(Low)* Cloud feedbacks

Graeme Stephens

- Perspective from observations - that a necessary test of feedbacks (in models) is that the key processes be realistic
- ΔT_s centric low cloud radiative feedbacks – key process I will highlight is the cloud (and preciptation) - radiation process
- ΔP centric high cloud radiative feedbacks – radiative heating of the atmosphere by high cloud serves to regulate convection and acts as a control on precipitation
- Toward a blue print for studying feedbacks

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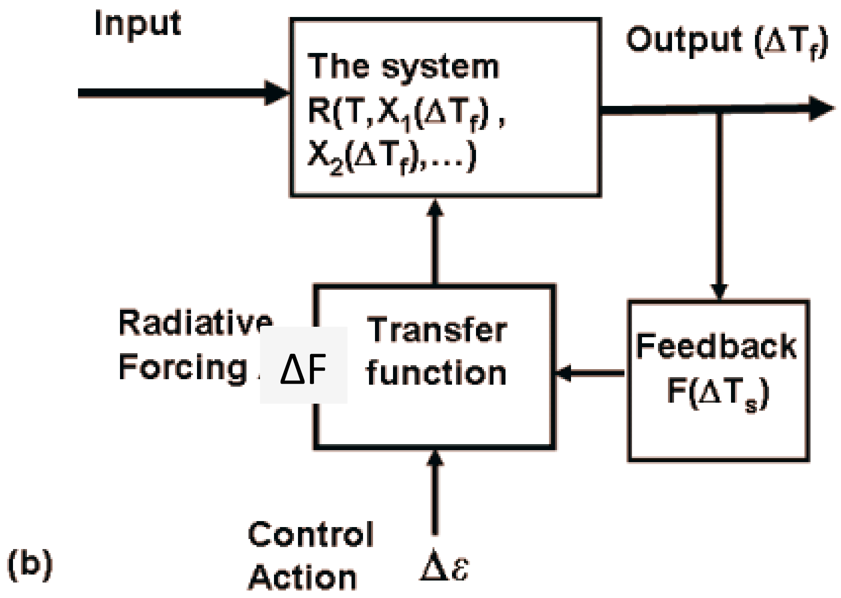
* Whimpy clouds

A global system with global feedbacks

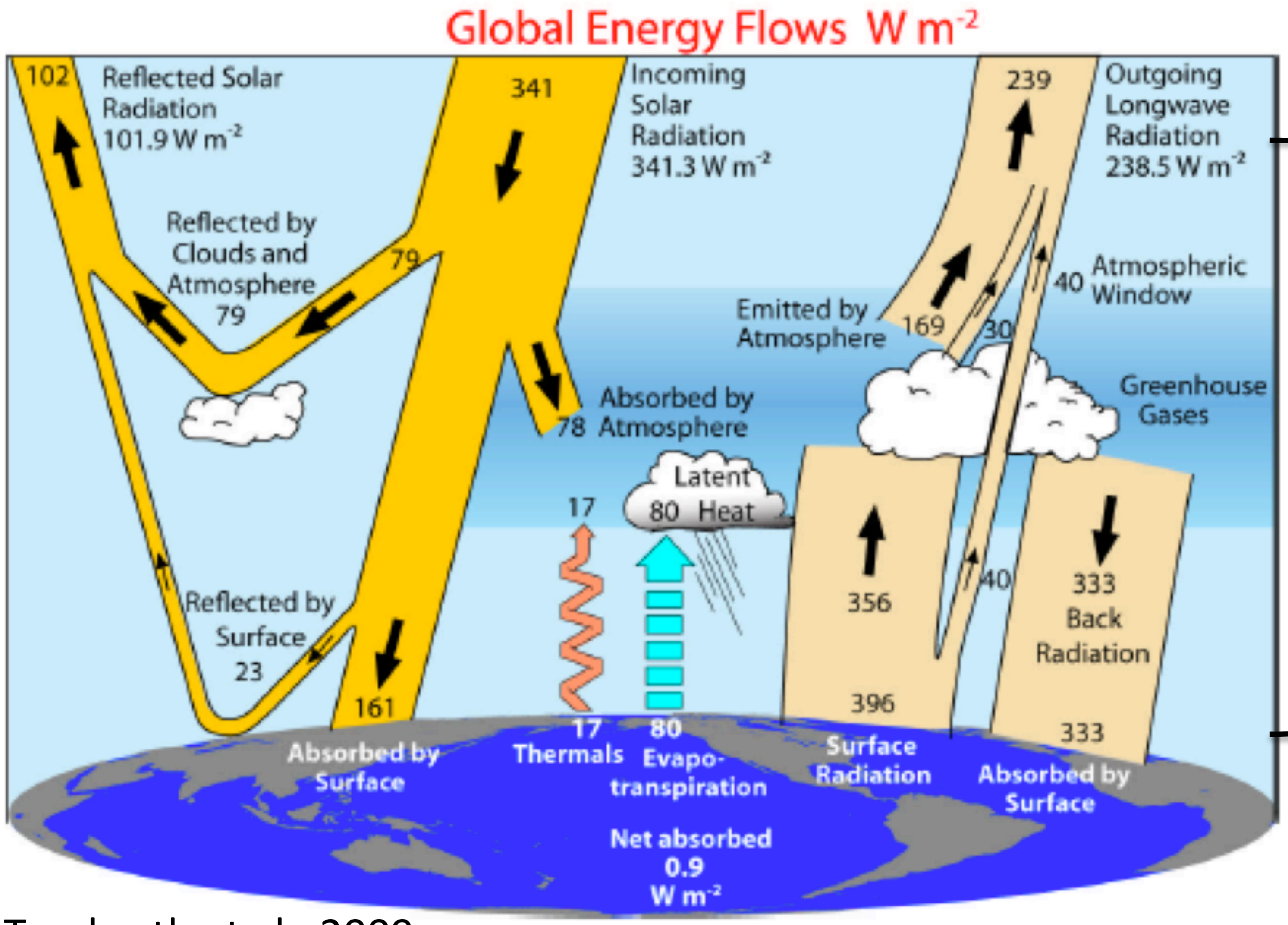
$$\Delta T = \lambda \Delta F$$



There are many issues to ponder:

- What is the real 'system' - most simple feedbacks (e.g iris, thermostat) are postulated in terms very simple systems, the validity to real Earth never justified.
- Why should physical feedback mechanisms be controlled by global mean temperature?
- How might we define the system for a different output like ΔP, and does this imply the existence of other (radiative) feedbacks?

The planet’s energy balance



Trenberth et al., 2009

Cloud radiative effects

-20 W/m2

+8 W/m2

A-Train cloud-profile resolved data

Cloud Radiative Effects (CREs)

$$F_{observed} = F_{clear}\,(1\text{-}A_{cld}) + A_{cld}\,F_{cldy}$$

$$= F_{clear} + A_{cld}\,(F_{cldy}\text{-}F_{clear})$$

$$C_{SW,LW} = -(F_{observed} - F_{clear}) \sim -\,A_{cld}\,(F_{cldy}\text{-}F_{clear})$$

Cloud radiative effects and feedbacks involving changes to CRE are influenced by changes in:

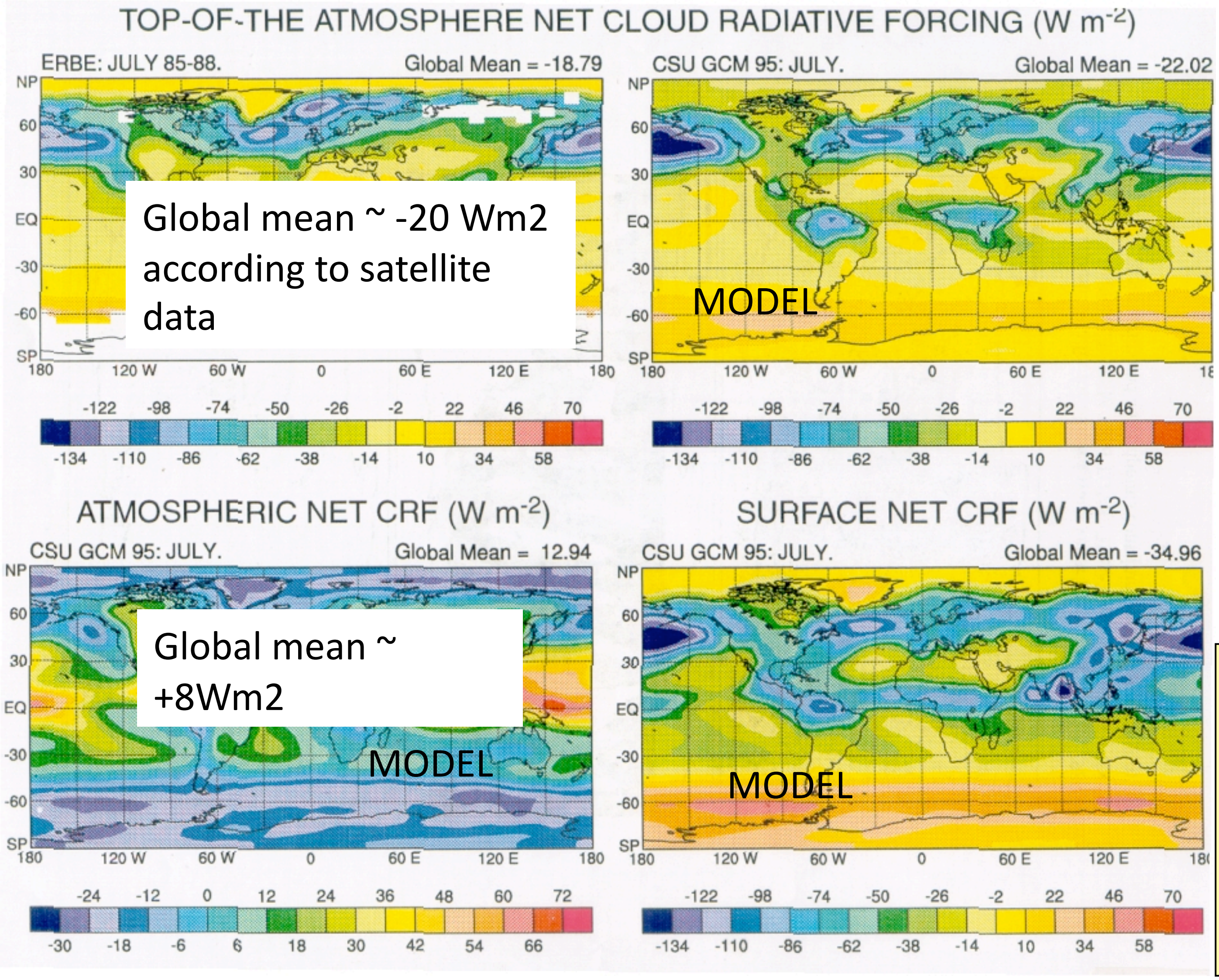
1) cloud amount A_{cld}

and/or

2) cloudy sky radiative fluxes F_{cldy}

Cloud radiative effects

CTOA = CATM + CSURF



Global mean ~ -20 Wm2 according to satellite data

MODEL

Global mean ~ +8Wm2

MODEL

MODEL

CTOA is formed as a reciprocal of CATM and CSURF (at least in low latitudes).

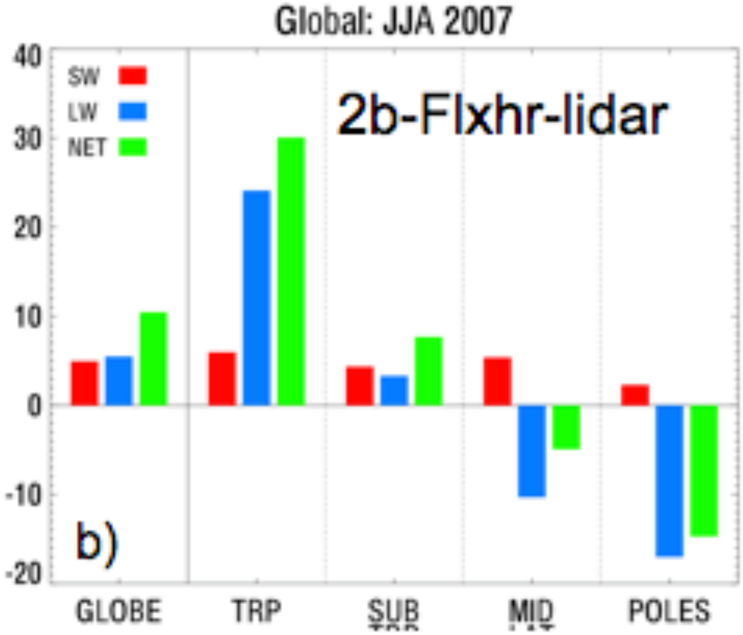
Solar effects dominate at surface

LW effects mostly in the atmosphere

clouds partition their effects between the atmosphere and surface

Atmospheric CREs

A-train observations now provide the means to determine/confirm the atmospheric CRE (>0)



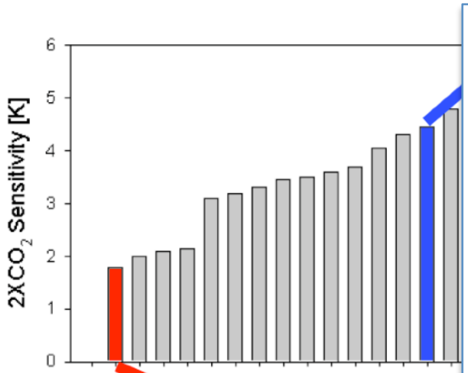
Stephens et al. 2008

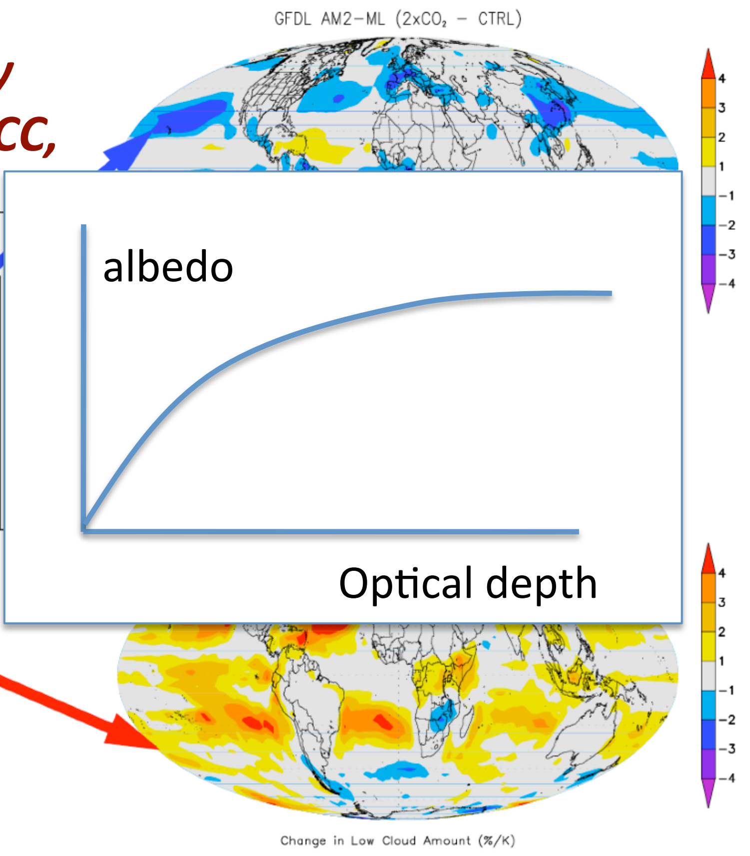
In contrast to TOA effects, globally clouds radiatively heat the atmospheric column and this heating is dominated by high clouds in the tropics – and this heating in turn is an important ingredient to other key cloud-radiative feedbacks

Low cloud feedbacks

Low cloud radiative feedbacks

Recent studies reaffirm that the spread of climate sensitivity estimates among models arises primarily from inter-model differences in cloud feedbacks (IPCC, 2007).





There are two parts to the low cloud feedback:

$$CRE_{SW,LW} = -(F_{observed} - F_{clear}) \sim - A_{cld}\,(F_{cldy} - F_{clear})$$

$$\frac{\Delta CRE}{\Delta T_s} \sim \boxed{-\frac{\Delta A_c}{\Delta T_s}} F_{cldy} - A_c \cancel{\frac{\Delta F_{cldy}}{\Delta T_s}} \sim 0$$

This is the cloud optical depth feedback factor

Thermodynamic? (EIS, Bretherton, Clement..)

Cloud radiative effects and low cloud feedbacks

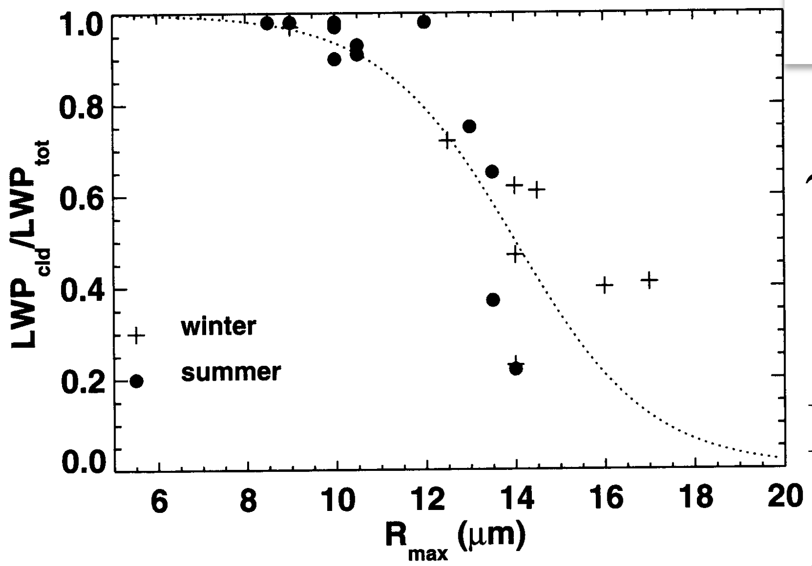
Solar fluxes (ie cloud albedo) are governed by cloud optical depth (and other factors) - Low cloud (radiative) feedbacks have been hypothesized as occurring via changes in A_{cld}, *LWP* and r_e

Stephens (1978) introduced

$$\tau = C_2 \frac{LWP}{r_e}$$

So two factors govern the low cloud optical depth feedback

Another complication - drizzle



$$\tau = C_2 \frac{LWP}{r_e}$$

Boers and Rotstayn propose

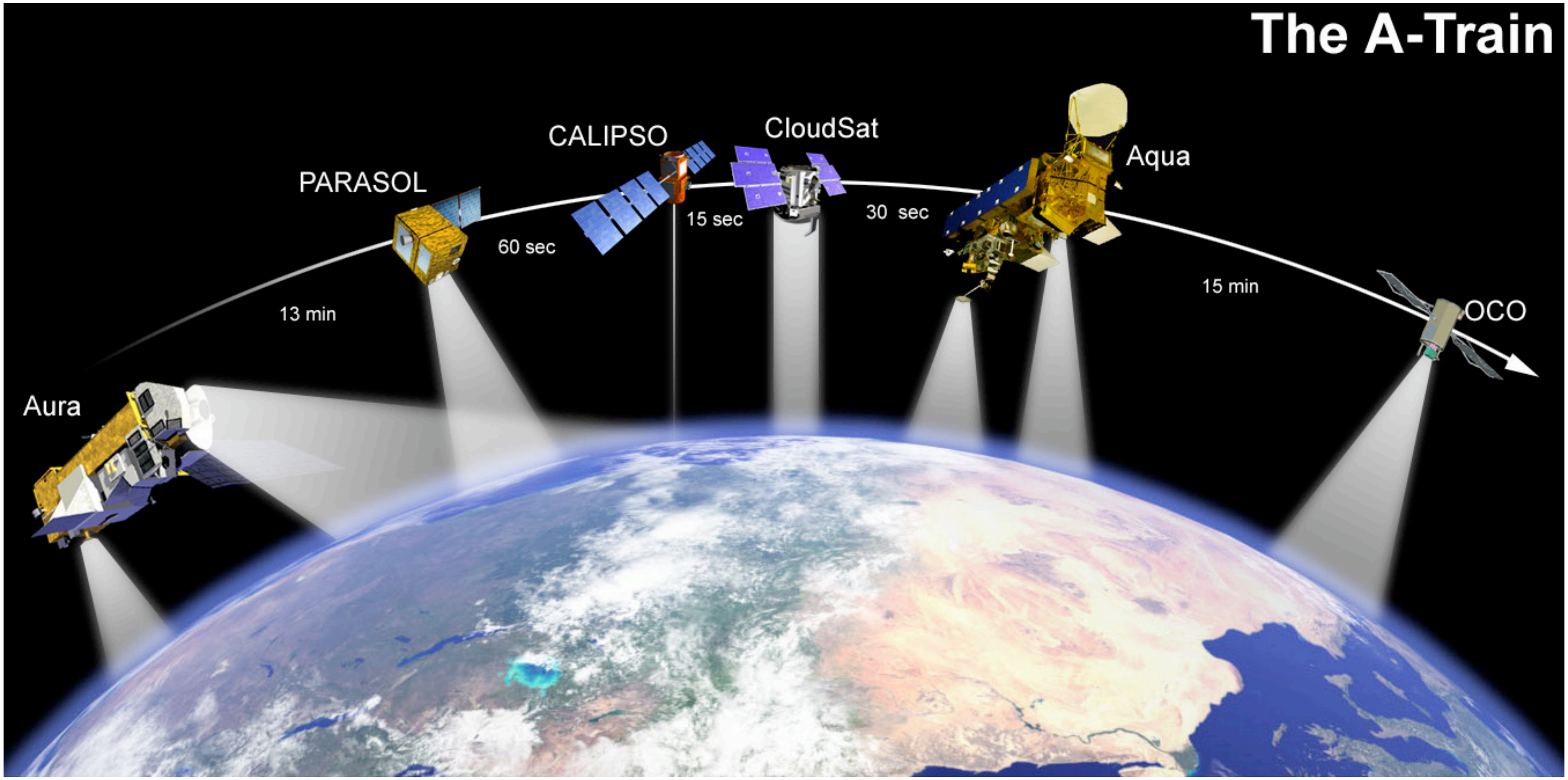
$$LWP_{cld} = LWP_{drizzle\_cld} f(R_{\max})$$

and an empirical relation

$$f(R_{\max}) = \frac{1}{2}\left\{1 - \tanh\left(\frac{R_{\max} - R_{crit}}{R_{rel}}\right)\right\}$$

But what about the radiative effects of drizzle itself?

What do Earth observations tell us?

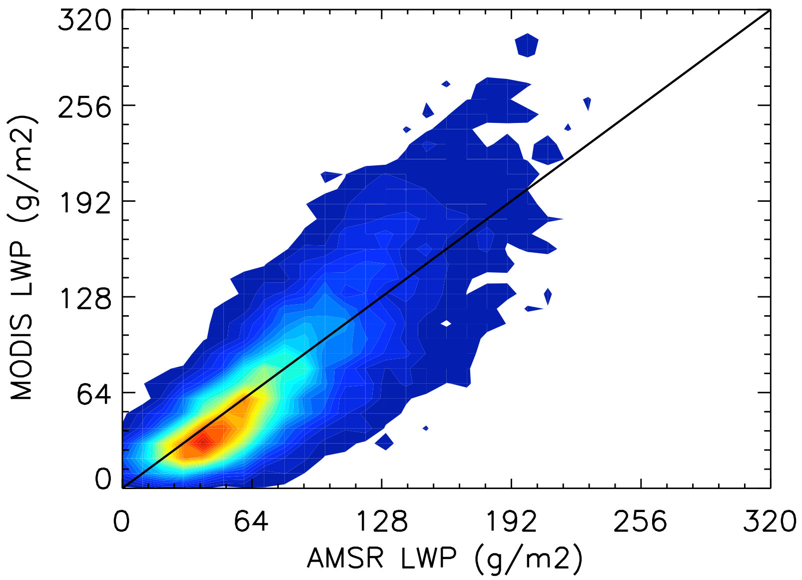


Focus on just two properties: LWP and r_e

This material is being documented in a paper that is in preparation

In-cloud LWP statistics of low clouds

Non raining clouds



Using combined MODIS and CloudSat observations, we can separate the properties for:

•All clouds (raining, non raining_) TWP
•Clouds only (non-raining, no drizzle) – CLWP

•Drizzle (Z>-15 dBZ)
•Raining (Z>-7.5 dBZ)

For the sampling applied, LWP derived from two different approaches methods agree over the range 20 - 200 g/m2 - ie I suggest we know the LWP of low clouds (and furthermore I suggest the 'reference' be MODIS)

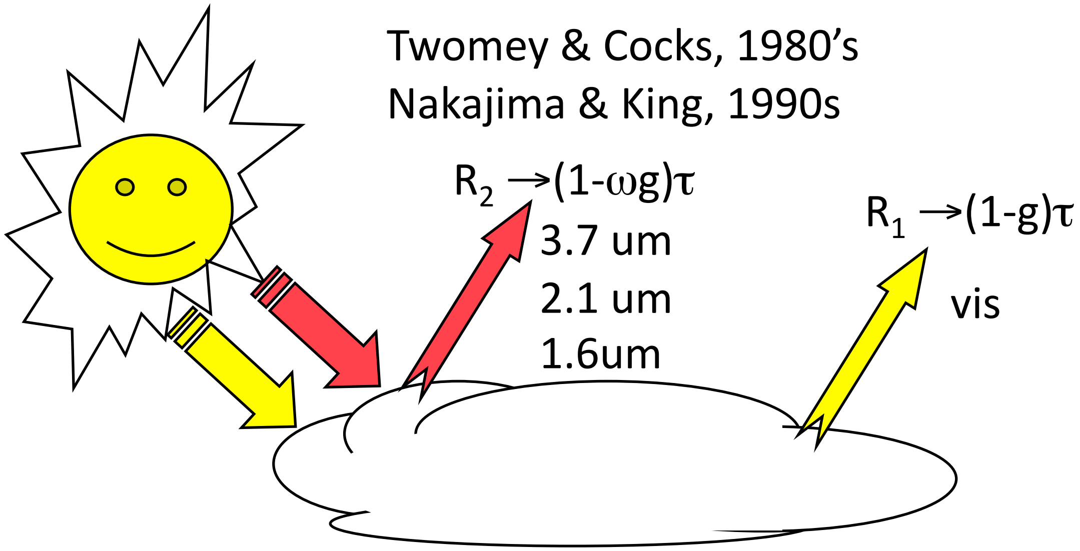
	Observations 2007	Model 1	Model 2	Model 3
Global Oceans	129 77	224 161	194	183 150
Tropics (35N/S)	130 87	271 196	170.	230 185
SH (35S-60S)	122 79	144 98	240	95 86
NH (35N-60N)	130 80	204 132	202	96 87

Total hydrometeor water path (TWP) in g/m2
Cloud liquid water path (CLWP) in g/m2

*** Range of CLWP AR4 53-434 g/m2 with ensemble mean of 200 g/m2**

Model 1= ECMWF IFS
Model 2=CAM (AR4) – rain has no water content
Model 3=NICAM (@7km)

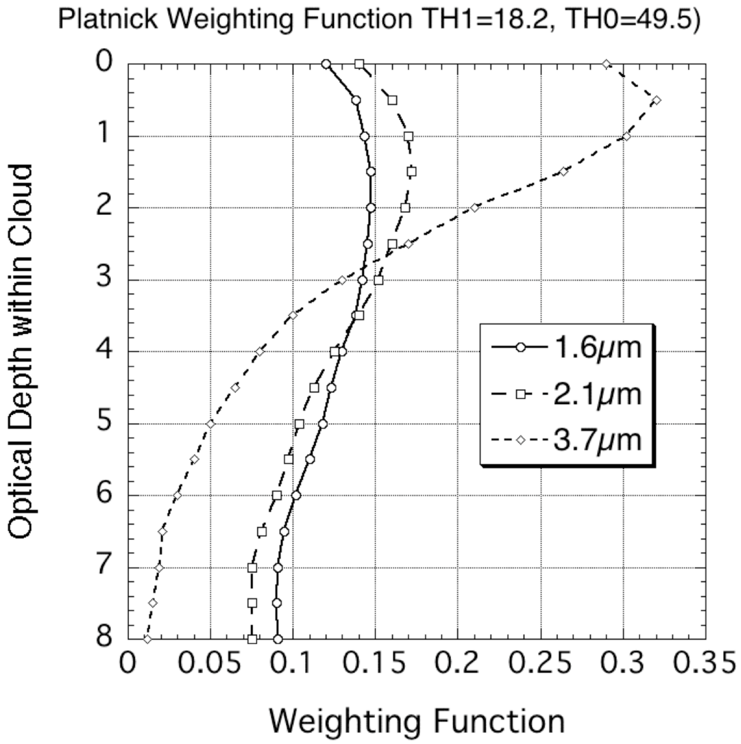
What about particle size?



Twomey & Cocks, 1980’s
Nakajima & King, 1990s

$R_2 \rightarrow (1-\omega g)\tau$
3.7 um
2.1 um
1.6um

$R_1 \rightarrow (1-g)\tau$
vis

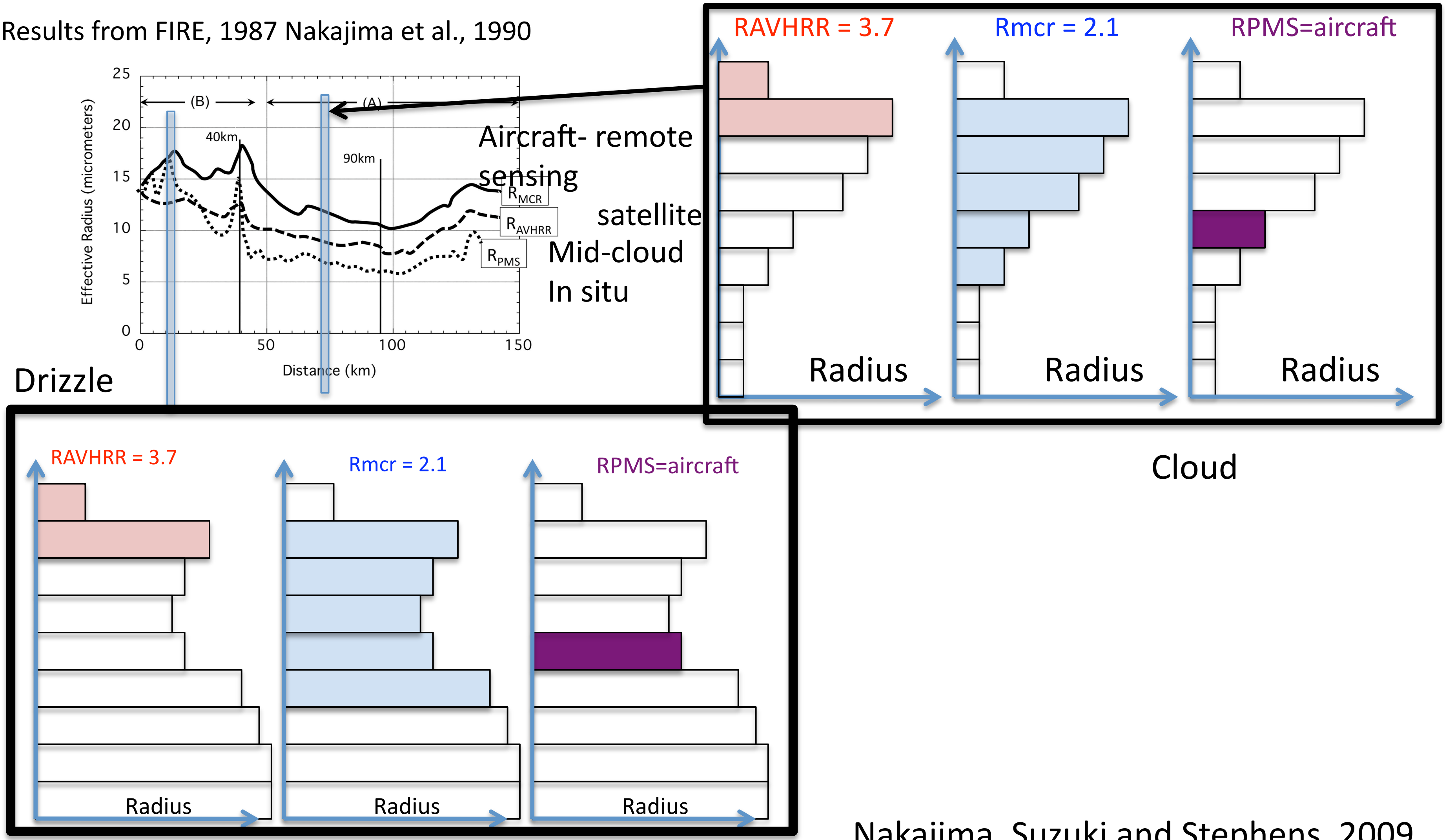


Platnick Weighting Function TH1=18.2, TH0=49.5)

Measurements of reflection at two wavelengths (or spectral bands) returns the pair of parameters τ and r_e and LWP

What about particle size - resolving a 20+ year conundrum

Results from FIRE, 1987 Nakajima et al., 1990



Aircraft- remote sensing

satellite

Mid-cloud In situ

Drizzle

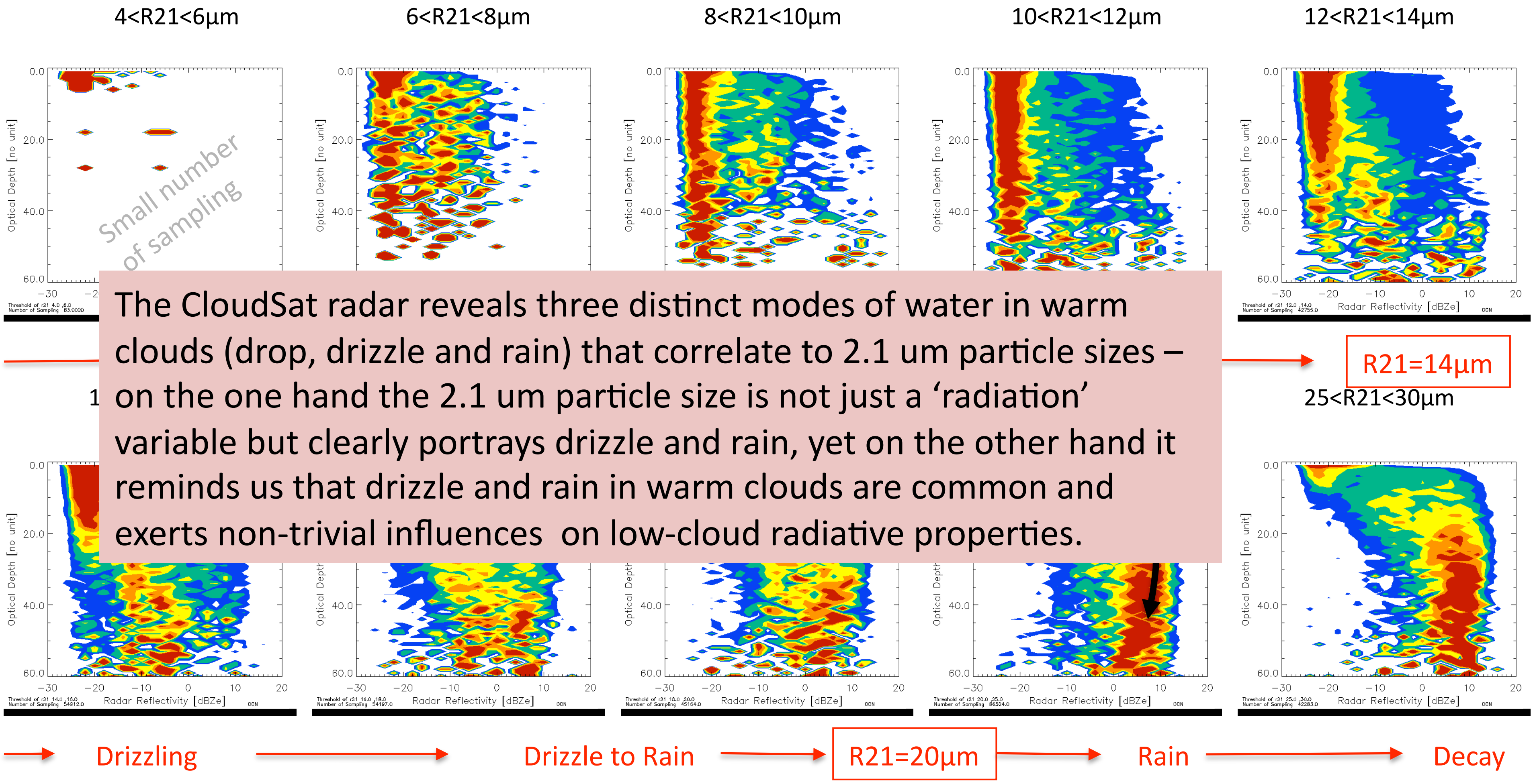
Cloud

Nakajima, Suzuki and Stephens, 2009

Particle sizes, drizzle and rain

Sampled only Tau_modis>1

Nakajima, Suzuki, Stephens (2009) in progress



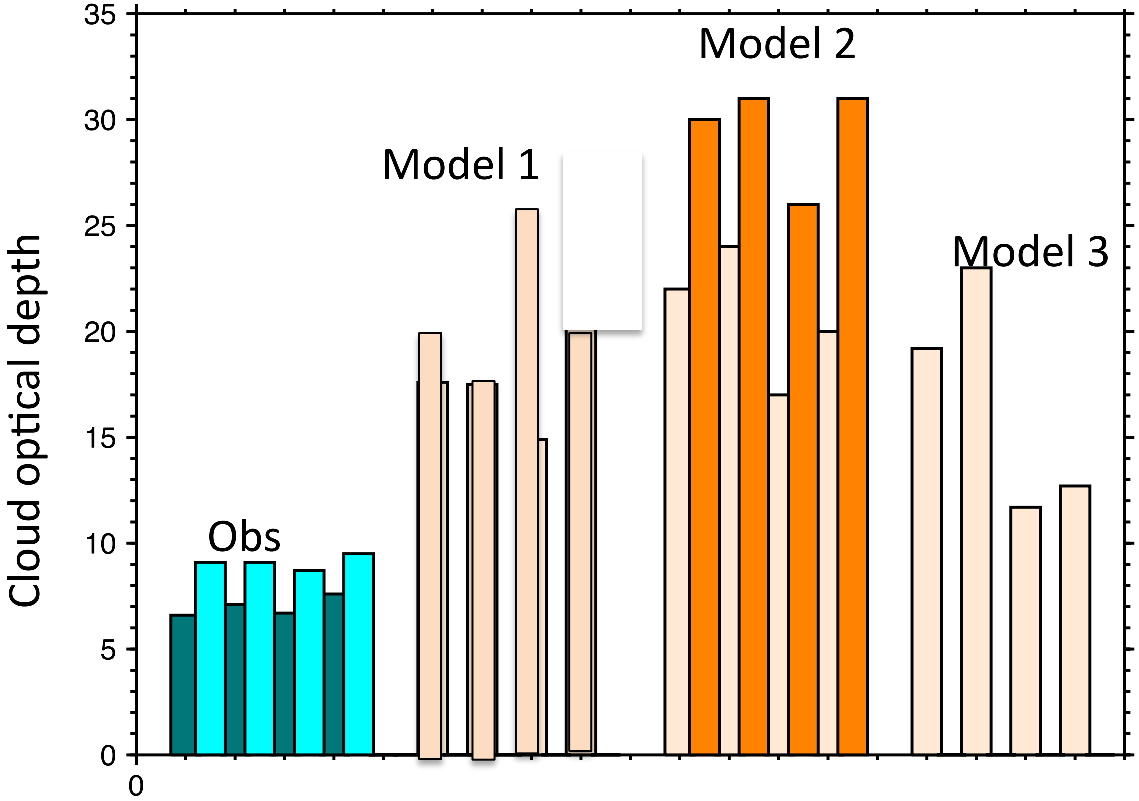
The CloudSat radar reveals three distinct modes of water in warm clouds (drop, drizzle and rain) that correlate to 2.1 um particle sizes – on the one hand the 2.1 um particle size is not just a ‘radiation’ variable but clearly portrays drizzle and rain, yet on the other hand it reminds us that drizzle and rain in warm clouds are common and exerts non-trivial influences on low-cloud radiative properties.

This particle size is a deeper layer average and reflects the significant effects of drizzle and rain on low cloud radiative properties

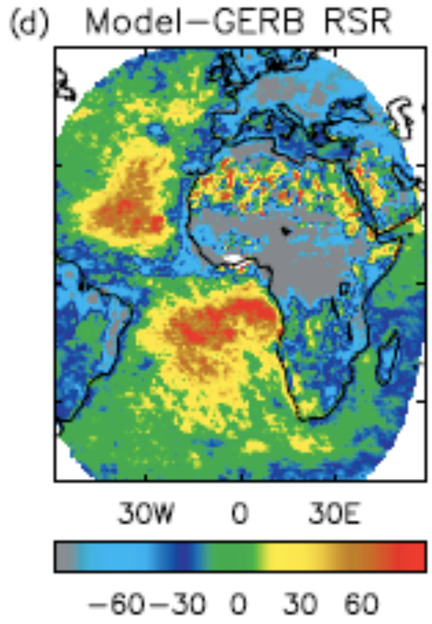
	All clouds	Clouds	Dizzle	Rain
LWP (g/m2)	123	81.4	276.7	332
Optical depth	10	7.9	17.6	19.6
CDR (um) MODIS	16.3	14.6	22.6	24.6
CDR (um) (AVHRR)	11.54			
Cloud top height (km)	1.44	1.26	2.02	2.28

Models assume values between about 8-12 um

Low cloud optical depth……



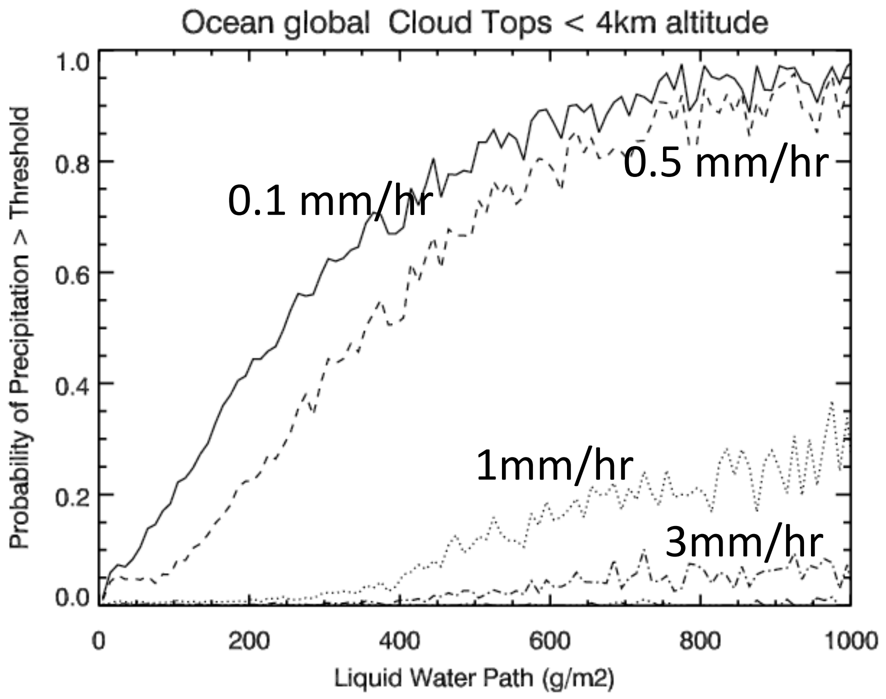
Yet another model



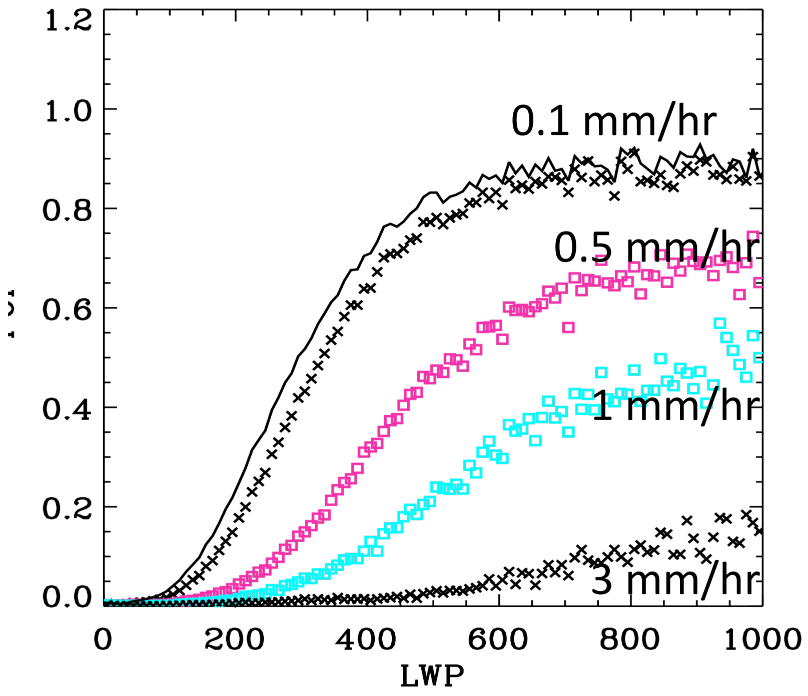
Model low, warm cloud optical and radiative properties are significantly different (biased) compared to those observed – two factors contribute to this <u>extreme</u> (bright) bias - the LWP is one, particle size is another.

Probability of rain in warm clouds

This and other results are beginning to reveal the issues in the way warm rain is parameterized in models – this process significantly affects the water balance in clouds and thus their radiative effects – this is clearly of some relevance to low cloud feedback



Model



Observations

Summary

- The optical properties of low clouds, in the mean, are affected (@ the 25% level) by the existence of rain and drizzle. This is not trivial and low cloud feedbacks are likely to involve these precipitation processes
- Model representation of low clouds contain serious biases (in both LWP and particle size) – the optical depths of low clouds appears to be more than a factor of 2 too large – resulting in and albedo –optical depth sensitivity that is artificially too small (by almost a factor of 4)
- Precipitation from low clouds occurs too frequently (drizzle/rain tends to be turned on immediately) with serious consequences to the water budget of model clouds and their radiative properties generally.
- This is a real time of opportunity to study feedbacks - we have very rich Earth observations that is begin to reveal aspects of key processes, a growing record in time capturing important climate variability.

A blue-print

Such a blue print might involve:

1 Hypothesis driven concept about feedback - e.g. that low cloud feedback in a warming climate occurs primarily as a consequence of atmospheric thermodynamic adjustments to the the warming (e.g. EIS) that then alter the planetary albedo – I frankly don’t believe such hypotheses can be meaningfully tested/refuted using current GCMs alone.

2. Construct/use simple models that address different aspects of this feedback - for example a simple RCE model with a cloud water path –temperature feedback will give you a sense for the importance of other processes that might contribute to albedo changes that might refute such an hypothesis.

3. Build on this exploring the extent that the salient features of these feedbacks (like the thermodynamic shifts if temperature, inversion strength etc) appear in more complex (realistic?) models. Convince yourself that such models are realistic by appealing to observations.

4. Examine observations, LWP from satellites and its relation to temperature as an example , the Clement et al type correlated trend study as another when possible, and develop other ways of gleaning tests of key processes (including surrogate natural climate change experiments when possible) all aimed at determining if key aspects of the hypothesized feedbacks reveal themselves in measurements.

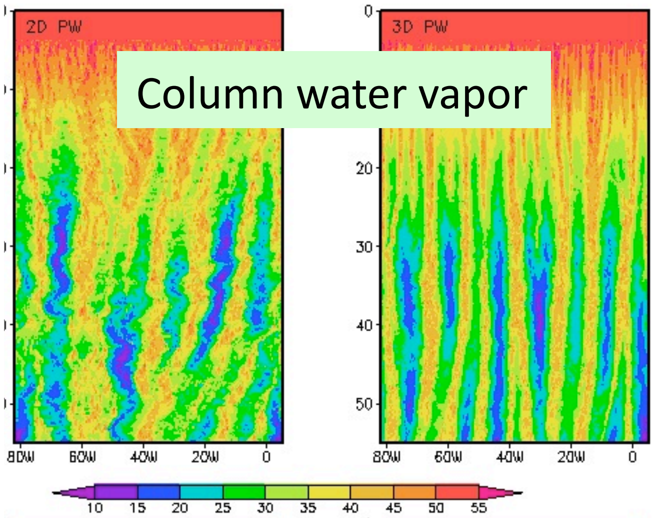
Don’t constrain yourself to flavor of the month themes – think outside he box

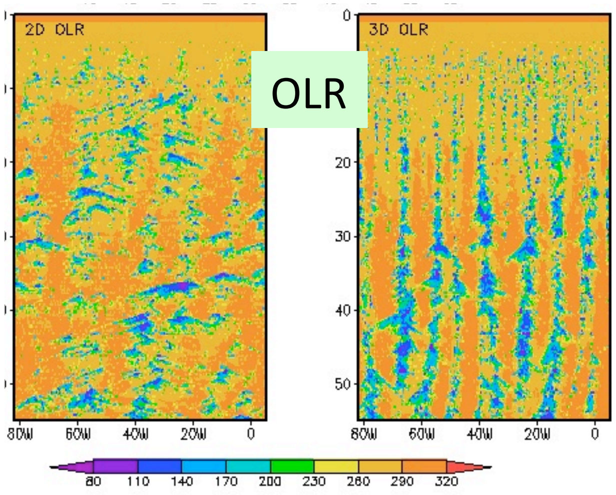
Radiative convective equilibrium as a paradigm for understanding feedbacks

Manabe & Moller,1961 Manabe & Strickler,1964 Manabe and Wetherald, 1967	Important studies that demonstrated how changes to GHG, solar forcings and water vapor feedbacks operate in a climate-like system. Some early ideas about cloud effects began to emerge.
Stephens and Webster, 1980	Demonstrated how clouds shape RCE state – introduced the important role of cloud water/ice path and the important differences between high and low clouds
Sommerville and Remer, 1984 Stephens et al., 1990	With water path now understood as pre-eminent, examined the water and ice path-Ts feedbacks first hypothesized by Paltridge (1980)
Held et al., 1994	Introduced a new paradigm – RCE with explicit convection using a cloud resolving model, on a small domain (100's of km) and O(4km) resolution

Radiative convective equilibrium

Grabowski et al ,2000s	Larger domain studies mostly in 2D – reaffirming the self aggregation of convection, hinting at cloud radiation feedbacks
Tompkins – 1998-2002	Tompkins performed a number of studies over this period, examining effects of shear, SST, and other factors on RCE.
Stephens et al., 2004	First use of the RCE-CRM to examine effects of cloud-aerosol interactions on RCE

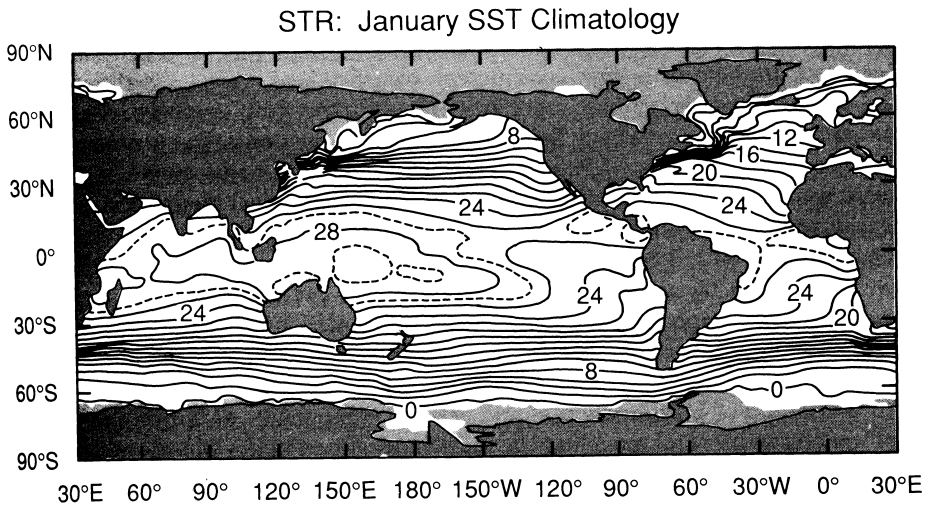

Column water vapor


OLR

Stephens et al. 2008

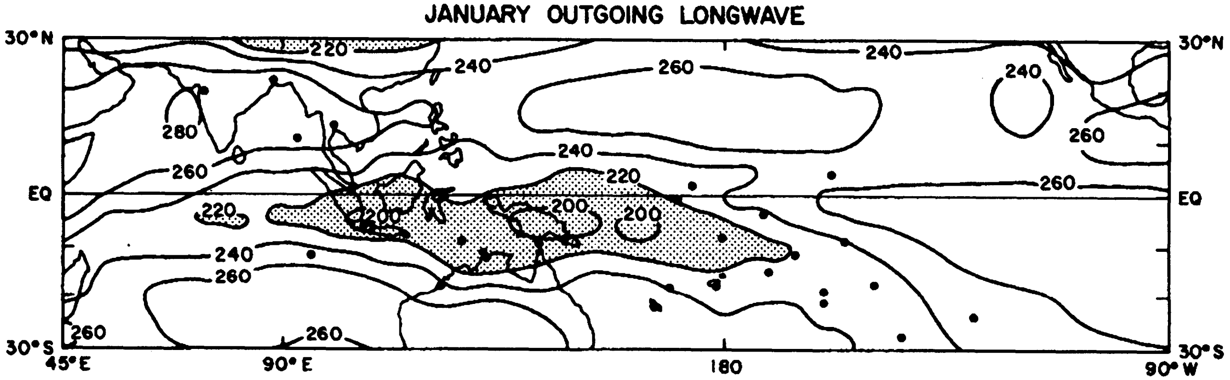
Backups

Cirrus detrainment –surface temperature feedbacks (e.g Chou & Neelin, 1999; Lindzen et al., 2001; Ramanathan and Collins, 1991)

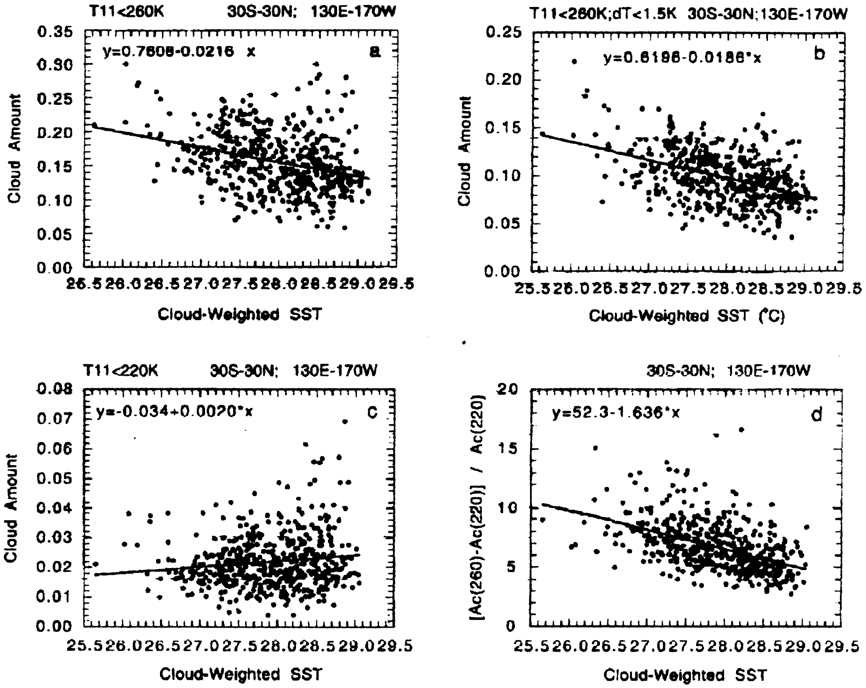


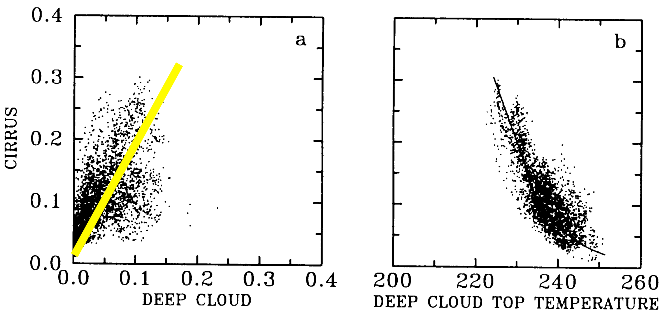
SST

c)



OLR





(i) Increasing SST

→ Increasing Convection

(ii) Increasing Convection

→ Increasing/decreasing cirrus/CsCu

(iii) Increasing cirrus →

decreasing SST (R&C- negative feedback)

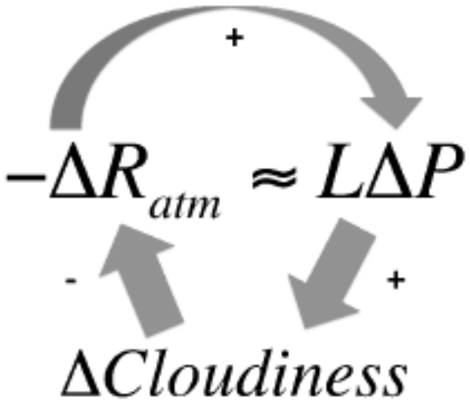
(iv) Decreasing cirrus →

decreasing SST (IRIS negative feedback)

??????????????????????

High clouds and convective feedbacks

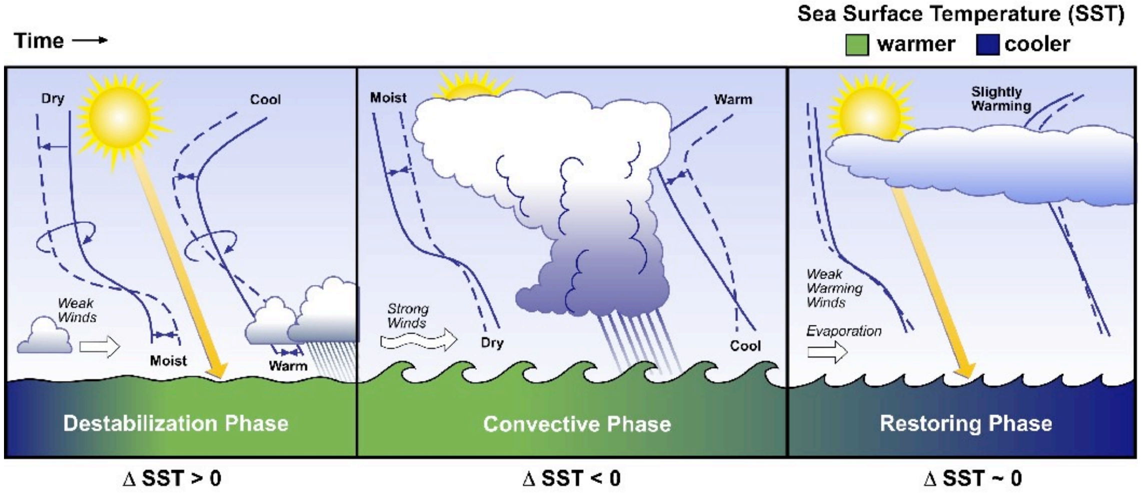
A number of studies have hypothesized on the importance of cloud radiative heating of the atmosphere and feedbacks related to it (Slingo and Slingo, 1988; Fowler and Randall, 1993; Stephens et al. 2004).



$$-\Delta R_{atm} \approx L\Delta P$$

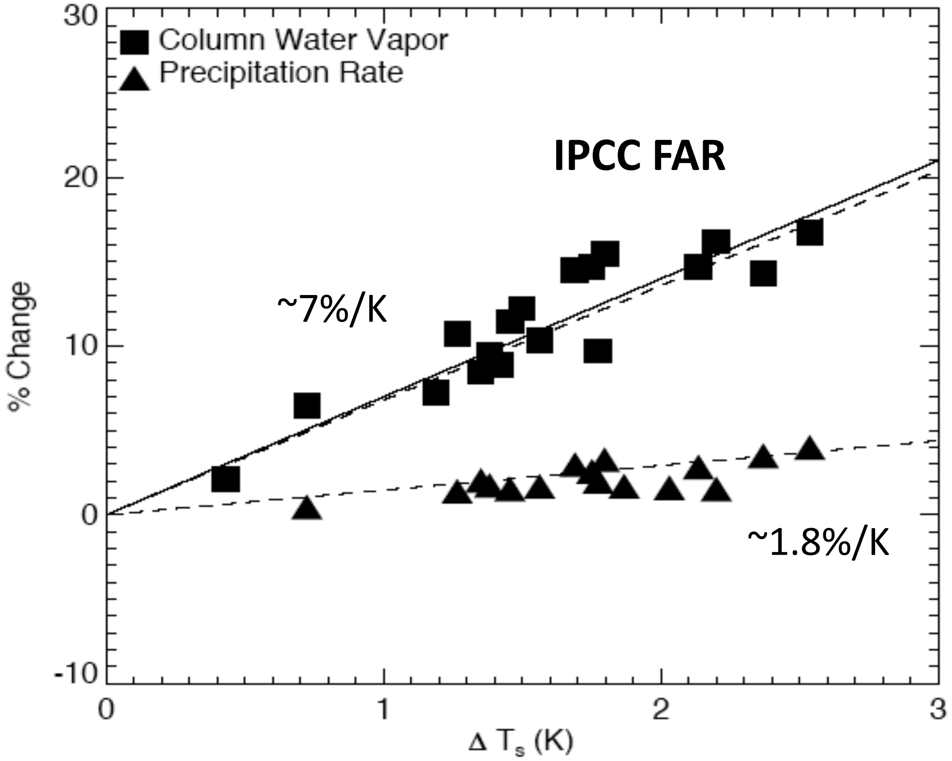
$$\Delta Cloudiness$$

(high)



e.g. Humidistat feedback of Stephens et al (2004)

Convective feedbacks and the control on global precipitation?



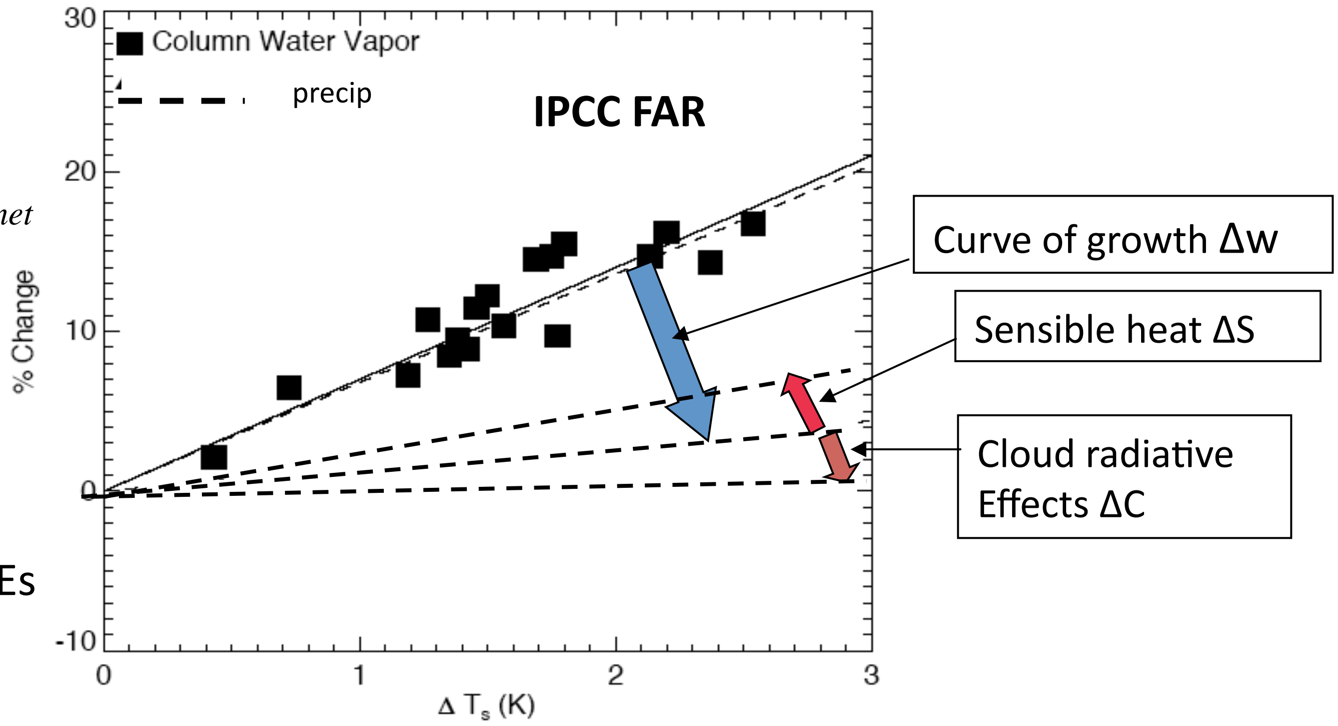
Convective feedbacks and the control on global precipitation?

$$\Delta R_{net,atm} = L\Delta P + \Delta S$$

$$\Delta R_{net,atm} = \Delta R_{net,clr} - \Delta C_{net}$$

Controlled by water vapor changes Δw

Changes in atmospheric CREs



Curve of growth Δw

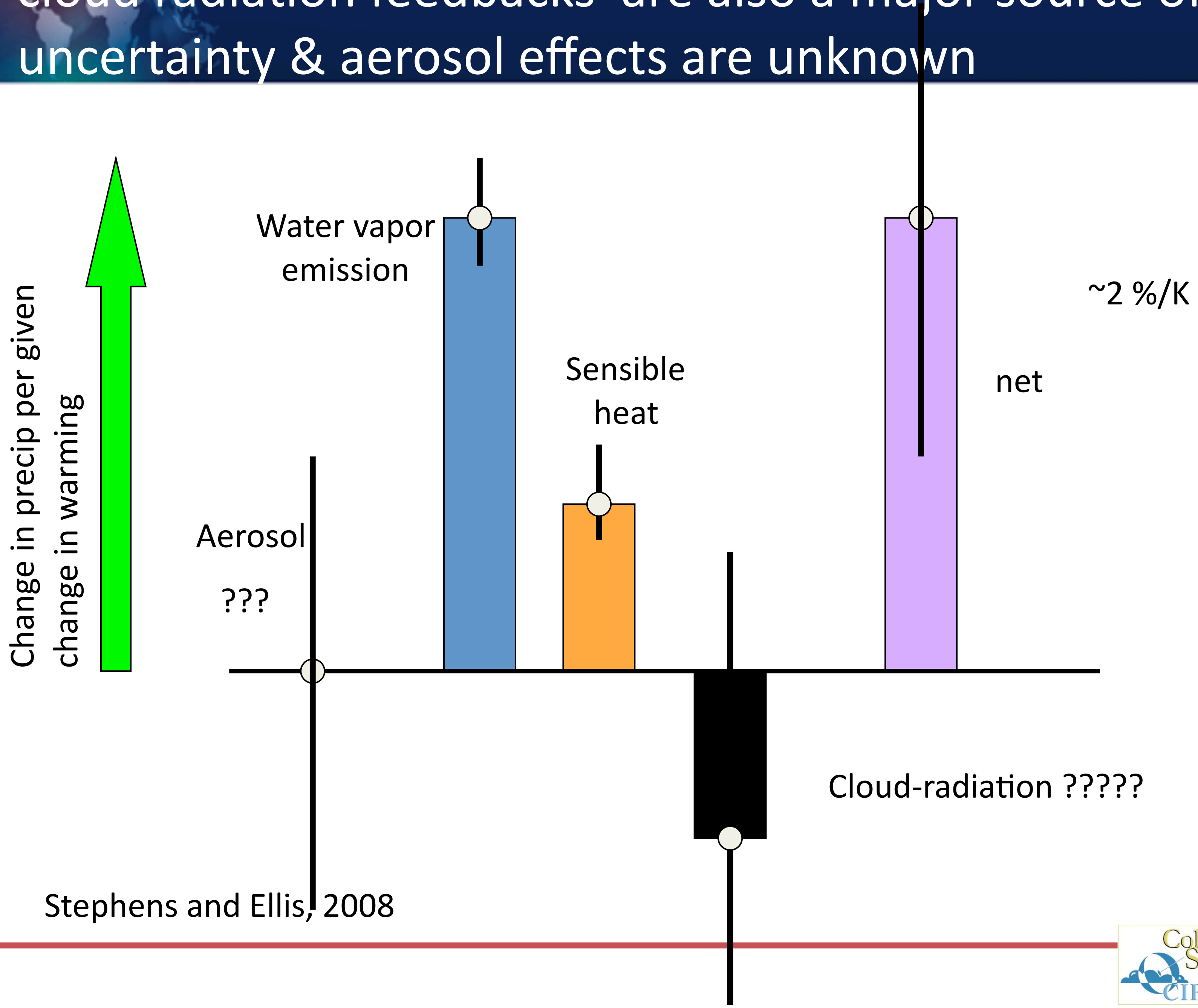
Sensible heat ΔS

Cloud radiative Effects ΔC

Cloud - radiative processes, sensible heating changes tug at the magnitude of the global change of precipitation which is to first order set by the water vapor feedback

Stephens and Ellis, 2008; J Climate

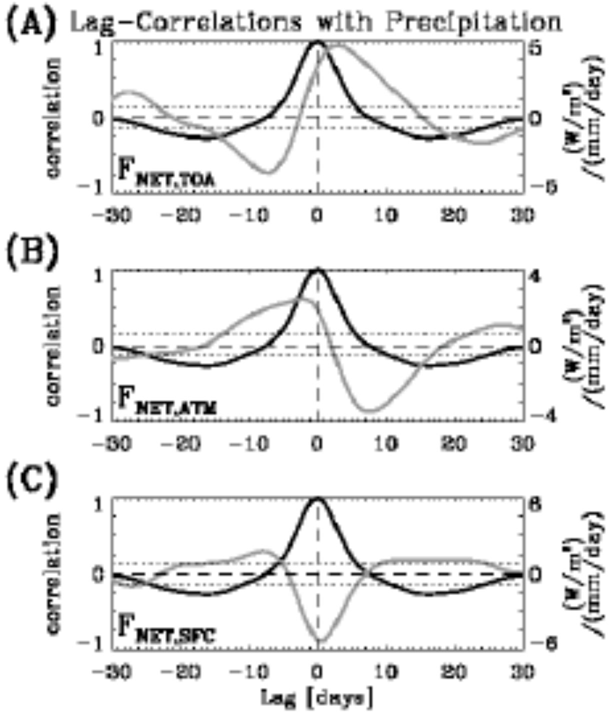
cloud radiation feedbacks are also a major source of uncertainty & aerosol effects are unknown



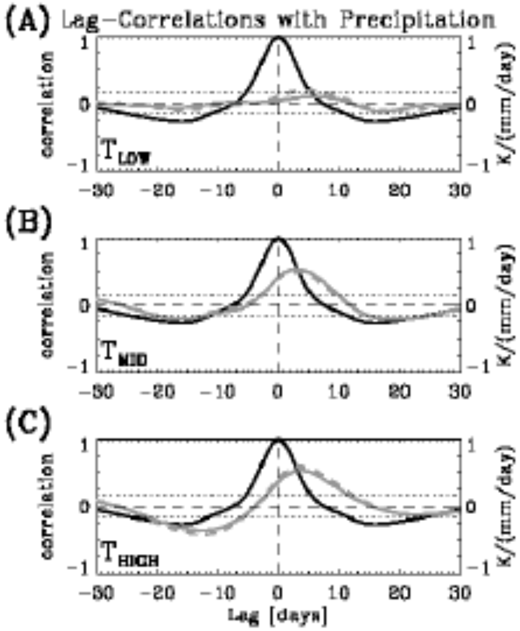
Stephens and Ellis, 2008

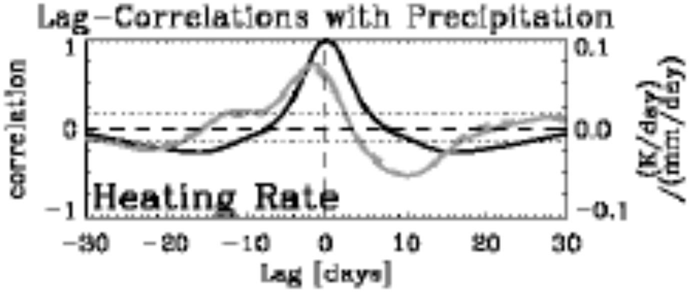
High clouds and convective feedbacks

Lebsock et al (2009) use A-Train observations to show tropic-wide radiative heating anomalies correlate with UT temperature anomalies and how the temps lags the heating – further hints at the existence of a radiation-convective feedback

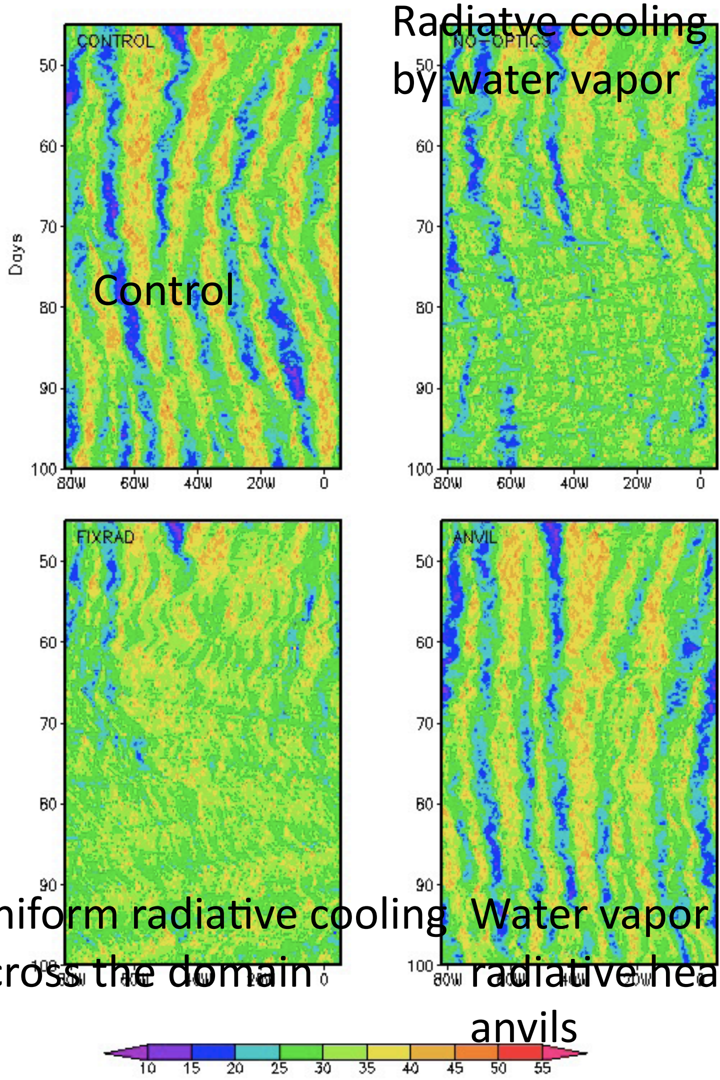


CERES based CREs





AIRS inferred heating rate

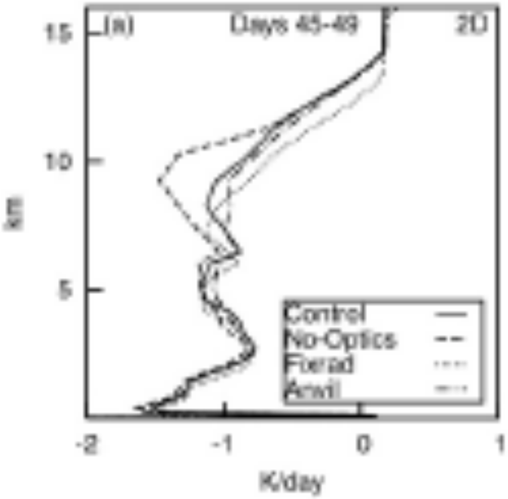


Radiatve cooling by water vapor

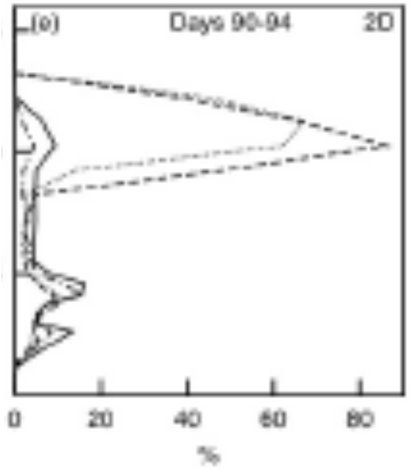
Control

Uniform radiative cooling across the domain

Water vapor plus radiative heating by anvils

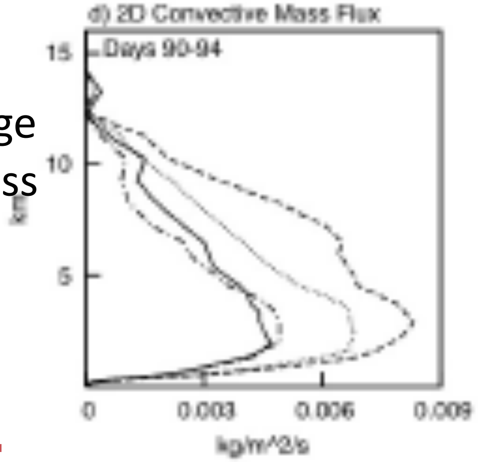


Domain average Radiative column



Domain average cloud fraction

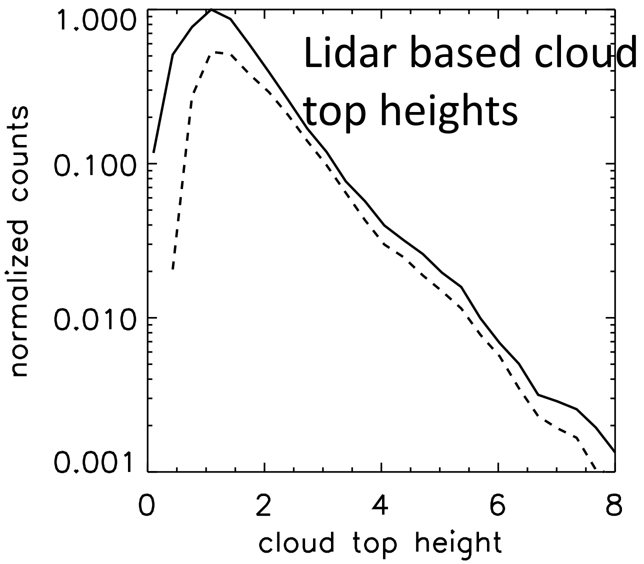
Domain average convective mass flux

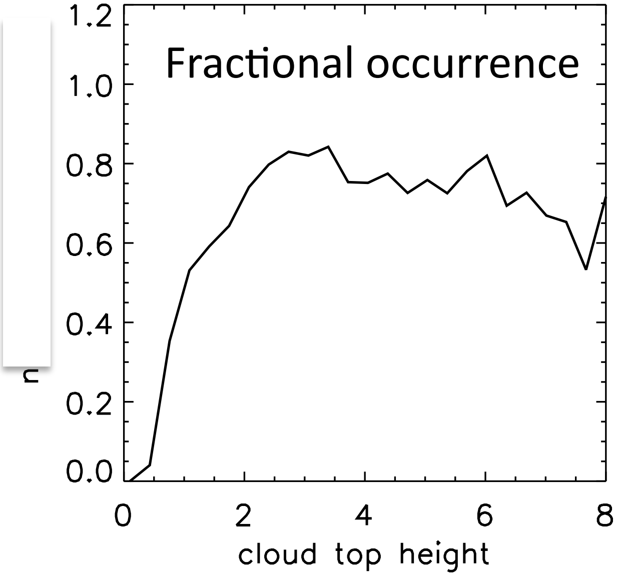


Steohens et al., 2008

Properties of Low oceanic clouds as revealed by the A-Train

- Low oceanic clouds = identified by MODIS low cloud mask (uses cloud top temp and other properties)
- Only single layer clouds (as determined by lidar info) analyzed
- Statistics accumulated over JJA and DJF seasons


Lidar based cloud top heights

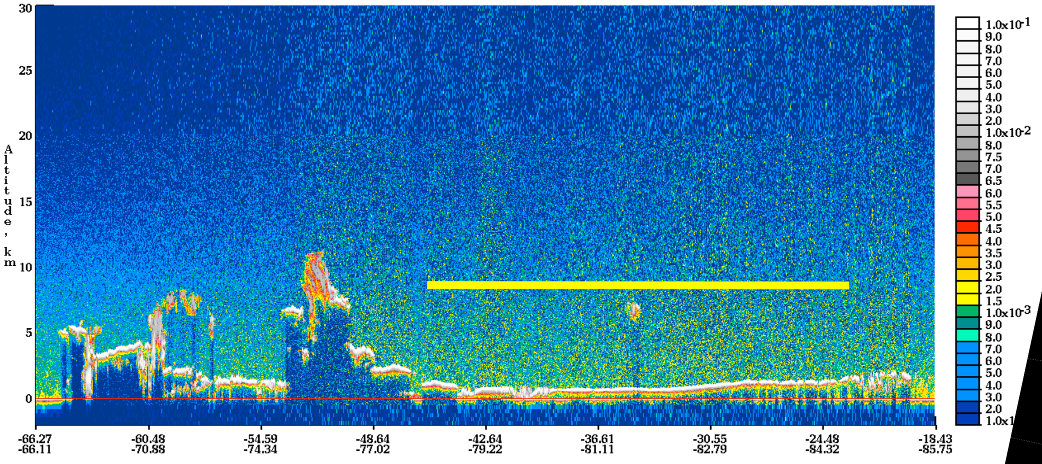

Fractional occurrence

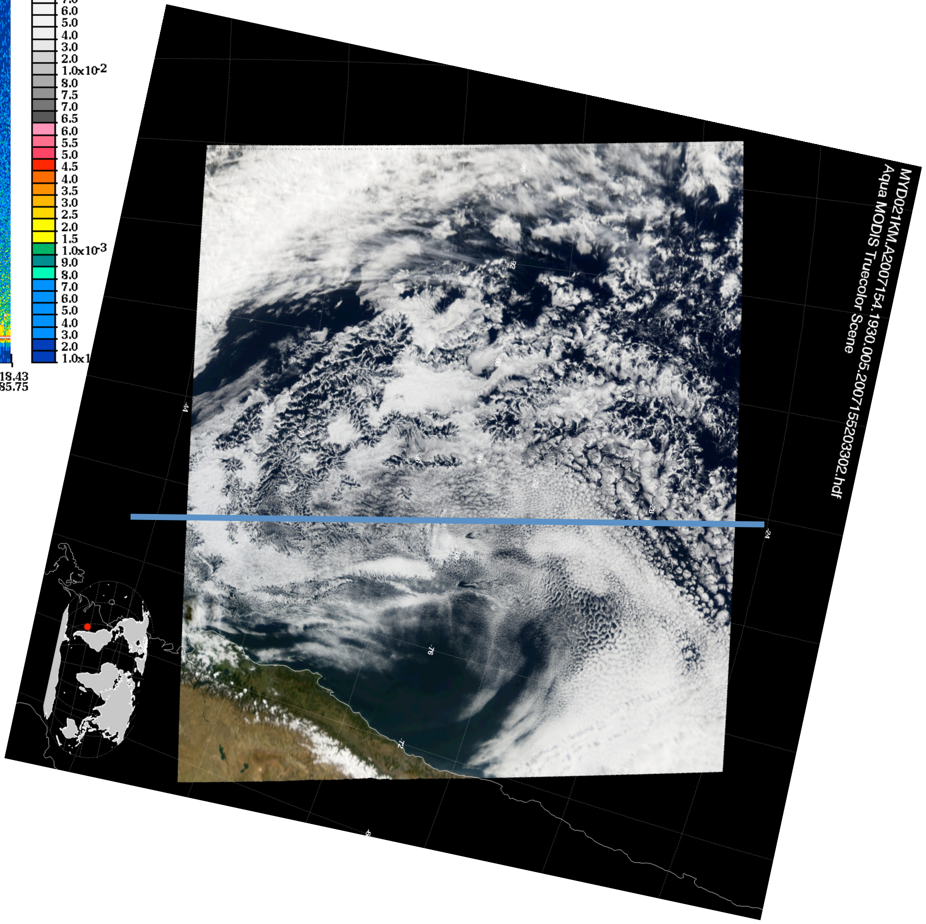
- These low clouds lie below 4km

Example orbit

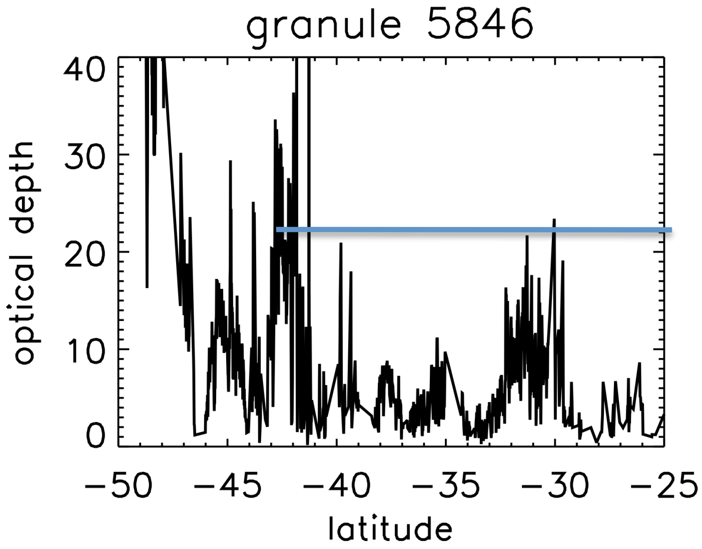
532 nm Total Attenuated Backscatter, /km /sr Begin UTC: 2007-06-03 19:24:48.8861 End UTC: 2007-06-03 19:38:17.5331

Version: 2.01 Image Date: 02/21/2008

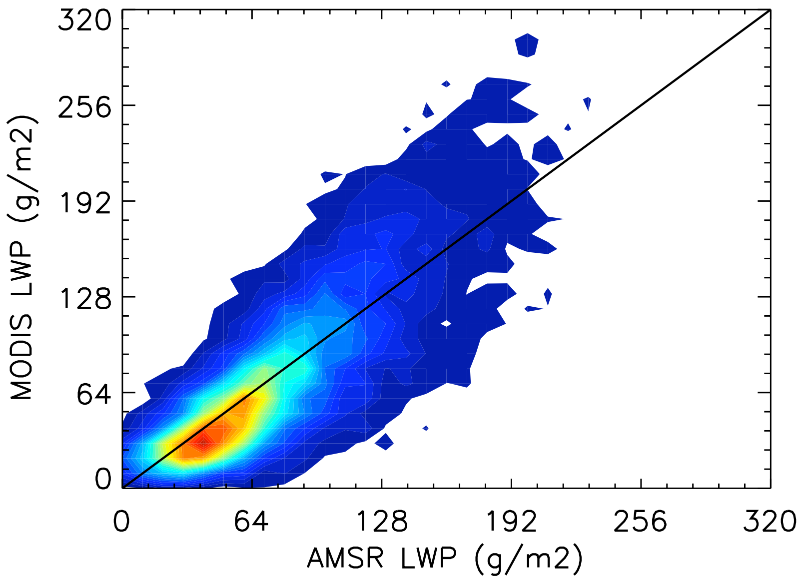




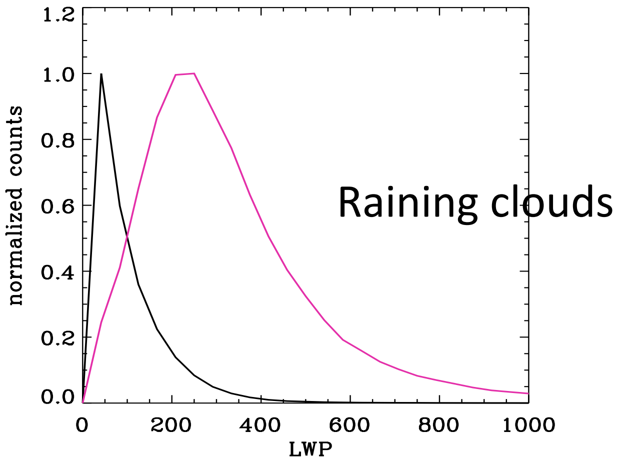
granule 5846

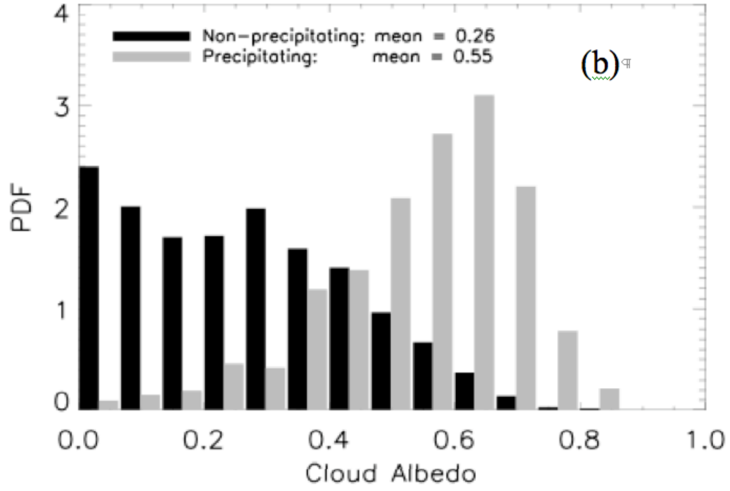


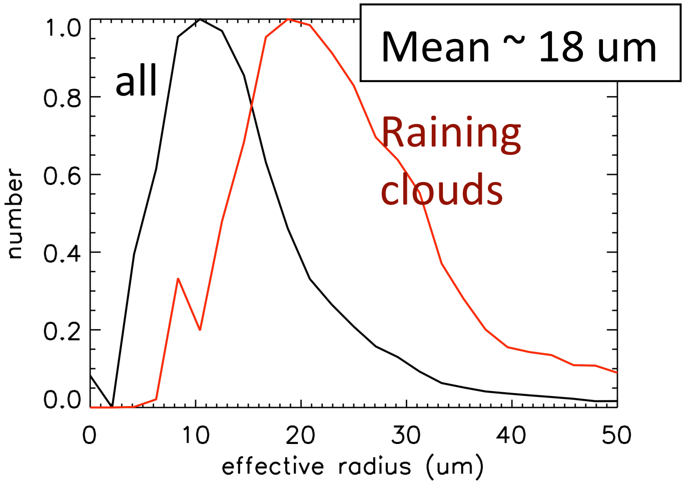
In-cloud LWP statistics of low clouds

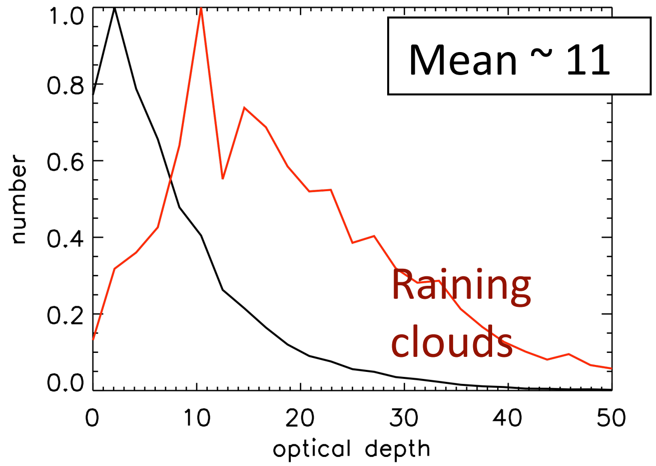


For the sampling applied, LWP derived from two different approaches methods agree over the range 20 - 200 g/m2









Drizzling/raining low clouds are wetter, contain larger particles are optically thicker and and reflect significantly more solar energy than non-raining low clouds

Summary:

1) Low clouds dominate the global TOA CRE via their influence on sunlight reflected to space.
2) The reflection of solar energy by a cloudy atmosphere is controlled by cloud amount, the water path and particle size and changes to these properties underlie hypothesized cloud-climate feedbacks.
3) The presence of drizzle in low clouds is prevalent enough that it has an observable consequence on the *mean* radiative properties of clouds (e.g. 18 µm mean particle size).
4) There are preliminary hints that the representation of low cloud radiative effects in models may be significantly biased high (water contents too large, particle sizes too small, optical depths too large and the amount of sunlight reflected by a given volume of cloud too large).

2) The nature of rain

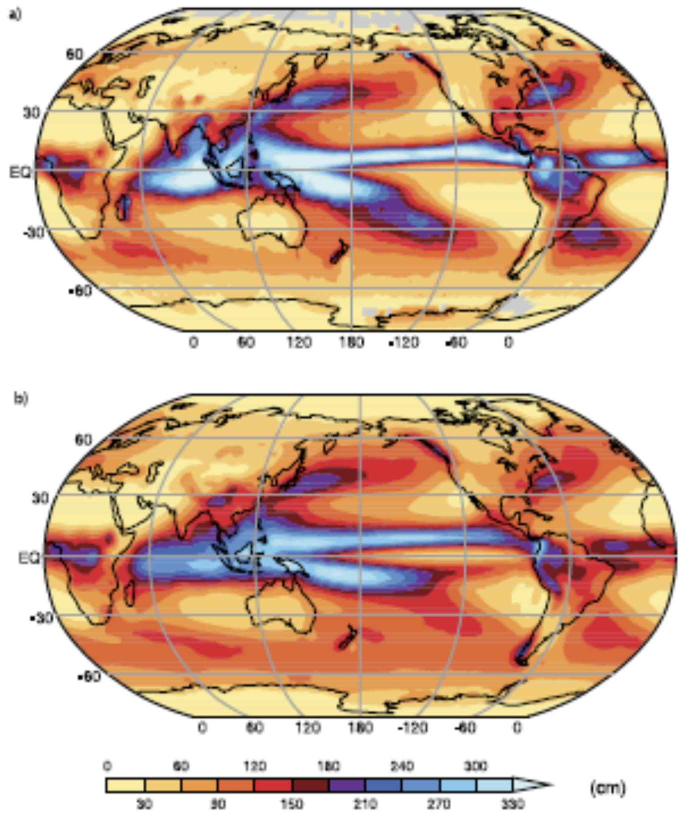


Figure 8.5. *Annual mean precipitation (cm), observed (a) and simulated (b), based on the multi-model mean. The Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) observation-based climatology for 1980 to 1999 is shown, and the model results are for the same period in the 20th-century simulations in the MMD at PCMDI. In (a), observations were not available for the grey regions. Results for individual models can be seen in Supplementary Material, Figure S8.9.*

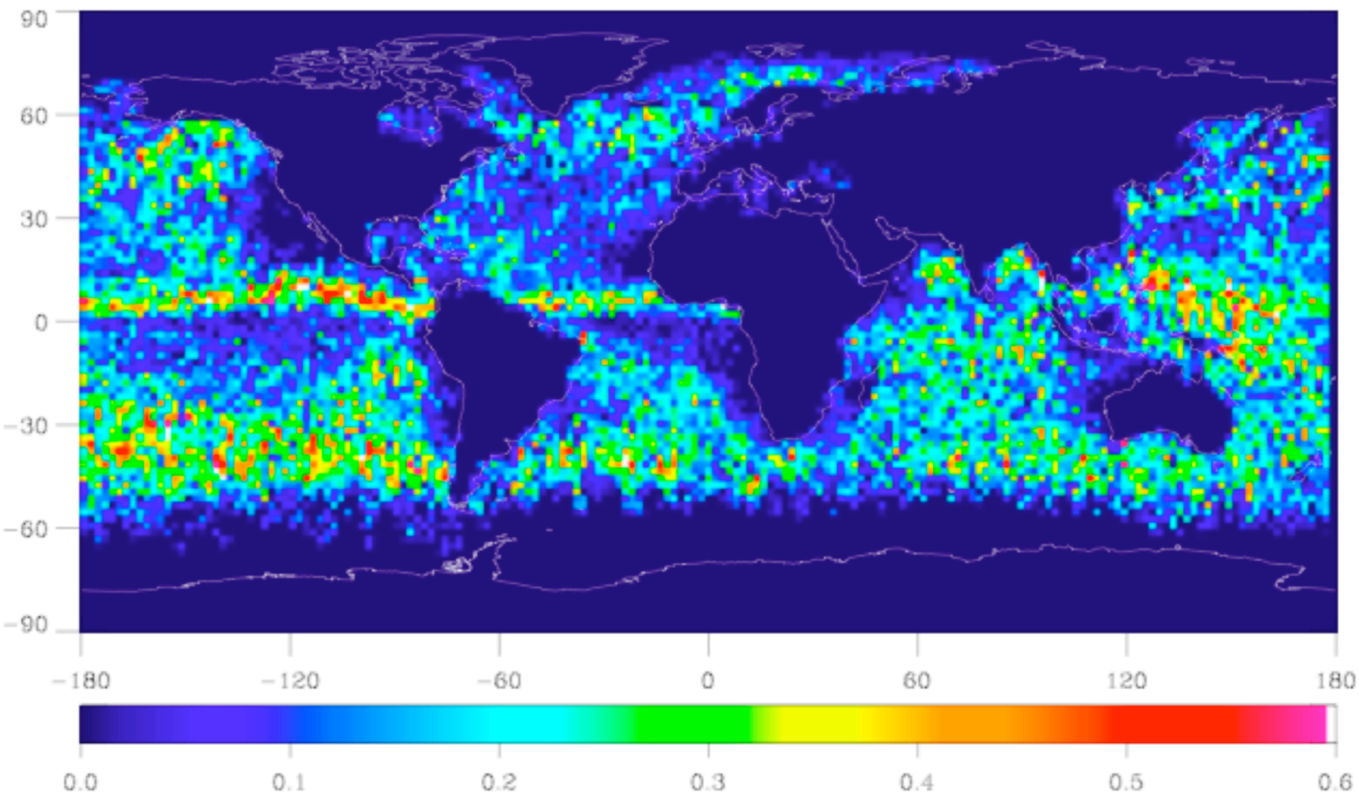
1. **Accumulation** - amount of precip accumulated over some time period – typically expressed as a rain rate – in climatological applications this is the most frequently analyzed form of precip used to compare to models – the accumulated precip on large space and long time scales is controlled (constrained) by energetics - ie it has to be ~ 3mm/day globally

2. **Character of precipitation** (accum = frequency X intensity) much less focus but essential to most hydrological applications and to many precip-related climate processes. There is no obvious constraint on this pair of characteristics.

- We use CloudSat observed frequency and intensity for JJA (2006)
- Special experiments performed using ECMWF forecast model (JJA 2006) and UMKO climate model (JJA 5 yr seasonal)
- Upscale CloudSat (1.7km) to model resolution (ECMWF, 0.5 degree, UKMO 1.25 degrees, 2 degrees for two models) via averaging along track
- Compare to model properties employing the lower CloudSat threshold of 0.05mm/hr also up-scaled to model resolution

Work in progress

Properties: JJA frequency (all sky) of liquid precipitation – ‘upscaled’ to 0.5 degrees



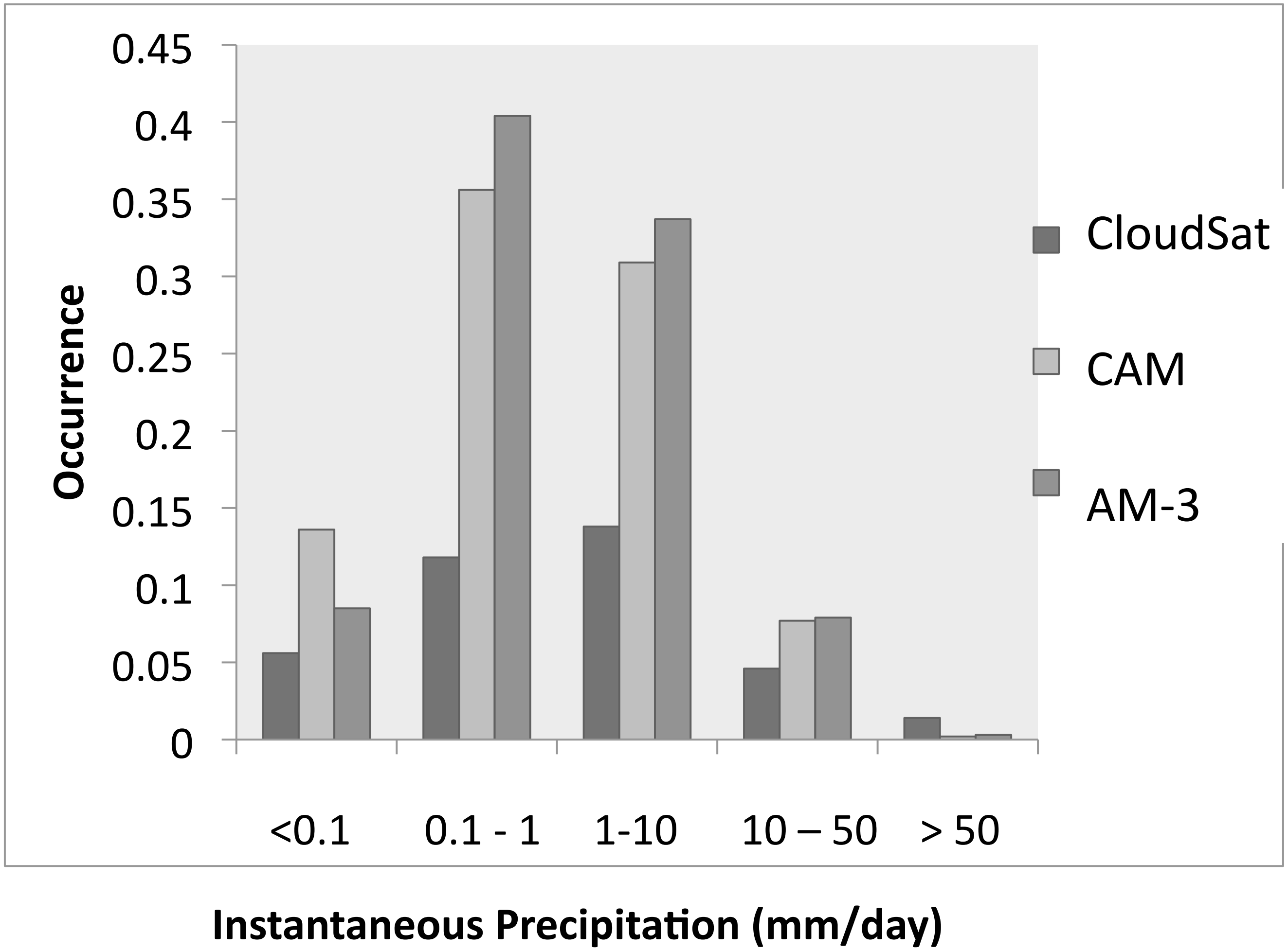
Frequency ~ 0.21 Mean rain rate slightly lower than model – obs slightly under represent the heaviest rain)

JJA Oceanic Precipitation Model Comparison Summary

Data Source	**Incidence**	**Mean Rain rate mm/day**
CloudSat (native)	0.11	2.86
CloudSat (0.5)	0.212	
ECMWF	0.679	2.83
CloudSat (1.25)	0.309	
UKMO	0.493	2.65
CloudSat (2)	0.372	
CAM	0.880	2.71
AM-3	0.908	2.94

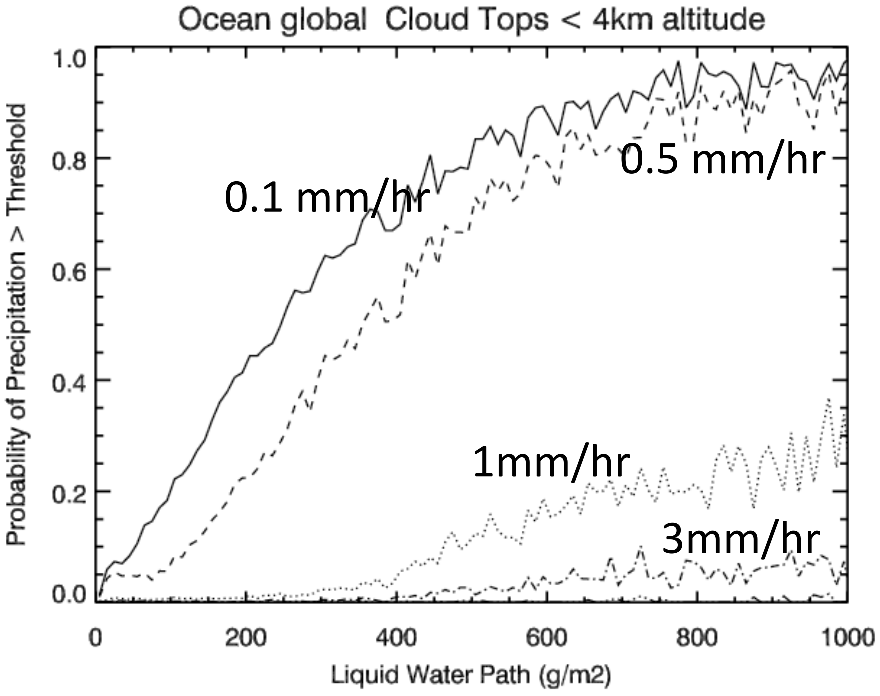
How often it rains at any CS footprint or model grid point

CloudSat 2 degrees

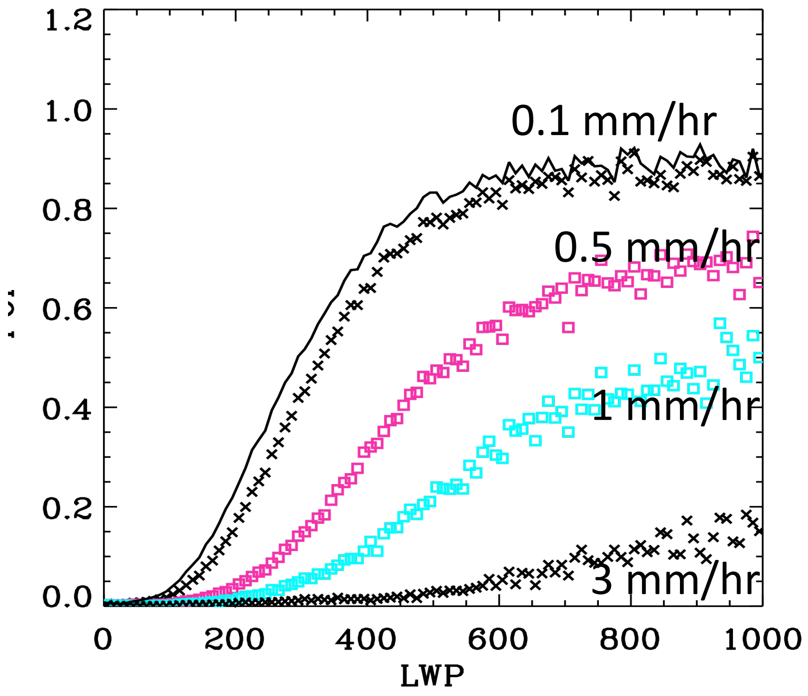


Probability of rain in warm clouds

Model



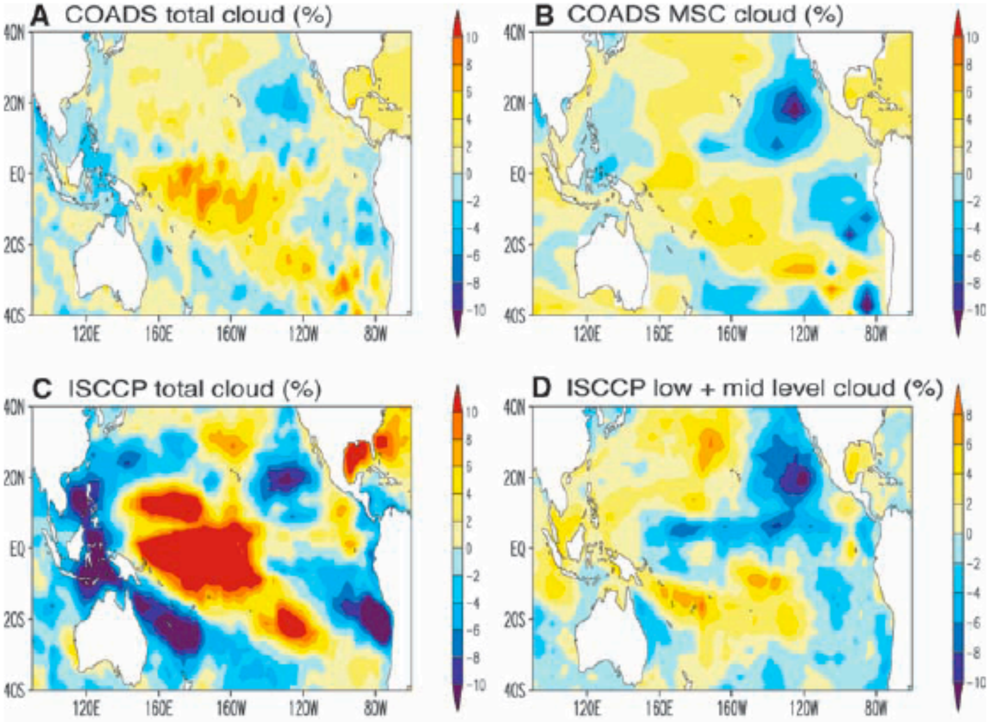
Observations



Many studies attempted to deduce $\frac{\partial C_{TOA}}{\partial A_c} = ?$

where A_c is the total cloud amount based on observations (Cess, 1976, Ohring & Clapp, 1980, Hartman and Short, 1980, ….) but these early estimates all suffered in one way or another -

An important step forward in TOA derived quantities came with ERBE and the improved ability to discriminate clear and cloudy schemes via the broad-band scanner instrument



$$\frac{\Delta A_c}{\Delta T_s}\ \%/\mathrm{K}$$

Cloud trends correlated with SST changes (Clement et al., 2009) – a very gross synopsis of cloud changes – this doesn't test feedbacks in models because these hinge on mechanisms and we need more quantitative understanding of how the *processes* of these mechanisms change