Connections between Water, Energy, Carbon and the Earth's Climate

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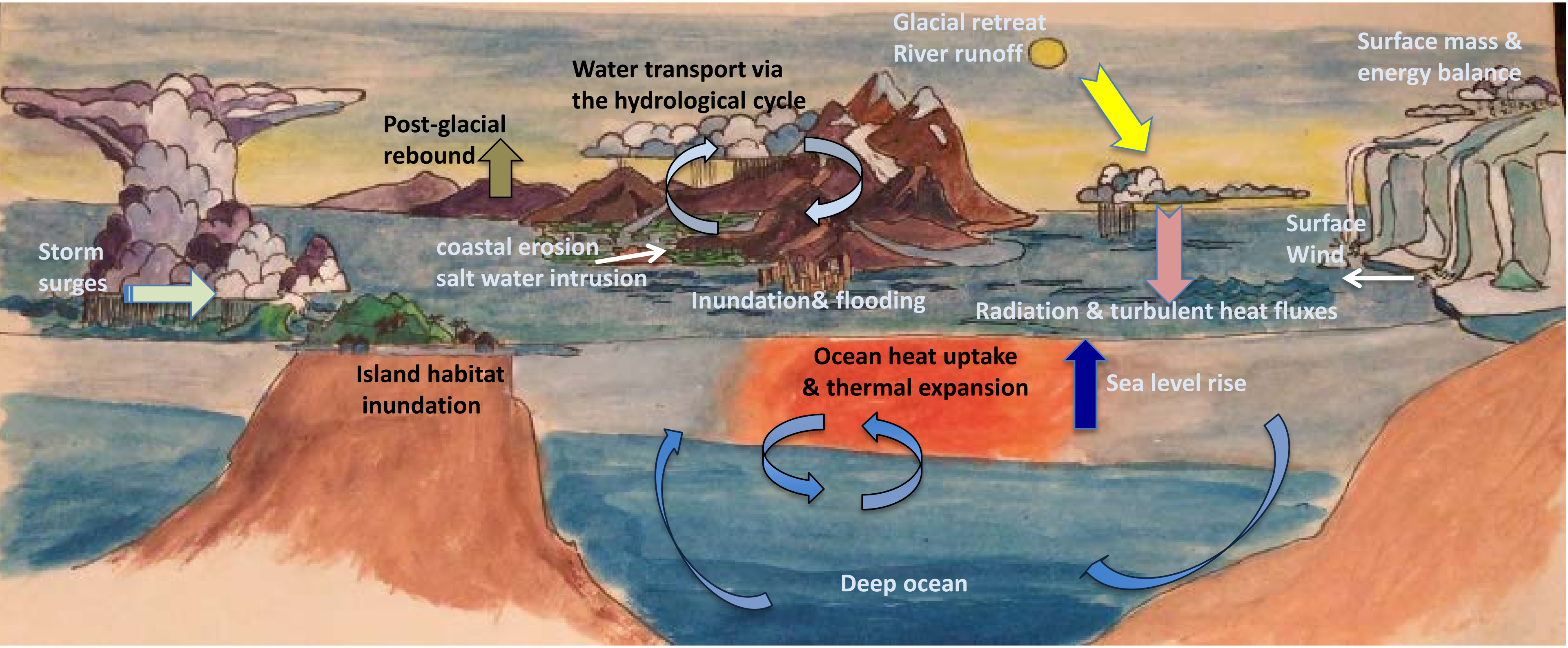
The EO challenge in a nutshell - Earth is a system, and our challenge is to observe & understand the interactions between its parts



The complex nature of sea level rise

Three Grand Earth Science questions

(1)Where does all the heat go?

Water, energy and

(2

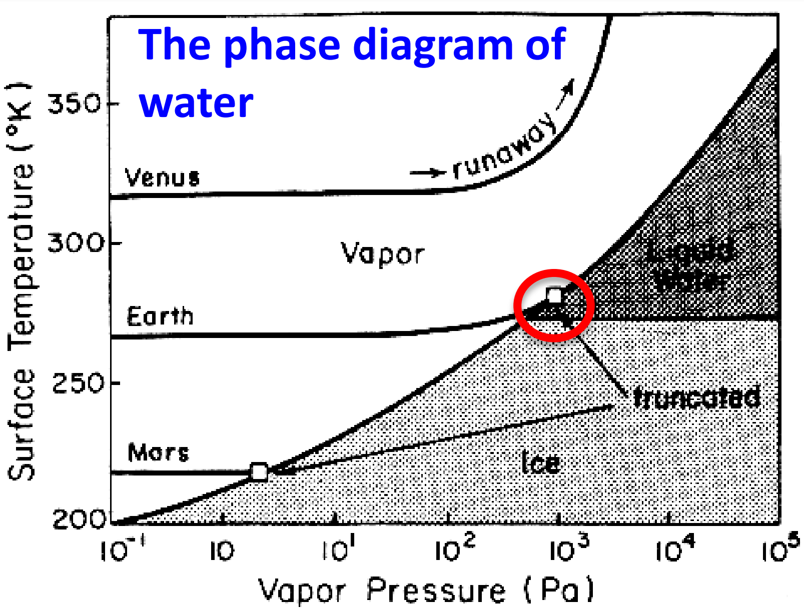
(3

All from an EO perspective

Outline

- Feedbacks & why the processes that connect water & energy are so fundamental to these challenges
- Highlight some of the puzzles about the energy balance of Earth
- Touch on some of the challenges in understanding changes to Earth's water cycle
- A look into the future

Earth – the 'Goldilocks' planet



The climate of Earth, to first order, is governed by the connection between radiation balance and the hydrological processes that regulate this balance.

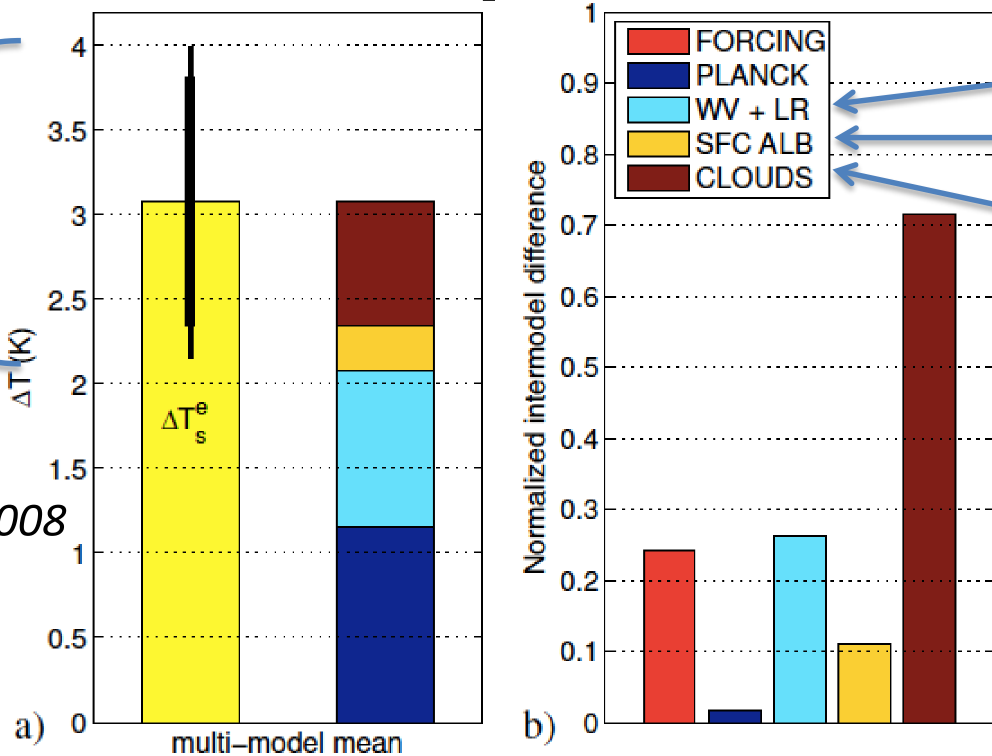
Fundamental is the exchange of water between its three phases and the resulting interactions with radiation.

1) Major climate feedbacks = water + energy (radiative processes) & later carbon

For a doubling of CO_2

Multi-model range

Dufresne & Bony, 2008



Water in gas form (+)

Frozen water on the surface (+)

Condensed water & ice (**+**/**-?**)

For later context an instantaneous 'doubling of CO_2' results in

~4Wm^{-2} perturbation in top-of-atmosphere (TOA) energy balance

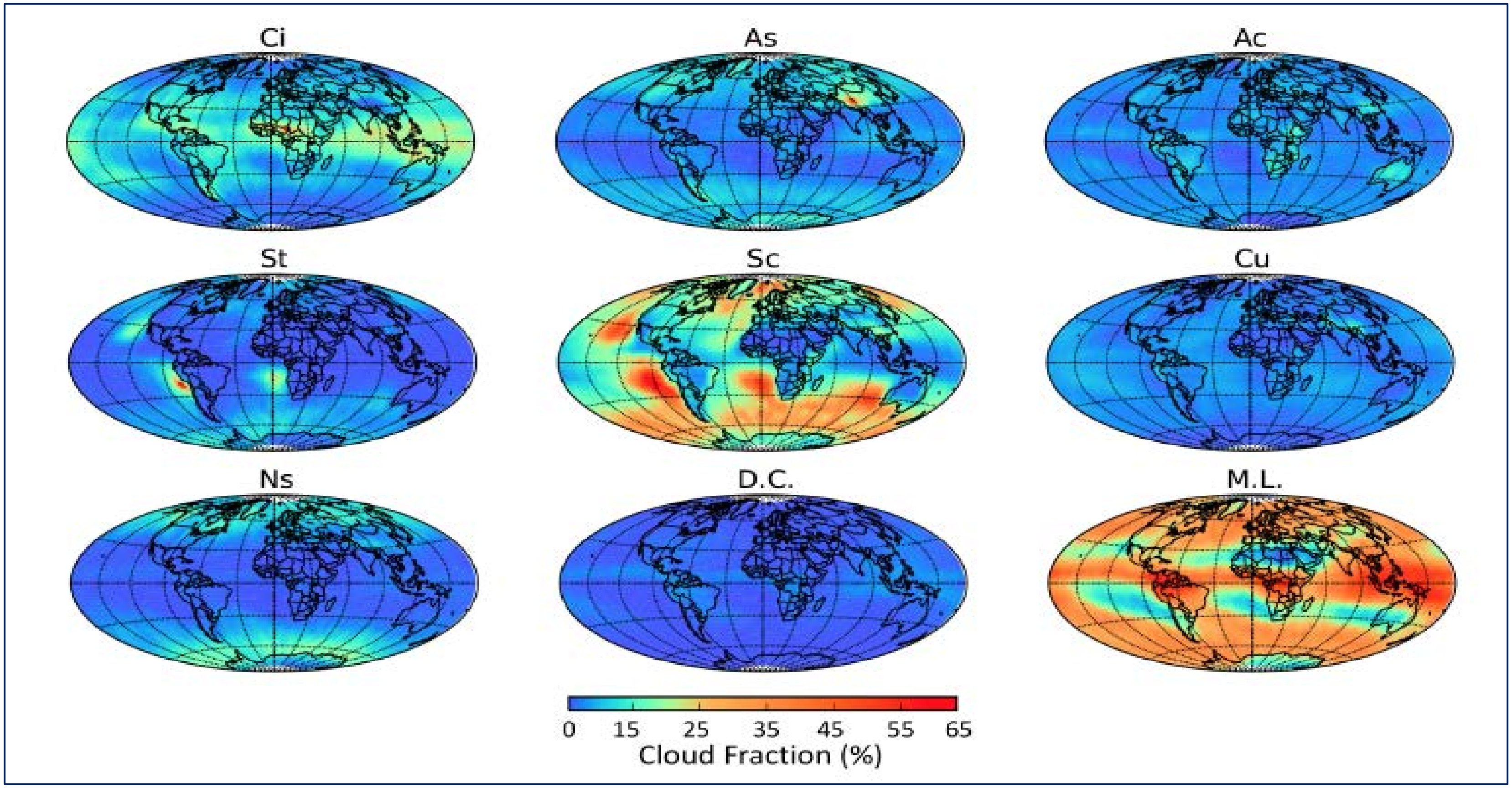
~1Wm^{-2} perturbation at the surface

A fundamental question to ponder is to what extent do these feedbacks regulate (negative) or destabilize (positive) Earth?

The net radiative feedback due to all cloud types is likely **(>66%** chance) positive, although a negative feedback (damping global climate changes) is still possible (IPCC, AR5).

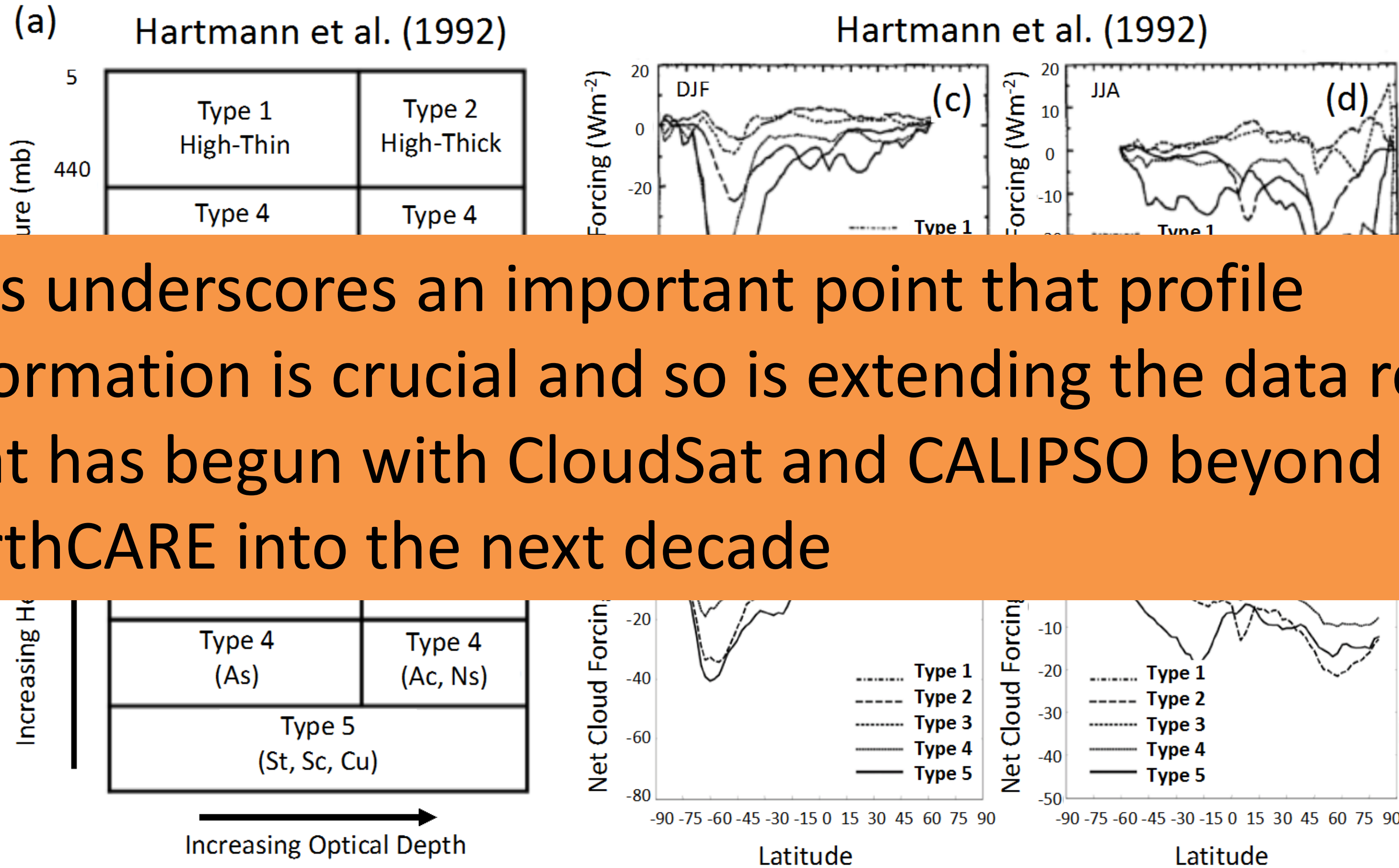
Frankly we do not know the extent to which Earth is a regulated system and cloud feedbacks are a highly uncertain factor in this lack of understanding. Our past EO of clouds have been quite misleading …

Distinguishing Cloud Regimes more precisely with CloudSat & CALIPSO



CLDCLASS-LIDAR

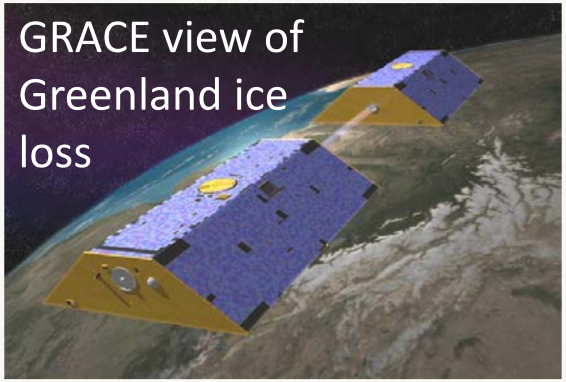
Hang et al, in preparation, 2017

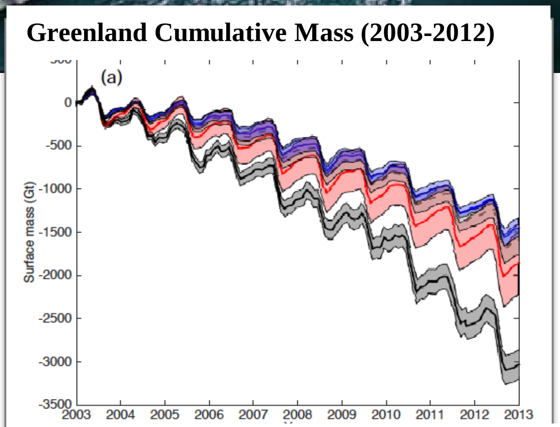


This underscores an important point that profile information is crucial and so is extending the data record that has begun with CloudSat and CALIPSO beyond EarthCARE into the next decade

What contributes to the largest cloud radiative effect is not solely low clouds but is more a mix of many cloud types

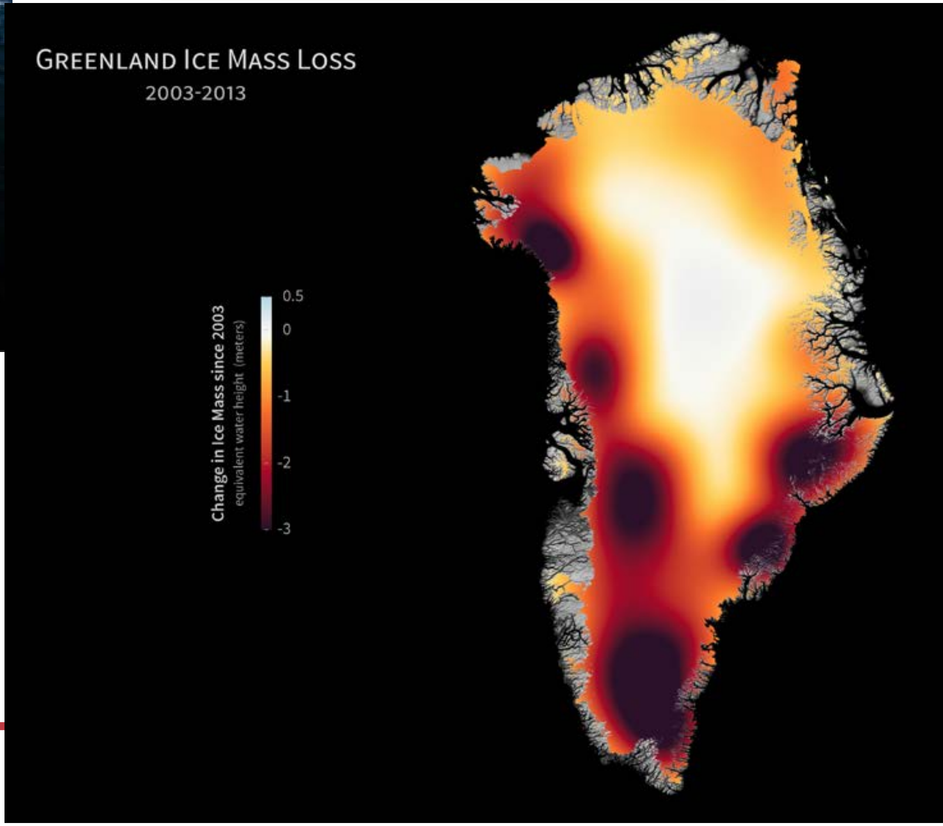
Furthermore feedbacks couple together producing a much more complicated interacting system



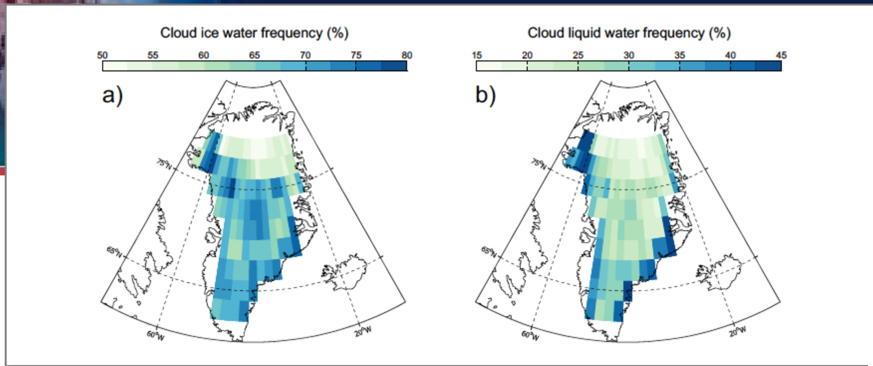


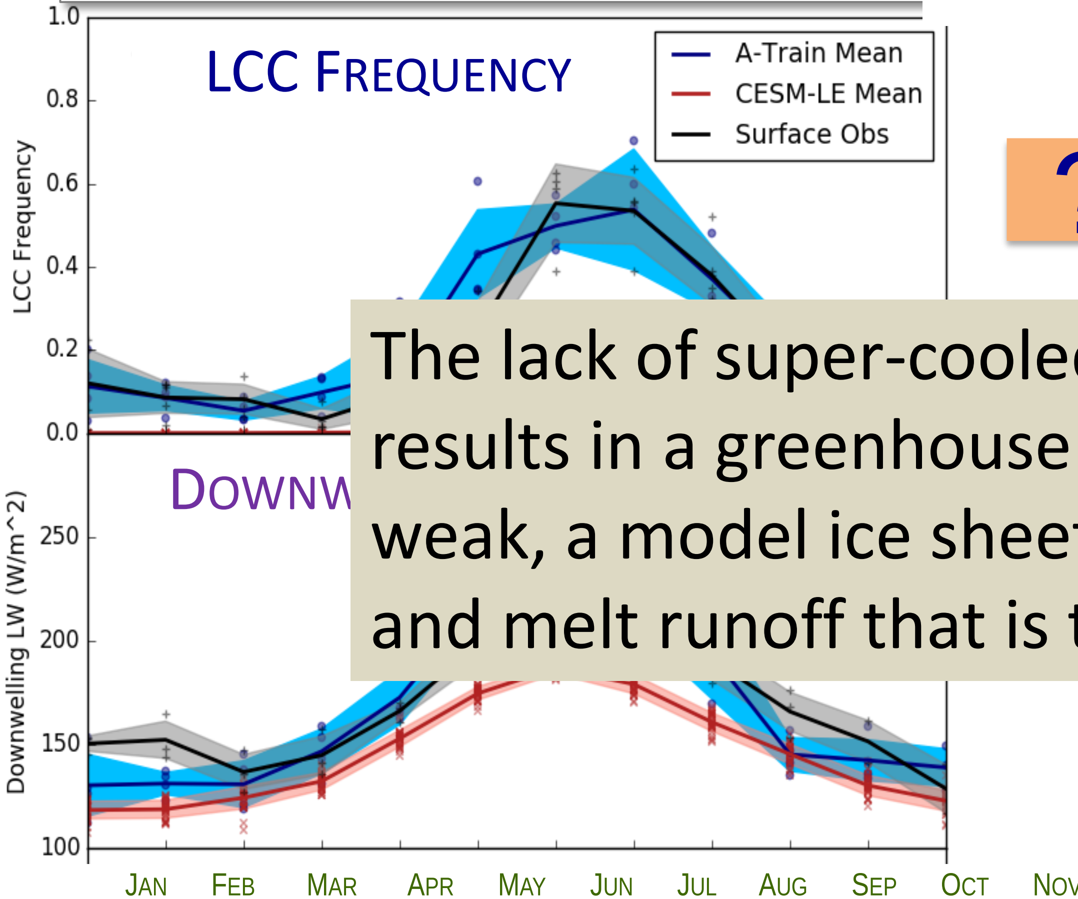
GRACE JPL
ISSM ice sheet plus ice caps
ISSM surface mass balance only
ISSM ice sheet only

Model estimates of Greenland ice mass change differ from observed.



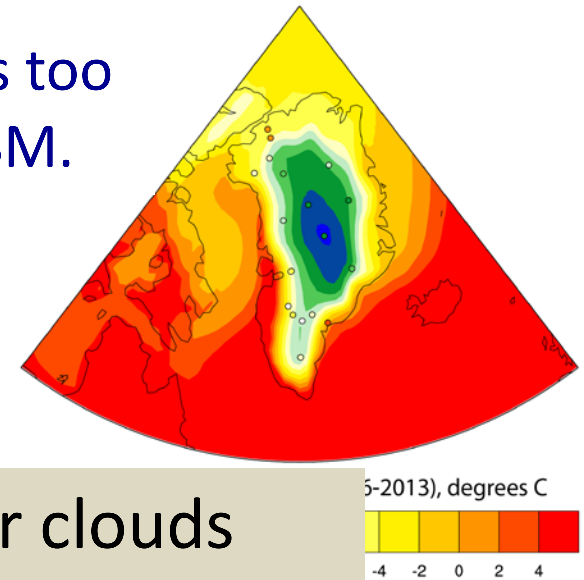
CESM Bias



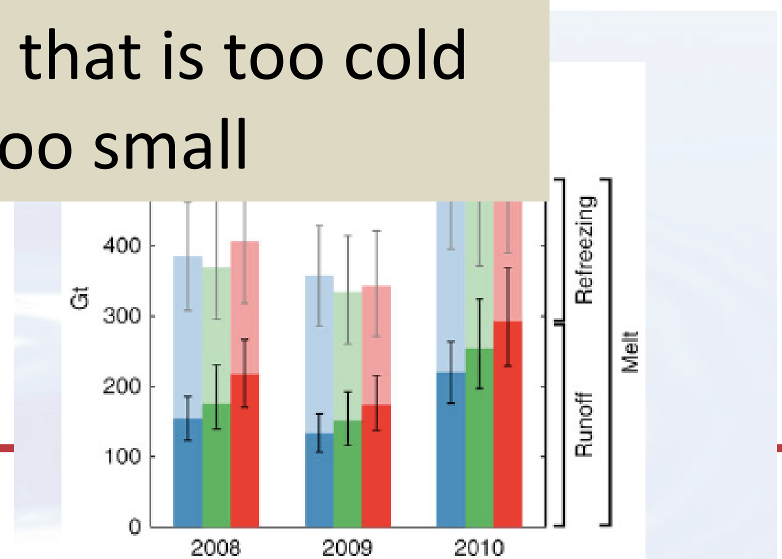


Greenland is too cold in CESM.

?



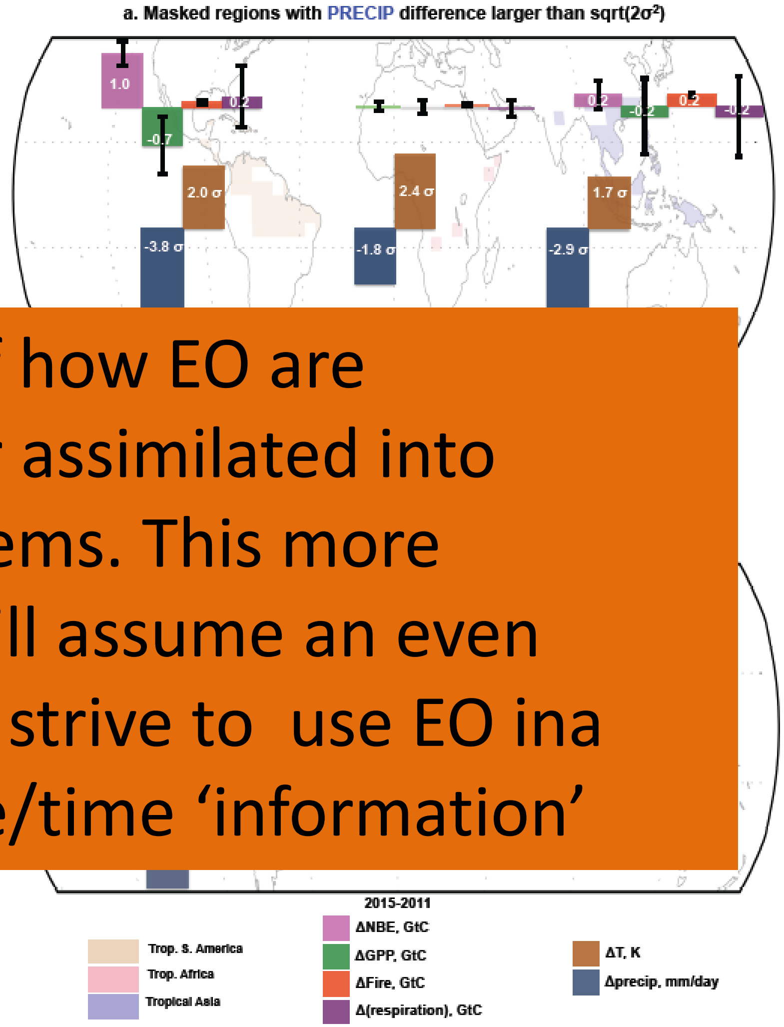
The lack of super-cooled water clouds results in a greenhouse effect that is too weak, a model ice sheet that is too cold and melt runoff that is too small



The coupling of water & energy to carbon feedbacks

ENSO-induced changes to Carbon flux

Liu et al., 2017, *Science* – assimilate OCO CO_2 and fluorescence , GOSAT CH_4 into an Earth system model of the carbon cycle.



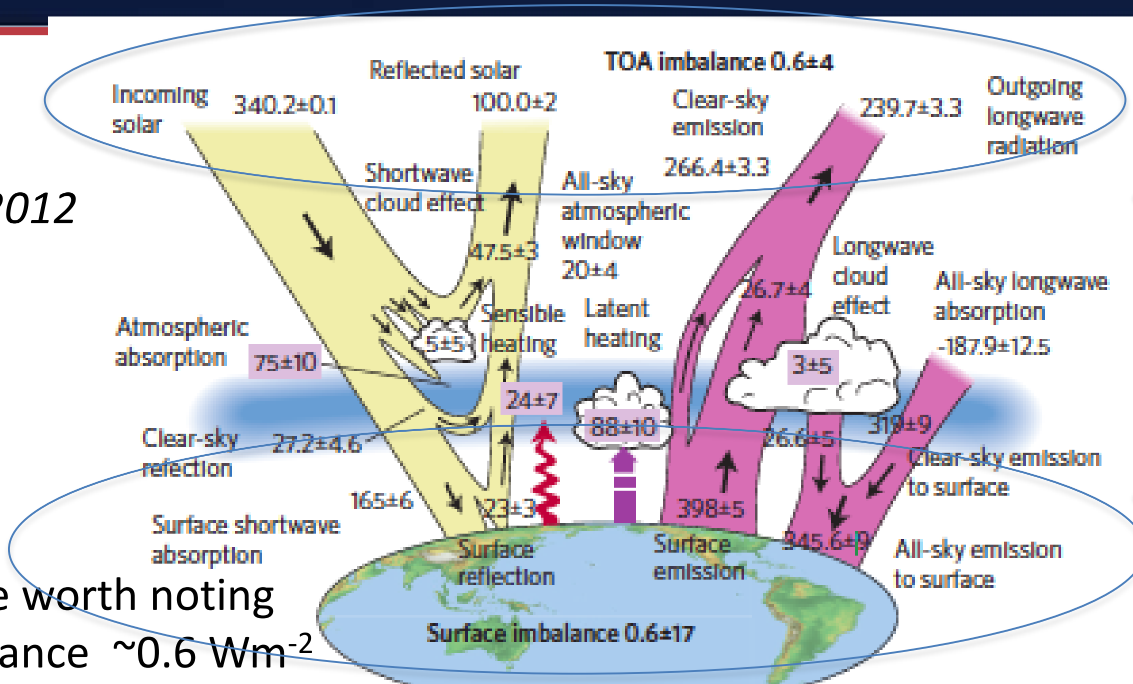
This is an important example of how EO are increasingly being integrated or assimilated into advanced analysis (model) systems. This more integrated analysis approach will assume an even greater role in the future as we strive to use EO ina pplications requiring high space/time 'information'

That is the strength of the terrestrial carbon 'sink' has been greatly reduced under these conditions

2) Earth’s energy balance

Stephens et al., 2012

units in Wm^{-2}



Top of atmosphere TOA

Within atmosphere

Surface

The following are worth noting

1) Energy imbalance ~0.6 Wm^{-2}
2) Direct TOA measurements lack the accuracy to ‘quantify’ the small energy imbalance
3) Our current state of knowledge of the surface energy balance is too crude for climate change studies (closure to O~ 15Wm^{-2}) – largest uncertainties attached to surface turbulent fluxes
4) The atmosphere is balanced by two large terms - loss energy through emission of radiation to space, and energy absorbed by transfer of heat from surface mostly as latent energy associated with precipitation that falls to the surface – this is clearly relevant to understanding how Earth’s hydrological cycle changes

Energy imbalance from different sources

Net heat flux

- TOA radiation budget — **4 ± 4 Wm^{-2}**
- surface observations — **Anything is possible.. Range -13 to +26 Wm^{-2}**
- reanalysis — **????**
- Ocean heat data — **0.4 – 0.9 ± 0.1 – 0.4 Wm^{-2}**
- climate models — **Impossible.** tuned within ± 3 Wm^{-2} (CMIP5)

To date ocean heat data are the **only** way to quantify net heat flux with meaningful uncertainty …..

Our global observations reveal a curious hemispheric symmetry

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Current Climate Change Reports
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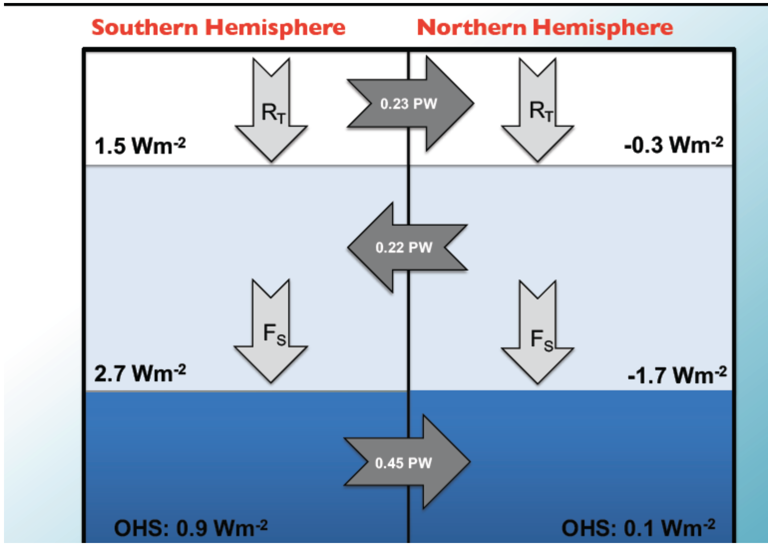
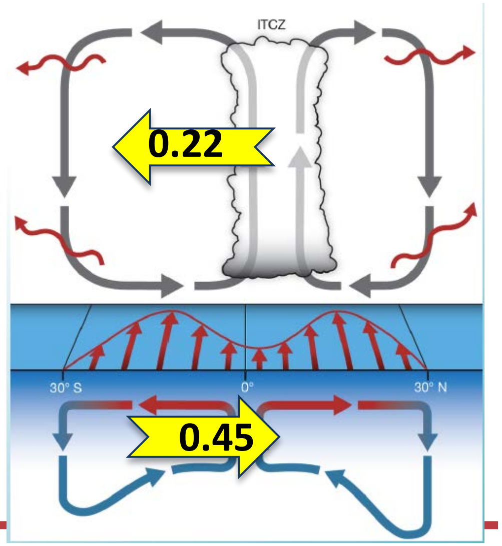
10.1007/s40641-016-0043-9





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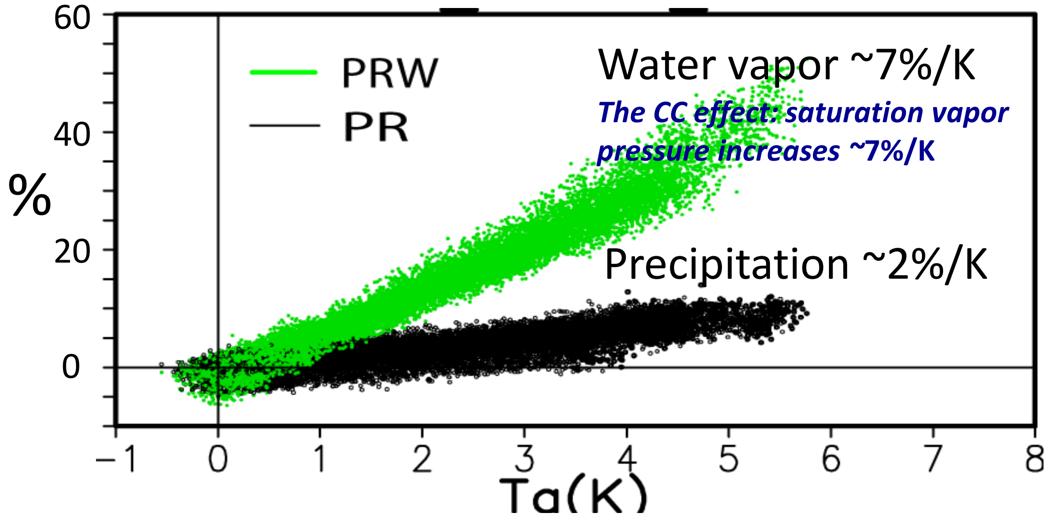
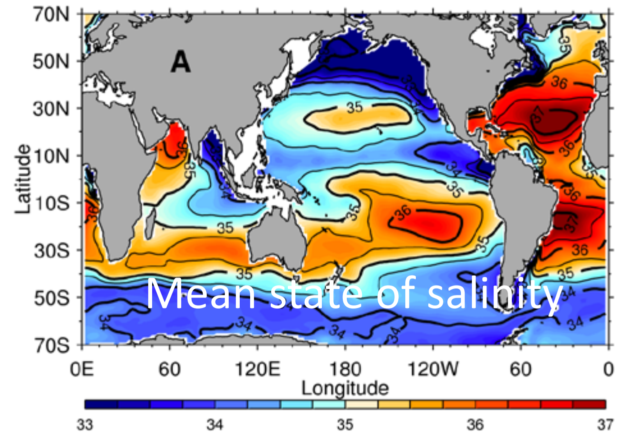
- Each hemisphere is very closely in balance. The opposing transports by the atmosphere and oceans determine the position of major tropical precipitation regions (the Intertropical Convergence Zone, ITCZ). **How will these storm regions change in the future?**
- The slight hemispheric imbalance induces a net heat flow across the equator.
- The albedo of Earth is completely symmetrical aboiut the equator- **WHY?**

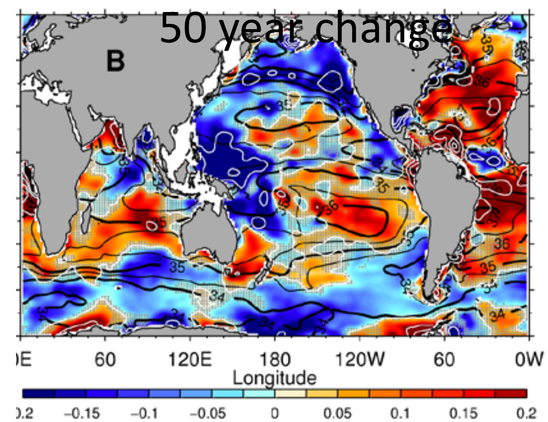
3) Fresh water changes – a precipitation perspective

Global change- CMIP5 model perspective



Regional changes
ocean salinity observations





Durack and Wiffels, 2010
Durack et al, 2012

Global changes are too small to be detected with the ~ 30 yrs of global observations of precipitation

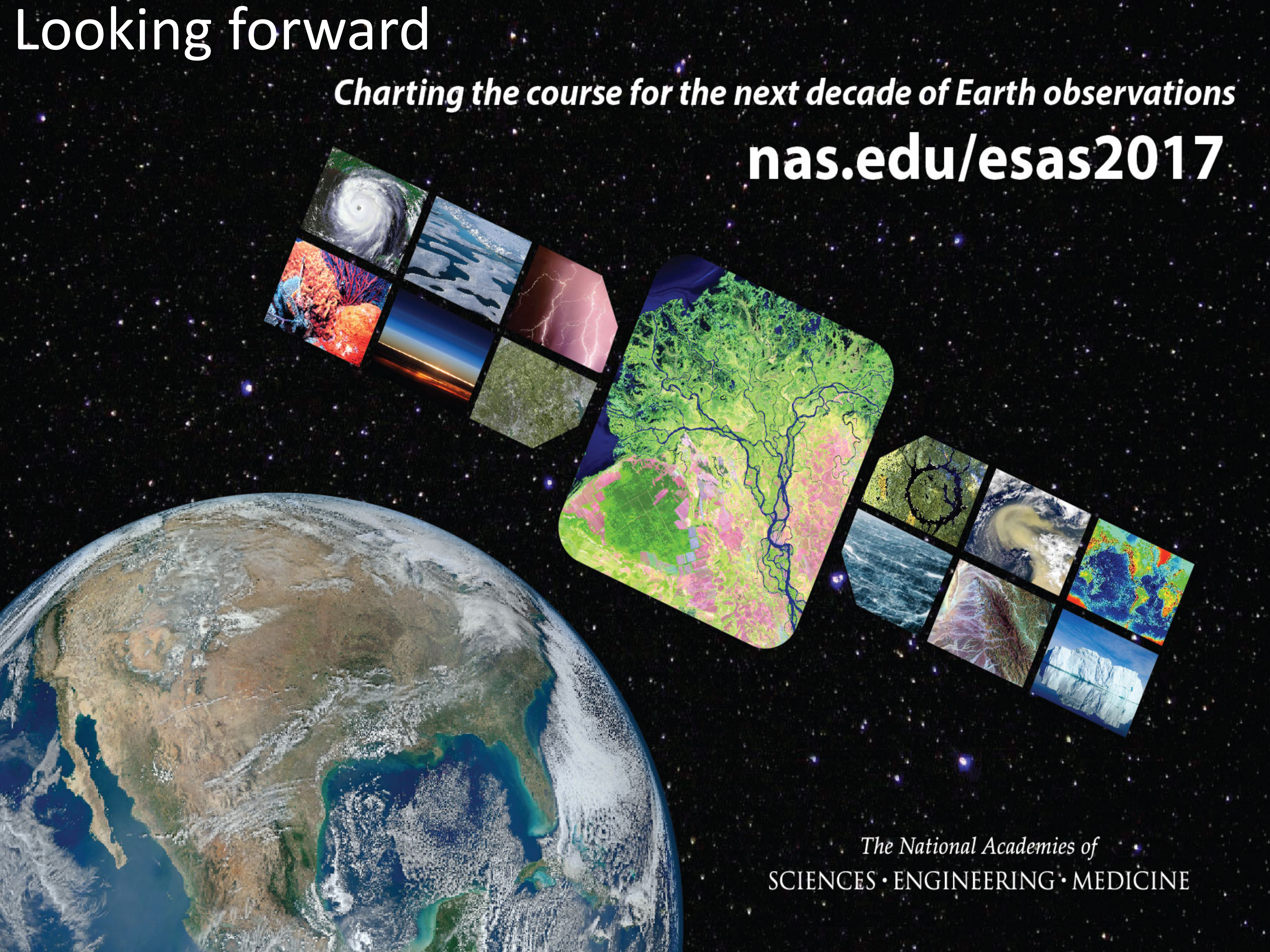
Pattern of change over ocean - wet areas are getting wetter and dry areas are getting drier

Amplitude of salinity changes ~7%/K change – **does this mean the pace of regional changes is set by water vapor changes? What about over land? We have no basic 'theory' to guide us**

Summary

- We face real challenges ahead
  - We need to make Earth science exciting, emphasize Earth still holds mysteries to understand and communicate this.
  - Earth sciences is unique in that it has direct societal applications but we need articulate a balance between science and applications otherwise we could become merely a service afterthought.
- Increasingly we address Earth science problems through a more integrated EO/modeling framework (e.g. Copernicus) , but….
- The coming decade will be an intersting one for EO pursuits .....

Looking forward



The technology innovation – its coming

Current Approach

Technology Investments

UClass Sat. approach

SWIS

Are these miniaturized sensors merely ‘toys’ or will they deliver real science?

The coming few years are designed specifically to answer these questions

March 2018

ATMS

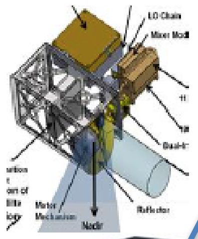
WF Optics

Microwave

HotBird Detectors

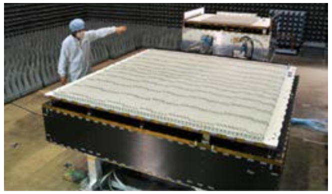
Radar

TEMPEST-D (Reising) MW Sounder

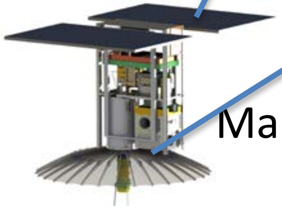


March 2018

GPM DPR



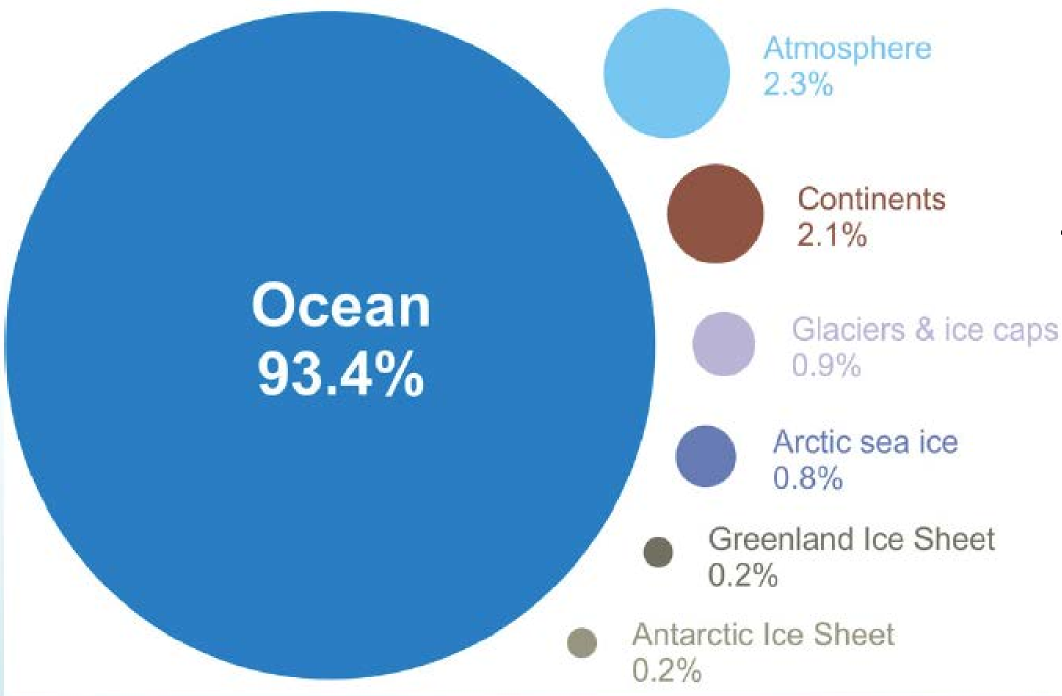
Raincube Ka band radar



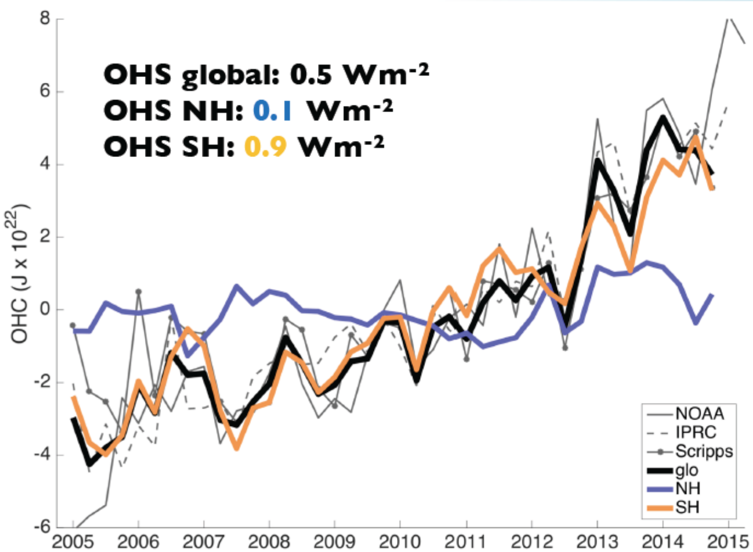
March 2018

And more

Summary

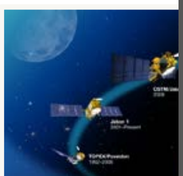


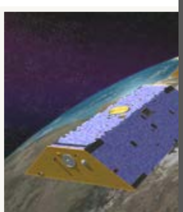
90% of heat storage occurs in SH oceans



Almost all (~93%) is taken up in the world's oceans & 90% of this occurs in the SH oceans

Sea level rise & Ocean heat content



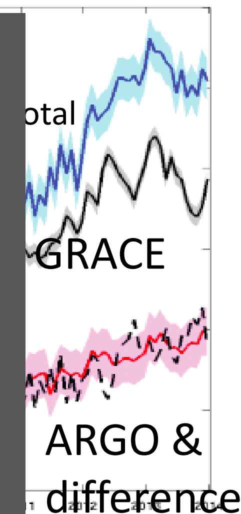


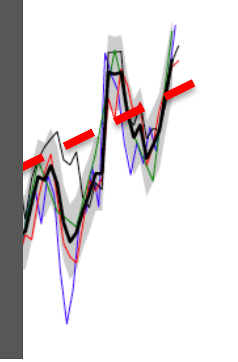
Llovel et al., 2014;

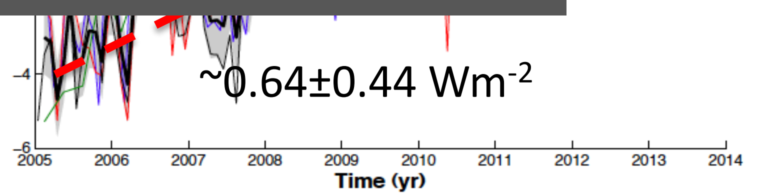
- These results suggest that the heat being added to the ocean over the Argo period is occurring between the surface and 2km.

BUT not so fast – when data are extended to 2017 we find ARGO and altimeter/graviometric data of last few years diverge ~0.4Wm^{-2} –suggests a changing role of deep oceans over time?

- This heat draw-down continued unabated during thesurface temp ‘pause’
- I would argue monitoring the EEI remains a challenge and alternative ways of doing this should be explored







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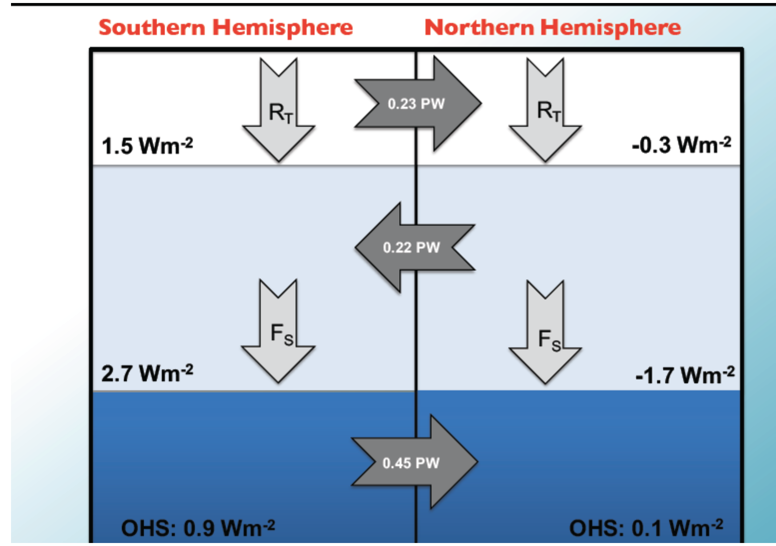

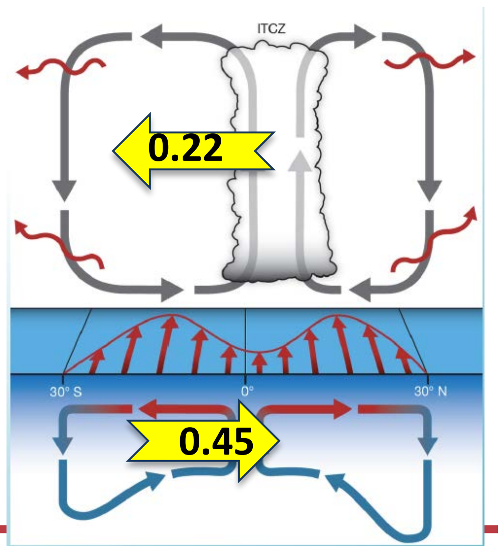

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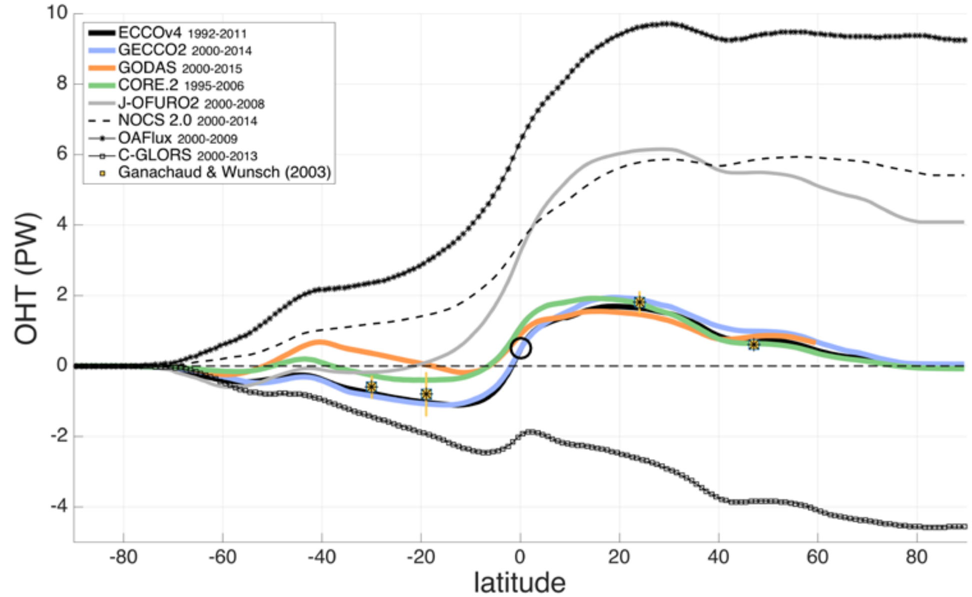
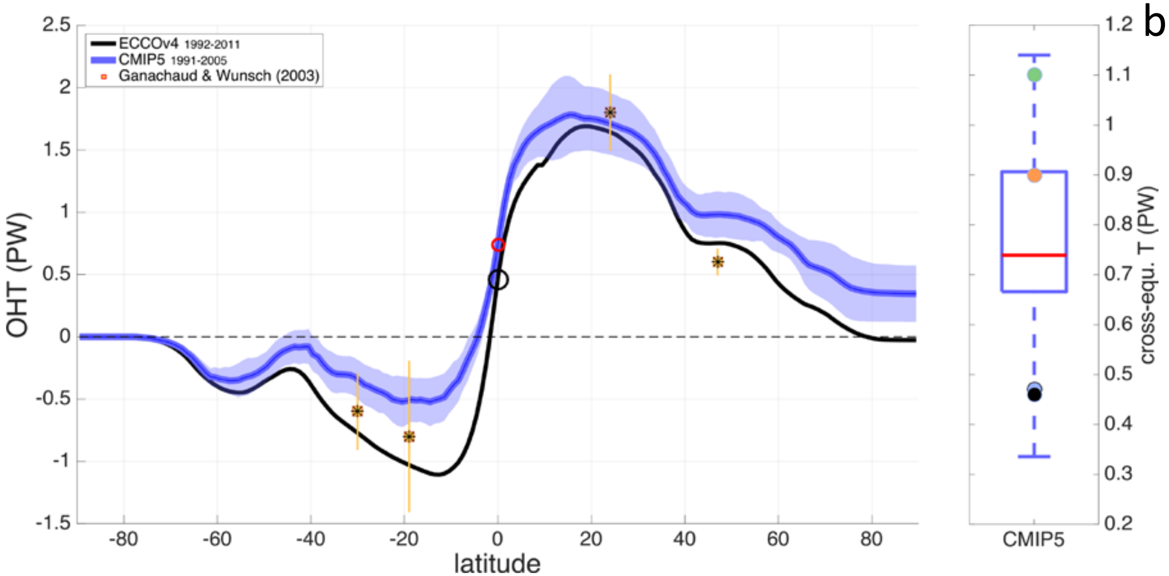
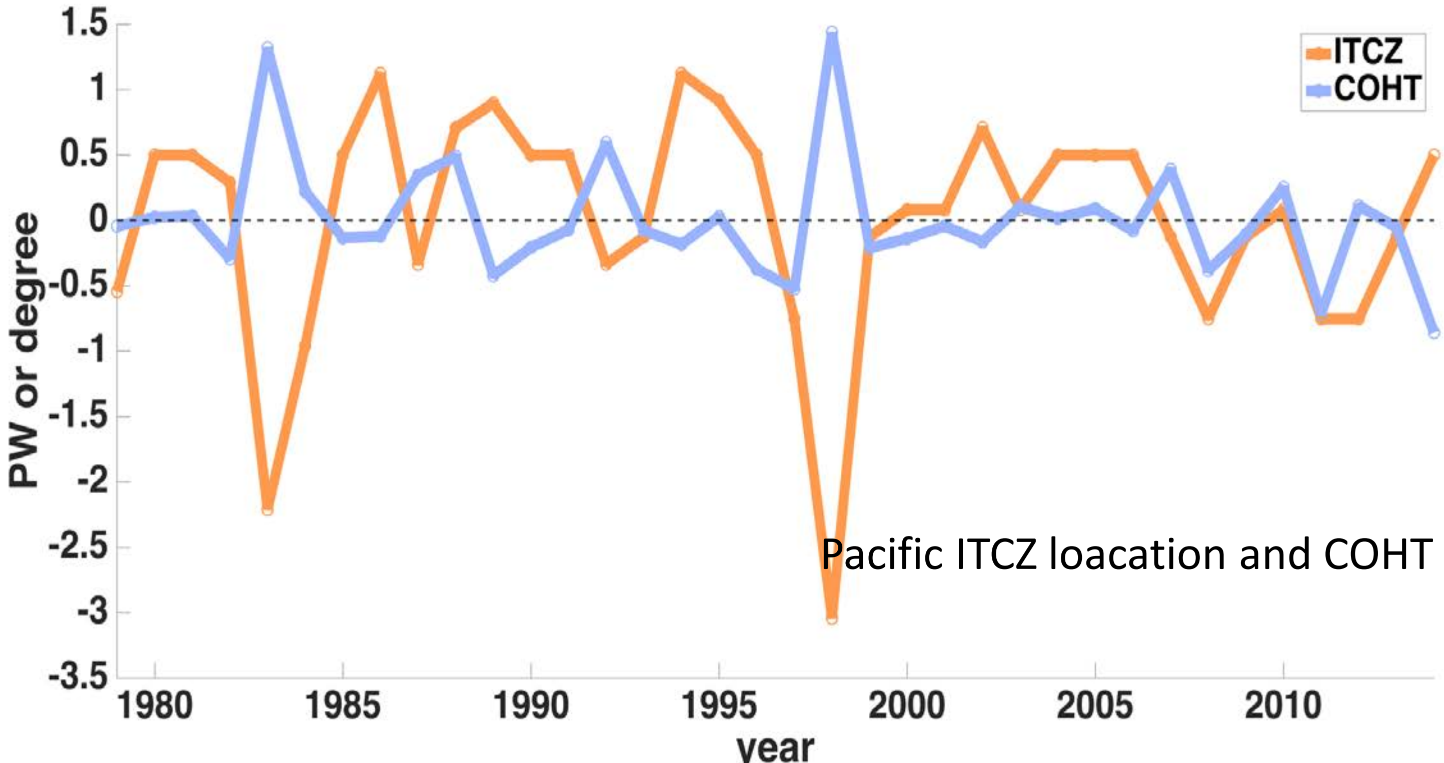




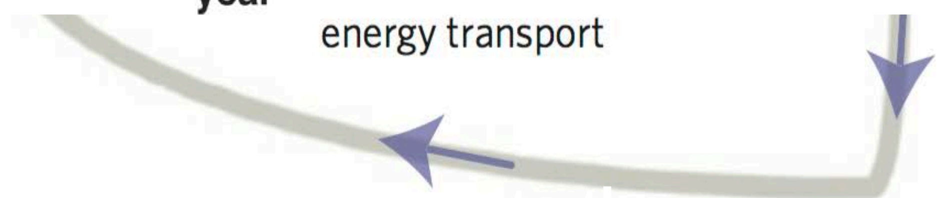
We base the cross equatorial heat transport on advanced ocean analysis – CMIP5 models vary widely in the COHT - this matter because..

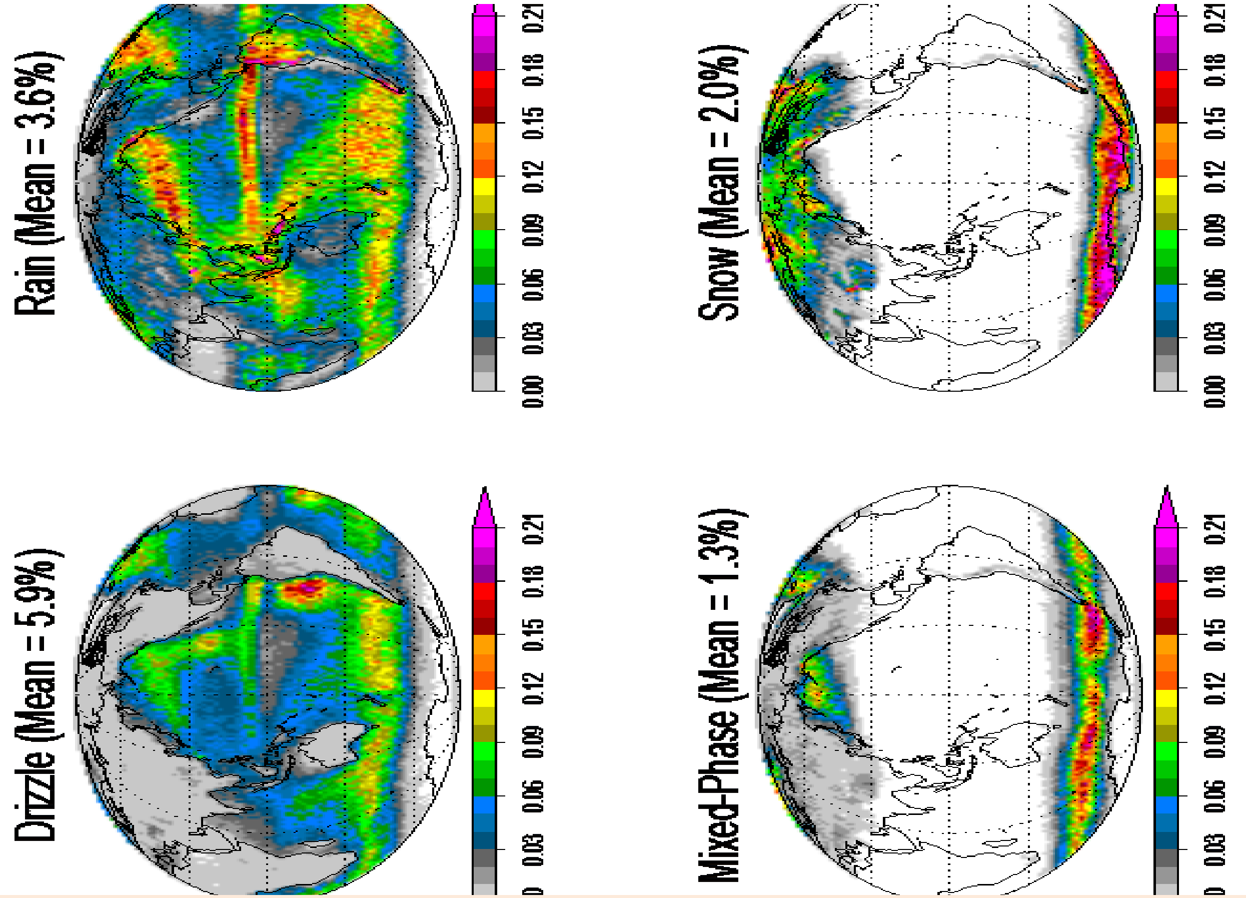
Heat transport and ITCZ



Pacific ITCZ loacation and COHT

Schneider et al., 2014





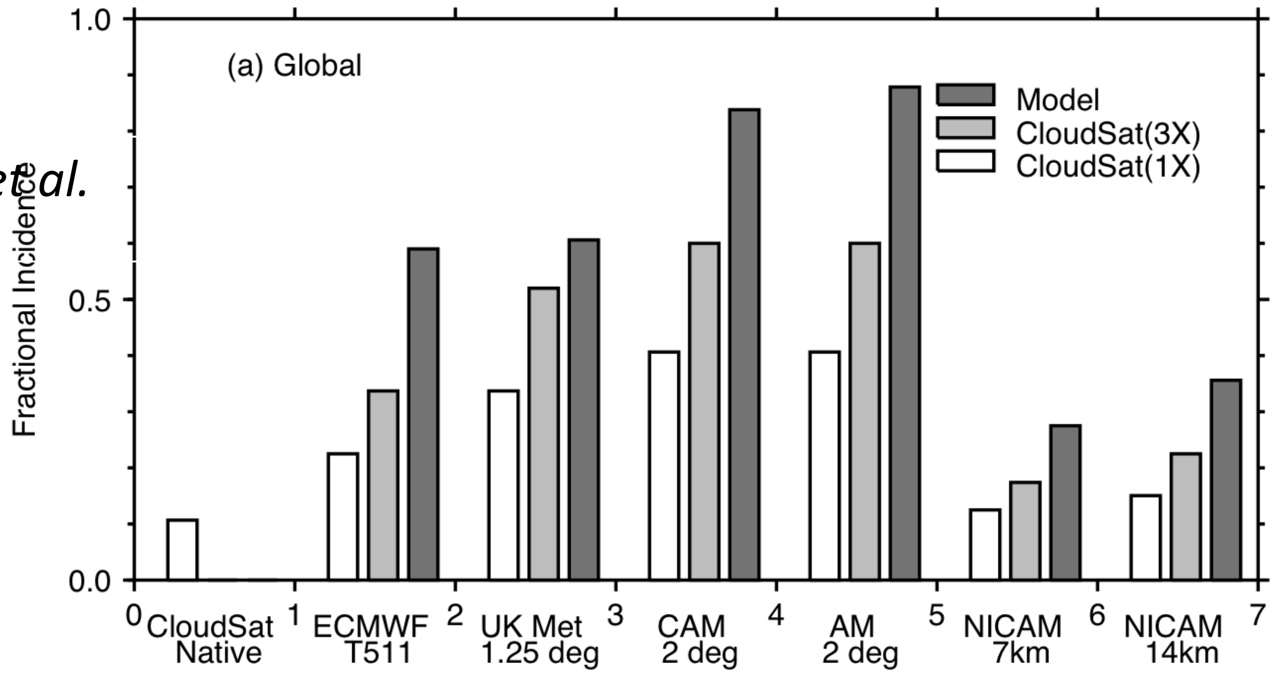
Results from CloudSat, Stephens et al., 2016

We now have a good idea of how often it precipitates around Earth, but we still have challenges to quantify how much and the intensity at which it falls

Drizzle bias

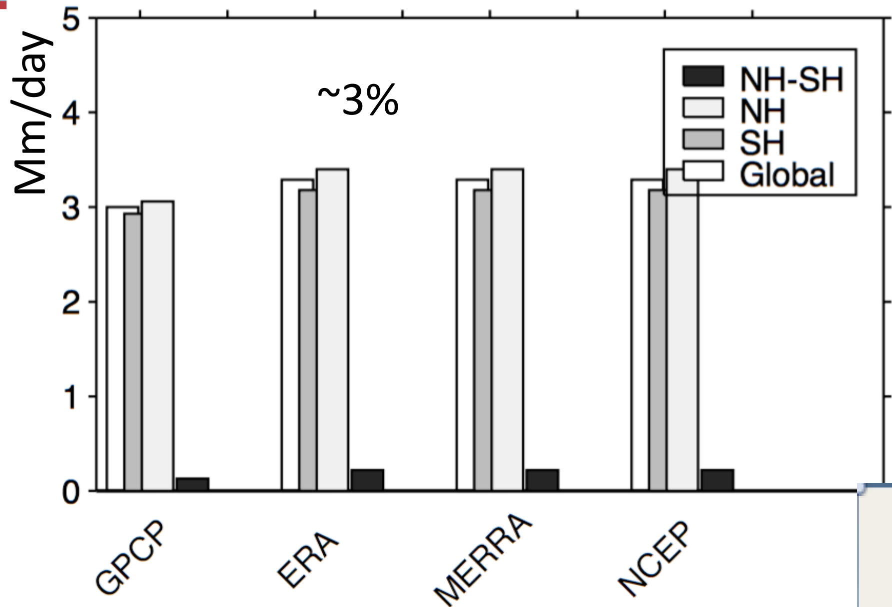
Fractional incidence (or frequency of occurrence) of rainfall as a function of rainfall rate over ocean (60° S to 60° N) derived from CloudSat and various global models.

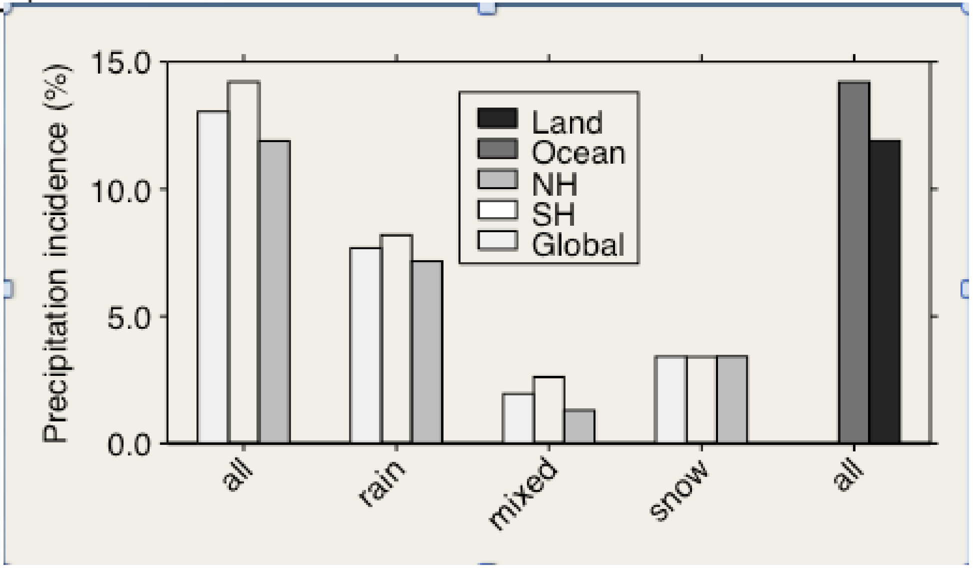
Stephens et al. (2010)



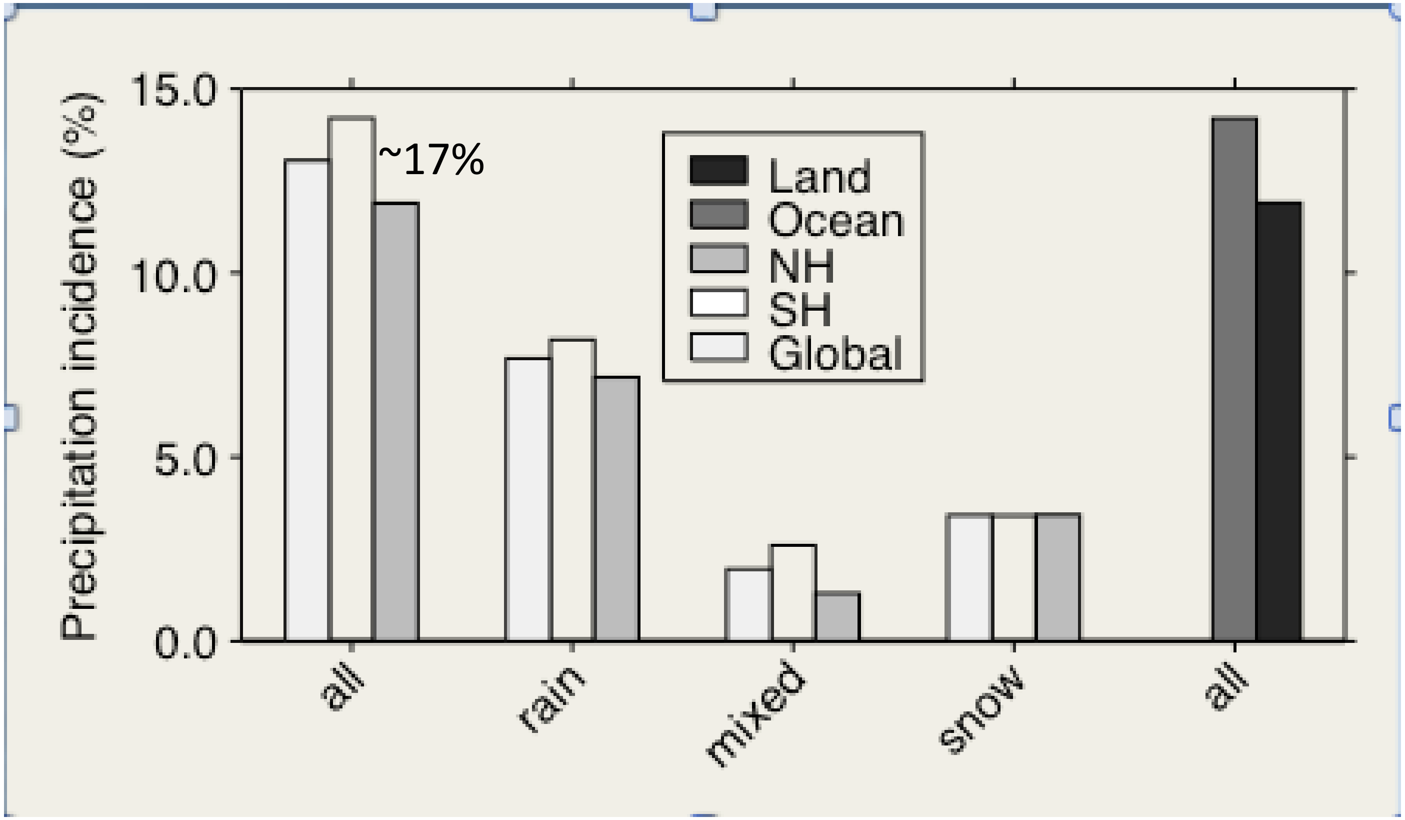
All models produce rain far too frequently, almost twice that observed. Because that total accumulation of precipitation, controlled by radiation processes, is less biased, then model rains are too light. The implications for modeling extreme rains under cliamte change are not fully understood

Annual accumulations (mm/day)

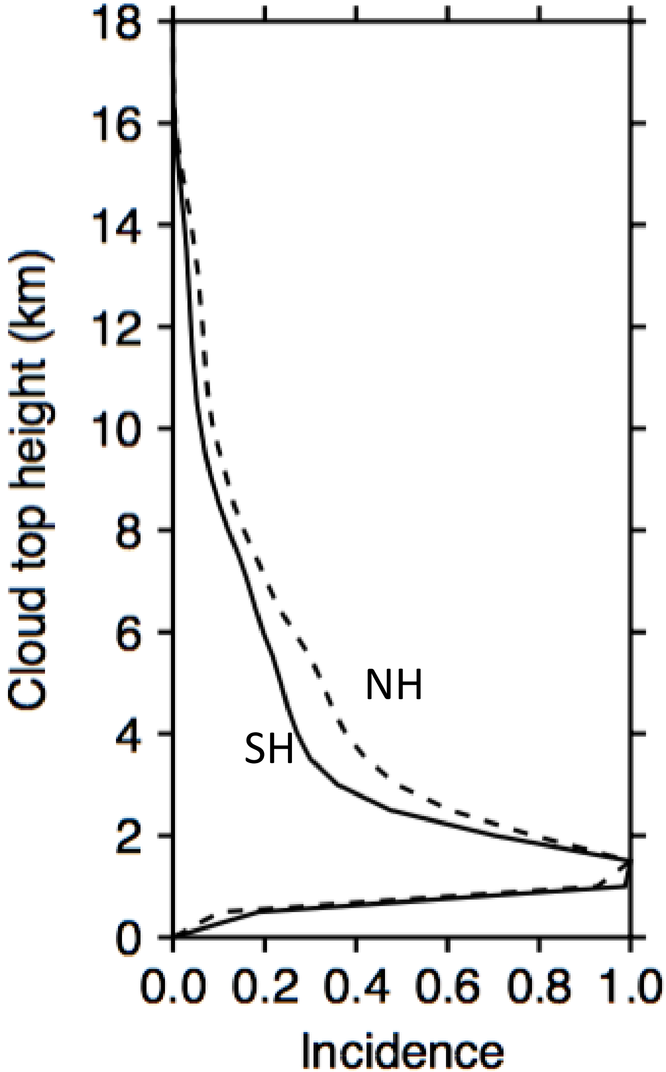




The SH precipitates about 17% more often than the NH

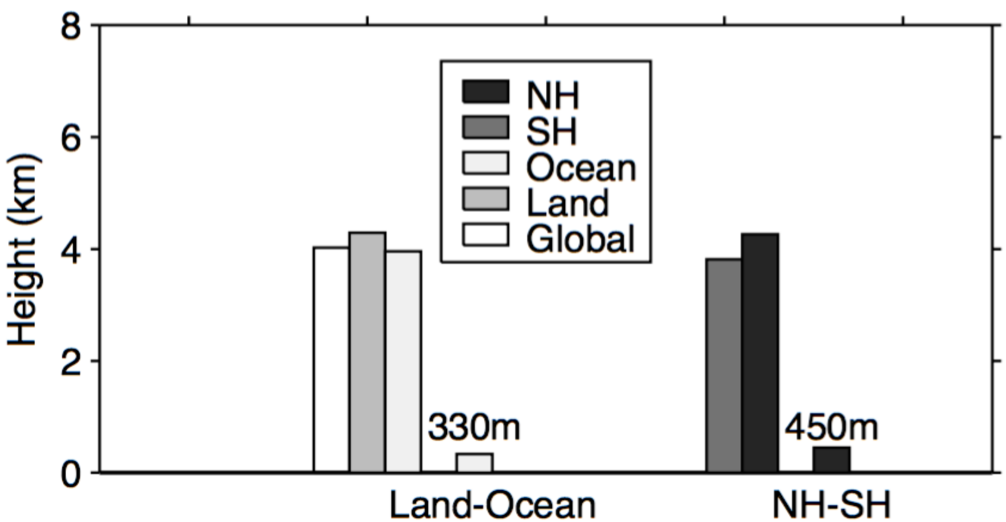


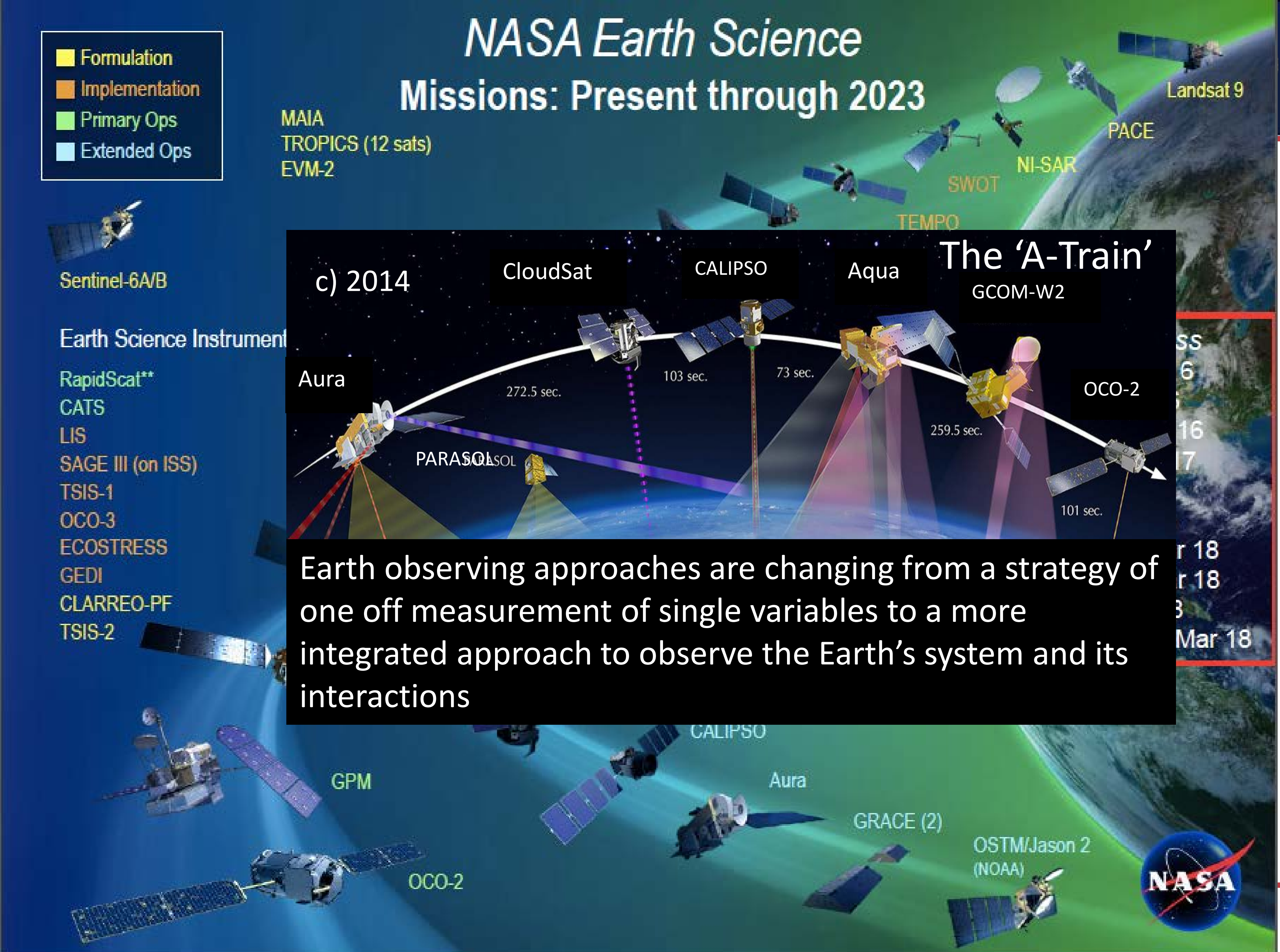
This implies NH precipitation is of order 10% more intense than SH precipitation



Further evidence of more intense NH precipitation

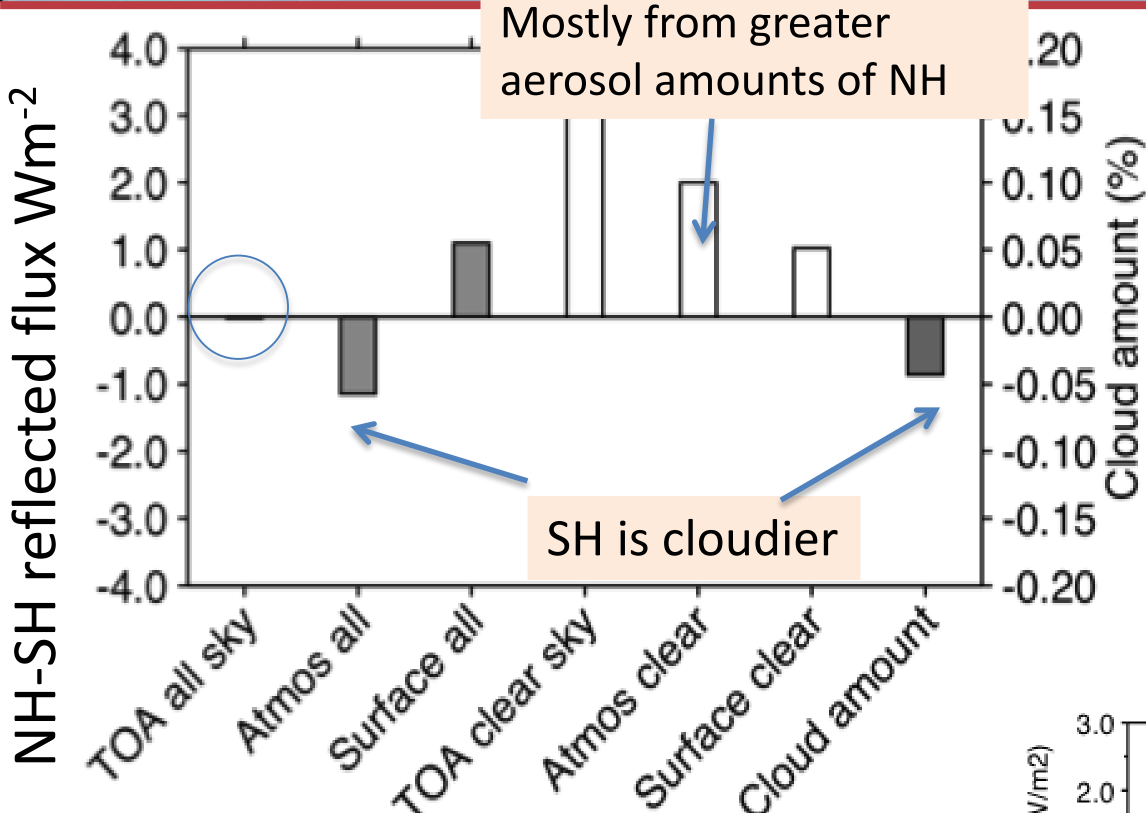
- NH clouds are deeper & deeper clouds = heavier rain
- The drizzle 'gap' over land (less dreary)





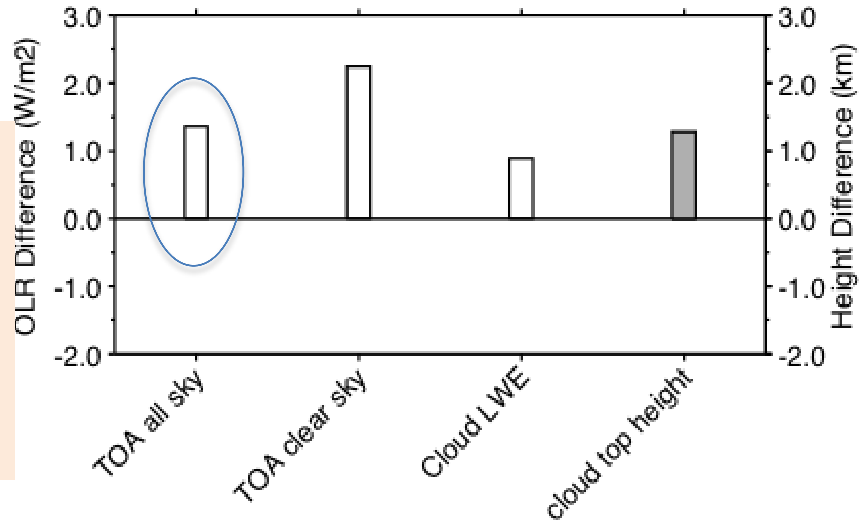
Earth observing approaches are changing from a strategy of one off measurement of single variables to a more integrated approach to observe the Earth's system and its interactions

The curious nature of hemispheric symmetry



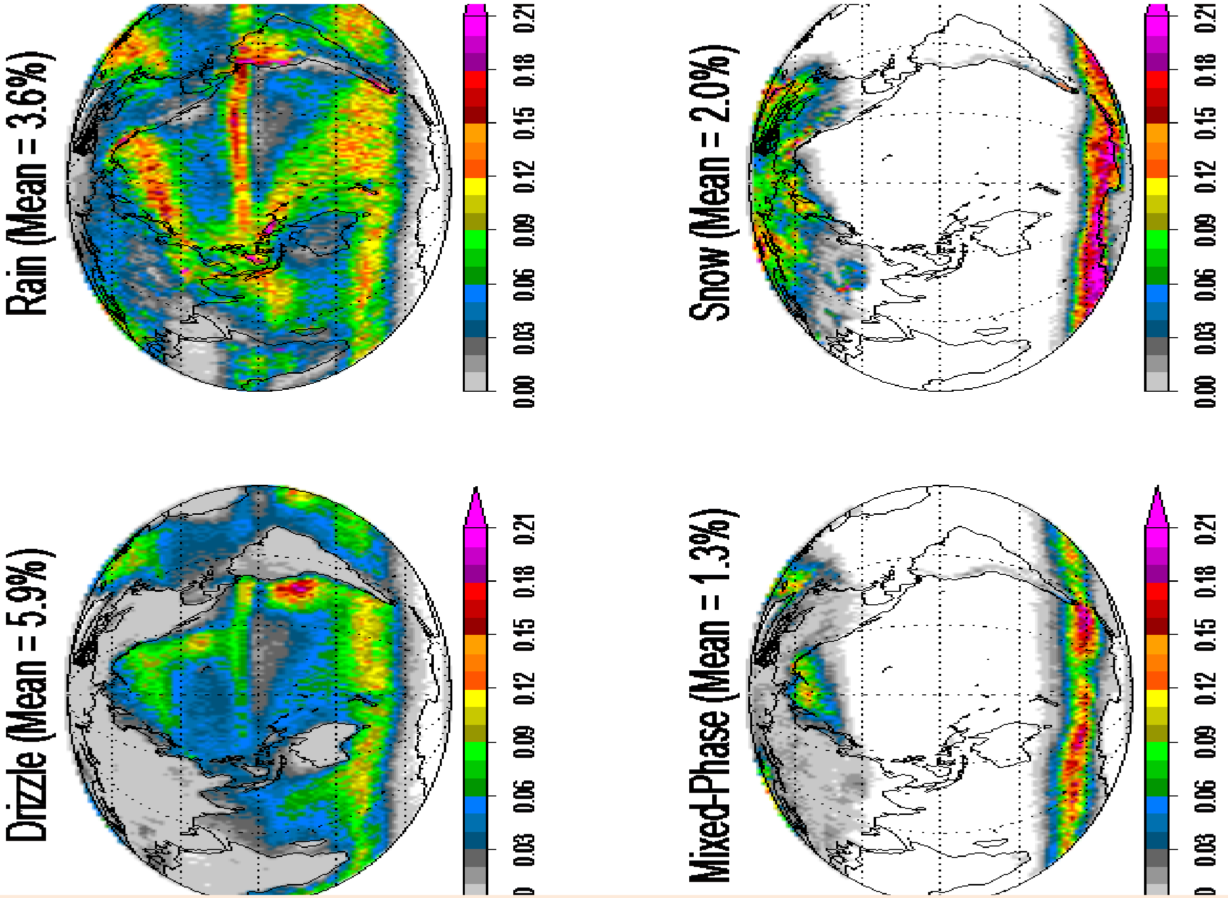
Sunlight reflected from both hemispheres is identical.

The radiation emitted to space by each hemisphere is ~ 1.5 Wm^{-2} different, with the SH emitting less than the NH



This approximate symmetry is established by the clouds

Why? Is such symmetry a preferred state of climate?



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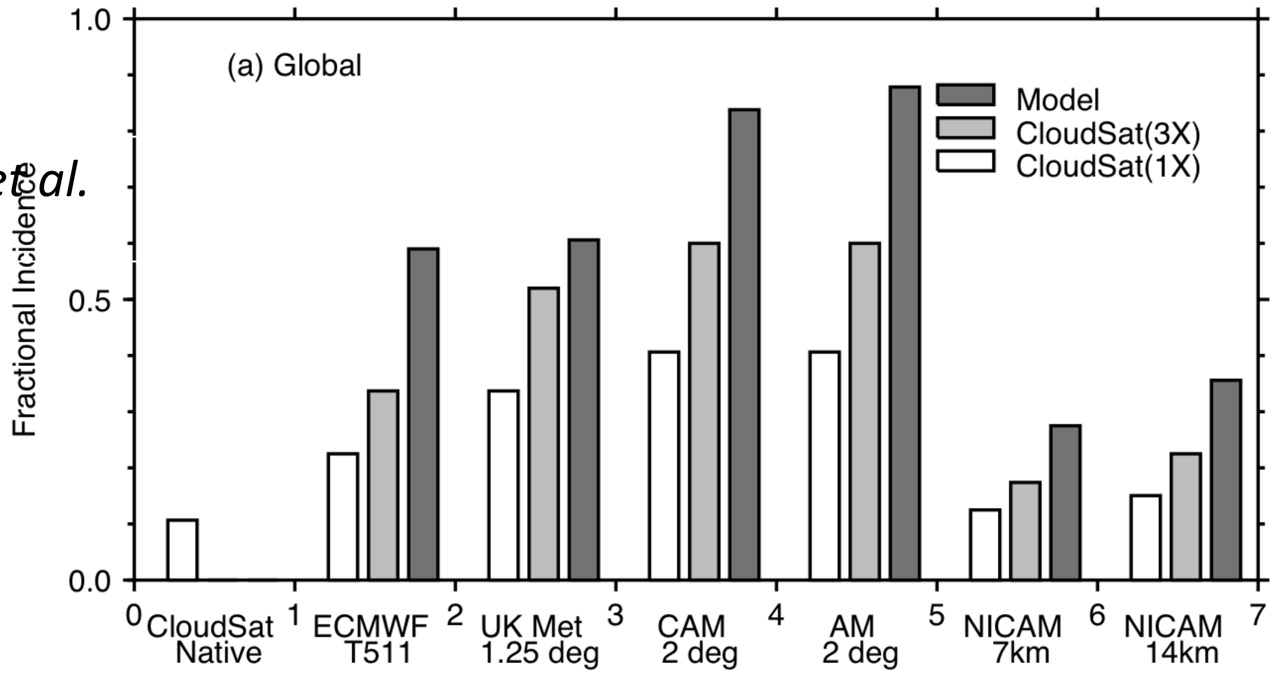

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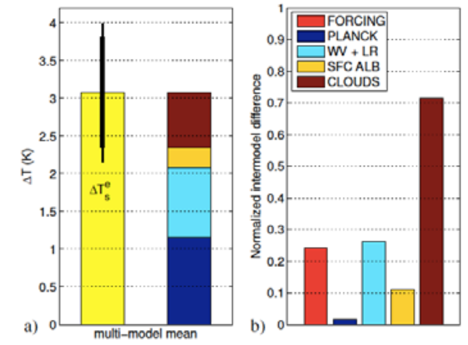
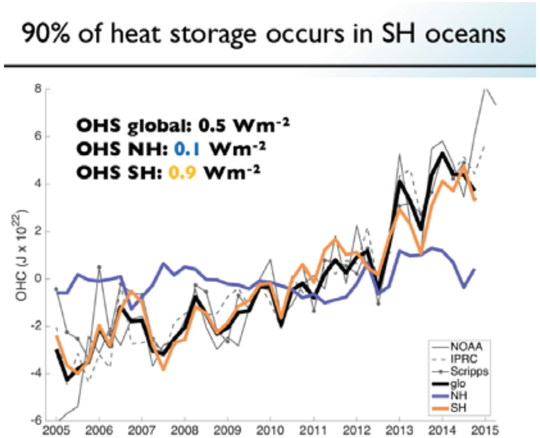
Summary: energy

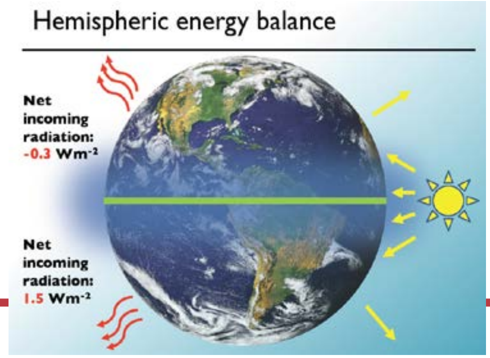
1) The feedbacks of the Earth system critical to its evolution involve the interaction of water and radiation and the exchanges of water between its three phases. Cloud feedbacks relate to all three phases of water and are highly uncertain.

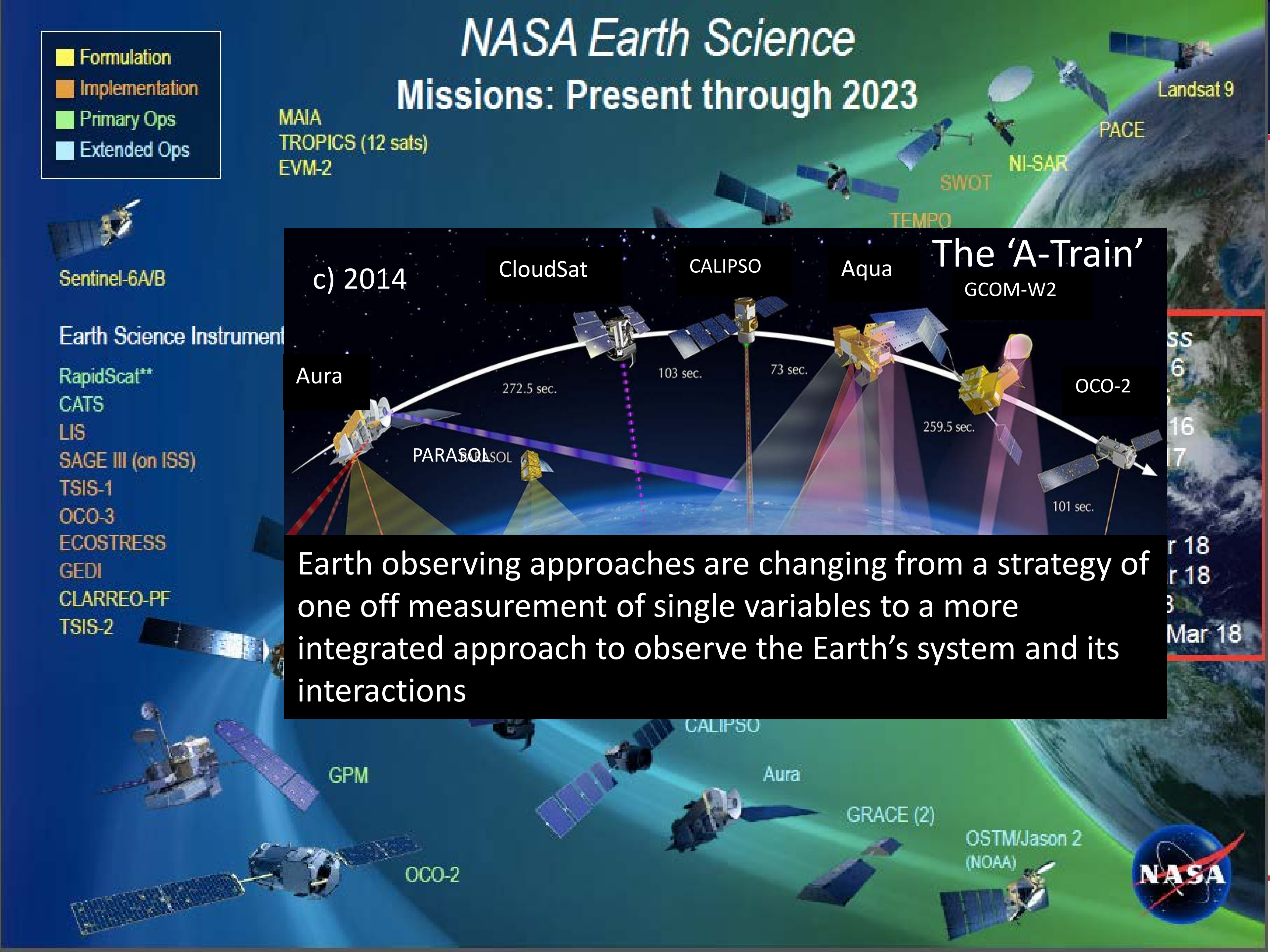


2) The Earth is currently out of energy balance by about 0.6 Wm^{-2} due to anthropogenic modulations of the balance. This additional heat is largely absorbed within the southern oceans. The consequences of this are not yet fully understood



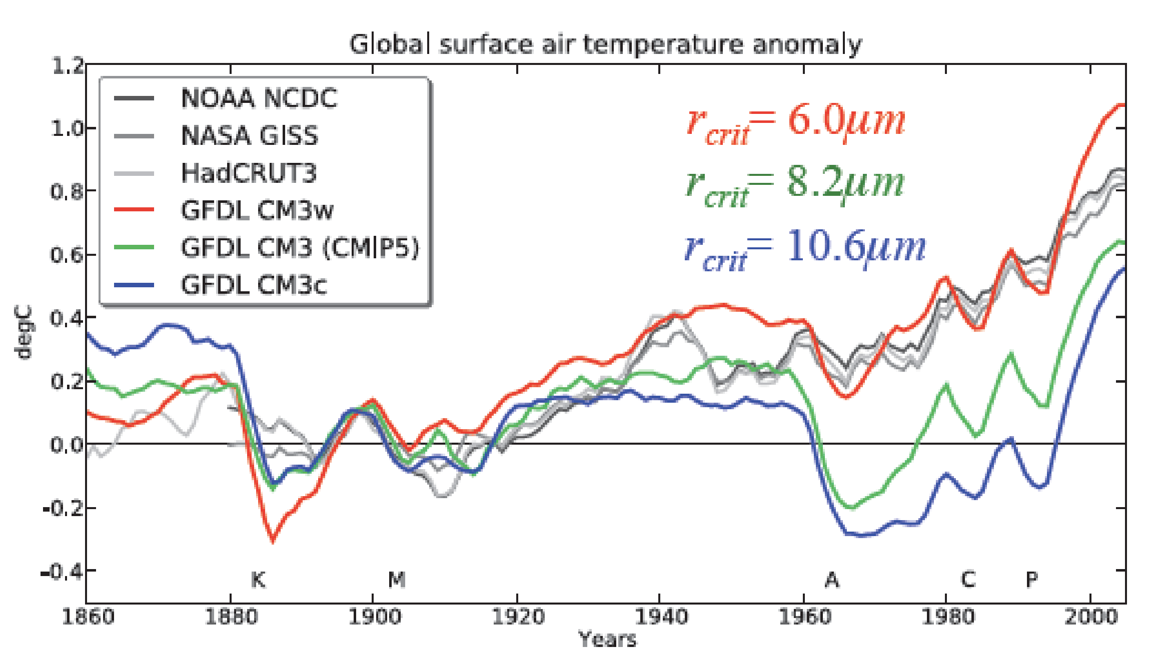
3) The planet's energy balance is very symmetric despite substantial asymmetries on the structure of each hemisphere. The symmetry is achieved by the way cloud patterns are created. The significance of this to how a forced system will evolve is not known

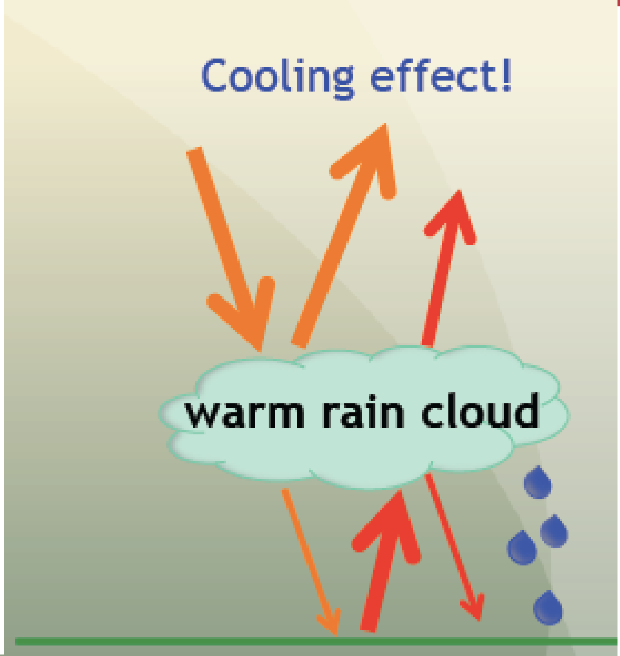




Earth observing approaches are changing from a strategy of one off measurement of single variables to a more integrated approach to observe the Earth's system and its interactions

Drizzle bias & the aerosol-indirect effect





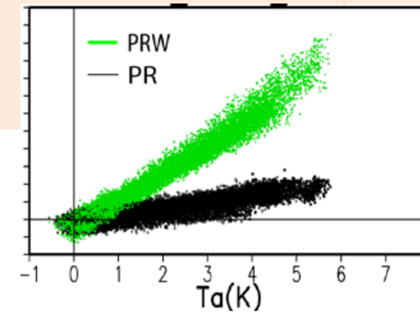
Golaz *et al.* (GRL ’13)

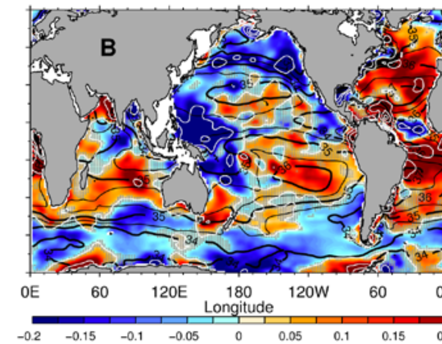
Conundrum: 6um case not physically plausible – too much drizzle, reduced low clouds, warmer Earth

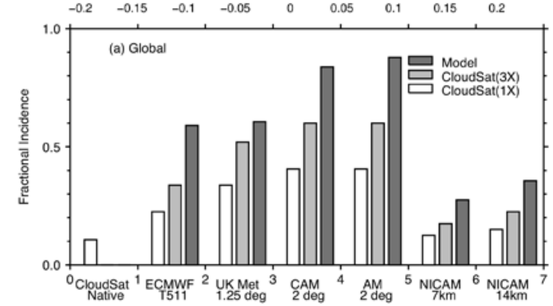
10um more plausible, but produces an over exaggerated aerosol indirect effect through increased low cloud (reduced drizzle), resulting in a much too cold Earth

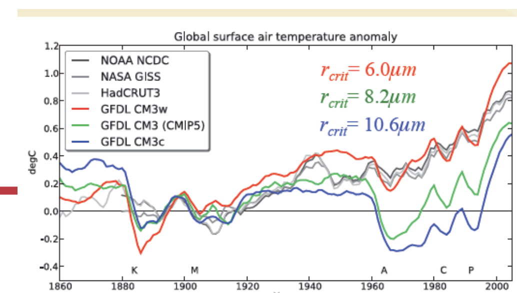
Summary:water

Global change-









4) We have a quantitative understanding of how precipitation is expected to change globally. This global change is largely controlled by radiative processes influenced by increased water vapor.

5) No equivalent level of understanding of how regional changes will evolve under a changing climate system. Regional changes over oceans suggest existing wet areas will get wetter and dry drier. The mechanisms of such change are very qualitative and does not appear relevant to changes observed over land.

6) Basic representation of precipitation processes in models produce significant biases in the nature of precipitation. While the total amount is controlled by energetics, local changes are shaped by atmospheric circulation. **Quantifying the connection between circulation, energy and water is at the heart of Earth science challenges.**