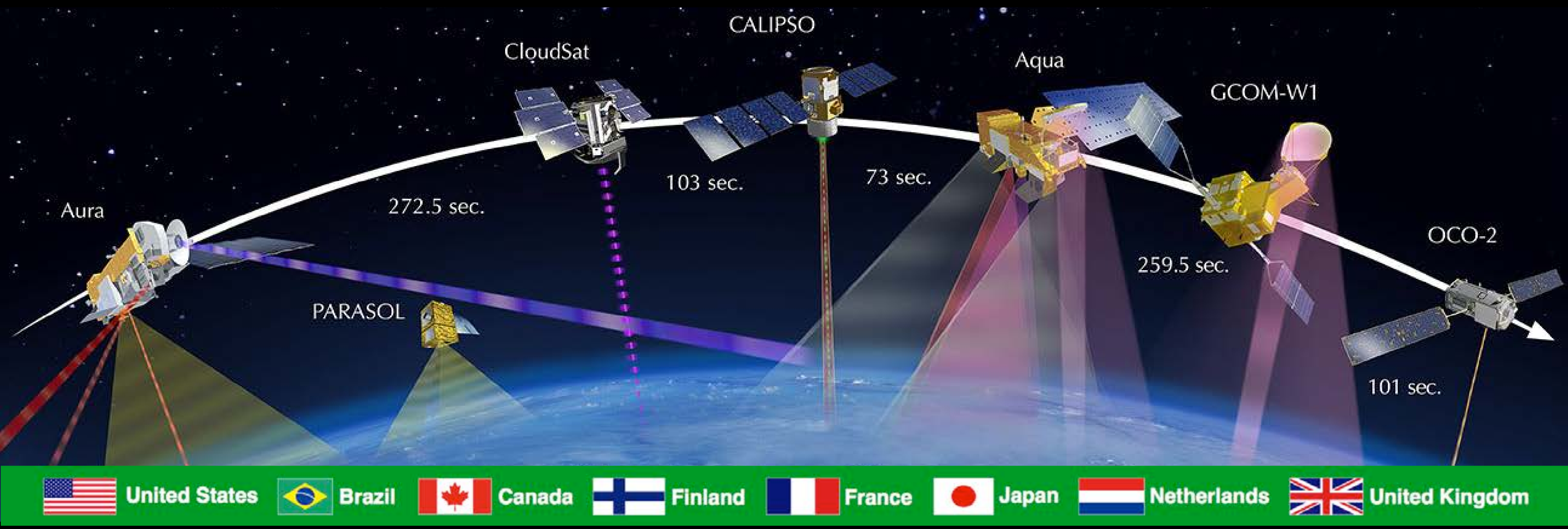
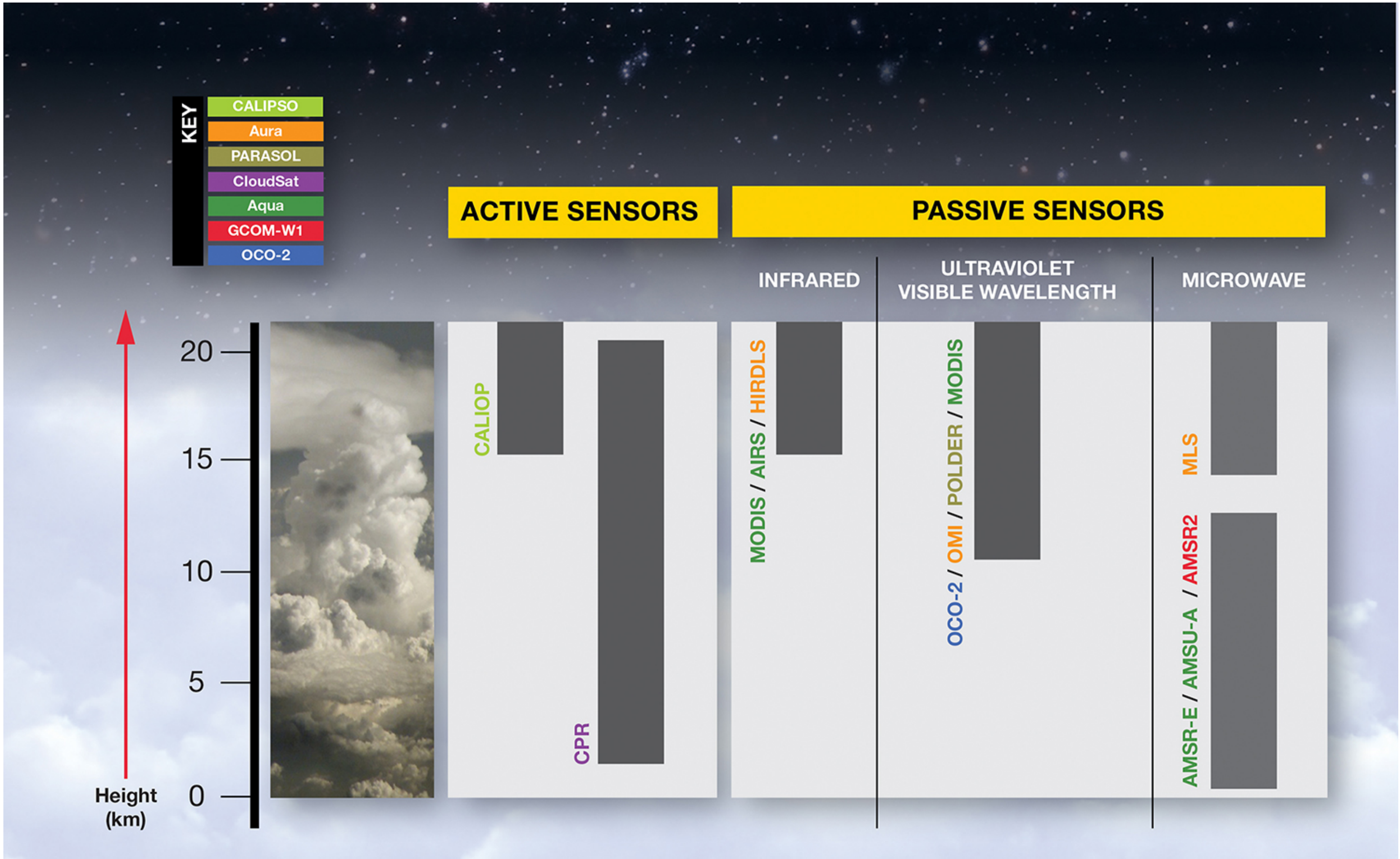


A-Train formulation with the arrival of CloudSat and CALIPSO as motivated to a large degree by a desire to better understand clouds and aerosols and their impact on the radiation budget and hydrological cycle

A-Train Sensor Diversity – when data are combined new insights on important processes are revealed



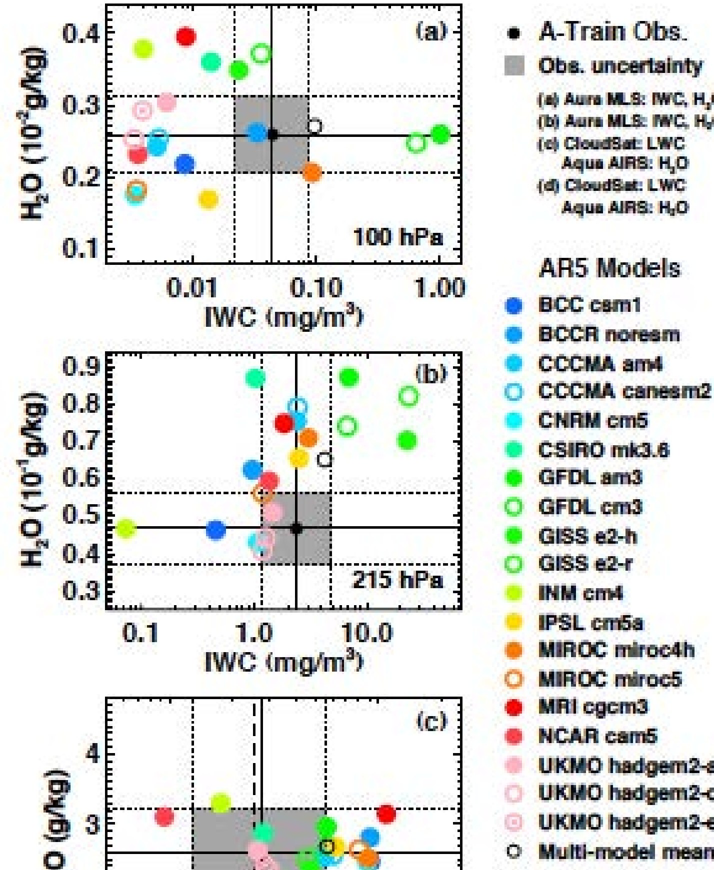
An example of the diversity

A-Train science is having an profound impact. There is a large & growing number of A-Train papers in the peer reviewed literature.

- Two CloudSat based papers were the #1 (Suzuki et al) and #2 (Riely & Mapes) downloaded papers of 2012 in AMS and a third AIRS paper was #7
- One multi-sensor A-Train paper was the #6 most downloaded JGR papers of 2012 (Jiang et al., 2012)

A-Train data are also impacting model development.

The value of A-Train data will only increase in time as the data record lengthens



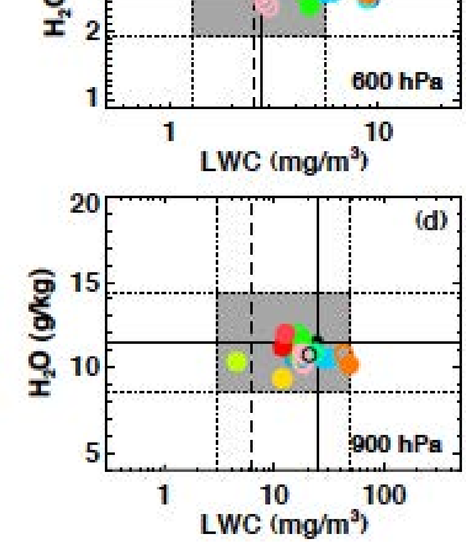


Figure 4: Scatte (30°N-30°S) oc means: H_2O versu 215 hPa, H_2O ve and 900 hPa. R AR5 models ar observations are area and the dot the observational dashed lines at indicate CloudSat discussed in the te

Jiang e

What are some new science achievements enabled by the A-Train?

Integration across different observations platforms & sensors leads to:
(i) Richer validation of key products and expansion to fill in voids
(ii) Extraction of new products from combinations of different matched observations,
(iii) Combination products to yield new insights on processes
(iv) With (i)-(iv), provide a more integrated view of Earth far beyond that which had been possible.

What has made A-Train multi-disciplinary science possible?

(i) Public availability of Level 1 and 2 data,
(ii) Public availability of key documents (instrument descriptions, ATBDs, , open documentation of known problems, etc),
(iii) Easy data access of data & sharing of data
(iv) Open science team meetings
(v) Careful management of constellation flying (e.g. MOWG)

What are some other advantages?

Ability to share calibration and validation efforts across missions (e.g. C3VP= Cloudsat+CALIPSO+GPM, LpVex)

The A-Train data depot

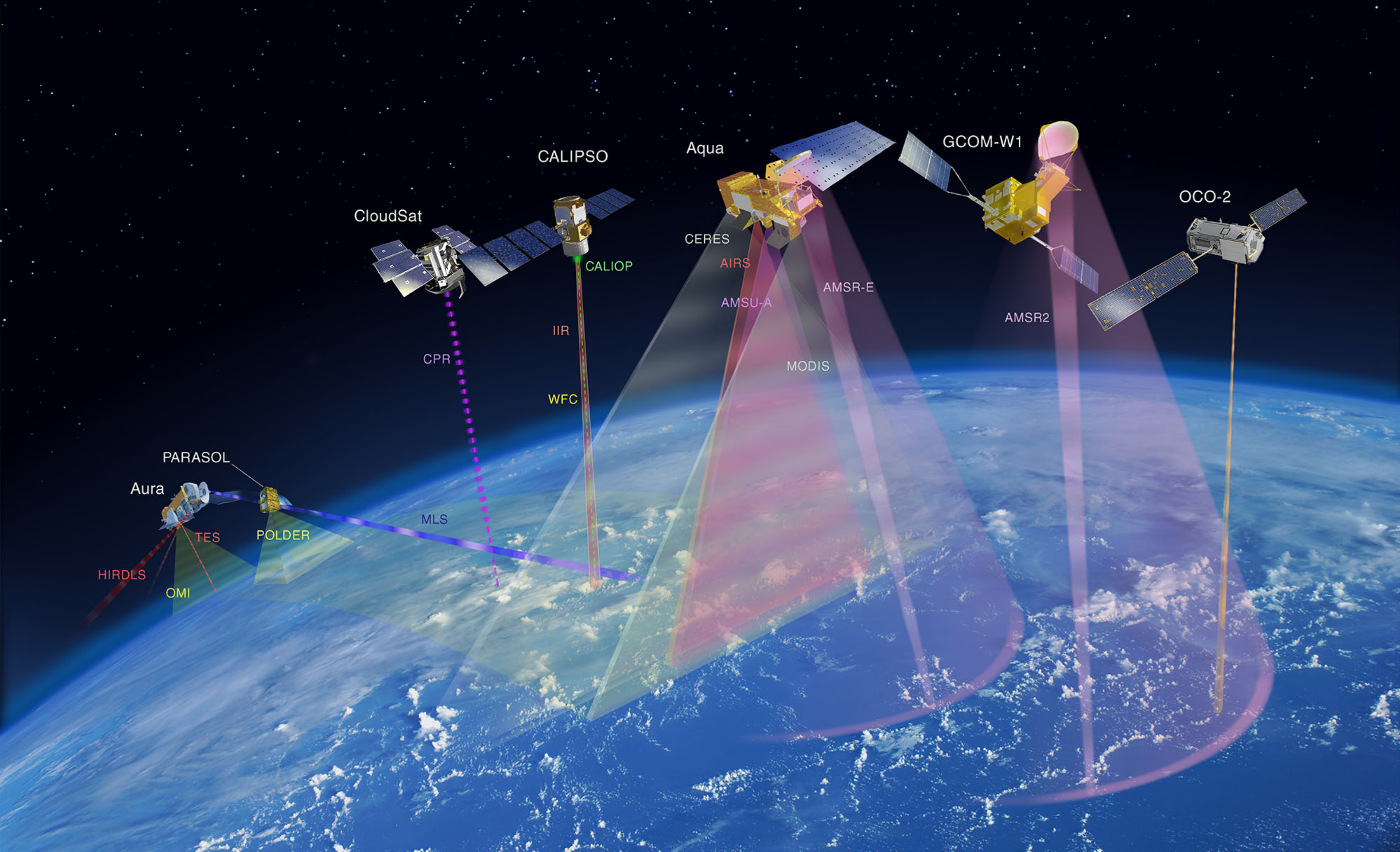
Selected highlights with a little illustration of AMSR-E A-Train science

Science highlights - the A-Train *constellation* science has two flavors

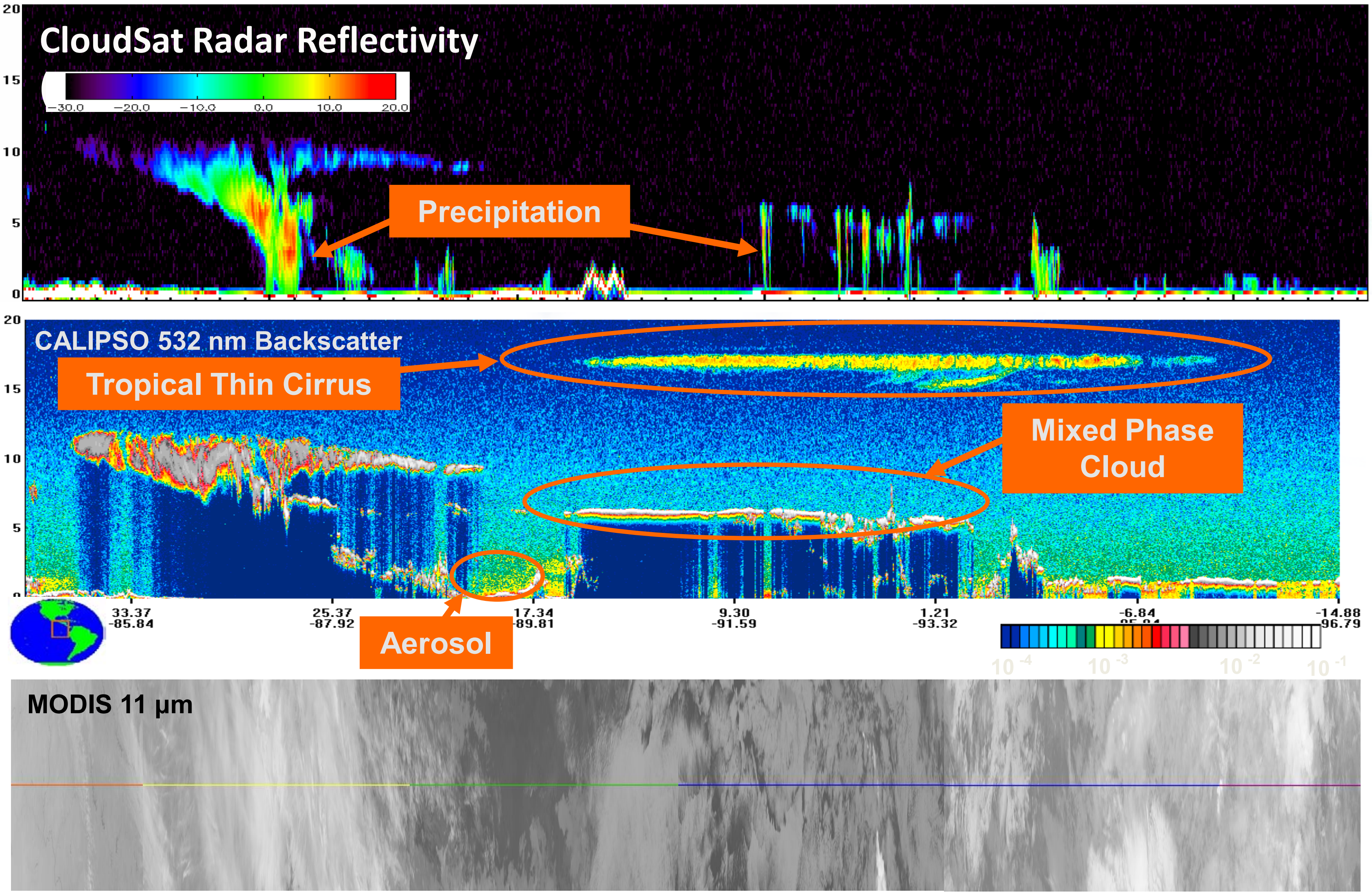
- – Science that results specifically from matching individual level 1 'footprint' data & integrating to produce new products
- – Science that results from matching level 2 (and level 3) product data more broadly to examine relations between variables

- The iconic A-Train result due to formation flying creating a virtual observatory
- Combining data for new insights on convection
- Combining data for new insights on aerosol/cloud/precipitation
- Enhancing global precipitation products

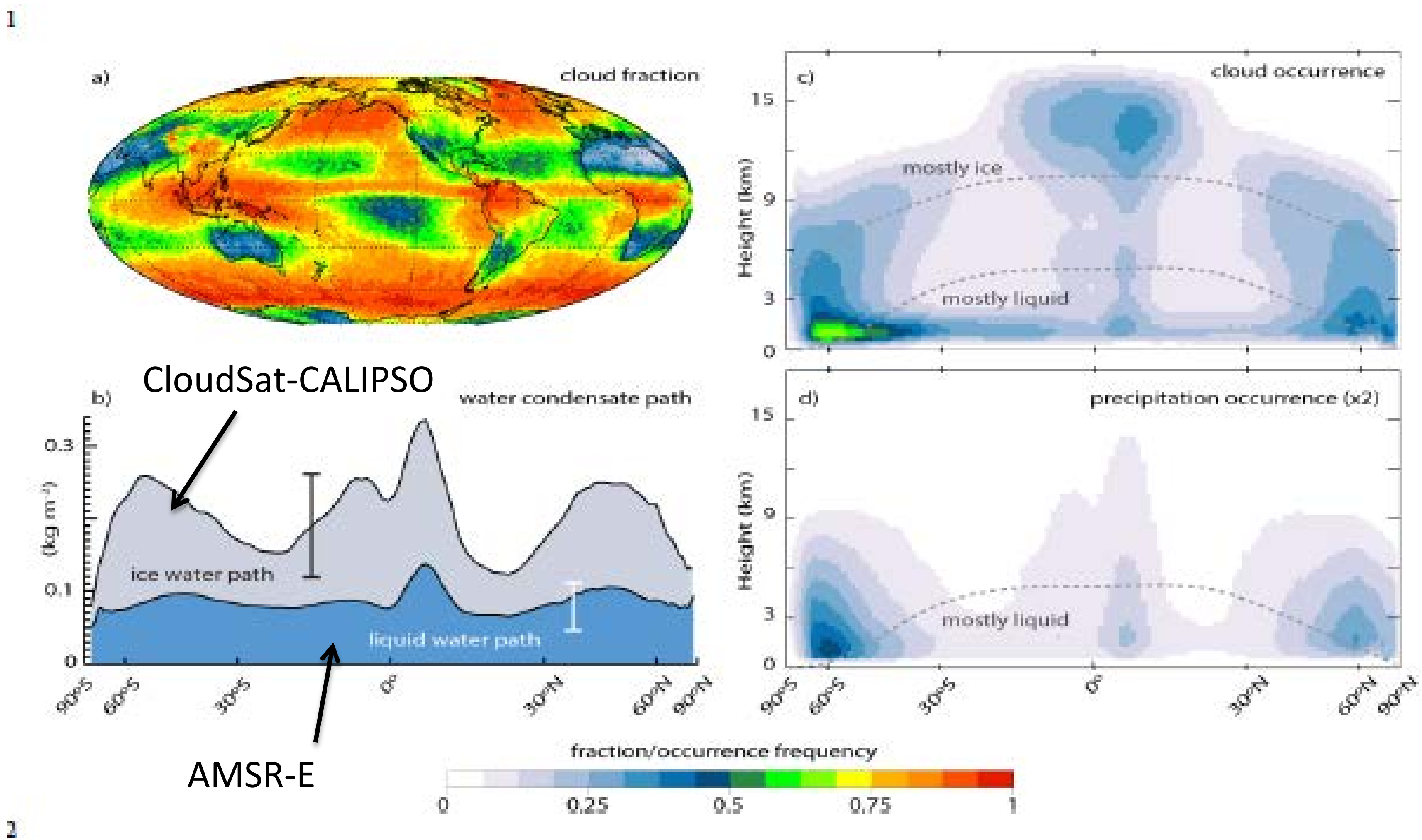
Formation flying enabling science



A-Train demonstrated how formation flying can create a virtual 2 satellite radar-lidar observatory. Matching footprints yielded important new products.

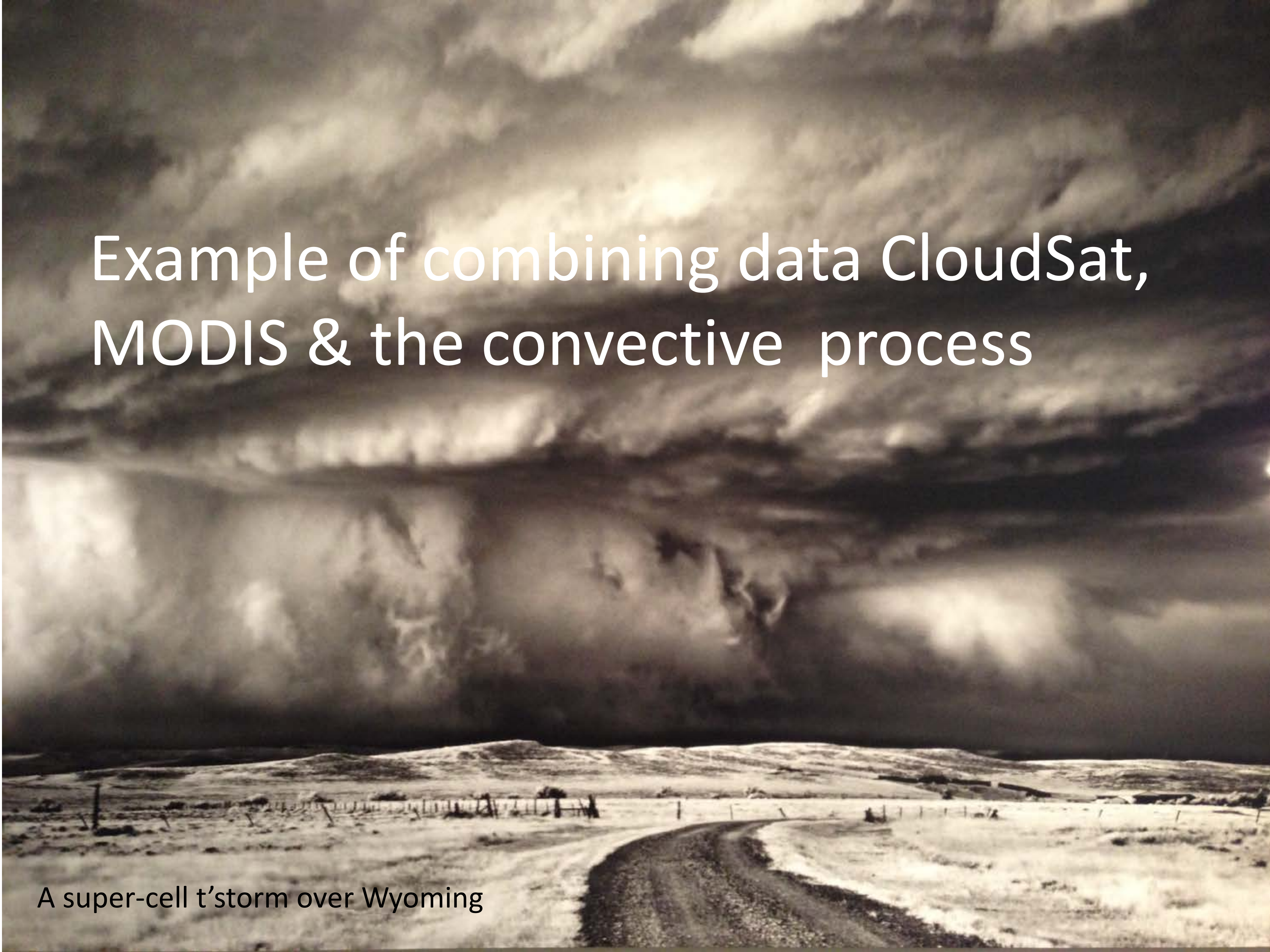


Iconic A-Train formation flying result



Cloud and precipitation frequency (Fig. 7.4, Chapter 7 of IPCC AR5) and ice and water contents adding truly a new dimension this could not have been possible without the careful matching of footprints that resulted from formation flying.

Example of combining data CloudSat, MODIS & the convective process



A super-cell t’storm over Wyoming

ON THE HEAT BALANCE IN THE EQUATORIAL TROUGH ZONE

by

HERBERT RIEHL

The University of Chicago

and

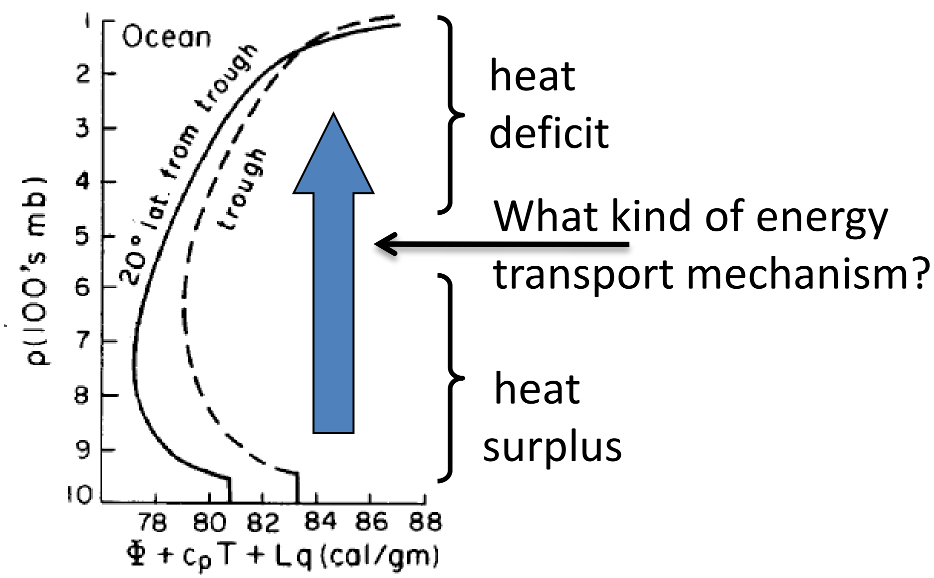
JOANNE S. MALKUS

Woods Hole Oceanographic Institution

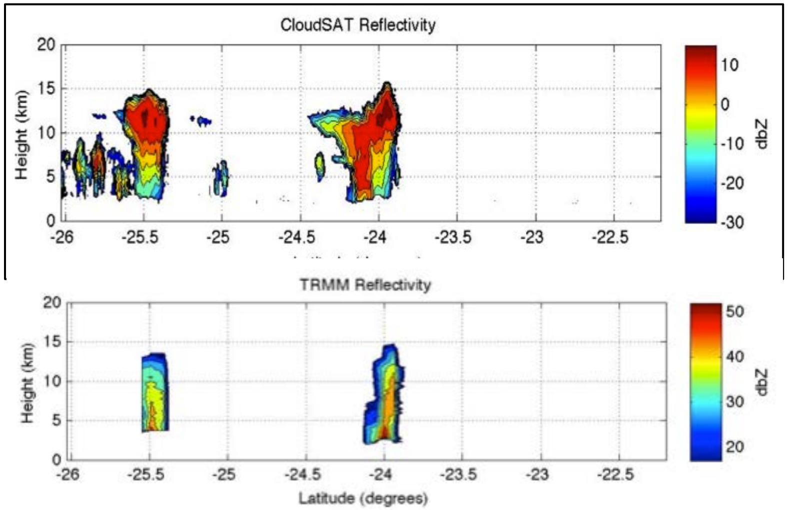
Abstract

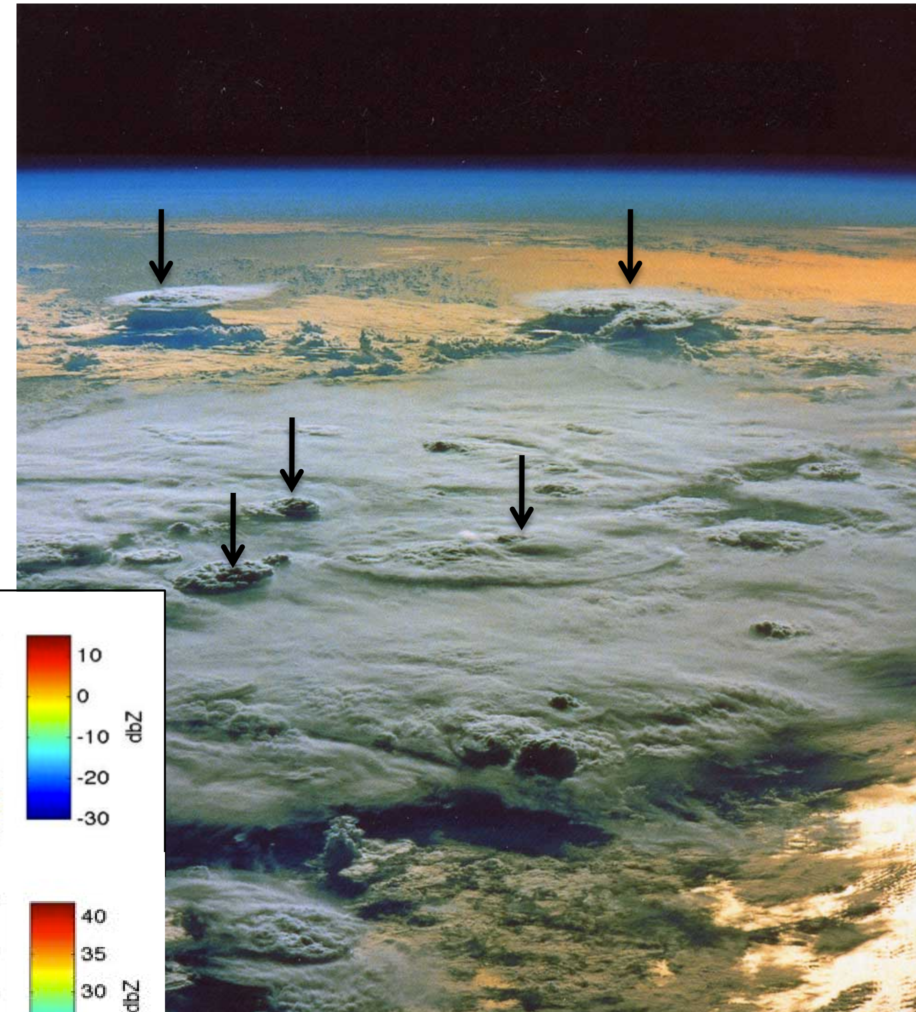
The equatorial trough zone receives the latent heat accumulated by the lower trades, lifts and converts the energy, balancing radiation losses, and exports the residue poleward aloft in the form of sensible heat and potential energy.

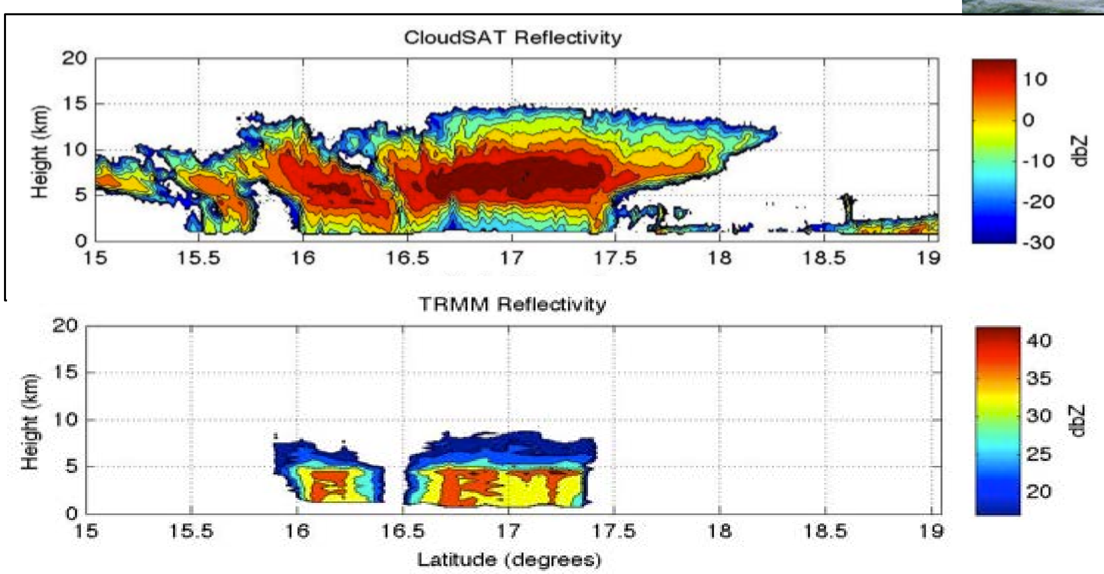
The classic Riehl and Malkus (1958) paper introduced the concept of “hot towers”.



The classic Riehl and Malkus "hot towers"







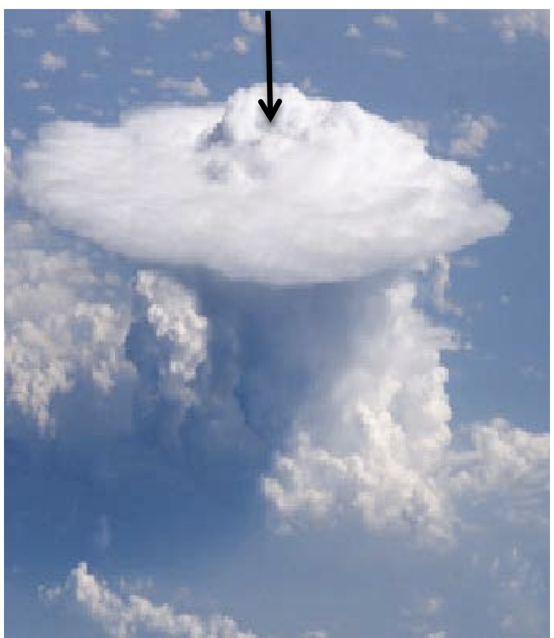
How tall are these hot towers (CloudSat/CALIPSO)?

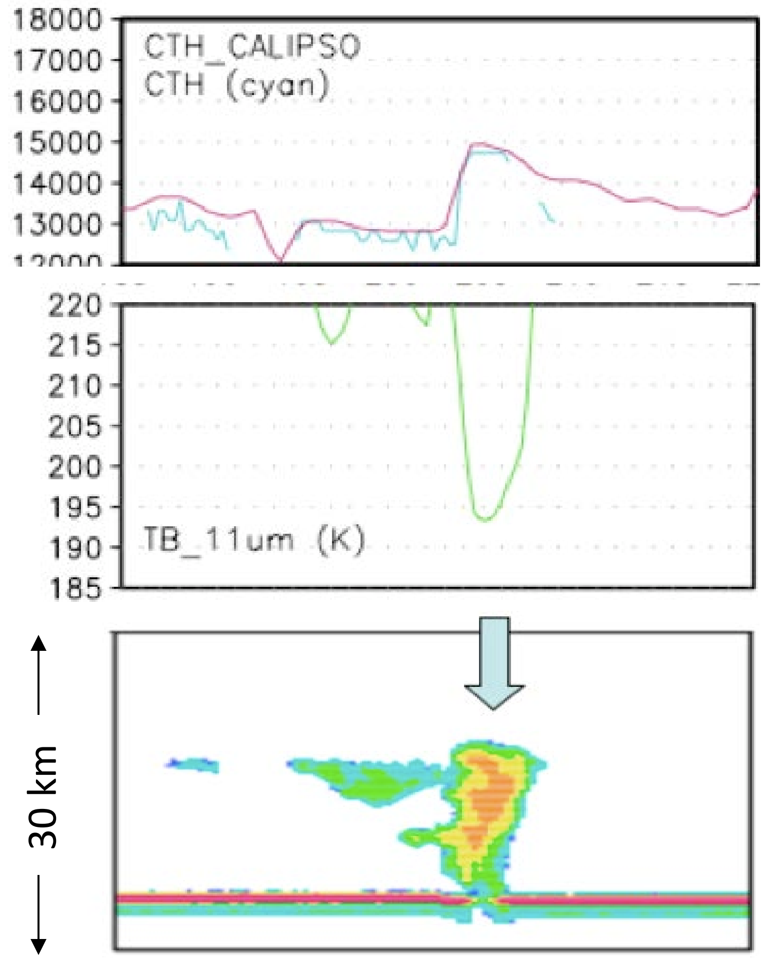
How cold are their tops (MODIS)?

How many hot towers?

(i) $T_{parcel} - T_{env}$
= bouyancy

(ii) $h = C_pT + gz + Lq$
h, h_{env} = entrainment

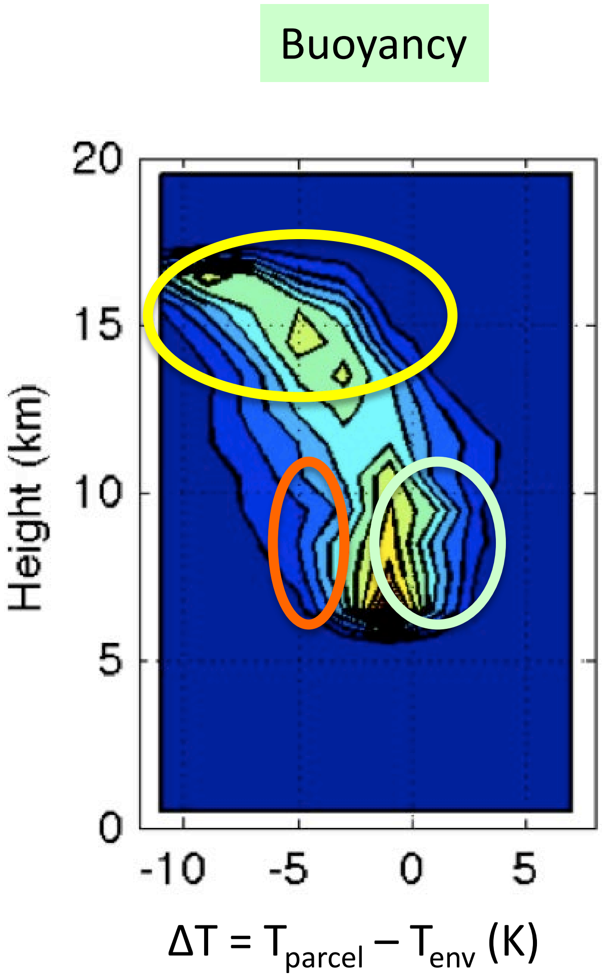


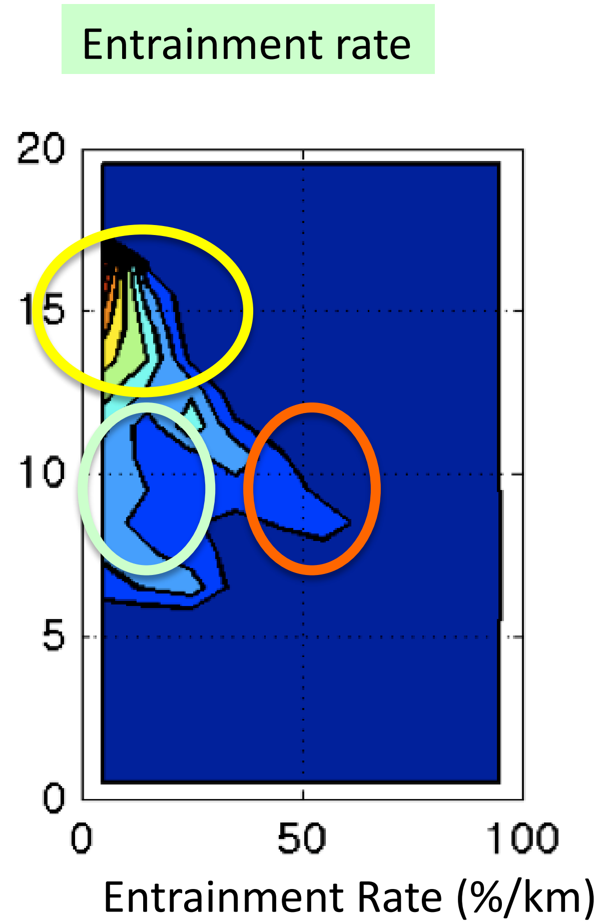


Cloud top height =z

Cloud top temperature (MODIS 11 μm TB) = T_{parcel}

CPR profile = identifies convective tower





Deep convection:
B <0 & λ < 10%/km

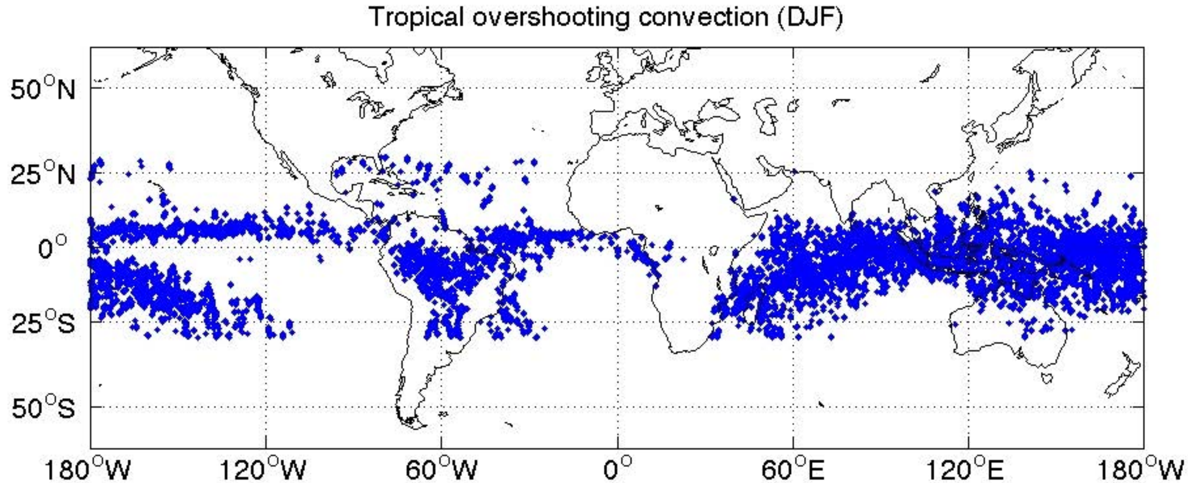
Luo et al. (2010)

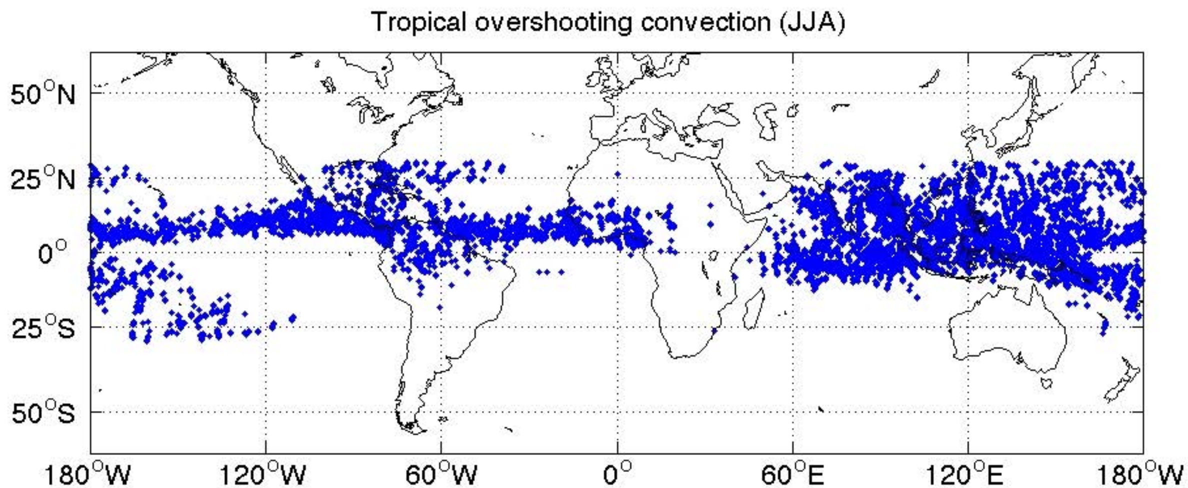
"Terminal" cumulus congestus:
B < 0 & λ up to 50%/km

"Transient" cumulus congestus:
B > 0 & λ ~ 10%/km

The combination of entrainment and bouyancy provides a tool to identify hot towers

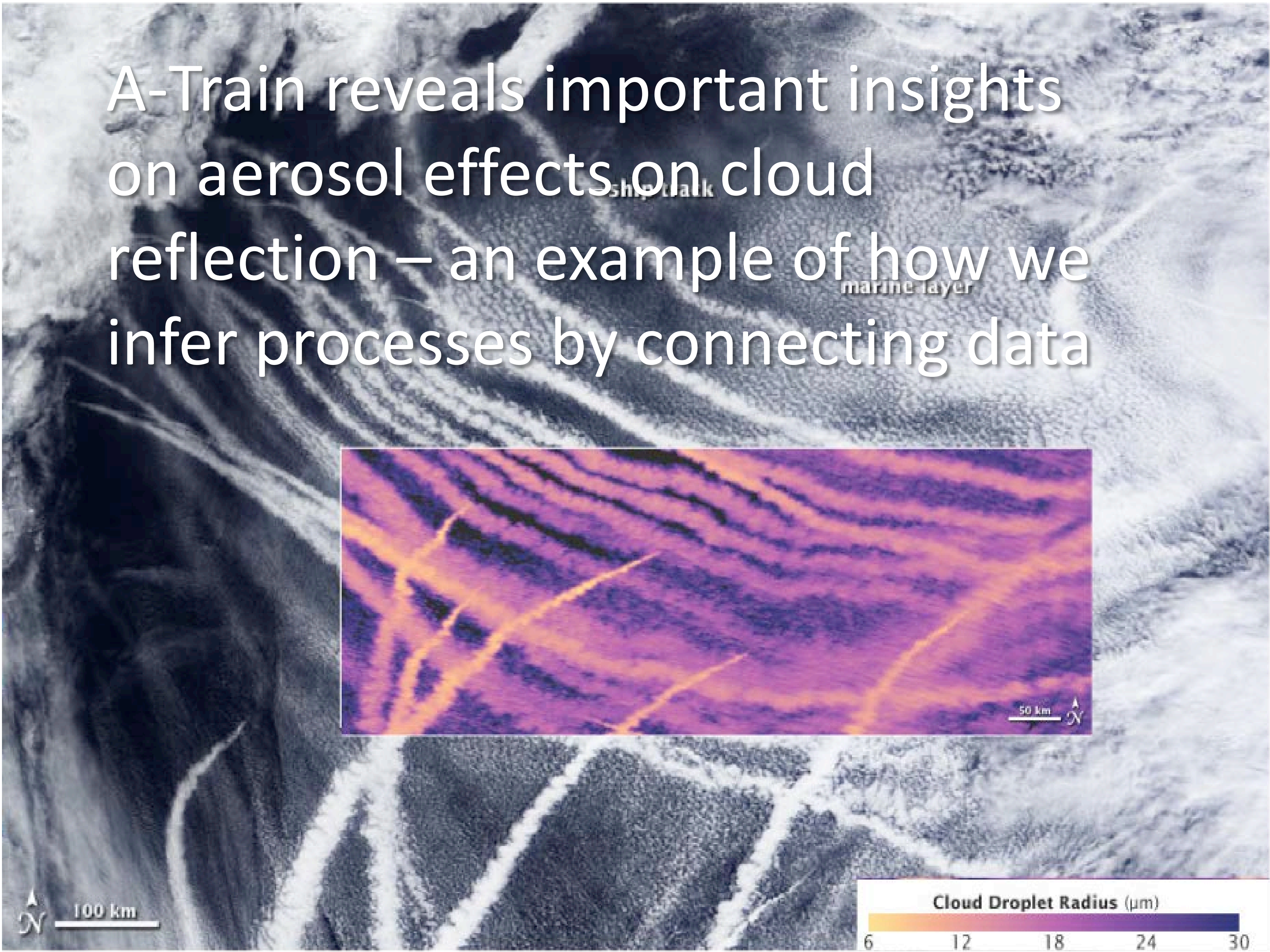
The first global map of hot towers





0.08% of tropics occupied by ‘hot towers’

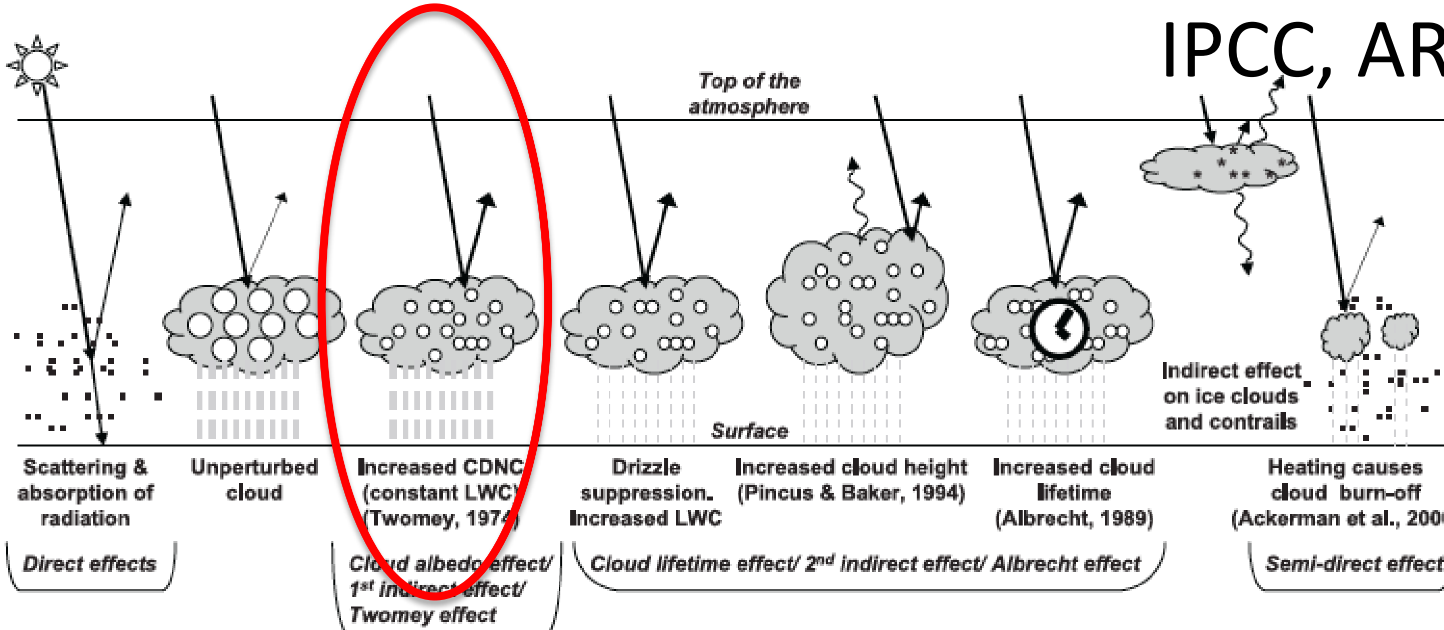
A-Train reveals important insights on aerosol effects on cloud reflection – an example of how we infer processes by connecting data

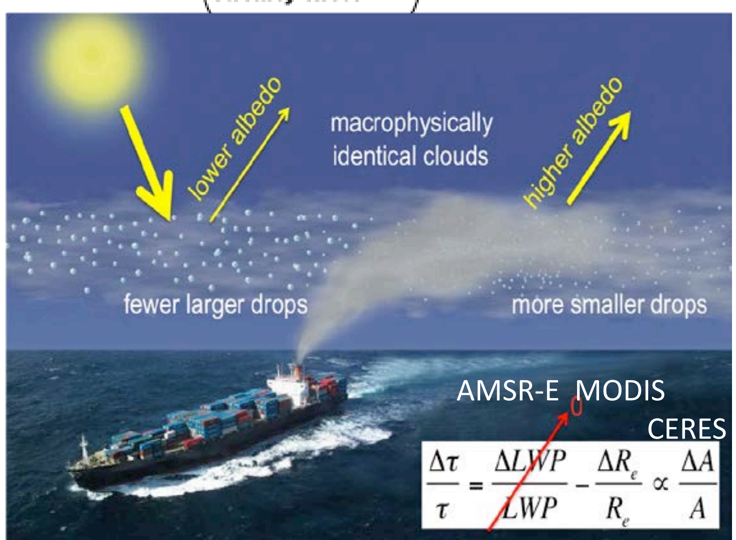


Aerosol indirect effects

The Twomey Effect

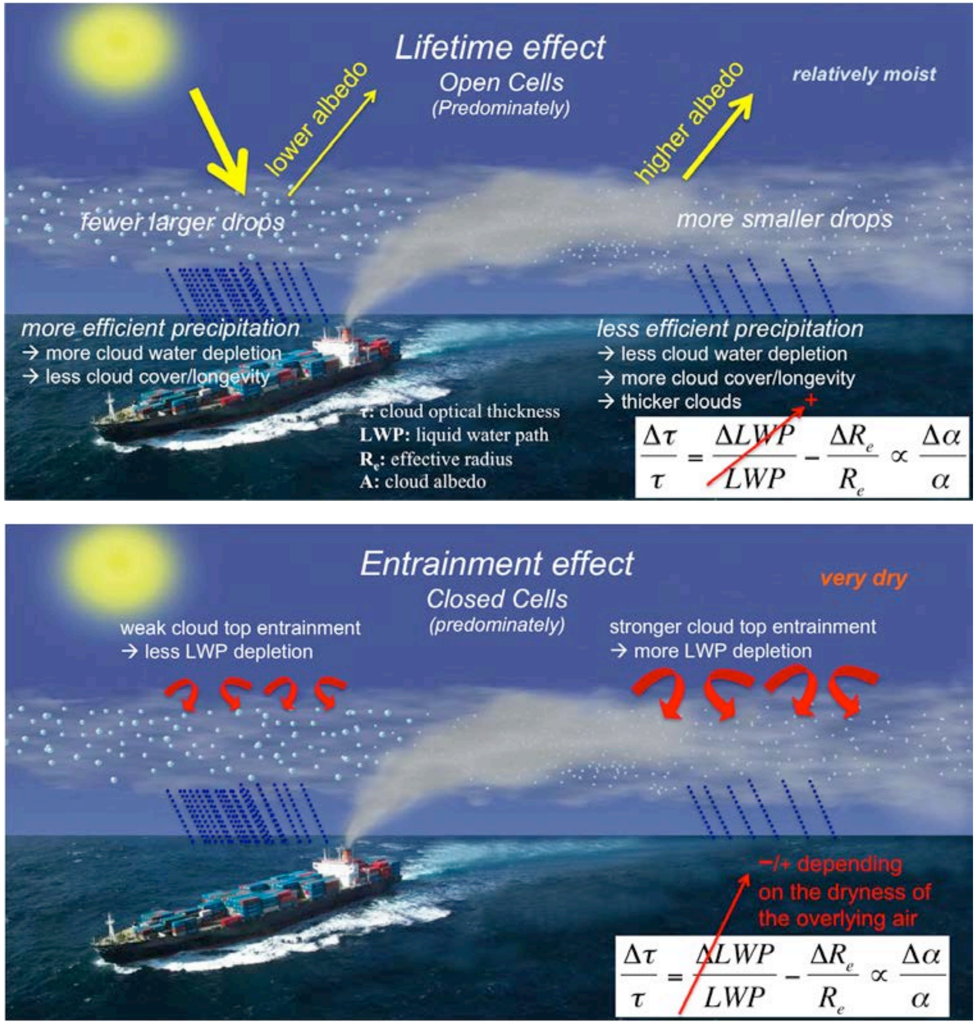
IPCC, AR4





Ship tracks are an example of how aerosol, interact with clouds. They are analogs for both the more global effects of aerosol on clouds and for geo-engineering concepts for modifying the albedo

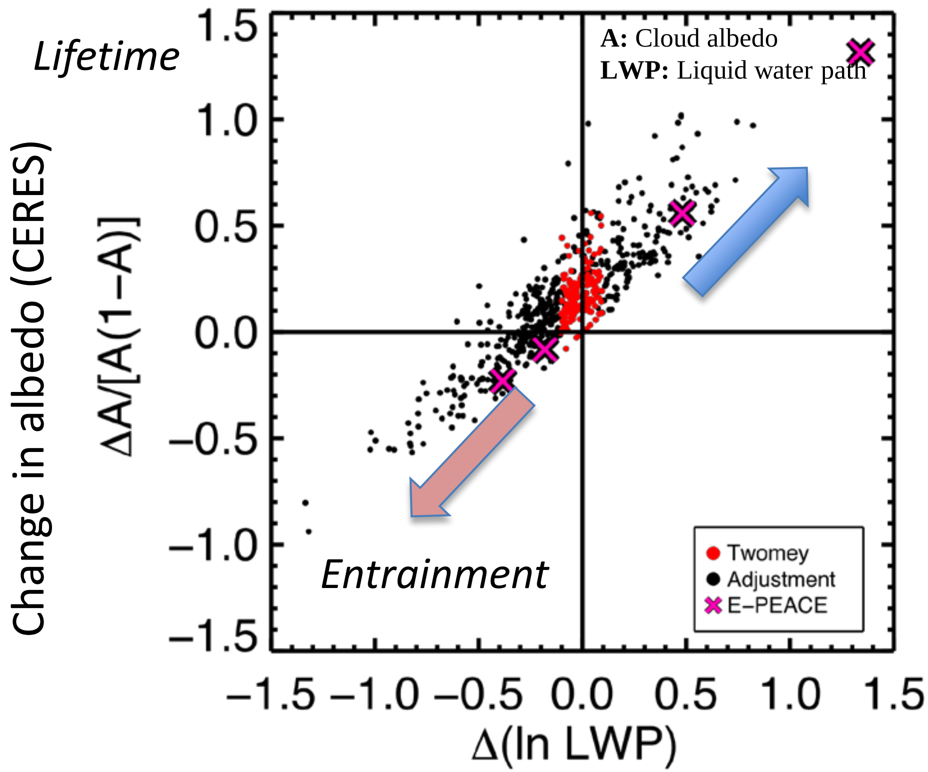
Aerosol effects on clouds – largest uncertainty in climate forcing and these too is shaped by the thermodynamic properties of the boundary layer/free troposphere



The buffering of cloud albedo

More aerosol does not always make clouds brighter

We have developed an A-Train ship track inventory that consists of Cloudsat, AMSR-E, CALIPSO, CERES and MODIS sensor data

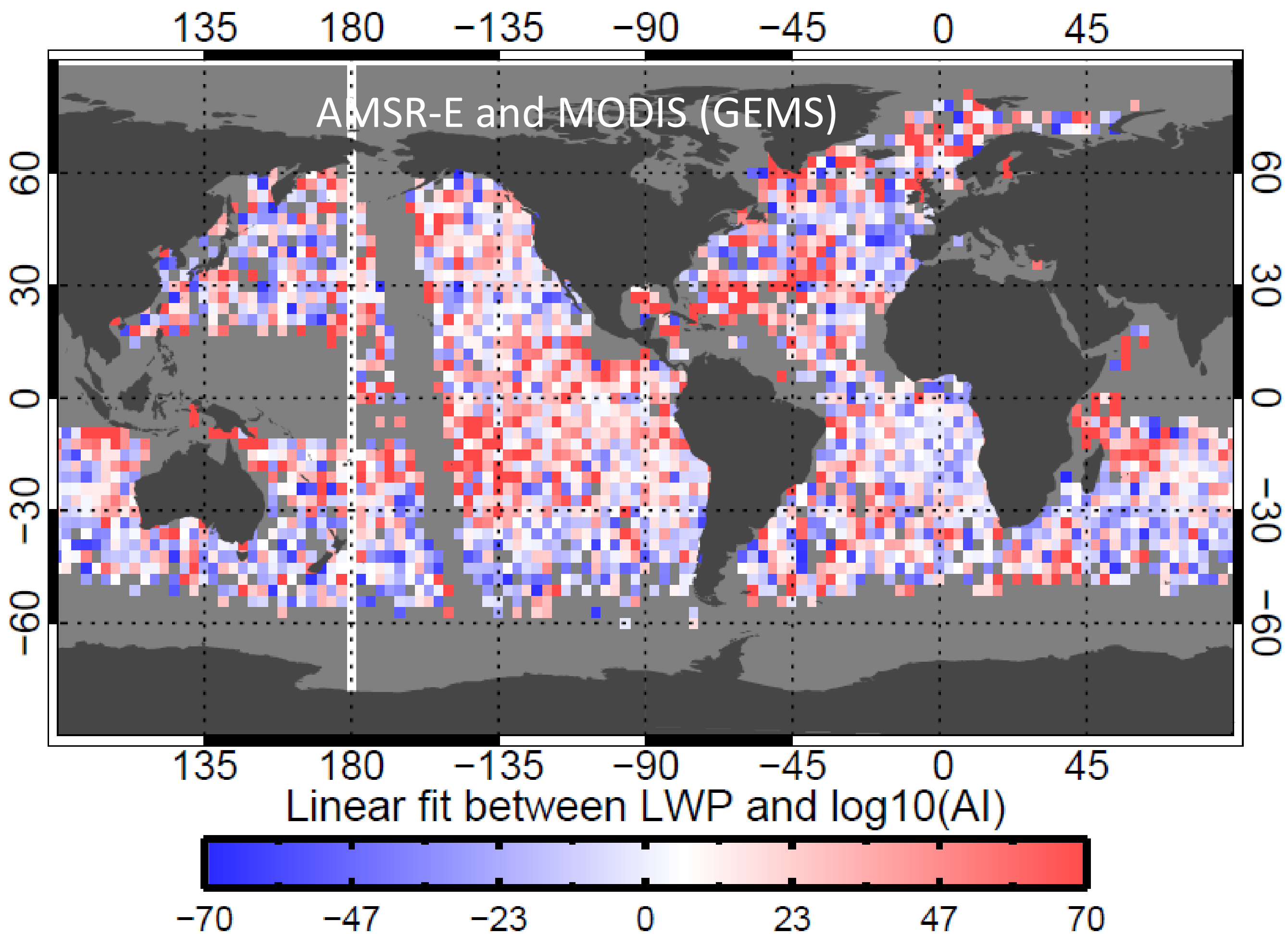


AMSR_E

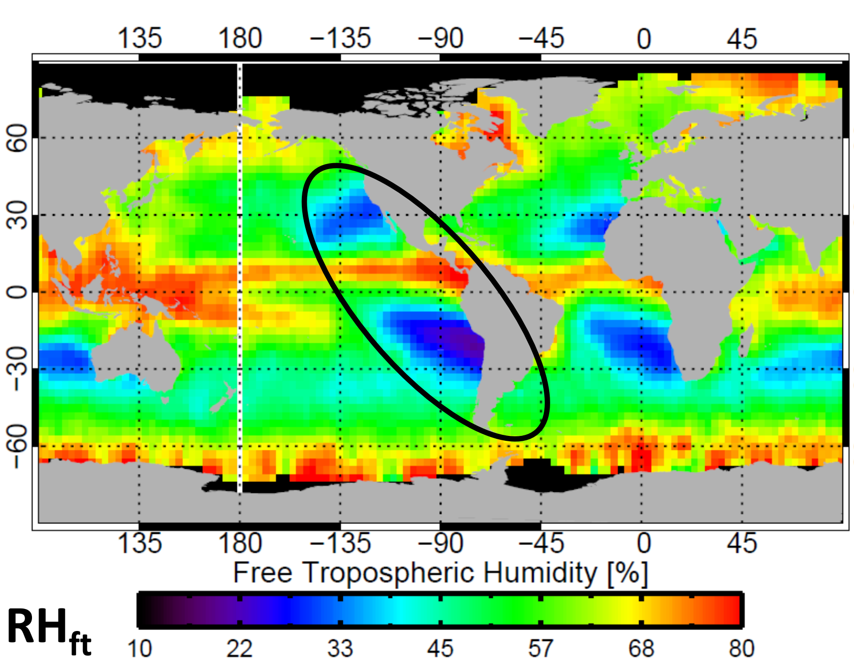
Chen, Christensen, Seinfeld & Stephens, 2012

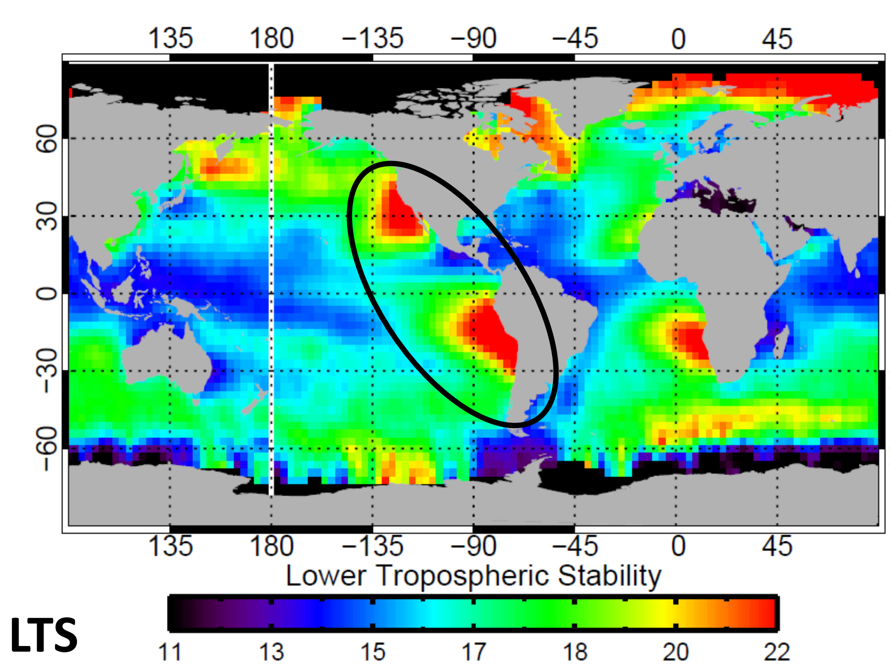
- Differences in liquid water path primarily determine the sign and strength of the cloud albedo response.
- Humidity above cloud tops is responsible for the differences in LWP.
- E-PEACE aircraft observations results agree with A-train observations.

The more global picture from the A-Train

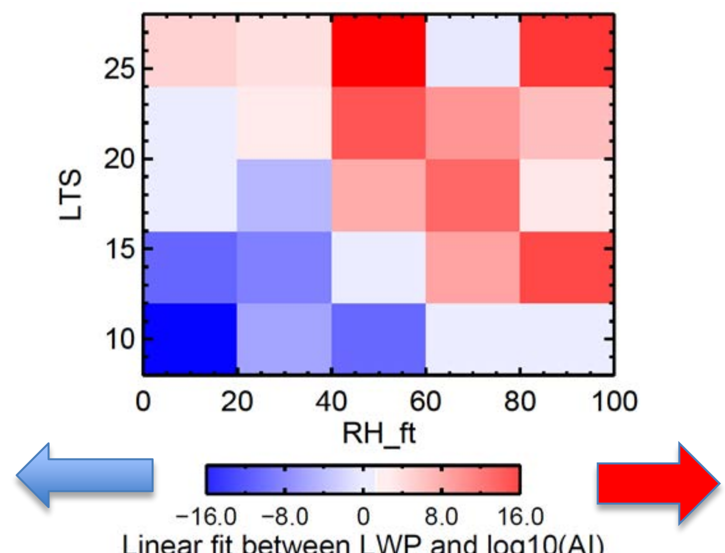


Correlation between AMSR-E lwp and aerosol





- Drier RH$_{ft}$ imply a decrease in LWP (through entrainment); yet higher LTS (more stable) inhibits entrainment restricting.
- Globally, dry areas with low RH$_{ft}$ correspond to areas of high LTS (where stratocumulus are prevalent). This confounds our ability to infer how LWP changes



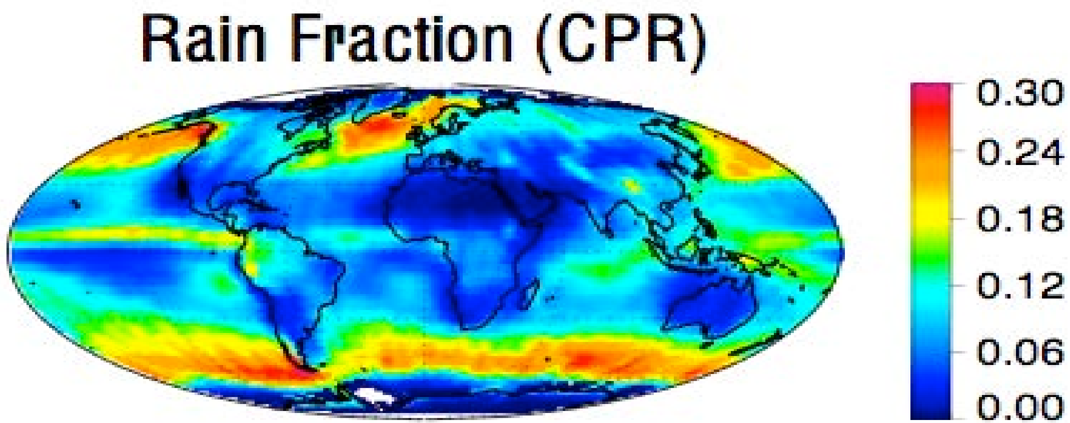
Chen, Christensen,Seinfeld and Stephens, 2013

More aerosol is associated with *less* liquid water implying a positive AIE

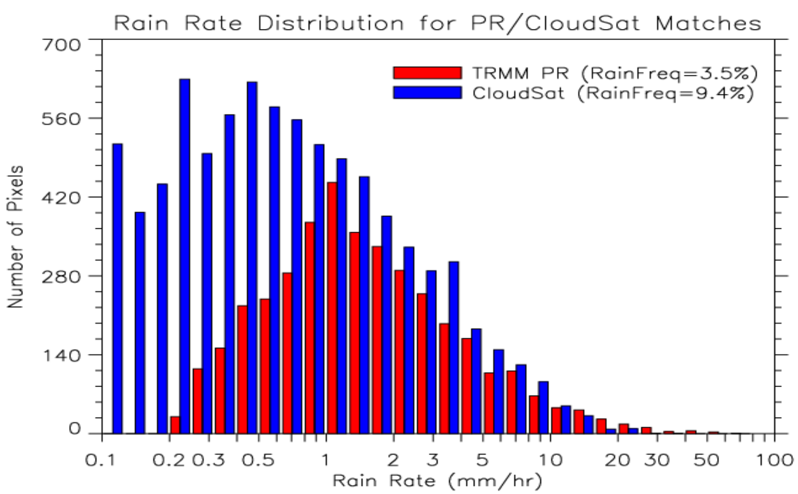
More aerosol is associated with more liquid water implying a negative AIE

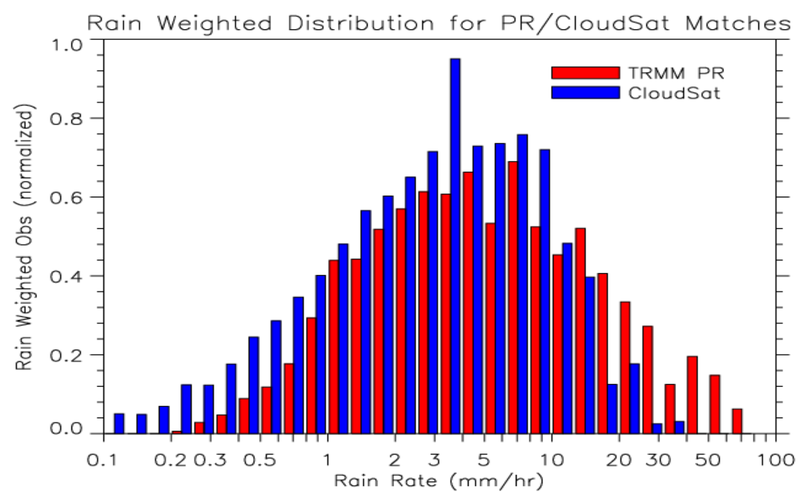
A- Train Precipitation

Precipitation



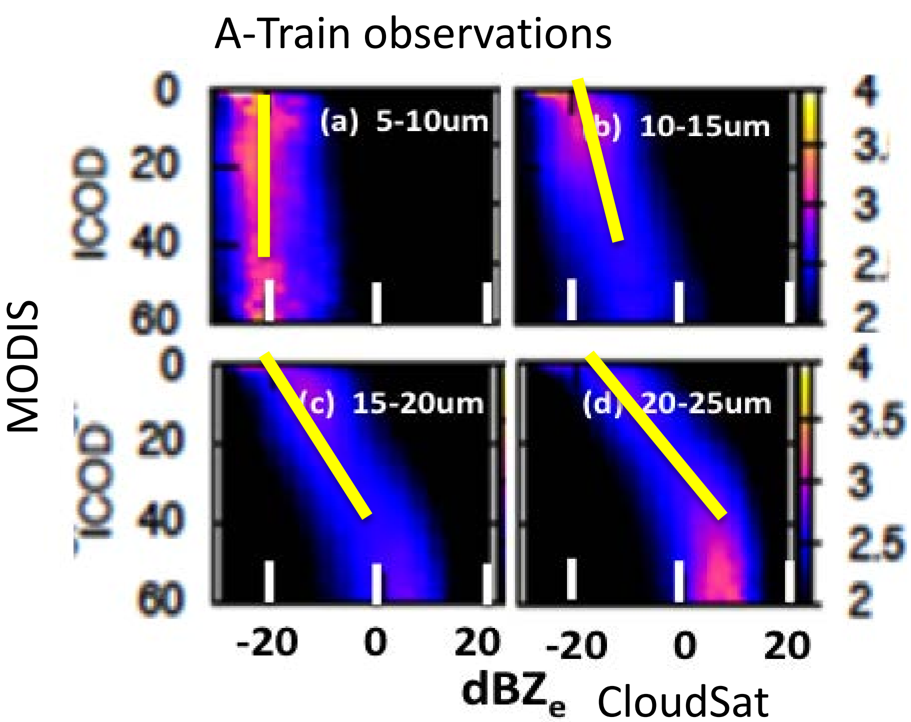
January-December 2007

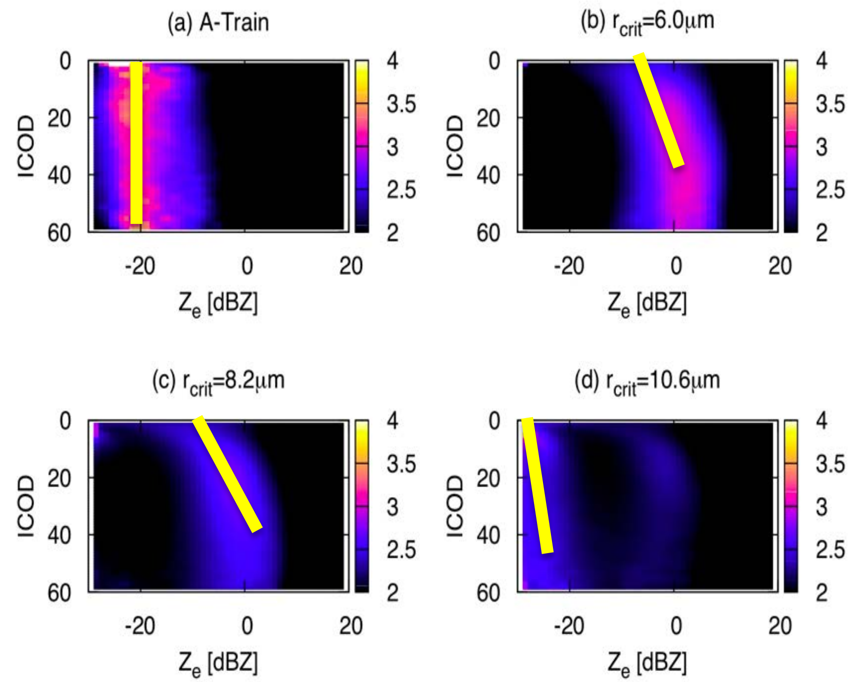




CloudSat and TRMM

Insight on the rain process - seeing rain form using combinations of CloudSat, MODIS,AMSR-E



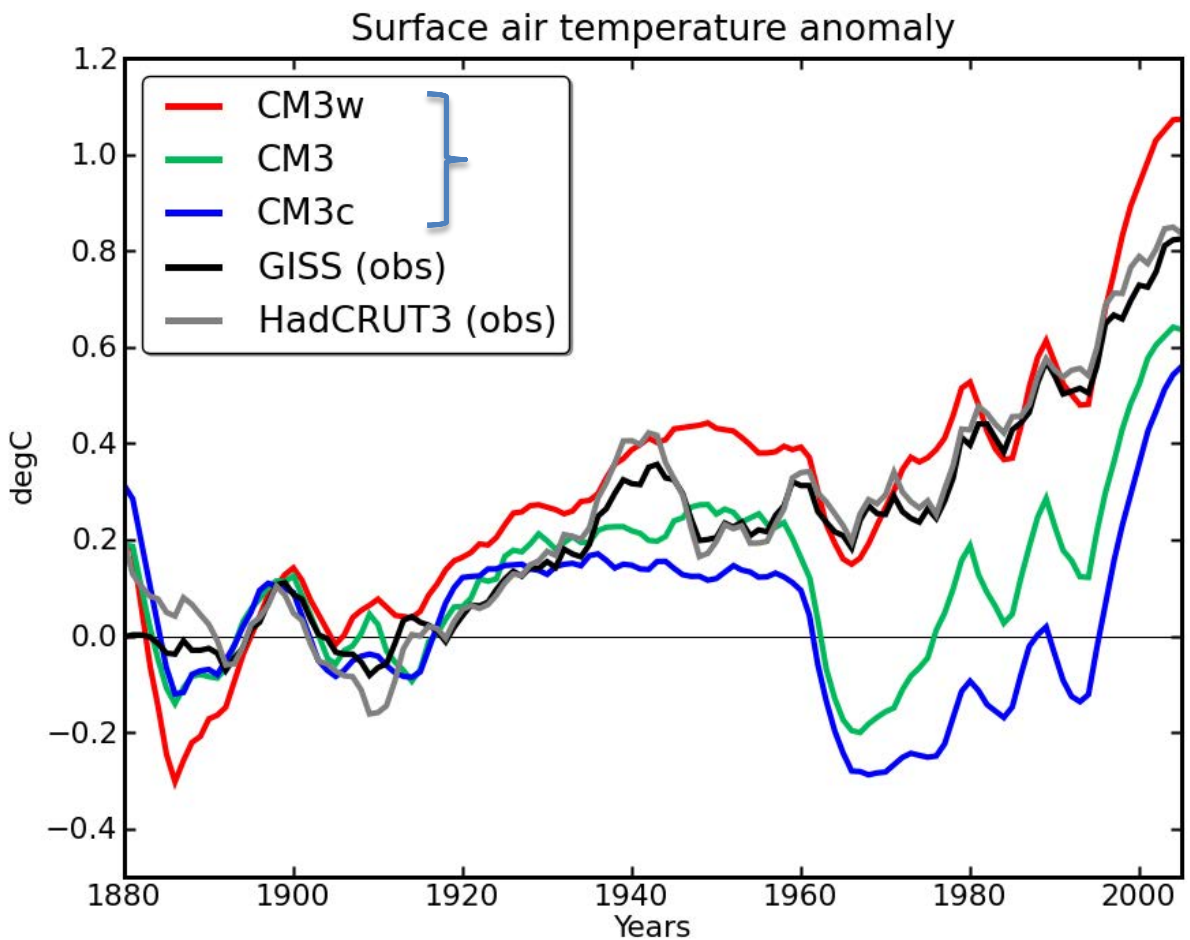


JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, D24211, doi:10.1029/2010JD014532, 2010

Dreary state of precipitation in global models

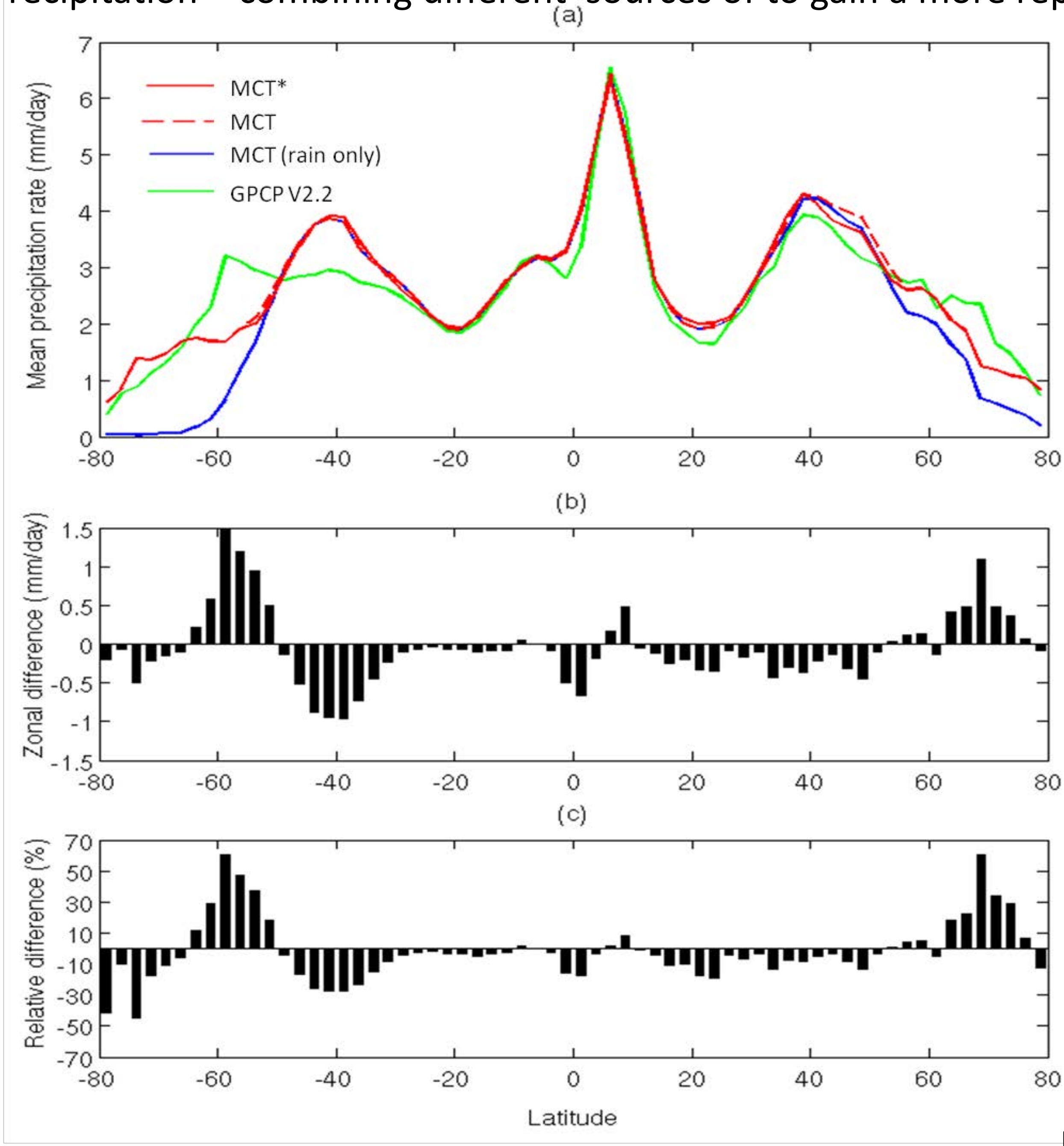
Graeme L. Stephens,[1] Tristan L'Ecuyer,[1] Richard Forbes,[2] Andrew Gettlemen,[3] Jean-Christophe Golaz,[4] Alejandro Bodas-Salcedo,[5] Kentaroh Suzuki,[1] Philip Gabriel,[1] and John Haynes[6]

The AIE is mostly about cloud water budget changes which is determined by precipitaion



Three different 20th century climate change experiments by the NOAA GFDL climate model group- the only difference is the strength of the AIE – and the A-Train can tell us which one is more correct

Global Precipitation – combining different sources of to gain a more representative global view



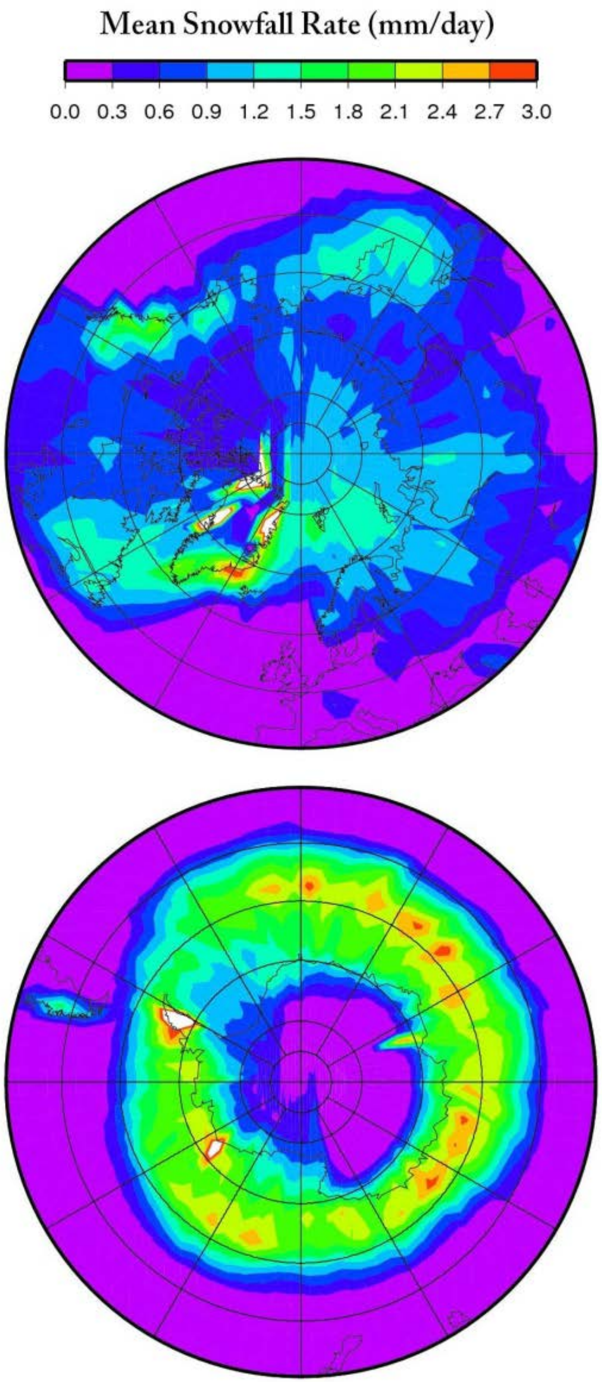
MCT*=TRMM+
CloudSat +AMSR-E
+ diurnal cycle
(Behrangi et al, 2012)

Global mean

MCT*-GPCP ~ 5%

I MCT*-GPCP I ~10%

Behrangi et al., 2013



Snowfall observations:
CloudSat provides the 1st real spaceborne global observations (IPWG) further adding valuable information about precipitation

CloudSat global snowfall product – the only real global product but how good is it? It’s a challenge to retrieve and a challenge to validate.

Summary

(i) New science continues to emerge as the A-Train data record continues to grow.

(ii) OCO is to join soon and it offers quite unique information about important components of the climate system <u>IN ADDITION TO CO2</u>

(iii) Steve Volz (HQ) has asked us to plan a 3rd A-Train science conference. Planning is underway

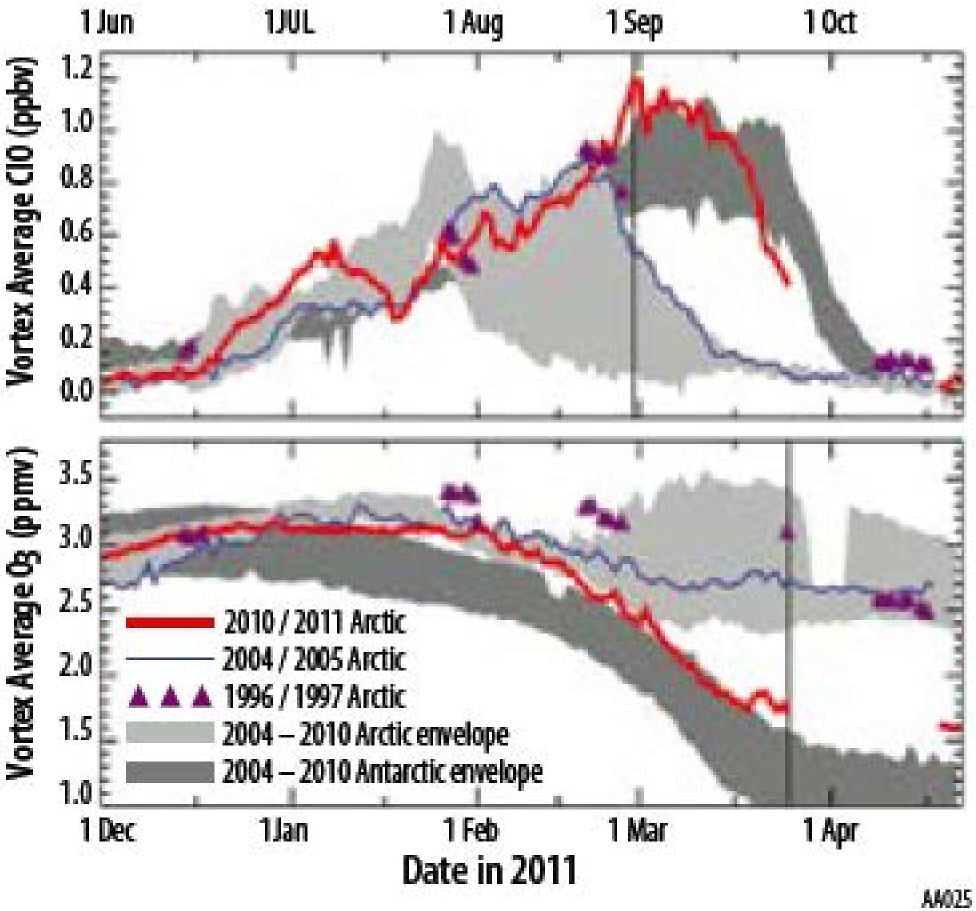
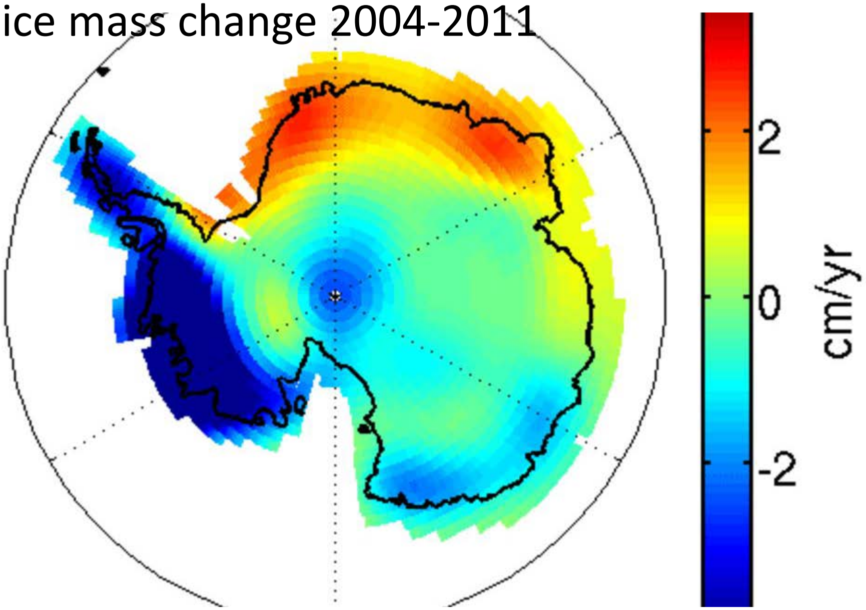
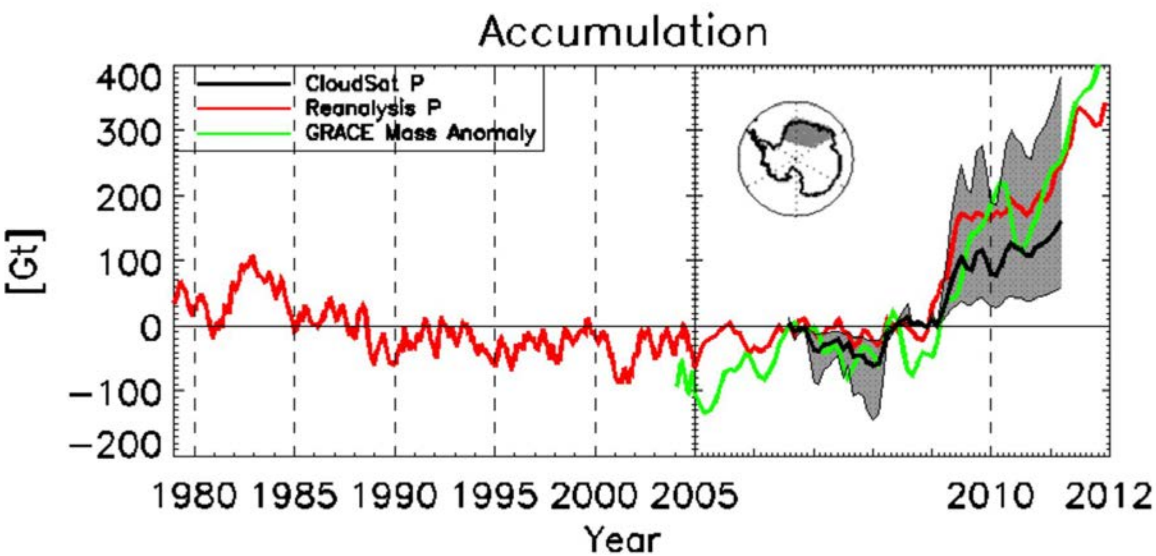


Figure 3: MLS observations of Arctic vortex average ClO (upper panel) and ozone (lower panel) at 485 K potential temperature (~18 km altitude) in 2010/2011 (red) compared to 2004/2005 (blue), the 2004-2010 envelope (pale grey) and observations from MLS on the UARS for 1996/1997 (purple triangles). Darker grey shading shows the comparable record for the Antarctic (shifted by six months, with dates shown on the top axis).

Connecting CloudSat snowfall to GRACE ice mass changes





Boening et al., 2012; GRL

The mass increase (red) is equivalent to about 10% of the annual sea level rise.

The mass increase is consistent with CloudSat snowfall accumulation.

The ice mass gain through snowfall is a consequence of the change in circulation and storm trajectory in 2009/2010

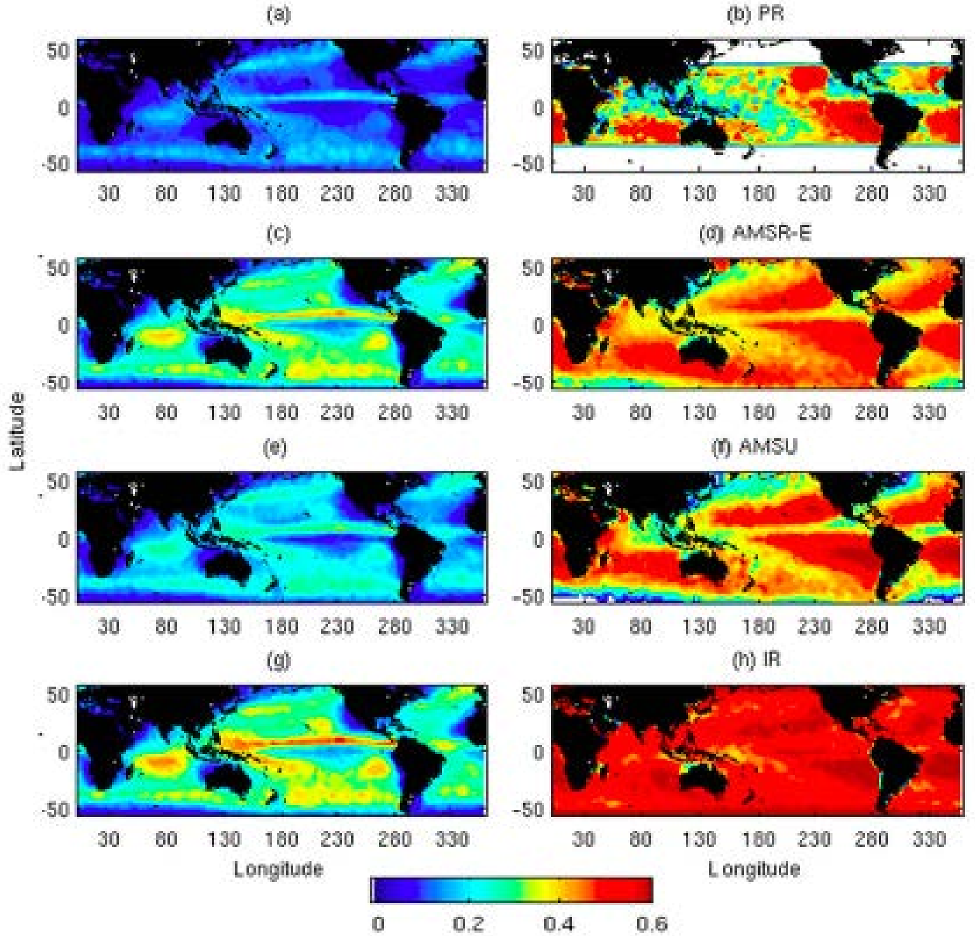


Figure 2. (a, c, e, and g) Maps of CS_b rain frequencies, corresponding to the footprint size of each studied sensor. (b, d, f, and h) Maps of fraction of missed rainfall (F_{mr}) for each sensor, calculated from equation (1) using its corresponding map of CS_b rain fraction. From top to bottom the rows represent maps for PR, AMSR-E, MHS, and IR, respectively. The results are based on 3 years (2007–2009) of rainfall data.

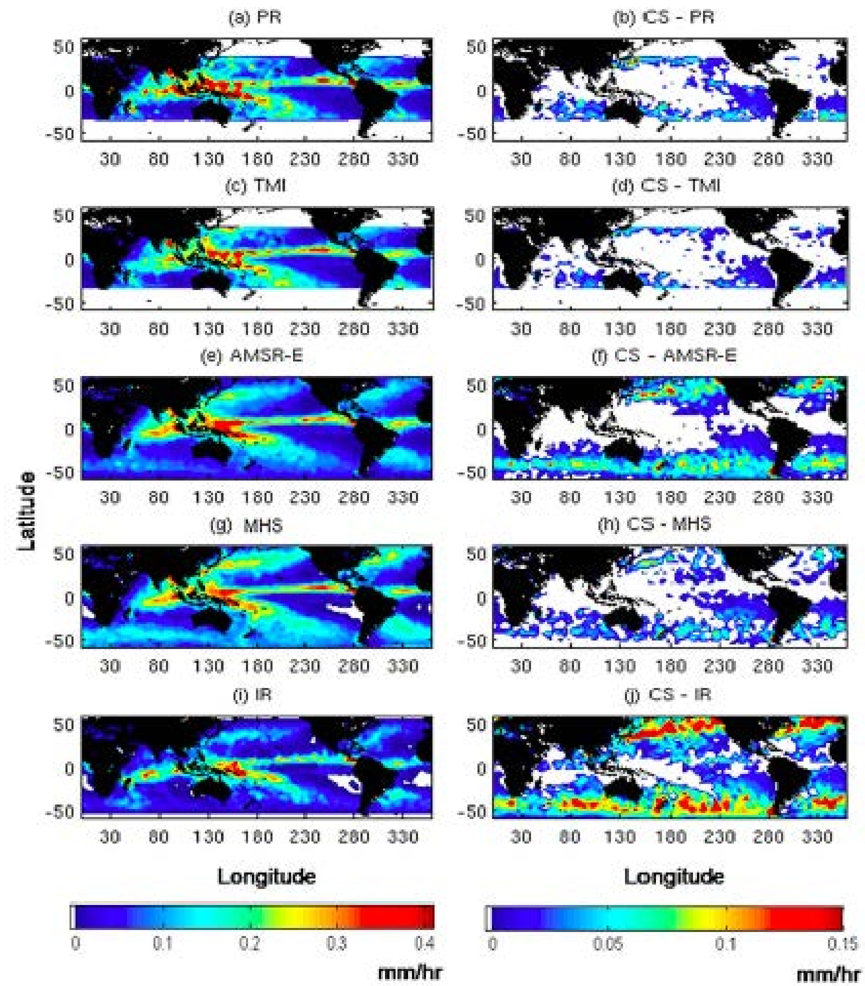


Figure 7. Maps of (a, c, e, g, and i) mean rain rate (MRR) and (b, d, f, h, and j) MRR differences for different sensors. The maps are constructed by calculating MRR or MRR difference in each 4° × 4° grid cell. The maps of MRR differences are plotted after subtracting sensors MRR maps from the MRR map of CloudSat. Cells with MRR difference equal or less than zero are shown as white.

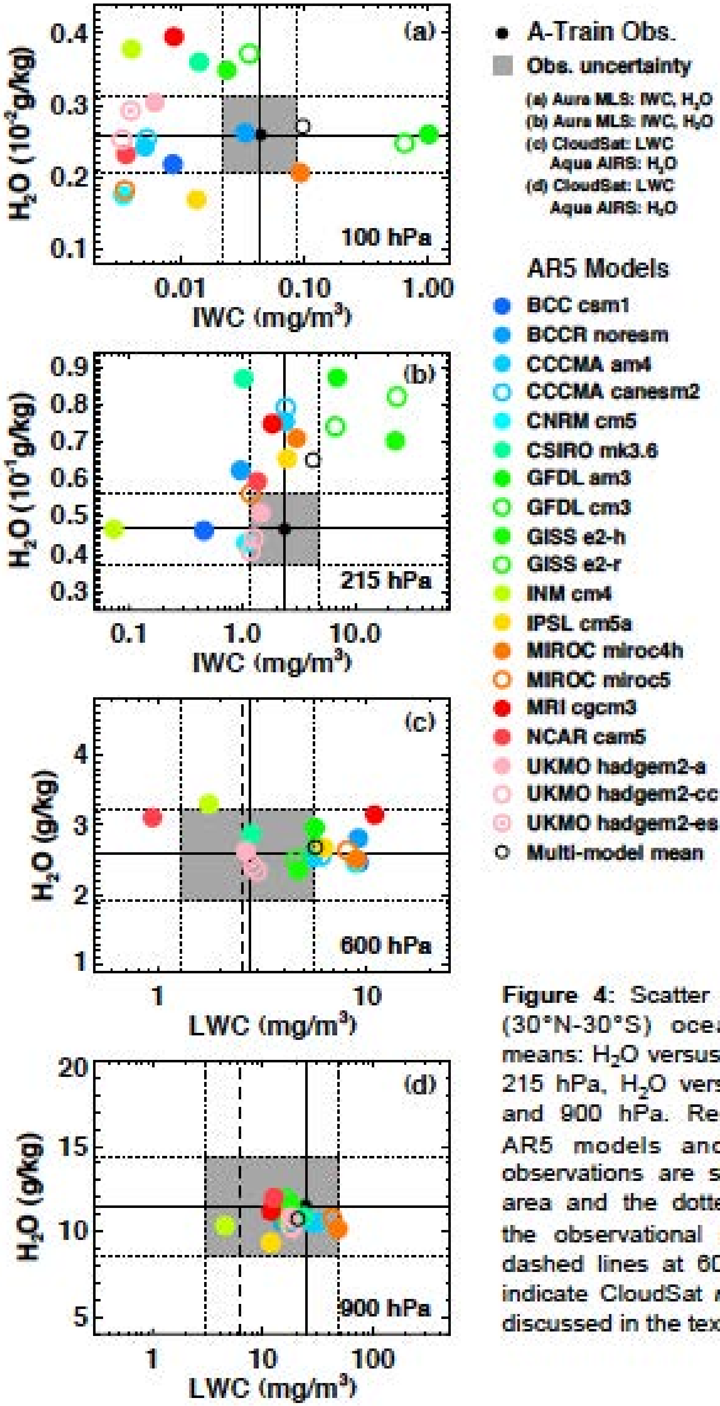
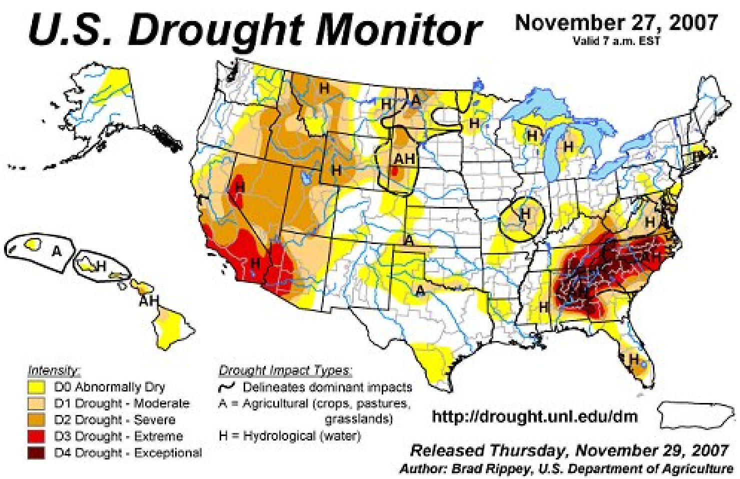


Figure 4: Scatter plots of tropical (30°N-30°S) oceanic multi-year means: H_2O versus IWC at 100 and 215 hPa, H_2O versus LWC at 600 and 900 hPa. Results from each AR5 models and from A-Train observations are shown. The grey area and the dotted lines indicate the observational uncertainty. The dashed lines at 600 and 900 hPa indicate CloudSat *noPcp* values as discussed in the text.

Comparison of level 2 products

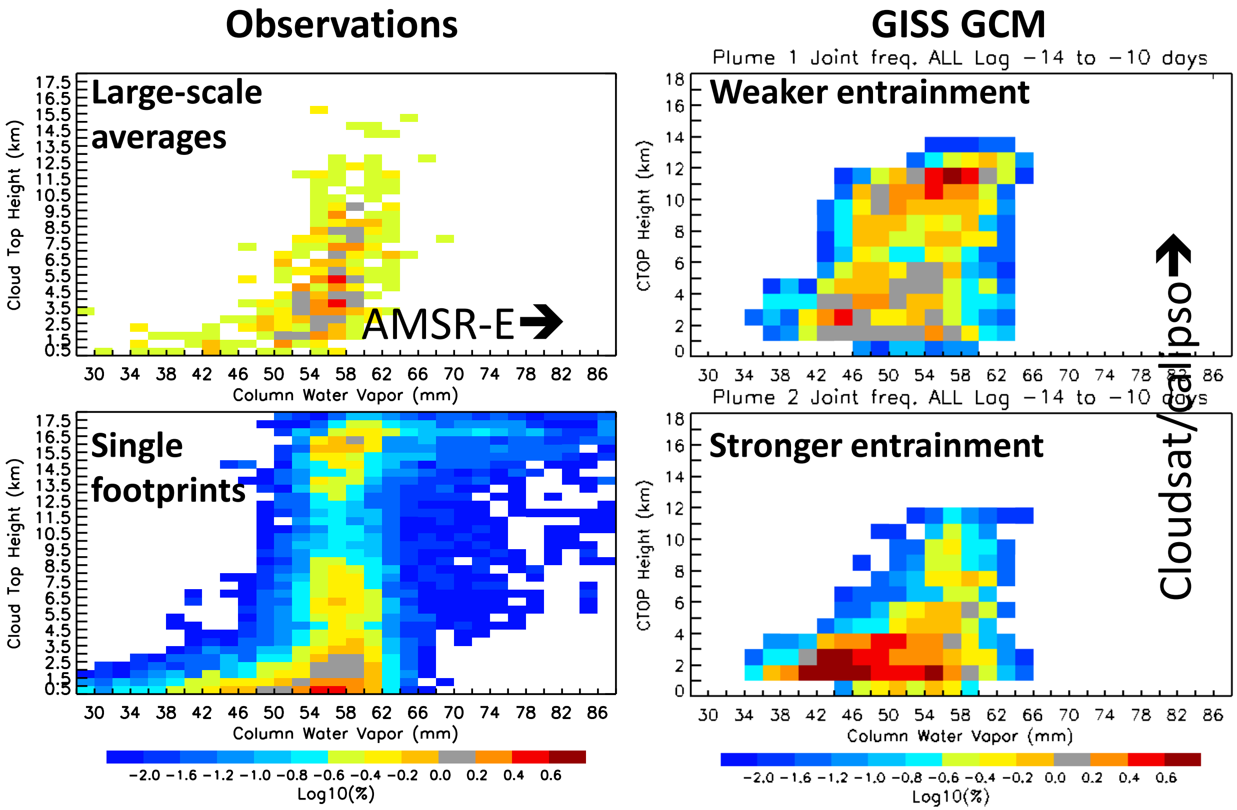
Assessment of global models

Insights on storms and climate change



Key modes of variability include MJO (interseasonal), El Nino (internannual)

CloudSat-CALIPSO-AMSR-E data document sensitivity of tropical convection to humidity during the Madden-Julian Oscillation



Context: GCMs poorly simulate the MJO because their convection schemes are insensitive to tropospheric humidity. CloudSat/CALIPSO/AMSR-E provides the first global direct detection of convection depth, while AMSR-E gives simultaneous water vapor. GEOPROF-LIDAR data were accumulated over the developing phase of 10 MJOs.

Left panels: A-train data show transition from shallow to deep convection at intermediate column water vapor amounts (50-68 mm), but with all depths possible at these values depending on details of the humidity profile.

Right panels: GISS GCM shallow-deep convection transition occurs too soon when too little dry air is entrained into clouds, but gets the correct transition with strong entrainment.

Del Genio et al. (2012), Journal of Climate

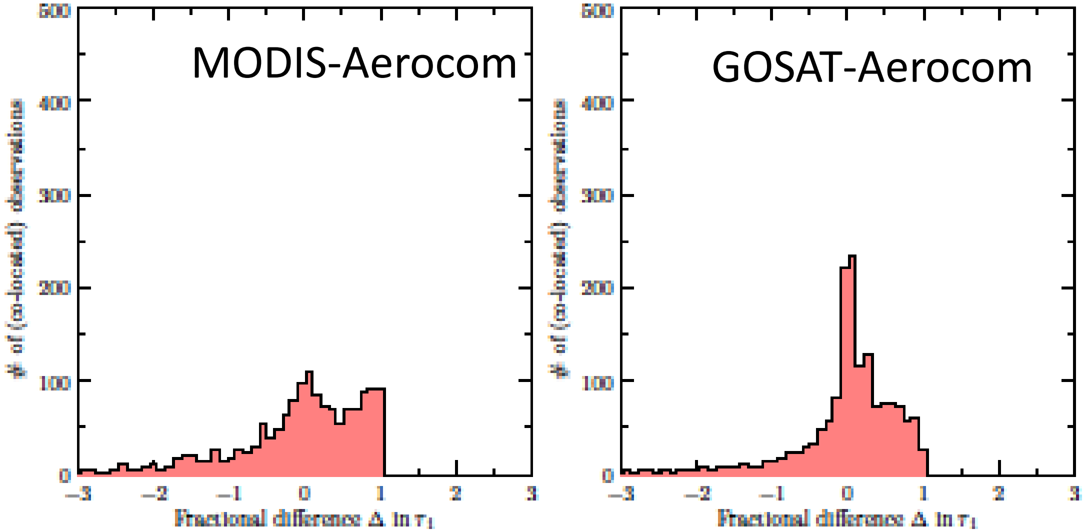


Figure 4: Fractional differences Δ for small mode optical thickness τ_1 between AERONET observations/retrievals and MODIS only retrievals (left) and between AERONET observa-

Aerosol optical depth

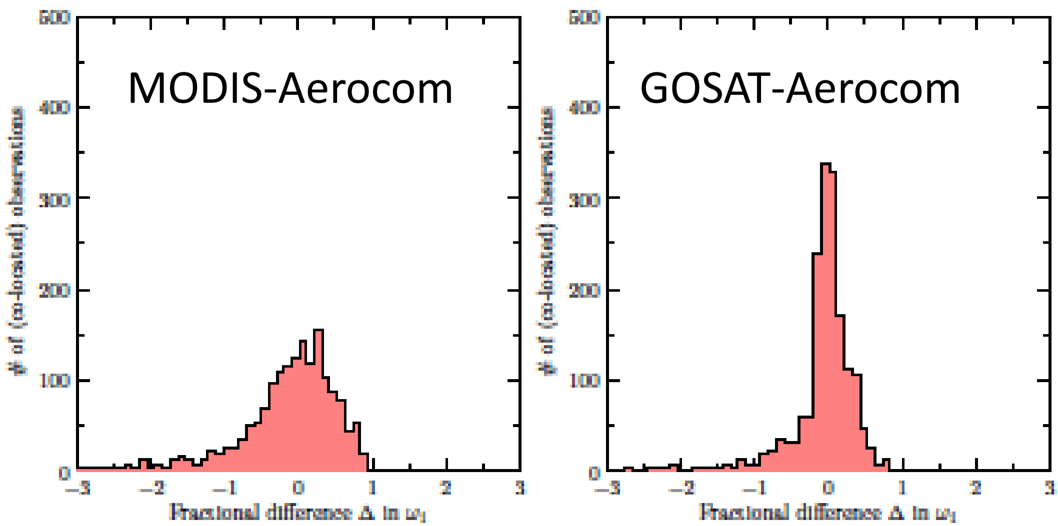
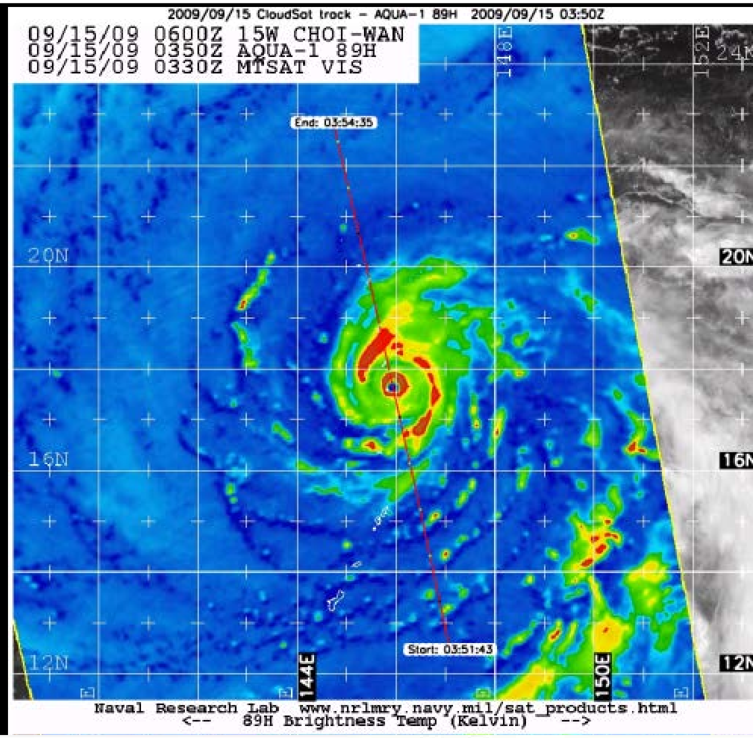


Figure 6: Same as figure 4 but for the small mode single scattering albedo ω_1.

Aerosol single scatter albedo

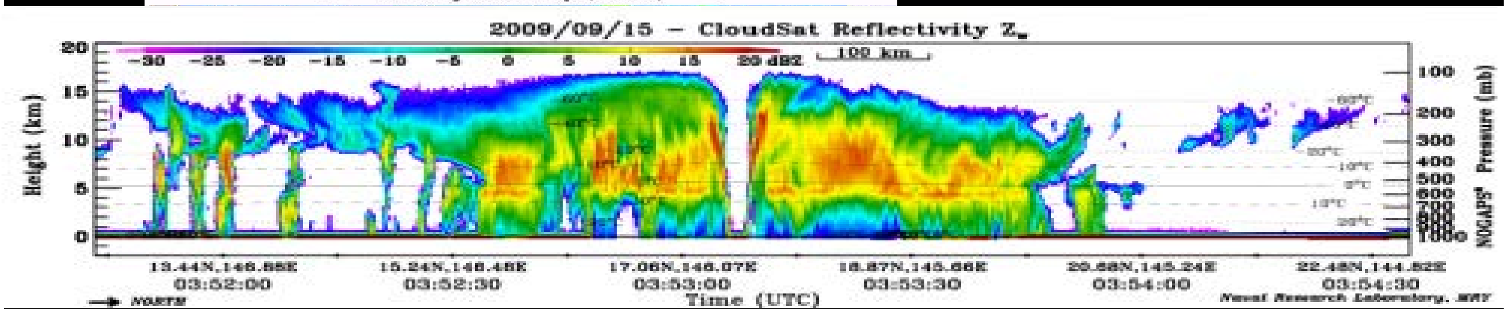
McGarragh & Stephens, 2013

Multi-sensor fusion - new insights on planets major storms



Tropical Cyclone Choi-Wen …

(Imagery Courtesy Naval Research Laboratory, Marine Meteorology Division, Monterey CA)



Access to Information

- Public availability of key documents
  - Mission and instrument descriptions
  - Algorithm Theoretical Basis Documents (ATBDs)
  - Data Catalogues and data set examples
  - Data Quality Summaries
- Open and advertised A-Train Data Policy
- Open and advertised Science Team meetings
- Public availability of Level 1 and 2 data products soon after start of operations (beta or provisional data quality)
  - Better to keep data formats simple
  - Near real-time access
- Creation of fused data sets (slow to develop for A-Train)

Example - initial data release for CALIPSO & CloudSat within first 6 months

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NASA ESD Operating Missions

(LDCM not shown, Launched 11 Feb 2013)

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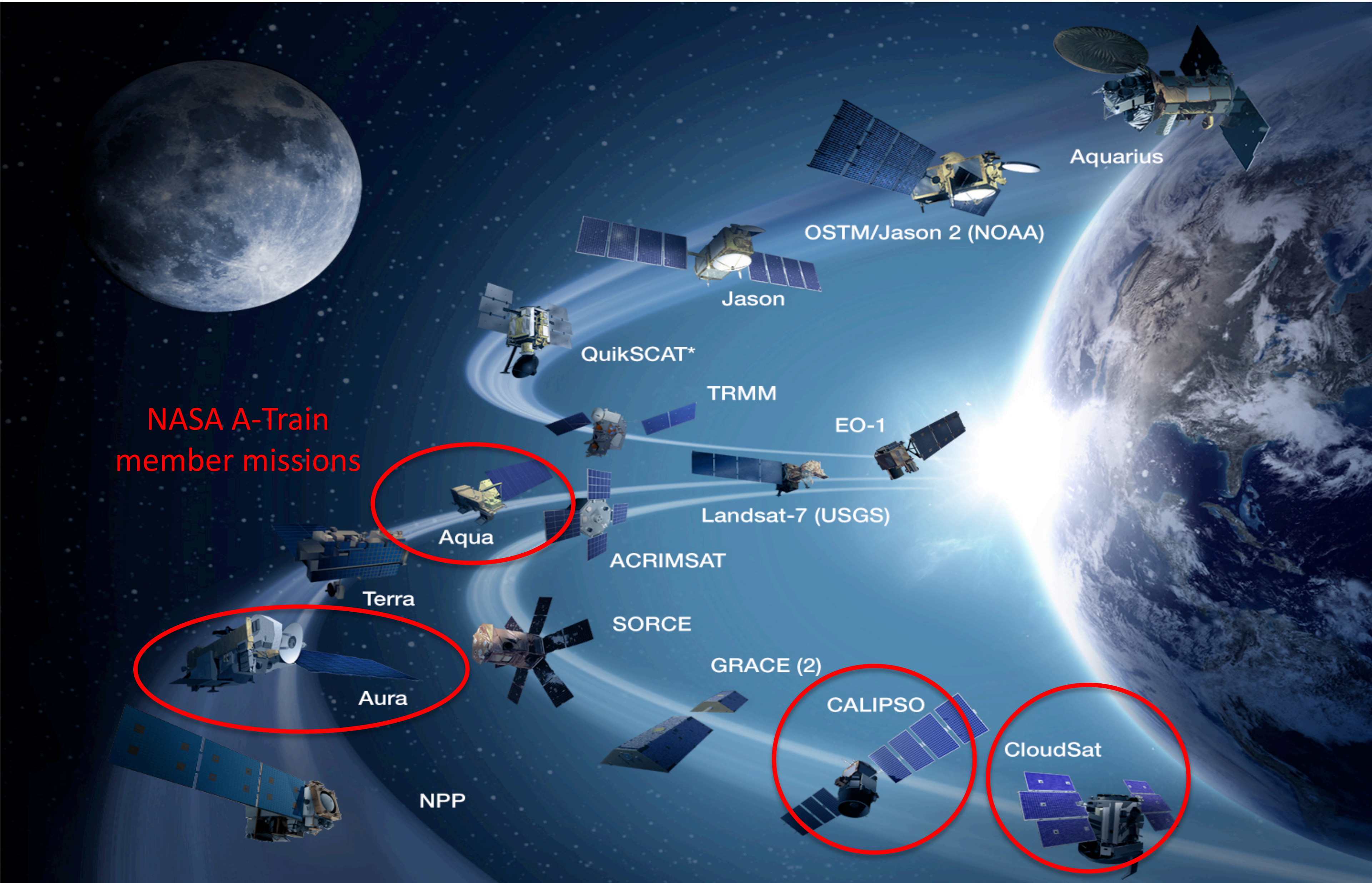


Anticipated A-Train highlights

Sensor data used	What is provided	Why useful	Interesting tidbits
CloudSat & CALIPSO	Vertical profiles of cloud occurrence, new definitions of high thin cloud, cloud base, cloud layering, etc	This vertical structure is required for many weather and climate related processes	Multiple layering is prevalent in tropics (60%), total cloud cover ~76%
MLS, CloudSat,AIRS	Ice water content and path comparison and relation to UTH	Important climate feedbacks revolve around high, thin ice clouds - agreement between these two data sets confirms validity of products	Connection to water vapor implies processes. Gross errors in the relation between UT ice and vapor in climate models -
AIRS, MODIS Cloudsat,AMSRE & CALIPSO	Cloud & precipitation information from different sensors can be tested including cloud liquid water path of raining/non-raining clouds	Can calibrate longer time records of other sensor data, like cloud top heights, precipitation, – useful for other applications like cloud track winds	Major biases in cloud/radiance climatologies exposed, AMSR-E precip occurrence is ~ 2X less than CloudSat, exposes large uncertainty in mid alt precipitation
AMSR-E, CERES, CloudSat, MODIS & CALIPSO	More integrated view of aerosol indirect effects on observed cloud albedos	Large uncertainties in AIE is one of the principle tools that constrain our ability to predict cliimate warming.	AIE are inferred to be small composed due to combination of processes that buffer one another. Production of precipitation grossly influences AIE

Sensor data used	What is provided	Why useful	Interesting tidbits
MODIS IR, CloudSat, CALIPSO	Convective buoyancy, entrainment	Provides unique, global information that is beginning to revolutionize model convection parameterization	Verified hot tower hypothesis – 0.02% of tropics contain undilute convective cores
AMSR-E, CALIPSO	Surface wind from lidar surface reflection	CALIPSO surface wind sees in between clouds and is less contaminated by cloud effects	1m/s rms, near zero bias compared to AMSR-E
CloudSat & CALIPSO	Aerosol optical depth via PIA –radar surface reflectivity is used to define lidar surface reflection	AOD much less sensitive to aerosol model assumptions that plague all other methods	

A-Train Serendipity

Sensor data used	What is provided	Why useful	Interesting tidbits
MODIS vis, nir, CloudSat,	Correlation between radar reflectivity and MODIS particle size	Provides unique identification of the transition from cloud to rain and time scale of rain formation	Time scale is much longer in nature than is assumed in models
OMIi , CloudSat,	Inferred cloud top heights fro UV scattering matched to cloud profiles	Impacts ozone estimation above clouds	Considerable UV multiple scattering makes OMI cloud tops appear many kms low
CloudSat & MODIS	A confirmation of MODIS particle size and its relation to precipitation	Passive measures particle size of low clouds can be used to characterize drizzle/precio occurrence.	Drizzle is so persistent in oceanic clouds that it measurably affects the mean particle size
ColudSat & CALIPSO	Identification of thin winter time ice clods and it precipitation	Explosive development of precipitation altered by aerosol affecting the rate of dehydration of polar clouds	

A-Train Science Concepts

4 slides from:

“ESA-NASA Constellation Management Workshop
May 17, 2011
Saint-Hubert, Quebec, Canada

Perspectives on Maximizing Science Return

Chip Trepte, CALIPSO Project Scientist, NASA/LARC”

Common Interests

- A-Train formulation motivated to a large degree by a desire to better understand clouds and aerosols and their impact on the radiation budget and hydrological cycle
- Prior to A-Train international science community was already engaged in collaborative research efforts across multiple fronts, for example:
  - climate and weather forecast modeling (GEWEX)
  - field measurement campaigns (Pinatubo eruption)
  - remote sensing research: vis/ir sensors, polarimeters, lidar, radar
- Deep seeded desire for global observations – time was ripe
- Recognition that multiple measurement approaches are needed

Example – large volume of publications using A-Train observations (Aqua > 500, CloudSat >300, CALIPSO >350, Aura >500, Parasol >150; may be some duplication between missions)

Leadership

- Mission leads (Principal Investigators, Project Scientists, Project Managers, Program Scientists, Agency Leads) recognize the value of collaborative efforts at an early stage
  - collaborations between missions and discipline communities evolved on their own
  - no centralized approach; self organizing
- Effective communication to the science community
  - well articulated expectations
  - routine meeting opportunities
  - strive to provide clearer messages to the public
- Effective Mission Operations Working Group
  - tight connection between science needs and capabilities
  - operates under clear and established procedures
  - Routine communication across management, science, and engineering sectors
- Funding for cross discipline/mission and multi-sensor research
- Supportive of new and young scientists

Access to Information

- Public availability of key documents
  - Mission and instrument descriptions
  - Algorithm Theoretical Basis Documents (ATBDs)
  - Data Catalogues and data set examples
  - Data Quality Summaries
- Open and advertised A-Train Data Policy
- Open and advertised Science Team meetings
- Public availability of Level 1 and 2 data products soon after start of operations (beta or provisional data quality)
  - Better to keep data formats simple
  - Near real-time access
- Creation of fused data sets (slow to develop for A-Train)

Example - initial data release for CALIPSO & CloudSat within first 6 months

Open Validation

- Sustained calibration and validation efforts
  - Formulation of pre-launch plans
  - Data processing effort includes iterative processing to capitalize on improved calibration/validation approaches
  - Committed funding from sponsoring agencies
- Coordinated comparison field missions
  - Optimizes resources (instruments, aircraft, ground systems)
  - Brings more eyes to a set of issues
  - Promotes additional interest
- Independent assessments

Example – ozone trend studies in late 1980: TOMS, SBUV, SAGE, HALOE, NDSC

Example – Cirrus optical thickness: CALIPSO lidar and IIR, MODIS, PARASOL, CloudSat, in situ measurements, CPL

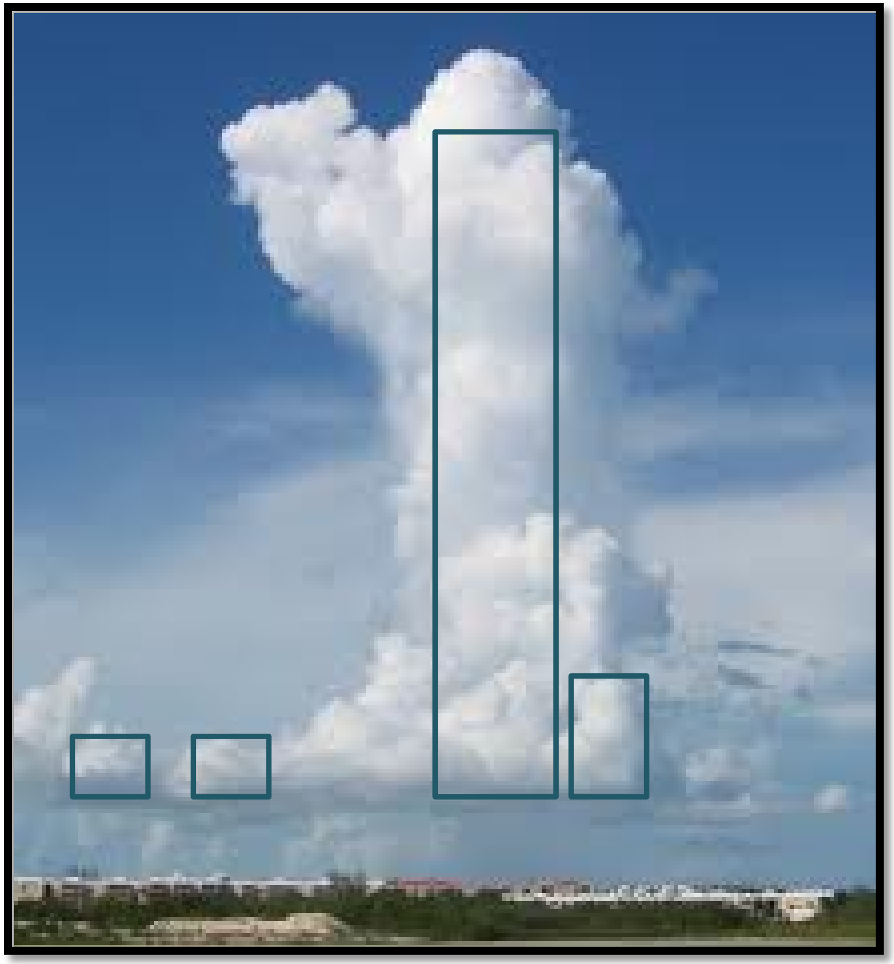
Convective core cloud

- Generally defined as **moist buoyant updrafts** in LES studies used to develop convection parametrizations (e.g. Siebesma & Cuijpers, 1995).

- **Area** (and hence radiative effect) of core **is relatively small** – probably less than 0.1 in typical global model grid

- Currently ignored in UM but test show **it does have an impact** (e.g. US surface temperature)

- **A good regime indicator for inhomogeneity?**

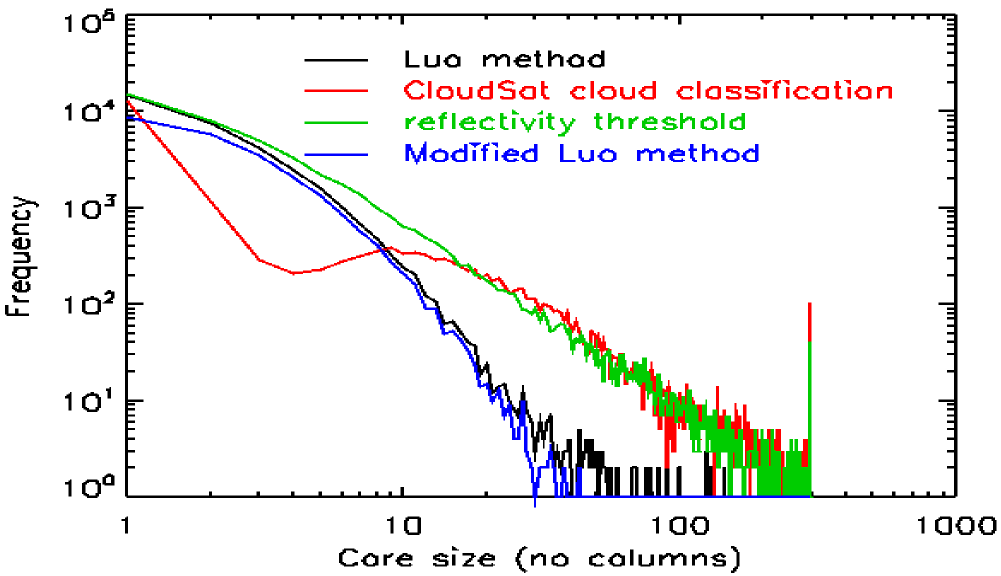


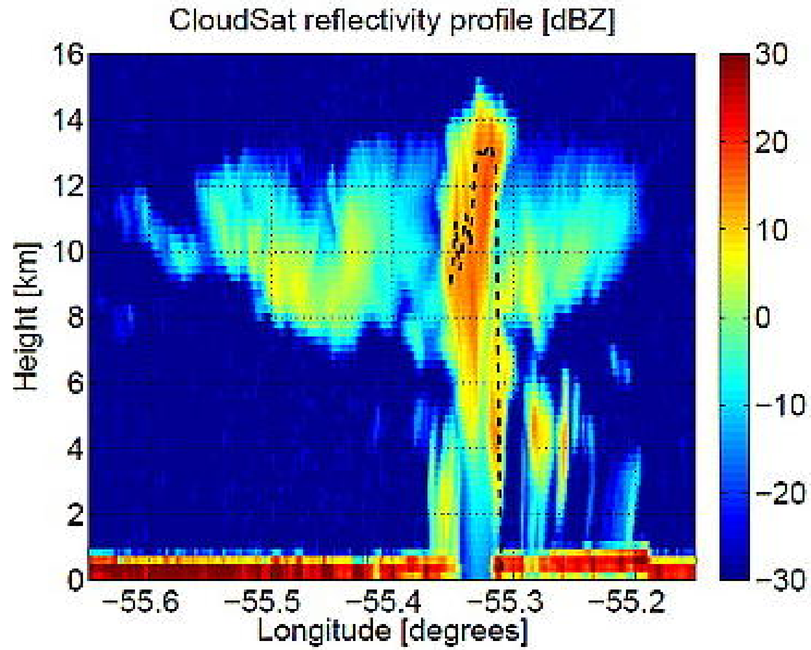
Identifying core cloud

Tested several methods but using method based on Luo et al 2009.

A column is designated as a core if:

- less than 5 layers between 0 dBZ echo top height and cloud top
- less than 9 layers between 10dBZ echo top height and cloud top
- at least 3 layers between cloud base and 10dBZ echo top

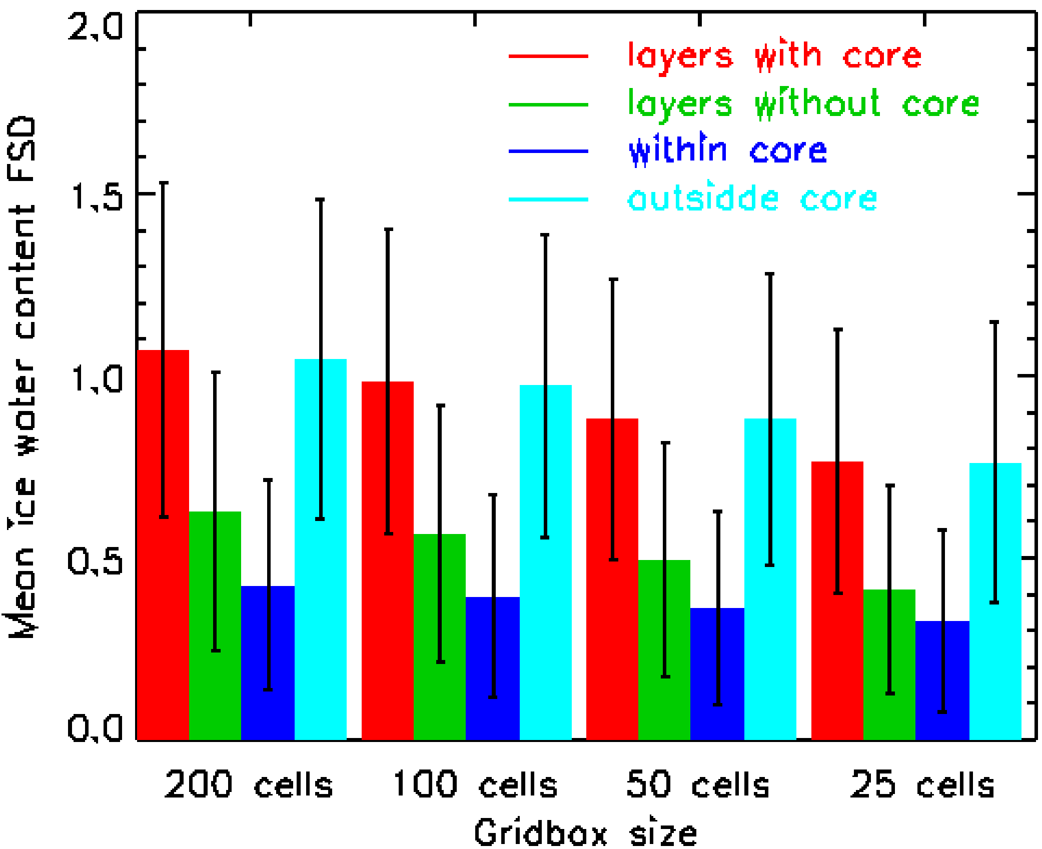




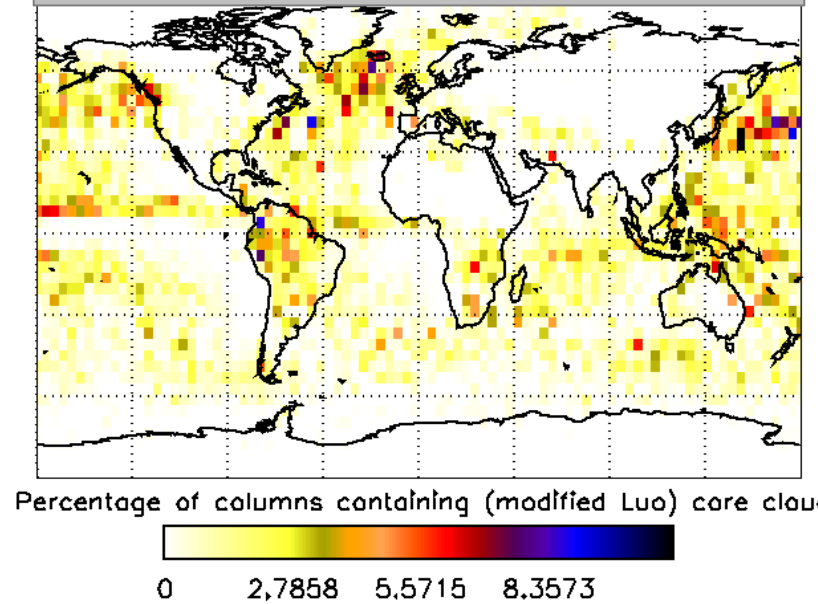
A convective cloud observed by CloudSat on 19/11/2009 at about 5:20 UTC above Brazil.

Battaglia et al (2011)

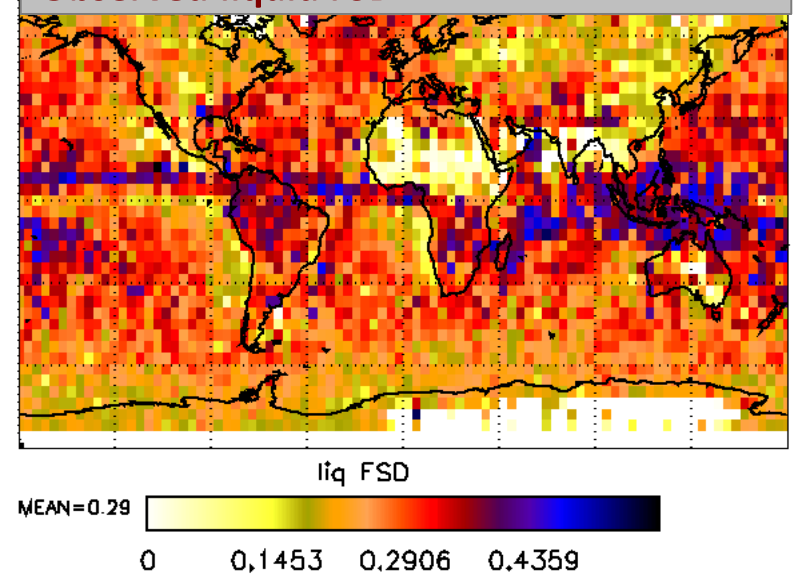
Using convective core information

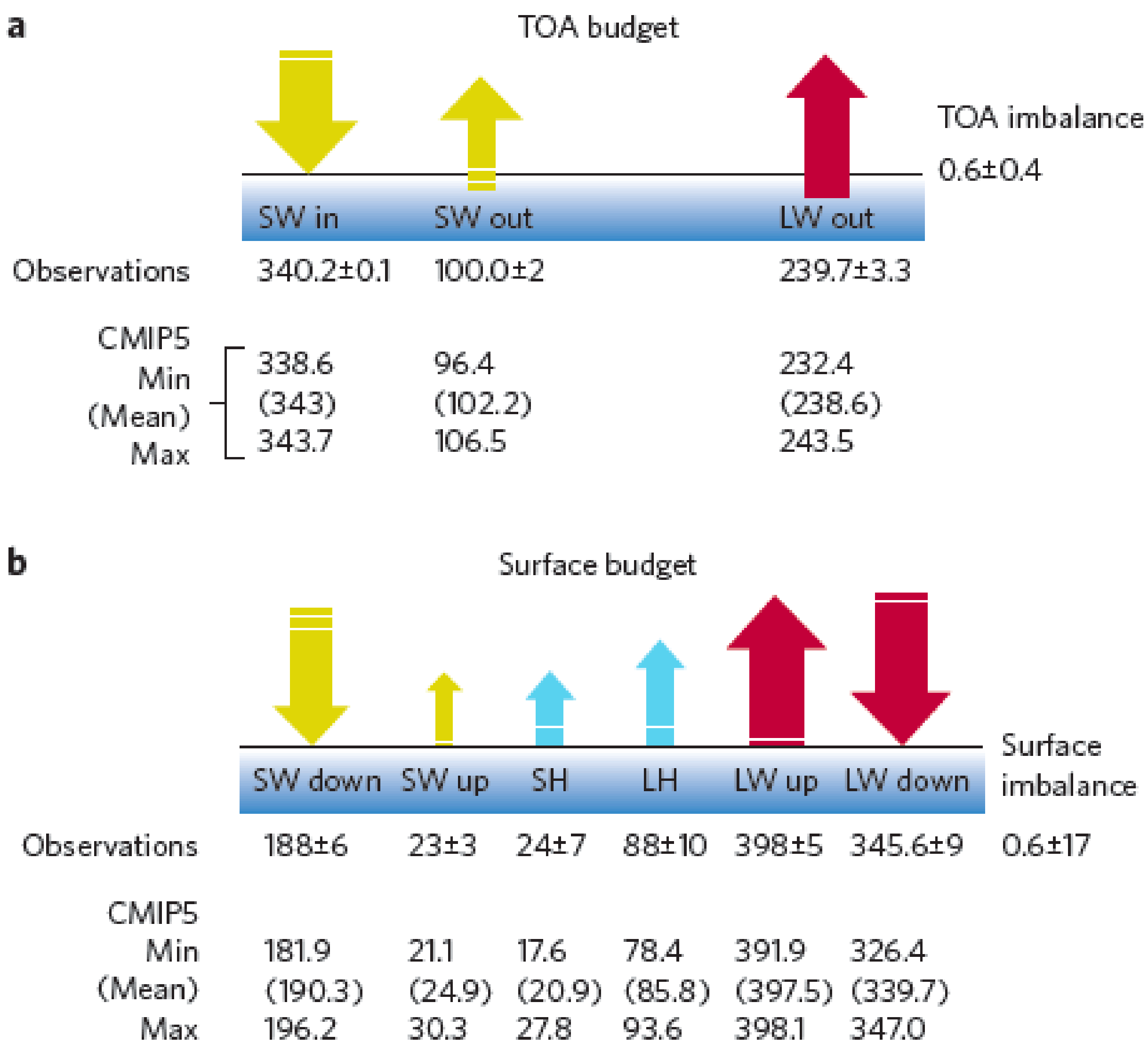


% of columns with cores

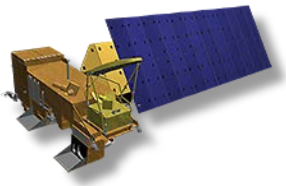


Observed liquid FSD

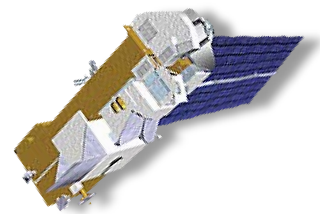



a
TOA budget
TOA imbalance
0.6±0.4
SW in
SW out
LW out
Observations
340.2±0.1
100.0±2
239.7±3.3
CMIP5
Min
(Mean)
Max
338.6
(343)
343.7
96.4
(102.2)
106.5
232.4
(238.6)
243.5
b
Surface budget
SW down
SW up
SH
LH
LW up
LW down
Surface
imbalance
Observations
188±6
23±3
24±7
88±10
398±5
345.6±9
0.6±17
CMIP5
Min
(Mean)
Max
181.9
(190.3)
196.2
21.1
(24.9)
30.3
17.6
(20.9)
27.8
78.4
(85.8)
93.6
391.9
(397.5)
398.1
326.4
(339.7)
347.0

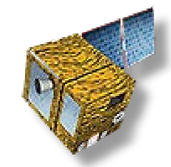
A-Train Constellation Evolution



Aqua
(May 2002)



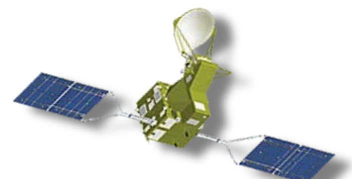
Aura
(July 2004)



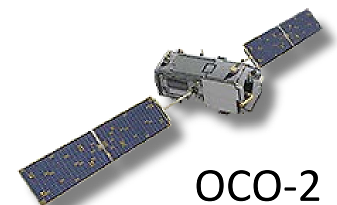
PARASOL
(Dec 2004; lowered orbit Dec 2009)

CALIPSO
(April 2006)

CloudSat
(April 2006; battery management orbit lowering June 2011, re-entered train May 2012)



GCOM-W1/Shizuku
(May 2012)



OCO-2
(~July 2014)

- Glory launch failure on 4 March 2011
- OCO launch failure on 24 Feb 2009

Aerosol effects on clouds – largest uncertainty in climate forcing and these too is shaped by the thermodynamic properties of the boundary layer/free troposphere