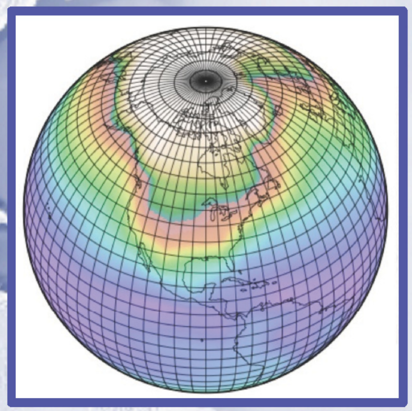
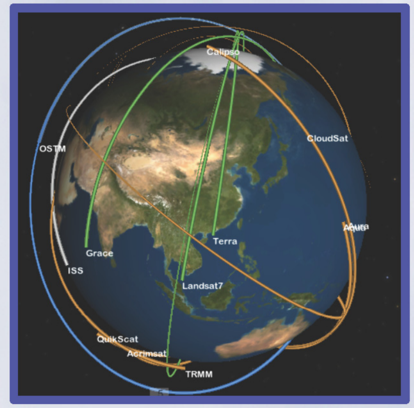
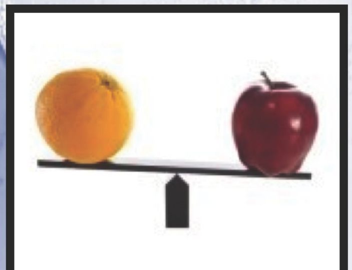
Climate Model Diagnostics and Evaluation

with a focus on satellite observations

Duane Waliser, JPL/Caltech

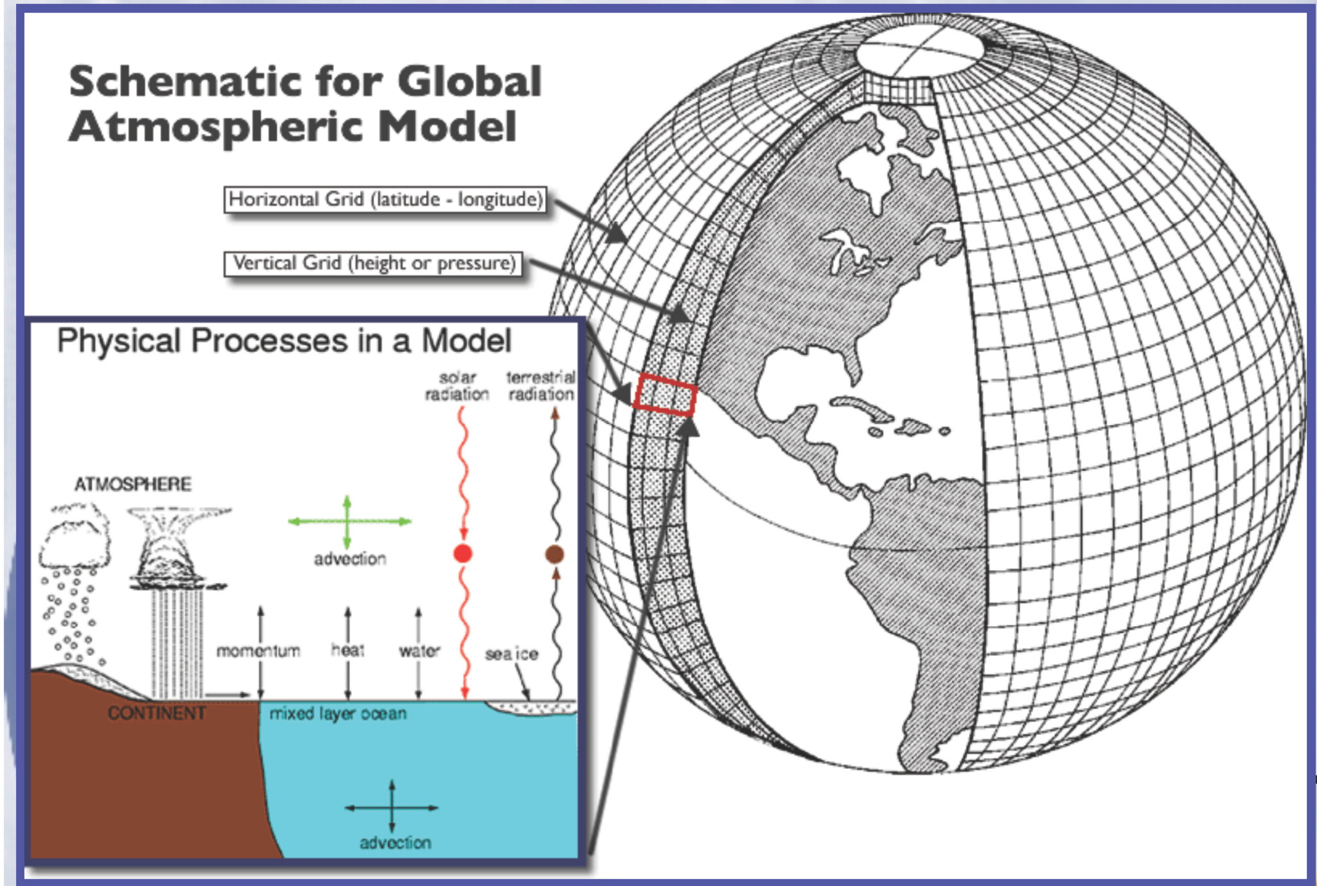






Wikipedia: A comparison of **"apples and oranges"** occurs when two items or groups of items are compared that cannot be validly compared.

JPL Center for Climate Sciences Summer School, August 8-12, 2011
Using Satellite Observations to Advance Climate
Models Keck Institute for Space Studies, Caltech, Pasadena



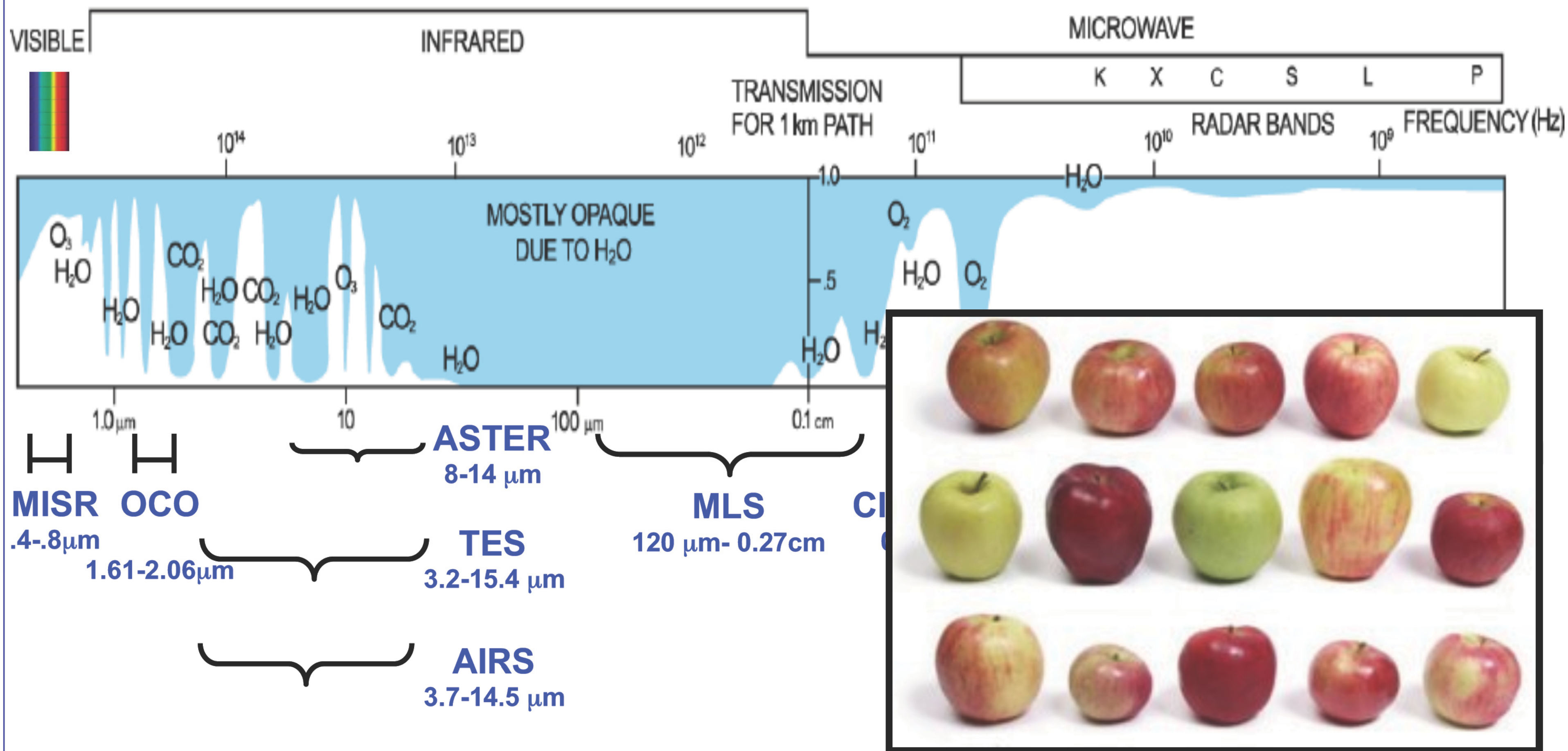
GCMs Trying Their Best to Represent the Climate System

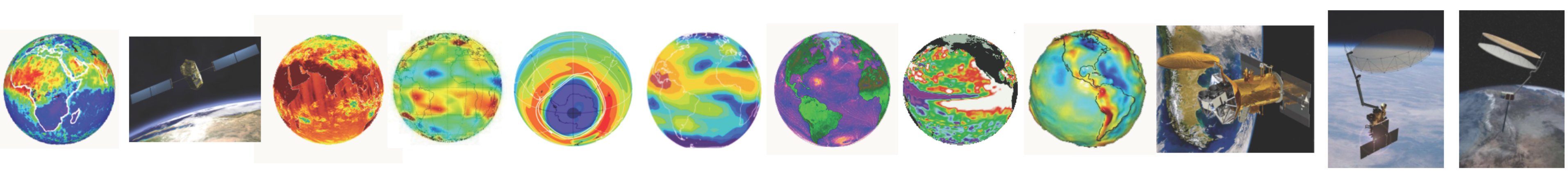
(lines of Fortran code executed on a computer)

- Subset of Earth System components / processes that are tractable and/or deemed most relevant
- Mix of prognostic, diagnostic and parameterized processes
- Many simplifying assumptions and under constrained parameters
- Time and space (box) averages – typically only of the mean value within the "box".

(Satellite) Measurements of the Climate System

Signatures of E&M radiation in one way or another

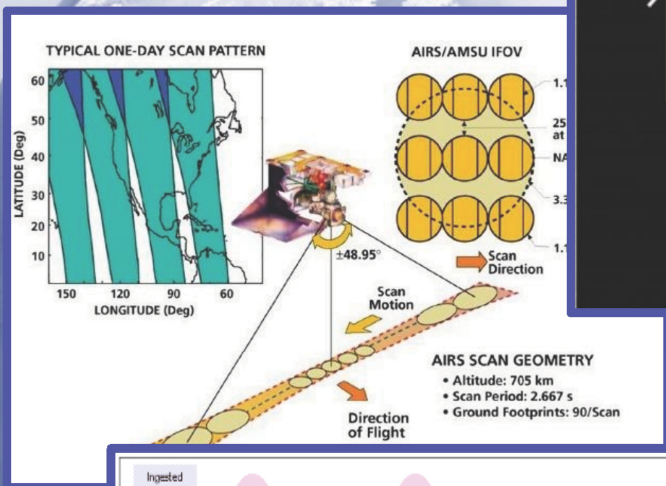


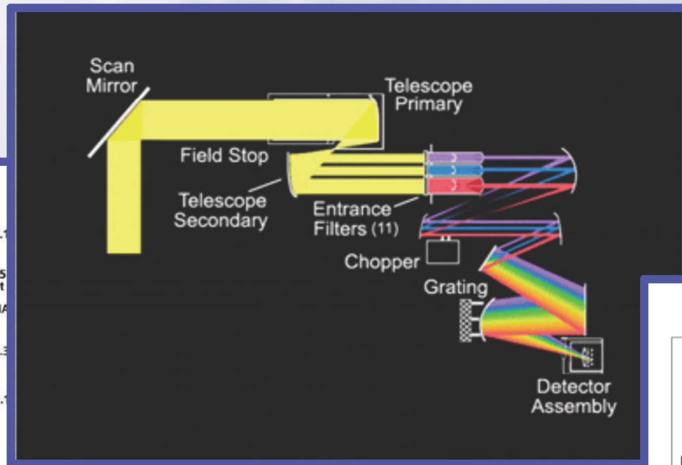


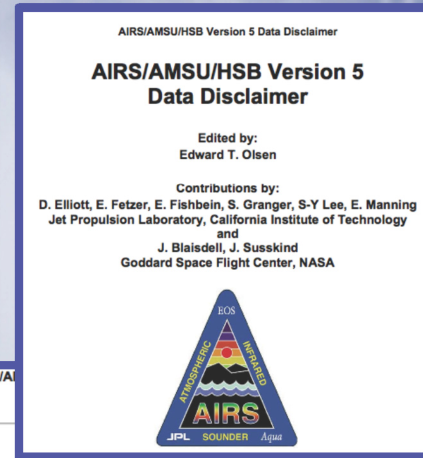
Aerosols | Carbon Dioxide | Water Vapor | Ozone | Cloud Properties | Ocean Winds | Sea Surface Height | Gravity | Ocean Salinity | Soil Moisture | Surface Change

(Satellite) Observation Products of the Climate System

Signatures of E&M radiation in one way or another






AIRS/AMSU/HSB Version 5 Data Disclaimer

AIRS/AMSU/HSB Version 5 Data Disclaimer

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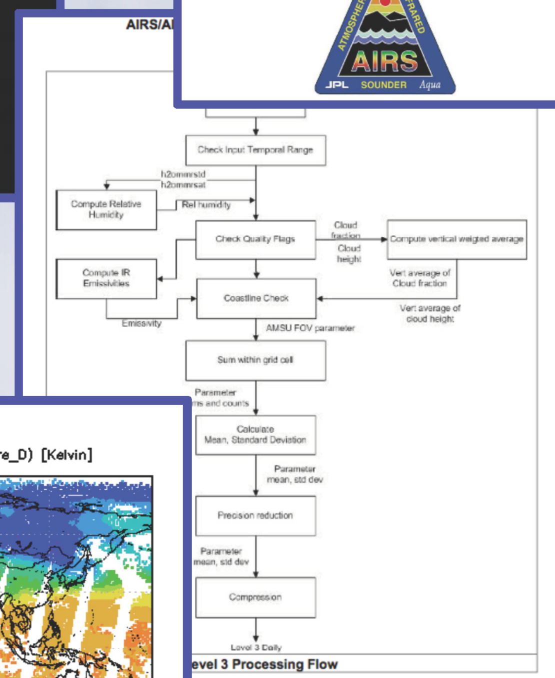
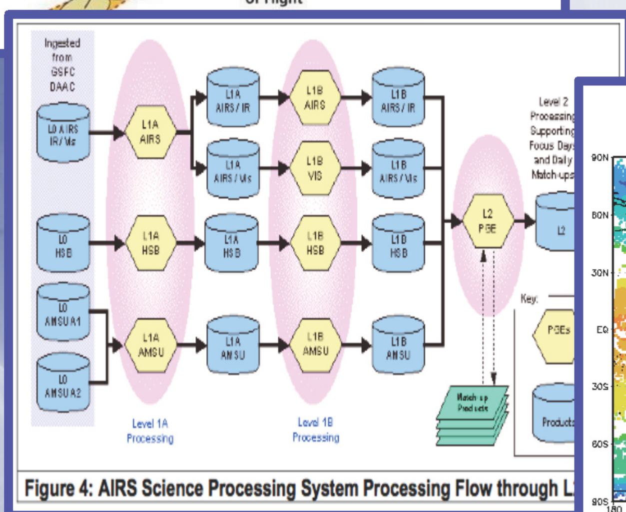
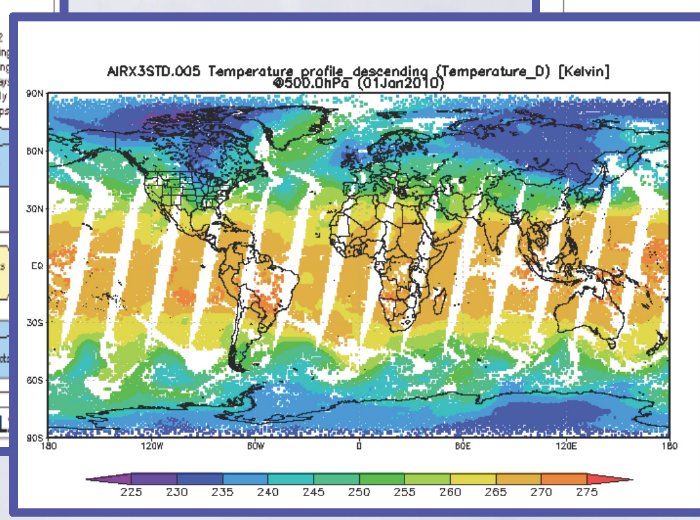


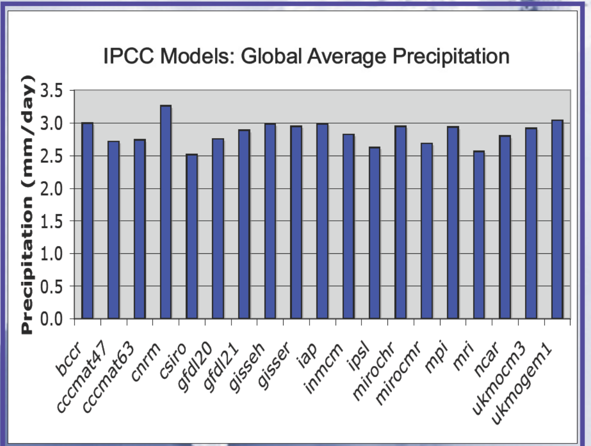
A complex process in its own right***

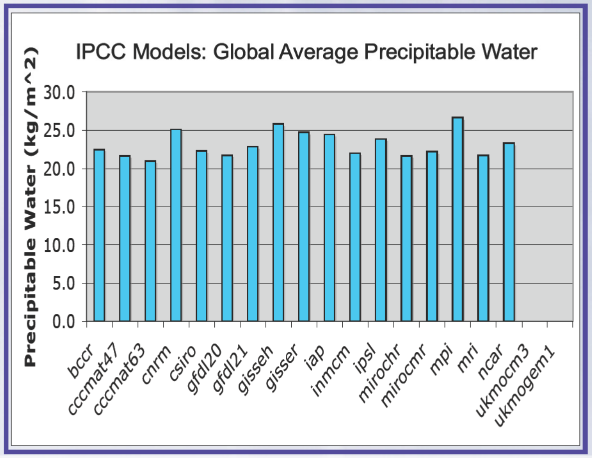


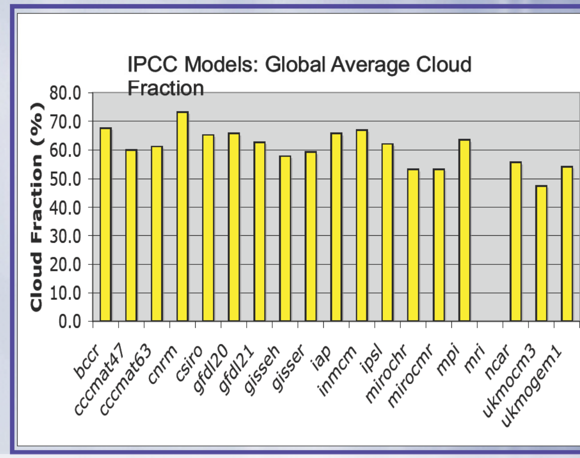


***often involving models

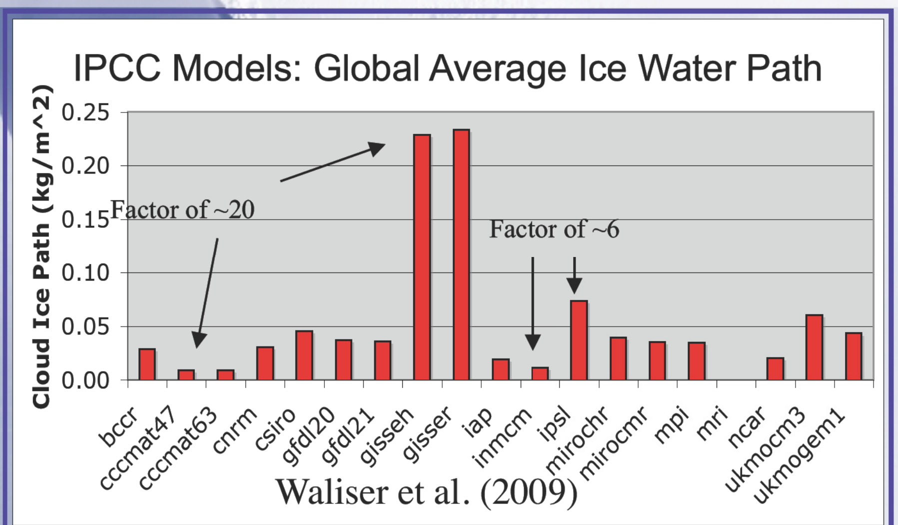
Despite Their Differences - Can Satellite Data Be Effective for Improving and Evaluating GCMs?







NASA/NOAA/DOD have produced observations of Precipitation (e.g., TRMM-NASA), Column Water Vapor (e.g. SSM/I - DOD), and Cloud Frequency (ISCCP-NASA/NOAA) that have led to RELATIVELY good model-model and model-obs (not shown) agreement.

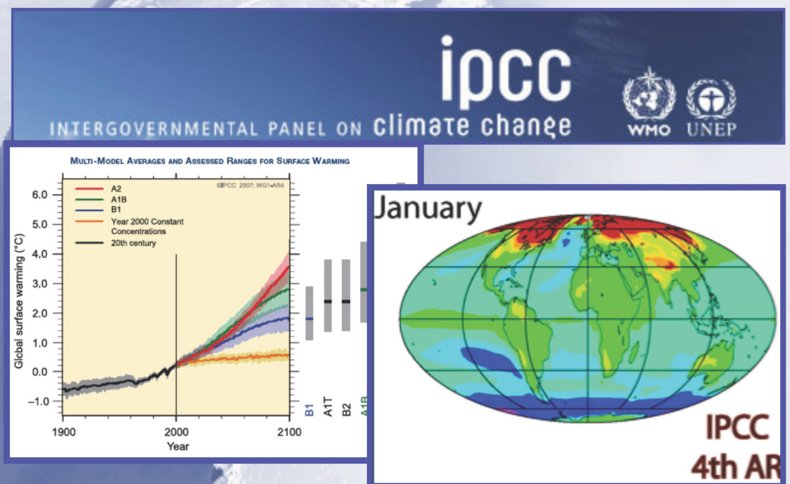


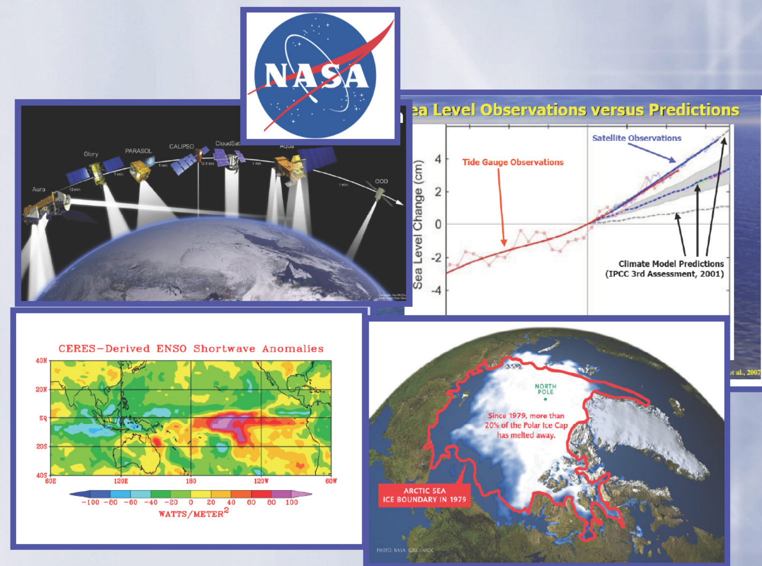
<u>BUT look at Cloud Ice –</u>
<u>No Robust Satellite Measurements Until</u>
<u>Very Recently with CloudSat</u>

MESSAGE

Given observations <u>akin</u> to modeled variables, they WILL <u>with time and effort</u> be utilized to good measure by the modeling community.

More Effective Use of Satellite Observations for GCM Model Evaluation – Particularly for CMIP/IPCC ARs





How to bring as much observational scrutiny as possible to the IPCC process?

How to best utilize the wealth of NASA Earth observations for the IPCC process?

NASA/JPL and DOE/PCMDI Collaboration

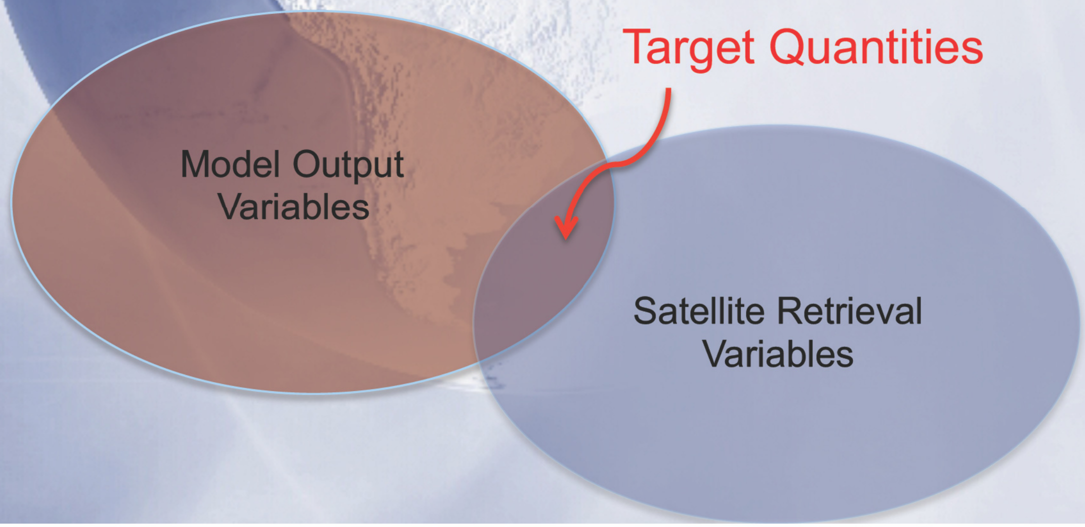
Satellite Observations for CMIP5 Simulations

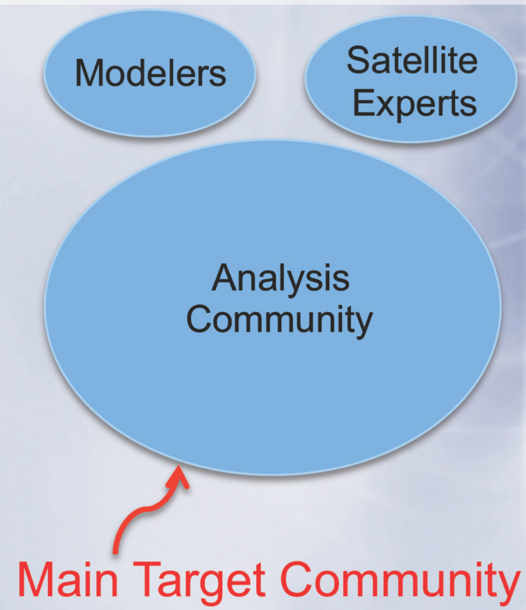
Basic Tenets of this Activity

- *To provide the community of researchers that will access and evaluate the CMIP5 model results access to analogous sets (in terms periods, variables, temporal/spatial frequency, dissemination) of satellite data.*

- *To be carried out in close coordination with the corresponding CMIP5 modeling entities and activities – in this case PCMDI and WGCM.*

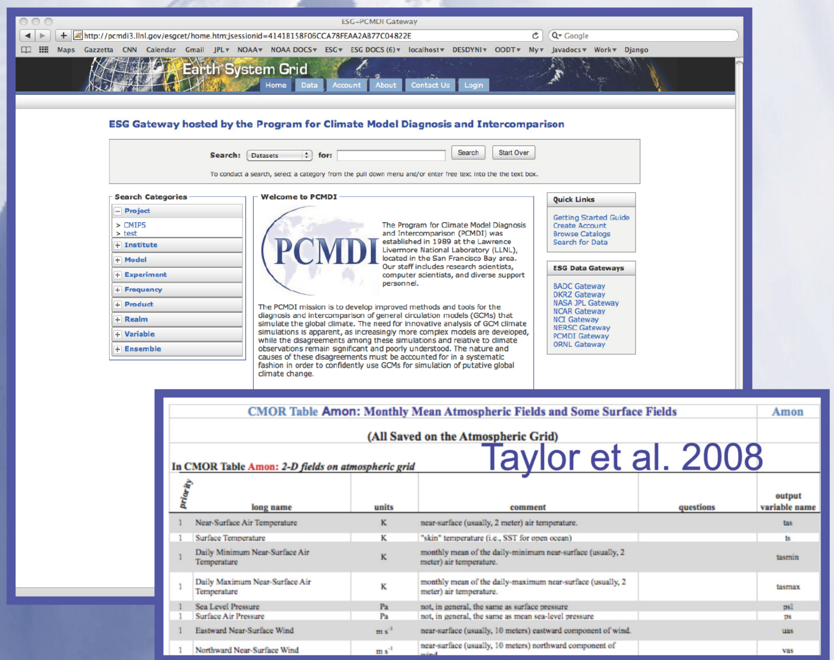
- *To directly engage the observational (e.g. mission and instrument) science teams to facilitate production of the corresponding data sets and documentation.*





Model and Observation Overlap

For what quantities are these comparisons viable?



CMOR Table Amon: Monthly Mean Atmospheric Fields and Some Surface Fields					Amon
(All Saved on the Atmospheric Grid)					
In CMOR Table Amon: *2-D fields on atmospheric grid*					
priority	long name	units	comment	questions	output variable name
1	Near-Surface Air Temperature	K	near-surface (usually, 2 meter) air temperature.		tas
1	Surface Temperature	K	"skin" temperature (i.e., SST for open ocean)		ts
1	Daily Minimum Near-Surface Air Temperature	K	monthly mean of the daily-minimum near-surface (usually, 2 meter) air temperature.		tasmin
1	Daily Maximum Near-Surface Air Temperature	K	monthly mean of the daily-maximum near-surface (usually, 2 meter) air temperature.		tasmax
1	Sea Level Pressure	Pa	not, in general, the same as surface pressure		psl
1	Surface Air Pressure	Pa	not, in general, the same as mean sea-level pressure		ps
1	Eastward Near-Surface Wind	$m\ s^{-1}$	near-surface (usually, 10 meters) eastward component of wind.		uas
1	Northward Near-Surface Wind	$m\ s^{-1}$	near-surface (usually, 10 meters) northward component of wind		vas

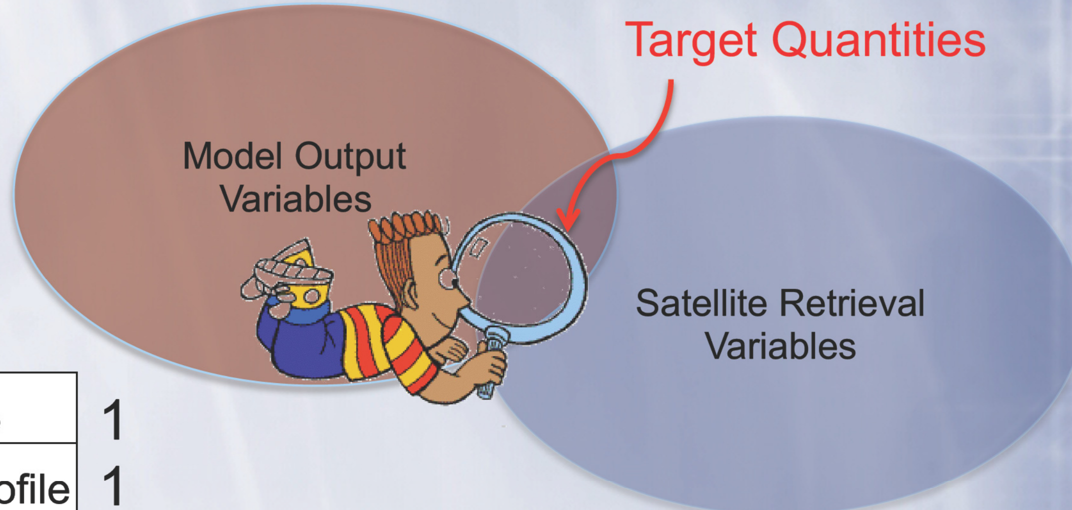
~120 ocean
~60 land
~90 atmos
~50 cryosphere

Current NASA Missions ~14
Total Missions Flown ~ 60
Many with multiple instruments
Most with multiple products (e.g. 10-100s)
Many cases with the same products

<u>Over 300 Variables in (monthly) CMIP Database</u> ⟷ <u>Over 1000 satellite-derived quantities</u>

Model and Observation Overlap

For what quantities are these comparisons viable?



AIRS (≥ 300 hPa)	Atm temp profile	1
	Specific humidity profile	1
MLS (< 300 hPa)	Atm temp profile	1
	Specifc humidity profile	1
QuikSCAT	Ocean surface winds	~8
TES	Ozone profile	1
AMSR-E	SST	1
TOPEX/JASON	SSH	1
CERES	TOA radiation fluxes	~6
TRMM	Total precipitation	1
MODIS	Cloud fraction	1
	Net primary production	3

After much scrutiny and two workshops, only ~25 variables were identified as being "safely" comparable in this first round – although still with caveats!

Keep in mind more learned users, such as graduates of the JPL's CCS Summer School, can make effective and safe use of considerably more satellite data.

Examples of sst, soil moisture, winds, precipitation

Satellite Observations for CMIP5 Simulations
Technical Documentation

Atmospheric Infrared Sounder (AIRS)
Specific Humidity Description

1. Intent of This Document

This document is intended to describe AIRS specific humidity observation data, which are specially prepared for scientists who would be engaged in using IPCC model data and observational data for model-to-observation comparisons, climate model diagnostics and evaluations, and climate changes and variability studies for the IPCC 5th assessment report (AR5). In particular, the document provides the user of the data with critical caveats of using the AIRS specific humidity observation data for those activities in comparison with CMIP5 model outputs.

2. Data Field

This data product is a regularly gridded, monthly averaged specific humidity measured by AIRS during 2002-2010. The product contains temporal and geometric fields (time, latitude, longitude, and vertical pressure levels) and atmospheric parameter (specific humidity). The time is given in terms of Julian day for the start of the month. The latitude (lat) and longitude (long) are regularly gridded in a 1 degree by 1 degree box. The longitude starts at 0.5 degree and ends at 359.5 degree. The latitude starts at -89.5 degree and ends at 89.5 degree. The vertical pressure levels (plev) include all the CMIP5 mandatory levels from 1000 hPa to 10 hPa. However, we only provide the data up to 300 hPa. For this version of the retrieval, the tropospheric moisture resolution ranges between 2.7 km near the surface and 4.3 km near the tropopause [1]. The specific humidity variable is reported as "hus(time, plev, lat, long)" and is in units of 1 (kg/kg).

3. Data Origin

The AIRS specific humidity is not an *in situ* measurement. The infrared emission radiations emitted by different Earth scenes are remotely sensed by a spectrometer. Among the 2378 spectral channels, 49 are especially used to sense water vapor, in the range 1250 to 1650 cm^{-1} [2]. First, measurements are transformed into calibrated radiances for all footprints and all channels. Then, physical quantities such as the specific humidity are derived from these geolocated radiance products. The physical quantities are then averaged over different periods, typically a month. At this stage, the water vapor is reported in terms of layer averages. In order to convert from layer amounts to level amounts, we treat the original layer averages at level amount at the midpoint (in log(pressure) of the layers and then logarithmically interpolate in log(pressure) to the desired levels. For the 1000 hPa level this interpolation is replaced by an extrapolation. The values reported are means of the day and night values, provided there are enough observations in each category to make the values statistically significant. The minimum is 20 observations each, except for latitudes beyond +/- 80 degrees, where we relax the limits to compensate for a much lower number of observations.

4. Validation

AIRS retrievals have been validated against a variety of in situ data (radiosondes, airborne sun photometer, ship based measurements), other remote measurements from other satellites and model-generated data (fully coupled global ocean- atmosphere General Circulation Models, collocated model forecasts compared with radiosondes). The table below summarizes these findings and can be found in reference **Error! Reference source not found.**.

Geophysical Conditions Studied	Uncertainty Estimate
Ocean, surface to 300 hPa	15-25% / 2 km
Non-polar land 2 km to 300 hPa.	15-25% / 2 km
Non-polar land, surface to 1-2 km	30-40% / 2 km
Polar land.	30-40% / 2 km
Tropical upper troposphere.	25% / 2 km
Middle and high latitude upper troposphere.	30-50% / 2 km

Table 1: uncertainty estimate for different conditions.

The uncertainty estimates are calculated based on the difference between AIRS retrievals and radiosonde observations. The horizontal resolution is 45km.

4. Consideration for Model-Observation Comparisons

Because this data product is observational data, there are several aspects that distinguish this product from model outputs. The user of this data product should be aware of them in order to make judicious model-observation comparisons.

4.1 Clouds influence

AIRS coverage is limited by the presence of optically thick clouds because it is an infrared instrument. Since microwaves can penetrate through most clouds, accurate moisture profile retrievals in the presence of clouds can be obtained with a combined analysis of AIRS infrared and AMSU microwave radiances **Error! Reference source not found.**. AMSU is a microwave instrument flown together with AIRS on AQUA.

Satellite Observations for CMIP5 Simulations
Technical Documentation

up to about 70% **Error! Reference source not found.**. This limitation of the infrared measurement makes the observation scene dependent and in turns, causes a spatially inhomogeneous sampling as illustrated on Figure 1. The AIRS sampling is low (~40) in cloudy regions, such as the Intertropical Convergence Zone (ITCZ) (e.g., the

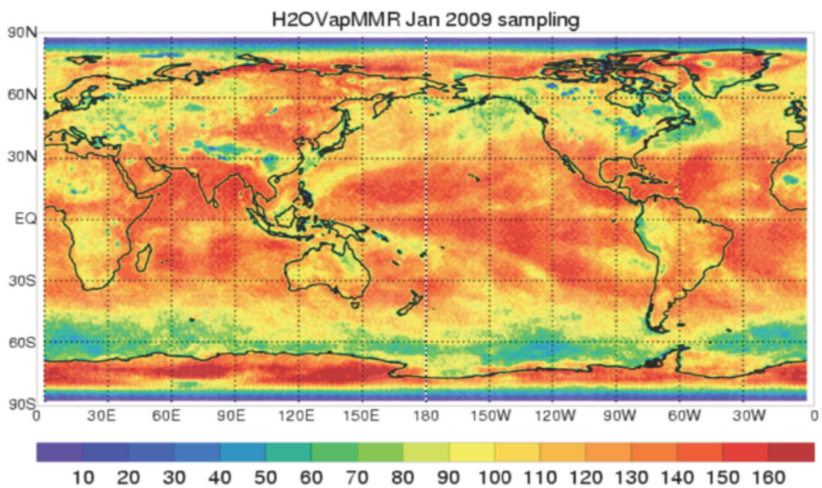


Figure 1: Water vapor sampling repartition at 550 hPa for the month of January 2009.

equatorial western Pacific warm pool) and the midlatitude storm tracks (e.g., north Pacific, north Atlantic and 60S latitude belt). The AIRS sampling is high (~150) in clear regions, such as subtropics and midltitude land regions.

4.2 Time Sampling Bias

Because AIRS is on board the Aqua satellite with a sun-synchronous polar orbit, it samples at the two fixed local solar times at each location (e.g. 1:30 AM and 1:30 PM at the equator) and does not resolve the diurnal cycle. AIRS observations at a given latitude on either the ascending (north-going) or descending (south-going) portions of the orbit have approximately (to within several minutes) the *same* local solar time throughout the mission. In contrast, typical model monthly averaged outputs contain the averaged values over a time series of data with a fixed time interval (e.g. every 6 hours). For many constituents in the upper atmosphere, this difference is not likely a problem although for regions influenced by deep convection and its modulation of the diurnal cycle (e.g. tropical land masses), this time sampling bias should be considered.

Because the monthly averaged value in this AIRS data product is an average over observational data available in a given grid cell, the number of samples used for averaging varies with the geo-location of the cell. Because of the convergence of longitude lines near the poles, the time range of data collection broadens as one moves from the equator toward either pole, with the ranges in the polar regions including all times of day and night **Error! Reference source not found.**. So, there are more observations near in the regions near the poles (~50° to ~85°) than the rest of the area.

5. Instrument Overview

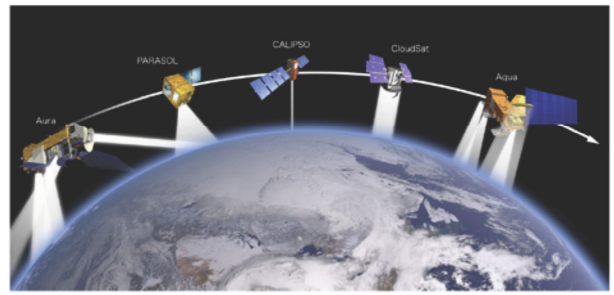


Figure 2: NASA's A-train group of Earth observing satellites.

Launched into Earth-orbit on May 4, 2002, the Atmospheric Infrared Sounder, AIRS, is one of six instruments on board the Aqua satellite, part of the NASA Earth Observing System. AIRS along with its partner microwave instrument, Advanced Microwave Sounding Unit (AMSU-A), observe the global water and energy cycles, climate variation and trends, and the response of the climate system to increased greenhouse gases. The term "sounder" in the instrument's name refers to the fact that temperature and water vapor are measured as functions of height**Error! Reference source not found.**.

AIRS and AMSU-A share the Aqua satellite with the Moderate Resolution Imaging Spectroradiometer (MODIS), Clouds and the Earth's Radiant Energy System (CERES), and the Advanced Microwave Scanning Radiometer-EOS (AMSR-E). Aqua is part of NASA's "A-train" satellite constellation (see Figure 2), a series of high-inclination, Sun-synchronous satellites in low Earth orbit designed to make long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans.

Satellite Observations for CMIP5 Simulations

Technical Documentation

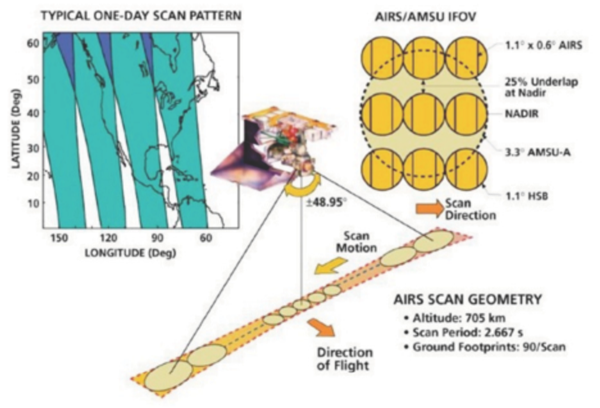


Figure 3: AIRS scanning and coverage geometry.

AIRS coverage is pole-to-pole and covers the globe two times a day. Because the swaths (scanning sweeps) do not overlap at low latitudes, some points near the equator are missed. However, these points are eventually scanned within 2-3 days. As depicted on Figure 3, AIRS scans laterally with respect to its direction of flight. With the scanning angle being 49.5 degree about nadir, the swath width is 1650 km. One orbit period is 98.8 minutes **Error! Reference source not found.**.

6. References

[1] Eric S. Maddy *et al.*, "Vertical Resolution Estimates in Version 5 of AIRS Operational Retrievals", IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 46, NO. 8, AUGUST 2008, page 2375.

[2] Joel Susskind *et al.*, "Accuracy of geophysical parameters derived from Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit as a function of fractional cloud cover", J. Geophys. Res., 111, D09S17, doi:10.1029/2005JD006272.

[3] V5_CalVal_Status_Summary.pdf, p8.

[4] Hartmut H. Aumann *et al.*, "AIRS/AMSU/HSB on the Aqua Mission: Design, Science Objectives, Data Products, and Processing Systems", IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 41, NO. 2, FEBRUARY 2003.

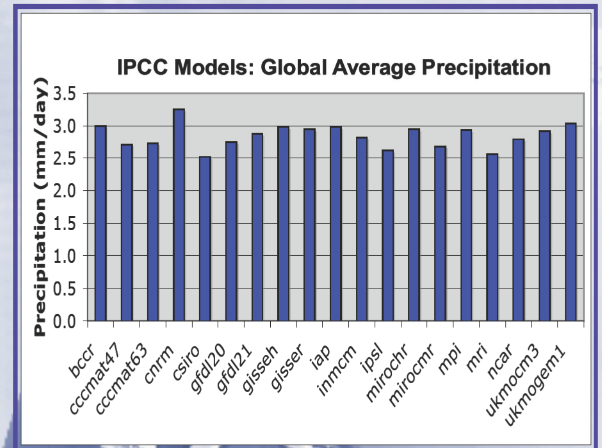
[5] Joel Susskind *et al.*, "Retrieval of Atmospheric and Surface Parameters From AIRS/AMSU/HSB Data in the Presence of Clouds", IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 41, NO. 2, FEBRUARY 2003, page 390.

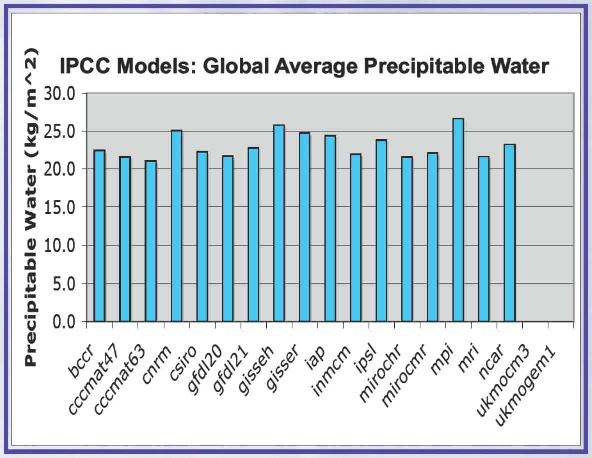
[6] Claire L. Parkinson, "Aqua: An Earth-Observing Satellite Mission to Examine Water and Other Climate Variables", IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 41, NO. 2, FEBRUARY 2003.

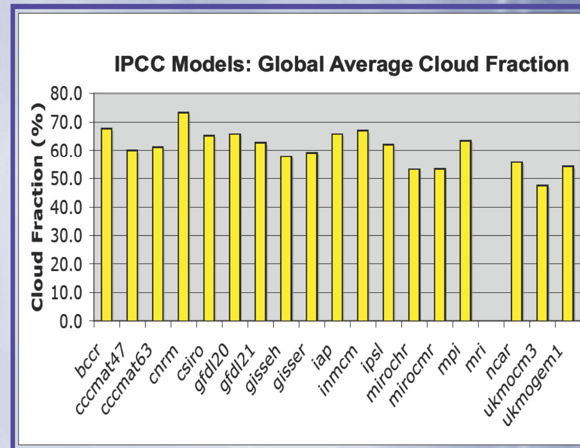
[7] http://airs.jpl.nasa.gov/instrument/coverage/

A Detailed Example for Ice Water Content or Path

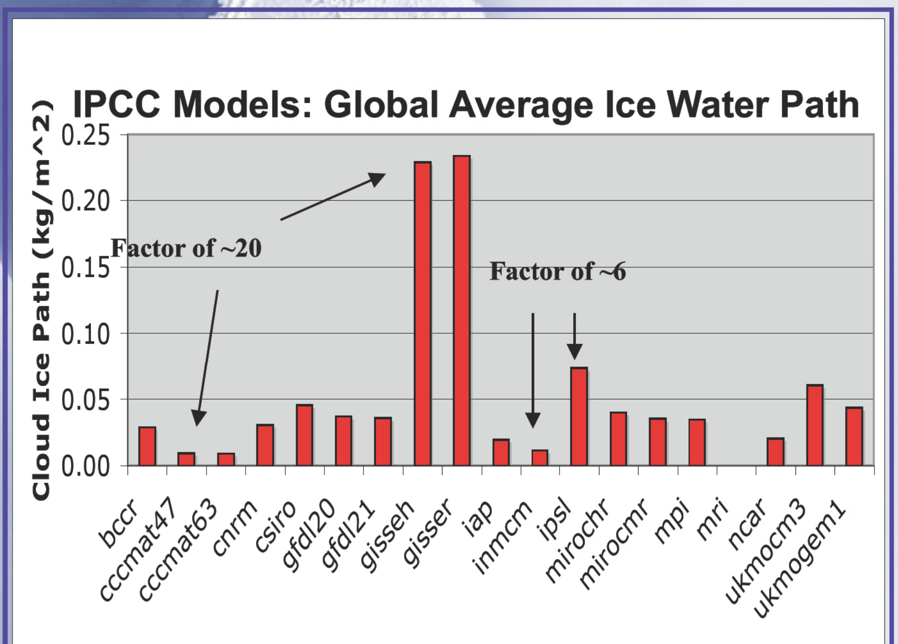
"Getting Your Hands Dirty" aka "Looking Under the Hood"







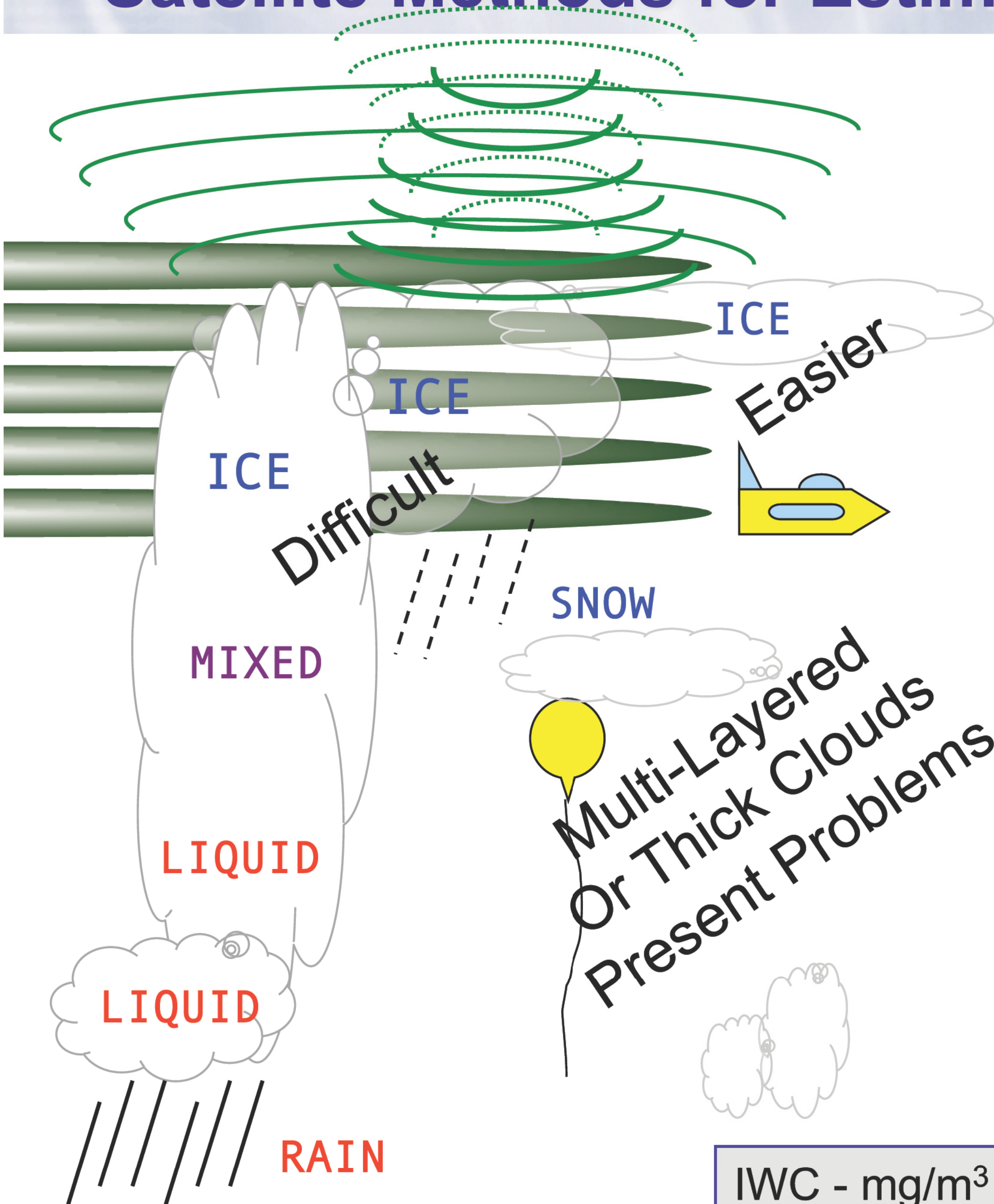
QUANTITIES THAT HAVE BEEN MEASURED BY A VARIETY OF SATELLITE AND OTHER DATA SOURCES FOR SOME TIME TEND TO AGREE RELATIVELY WELL.



<u>CLOUD ICE HAS HAD POOR OBSERVATIONAL CONSTRAINTS AND MODELS EXHIBIT WIDE DISAGREEMENT.</u>

<u>TO REDUCE UNCERTAINTIES IN CLOUD-CLIMATE FEEDBACK, THIS LEVEL OF DISAGREEMENT MUST BE REDUCED!</u>

Satellite Methods for Estimating Atmospheric Ice

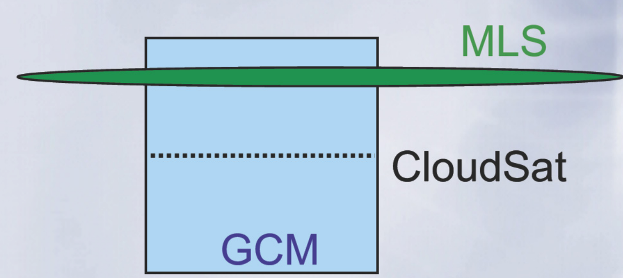


Passive Techniques such as those used in the CERES/MODIS, ISCCP, MODIS, and NOAA/MW products only provide Total IWP estimates - challenging in multi-layer, mixed and thick clouds.

MLS - a limb sounder - can probe the upper troposphere to estimate IWC (but not Total IWP)

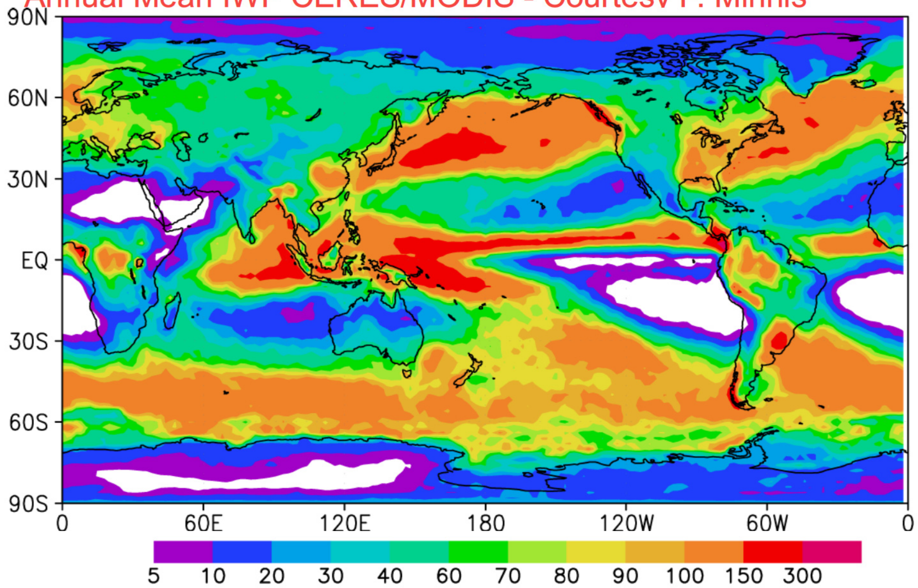
CloudSat (cloud radar) and CALIPSO (lidar) can probe the cloud structure and provide estimates of IWC.
CloudSat also provides IWP.

IWC - mg/m^3
IWP - gm/m^2

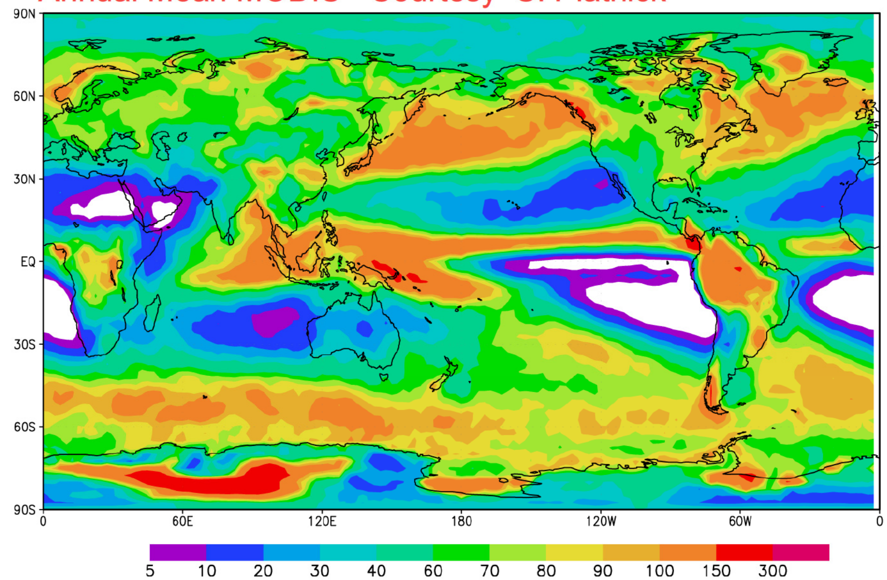


Satellite Estimates of Cloud Ice Water Path

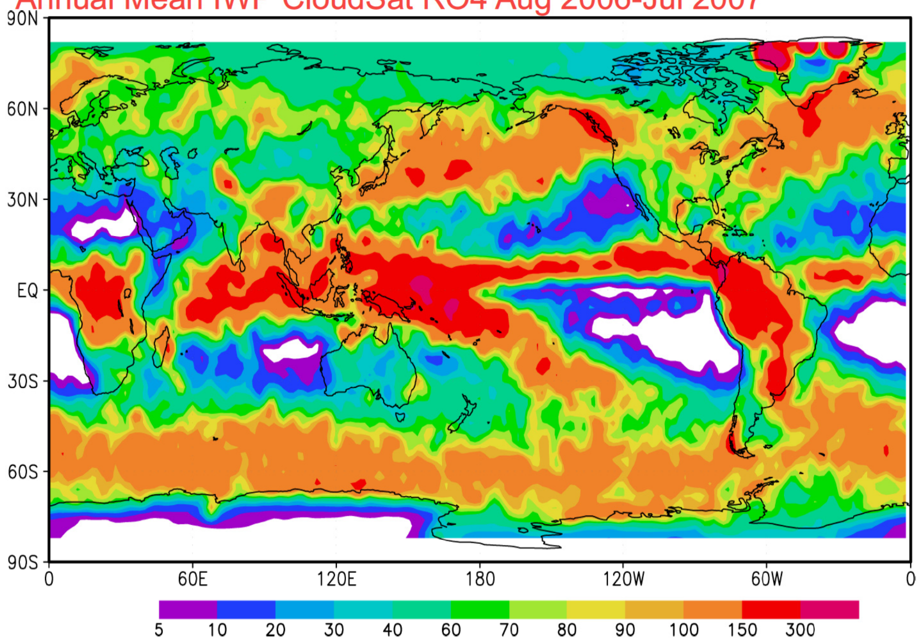
Annual Mean IWP CERES/MODIS - Courtesy P. Minnis



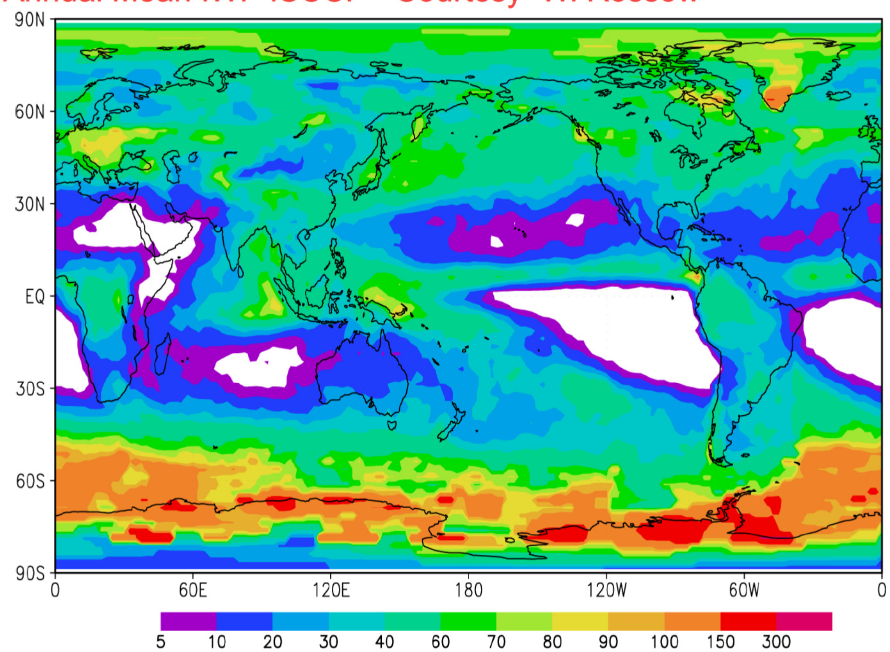
Annual Mean MODIS - Courtesy S. Platnick



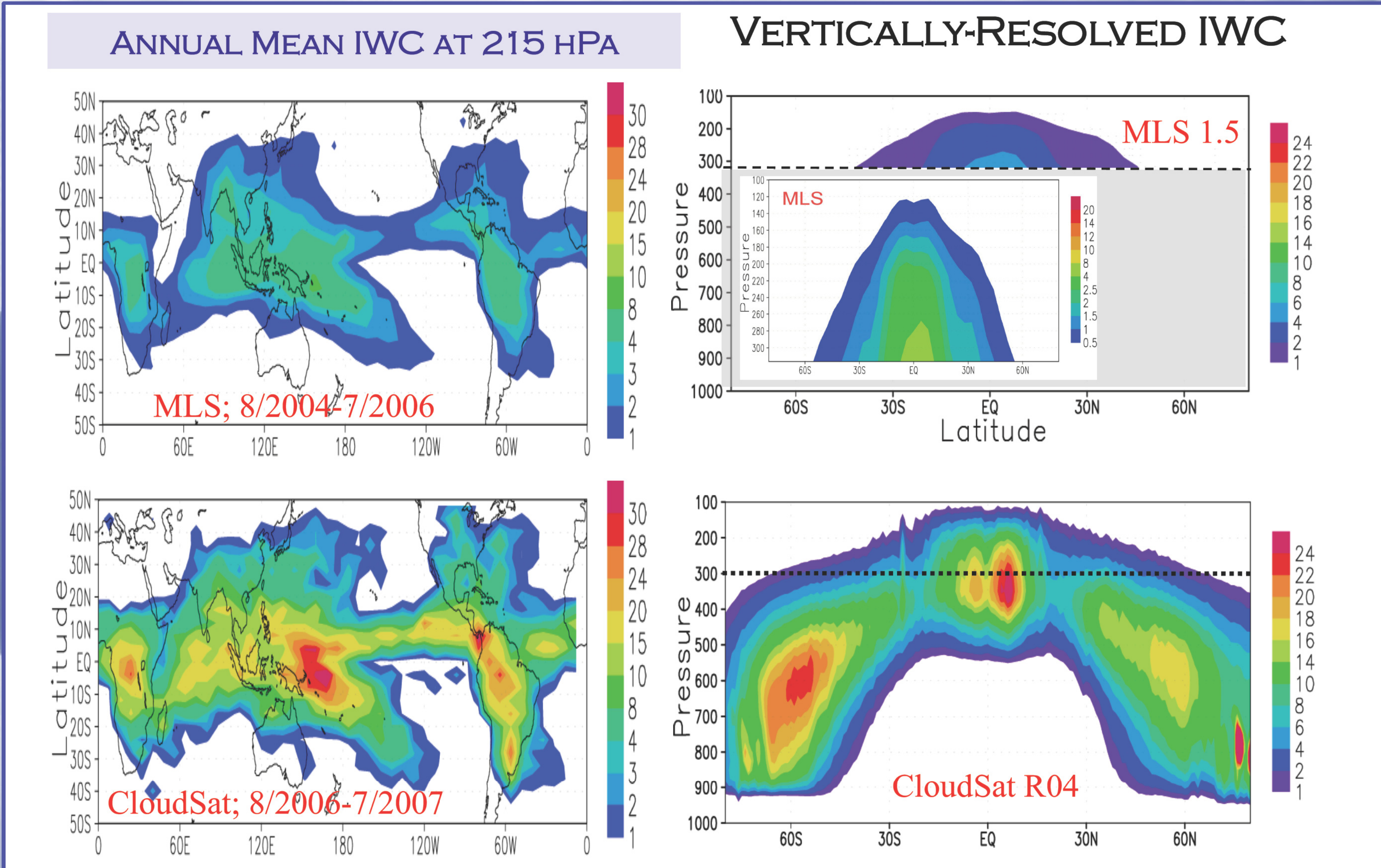
Annual Mean IWP CloudSat RO4 Aug 2006-Jul 2007



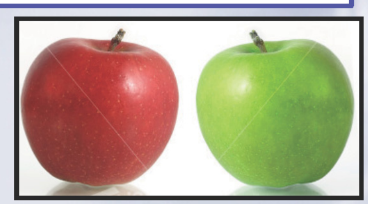
Annual Mean IWP ISCCP - Courtesy W. Rossow



Vertically-Resolved IWC Values: MLS and CloudSat



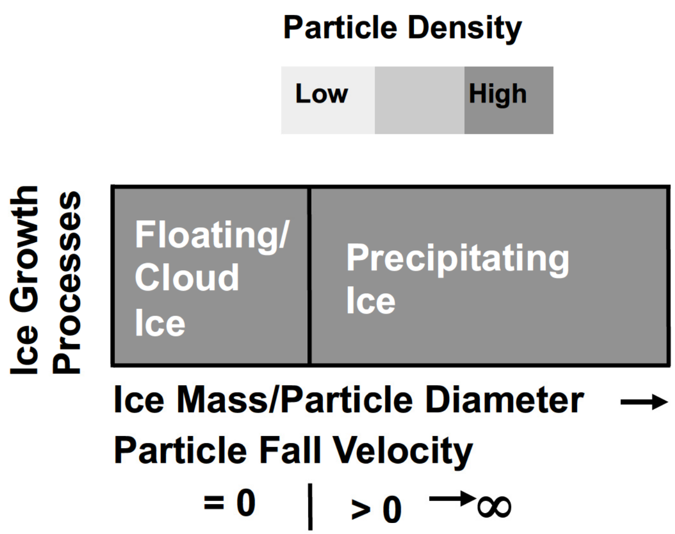
Different Methodologies Make Different Apples



Similarly, it is necessary to know what GCM representations imply by “IWC/IWP”, “cloud ice” and other frozen hydrometeors

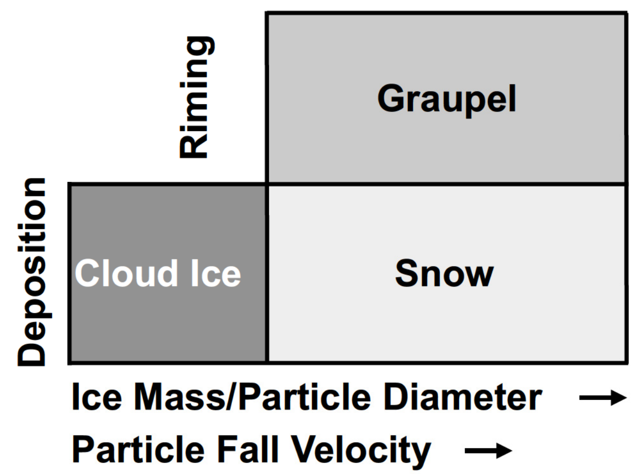
Typical GCM

e.g., Most CMIP GCMs



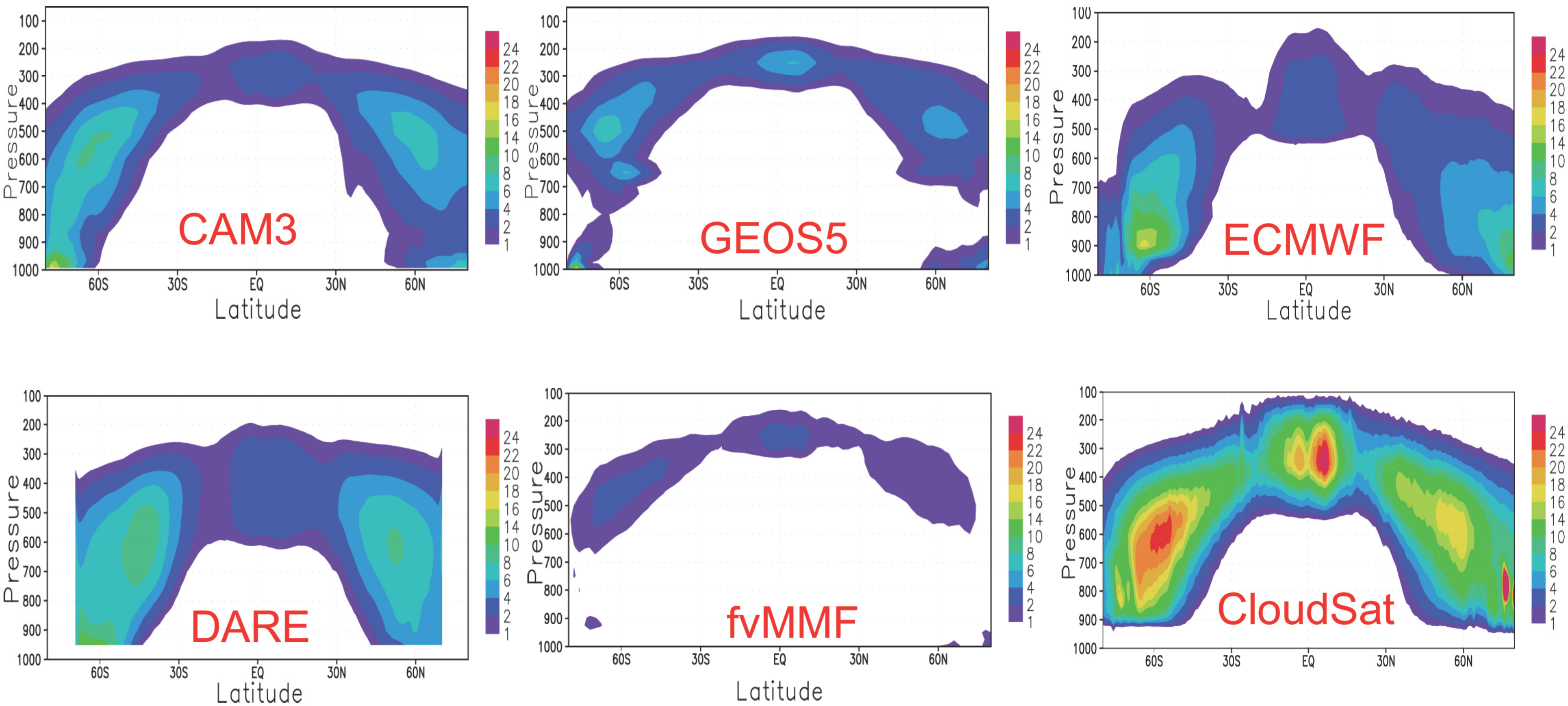
More Complex Model

e.g. fvMM5, WRF, ECMWF

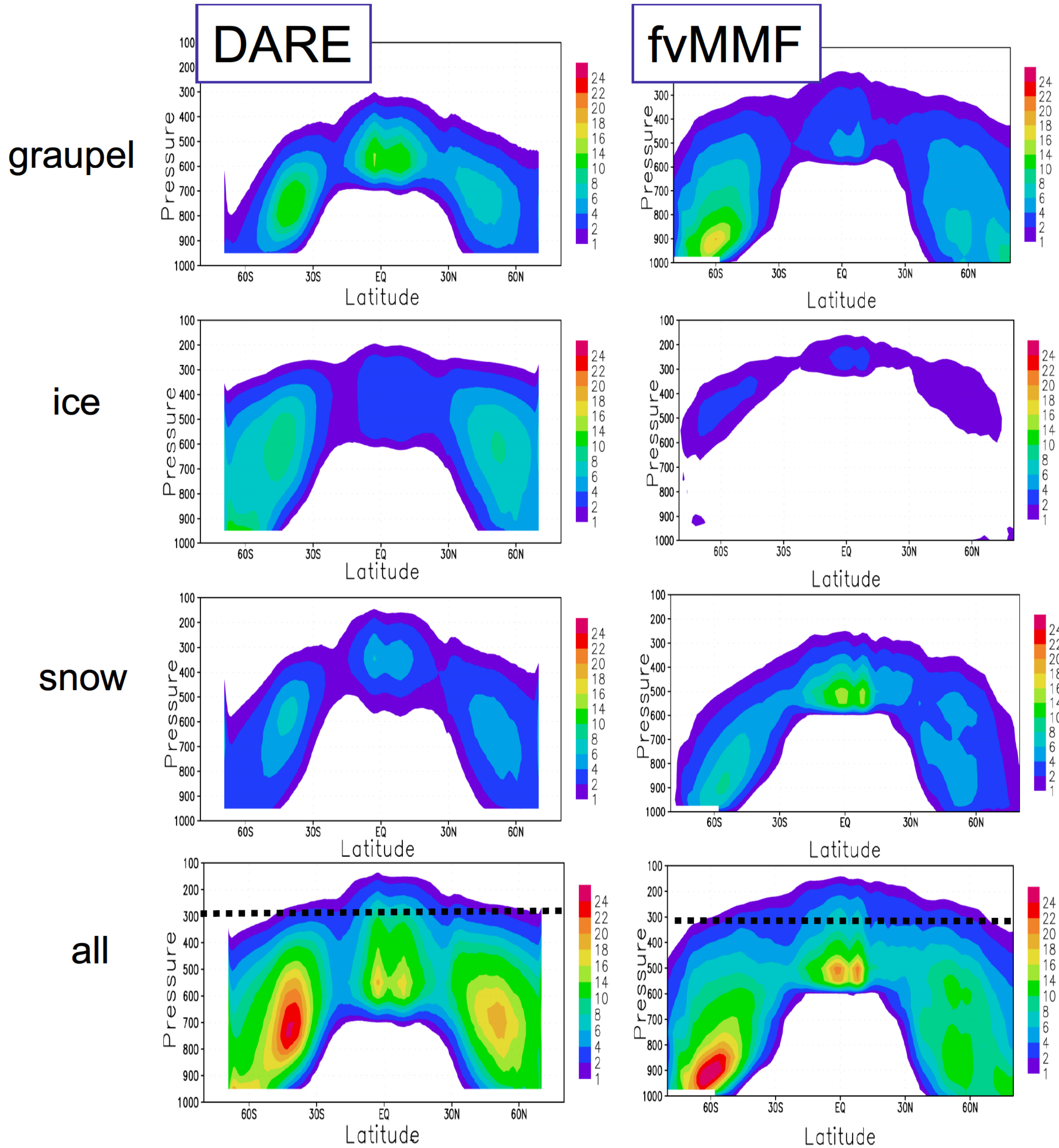


GCM Cloud Ice Water Content (IWC)

Annual Mean Values



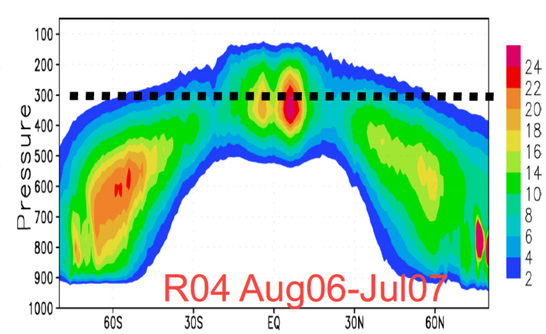
CloudSat is sensitive to larger/ precipitating hydrometeors and thus is not - as is - an appropriate "validation" field for GCM IWC



All make order one contributions to total ice water path?

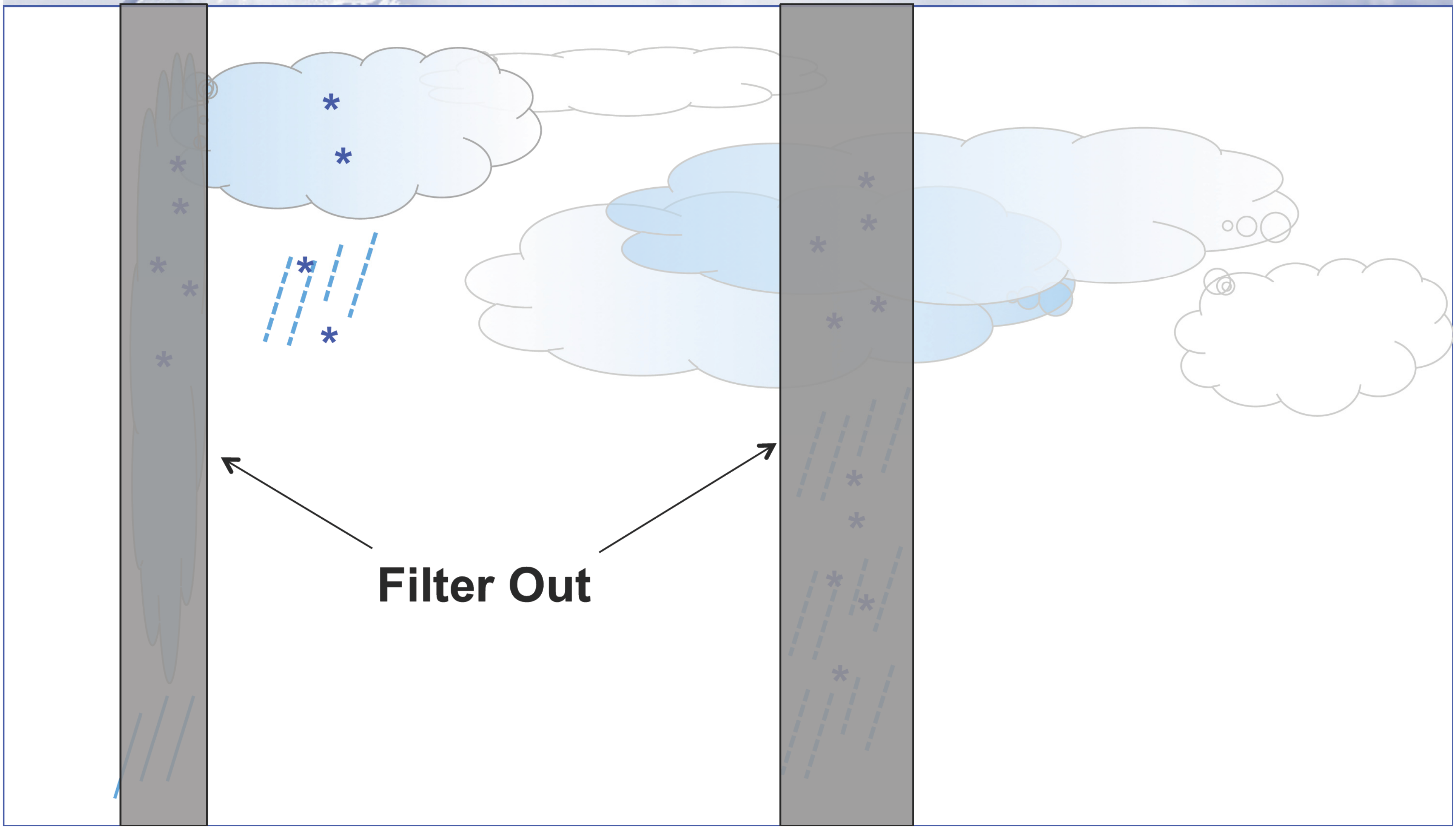
Can CloudSat Be Used as a Preliminary Estimate of the Total IWC Field to compare to GCMs that represent this?

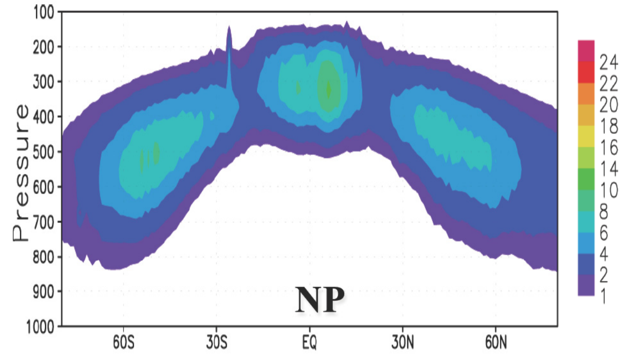
Can we judiciously sample/filter Cloudsat to use for GCM Cloud IWC?



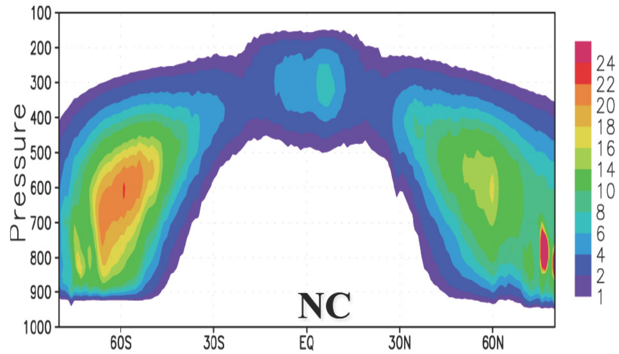
Bigger Falling Ice vs Smaller Suspended Ice

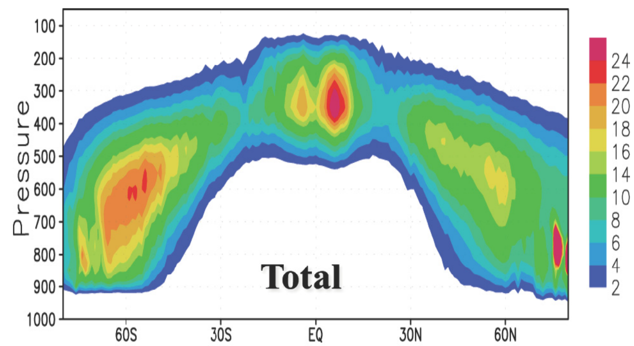
Use CloudSat Convective Cloud Classification & Surface Precipitation Flag to filter out the larger falling ice hydrometeors.

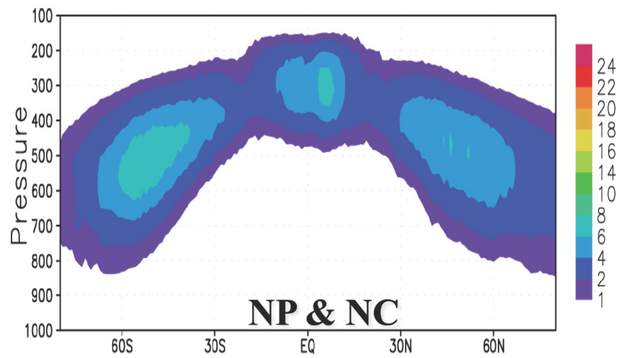




NP - Non-Precipitating at Surface
NC - Non-Convective





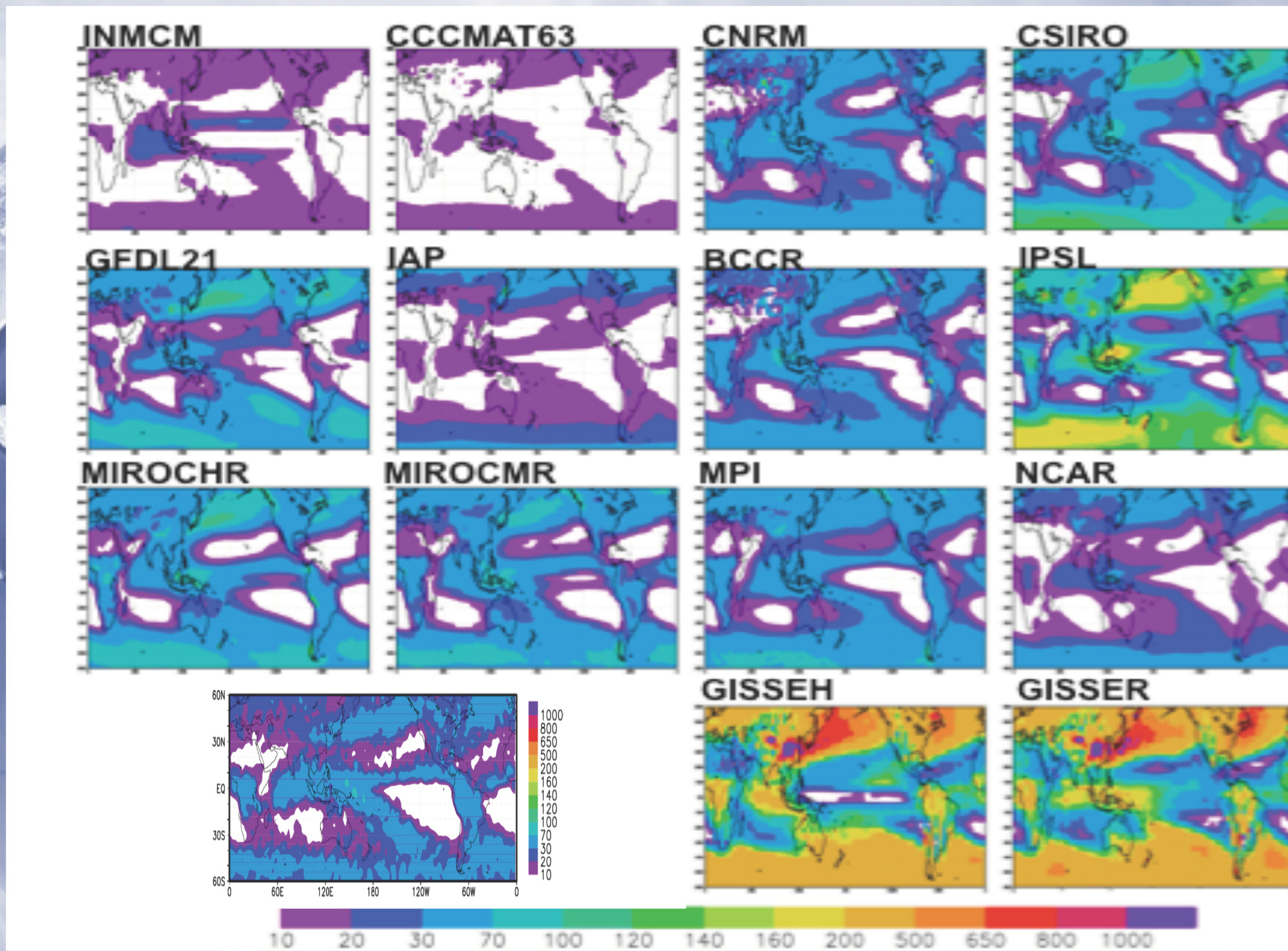


Can this be considered a preliminary estimate of cloud IWC to use for GCMs?

CloudSat has cloud classification and surface precipitation flags

Can we put these to use to get an estimate of cloud iwc?

Apply to CMIP Evaluation - CloudSat “Cloud” IWP



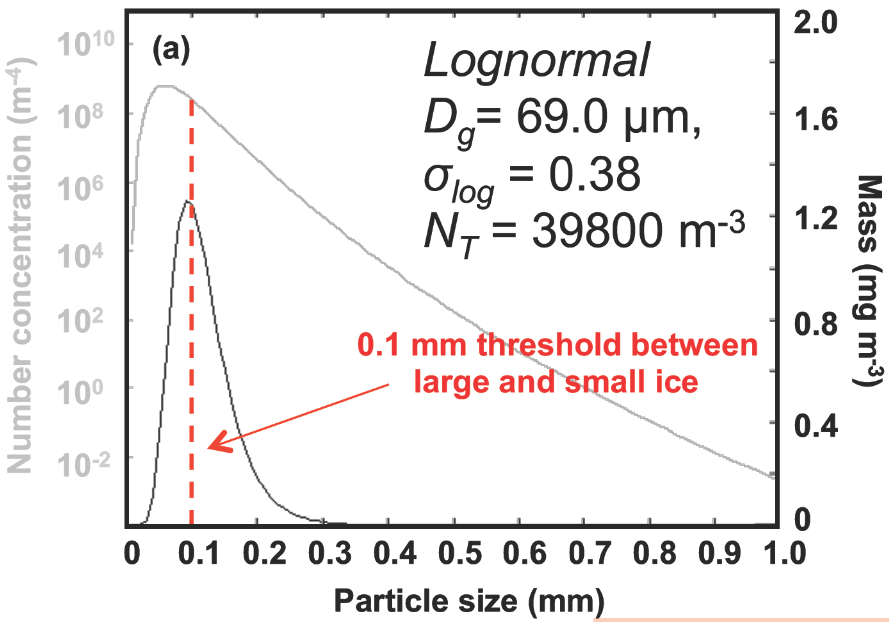
MEAN IWP FROM 14 IPCC CONTRIBUTIONS OF 20TH CENTURY CLIMATE
COLOR SCALE ~ LOG10: RAISES UNCERTAINTY ABOUT CLOUD FEEDBACK REPRESENTATION

Waliser et al. 2009, JGR

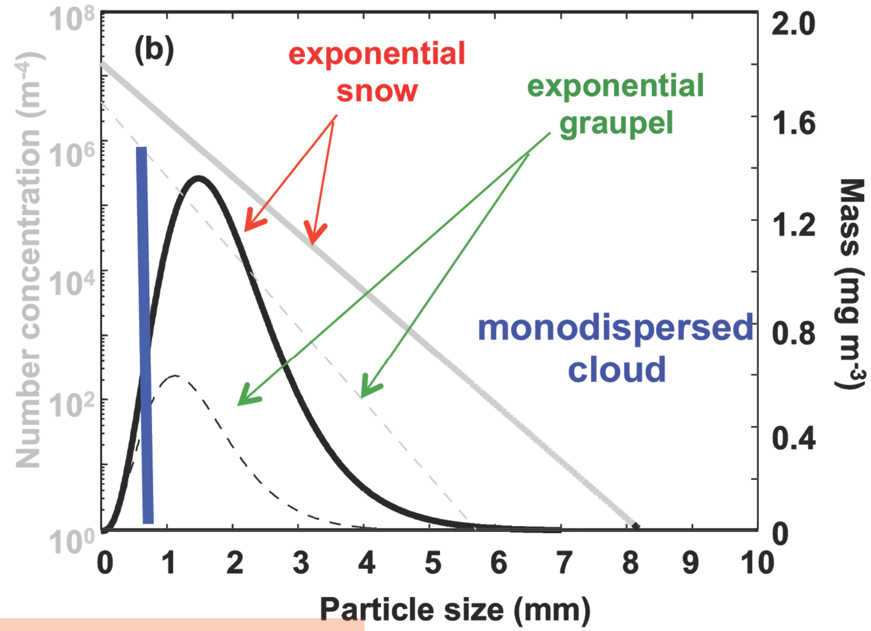
A Better Way? : Getting Better Ice Constraints

Exploring Use of CloudSat-Provided PSD Information

Example CloudSat IWC PSD



fvMMF PSDs



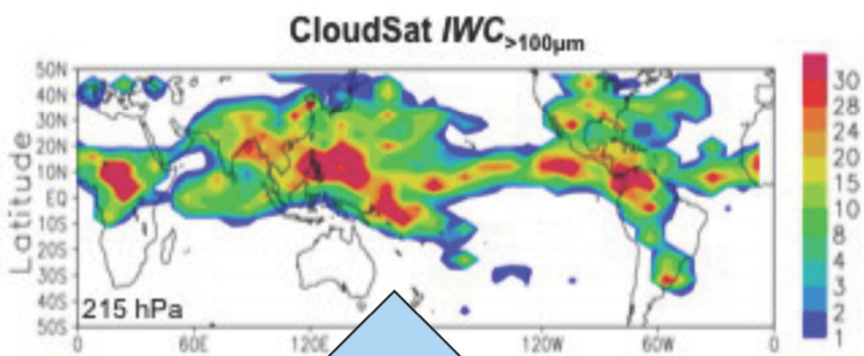
Chen, Li, Waliser et al. 20101 GRL, In Press

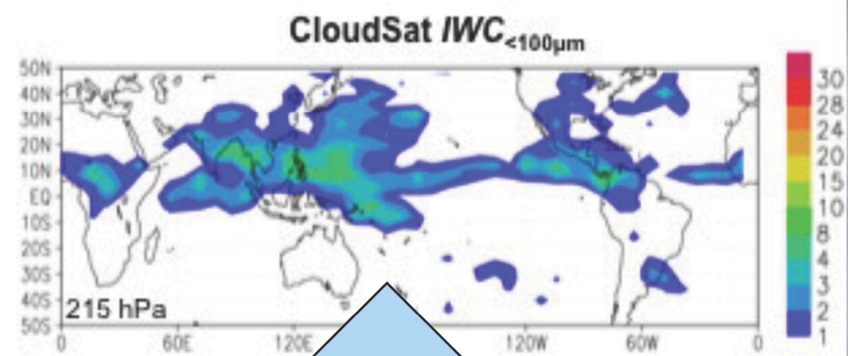
Divide ice into large and small and integrate

Sum species, then divide ice into large and small and integrate

A Better Way? : Getting Better Ice Constraints

Exploring Use of CloudSat-Provided PSD Information





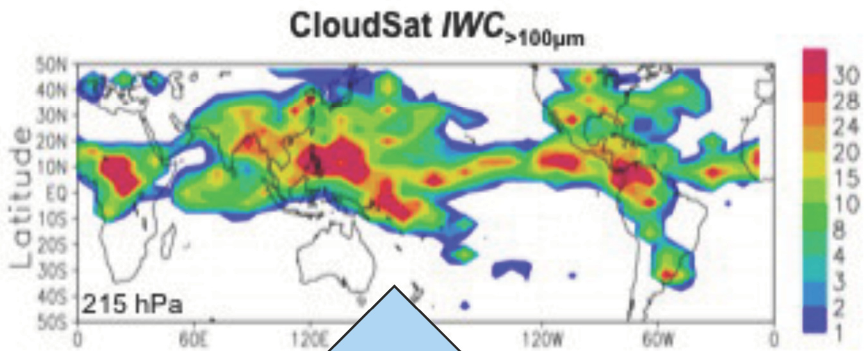
Estimates of

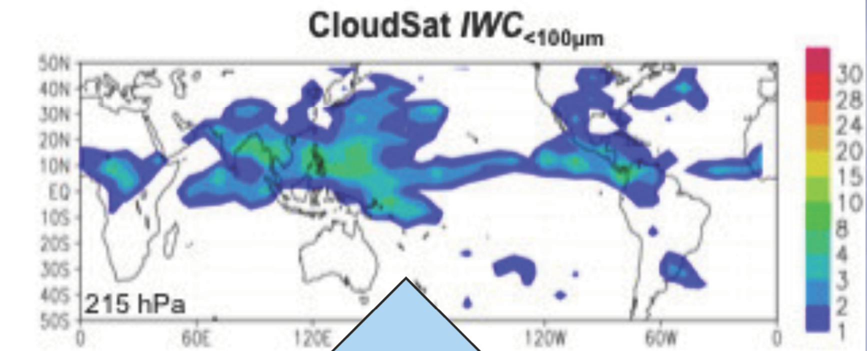
precipitating ice mass **cloud ice mass**

using 100 um threshold (e.g., Ryan 2000)

A Better Way? : Getting Better Ice Constraints

Exploring Use of CloudSat-Provided PSD Information



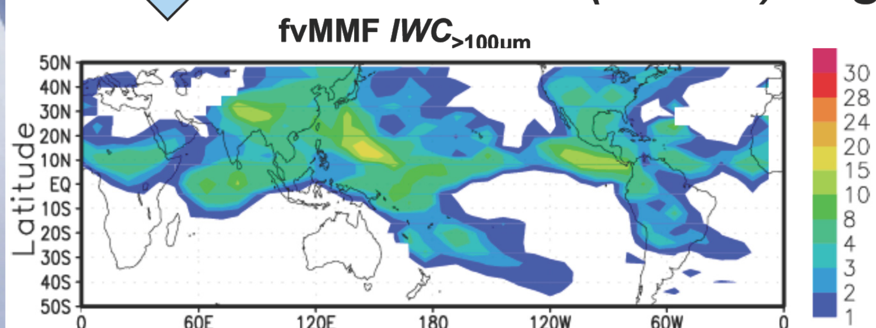


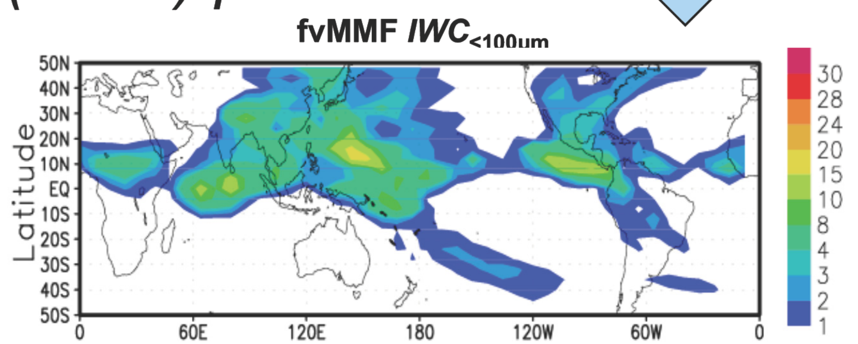
Estimates of

precipitating ice mass **cloud ice mass**

Comparison to fvMMF

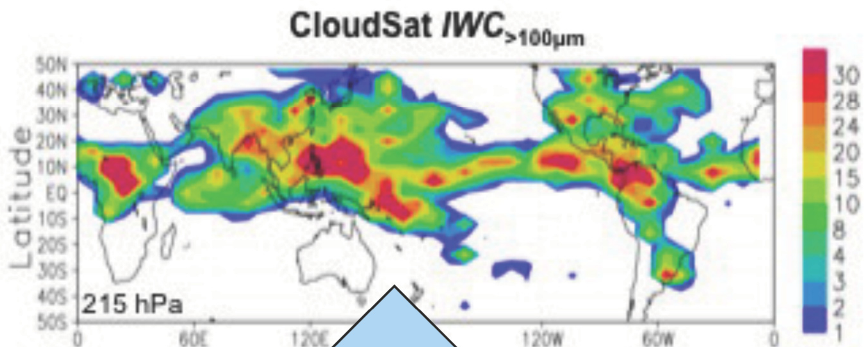
-> too little (much) big (small) particle mass

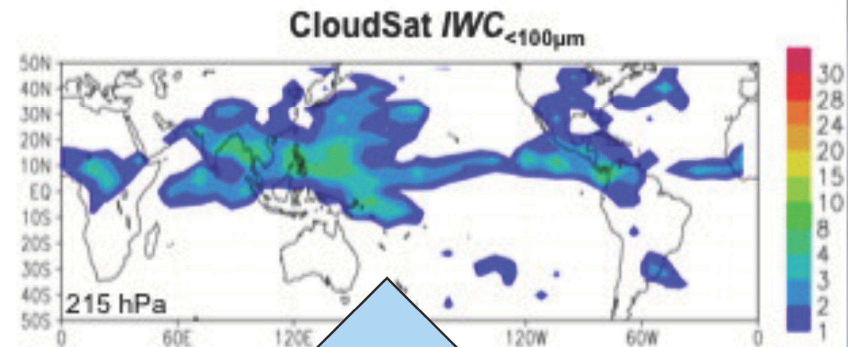




A Better Way? : Getting Better Ice Constraints

Exploring Use of CloudSat-Provided PSD Information



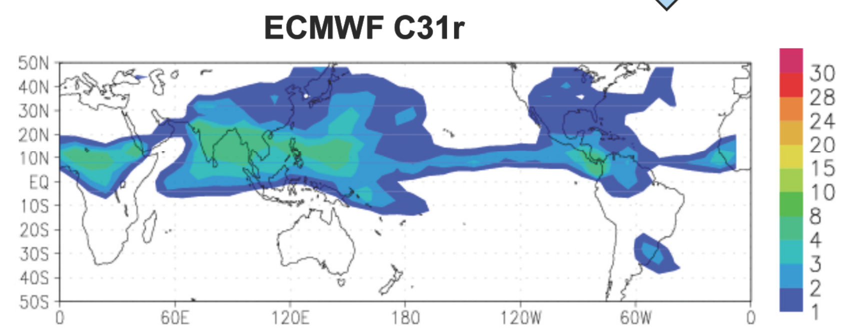


Estimates of

precipitating ice mass **cloud ice mass**

Comparison to ECMWF

-> good agreement on "cloud" mass

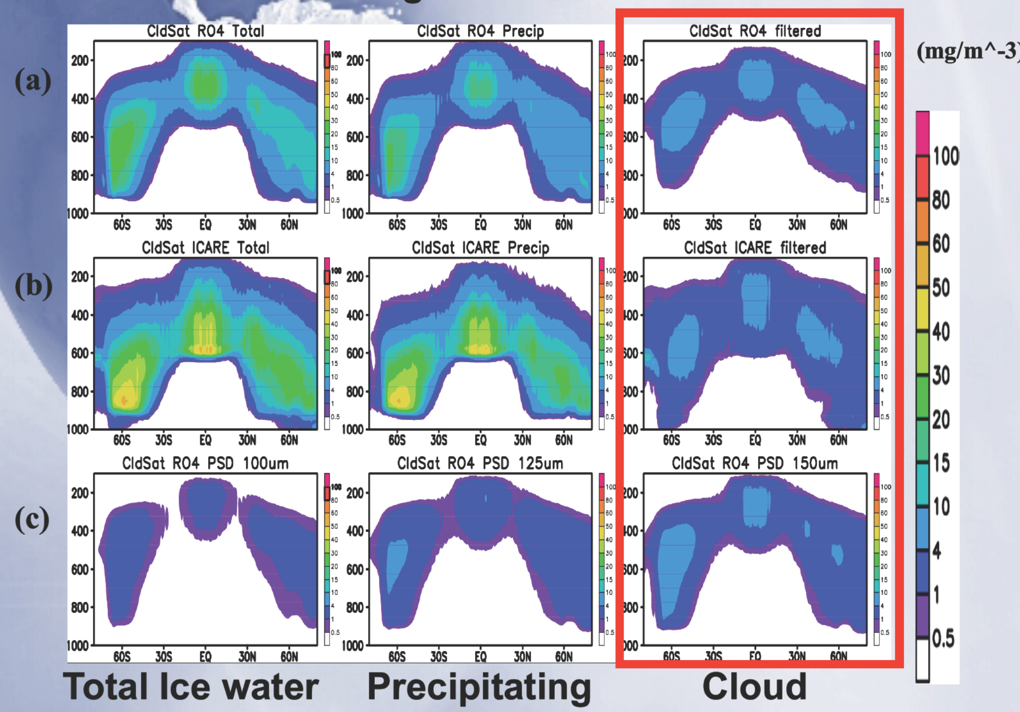


Model Evaluation of Ice/Liquid Water Content, Radiation and Energy budget for 20th Century IPCC AR 4th and 5th Simulations (Frank, Duane and Graeme)

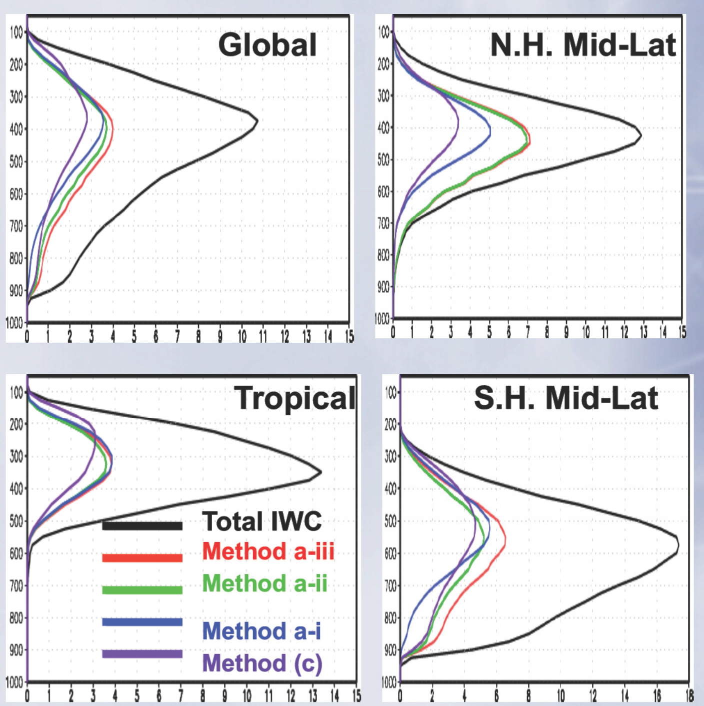
- Precipitating and convective core cloud hydrometeors and their radiative effects are generally ignored in global climate models (GCMs) such as those used in IPCC AR 4th and 5th.
- Remote sensing, such as CloudSat and CERES, are sensitive to all particles including precipitating and floating cloud hydrometeors and their radiation.
- Methods used to filter out cloud hydrometers in convective/precipitation cases to get ballpark estimates of clouds for use in IPCC model evaluation are <u>based on:</u>

(a) Cloud (i),column classification(ii), precipitation surface flag (iii) (Li et al., 2008; Waliser et al., 2009)
(b) same as (a) but using CloudSat+CALIPSO combined products (Delanoe et al., 2010)].
(c) estimated particle size distribution (Chen, Waliser, Li et al. 2011).

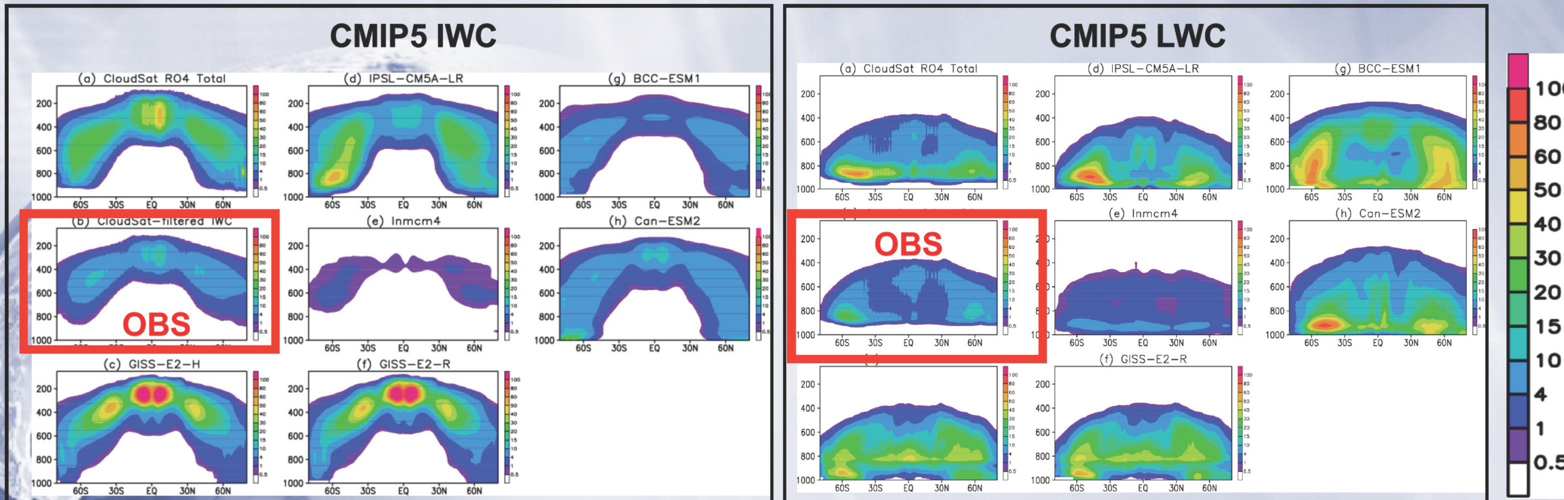
Zonal Average CloudSat Estimates

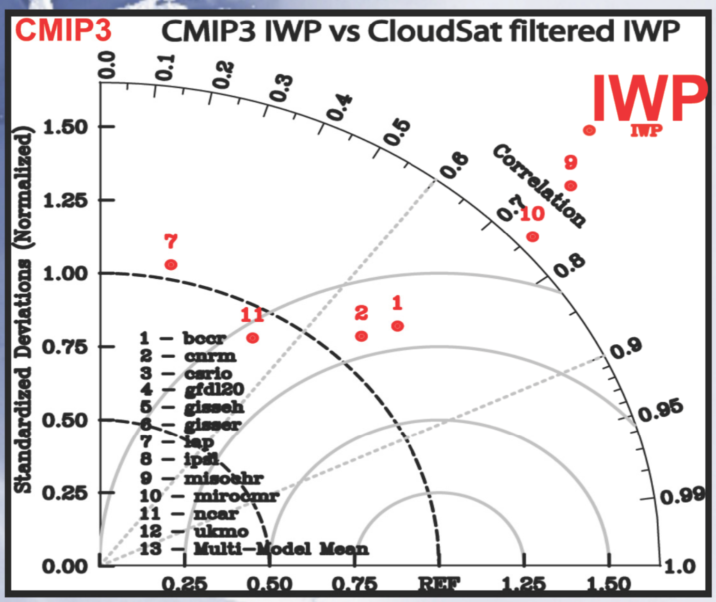


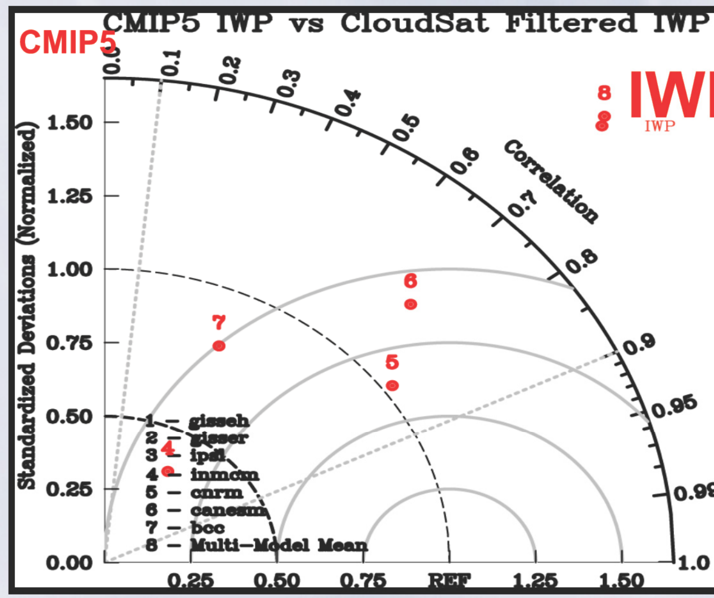
CloudSat Estimates of Ice Cloud Profiles



CloudSat IWC/LWC Estimates for Model Evaluation for 20th Century CMIP3 and CMIP5 Simulations



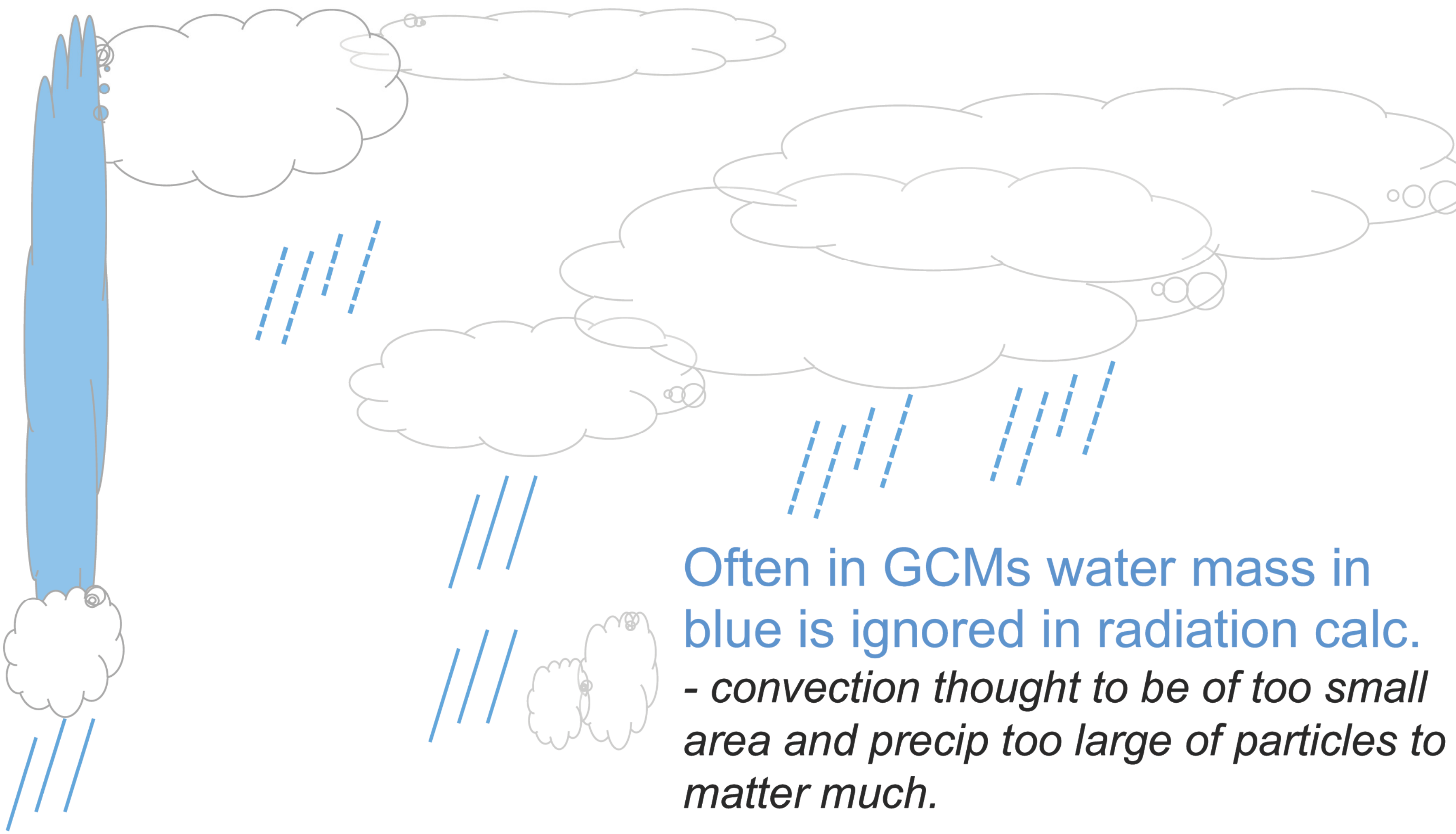




Significant biases are identified in IPCC CMIP3 and CMIP5 against CloudSat estimates. This implies that the conventional GCMs might give excessive surface SW and TOA LW fluxes

Cloud-Radiation Application of above IWC Considerations

Issues of GCM specification of particle type and sizes have important implications for radiation calculations

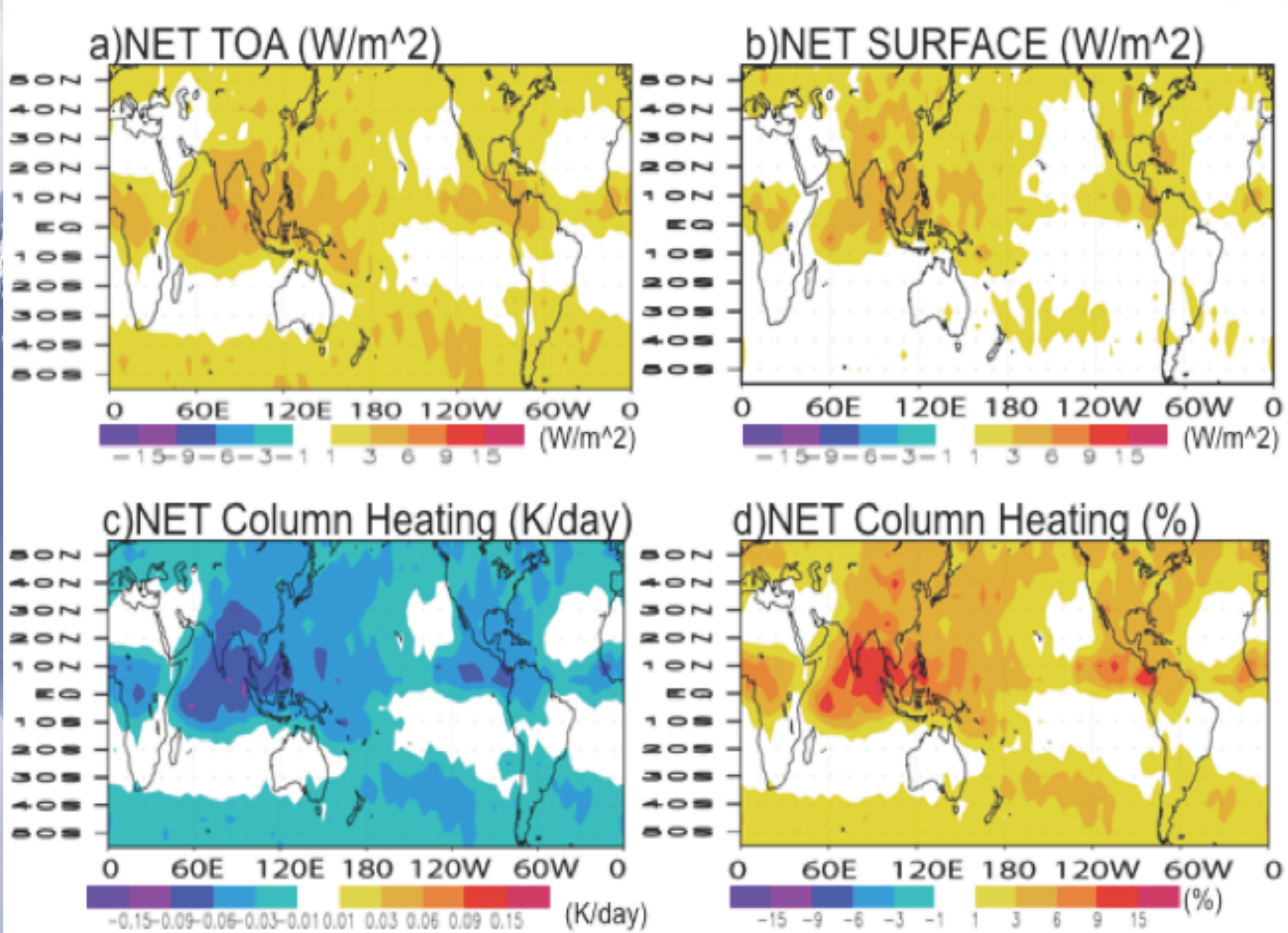


Often in GCMs water mass in blue is ignored in radiation calc.

- convection thought to be of too small area and precip too large of particles to matter much.

Net Radiative Heating: Exp – Control

June – August 2007



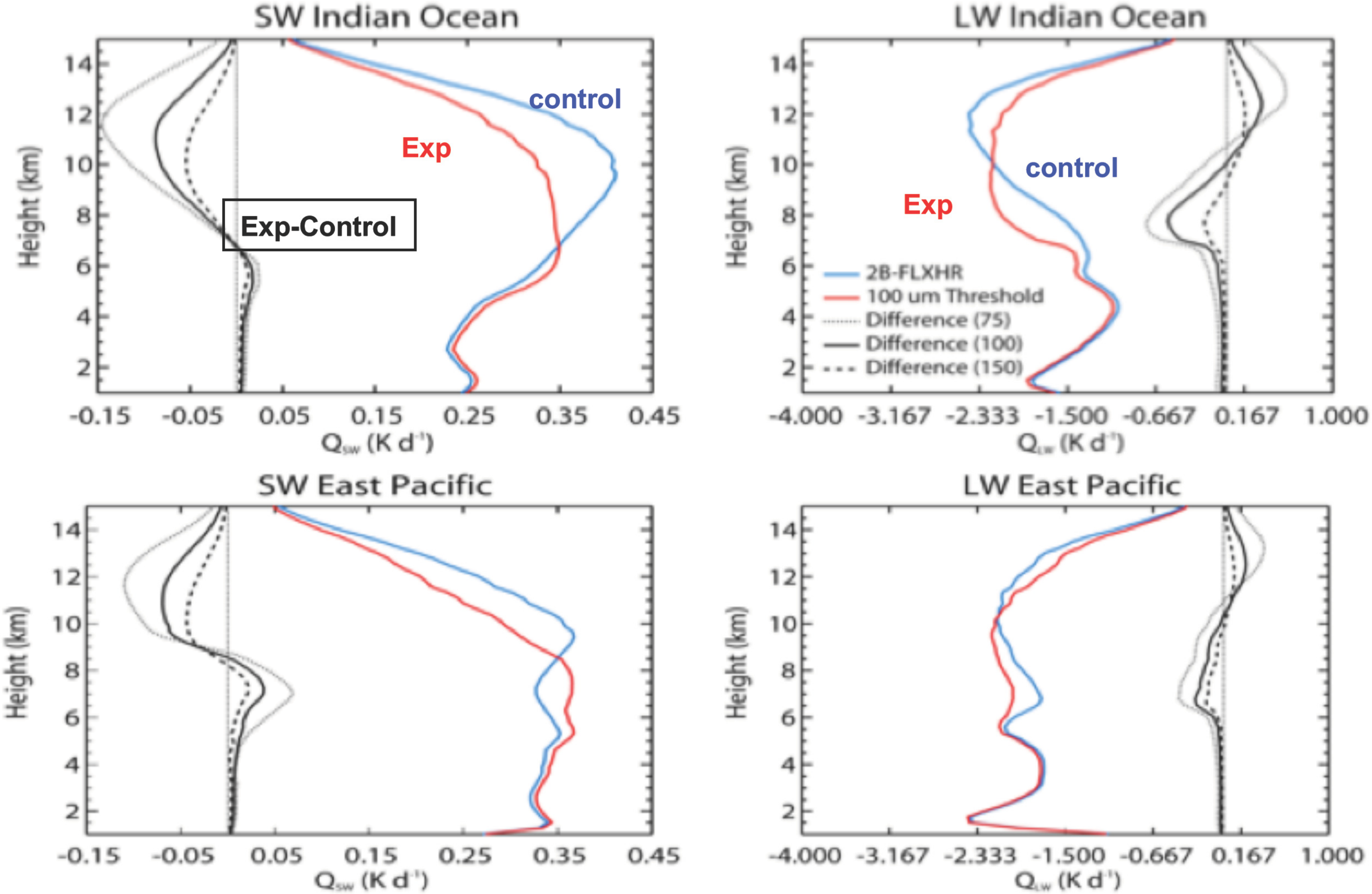
Waliser, Li, L'Ecuyer, 2011, GRL, In Press.

Impact on Radiative Heating Profiles

Shortwave heating profile | **Longwave heating profile**

Indian Ocean

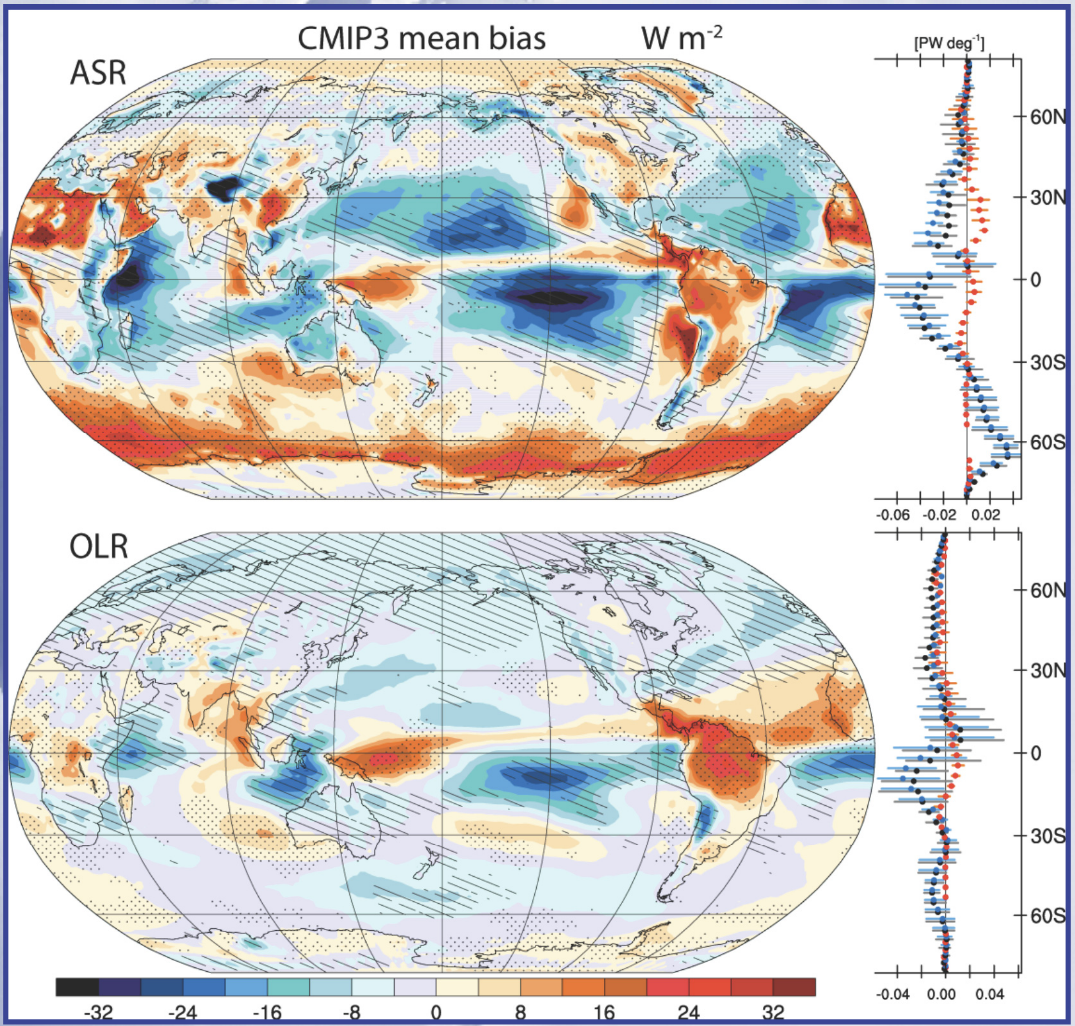
Eastern Pacific Ocean



Errors in the vertical distribution of heating will negatively impact the circulation as well as possibly the response to external forcings such as changes in GHGs.

Implications and Impacts

Annual Means



Trenberth and Fasullo, 2009

1. Models not accounting for this are getting TOA balance *incorrectly* with compensating errors in quantities such as cloud cover, cloud particle effective radius and/or cloud mass AND/OR regional biases

2. Errors in the vertical distribution of heating will negatively impact the circulation as well as possibly the model response to external forcings such as changes in GHG

3. Next steps: Examine within GCM to find supportive evidence and impact on dynamics & do for liquid.

Summary

- There are a wealth of opportunities to apply satellite data to the evaluation and improvement of climate models.
- Understand and scrutinize both the model representation and the observati … ke meaningf …
- Ask ques … vity of the measurer … gnostic, what is modele …
- Satellite s … g model – measurer … s significant care and …
- Consider … on diagnostics/metrics and explore new ones.
- Don't hesitate to consult the observation and/or modeling teams & experts. Both will be glad you are using/evaluating their product.