduction in UTH with warming

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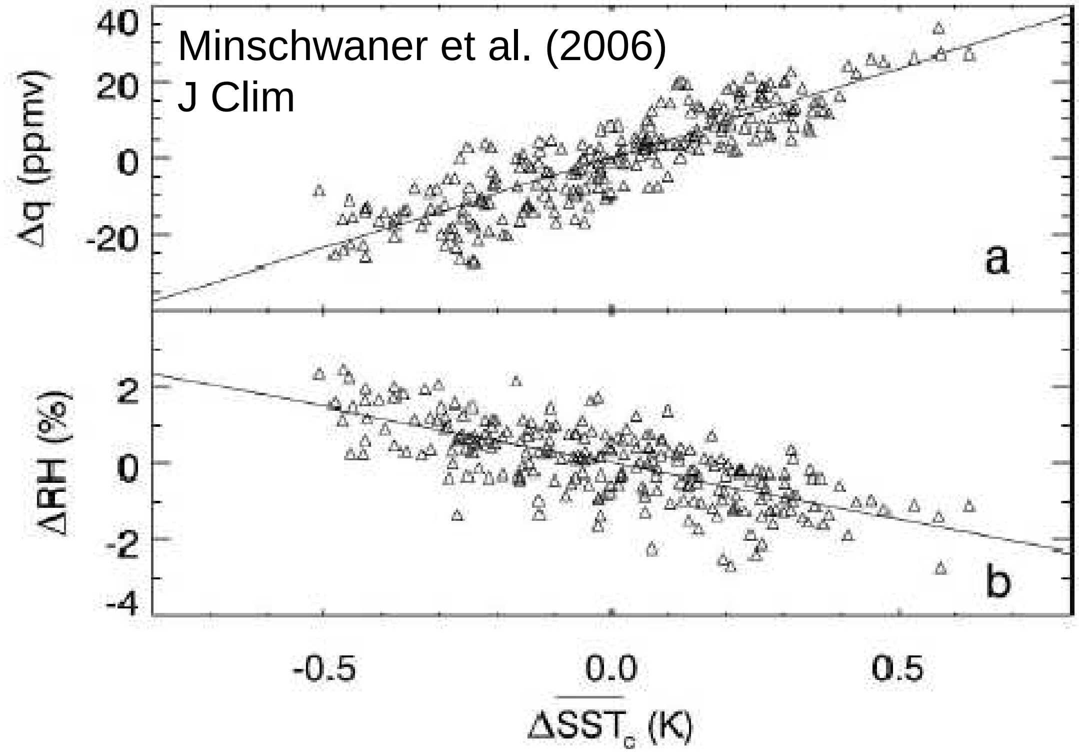
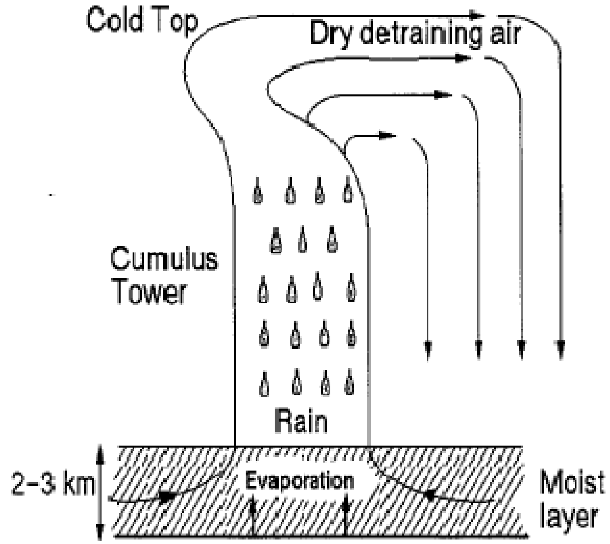
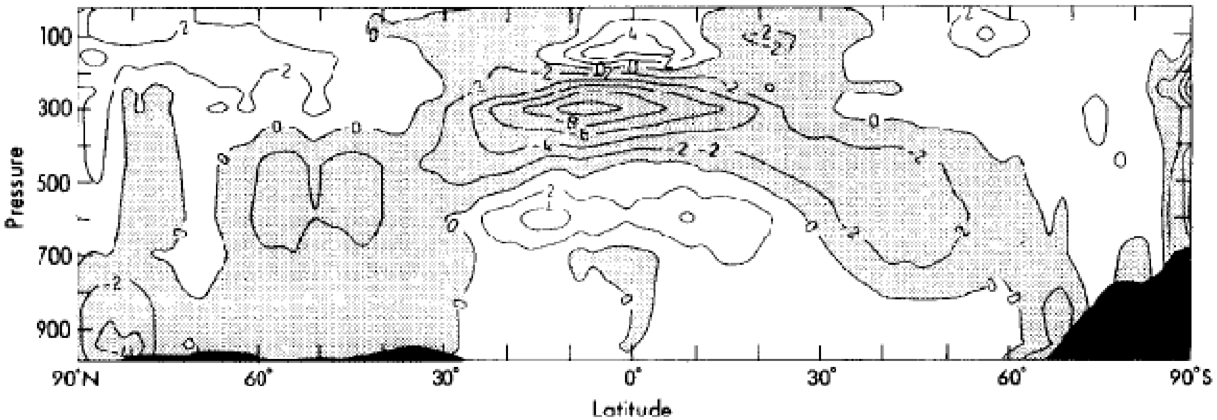


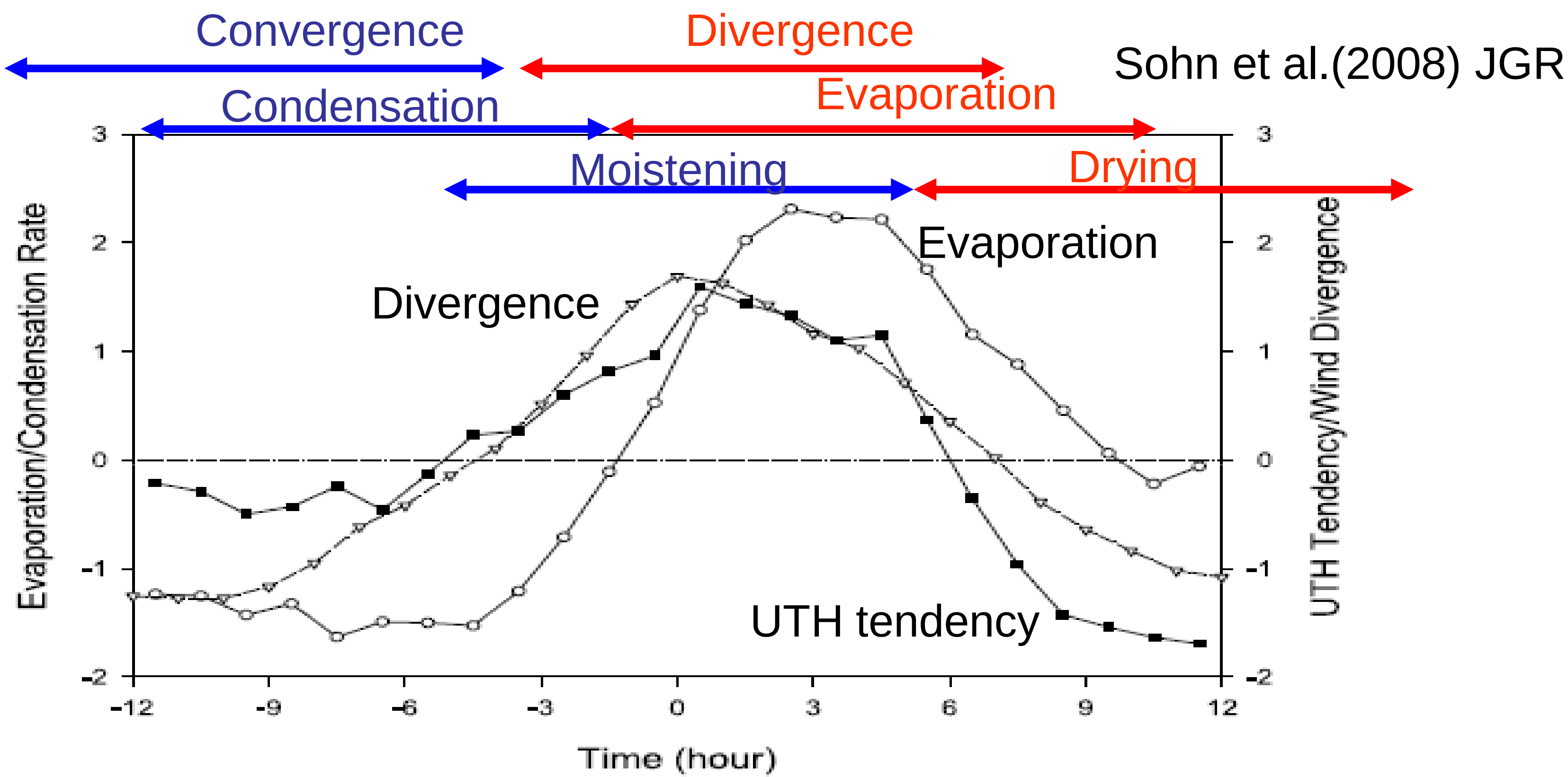


Lindzen (1990) BAMS



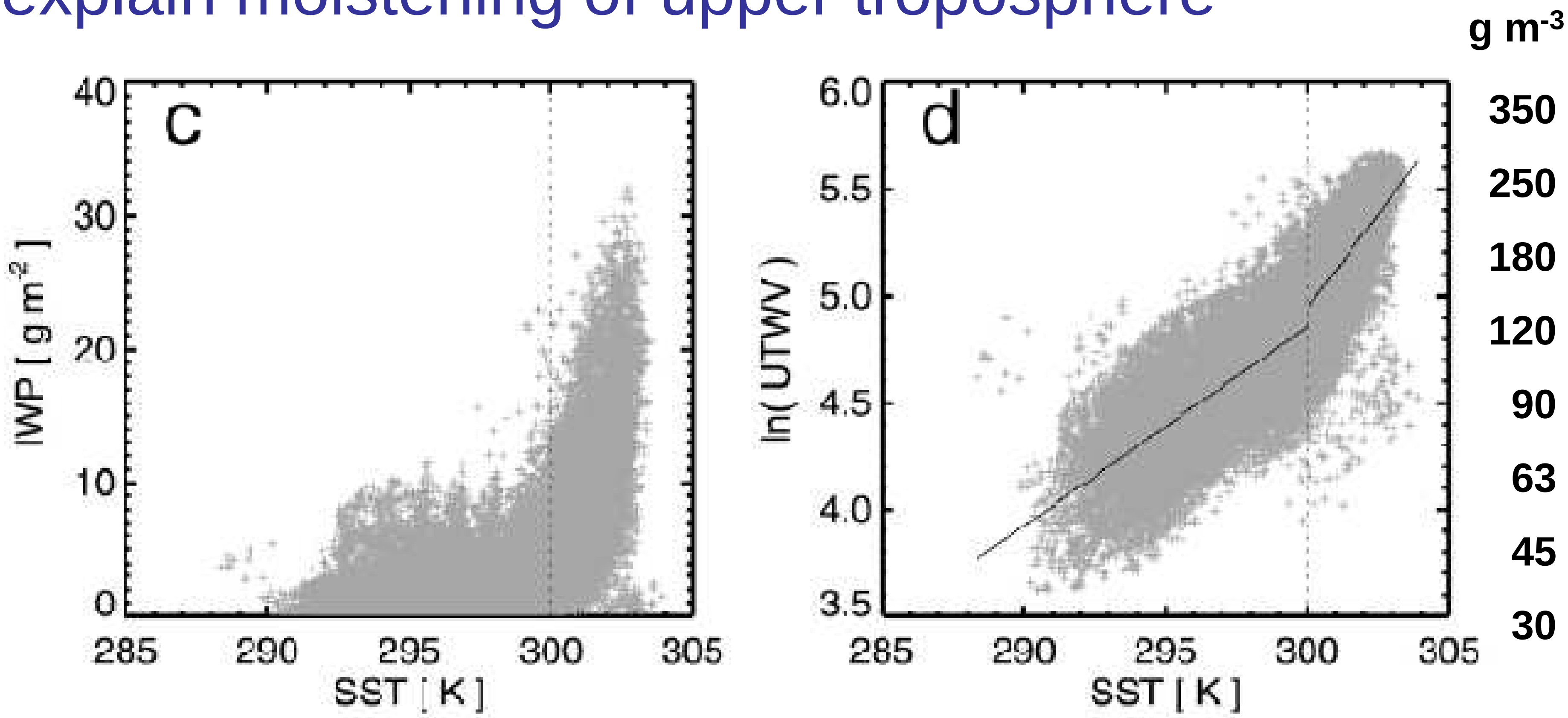
Mitchell et al. (1987)
QJRMS

Moistening processes: diurnal cycle (SEVIRI)



See also Soden et al. (2004) GRL

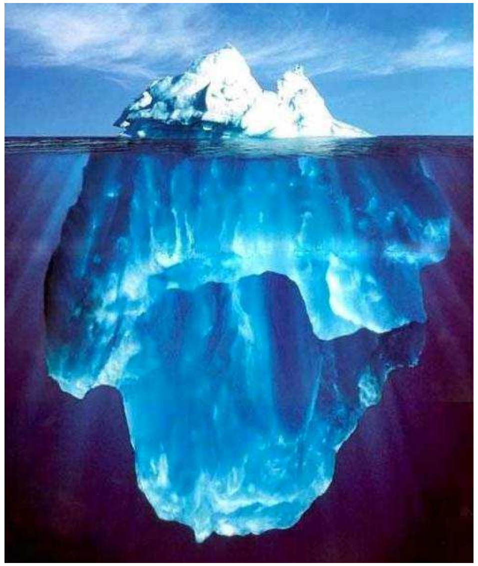
Evaporation of condensate cannot explain moistening of upper troposphere



John and Soden (2006) GRL; Luo and Rossow (2004) J Clim

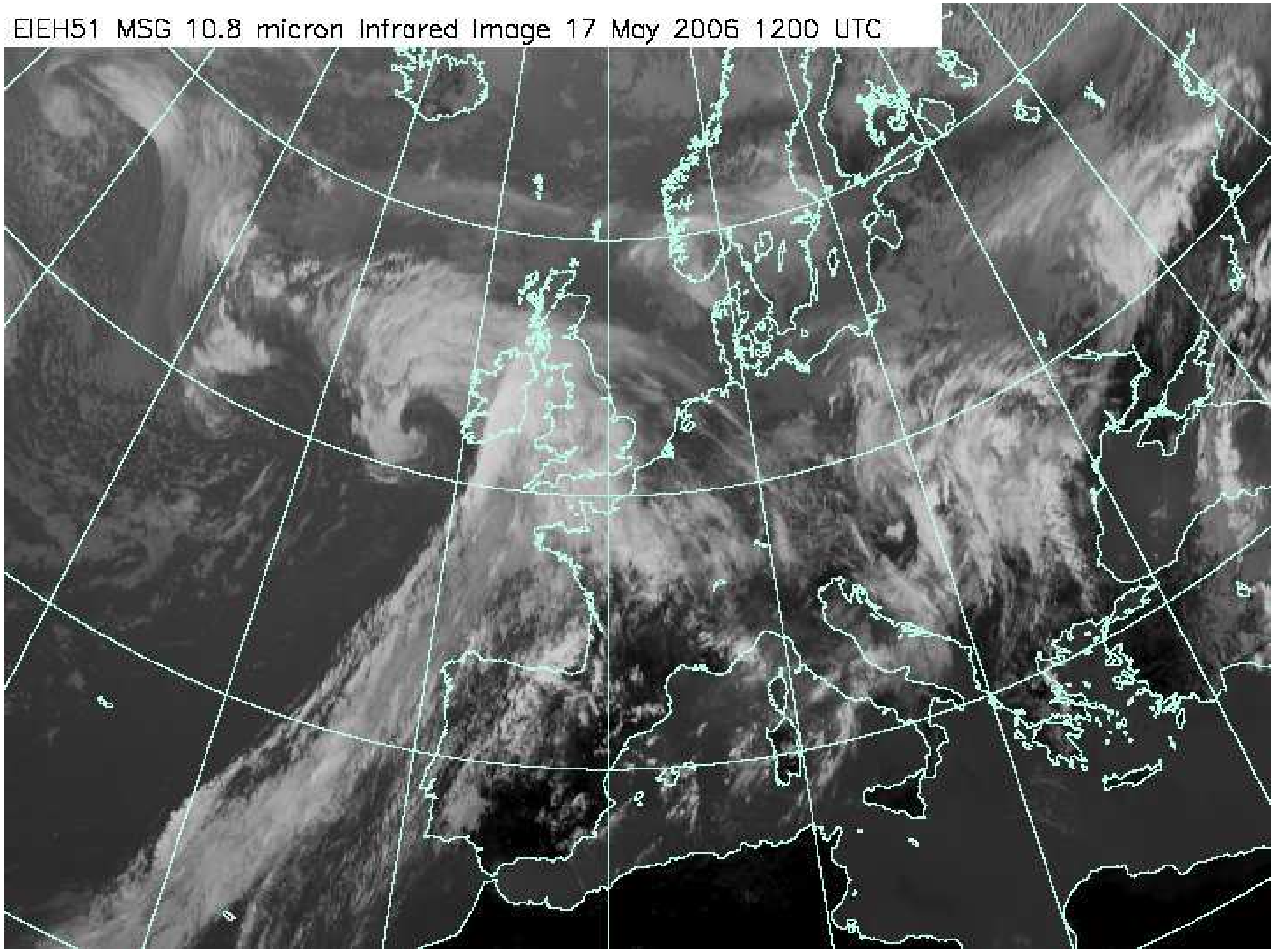
Evaluating Cloud Feedback in Models

What about liquid and frozen water in the atmosphere?

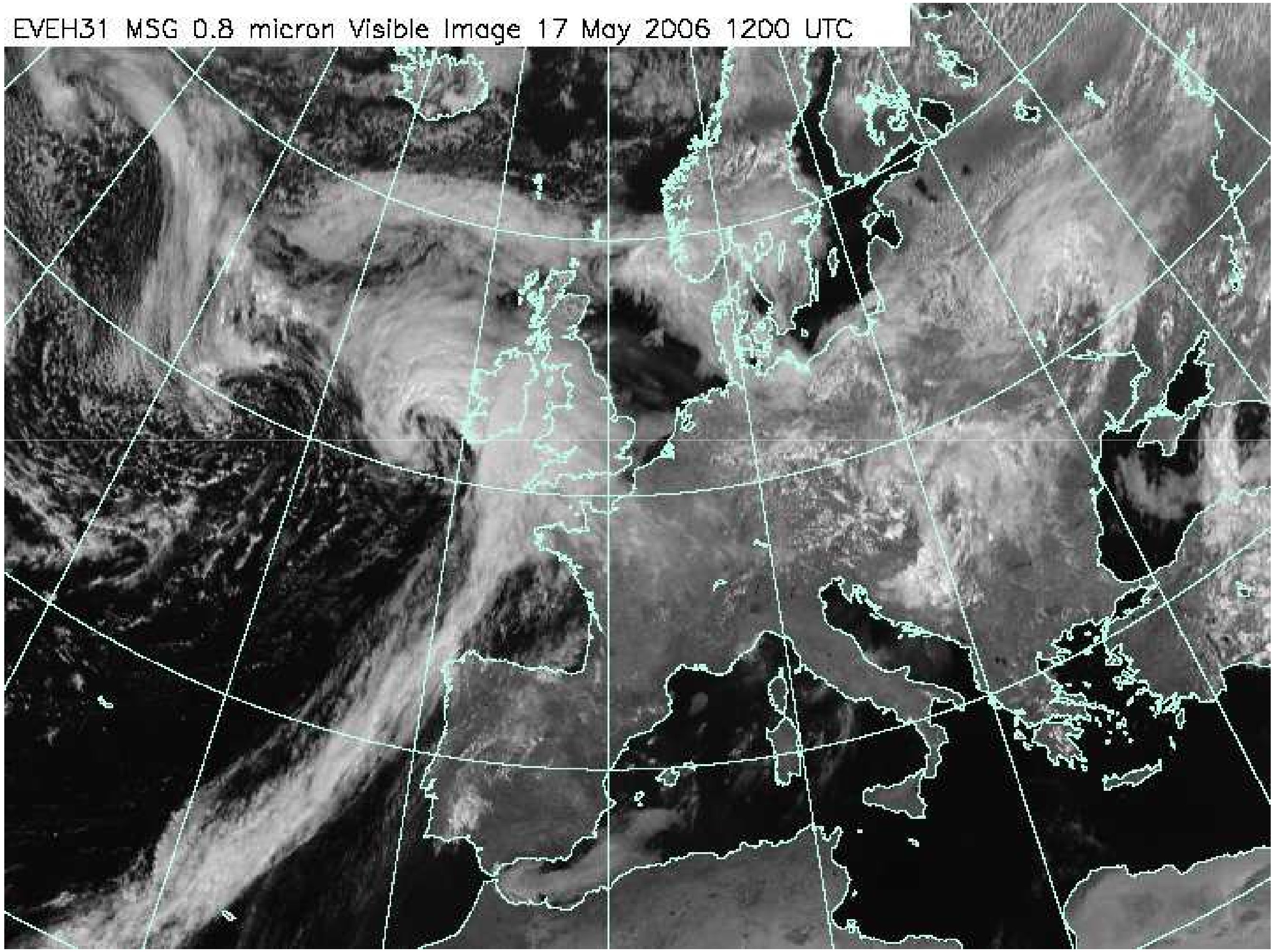


- Most of the water in the atmosphere is invisible vapour
  - Clouds are the tip of the iceberg
  - …water vapour with attitude
- Strong interaction with longwave and shortwave radiation (emission, absorption, scattering)
- Many types of cloud feedbacks are plausible

Infra-red/thermal radiation

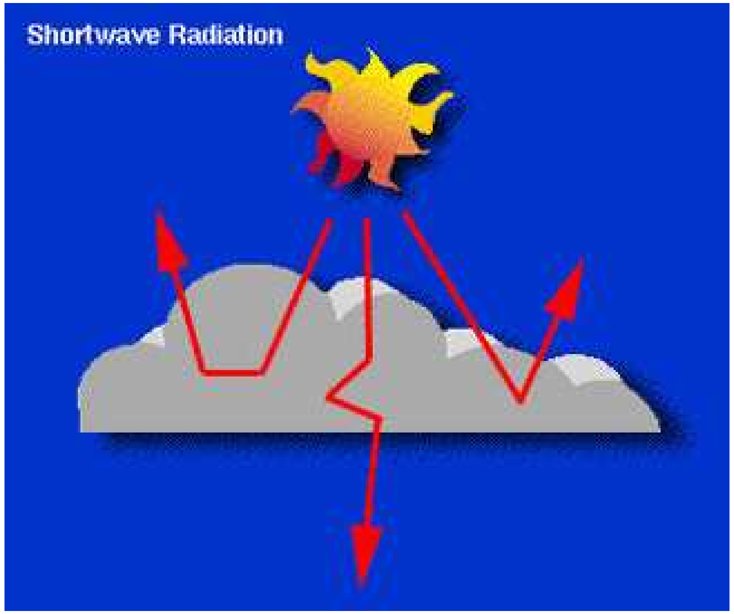


Visible/solar reflected radiation



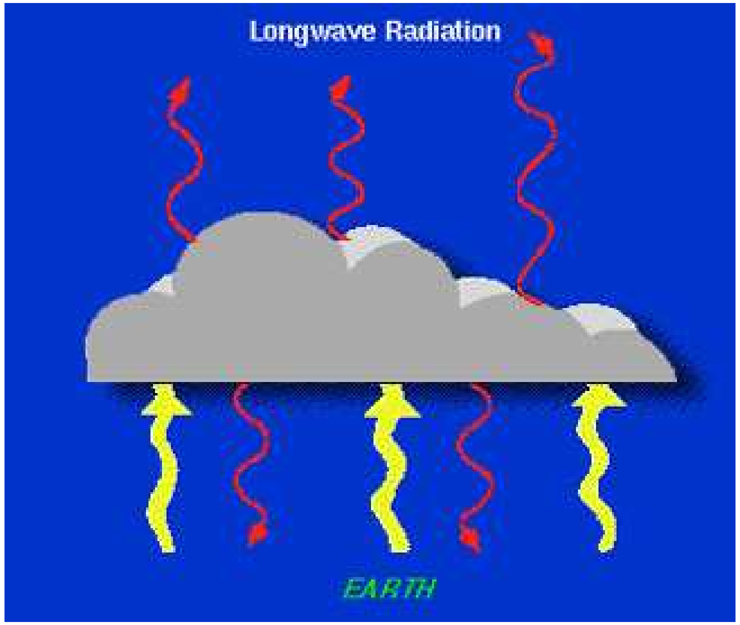
The two competing effects of clouds:

Cooling



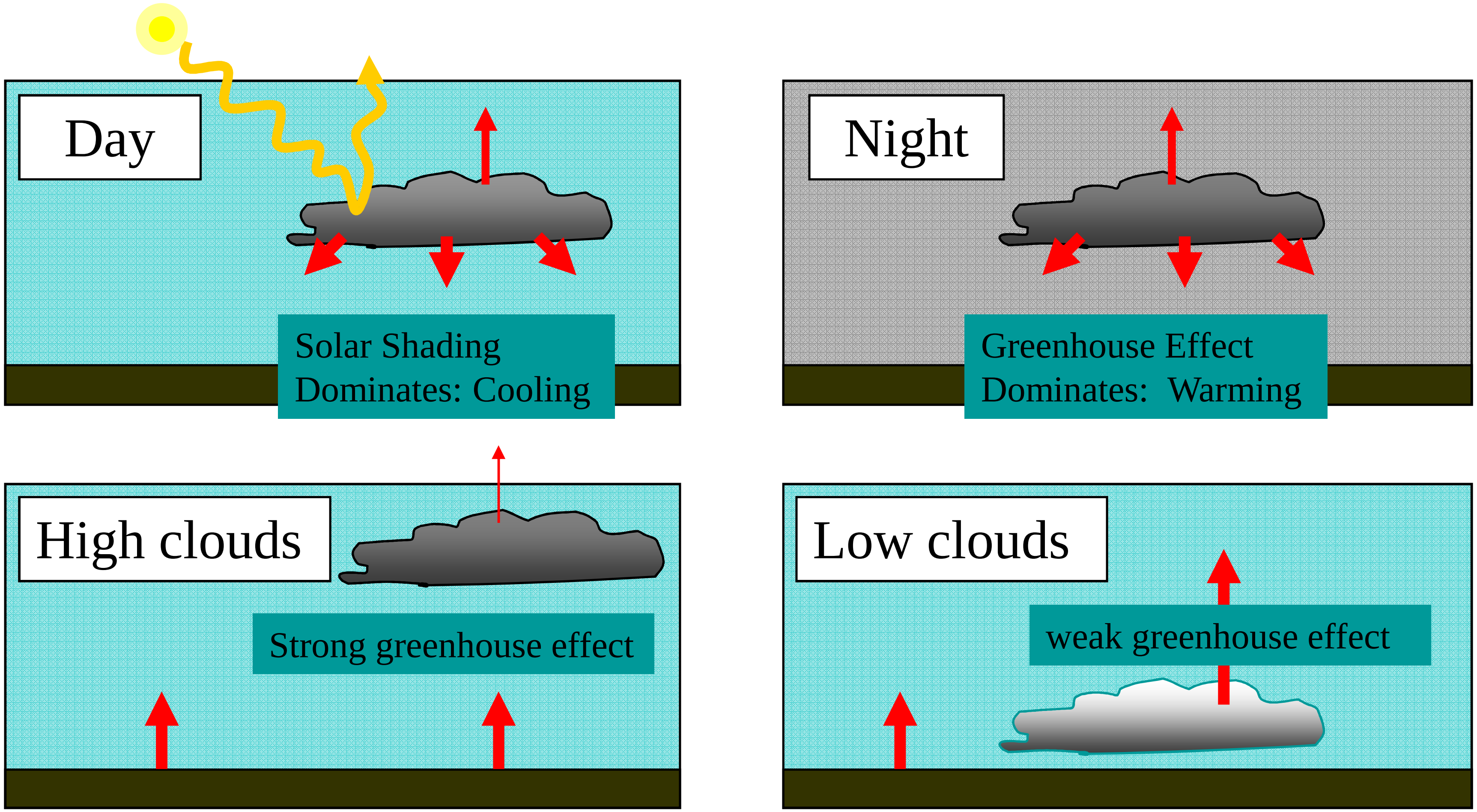
Cloud albedo effect

Warming



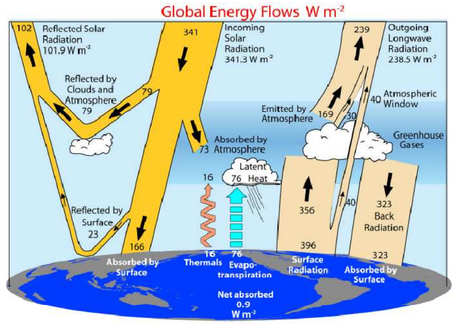
Cloud greenhouse forcing

Cloud Feedback: a more complex problem



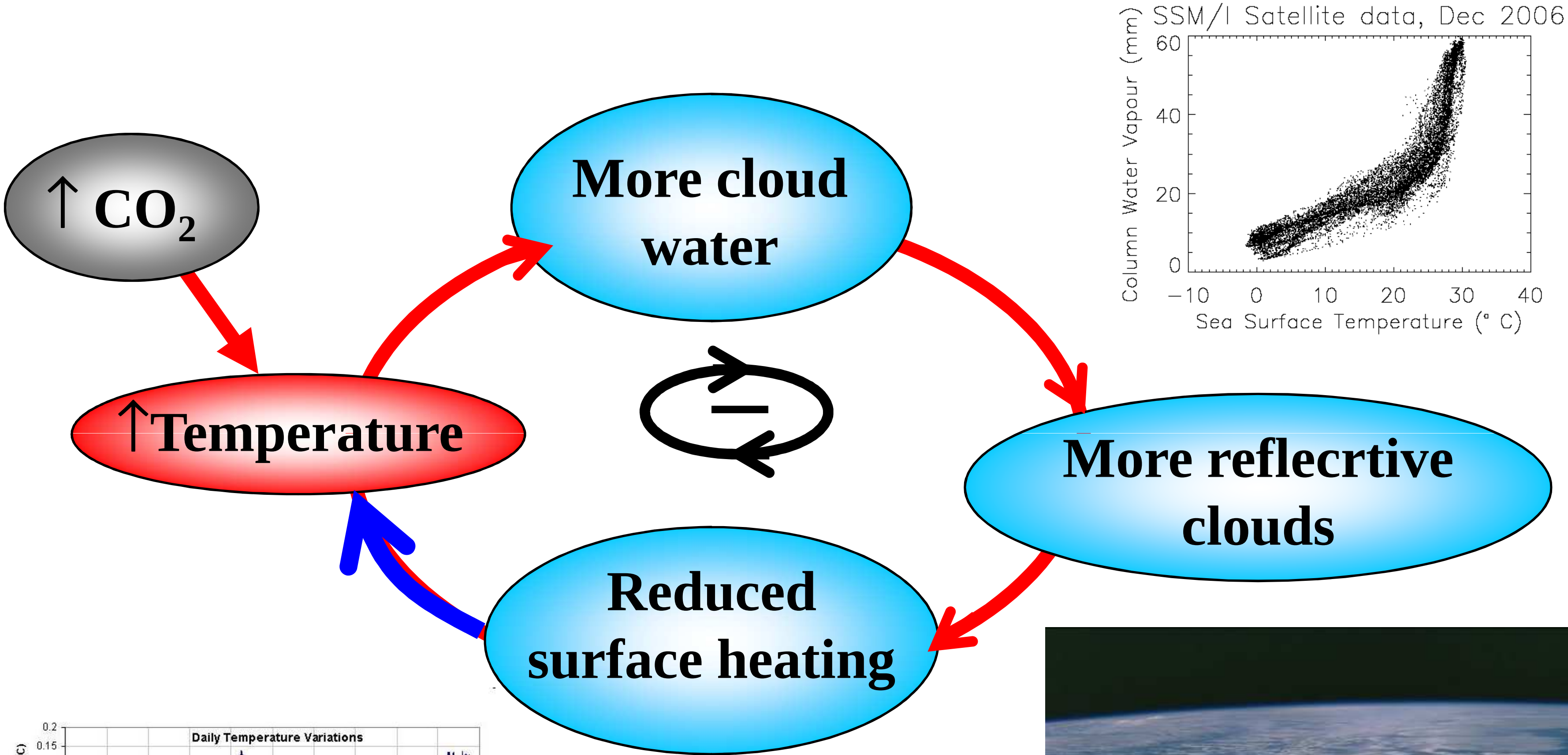
How will cloud properties respond to warming? Will they amplify or diminish warming? How are cloud height, water content, ice content, droplet sizes, thickness, duration, time of occurrence, expected to vary?

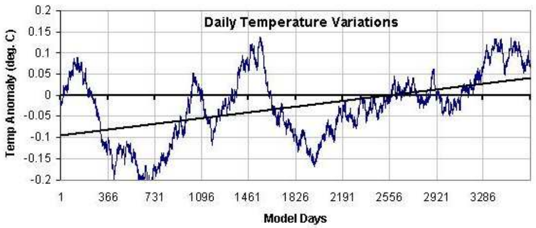
Global effect of clouds on radiation balance



- 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

Hypothetical cloud feedback





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

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

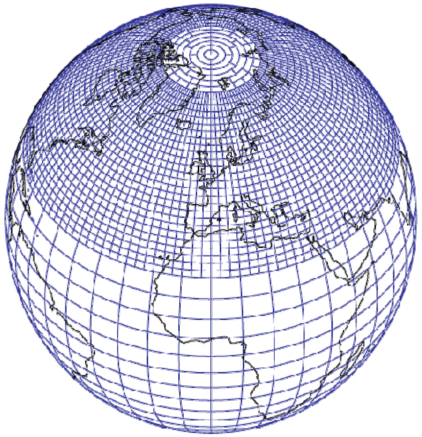
Cloud feedback: a more complex problem

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

- 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



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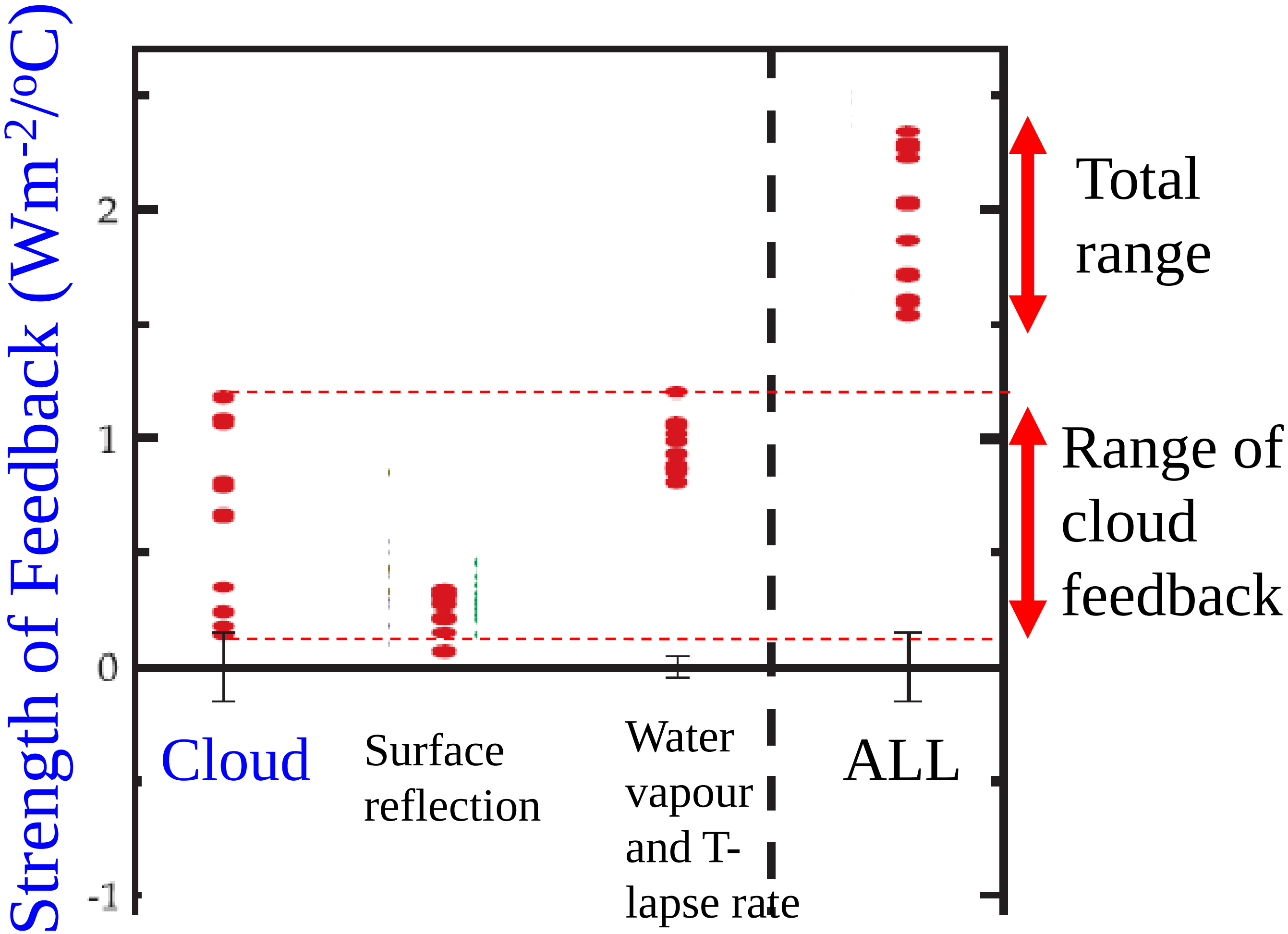
What do the models tell us?

- 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

Uncertainty in the strength of cloud feedback



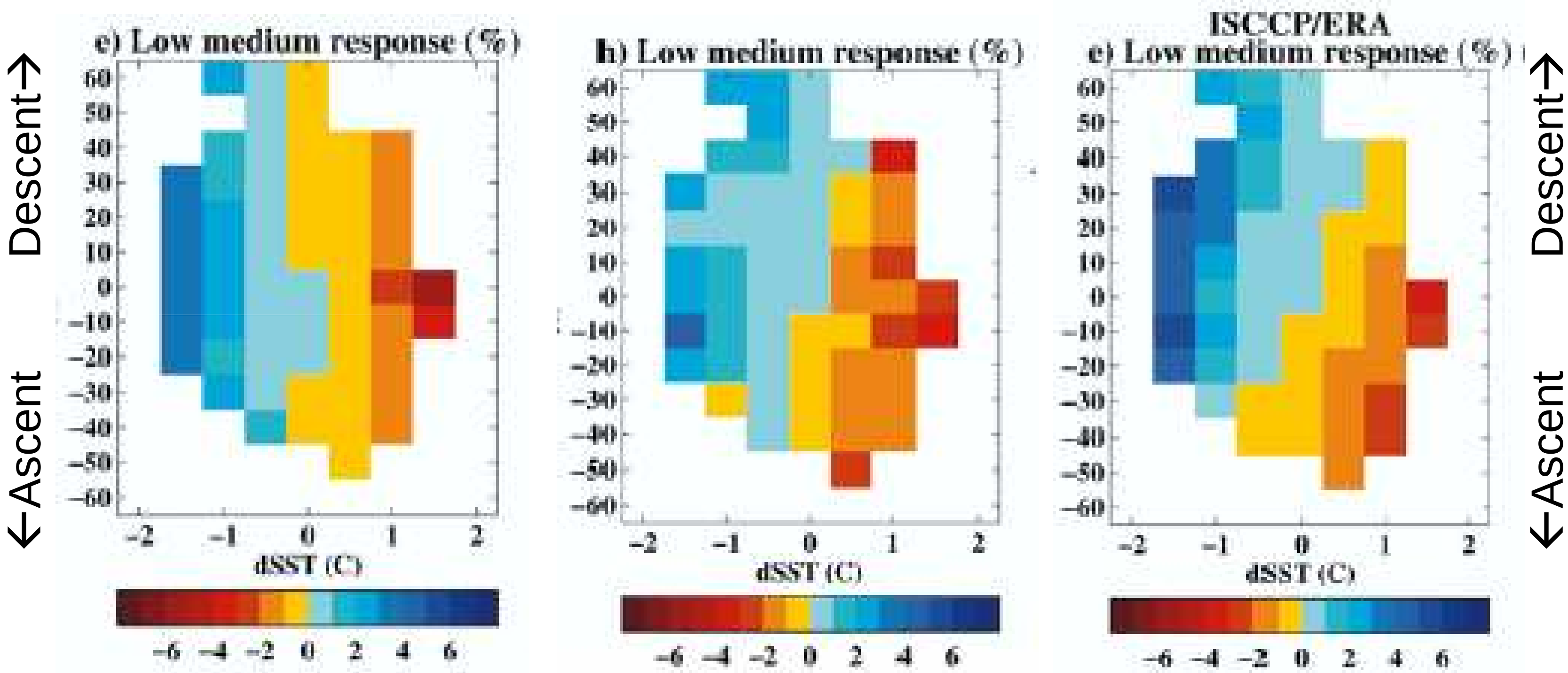
See www.ipcc.ch reports. Each red dot is a different agencies climate model.

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-$1.1\ Wm^{-2}K^{-1}$)
- This spread is the single largest contributor to uncertainty in climate sensitivity
- What is the real cloud feedback?

Climate Model Evaluation

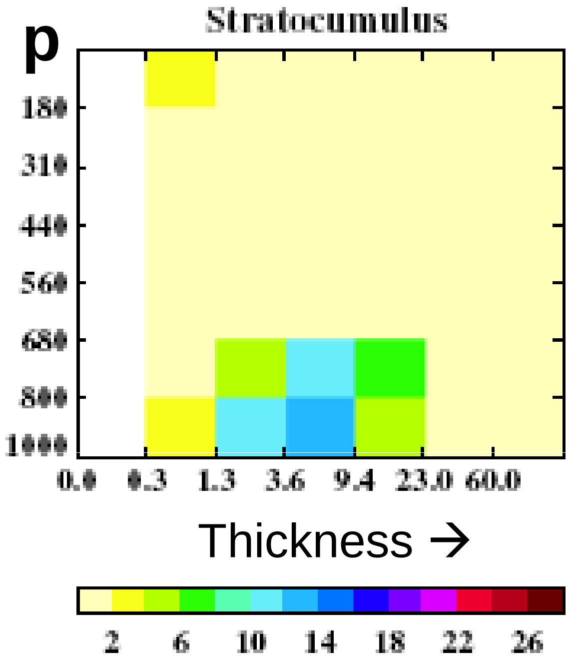
2xCO2 response	SST-forced response	Observed Response

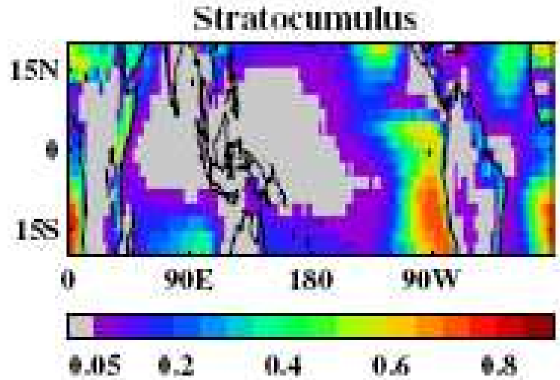


Williams et al. 2003 Clim. Dyn. **20** p.705

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





Dynamic/thermodynamic components

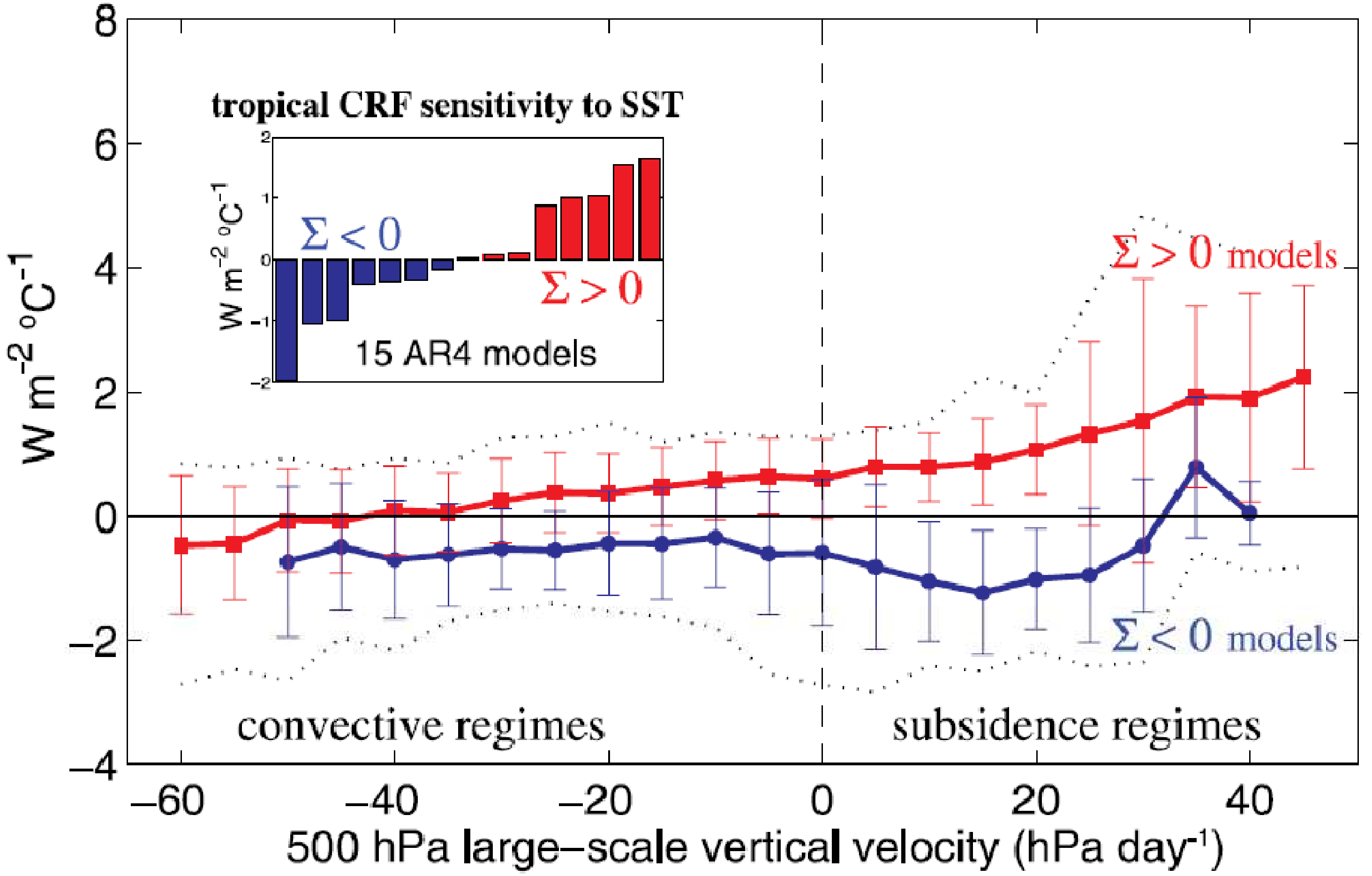
- In assessing cloud feedback, need to distinguish dynamical component
  - e.g. local change in cloud due to subtle shift in large scale circulation is not feedback

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

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**

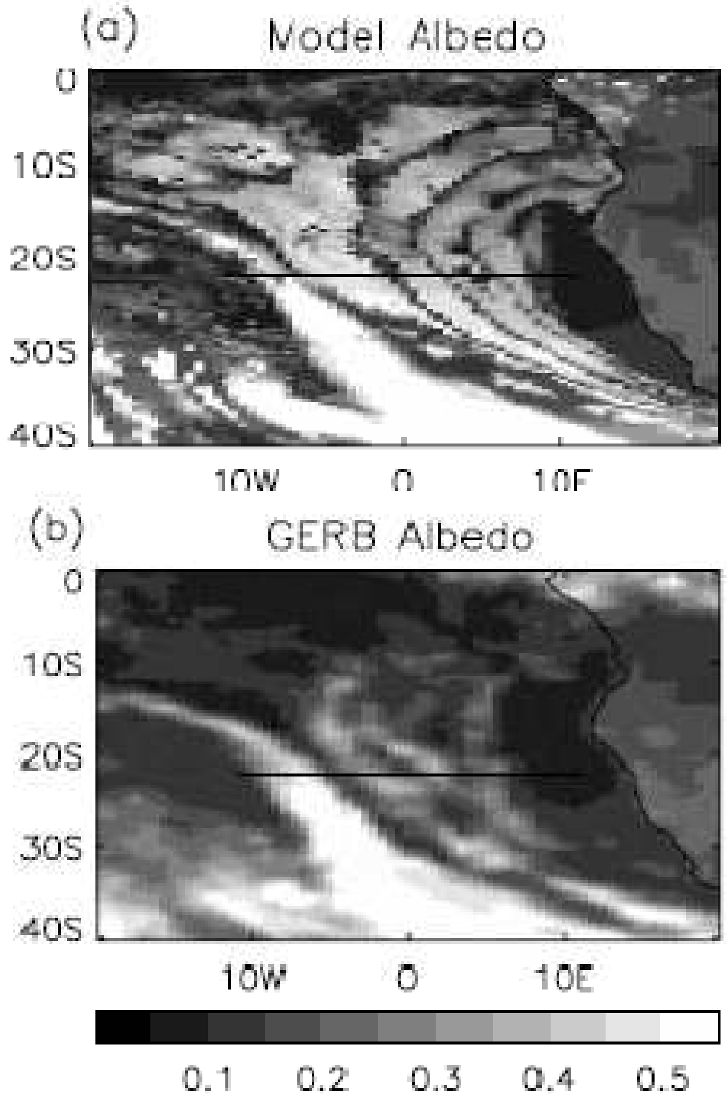


IPCC (2007), after Sandrine Bony and colleagues

Marine Low-level Clouds: too reflective in models?

Cloud albedo or reflection is a function of:

Cloud amount x Liquid water / effective radius



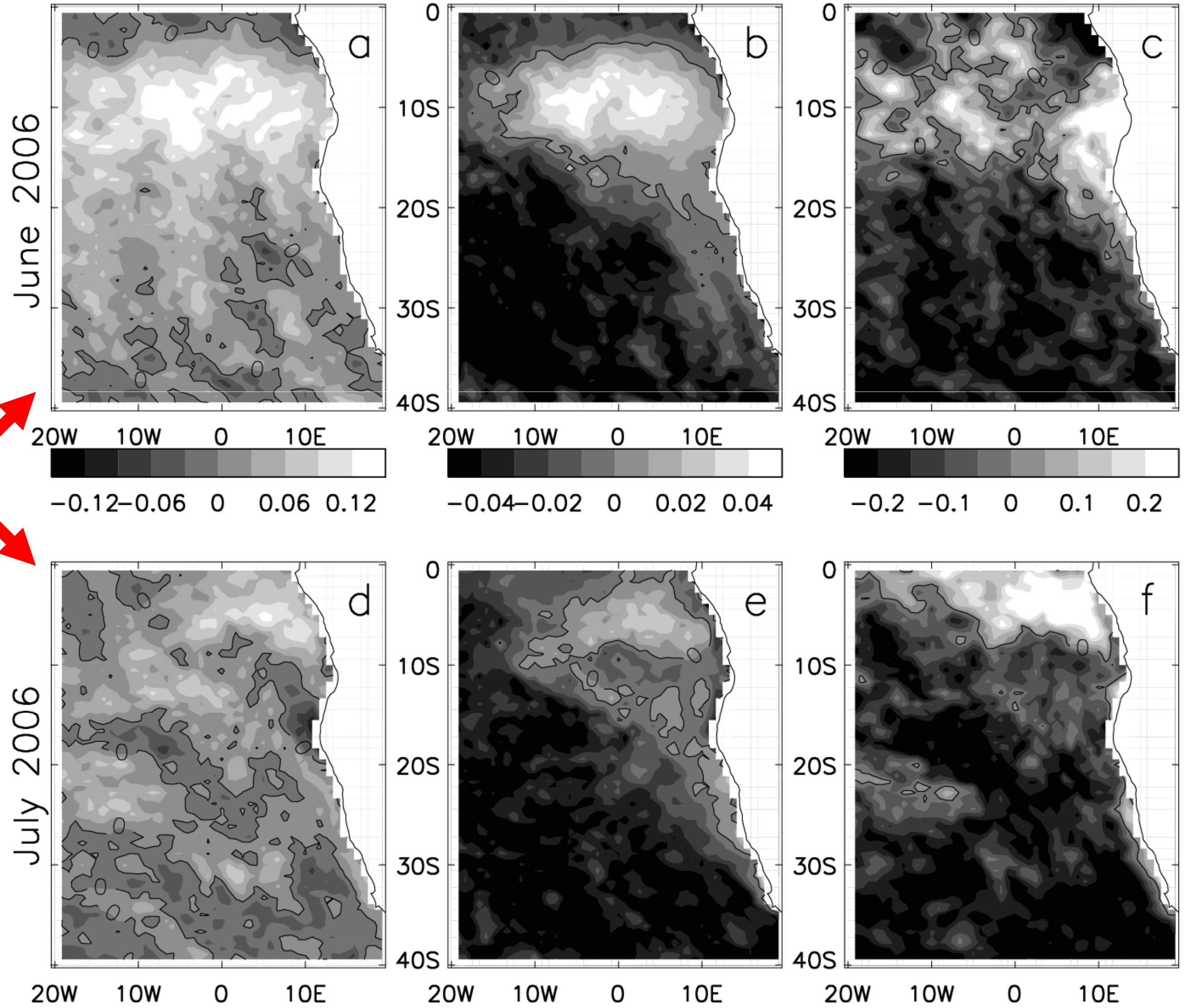
Allan et al. (2007) Q.J.R.M.S.

See also: Klein and Hartmann (1993) J.Clim; Wyant et al. (2006) Clim. Dyn.; Wood and Bretherton (2006) J. Clim, Karlsson et al. (2007) Clim. Dyn,etc

Cloud liquid water path

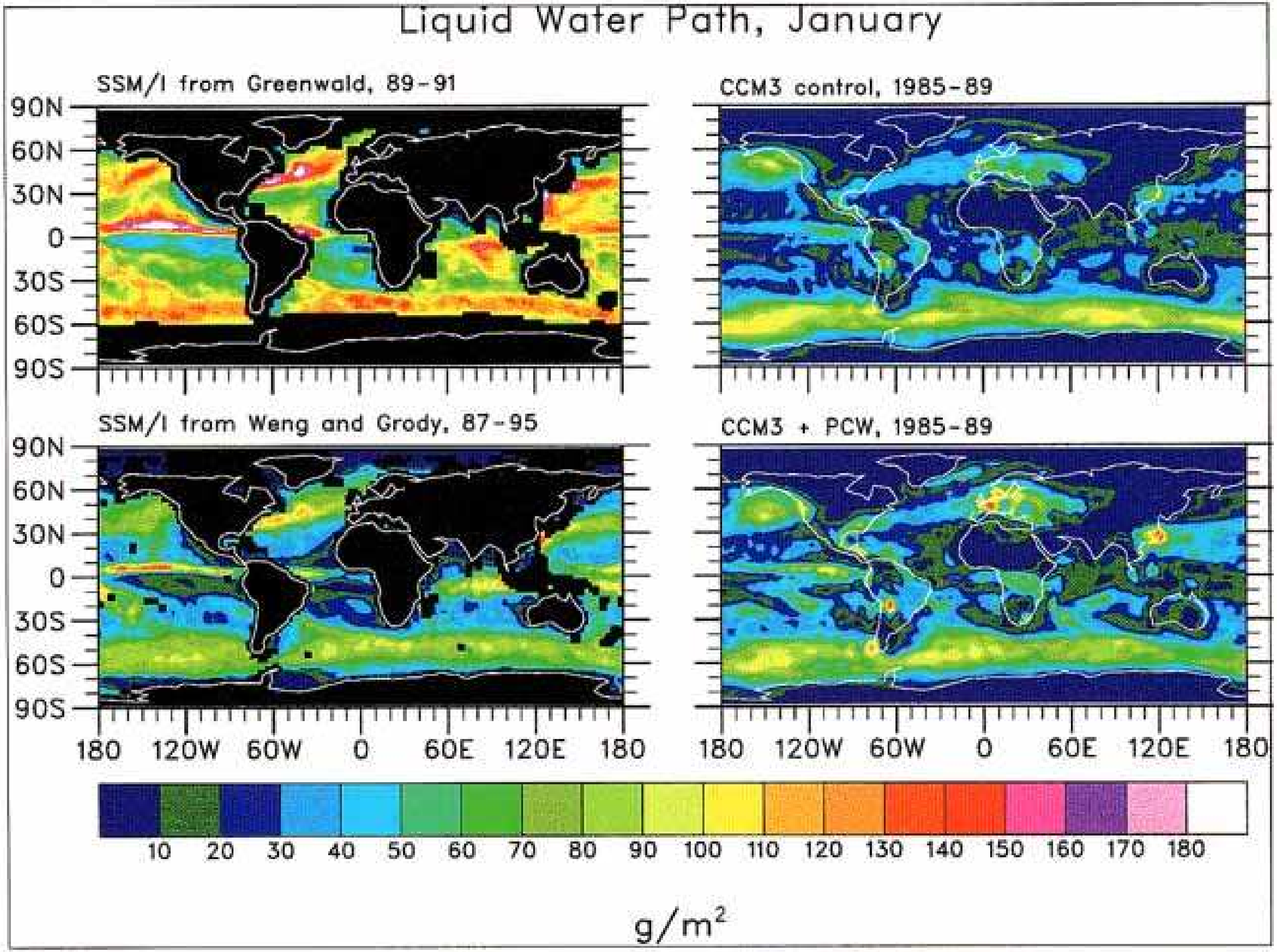
Bias: model minus GERB; SSM/I; SEVIRI

Albedo | Liquid Water Path | Cloud



Reduction in model bias from June to July 2006 - relates to cloud liquid water?

Allan et al. (2007) QJRMS



Liquid Water Path, January
SSM/I from Greenwald, 89-91
CCM3 control, 1985-89
SSM/I from Weng and Grody, 87-95
CCM3 + PCW, 1985-89
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
g/m2

Water cloud effective radius (microns)

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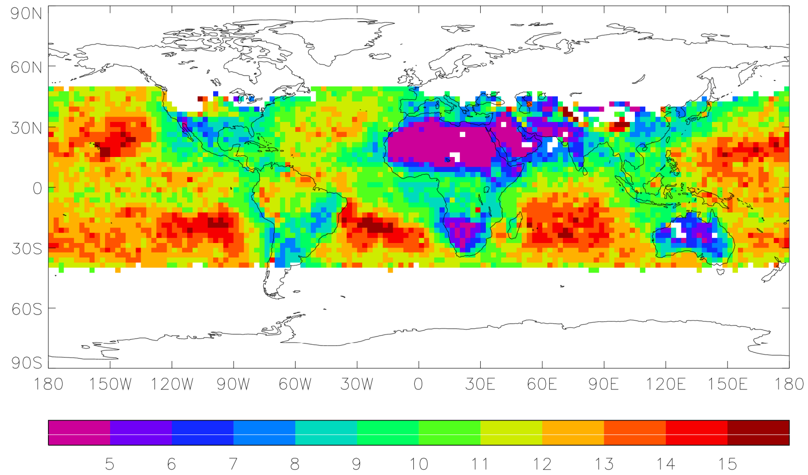
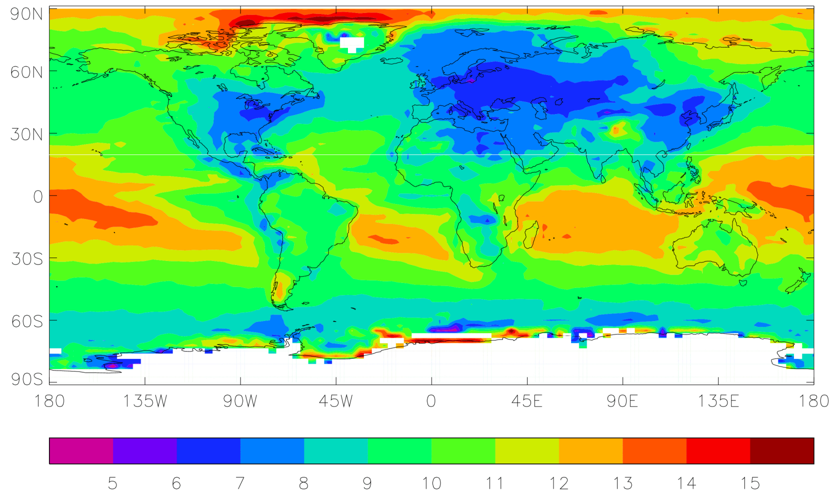
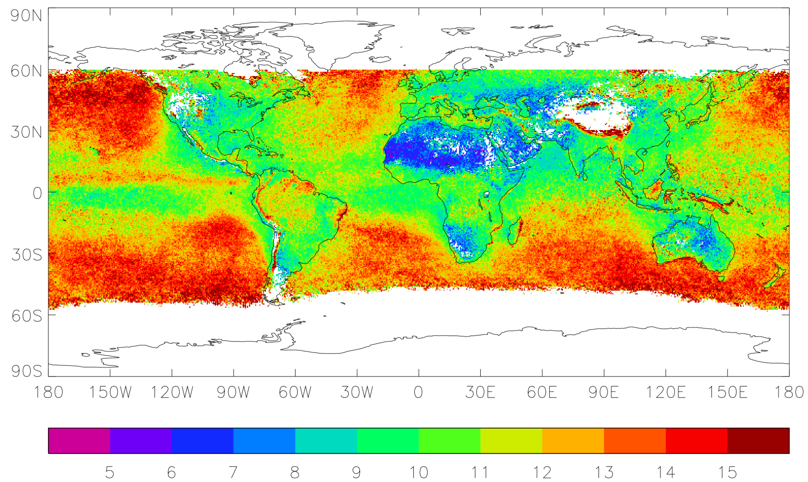
Han et al.



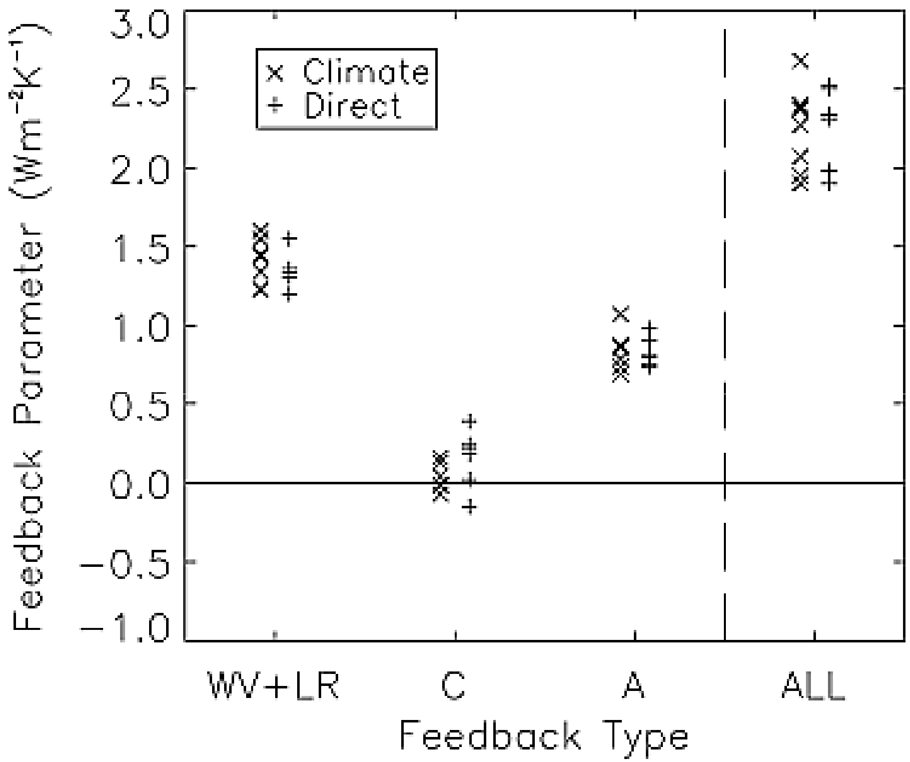
HadAM4



Yamamoto



Recent Advances

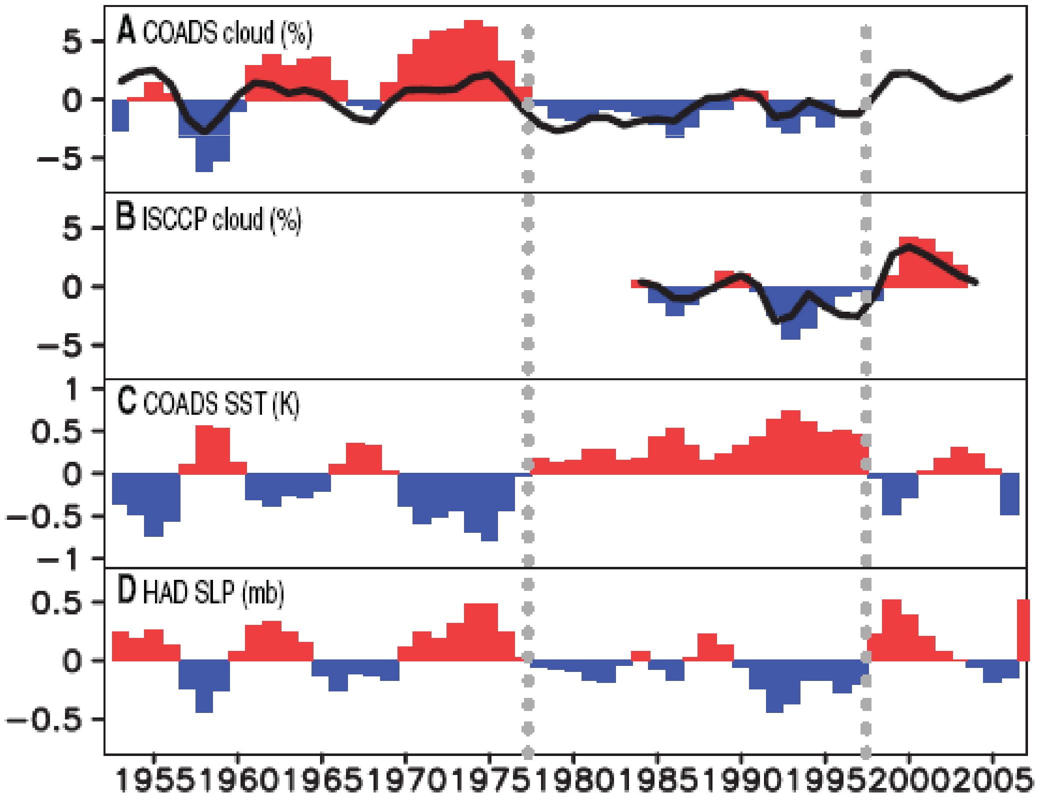


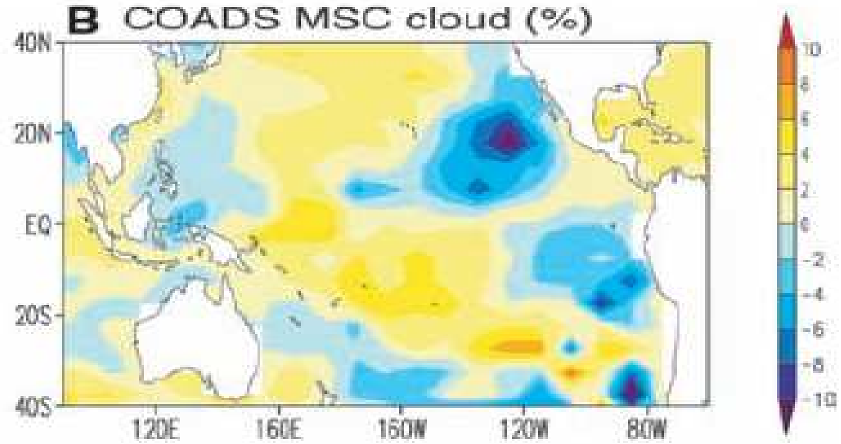
- Clouds respond to
  - direct forcing from CO_2
  - climate response to ΔSST
- Does cloud feedback uncertainty stem from direct response rather than climate feedback response?

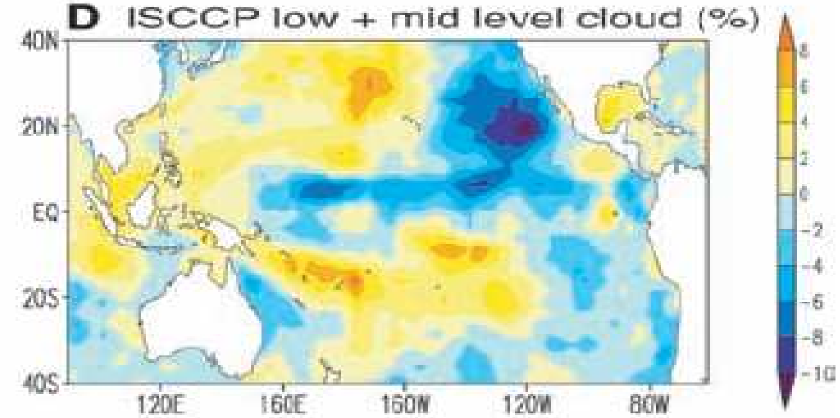
Andrews and Forster (2008) GRL (above); Gregory and Webb (2008) J Clim

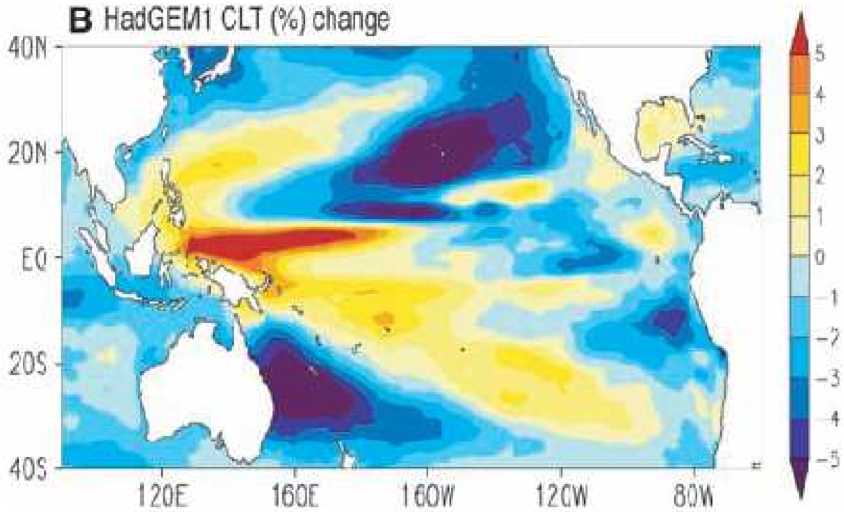
Clement et al. (2009) Science: observational evidence of marine stratocumulus response to warming, a positive cloud feedback?

Relationships captured to some extent by Hadley Centre model

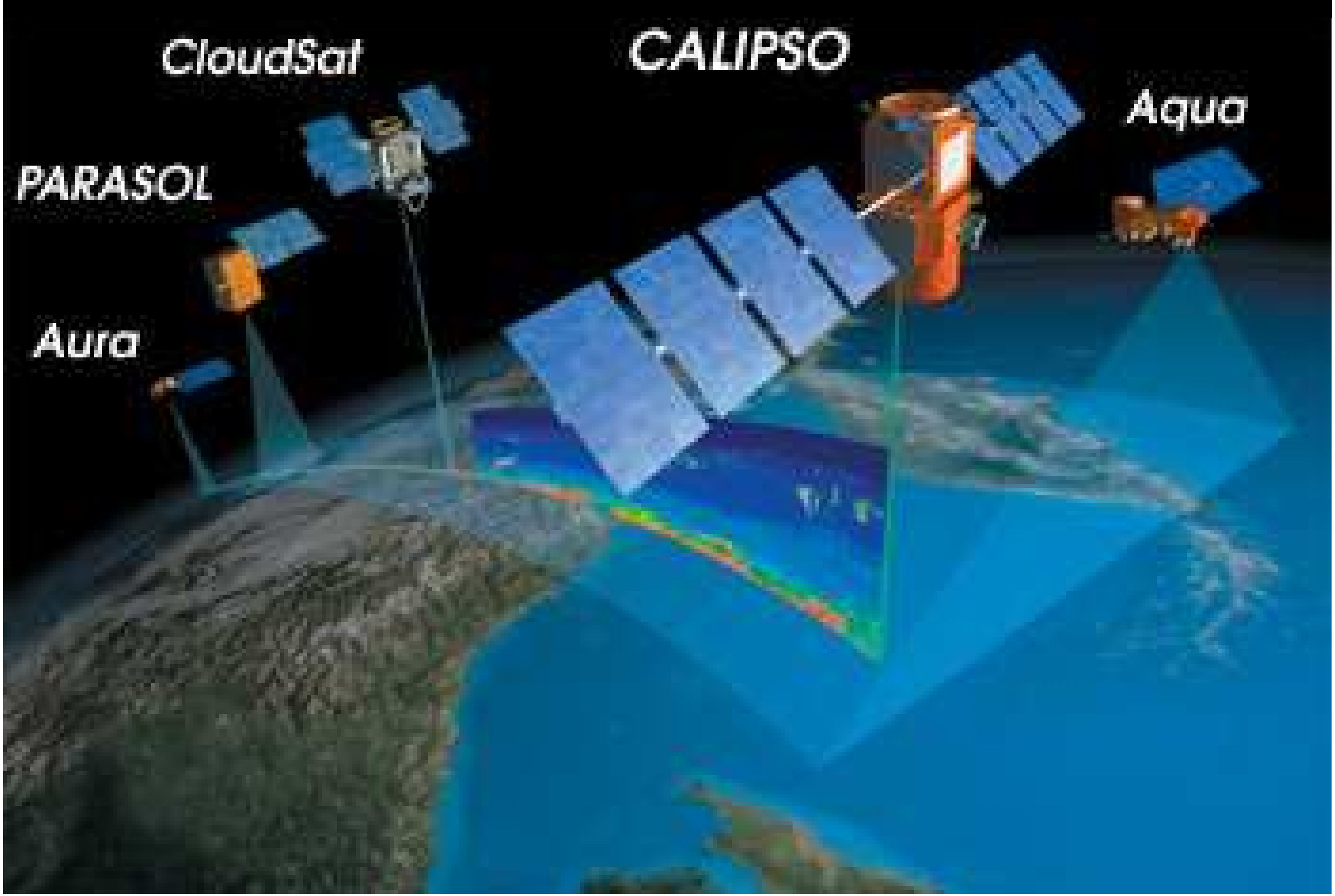








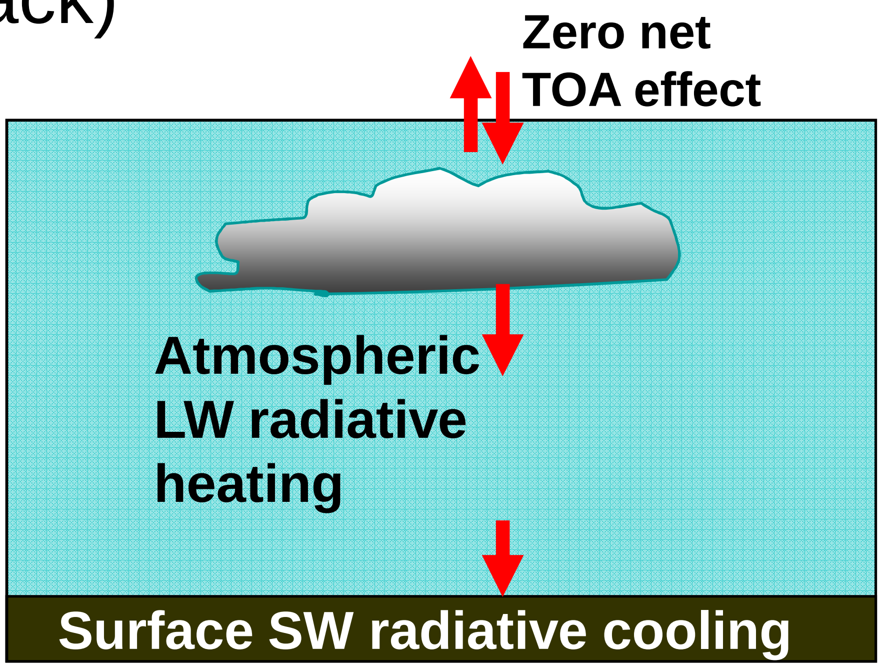
New satellite observations and cloud feedback



A final thought...

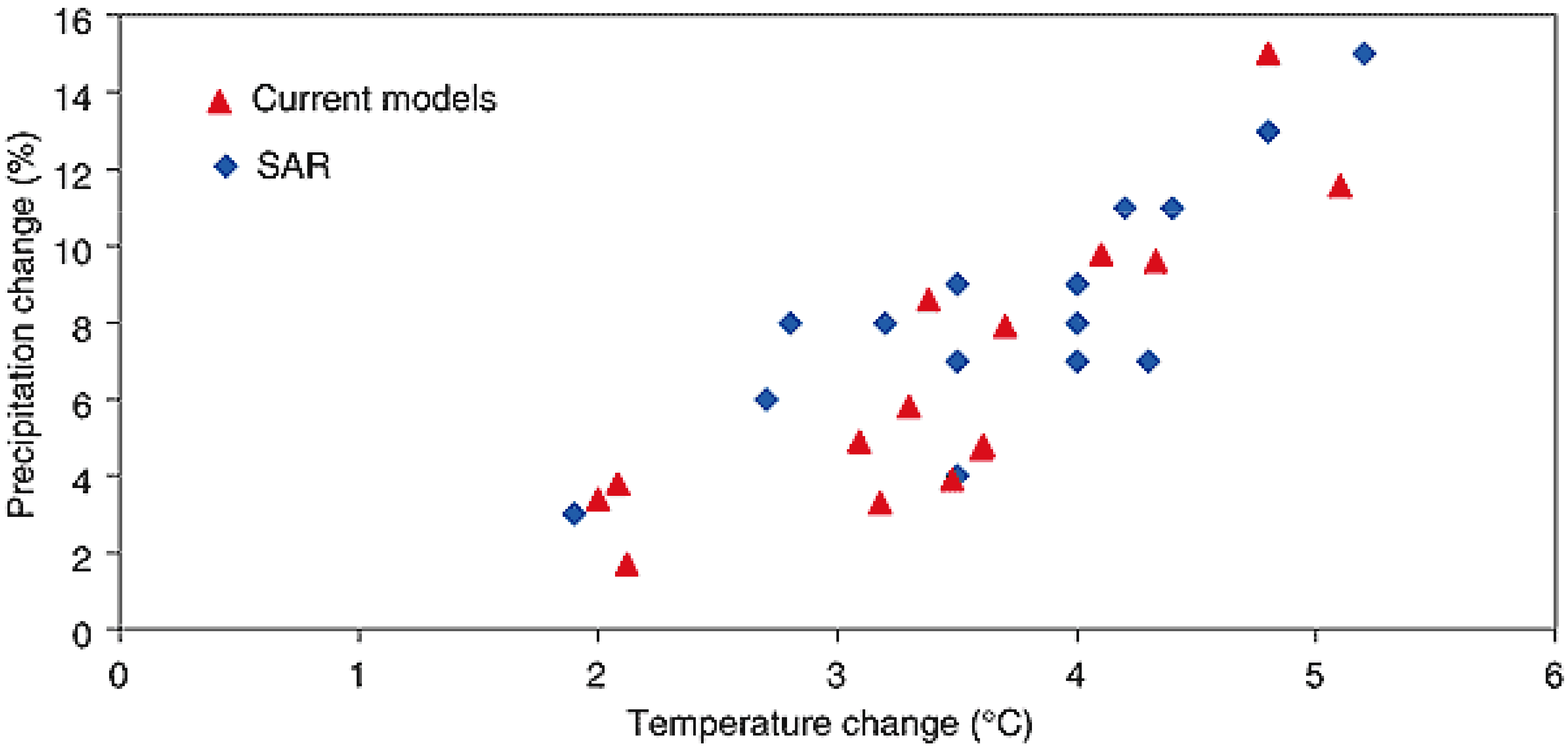
- Suppose there is an increase in high-level cloud which on average has a balancing shortwave (SW) and longwave (LW) radiative effect (ie no net radiative feedback)

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



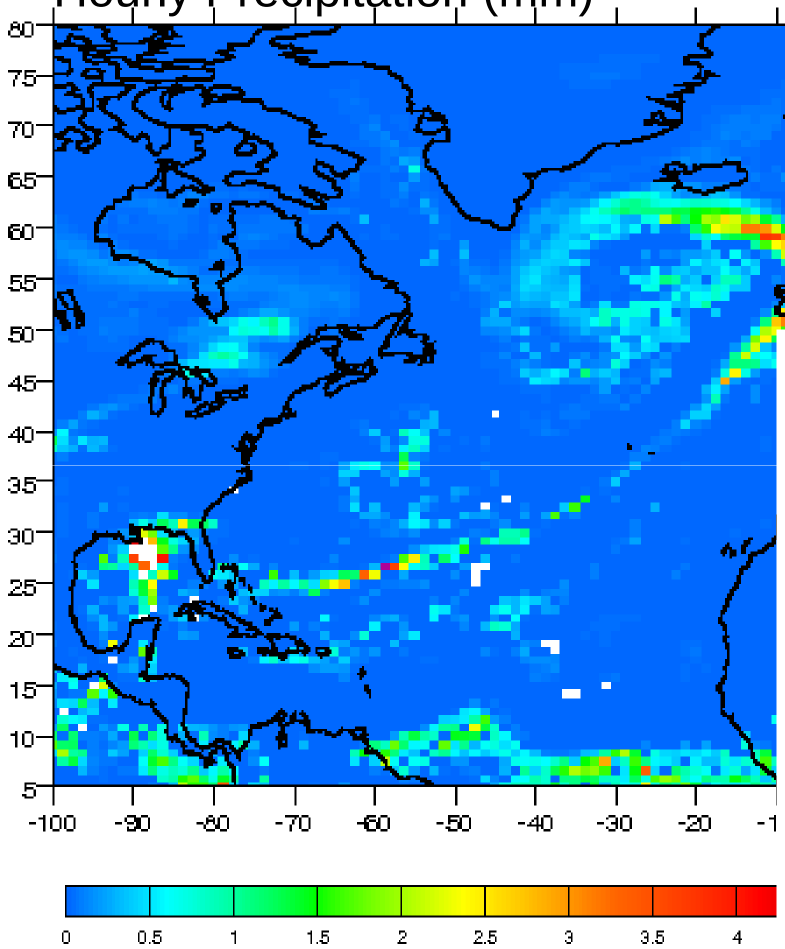
How will precipitation respond to climate change?

See: Allen and Ingram (2002) Nature; Trenberth et al. (2003) BAMS; Held and Soden (2006) J Clim



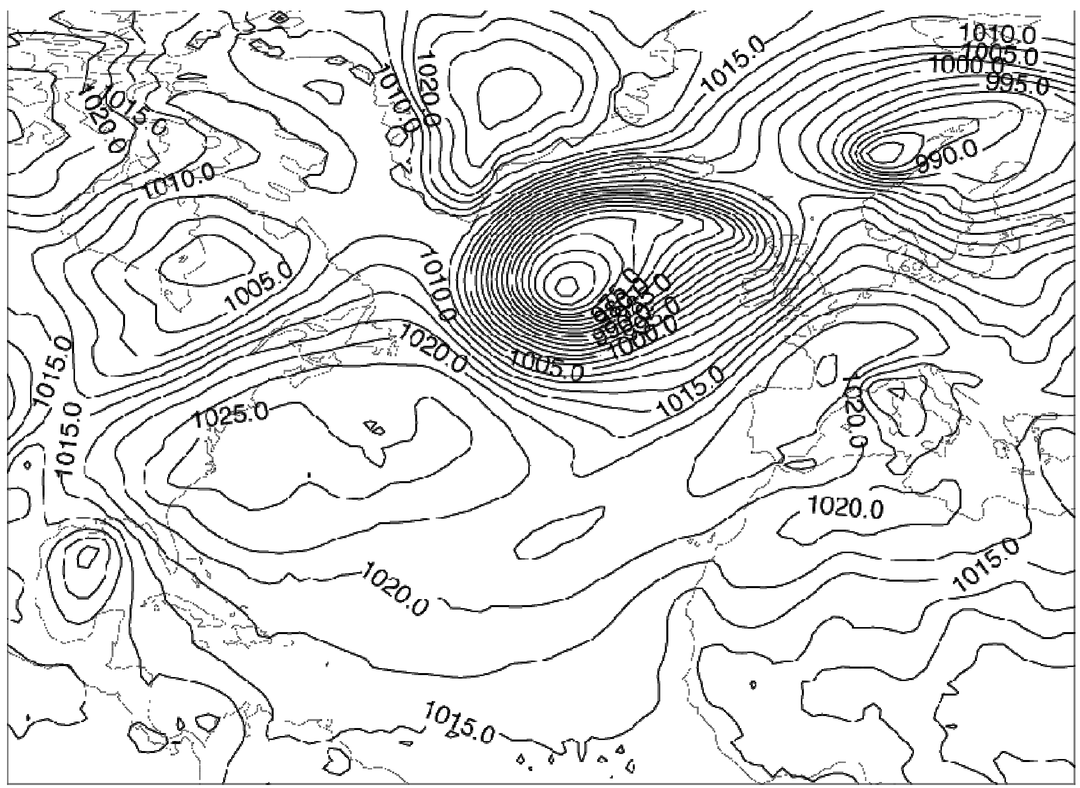
HiGEM and Weather Extremes

Hourly Precipitation (mm)



Snapshot for October simulation

Mean Sea Level Pressure



Water vapour in the climate system

- Weather and climate:

  - Climate is fundamentally the statistics of weather – weather provides the building blocks of the climate system.

  - Extreme weather may present some of the most severe impacts of climate variability and change.

  - Climate models **must** be able to simulate the weather and must therefore adequately resolve it.

Summary

- Detailed Models are required to resolve the important processes that determine climate response to a forcing
- Current models can only reproduce 20th century warming by including natural *and* anthropogenic forcings
  - But have highly uncertain aerosol parameters been tuned to improve the comparison? Kiehl (2007) GRL
- Future projections are dependent upon future emissions but also feedbacks involving the water cycle
- Climate Feedbacks dependent upon parametrizations in models
- Satellite data widely used to evaluate simulations by climate models
- Water vapour feedback relatively robust across models/observations
- cloud feedbacks are difficult to detect and to represent in models
  - Model cloud microphysics are relatively crude
  - Many possible types of cloud feedback plausible but difficult to observe
- Future changes in the water cycle, including extremes of precipitation, are highly dependent upon reliable representation of the global water cycle and cloud feedback processes

Some references

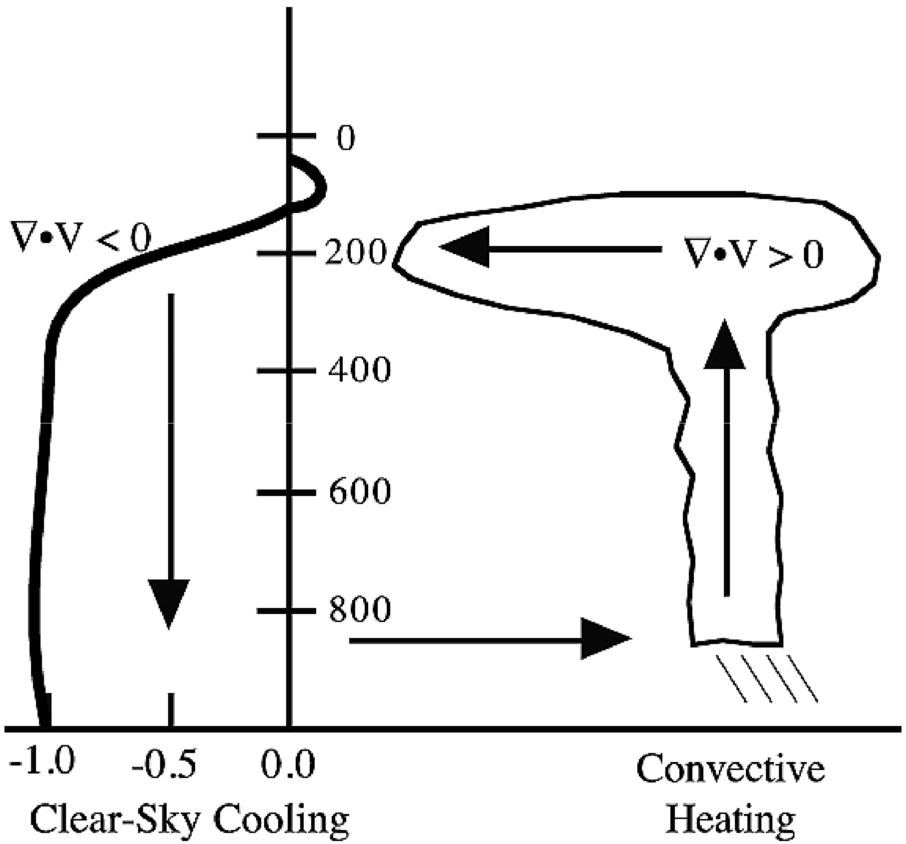
- Overview of feedbacks:
  - Bony et al. (2006) J Clim
  - Stephens et al. (2006) J Clim
  - IPCC (Chap 8)
  - UTH/WVF – Box 8.1, p.632
- Water Vapour Changes in models and observations
  - Soden et al. (2002, 2005) Science
  - Minschwaner et al. (2006) J Clim; Folkins et al. (2002) JGR; Sherwood and Meyer (2006) J Clim, Ingram (2009), also Simpson (1928) QJRMS
- Changes in the water cycle
  - Allen and Ingram (2002) Nature
  - Held and Soden (2006) J Clim
  - Trenberth et al. (2003) BAMS
  - Allan and Soden (2008) Science

Extra Slides

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?

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°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)

Another example: ice-albedo feedback

↑ CO_2

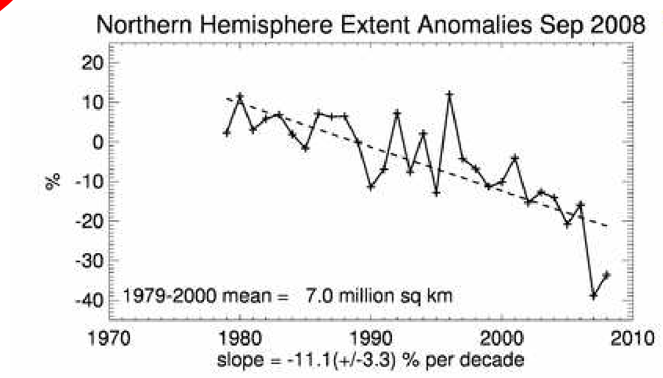
Melting ice and snow

↑Temperature

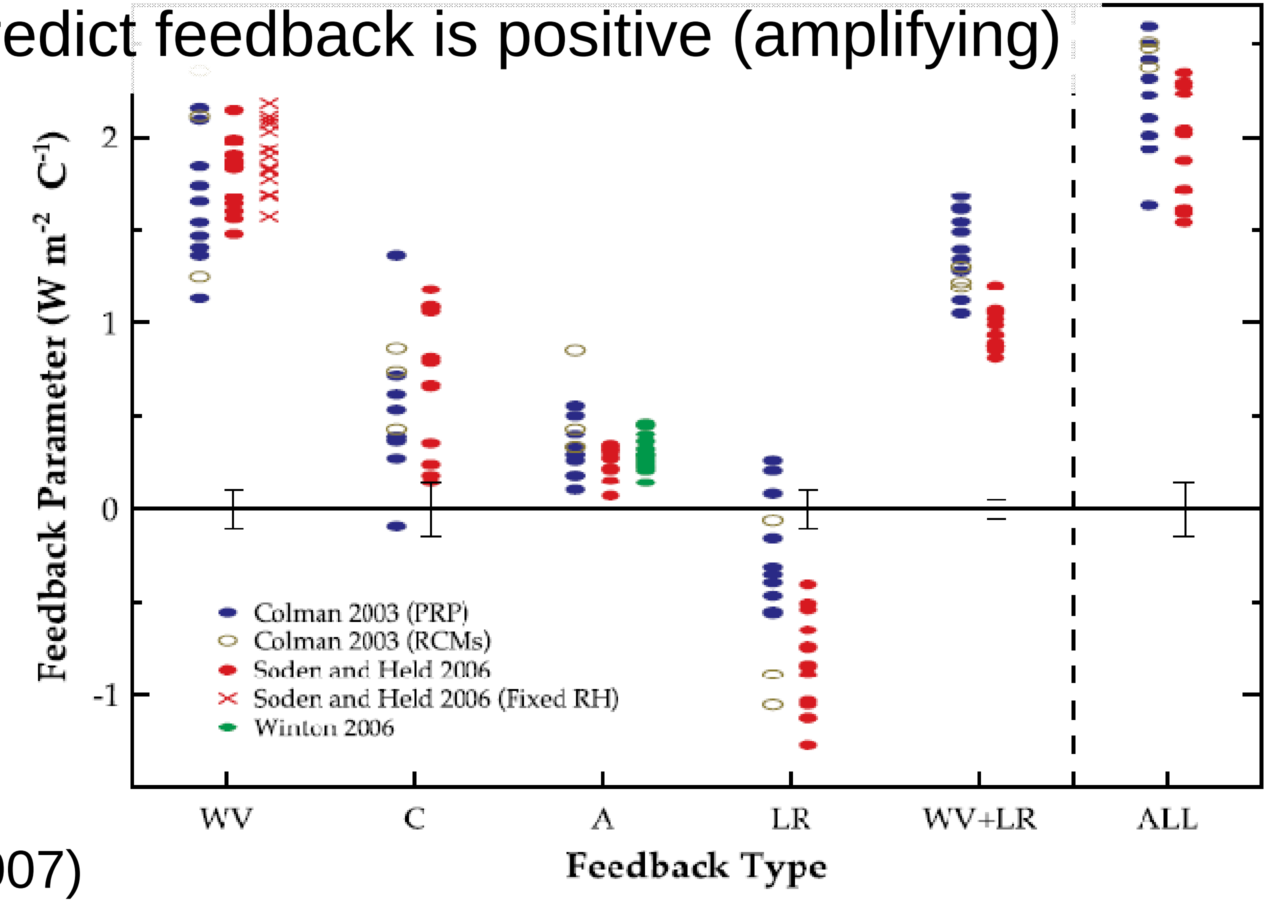
+

Reduced reflection of suns rays

Additional surface heating



- 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)