REVEX 2015

PI Science Presentation

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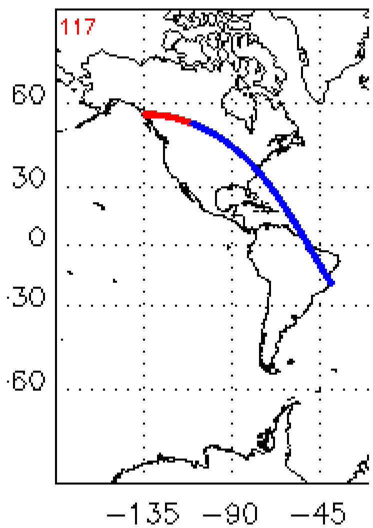
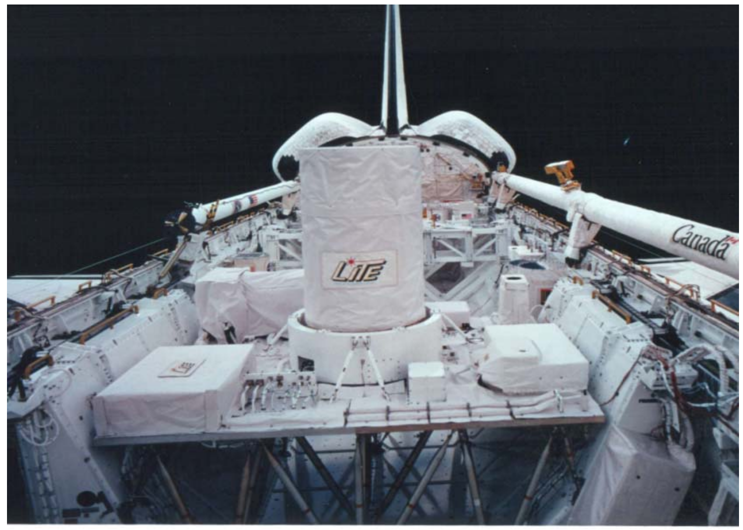
NASA/LaRC

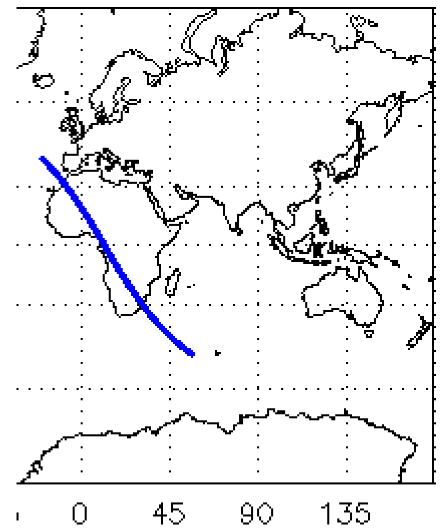
Outline

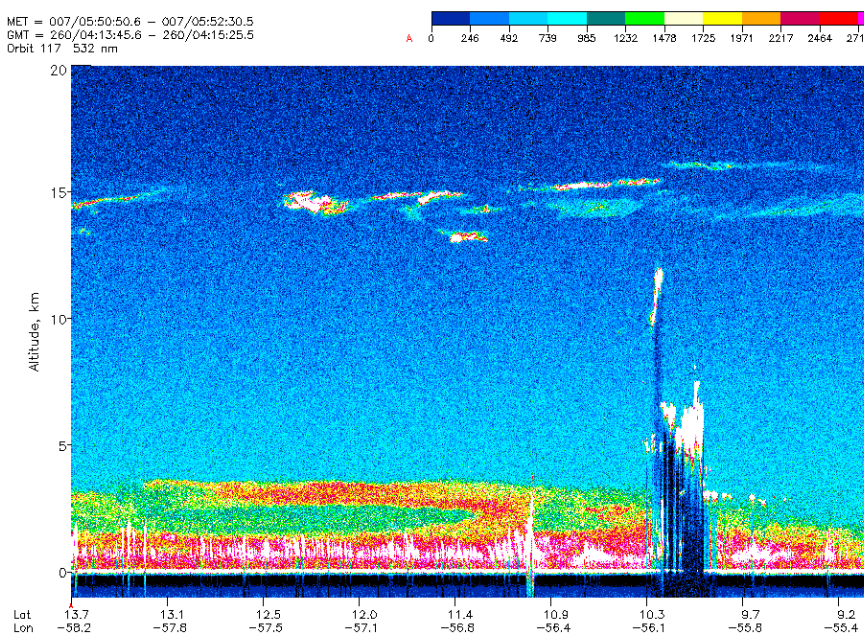
- **Overview of major achievements**
    - Closure of sfc adiation budget
    - Uncovered/quantified issues with passive sensors
    - GOCCP/Nam study
    - Aerosol assimilation at NRL
- **Lessons Learned**
    - Profiling
    - Radar/lidar synergies
    - A-train/constellation
- **Looking toward the future**
    - Active profiling as part of core observing system
    - CDRs, timeseries, justification for future missions

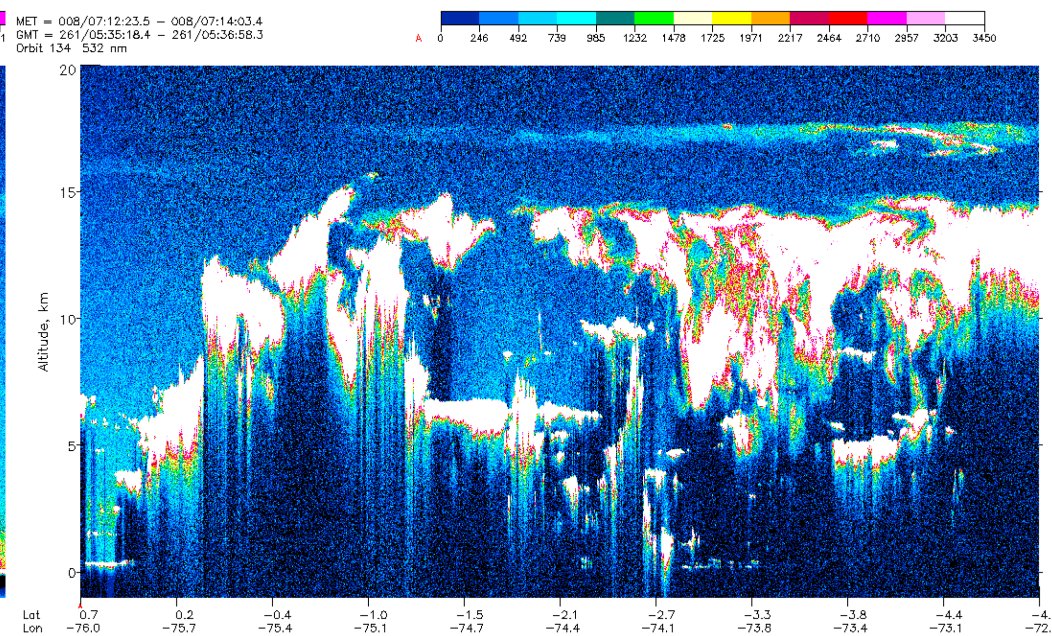
Our first look: LITE (1994)









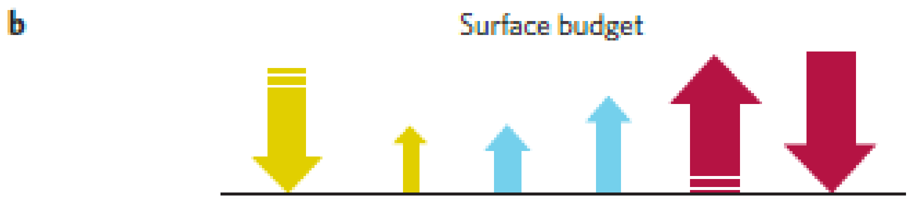


Science Highlights

- **Better constraints on the surface radiation budget**
  - Have closed SRB for the first time
- **Recent:**
  - Attribution of stratospheric AOD trends (Solomon, Fyfe, Santer)
  - Insight into Amazonian fertilization constraints (Yu et al, 2015a,b)
    - Climatology of Sahara dust transport
  - Insights into mechanisms of ACI (Chen et al, 2014; A&Z, 2015)
  - Characterized coupling of TTL clouds to circulation (Zhou et al, 2014; Li and Thomson, 2013; Q. Fu)
  - Successful assimilation experiment at NRL

Chapter 7 – Clouds and Aerosols

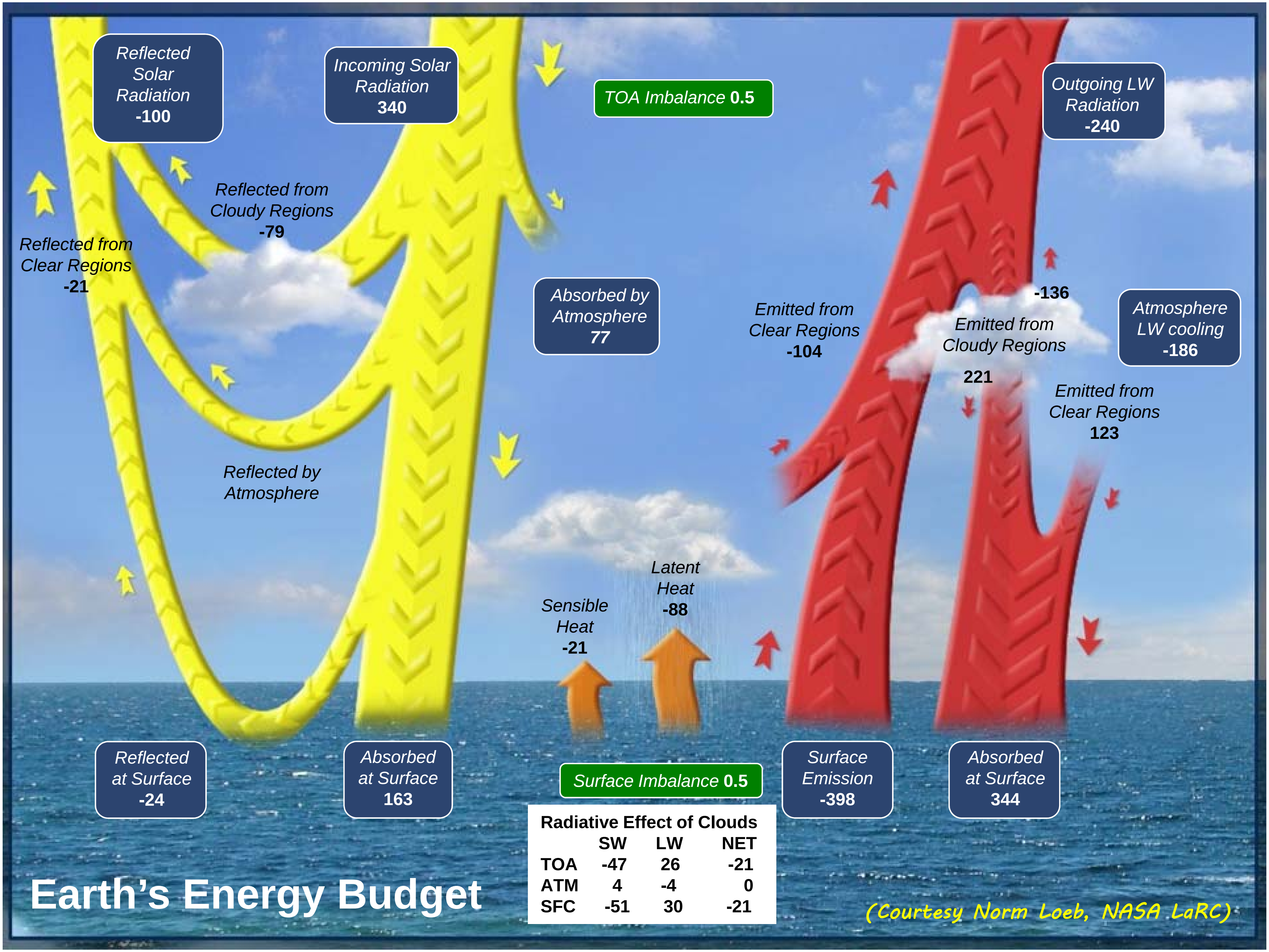
"The net downward flux of radiation at the surface is sensitive to the vertical distribution of clouds. It has been estimated more accurately through radiation budget measurements and cloud profiling (Kato et al. 2011). Based on these observations the global mean surface downward longwave flux is about 10 W/m^2 larger than the average in climate models, probably due to insufficient model-simulated cloud cover or lower tropospheric moisture (Stephens et al. 2012)."



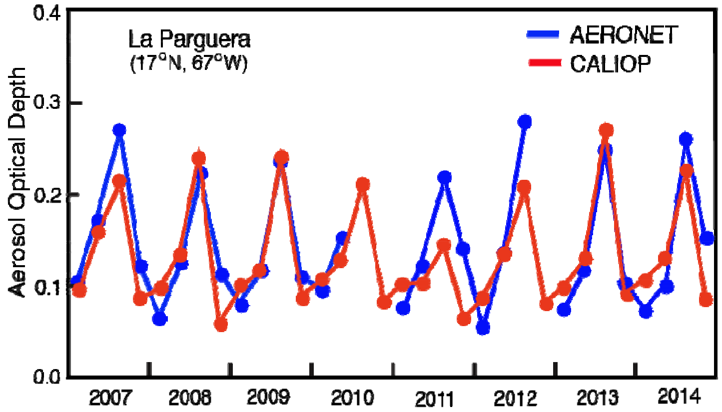
	SW down	SW up	SH	LH	LW up	LW down	Surface imbalance
Observations	188±6	23±3	24±7	88±10	398±5	345.6±9	0.6±17
CMIP5							
Min	181.9	21.1	17.6	78.4	391.9	326.4	
(Mean)	(190.3)	(24.9)	(20.9)	(85.8)	(397.5)	(339.7)	
Max	196.2	30.3	27.8	93.6	398.1	347.0	

Surface energy balance. Observed and climate model deduced energy fluxes at the surface. The climate model fluxes are from CMIP5 twentieth-century experiments. The fluxes from a 16-model ensemble are summarized in terms of the range in model values with the ensemble mean fluxes given in parenthesis.

Stephens et al. (NatGeo, 2012)


Earth's Energy Budget
Reflected Solar Radiation -100
Incoming Solar Radiation 340
TOA Imbalance 0.5
Outgoing LW Radiation -240
Reflected from Cloudy Regions -79
Reflected from Clear Regions -21
Absorbed by Atmosphere 77
Emitted from Clear Regions -104
-136
Emitted from Cloudy Regions
221
Atmosphere LW cooling -186
Emitted from Clear Regions 123
Reflected by Atmosphere
Sensible Heat -21
Latent Heat -88
Reflected at Surface -24
Absorbed at Surface 163
Surface Imbalance 0.5
Surface Emission -398
Absorbed at Surface 344
Radiative Effect of Clouds
SW LW NET
TOA -47 26 -21
ATM 4 -4 0
SFC -51 30 -21
(Courtesy Norm Loeb, NASA LaRC)

Sahara Dust Transport



Surface dust mass concentrations sampled at Barbados compared with seasonal-mean upwind dust mass flux estimated from CALIOP dust AOD retrievals.

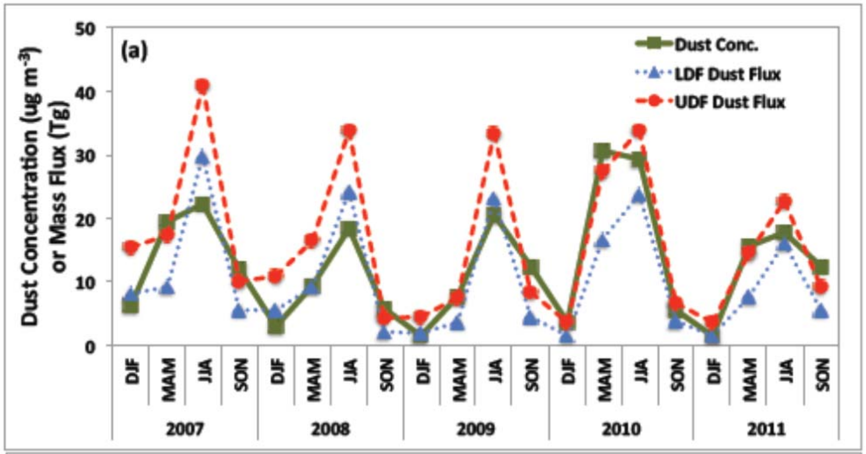


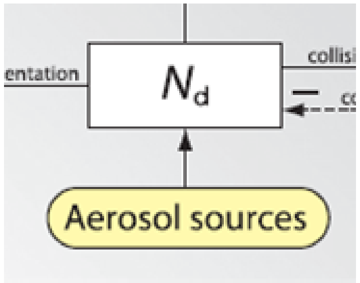
Figure 9: Comparisons of seasonal and interannual variations of AOD between AERONET (blue) and CALIOP (red) at (a) Cape Verde (16°N, 22°W) and (b) La Parguera (17°N, 67°W). DOD estimated from CALIOP is also shown, with cyan for LDF and green for UDF scenario. CALIOP values are averages over the 10°x10° box centered at (15°N, 15°W) for Cape Verde and (15°N, 75°W) for La Parguera, respectively. In both sites, CALIOP and AERONET AOD have a linear correlation coefficient of about 0.87. On a basis of 7-year average, the AOD bias (CALIOP/AERONET) at Cape Verde is 0.77, 1.12,1.19, and 0.87 in DJF, MAM, JJA, and SON, respectively. Corresponding AOD biases at La Parguera are 1.27, 0.97, 0.90, and 0.65.

(Hongbin Yu, GRL, 2015)

Aerosol-Cloud Interactions

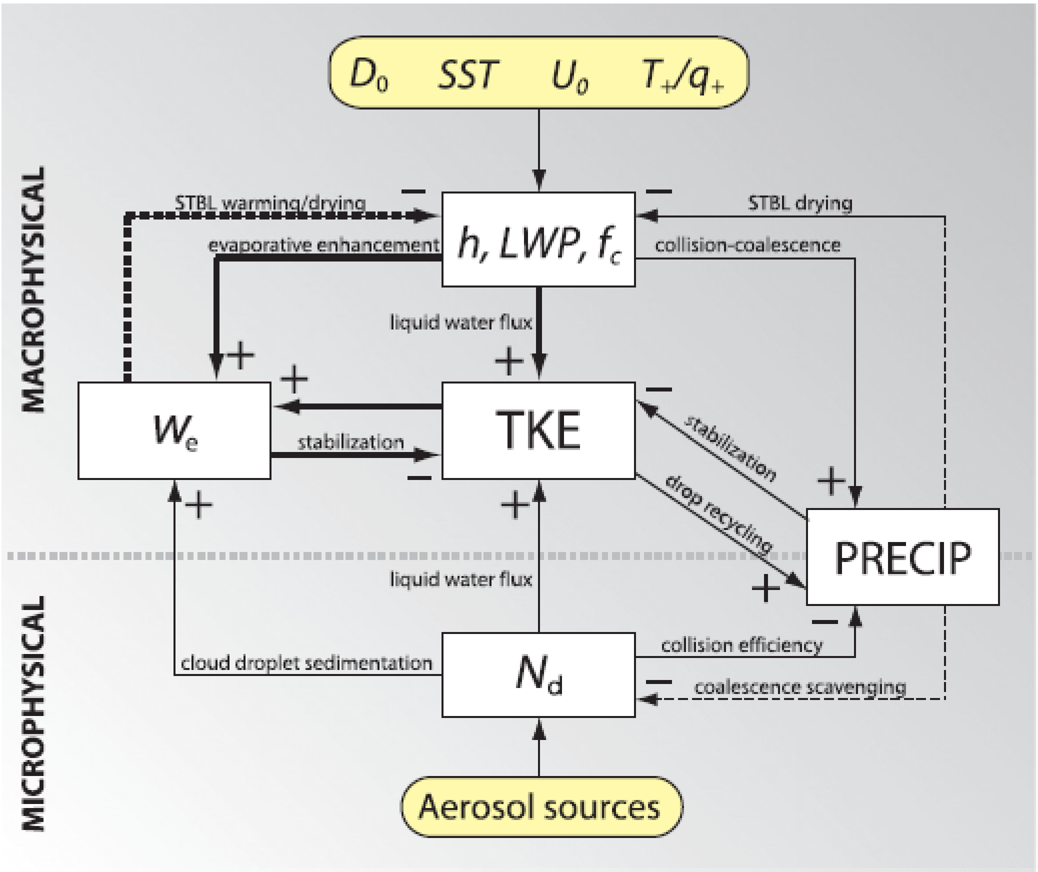
Twomey effect (c. 1995)

more aerosol → smaller cloud droplets → higher cloud albedo



Early investigations looking for aerosol-albedo correlations (Han et al 2004): little success

Now understand that life is more complicated. "Twomey effect" overestimates magnitude of AIE due to simplified assumptions on cloud processes



(Wood, MWR, 2012)

Multiple feedback processes, operating on multiple timescales, play significant roles in regulating the response of clouds to aerosol perturbations

Solid lines: feedbacks that operate on time scales comparable with the eddy turnover time scale (an hour or less)
Dashed lines: feedbacks that operate on markedly longer time scales.

Yet, signs of progress from the A-train

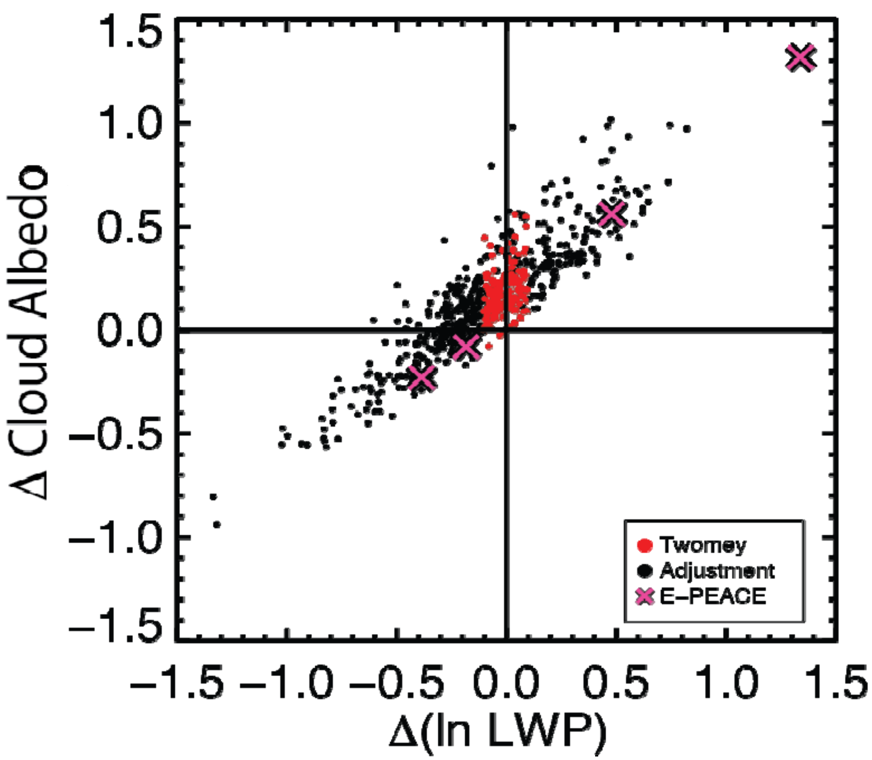
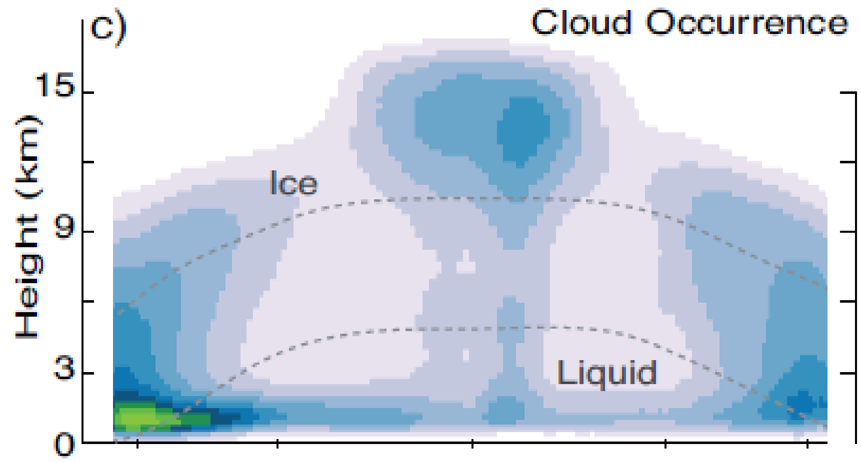


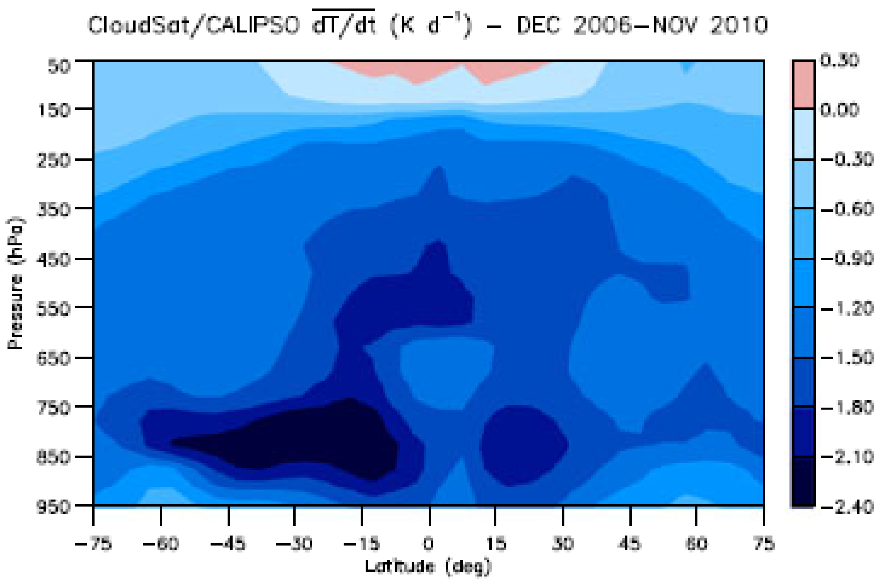
Fig. 6. Fractional change in cloud albedo versus fractional change in log (LWP). Red dots indicate the regime of the Twomey effect. Black dots indicate LWP feedback adjustment. The four E-PEACE data points (pink) are shown.

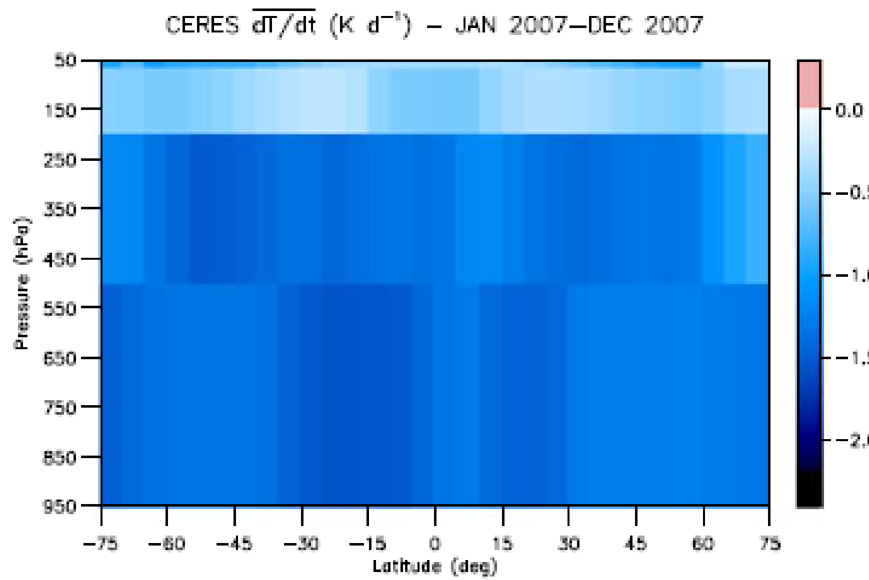
(Yi-Chun Chen, et al. 2012)

New capabilities from A-train merged products

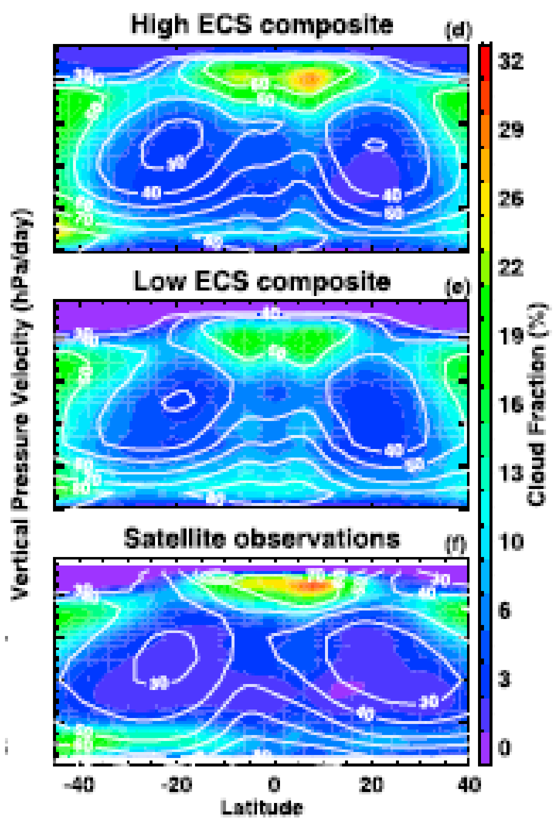


(Haynes et al 2013)





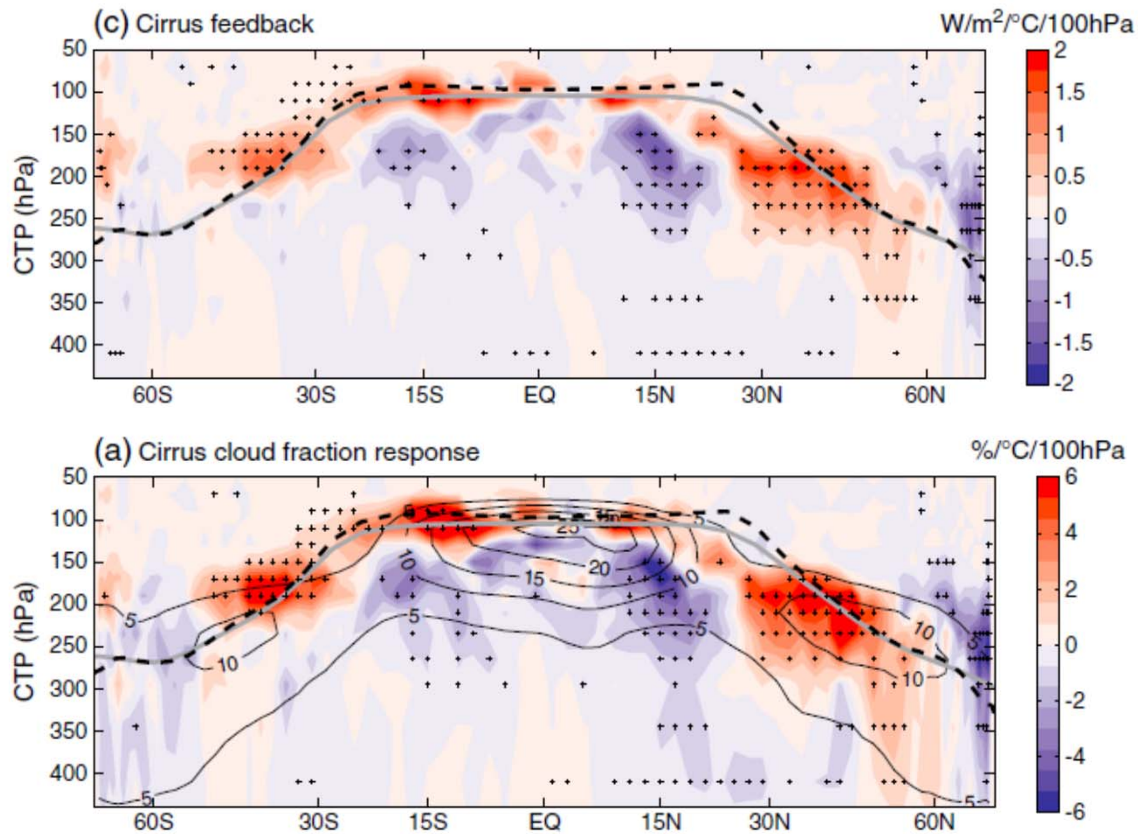
New research area: coupling of clouds to circulation



Three mechanisms (Bony et al):

- radiative heating/cooling
- latent heating
- mechanical uplift

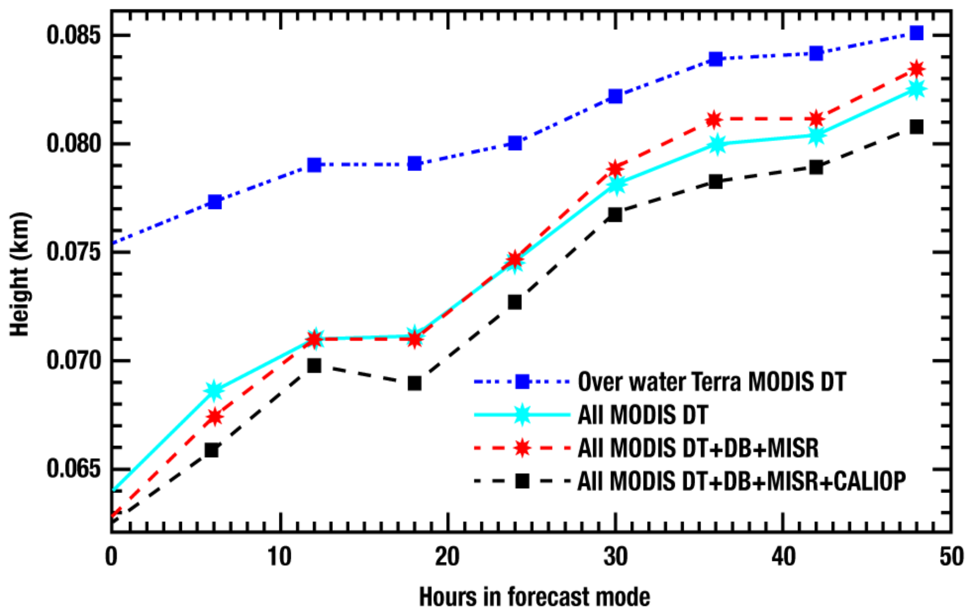
H. Su et al, 2014: Vertical cloud structures in high-sensitivity models more similar to observations than in low-sensitivity models



(Zhou and Dessler, GRL, 2014)

Figure 3. Zonal mean cirrus feedback. (a) Response of cirrus clouds fraction to interannual surface warming (shading), calculated by regressing monthly mean anomalies of cloud fraction against monthly mean anomalies of global mean surface temperature (from ERA-Interim). Contours are the 6 year mean cirrus cloud fraction (in %/100 hPa), the gray solid line denotes the ERA-Interim climatological tropopause pressure, and black dashed line is the climatological value plus the response to 1 K surface warming

Successful aerosol assimilation experiment at NRL



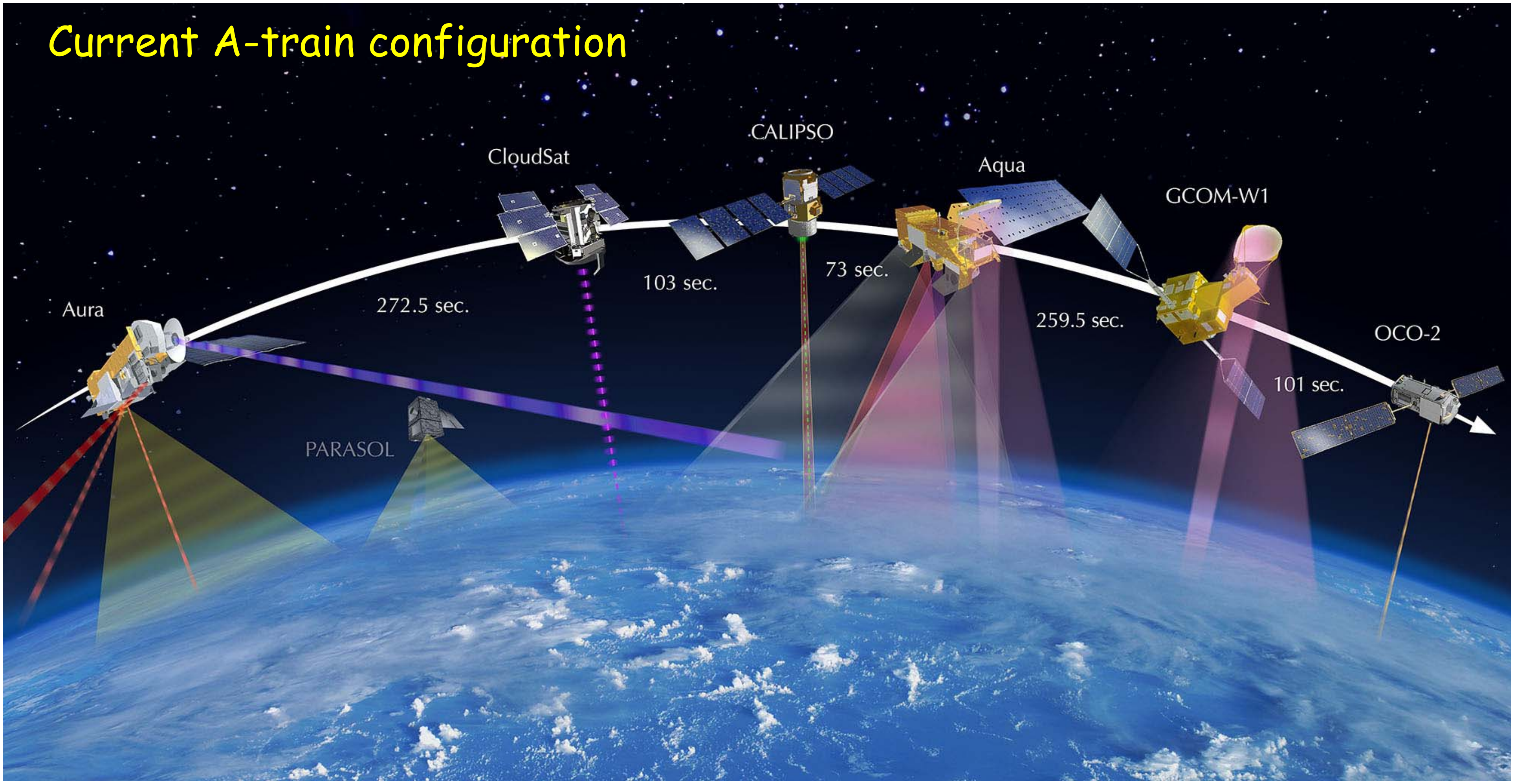
Globally averaged absolute error in NAAPS AOD (NAAPS – Aeronet) as a function of 48 hour forecast time in 6 hour intervals for four successive model runs (Zhang et al. 2014).

(CALIOP AOD is normalized to MODIS, improvement with CALIOP is strictly from improved vertical distribution)

Lessons Learned

Major advances in knowledge rely on combining CALIPSO with other measurements

- **Biases in Southern Ocean surface radiation (Bodas-Salcedo, 2012, 2014)**
  - CALIPSO, CloudSat, MODIS, CERES
- **Coupling of clouds and circulation (Su and Jiang, Dessler)**
  - CALIPSO, CloudSat, …
- **Aerosol-cloud interactions (Chen et al., Zuidema, 2015)**
  - CALIPSO, CloudSat, MODIS, AMSR, CERES



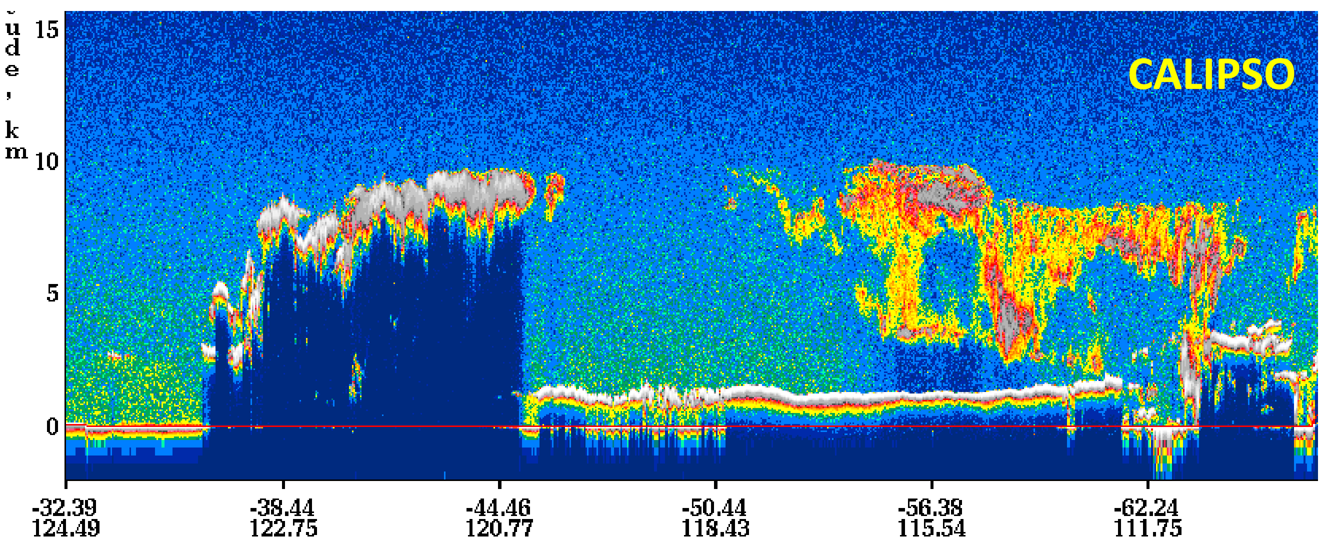
A-train synergies:

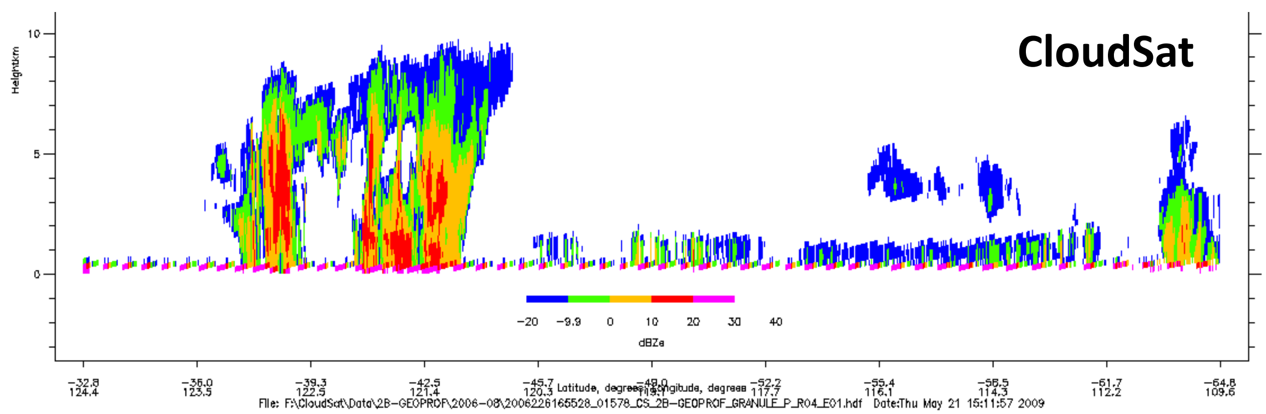
CALIPSO + CloudSat: cloud profiles, microphysics, IWC
CALIPSO + CERES + MODIS: cloud optics, radiative fluxes/energy budget
CALIPSO + MODIS + OMI + OCO-2: aerosol radiative forcing
plus AMSR and CloudSat (LWP, drizzle): aerosol-cloud –precip interactions
and many more …

Lidar vs. Cloud Profiling Radar

CloudSat radar profiles deep convective cloud and light precipitation

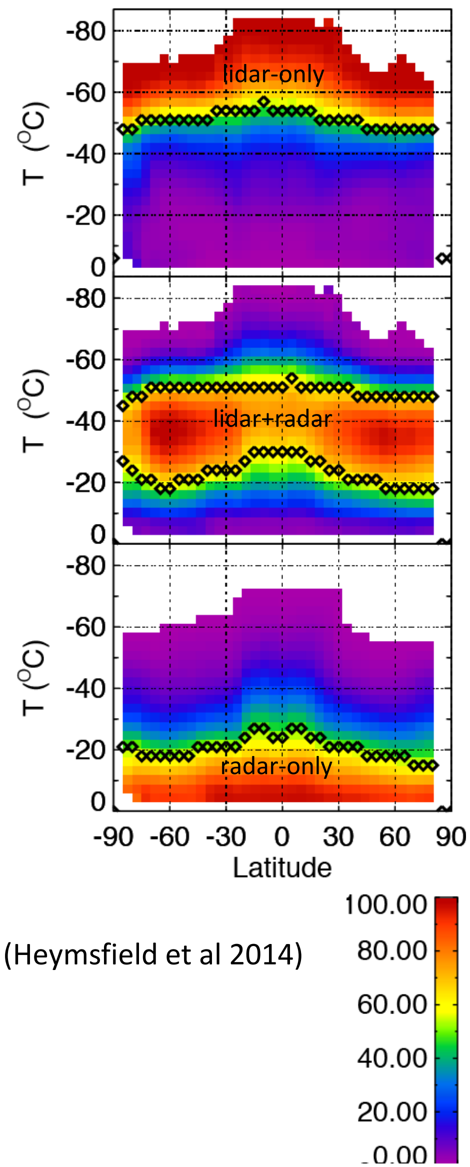
CloudSat observes drizzle under optically thick stratiform cloud





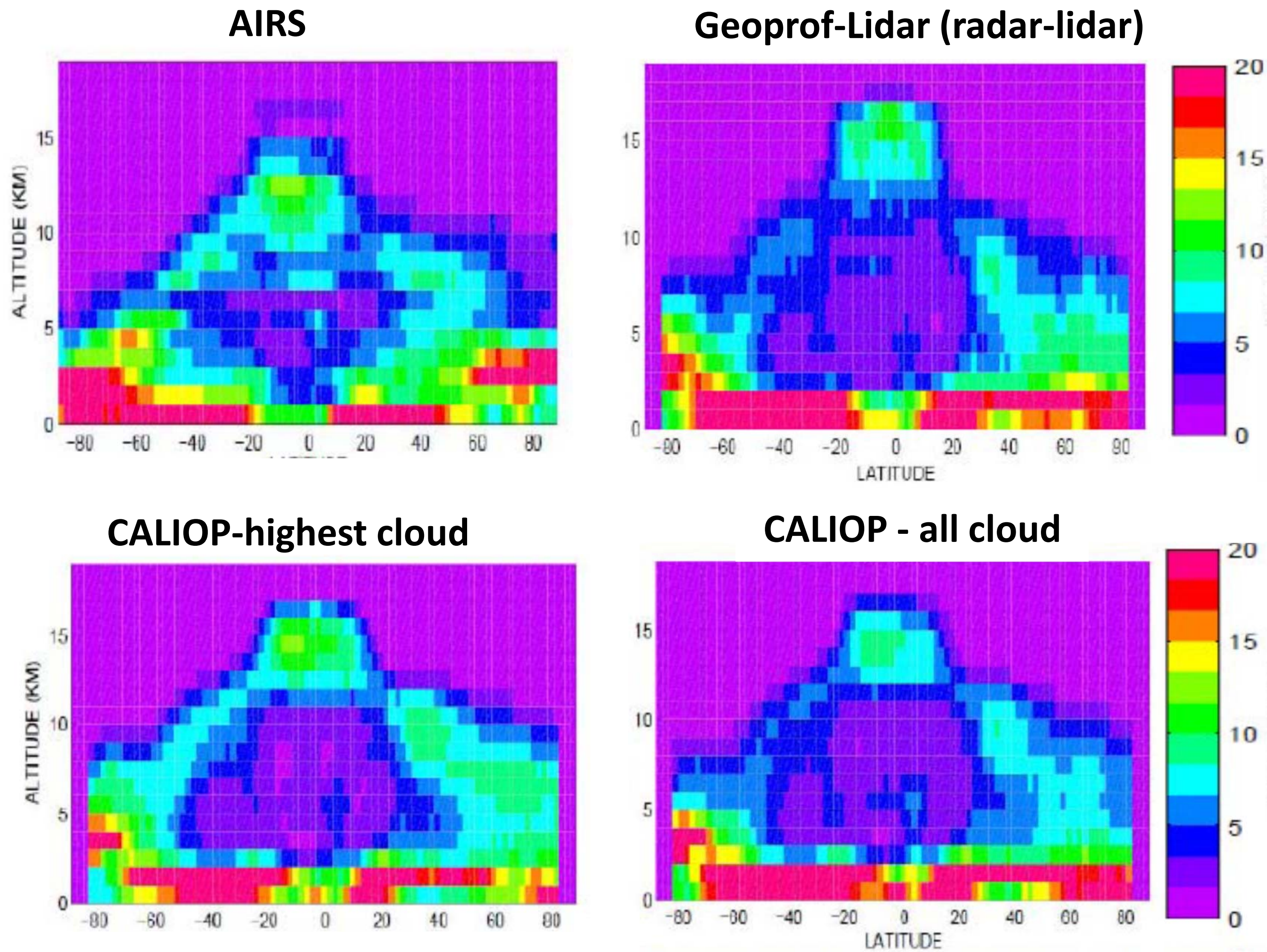
CALIPSO/CloudSat Observations over the Indian Ocean

Probability of cloud detection as a function of temperature



(Heymsfield et al 2014)

Zonally averaged cloud occurrence



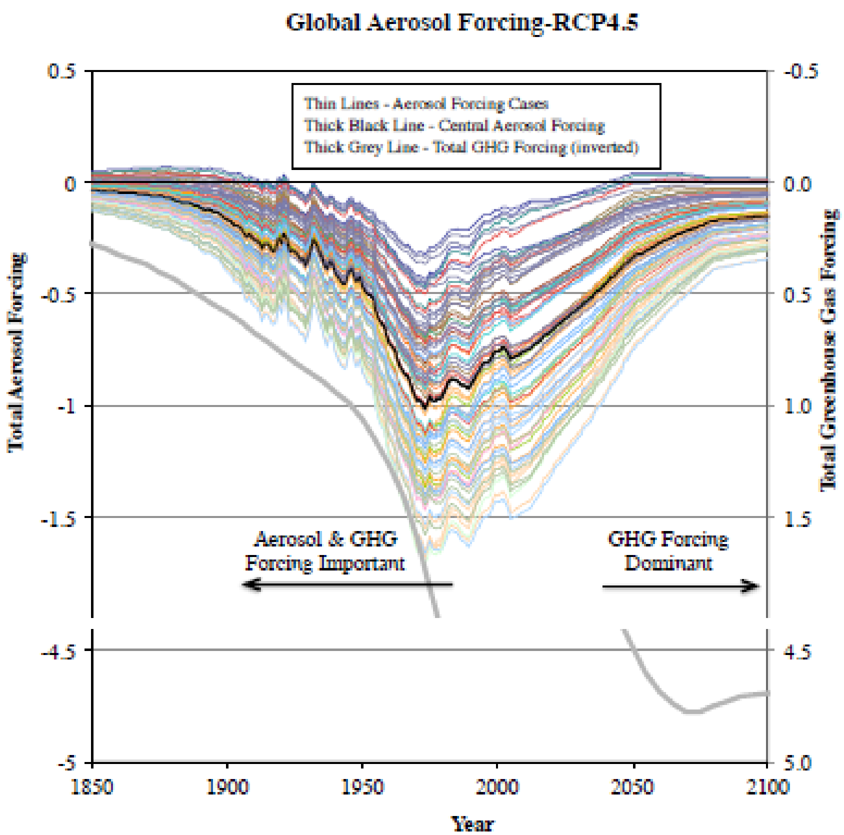
(Stubenrauch et al. 2010)

Way Forward / The Future

Synergies with new and future sensors:

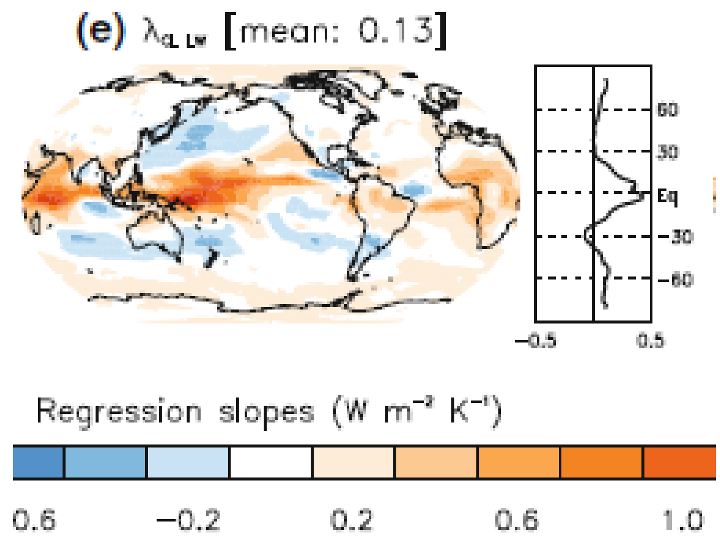
- **OCO-2 (July 2014)**
  - OCO-2 cloud-masking algorithm needs validation
  - Synergistic aerosol retrieval (simulated results) → co-location
- **CATS (Jan 2015) – (?)**
  - More limited than anticipated
- **SAGE-III (2016)**
  - A reference stratospheric product
  - Bridge SAGE-II, SAGE-III record
- **ADM/Aeolus (2017)**
  - CP validation of Aeolus aerosol and cloud products
- **EarthCARE (2018)**

A 'reverse' aerosol radiative effect is predicted through the rest of this century
 - need AOD retrievals stable on the order of 0.001/decade



(Smith and Bond. 2014)

Positive longwave cloud feedback is predicted due to rising cloud altitudes in a warming climate
 - requires cloud altitudes accurate to 10s of meters



(Zelinka and Hartmann, 2012)

What's a Climate Data Record?

Why do we want them?

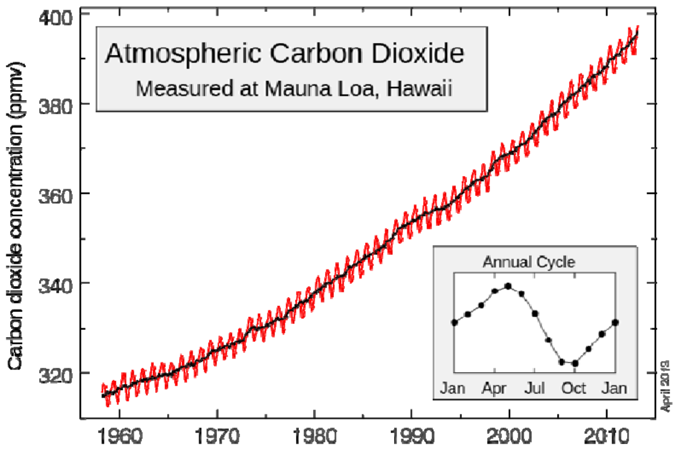
"A time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change"

(Nat'l Acad. Sci., 2004)

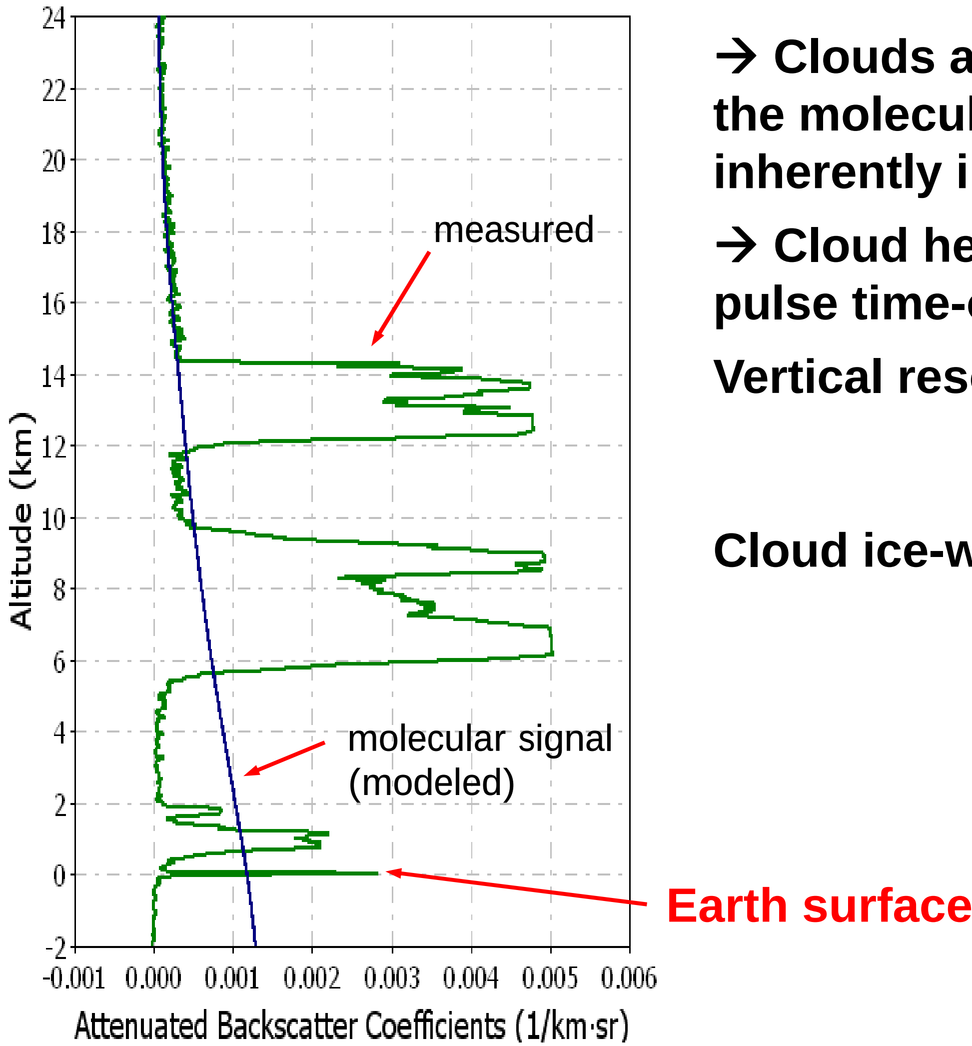
- **Length**
  - Climate timescales: multiple decades
- **Accuracy**
  - Uncertainties are less than the climate variability of interest
- **Stability**
  - Calibration, consistency between multiple satellites

- **8-years → climatology → Climate Data Record**
- **Definition (NRC 2004):**
  - "A Climate Data Record is defined as a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change."
  - Accuracy and stability are critical
- **Requirements**
  - "CDRs require continuing calibration, validation, and algorithm refinements, all leading to periodic reprocessing and reanalysis to improve error quantification and reduce uncertainties"

Recall 2014 ...



Measurement vs Retrieval



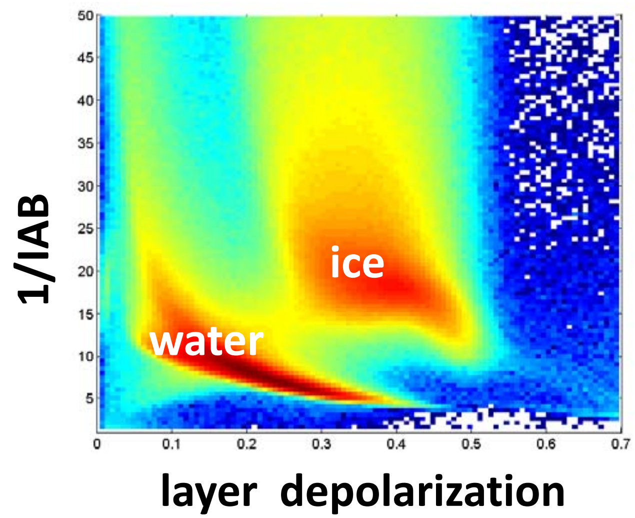
Lidar measurements of cloud height:

→ Clouds are detected via contrast with the molecular background, thus inherently insensitive to calibration error

→ Cloud height measured directly from pulse time-of-flight

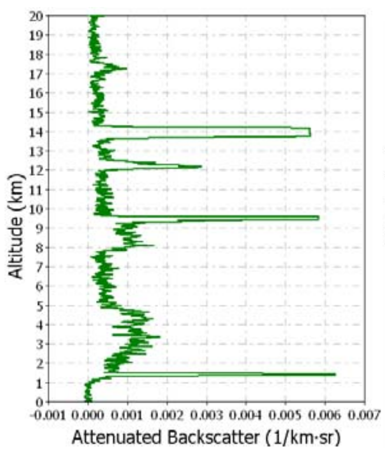
Vertical resolution: 30 m (radar: 500 m)

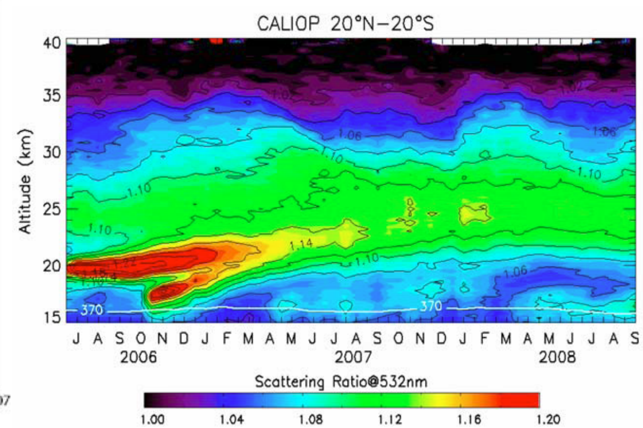
Cloud ice-water phase from lidar profiles:

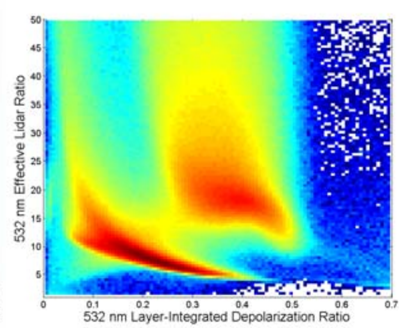


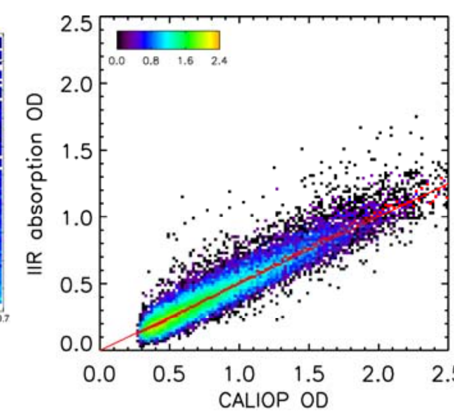
CDRs from CALIPSO

- **What CALIPSO products are suitable for CDRs?**
  - Accuracy to detect trends without time-overlap of satellite missions
  - Direct measurements vs. retrievals
- **With improved Version 4 calibration, Level 1 profile data:**
  - Stratospheric aerosol
  - Level 1.5 (figure from Jason): MERRAero, PCMDI, aerosol simulator (COSP fig)
- **Level 2 CDRs**
  - Cloud height, ice-water phase, cirrus optical depth (CALIOP+IIR)







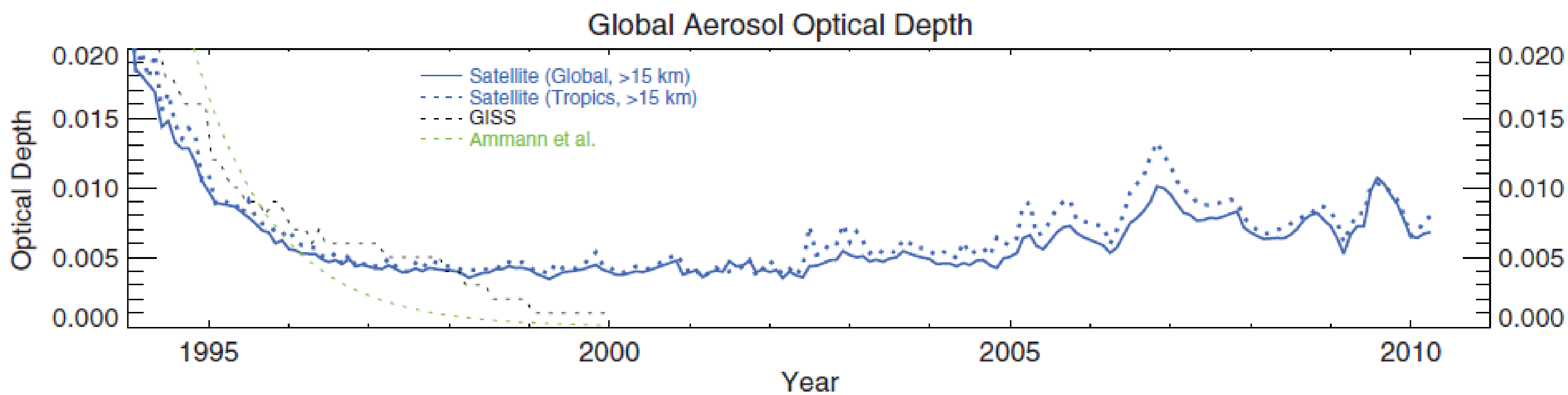


The Persistently Variable "Background" Stratospheric Aerosol Layer and Global Climate Change

S. Solomon,[1,2*] J. S. Daniel,[1] R. R. Neely III,[1,2,5,6] J.-P. Vernier,[3,4] E. G. Dutton,[5] L. W. Thomason[3]

Science **333**, 866 (2011);

Stratospheric normalization:
long-term calibration stability



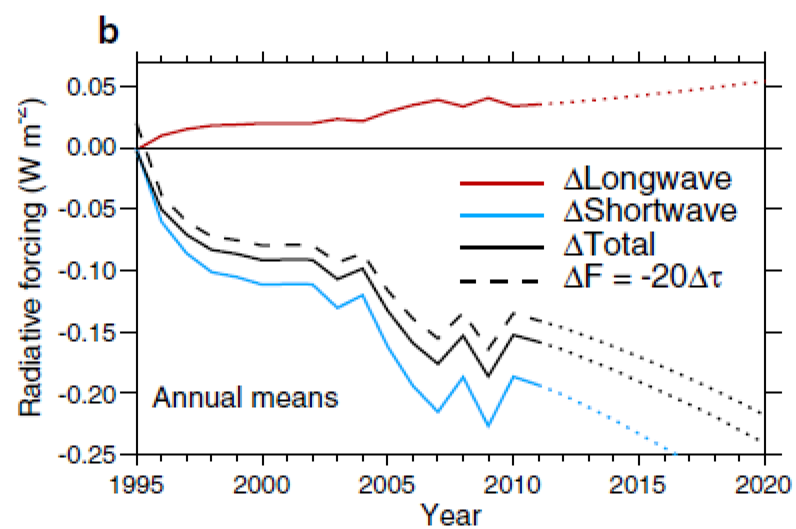
SAGE

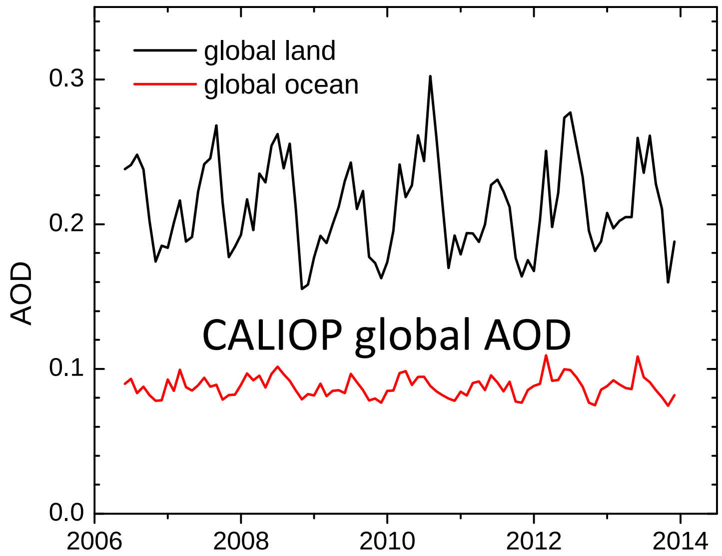
CALIOP

GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 584–588, doi:10.1002/grl.50156, 2013

Surface response to stratospheric aerosol changes in a coupled atmosphere–ocean model

J. C. Fyfe,[1] K. von Salzen,[1] J. N. S. Cole,[1] N. P. Gillett,[1] and J.-P. Vernier[2,3]





Our longest global AOD record: AVHRR

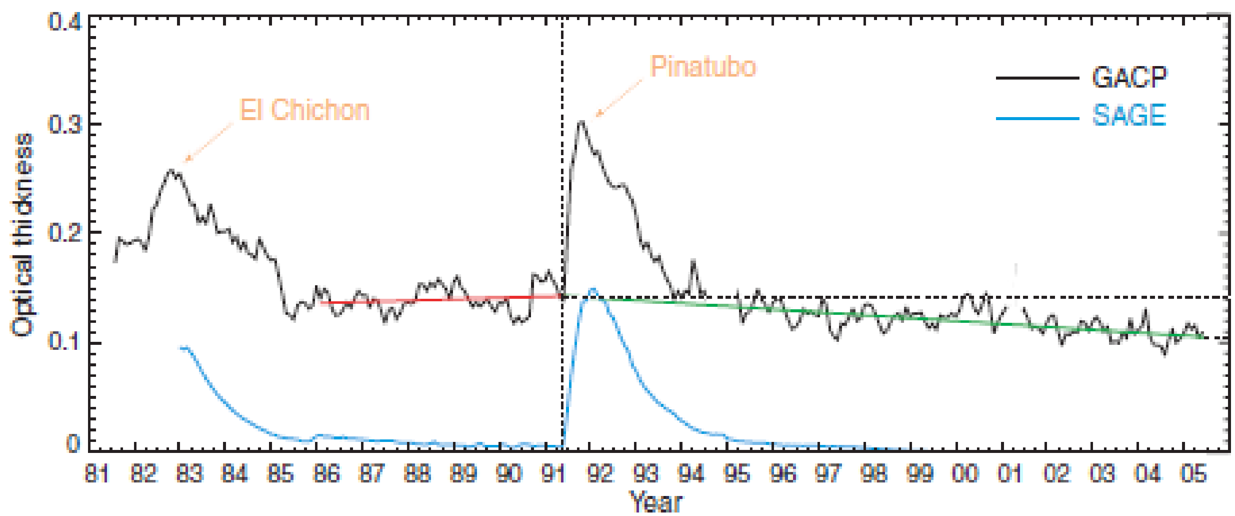


Fig. 1. GACP record of the globally averaged column AOT over the oceans and SAGE record of the globally averaged stratospheric AOT.

Mishchenko et al., Science (2007)

Ch 8 - Anthropogenic and Natural Radiative Forcing

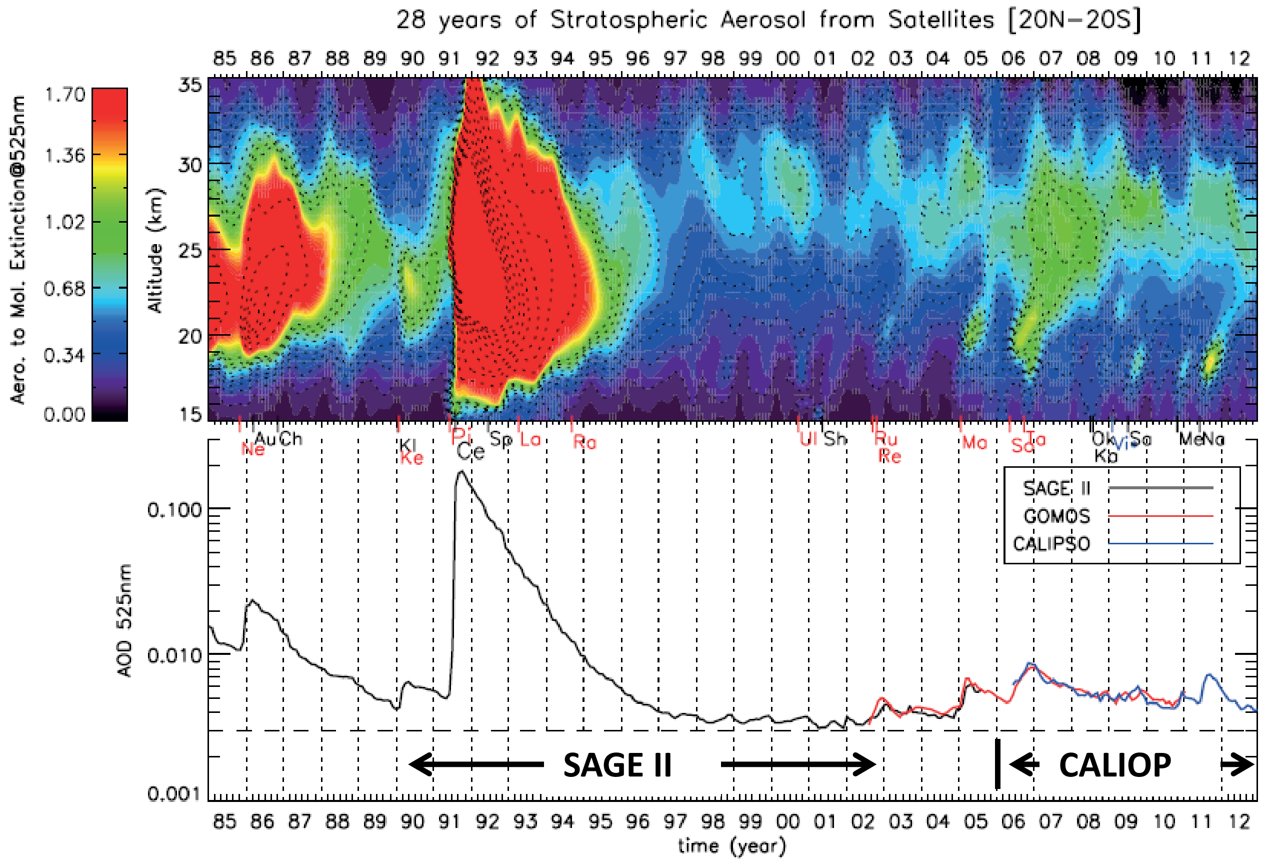


Figure 8.13 (Top) Evolution of extinction ratio profile in the tropics from SAGE II (1985-2005) and CALIPSO (2006–2012)

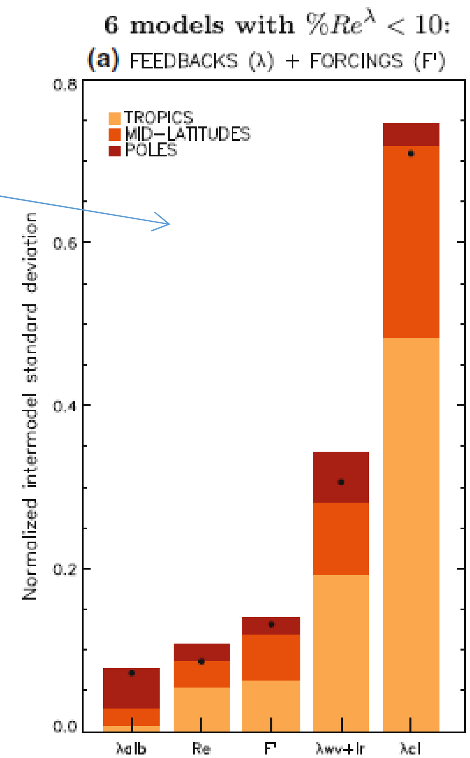
AR5, Ch. 8 (see also Santer et al.)

"The radiative forcing of volcanic aerosols is well understood … There have been no major volcanic eruptions since Mount Pinatubo in 1991, but several smaller eruptions have caused an average radiative forcing for 2008–2011 of –0.11 W m^{-2} compared to 1750." (Solomon et al., Science, 2011)

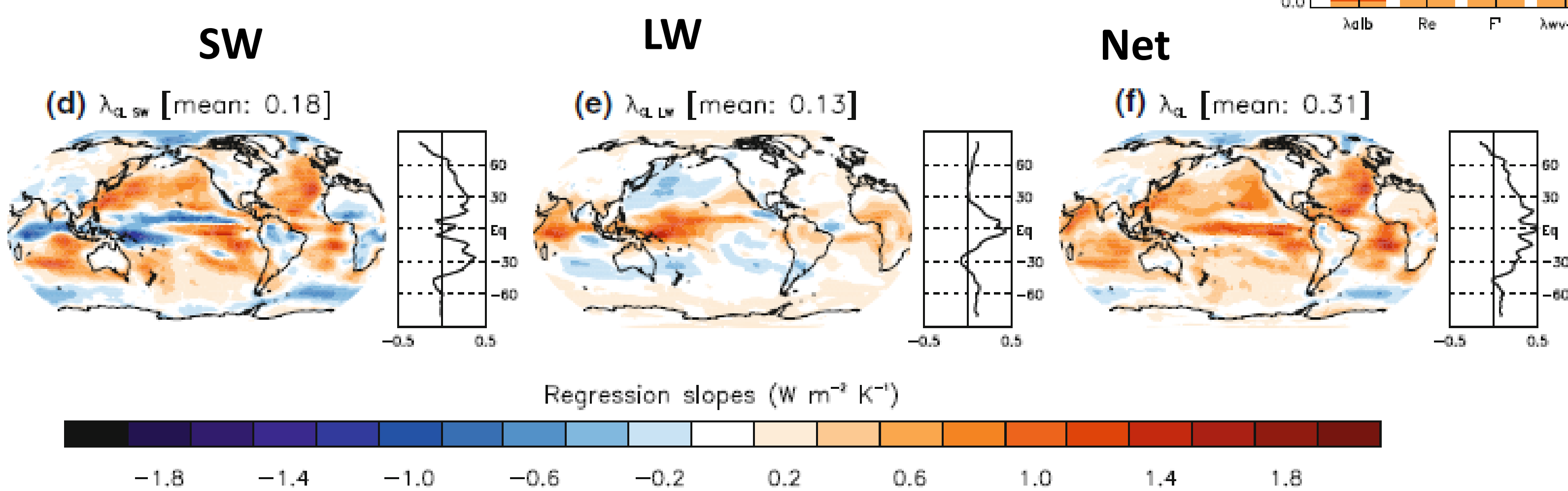
For some time now, models have consistently shown:

1) clouds are the dominate source of feedback uncertainties

2) shallow marine clouds are the dominant source of cloud feedback uncertainties



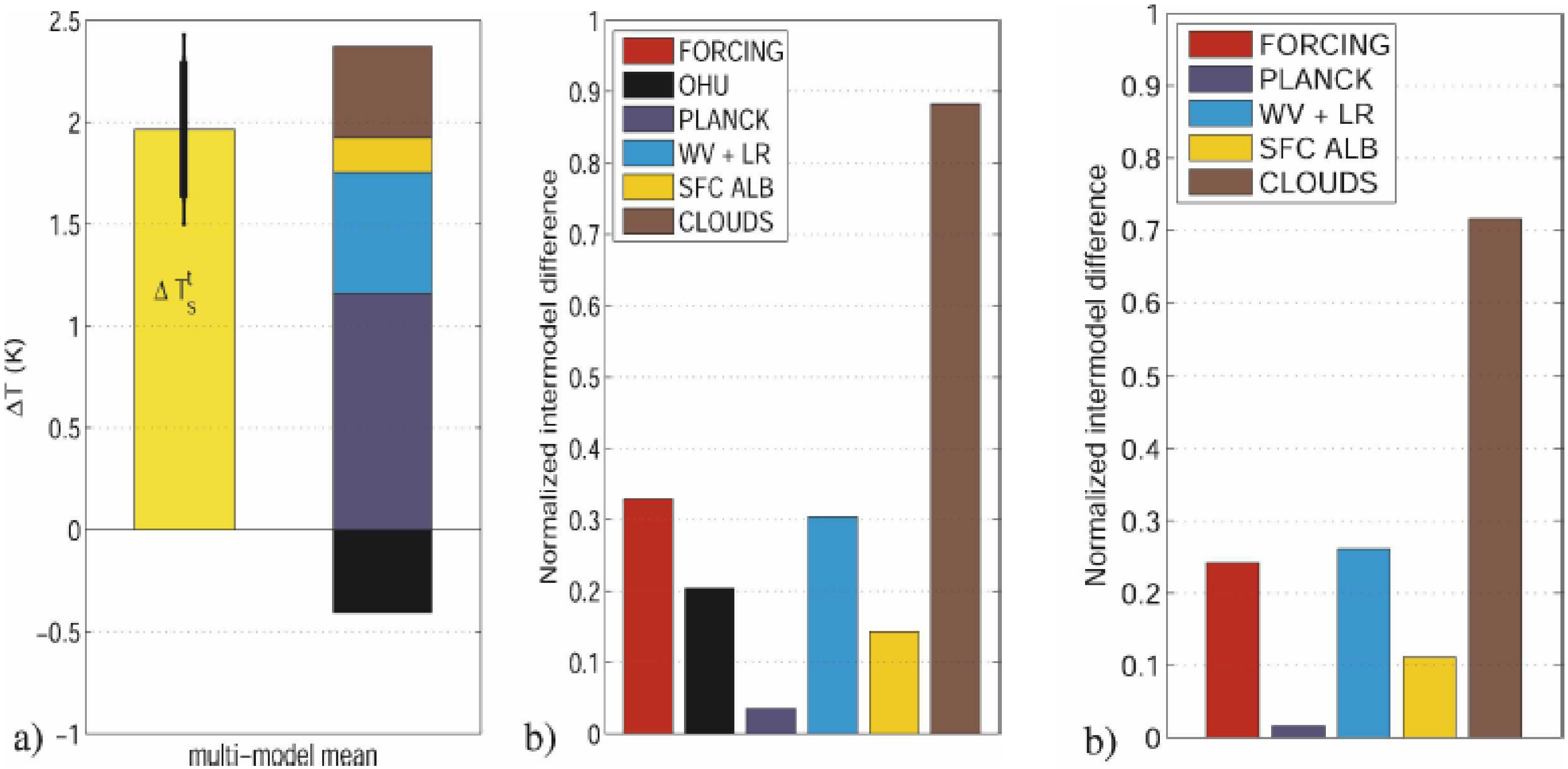
Vial, Dufresne, and Bony (Clim Dyn, 2013)



Cloud feedbacks are the dominant source of uncertainty in climate sensitivity

transient response

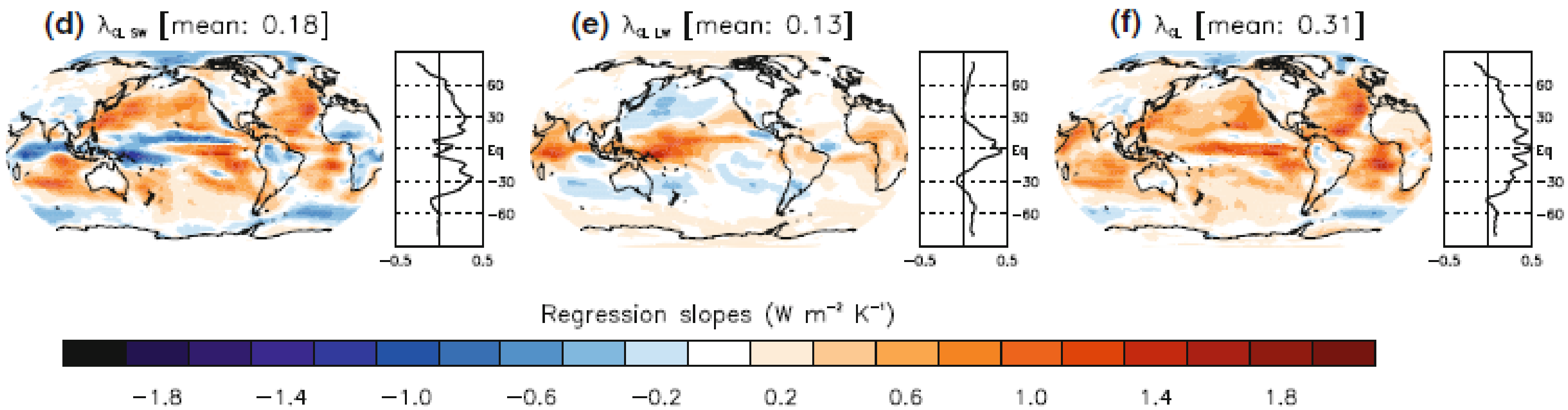
equilibrium response



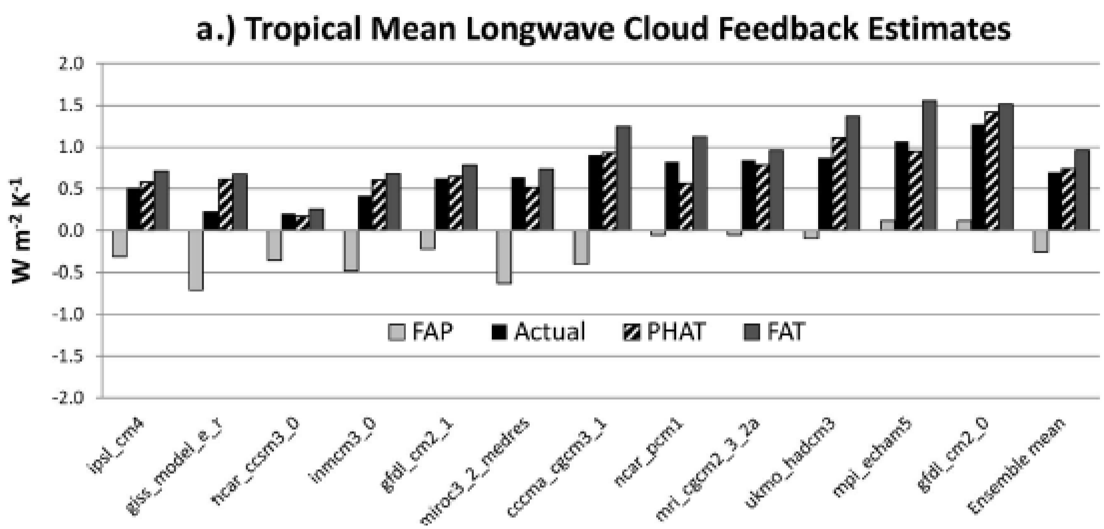
(Dufresne and Bony, 2008)

Regional pattern of SW, LW cloud feedbacks

SW **LW** **Net**



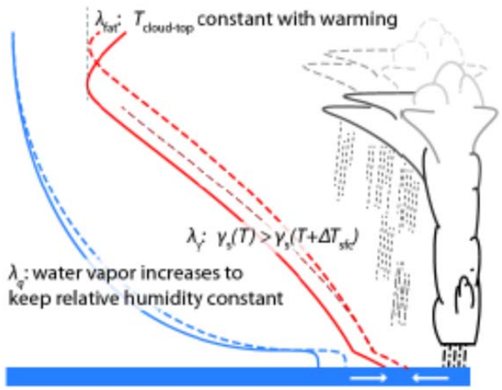
Vial, Dufresne, and Bony (Clim Dyn, 2013)



Zelinka and Hartmann (JGR, 2010)

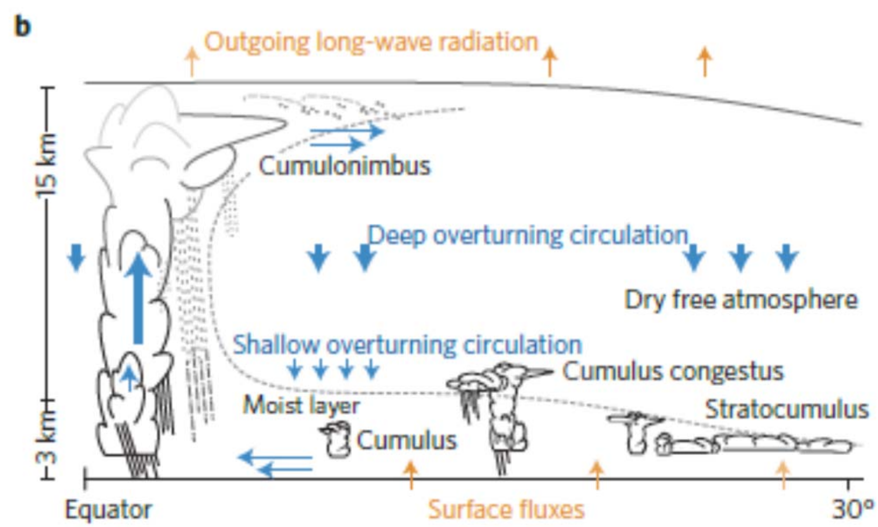
Mechanisms of Cloud Feedback

Deep Convection



(courtesy Sandrine Bony, LMD)

Shallow Convection

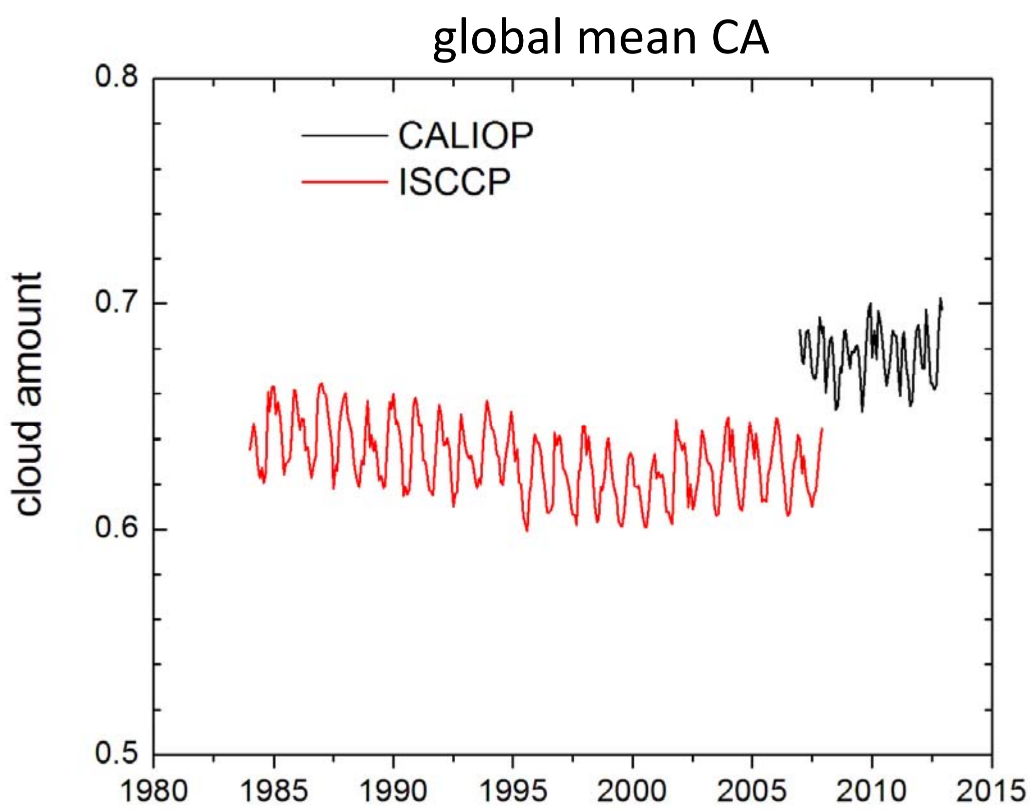


(Boney et al, Nat Geo, 2015)

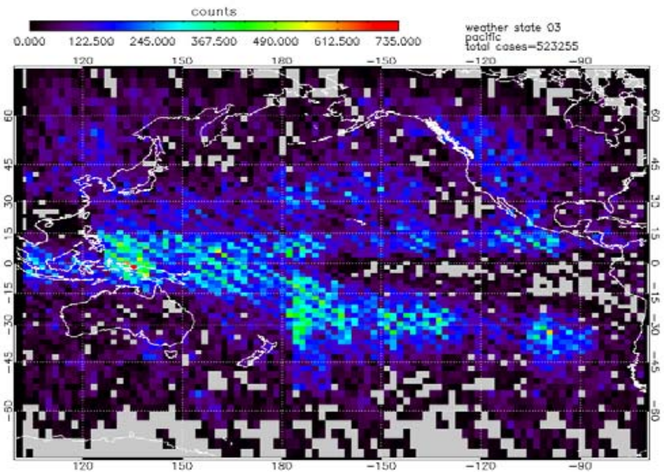
Climate models are very sensitive to how shallow convective clouds are coupled to the larger-scale circulation, and to the vertical distribution of water vapor, surface turbulent fluxes and atmospheric radiation. This coupling links regions of shallow convective clouds with remote areas of deep convection

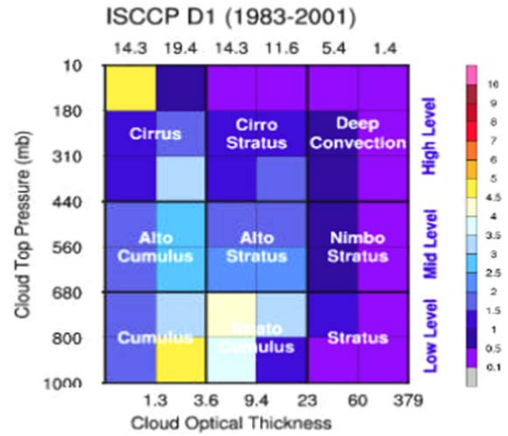
Long-term records: from multiple satellites

Lacking a planned climate observing system, we must deal with differences in techniques, instruments, and algorithms

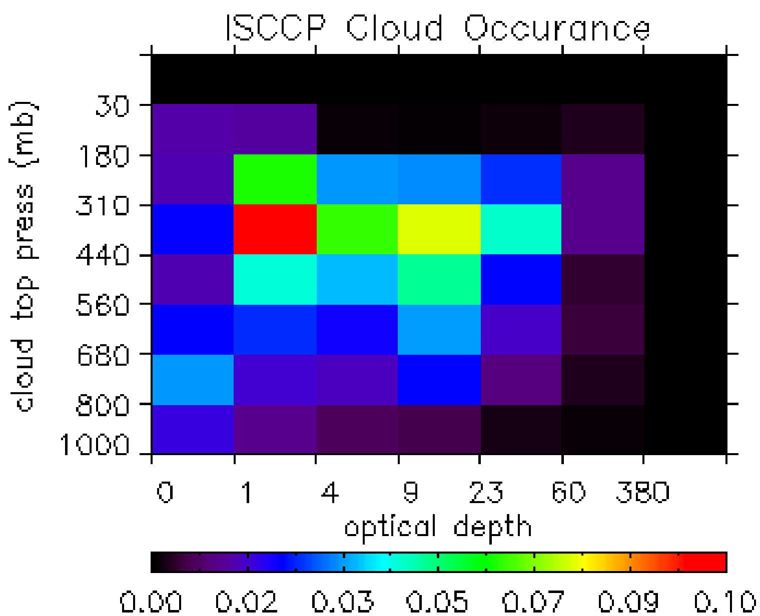


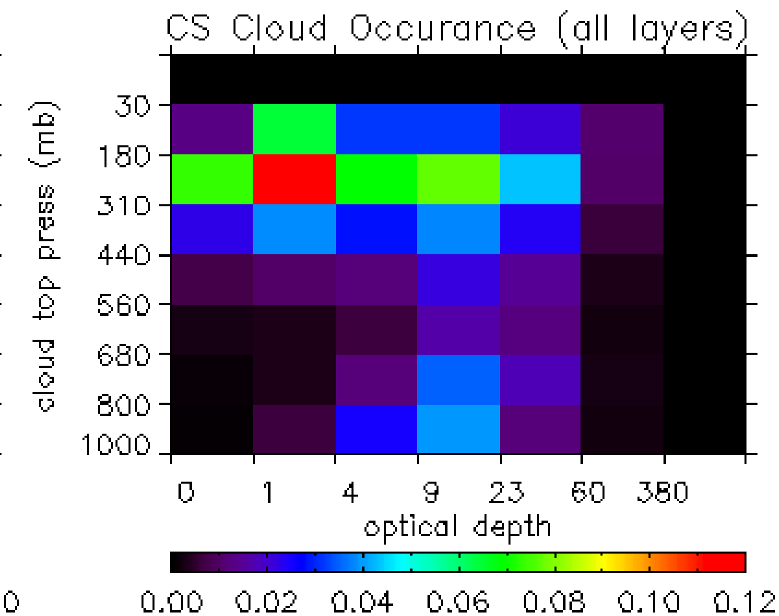
Weather State-3: Anvils and Isolated Convection





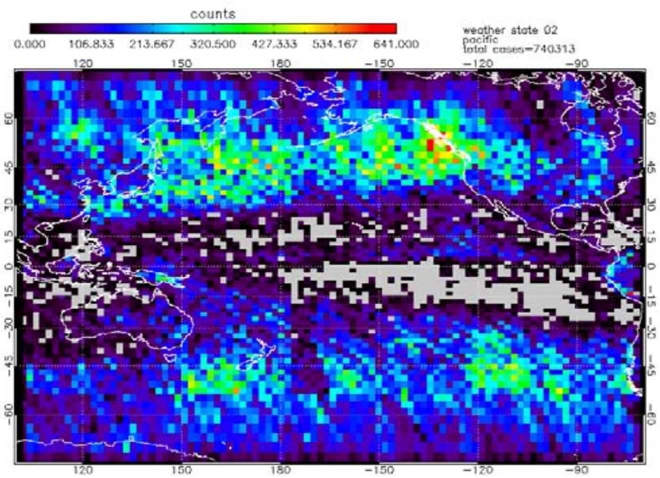
ISCCP's 'pc-τ' diagram





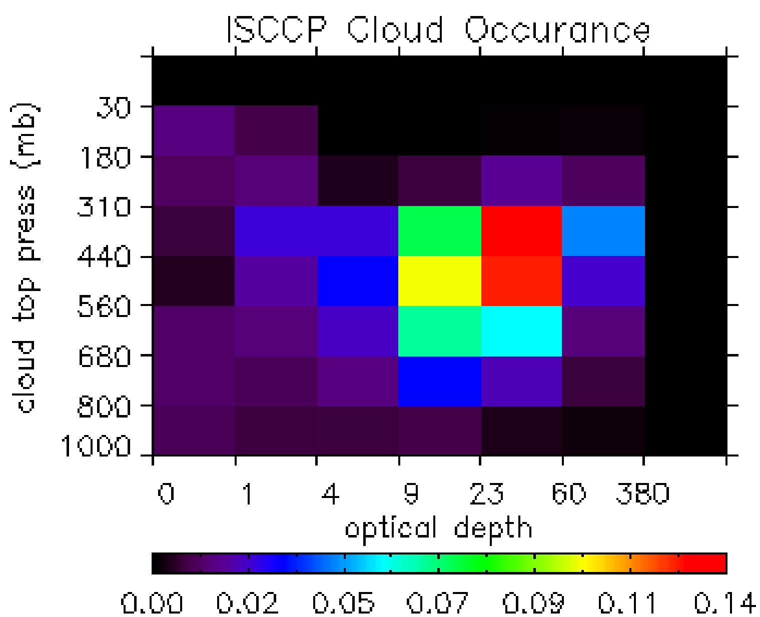
(courtesy, Jay Mace)

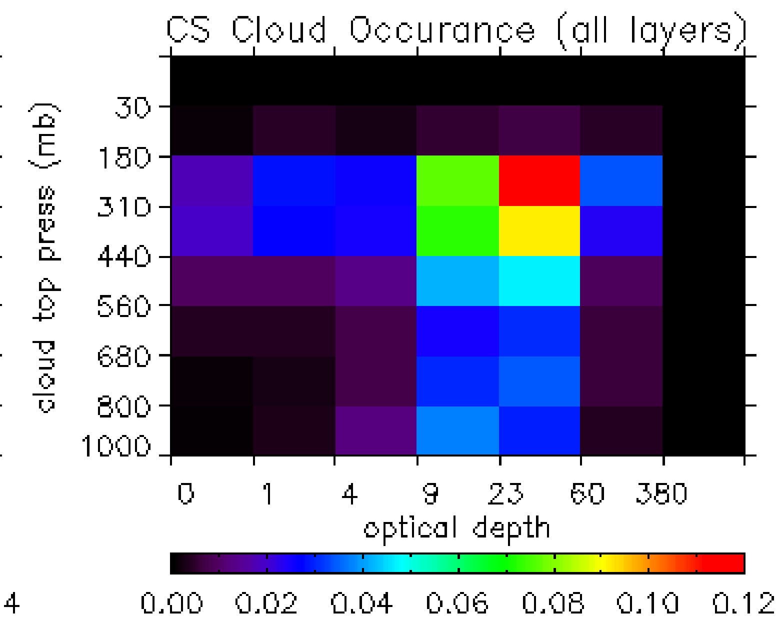
Weather State-2: Mid-latitude Storms



from ISCCP, only a fuzzy picture of cloud vertical structure:

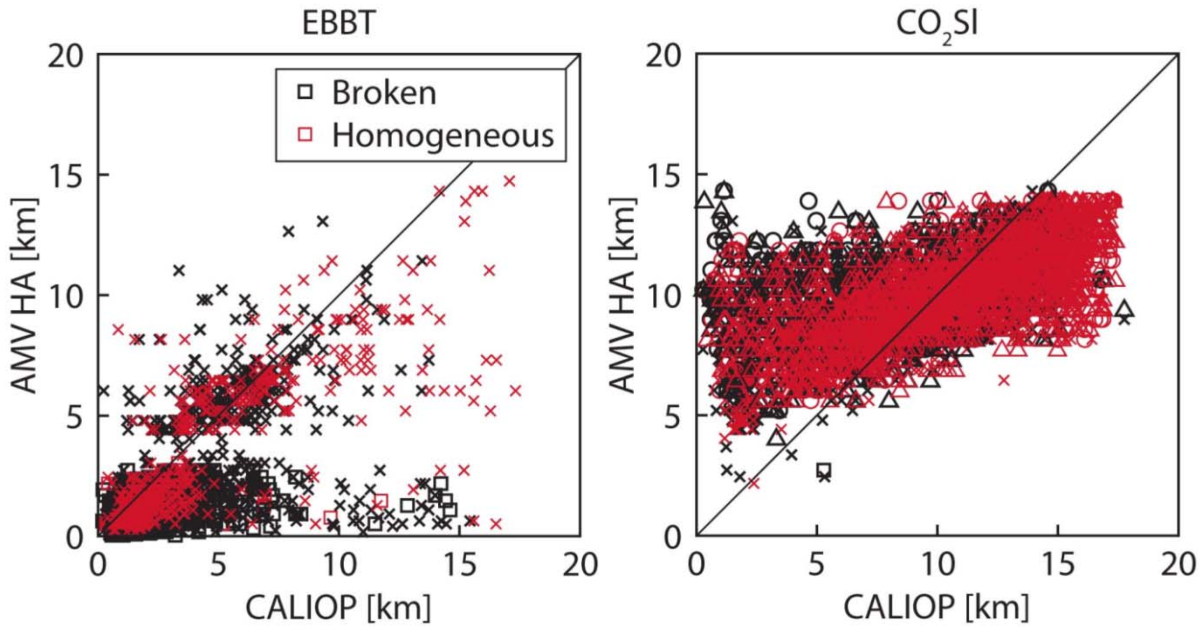
- too many clouds at mid-levels
- high and low clouds under-represented





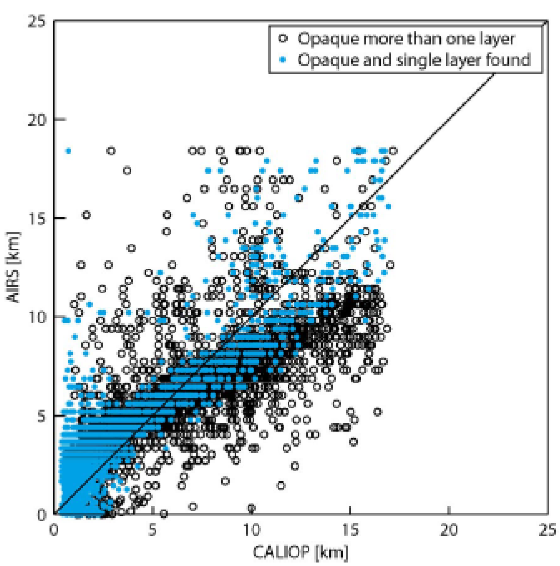
(courtesy, Jay Mace)

Cloud Height Assignments for AMVs



SEVIRI HA vs. CALIOP homogeneous vs. broken

← Two of four HA methods:
Equiv. Black Body Temp
CO2 slicing



AIRS cloud heights vs. CALIOP opaque single-layer vs. multi-layer

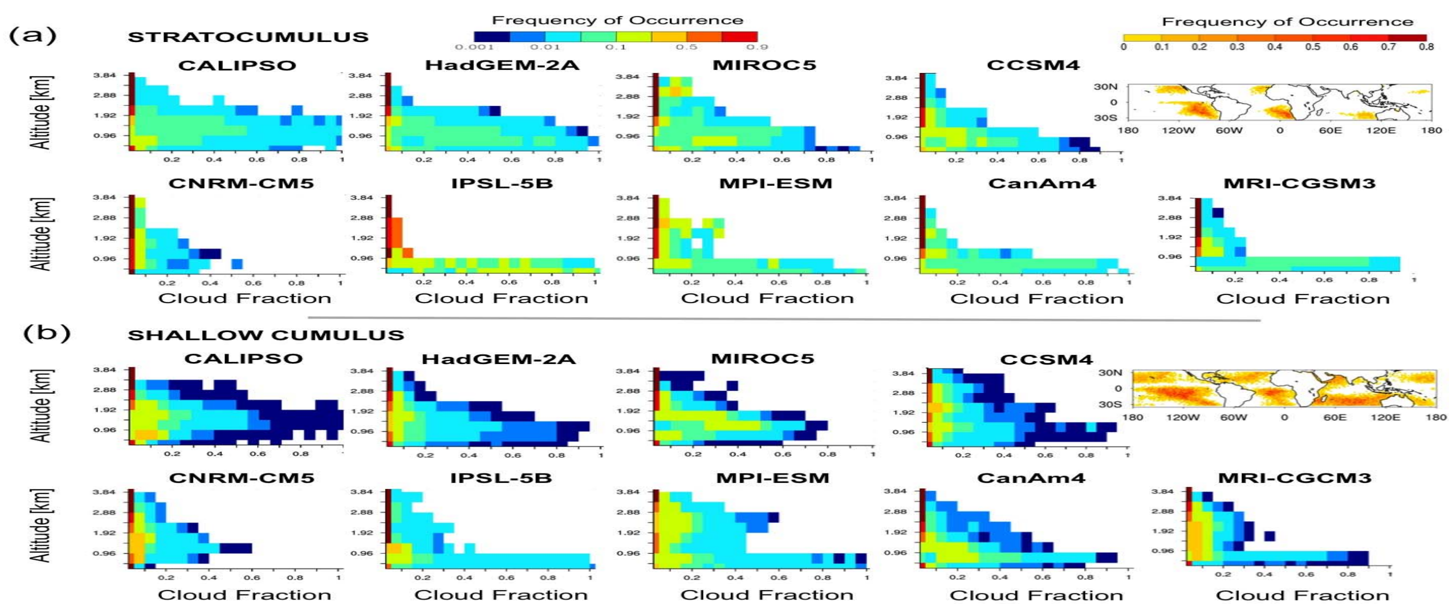
And MODIS validation ...?

(Di Michele et al., 2012)

AR5, Ch 9: Evaluation of Climate Models

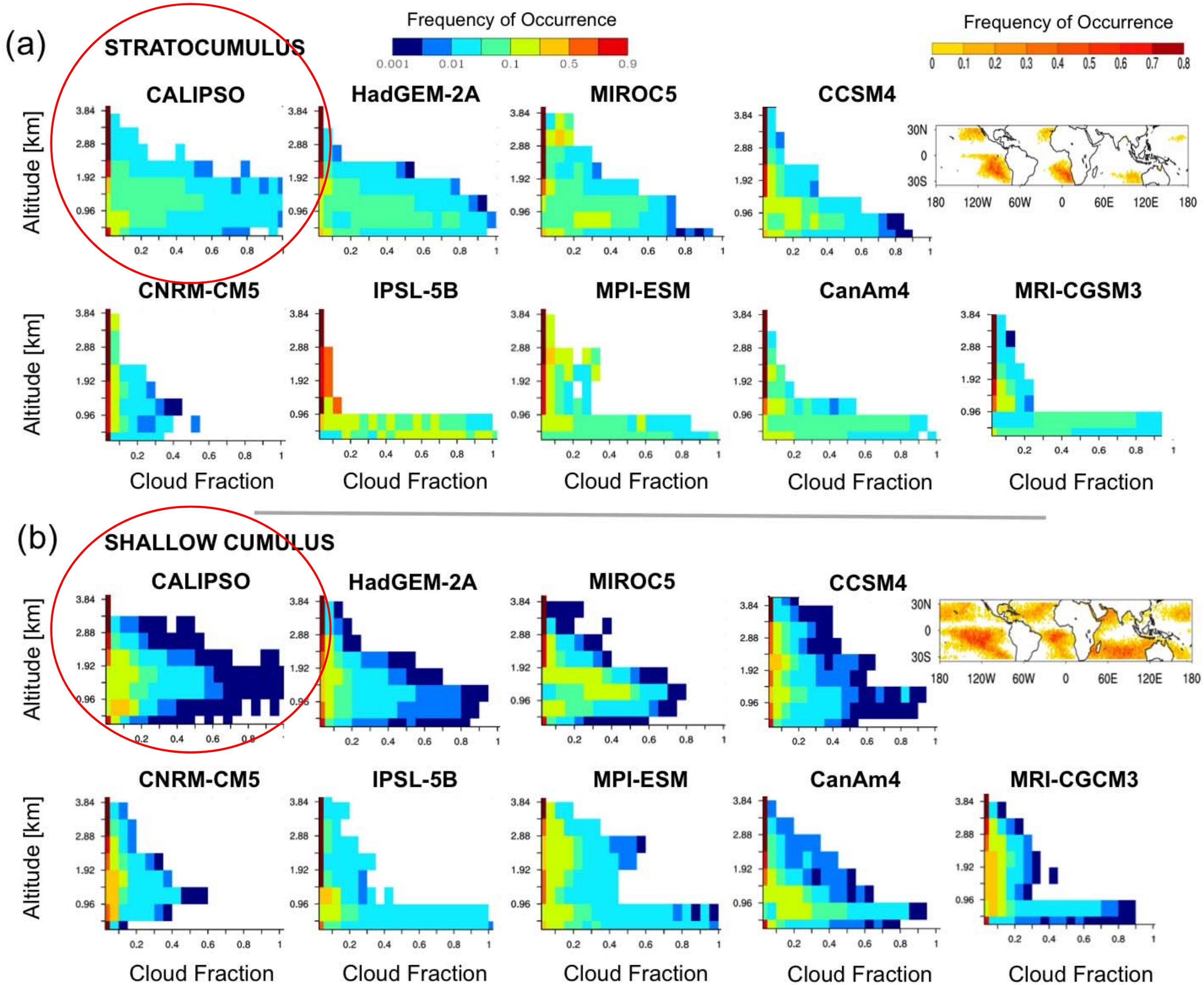
"The application of new observations, such as vertically resolved cloud information from satellites … has enhanced the ability to evaluate processes in climate models … Major progress in this area has resulted from both the availability of new observational data sets and improved diagnostic techniques, including the increased use of instrument simulators."

Models show large regional biases in shortwave cloud radiative effects, and these are particularly pronounced in the subtropics …



(Nam et al. 2012)

New tool for evaluation of shallow clouds in GCMs

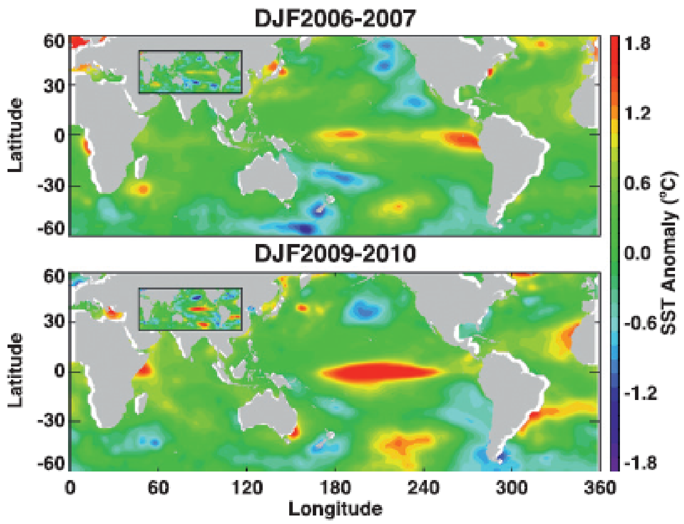


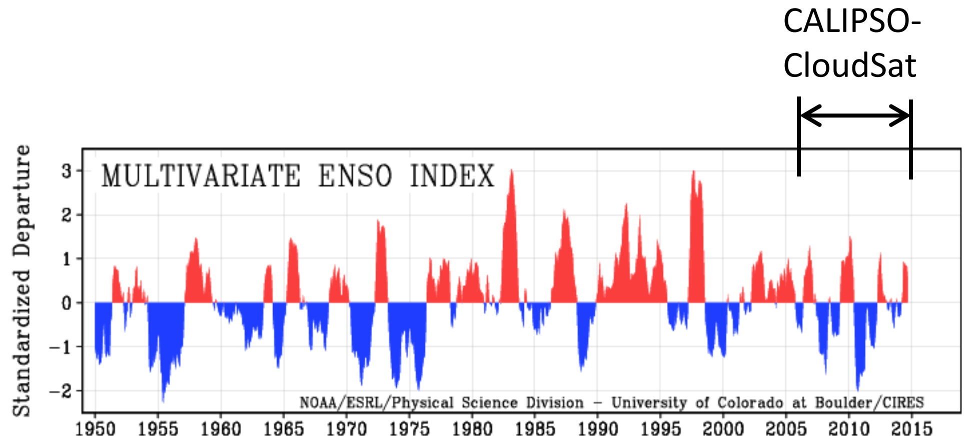
(Nam et al. 2012)

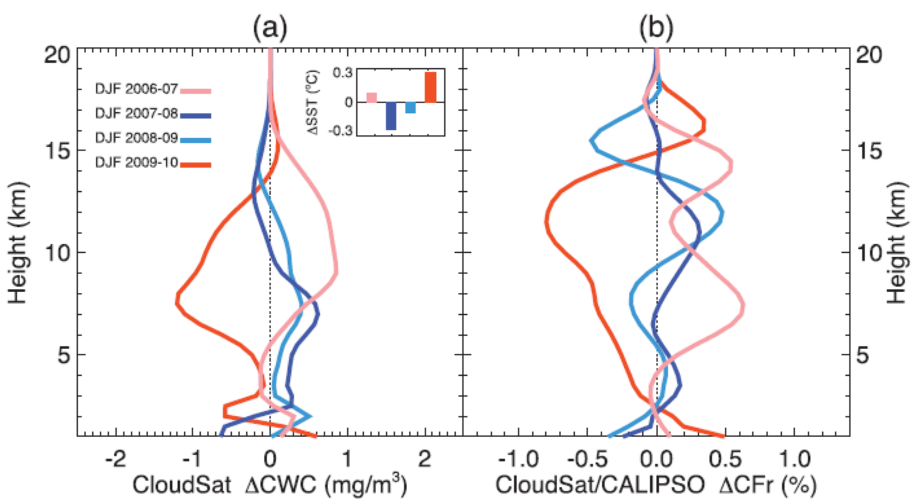
Cloud coupling to large-scale circulations

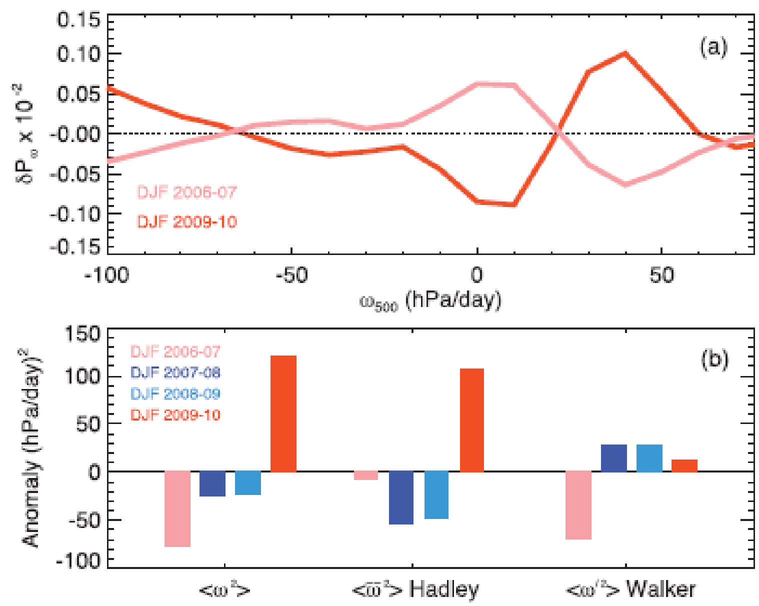
CP-El Nino 2009-10 DJF

EP-El Nino 2006-07 DJF



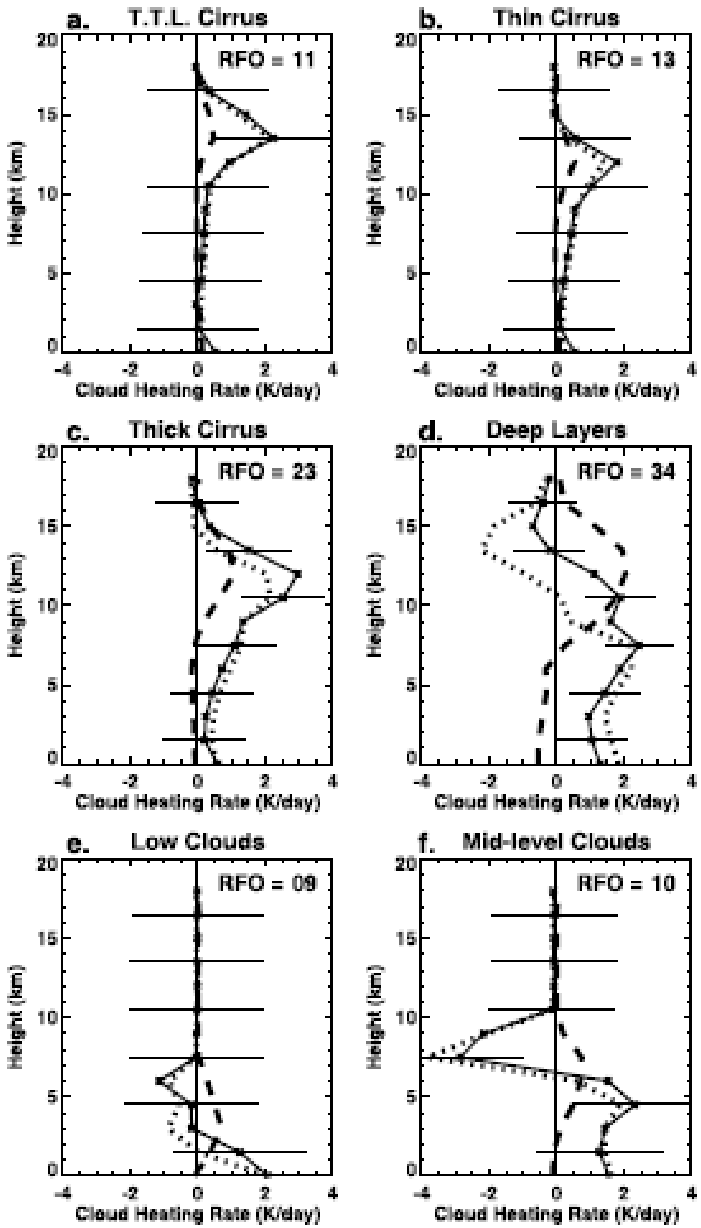






Su and Jiang (JGR, 2012)

Heating Profiles by Cloud Type



Mean cloud heating profiles:

- solar (dashed)
- thermal (dotted)
- net (solid)

Berry and Mace (2014)

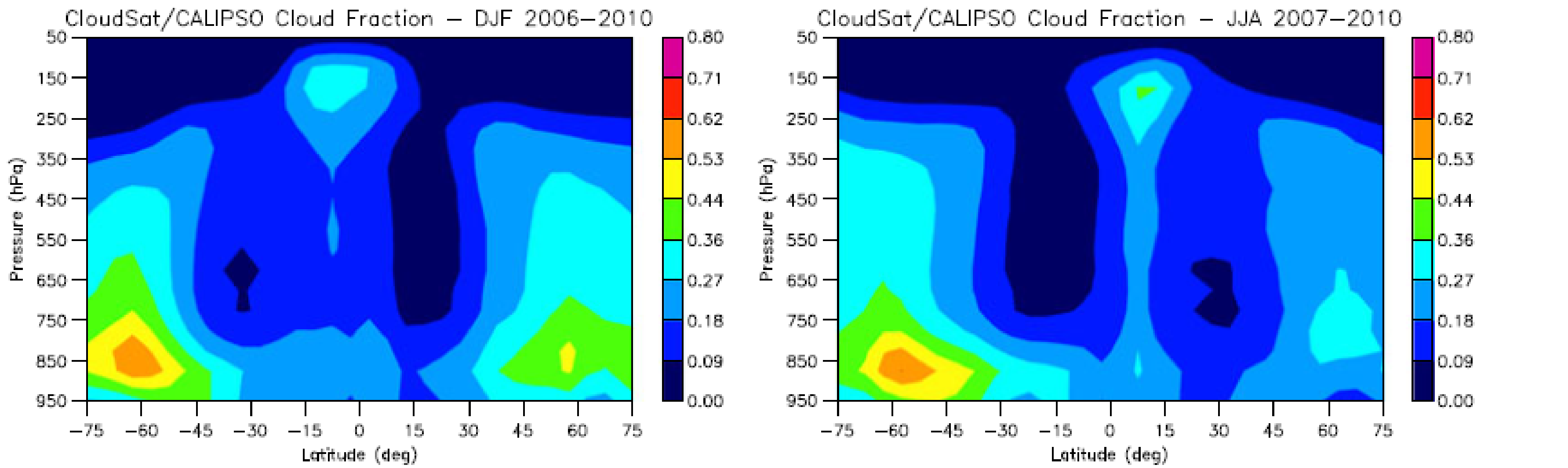
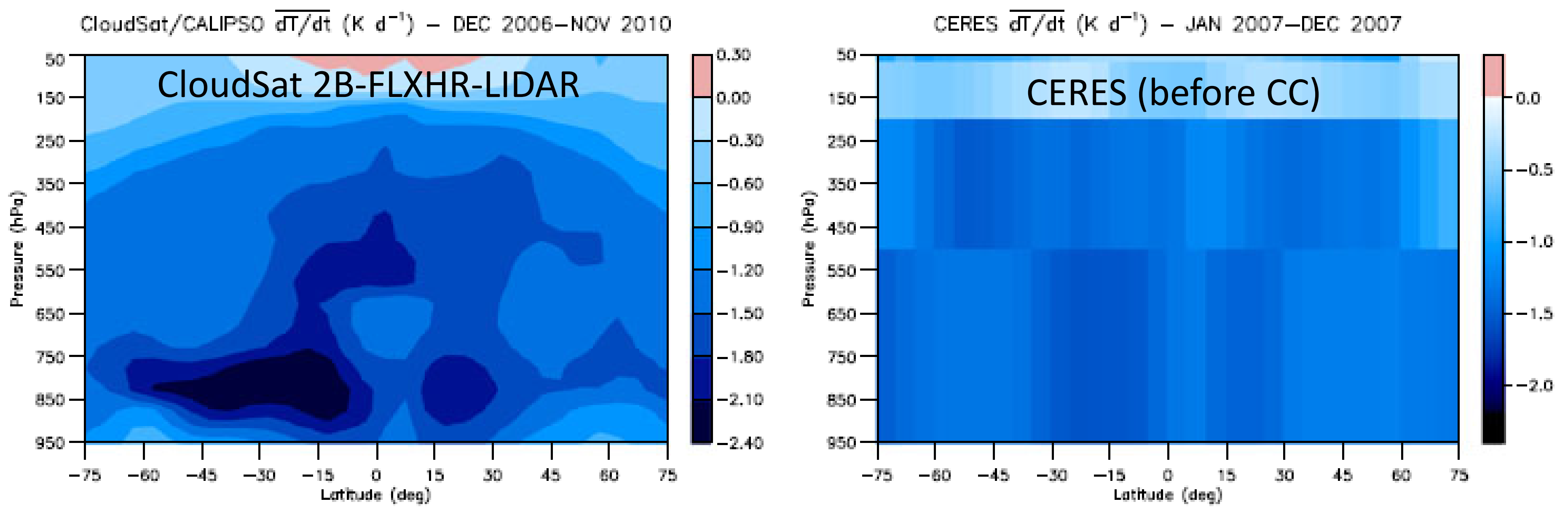


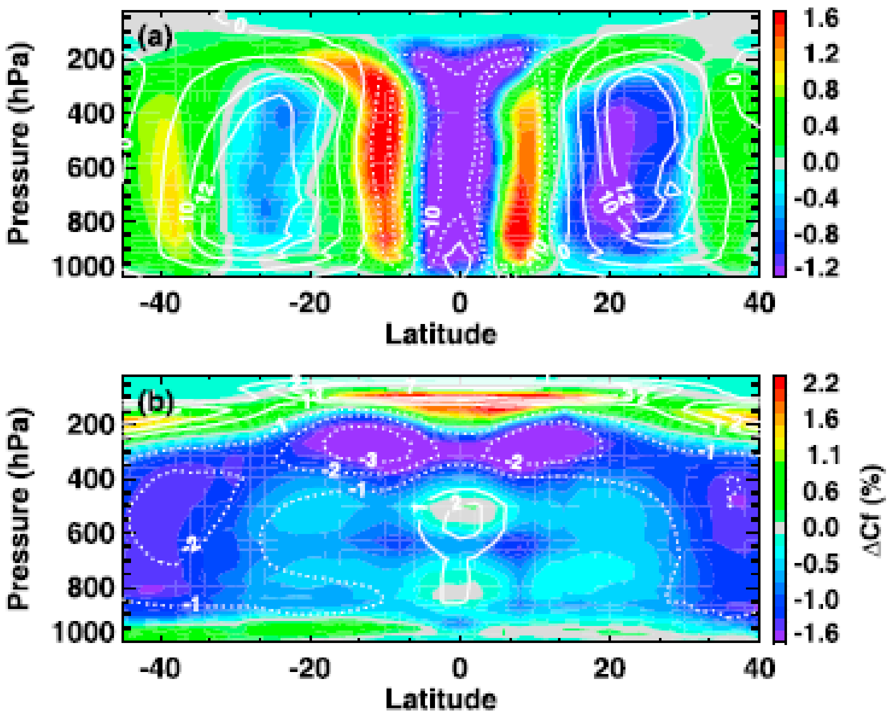
Figure 2. Cloud fraction for DJF 2006–2010 (left) and JJA 2007–2010 (right).

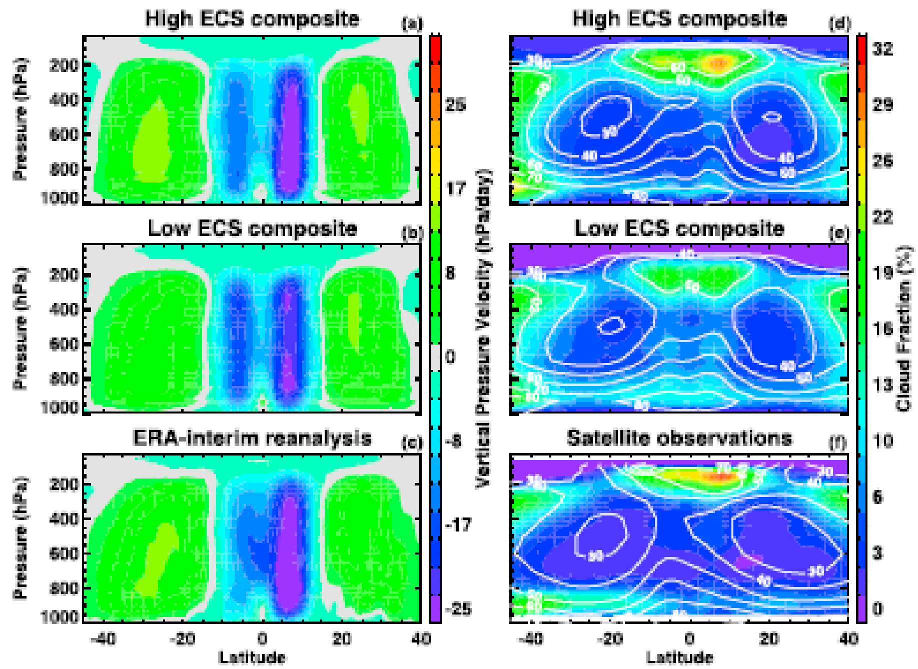


(Haynes et al., 2013)

Clouds and Moisture as Proxies for Circulation?

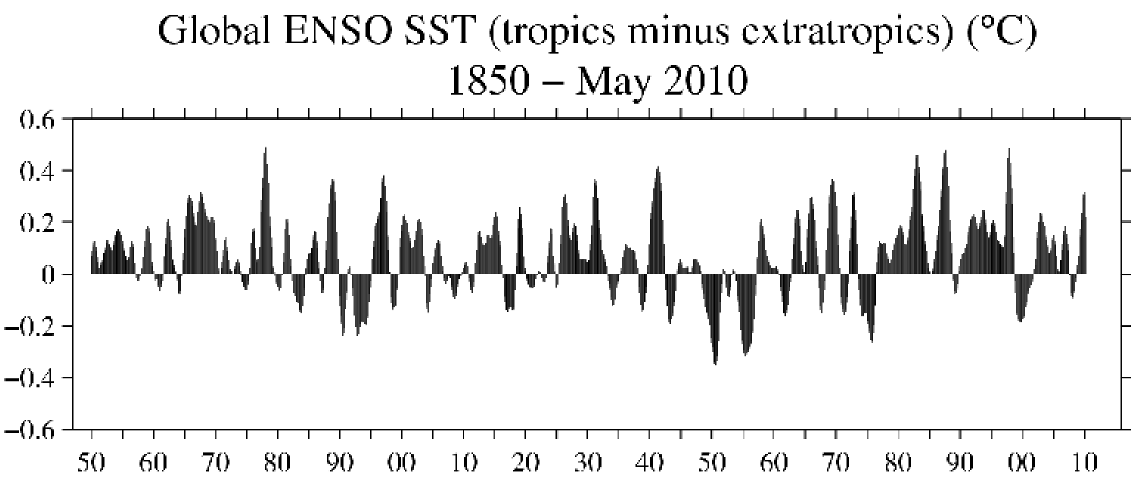
Predicted changes in vertical motion, cloud occurrence over the 21st century (RCP 4.5)



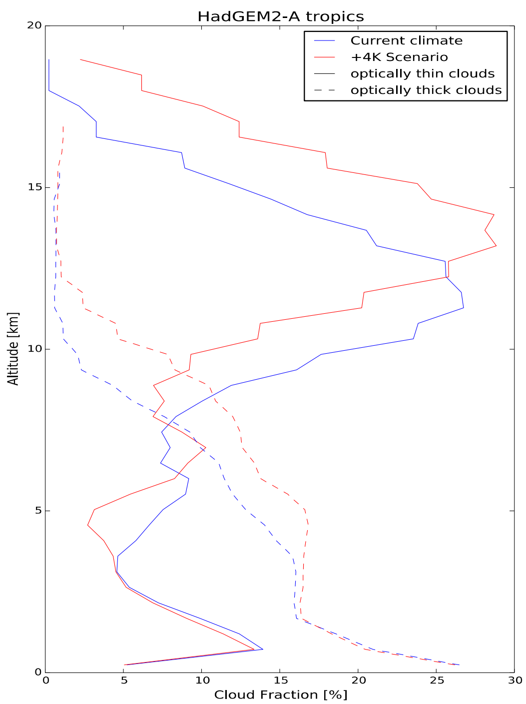


Vertical cloud structures in high-sensitivity models more similar to observations

(*Hui Su et al. JGR, 2014)*



Mean 20N–20S minus 20–90N, 20–90S. 1950–79 climatology.
Anomalies filtered with 11– and 9–month running means, and the endpoint (June 2010 through February 2011) removed.

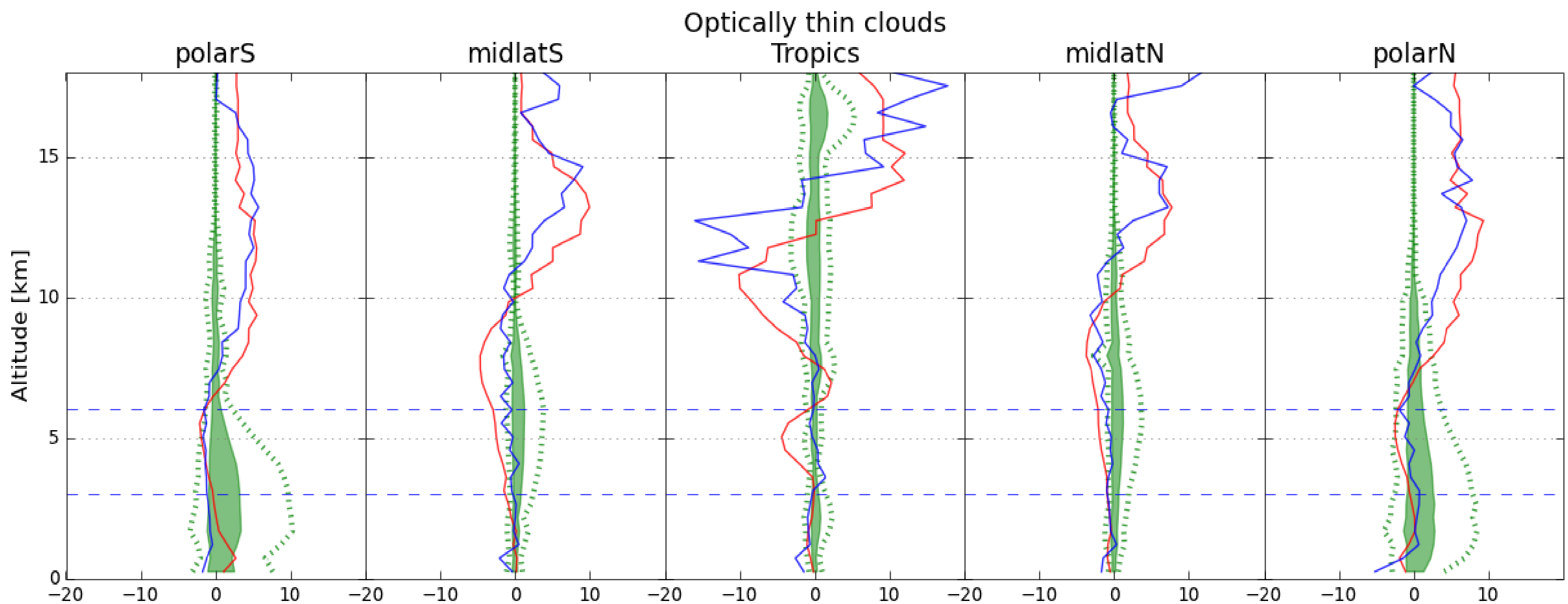


(Chepfer et al., GRL, 2014)

Synthetic lidar-like cloud fraction profiles for optically thin and thick clouds, based on output from the HadGEM2-A model+COSP/lidar for the current climate and the +4K scenario in the Tropics (30°S-30°N). When comparing profiles for the current climate and for the +4K scenario, the shape of the profile is retained but a given fraction is shifted about 1km higher in the future climate for all altitudes above 3km.

LW cloud feedbacks: rising cloud height with warming, driven by conservation of mass and energy (Larson and Hartmann, 2002)

From application of "CALIPSO simulator" to +4K climate simulations: Observable signatures of cloud feedback show up in vertically resolved cloud profiles



Green: observed variability (2006-2012) from CALIPSO-GOCCP
Red/blue: Synthetic lidar cloud fraction profiles for optically thin clouds (+4K scenario)
(HadGEM2 and CanAM4 using CALIPSO simulator)

(Chepfer et al., GRL, 2015)

Final Thoughts

- **CALIPSO and CloudSat have opened a new era of satellite active remote sensing**
- **Active measurements shown to be critical for:**
  - Observing vertical cloud structures
  - Characterizing cloud-aerosol-precipitation processes
  - Revealing the linkages between clouds and circulation
- **Long term measurements are required to:**
  - Study the mechanisms which couple clouds and circulation
  - Characterize key modes of climate (natural) variability and the response of clouds to GHG forcing
  - Identify, understand, and characterize cloud-climate feedbacks
- **Active measurements of cloud-aerosol-precipitation are an essential part of a global climate observing system**