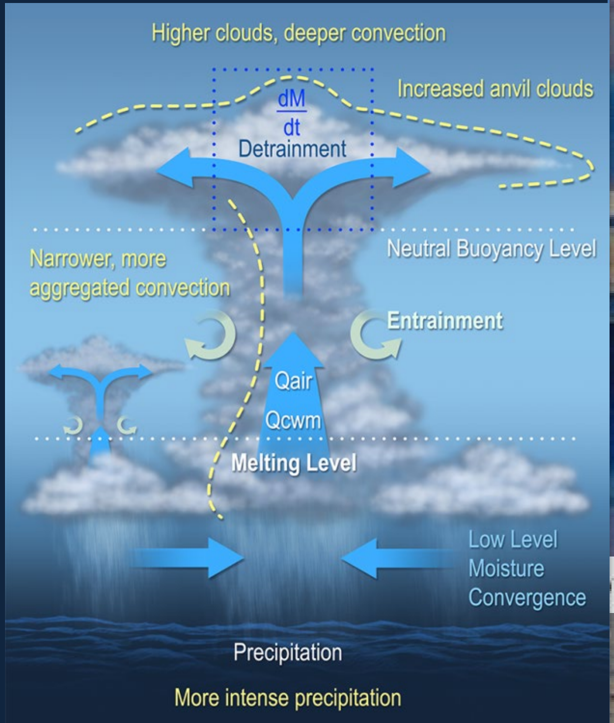
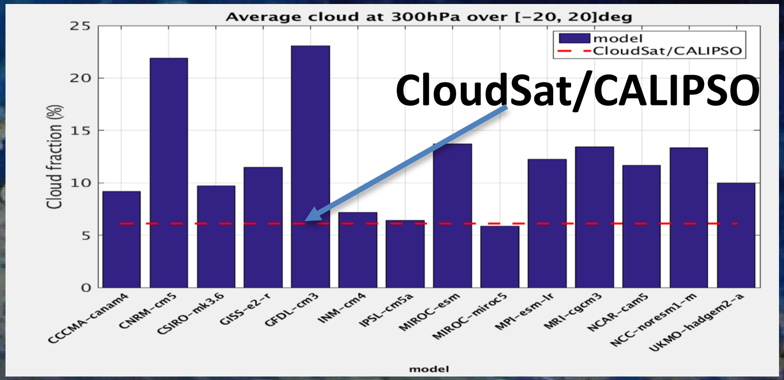
Some Thoughts on Cloud-convection feedbacks

Graeme Stephens, JPL



Some ways convection is thought to change with warming

High Clouds – the climate modeler's canary *"High clouds are the modeling communities last line of defense against top-of-atmosphere observations of energy fluxes", A DelGenio, 2002, ECMWF, Reading UK.*



Outline

Why do we care about high clouds ?

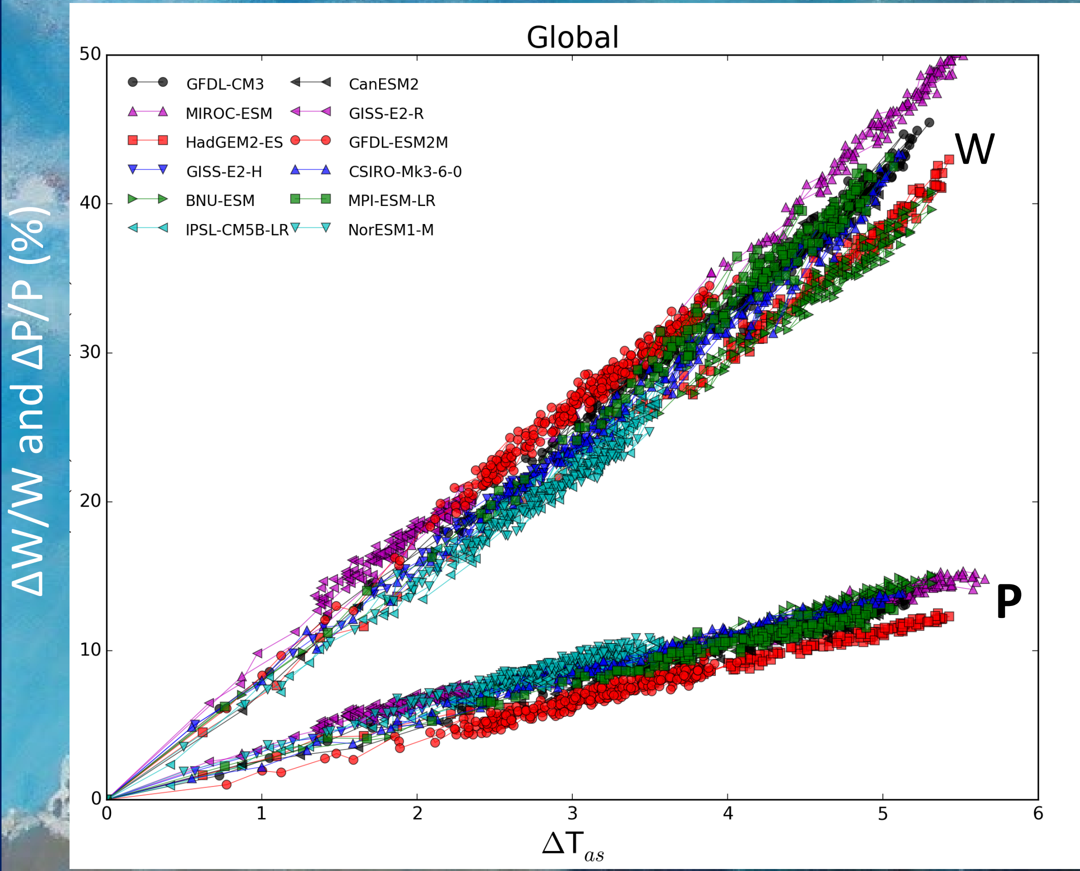
1) Their impact on radiative heating is central to how convection gets aggregated and how the hydrological cycle associated with convective storms gets modified
2) They represent important feedbacks that influence both climate sensitivity and the hydrological sensitivity

What steps are underway to address questions about the relation between high cloud and convection?

1) GEWEX Upper tropospheric clouds and convection PROES
2) The D-Train concept

1) Climate change sensitivities

-Hydrological sensitivity
- climate sensitivity (feedback)



Questions

- **Why is ΔP/P < ΔW/W?**
- **What determines the magnitude of ΔP/P?**
- **What contributes to the model-spread in ΔP/P?**

Tools typically used

- **CMIP5 analysis of abrupt CO2 quadrupling- e.g. Deangelis et al. 2015**
- **Clear-sky Radiative Kernel analysis, e.g. Soden and ; Previdi, 2010**

The global (atmospheric) energy balance

LP + H = R_{atm} = LW_{atm} + SW_{atm}

82±7 25±5 -180±9 73±8

R_{atm} = $LW_{atm,clr}$ + $LW_{atm,cld}$ + $SW_{atm,clr}$ + $SW_{atm,cld}$

-183±9 3±5 68±8 5±5

$L\Delta P = \Delta R_{atm} - \Delta H$

Consider the case of ΔH, suppose cloud terms~0

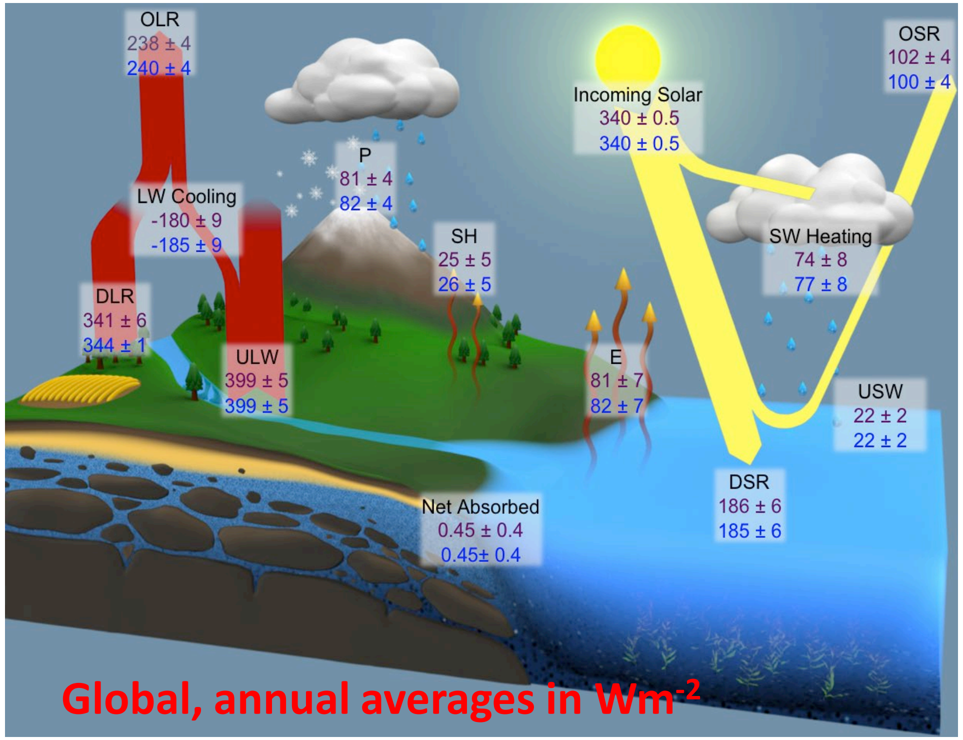
$$R_{net,atm,clearsky} \sim W^b \quad ;$$

$$W = \text{total column vapor}$$

$$b < 0.5 \quad \text{('curve of growth' effects)}$$

$$\frac{\Delta R_{net,atm}}{R_{net,atm}} = b\frac{\Delta W}{W}$$

$$\frac{\Delta P}{P} \sim b\frac{\Delta W}{W}$$



L'Ecuyer et al., 2015
Stephens & L'Ecuyer, 2015

$$\frac{\Delta P}{P} \sim b\frac{\Delta W}{W} < 0.5X0.07 \sim 0.035/\text{K}$$

more or less an upperbound

Changes to the global (atmospheric) energy balance e.g. Abrupt 4XCO2 example

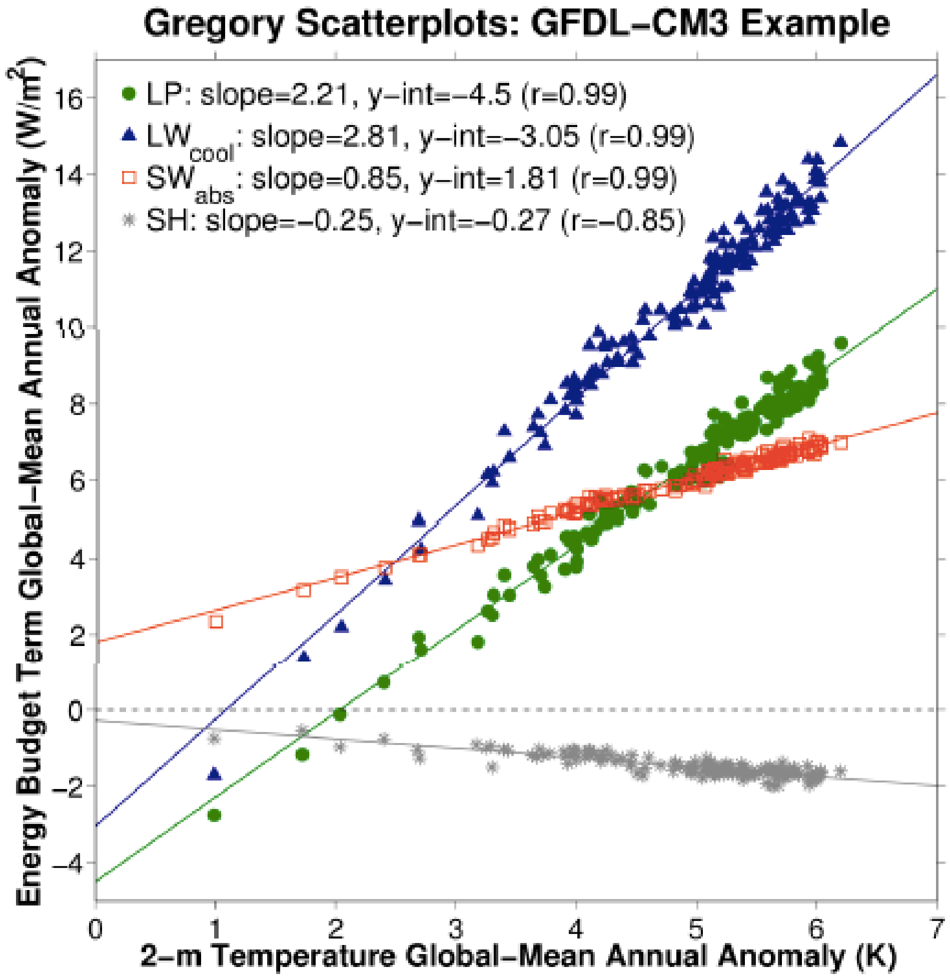
Multi-model mean

2.2 -1.93 - 0.28 $Wm^{-2}K^{-1}$

$$L\Delta P = \Delta R_{atm} - \Delta H$$

$$\Delta R_{atm} = \Delta LW + \Delta SW$$

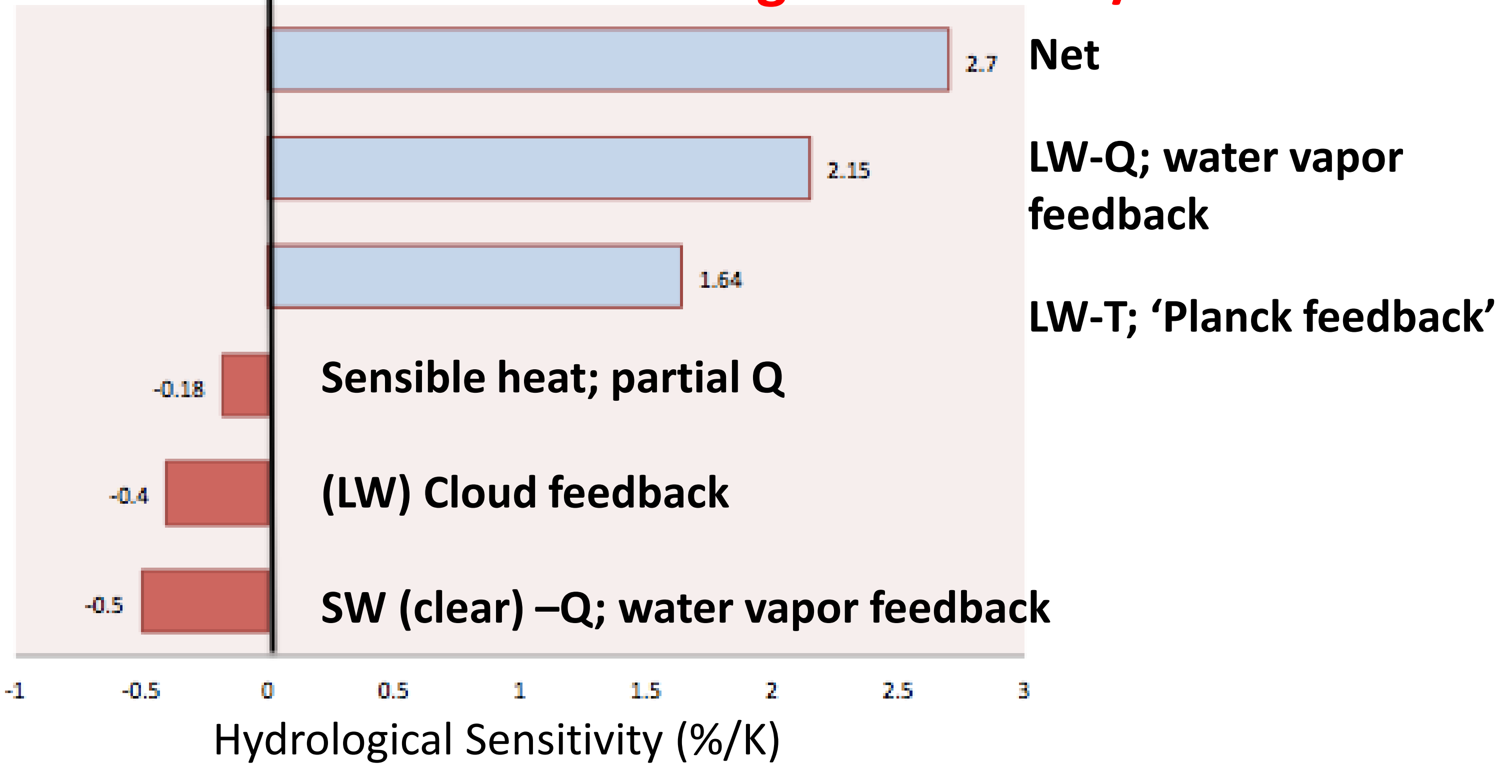
$$\Delta R_{atm} = \Delta LW_{clr} + \Delta LW_{cld} + \Delta SW_{clr} + \Delta SW_{cld}$$

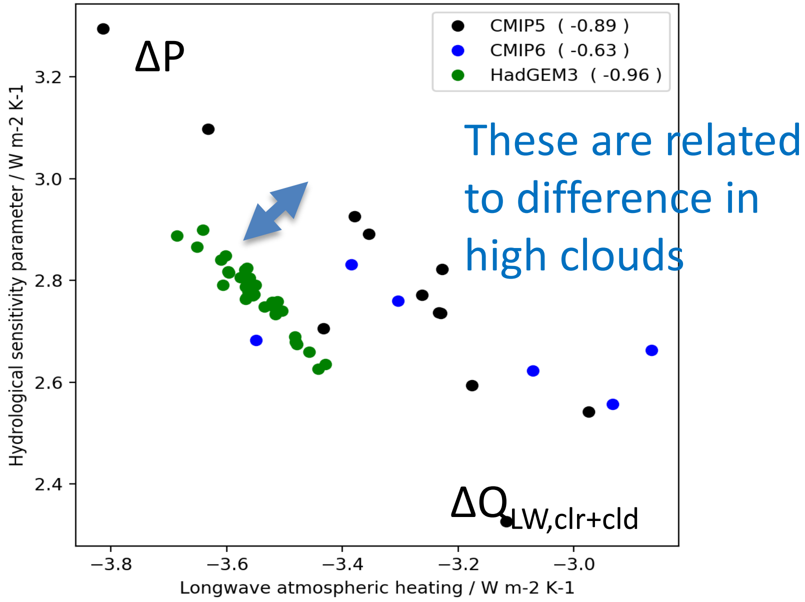


DeAngelis et al., 2015
CMIP5 4XCO2 experiments

Summary

- **Why is ΔP/P < ΔW/W?** - **This is set by the absorption/emission physics, largely water vapor controlled (~2%/K), and non-linear. The 'Planck' response too is small (~1.6%/K)**
- **What determines the magnitude of ΔP/P?**



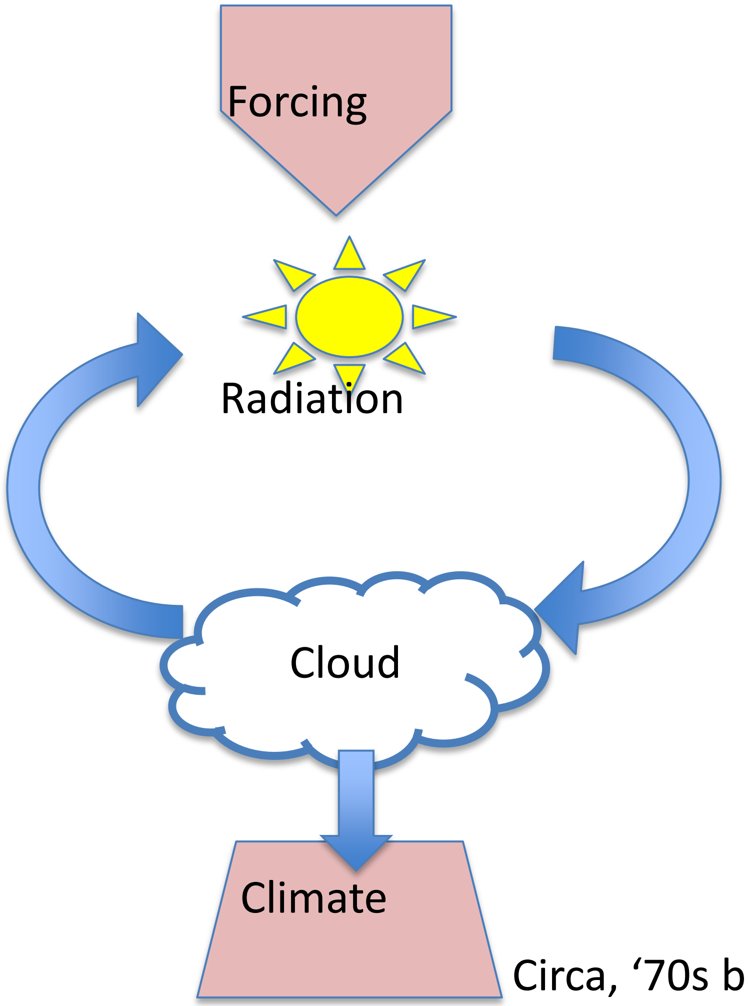


19 different configurations of HadGEM, Bodas-Salcedo et al., 2018)

- **What contributes to the model-spread in ΔP/P?**
  Absorbing aerosol (black carbon) and high clouds

Climate Sensitivity: The cloud-radiation-climate feedback cycle

Much of the decade of the 70's and 80's focused on advancing radiative transfer tools and quantifying effects of clouds on radiation. This is the easy part of the problem and today we have many tools (e.g radiative kernels) to test understanding.



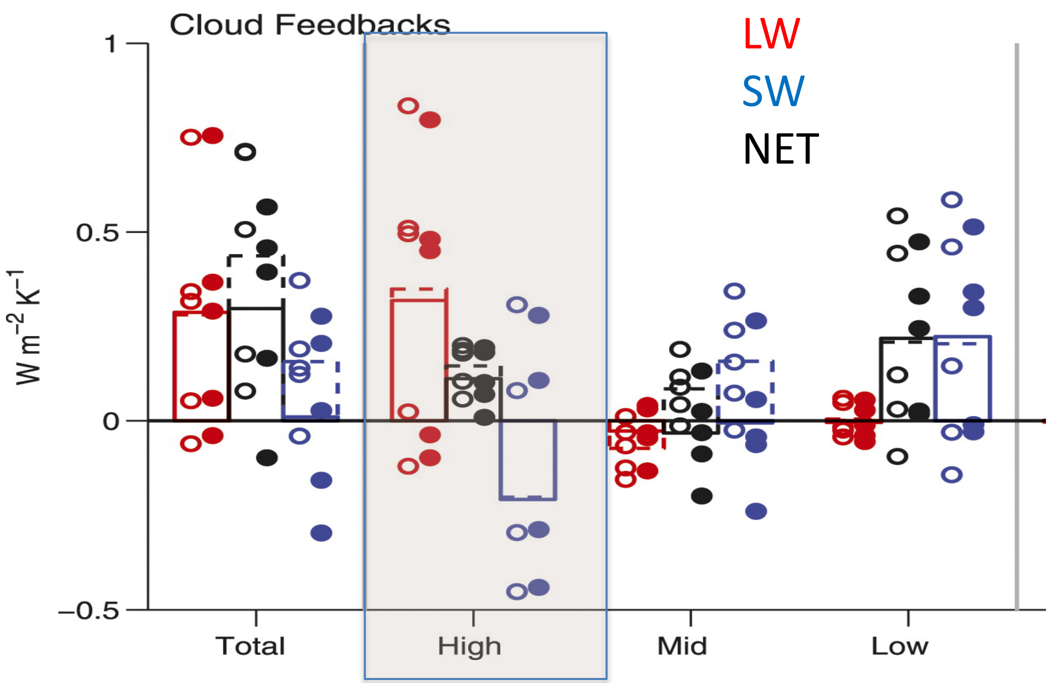
Circa, '70s but still relevant today

The 70's-80's was followed by the present period where focus shifted to how radiation (and the climate environment) shapes clouds. This is " the cloud parameterization or prediction problem" & is the hard part of problem that intimately engages cloud physics, circulation, etc .

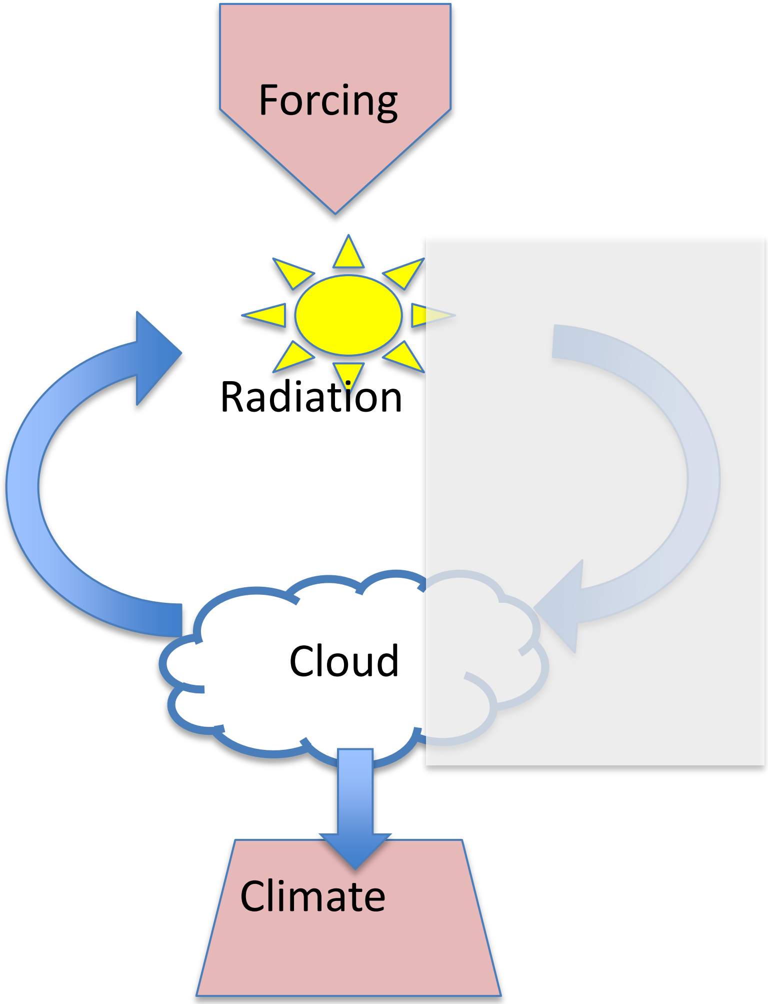
OUR basic dilemma– how does one go from mostly hypothesis forming science around this cycle to a truly knowledge based science about it

The cloud-radiation-climate feedback problem: radiation sensitivities

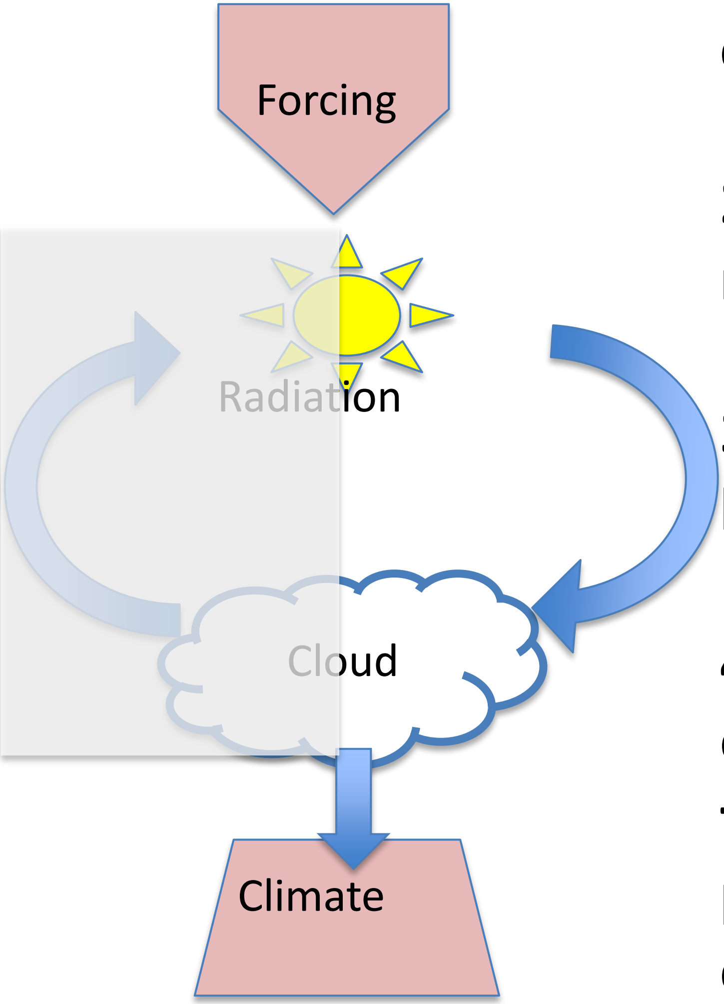
Zelinka et al., 2013



For high clouds, the intermodal spread in LW and SW sensitivities is as large as for any other clouds – this spread in response curiously cancels producing a smaller net response than, for example, that of low clouds. This is often mistakenly interpreted to mean high cloud feedbacks are small



The cloud-radiation-climate feedback 'cycle'



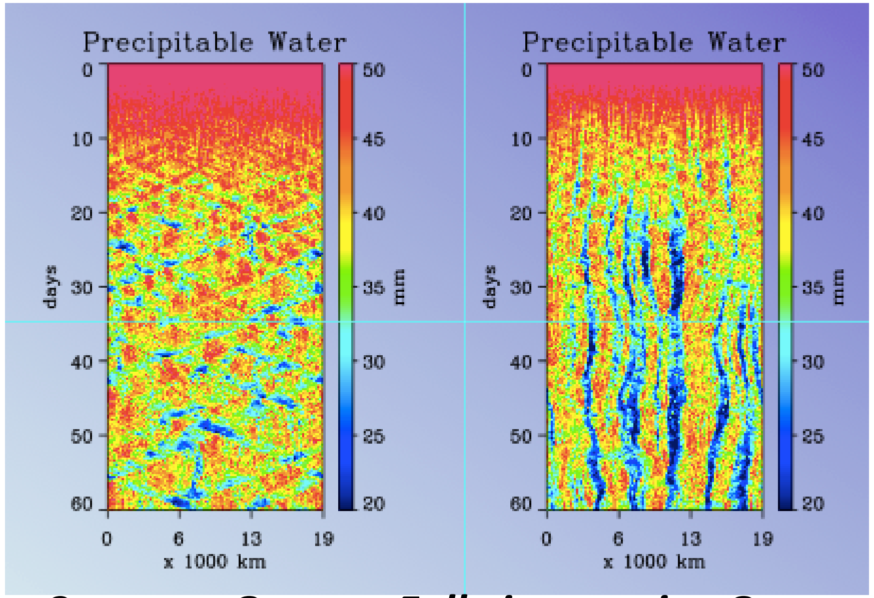
1) Model based climate change expts,MIPs

2) Process models,studies married to obs

3) RCE sensitivity expts, high res modeling

4) Climate variability - an observational window into the cloud response processes & the complete cycle, but is it c/c feedback?

RCE
- early experiments , simple RCE in 70s,80s postulated IWC,LWC feedbacks
- CRM the more explicit role of convection – e.g. convective aggregation – the role of differential heating & high clouds, (e.g Stephens et al., 2008; Gray and Jacobsen, 1977)



Constant Q_{rad}   ***Fully interactive Q_{rad} ie differential heating***

Two studies on climate variability analysis

Decade plus time series of:

- GPS tropospheric heights,
- TOA radiation budget (EBAF),
- (MODIS) cloud properties,
- CALIPSO opaque cloudiness
- CloudSat convection intensity
- ENSO,BDC indices

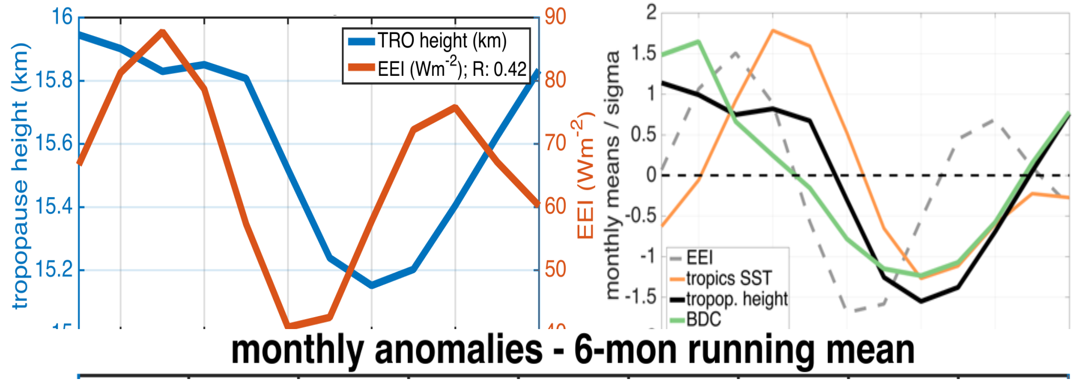
Hakuba et al.,2019

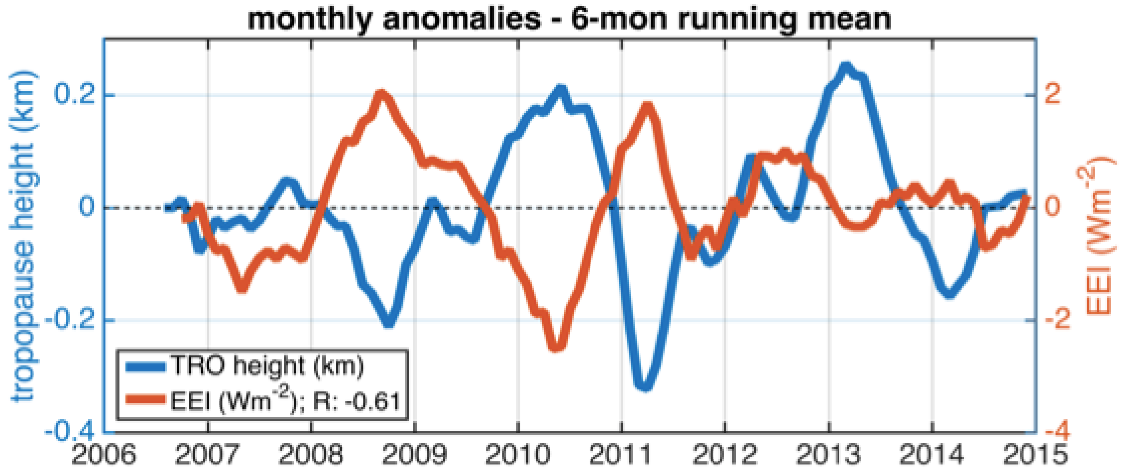
Multi decadal time series of

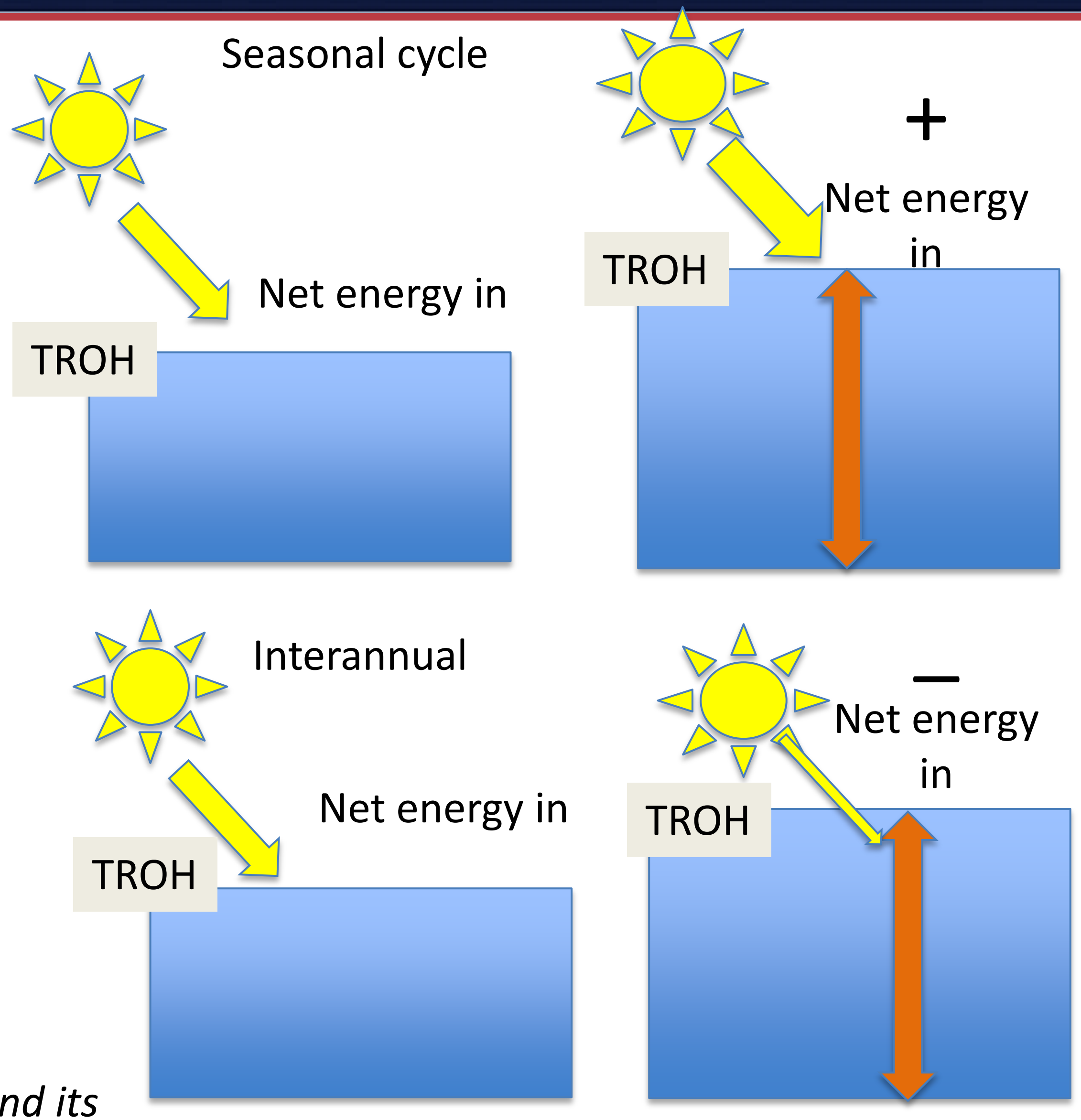
- GISS SST
- CERES EBAF 2000-2015
- Scatterometer 2000-2009
- Aqua – AIRS,MODIS 2003-2015
- CloudSat-CALIPSO 2006-2011
- GPCP – 1978-2015
- DMSP-based microwave 1984-2015 climatology
- OA Woods Hole turbulent fluxes
- MERRA & ERA reanalysis

Stephens et al., 2018

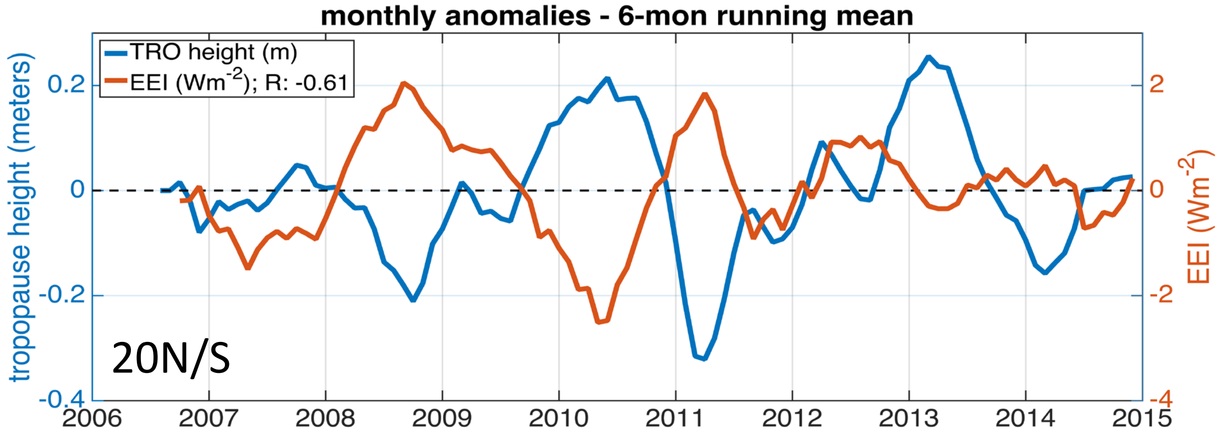
The ‘breathing’ of the (deep) tropical troposphere



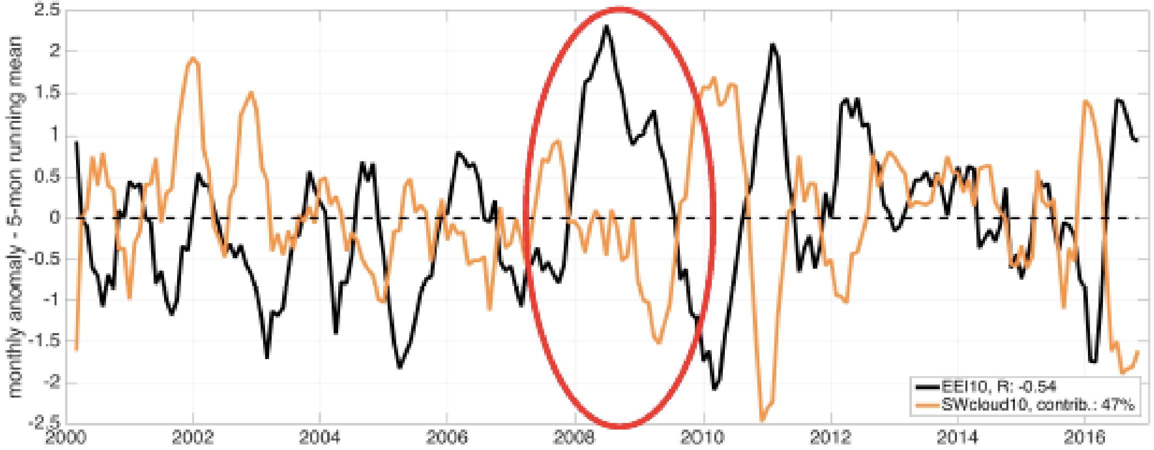




Hakuba et al., 2019; *On the Breathing of the Tropical Troposphere and its relation to the Tropical energy balance* J Climate in review



SW cloudy 47%

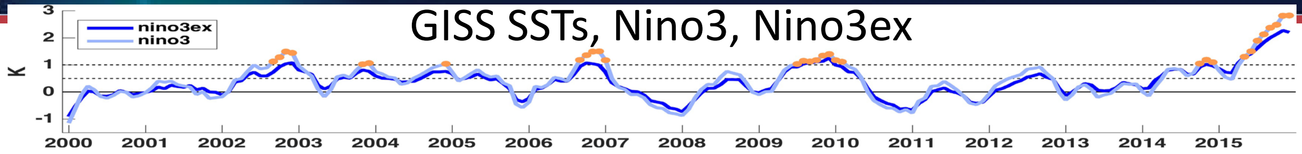


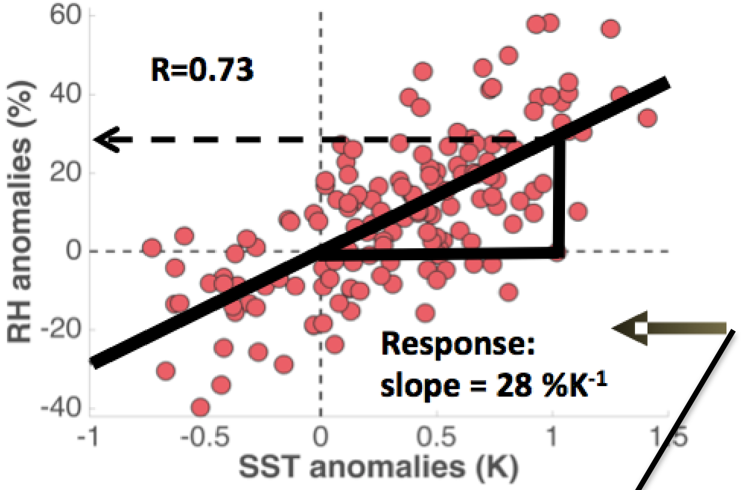
1) We observe a strong anti- correlation between interannual variations of energy into the tropics and the height of the tropopause - ie less energy in, the deeper the atmosphere

2) The interannual variation of EEI arises in part from variations in clear sky LW emission (not shown) and significantly from cloudy sky **shortwave reflection by anvil thickening**

Does this correlation between EEI and tropopause height expose feedbacks between clouds & their SW radiation properties and the depth of the troposphere and the subsequent ability of the tropics to remove heat build up by emission?

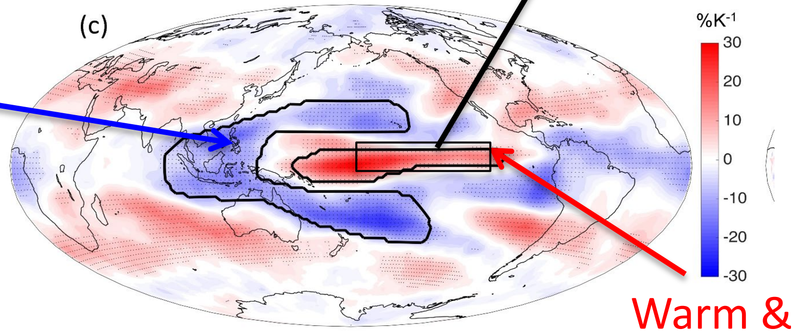
Convection – high cloud related feedbacks within ENSO





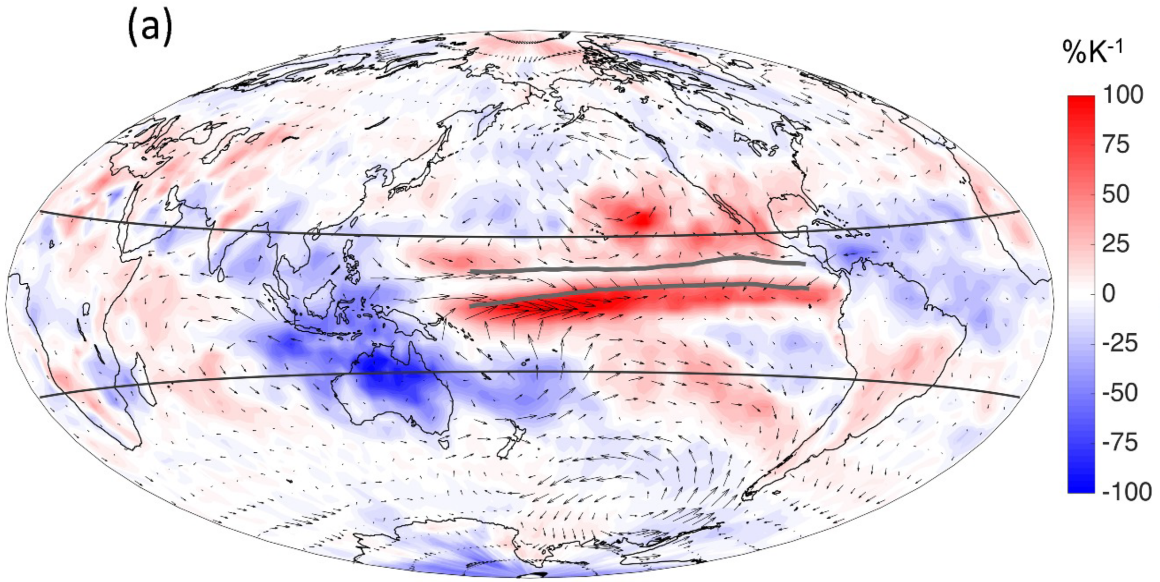
The global UTH response to Nino3 warming

Cold & dry



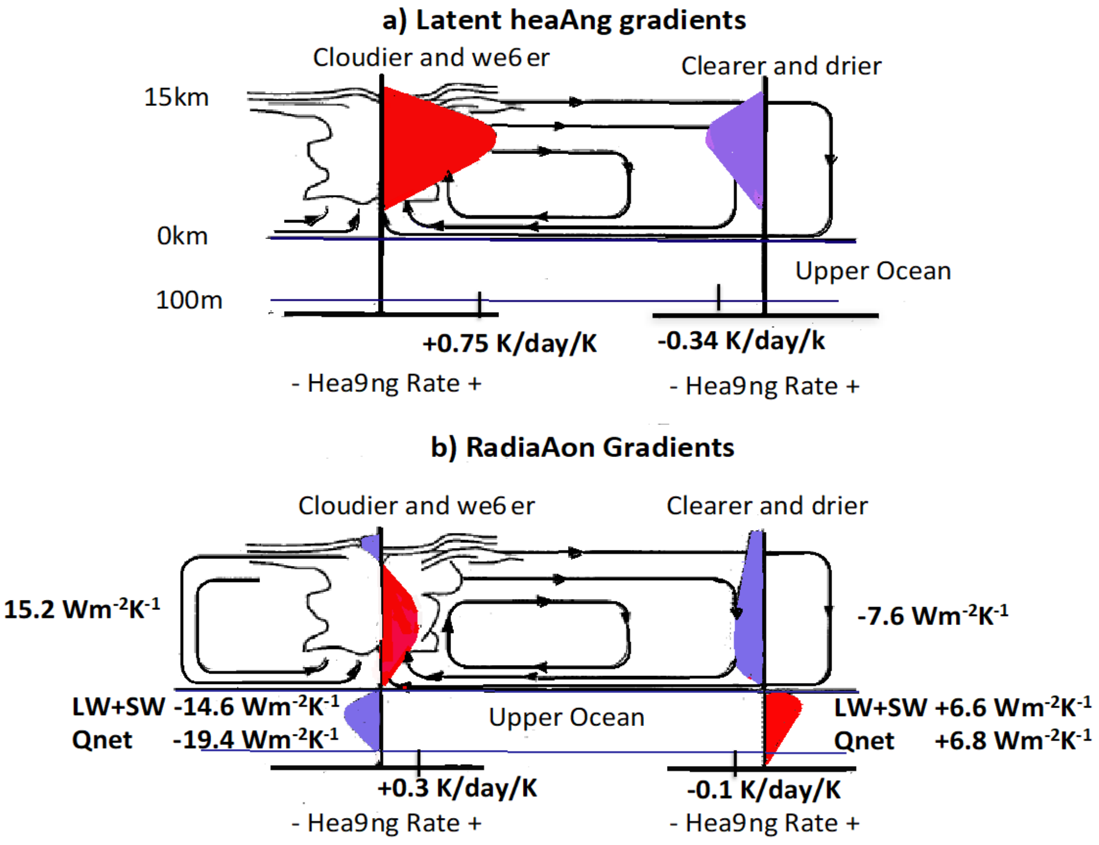
Warm & moist

Stephens et al., 2018



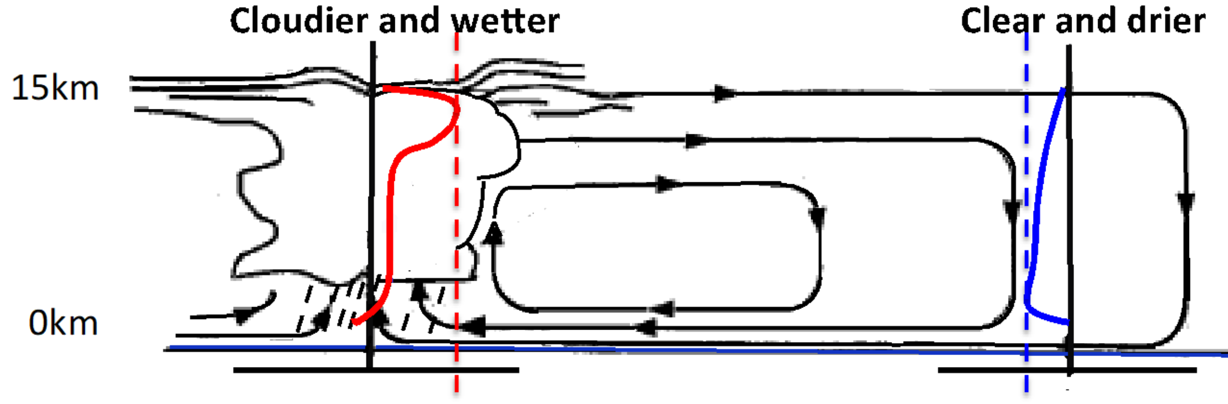
GPCP precipitation response (relative)
Surface wind response (MERRA)
Mean location of ITCZ

'Measures of feedback'



Differential heating

Hydrological changes



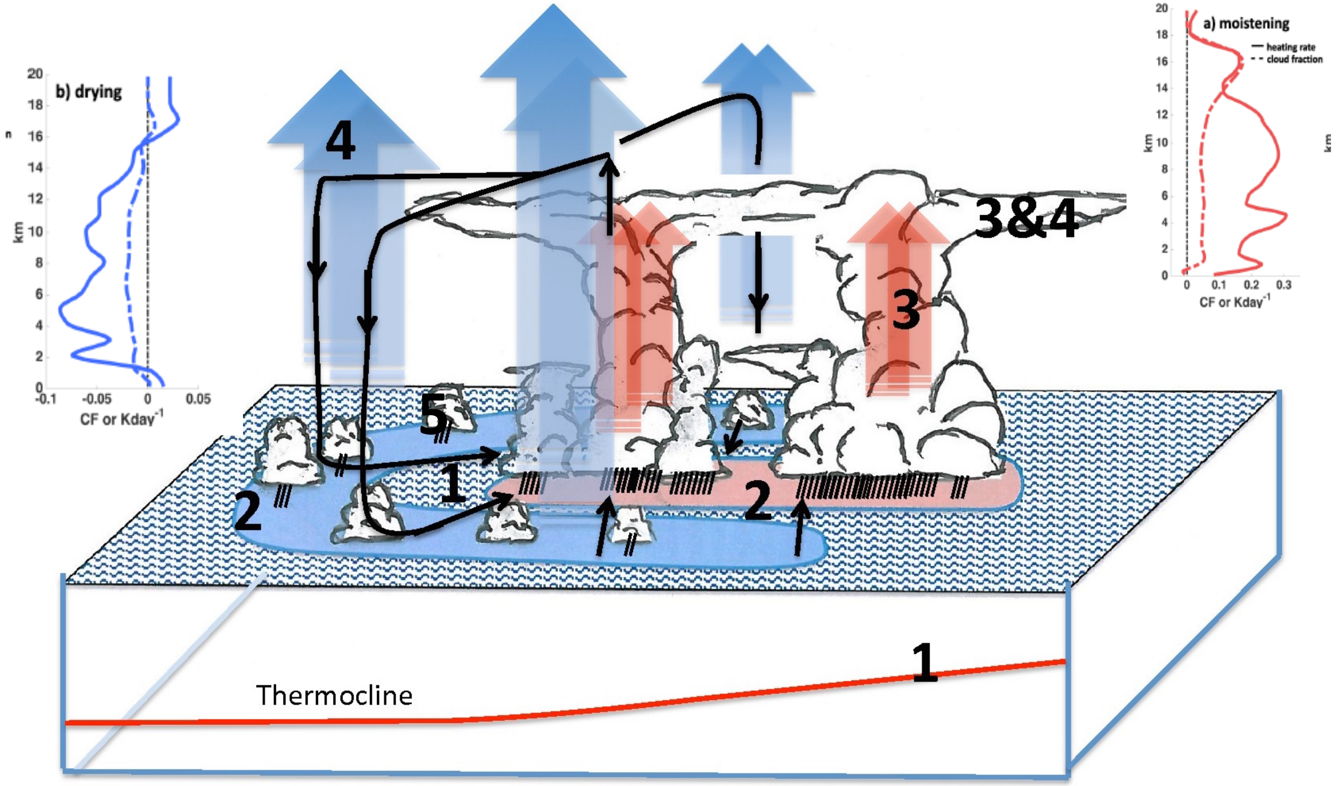
Cloud amount	**18%/K**	**-2%/K**
High Cloud amount	**15%/K**	**-8%/K**
Cb/CA	**5 %/K**	**-3 %/K**
Ci/CA	**7 %/K**	**-4 %/K**
thinCi/CA	**-10 %/K**	**4 %/K**
Cloud LWP	**37.1 gm^{-2}/K**	**-10.3 gm^{-2}/K**
Precipitation	**2.9 $mm.day^{-1}$/K**	**-1.3 $mm.day^{-1}$/K**
Column WV	***9%/K***	***-5%/K***
RH 200-500 hPa	***16 %/K***	***-10 %/K***

ENSO is an example of a coupled dynamical-radiative-convective system
Atmosphere produces reinforcing (+ve) feedbacks and the surface opposing (-ve) feedbacks as envisaged in Webster 1994 and others

Regional responses of the condensed water properties (clouds and precipitation) are far from linear and do not follow the responses expected from simple CC thermodynamic arguments.

4 Reduced high clouds, drier troposphere and enhanced radiative cooling to space and increased subsidence

4 Enhanced surface heat flux



1 Weakened easterlies, weakened ocean mixing and increases SST *+ve Bjerknes feedback*

2 Warmer SSTs & reduced surface heat fluxes *-ve heat flux feedback*

3 Enhanced precipitation, latent & radiative heating

3 & 4 Increased high clouds

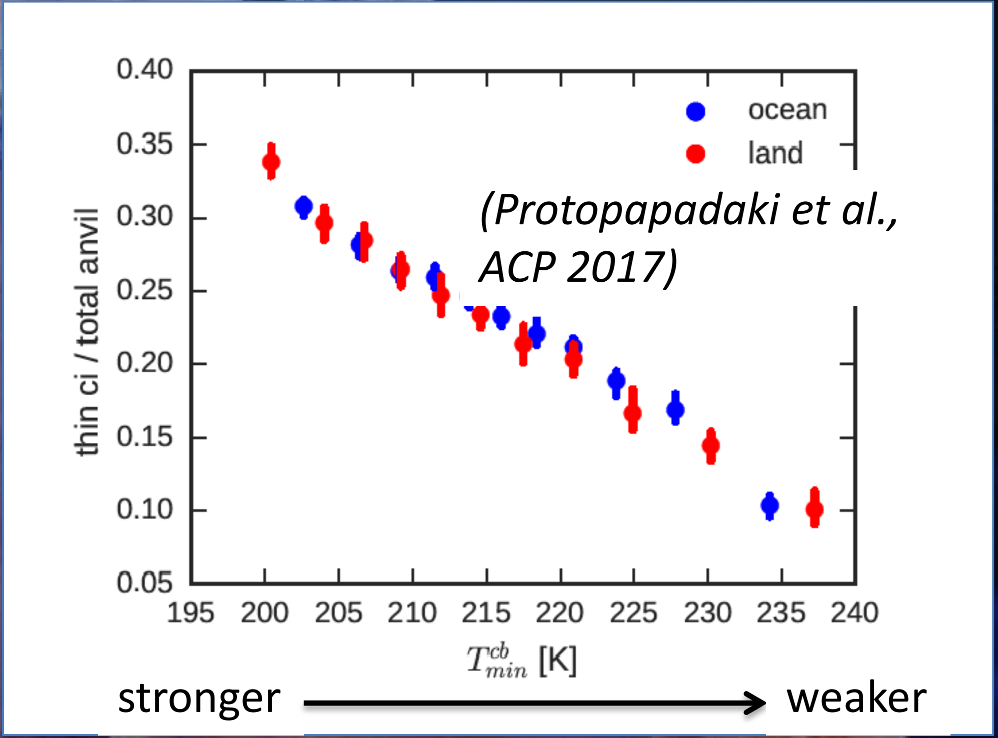
5 Enhanced low-level convergence

2) Toward understanding the relation between convection and high clouds

- UTCC PROES
- The D-Train initiative

Uses AIRS hyperspectral sounder

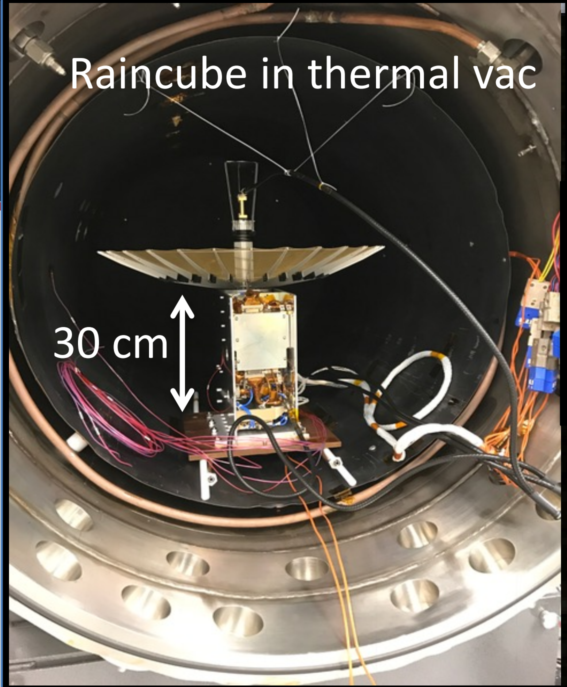
Provides both Tb and cloud emissivity ε
Tb cold:
ε ~1 deep core & Tmin
ε <1 high anvil cloud
ε <0.5 thin cirrus



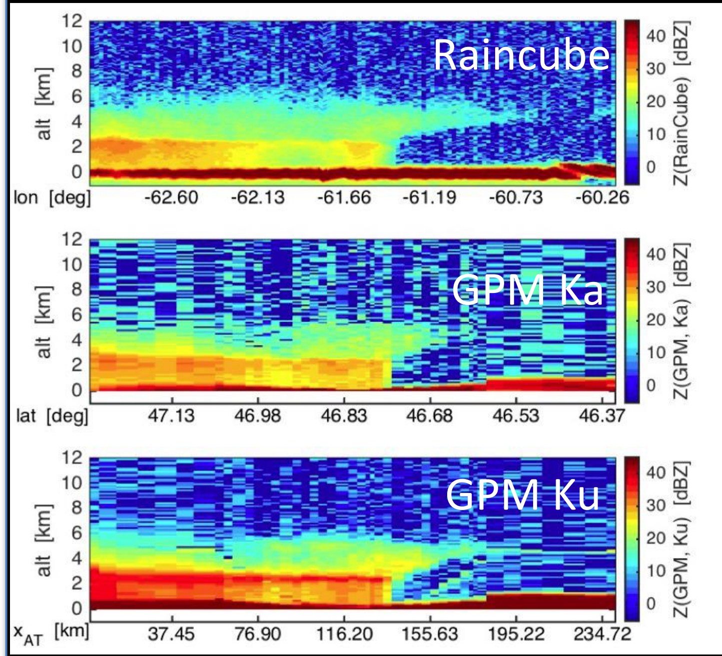
(Protopapadaki et al., ACP 2017)

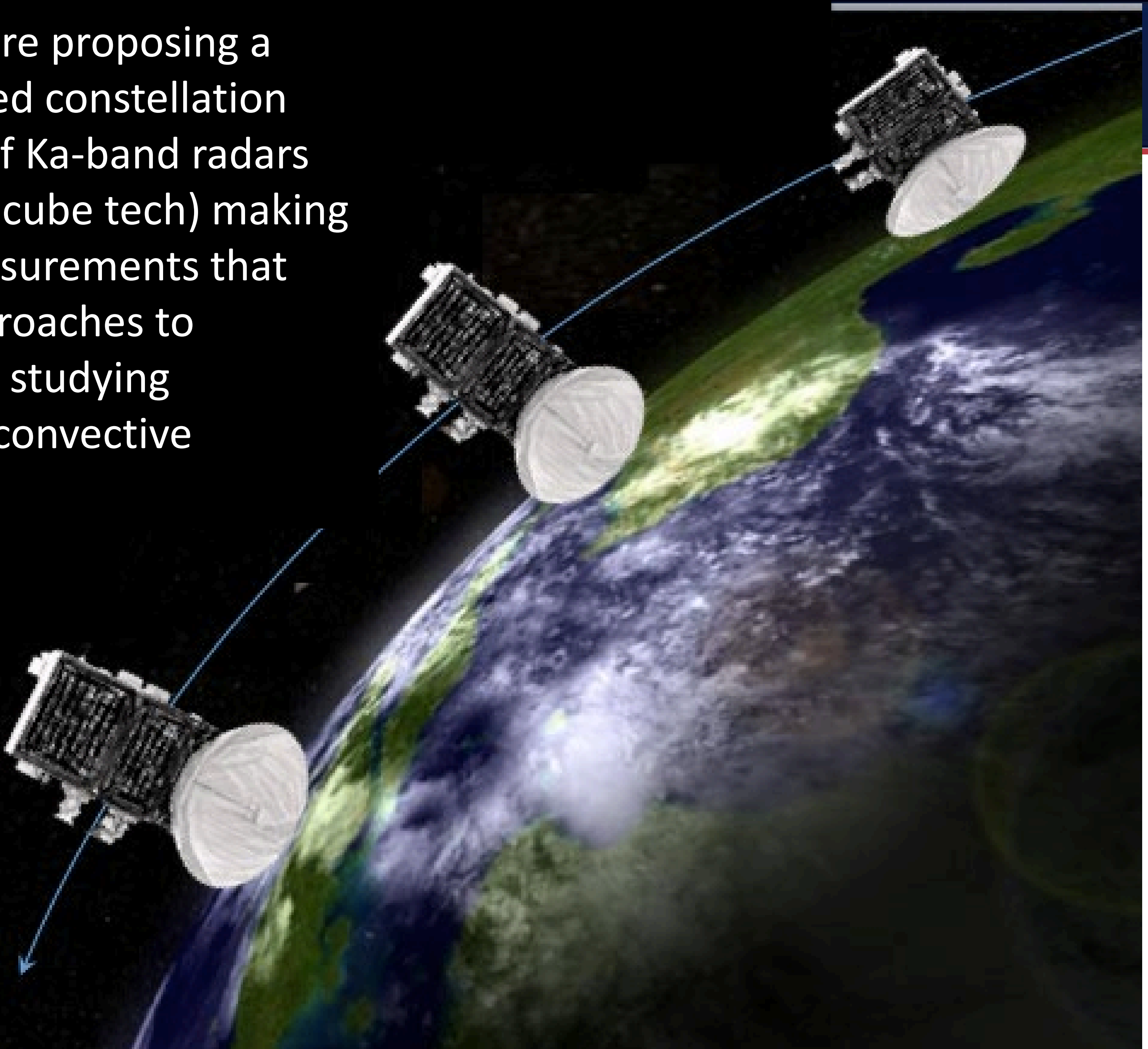
The fraction of thin cirrus (ε<0.5) increases as min CTT within convective core decreases.

- ➢ Stronger convective cores (Tmin) associated with larger fraction of thin cirrus coverage.

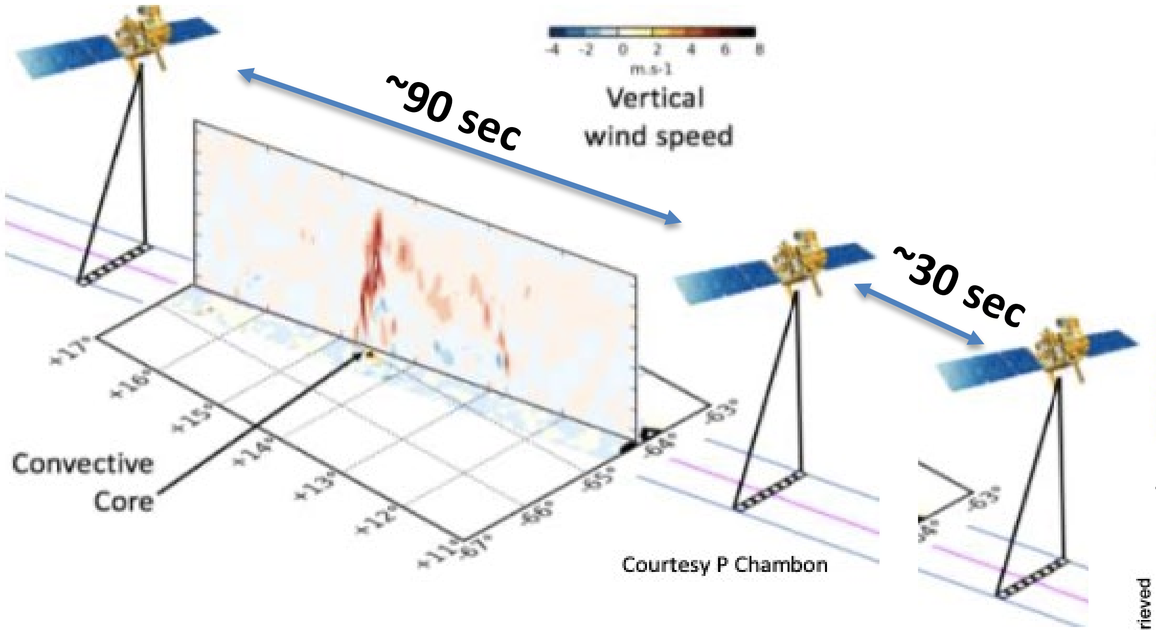


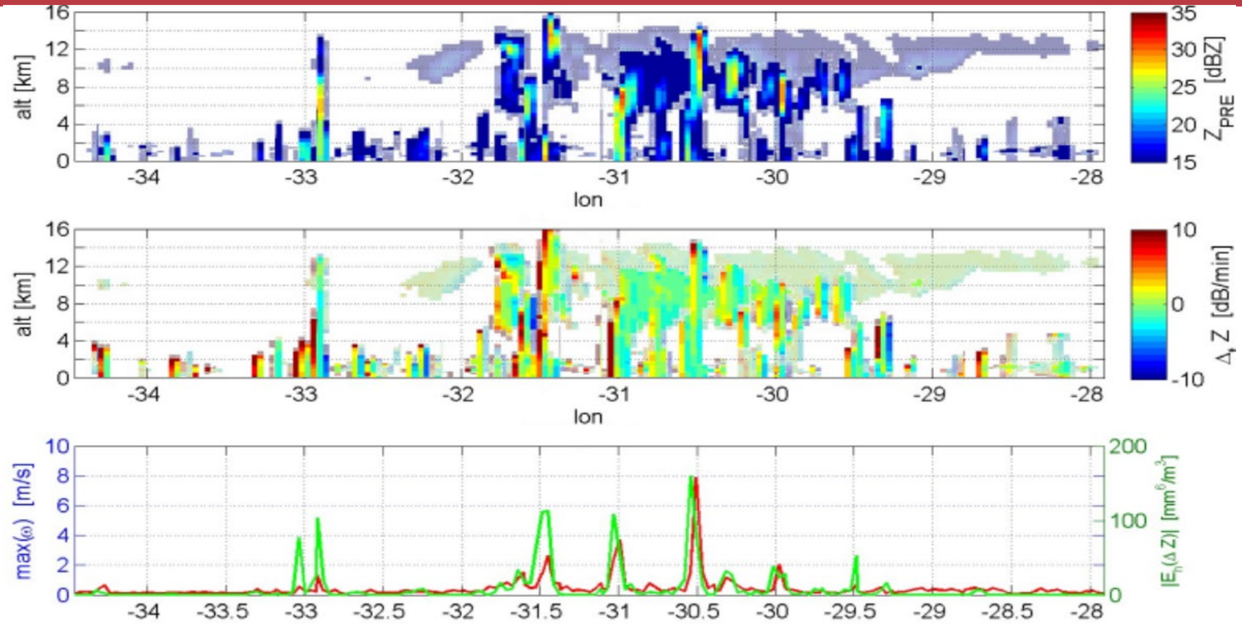
D-Train – we are proposing a tropical inclined constellation concept and of Ka-band radars (based on raincube tech) making clustered measurements that offer new approaches to observing and studying convection & convective transports



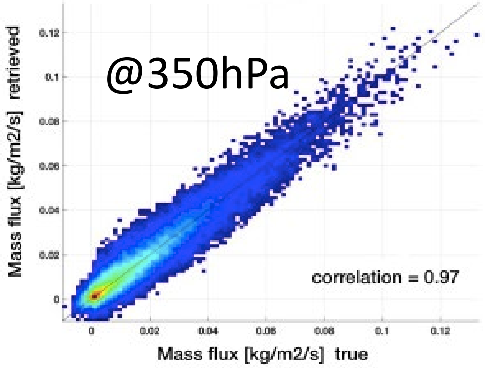


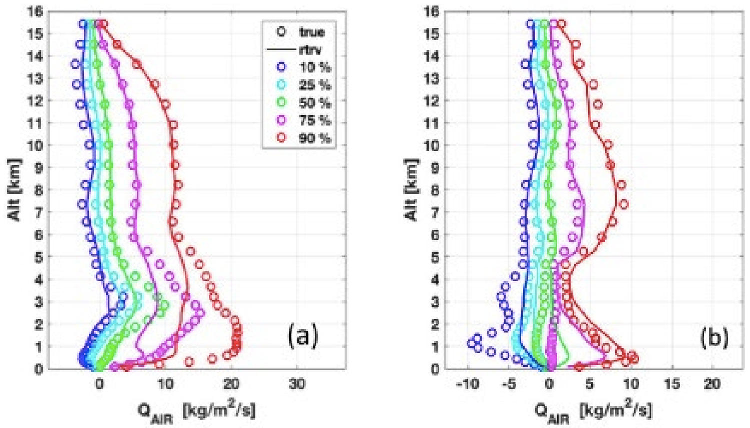
D-Train





Two basic observables, Z and ΔZ provides info on vert motion, water





Z. S. Haddad, et al.,2017; *IEEE Trans. Geosci. Remote Sens.*, vol. 55, no. 6, pp. 3441–3453, Jun. 2017

Stephens et al., 2019; A Distributed Small Satellite Approach for Measuring Convective Transports in the Earth’s Atmosphere, *IEEE Trans. Geosci. Remote Sens.*

Summary

Why do we care about high clouds ?

1) Their impact on radiative heating is central to how convection gets aggregated and how the hydrological cycle associated with convective storms gets modified
2) They represent important feedbacks that influence both climate sensitivity and the hydrological sensitivity

What steps are underway to provide some sort of understanding of the relation between high cloud and convection?

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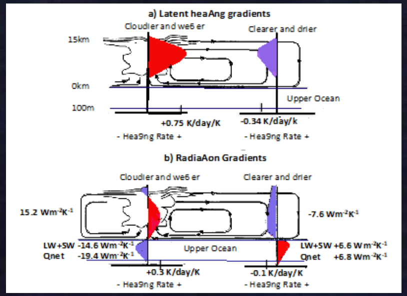
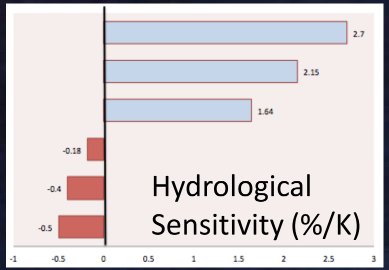
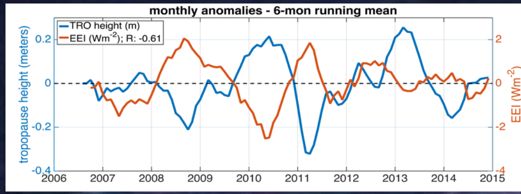
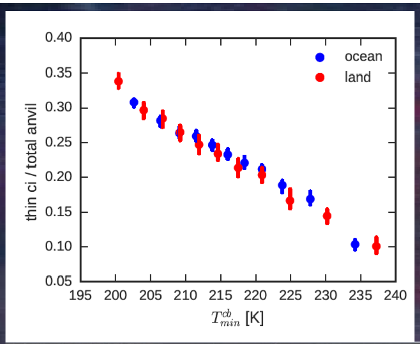
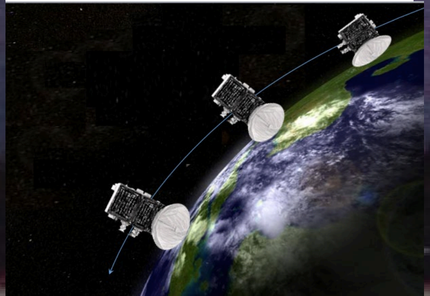
2) The D-Train concept









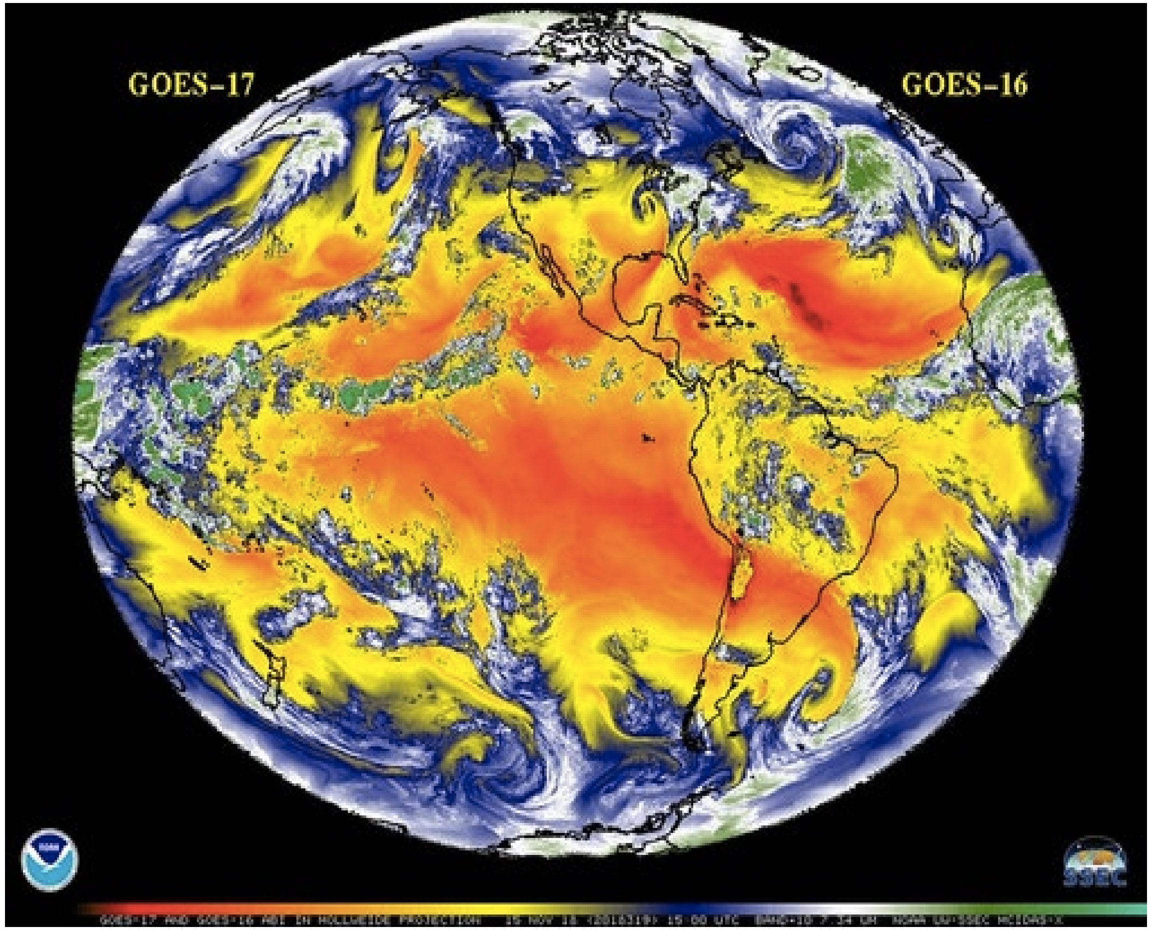


Three major initiatives/activities that will shape the EO of the coming decade

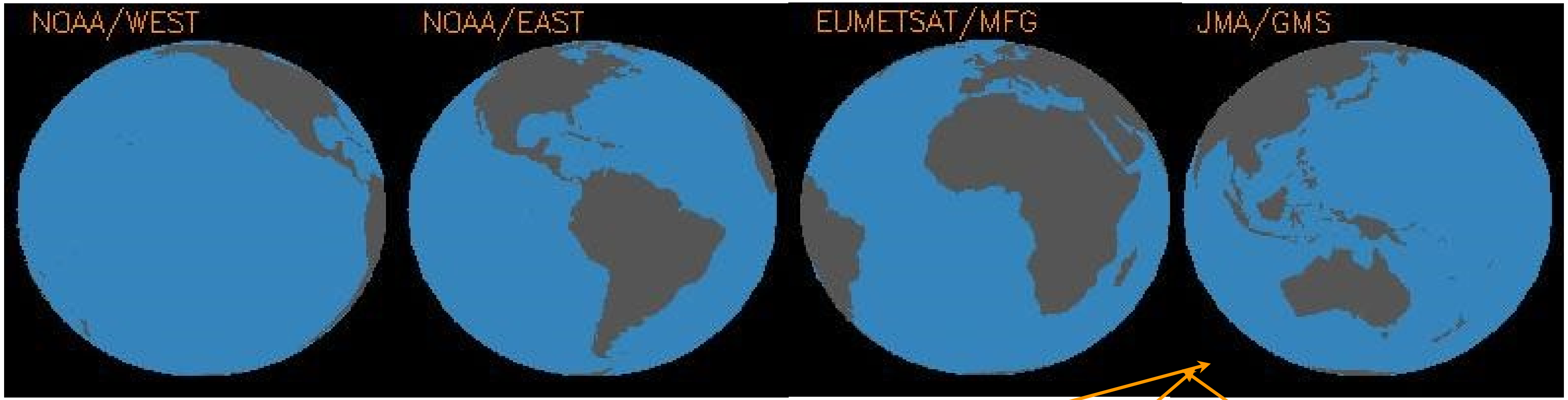
1) The spectral radiance geo-ring: ‘global’ 2km, 10min ~10 channel

2) Implementation of the recommendations of the US academy recommendations

3) A (technical) revolution of sorts

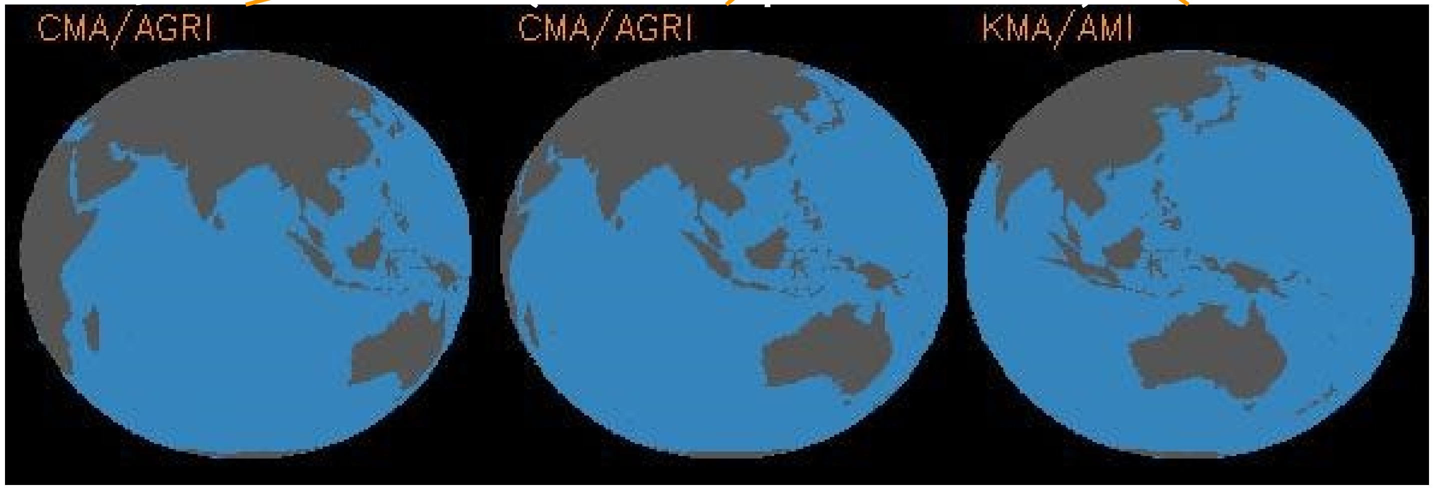


Exploiting geostationary advanced imagery – ISCCP next generation



ISCCP-NG: Sub-Longitudes -135, -75, 0, 86.5, 128, 105, 140

Oversampling of Asia



How should ISCCP-NG Exploit this overlap?

This ignores any EUMETSAT satellite over the Indian Ocean and the Russian Geos.

Spectral and Spatial Solar Reflectance Channels

Nom Wvl	GOES E/W	MTG	FY4A	GEOKOM	HIM8	Common
0.47	1	1	1	1	1	✔
0.51		1		1	1	
0.65	0.5	0.5/1	0.5	0.5	0.5	✔
0.86	1	1	1	1	1	✔
0.91		1		2		
1.38	2	1	2	2		
1.6	1	1	2	1	1	✔
2.2	2	0.5/1	2		1	

Spectral and Spatial IR

Nom Wvl	GOES E/W	MTG	FY4A	GEOKOM	HIM8	Common
3.8	2	1.0 / 2.0	4	2	2	✔
6.2	2	2	4	2	2	✔
6.9	2			2	2	
7.3	2	2	4	2	2	✔
8.5	2	2	4	2	2	✔
9.6	2	2		2	2	
10.4	2	1.0 / 2.0		2	2	
11.2	2		4	2	2	✔
12.4	2	2	4	2	2	✔
13.3	2	2	4	2	2	✔

The coming decade (2017-2027)

First designated observables under study

- SBG (surface biology and geology)
- A +CCP (aerosol+clouds, convection & precipitation - rebuilding the A-Train)