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Spaceborne Hyperspectral Infrared Observations of the Cloudy Boundary Layer

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With contributions by Alex Guillaume, Tom Pagano, John Worden and Qing Yue

Jet Propulsion Laboratory, California Institute of Technology JPL

KISS Workshop on the Cloudy Boundary Layer

September 21, 2010

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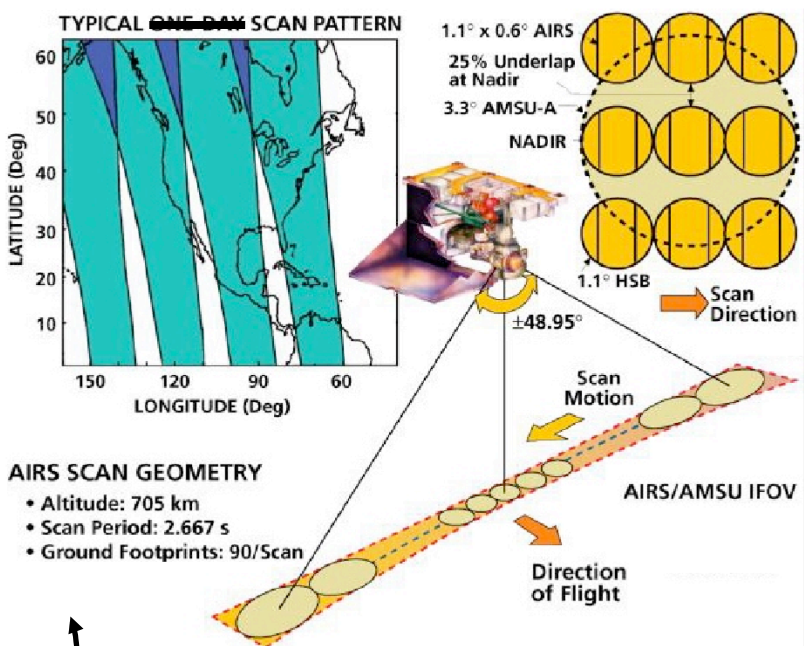
AIRS Geometry and Sampling



1. AMSU footprint, 45 km across at nadir, contains 9 AIRS spectra
   – THIS IS THE RETRIEVAL GRANULARITY.
2. Viewing swath 30 AMSU footprints or ~1650 km wide.
3. The result: 2,916,000 IR spectra and 324,000 retrievals per day

Theme 1: Inconsistency of Models with Observed Means

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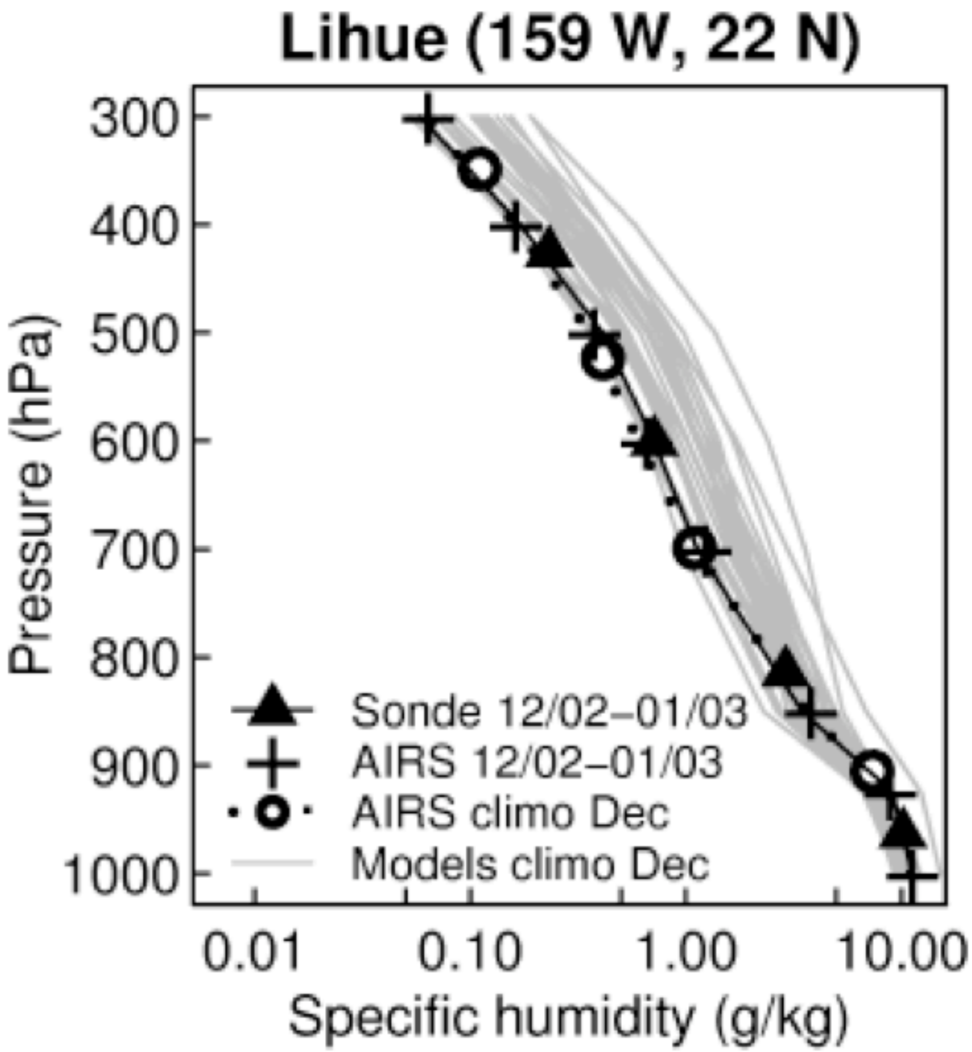
Mean Climatologies of AIRS and 17 IPCC AR 4 Models.



From:
Pierce, D. W., T. P. Barnett, E. J. Fetzer, and P. J. Gleckler (2006), Three-dimensional tropospheric water vapor in coupled climate models compared with observations from the AIRS satellite system, *Geophys. Res. Lett.*, *33*, L21701, doi: 10.1029/2006GL027060.

3

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Water vapor and lapse rate feedbacks vary, but independently of T and q details

John and Soden, GRL, 2007

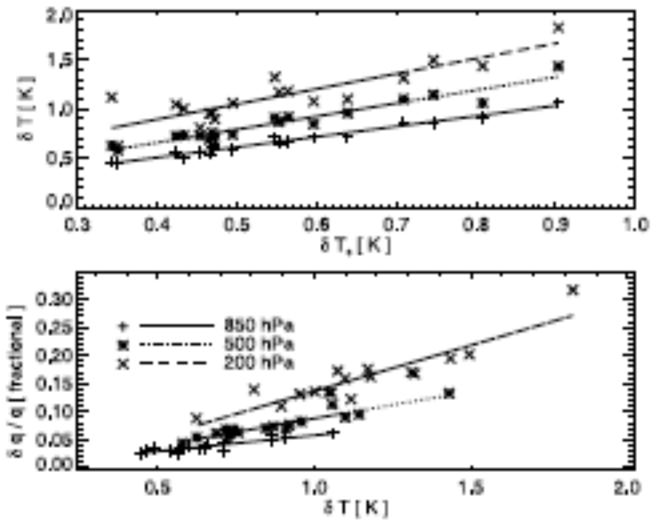

Figure 2. (top) Response of T at three different atmospheric levels (850, 500, and 200 hPa) to change in surface temperature (T_s). (bottom) Fractional response of q at three different atmospheric levels (850, 500, and 200 hPa) to change in T at those levels. Different symbols represent different coupled GCMs used in this study. Tropical means are used. δT, δT_s, and $\frac{\delta q}{q}$ are the difference between the first 10 year and the last 10 year means of 20th century of each variable.

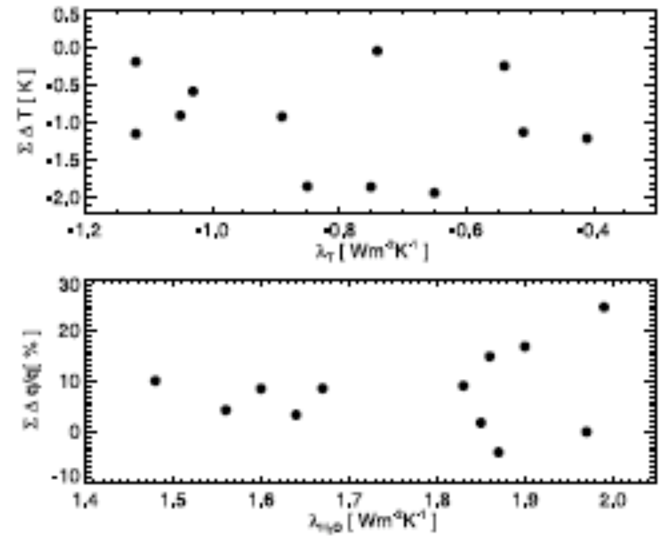

Figure 3. (top) Vertically integrated global mean T biases from 1000 to 100 hPa in the models versus temperature lapse-rate feedback (λ_T). (bottom) Vertically integrated fractional q biases from 850 to 200 hPa versus water vapor feedback (λ_{H_2O}). The feedback values simulated by the models are taken from *Soden and Held* [2006].

All models respond positively to increasing surface T.

All models are too cold (top) & too wet at 850-200 hPa (bottom). But model feedback strengths are uncorrelated with T & q diffs.

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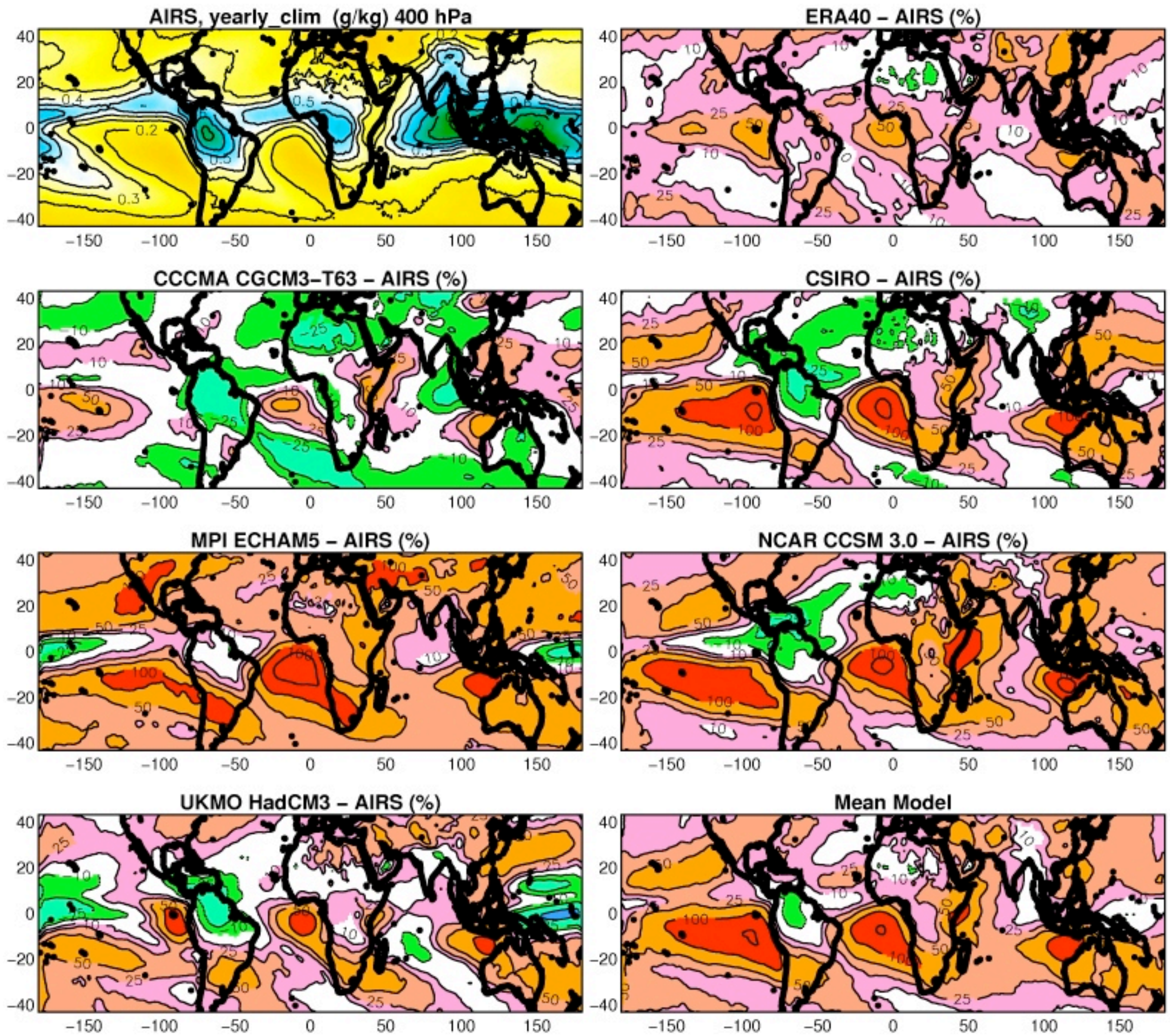
It's not just about deep convections: *Model performance is worst in trade Cu.*

Model-AIRS
Absolute Differences
(g/kg)

Model-AIRS
Relative Differences
(Percent)
Red & Orange
= 50-100 %



/data/obs/AIRS/H2OVapMMR/plot_seas_avg.grl_version.v2.yearly_clim.lev_7.diff_pct.R Tue Aug 22 16:07:55 2006

Biases matter for chemistry.

O'Connor, F. M., C. E. Johnson, O. Morgenstern, and W. J. Collins (2009), Interactions between tropospheric chemistry and climate model temperature and humidity biases, *Geophys. Res. Lett.*, 36, L16801, doi: 10.1029/2009GL039152.

From abstract:

"Removing the humidity bias alone causes a reduction in both the global annual mean tropospheric ozone burden of greater than 2% and the methane lifetime of 3.6–4.2%."

What about cloud physics, or,
large scale controls like radiative heating?

Next: the effects of clouds on IR sampling.

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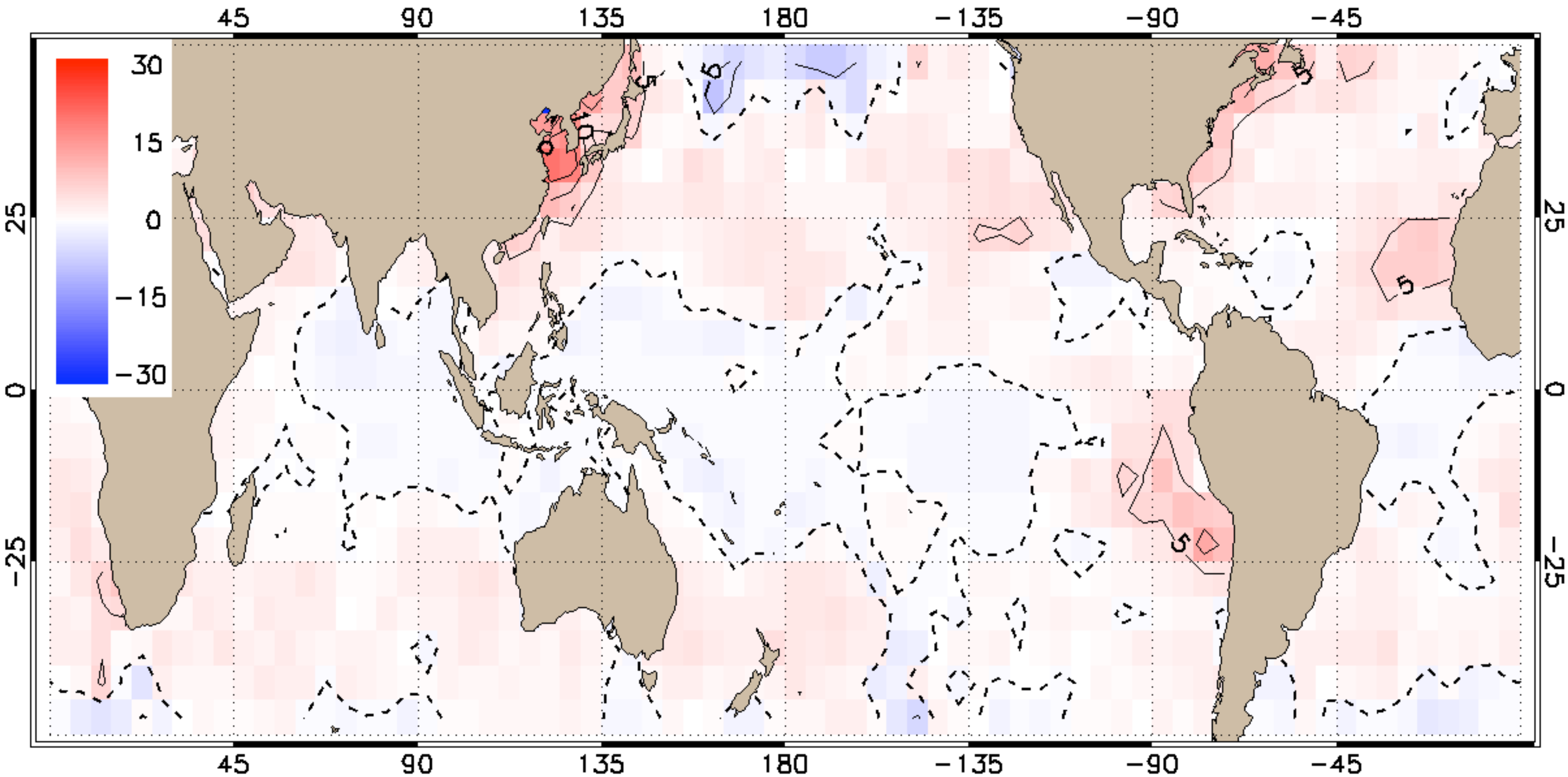
The good news: A-train sensors are consistent for mutually-observed scenes



,

AIRS-AMSR-E as percent of AMSR-E mean)

More agreeing measurements:
AIRS and MLS Water Vapor at 250 hPa

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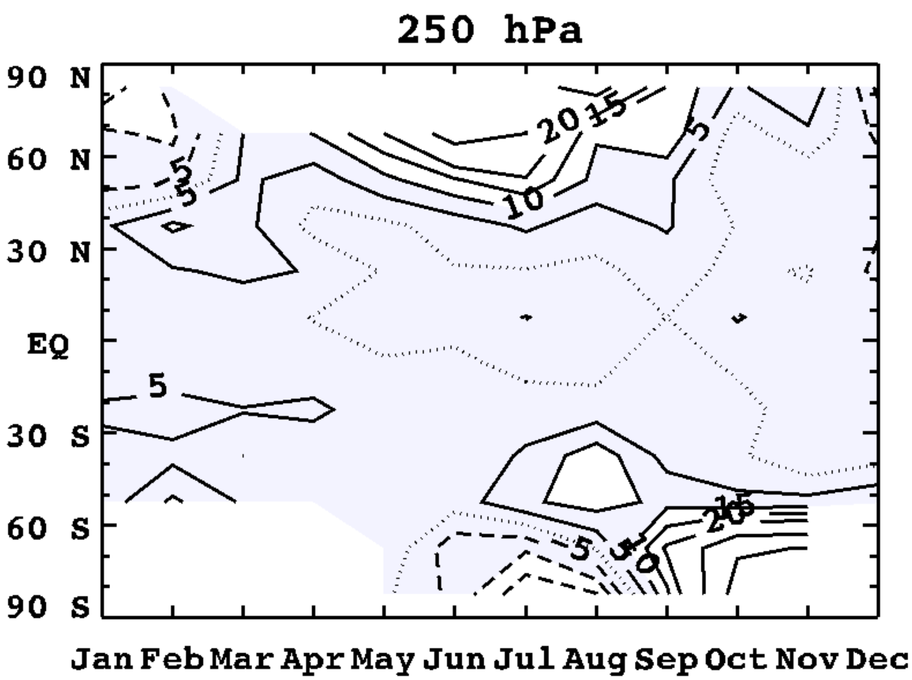
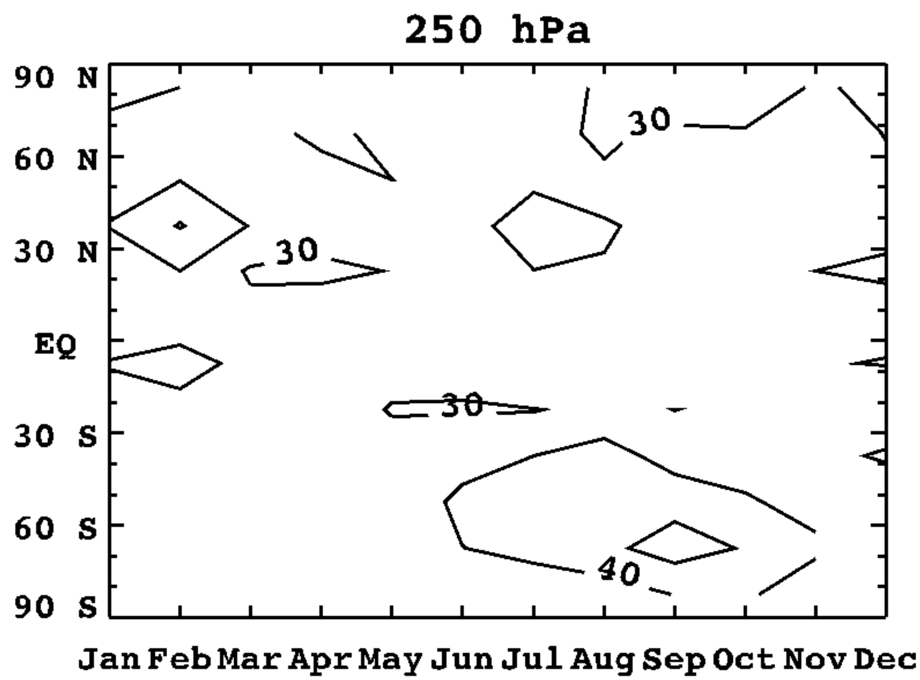
Matched obs. for twelve months in 2005, twelve zonal bands.





Biases: ±10% values shaded.

RMS of differences

8

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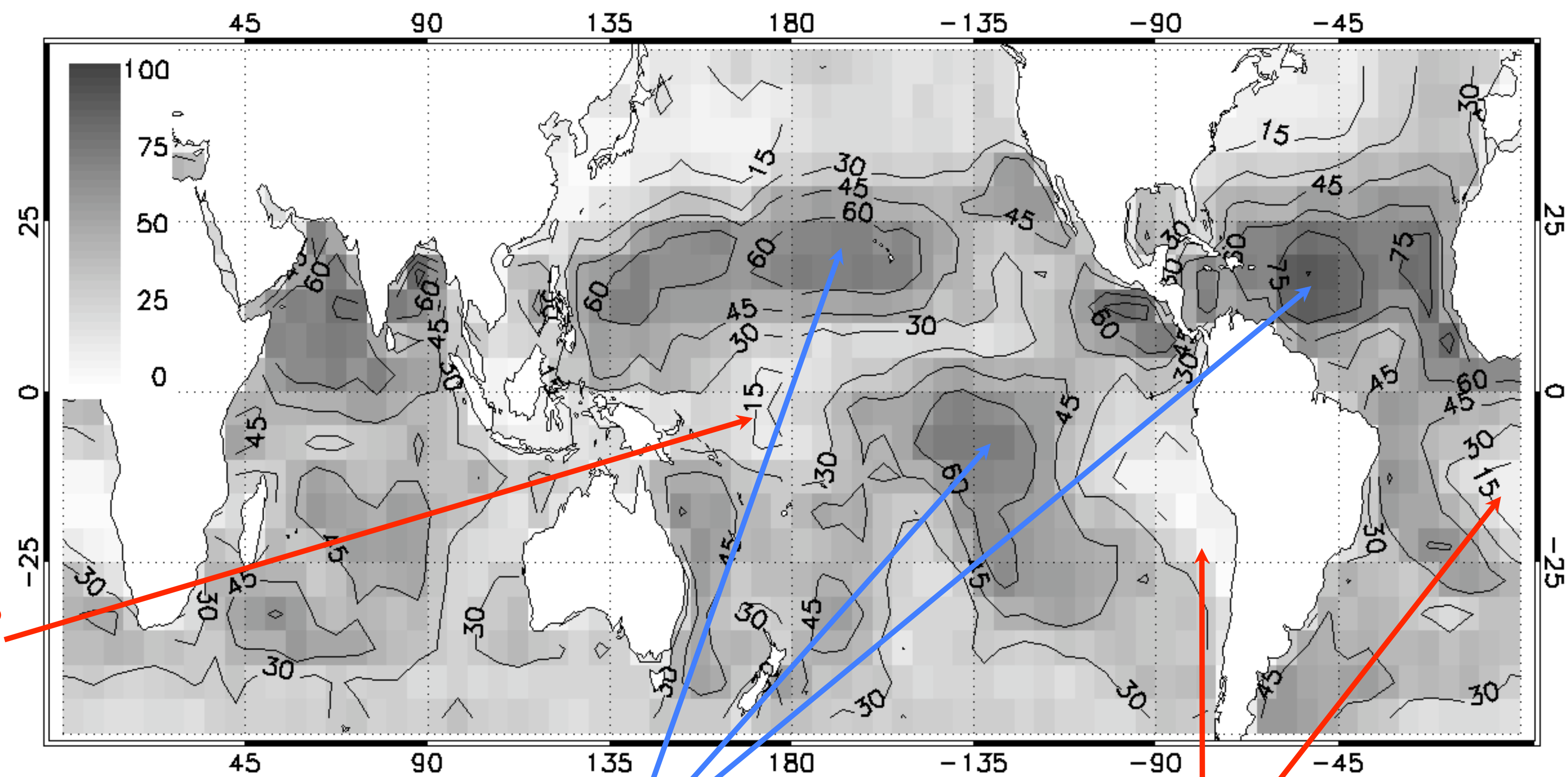
AIRS retrieval yields vary with location

Fraction of 'good' retrievals (percent)

25 Dec 2002 to 15 Jan 2003



!!??

Highest yields in trade cumulus.
Good news for Fetzer et al. 2004.

Poorer coverage in stratocumulus;
use with caution here.

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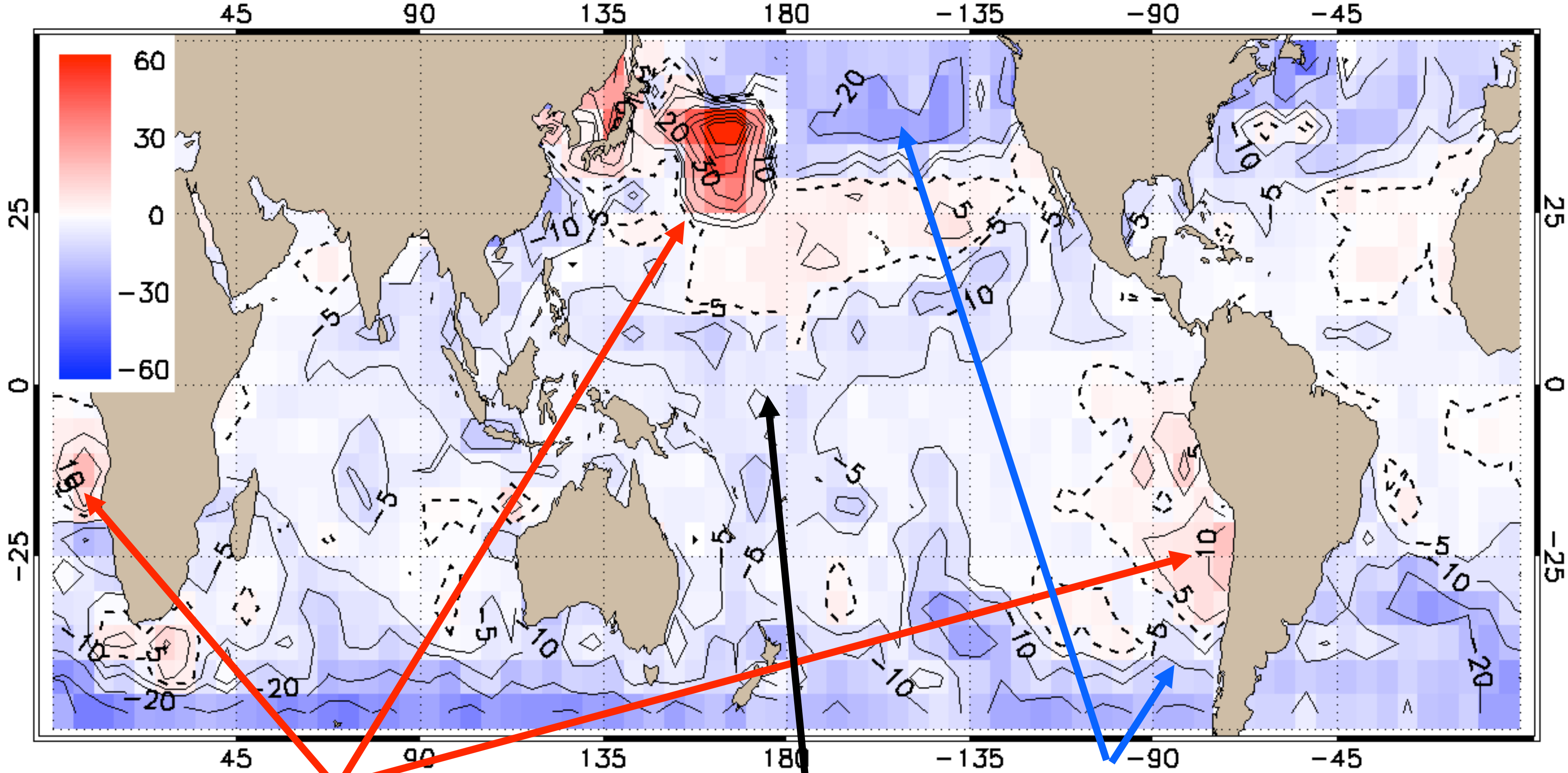
Percent Differences in Mean Water Vapor Climatologies

AIRS can be drier OR wetter than AMSR-E

because of cloud-induced sampling effects

25 Dec 2002 to 15 Jan 2003



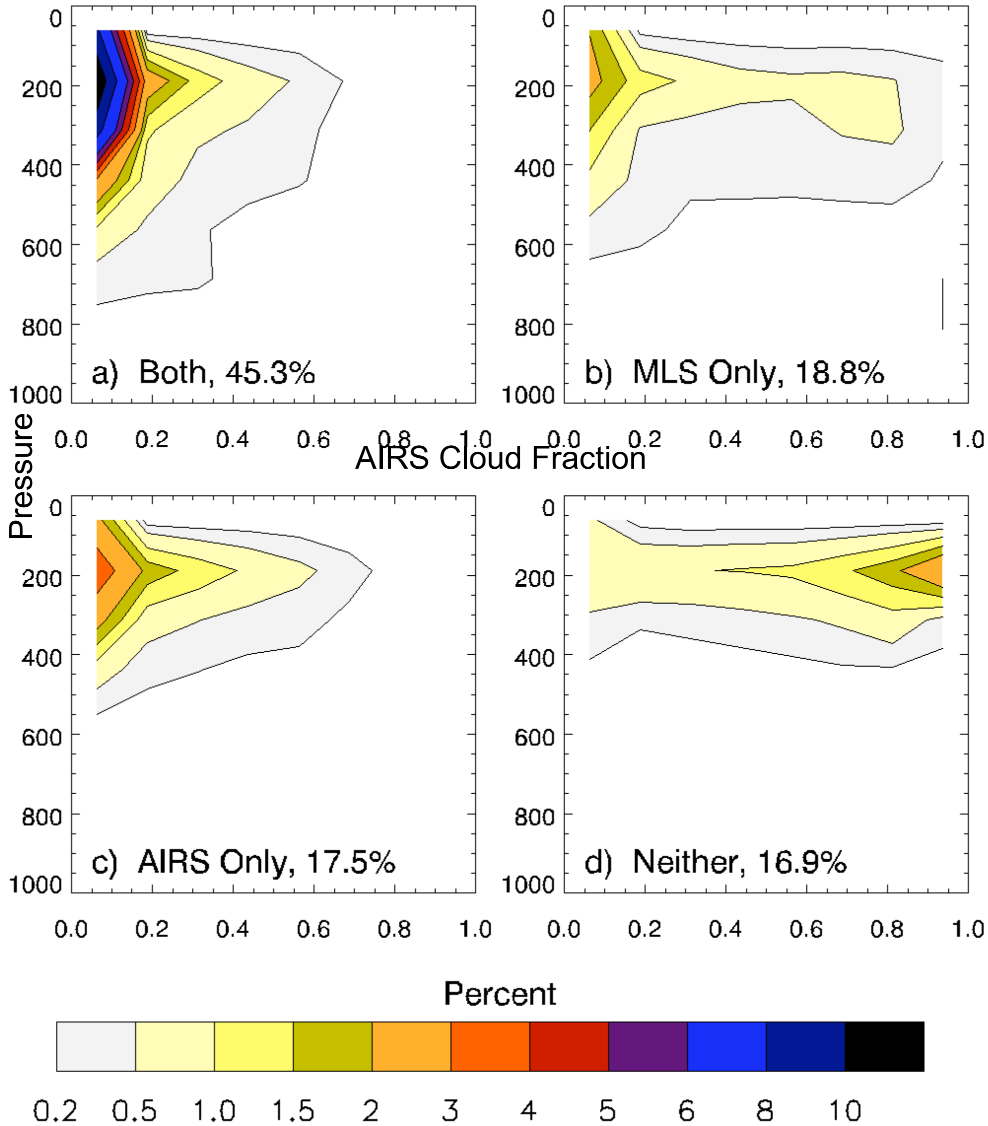
AIRS climatology is *wetter* than AMSR-E in stratus regions

Small difference in tropics !!??

AIRS climatology is *drier* than AMSR-E at high latitudes

10

Both AIRS and MLS preferentially sample clear scenes in tropics



MLS samples within thicker clouds.

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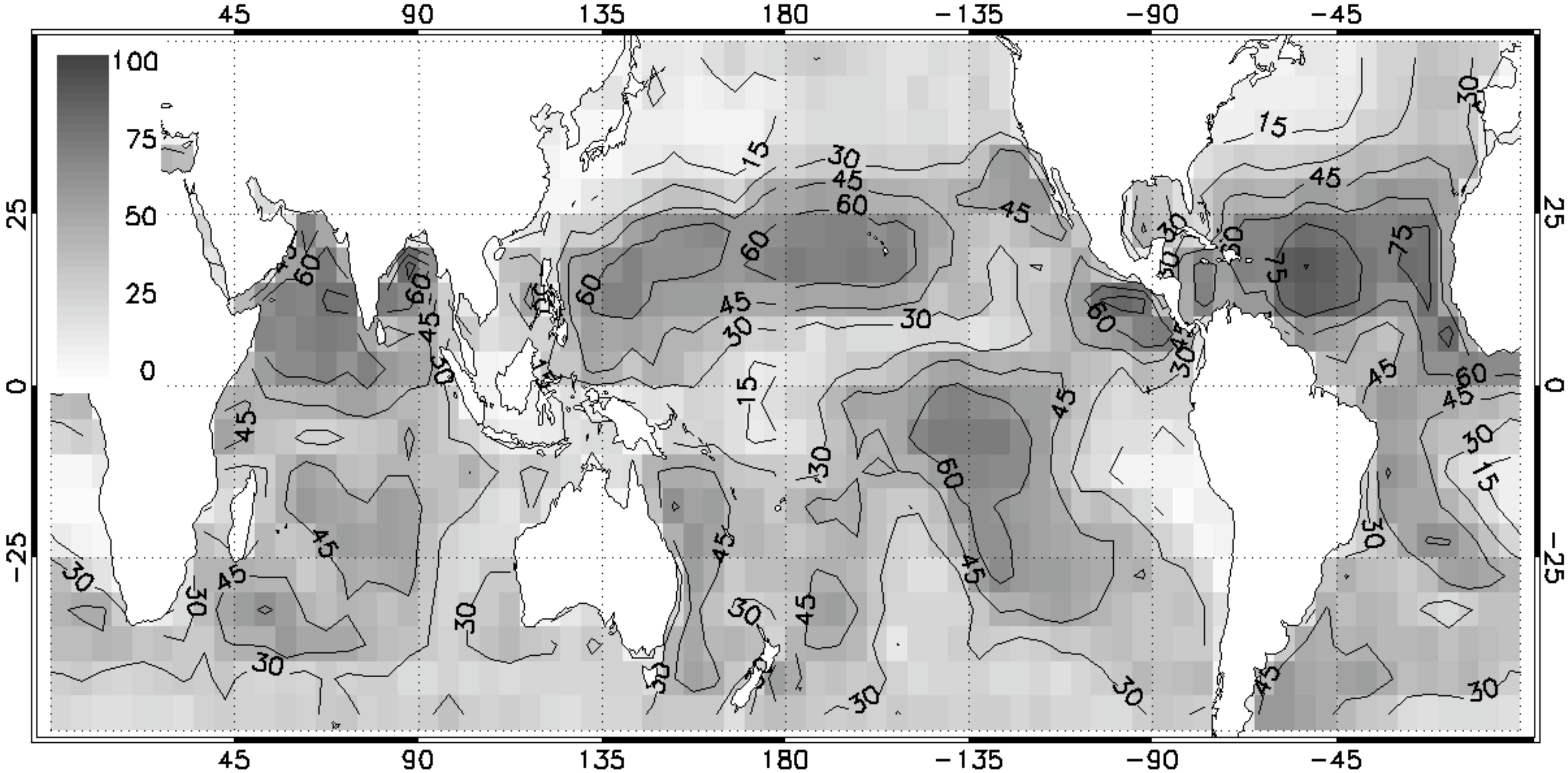
Challenge: Calculate a climatology over this sample.

***Note*: It is the only sample with:**
1) global coverage
2) high vertical resolution in the troposphere.



AIRS Yields

12

Theme 2: Exploiting NASA's A-Train Constellation

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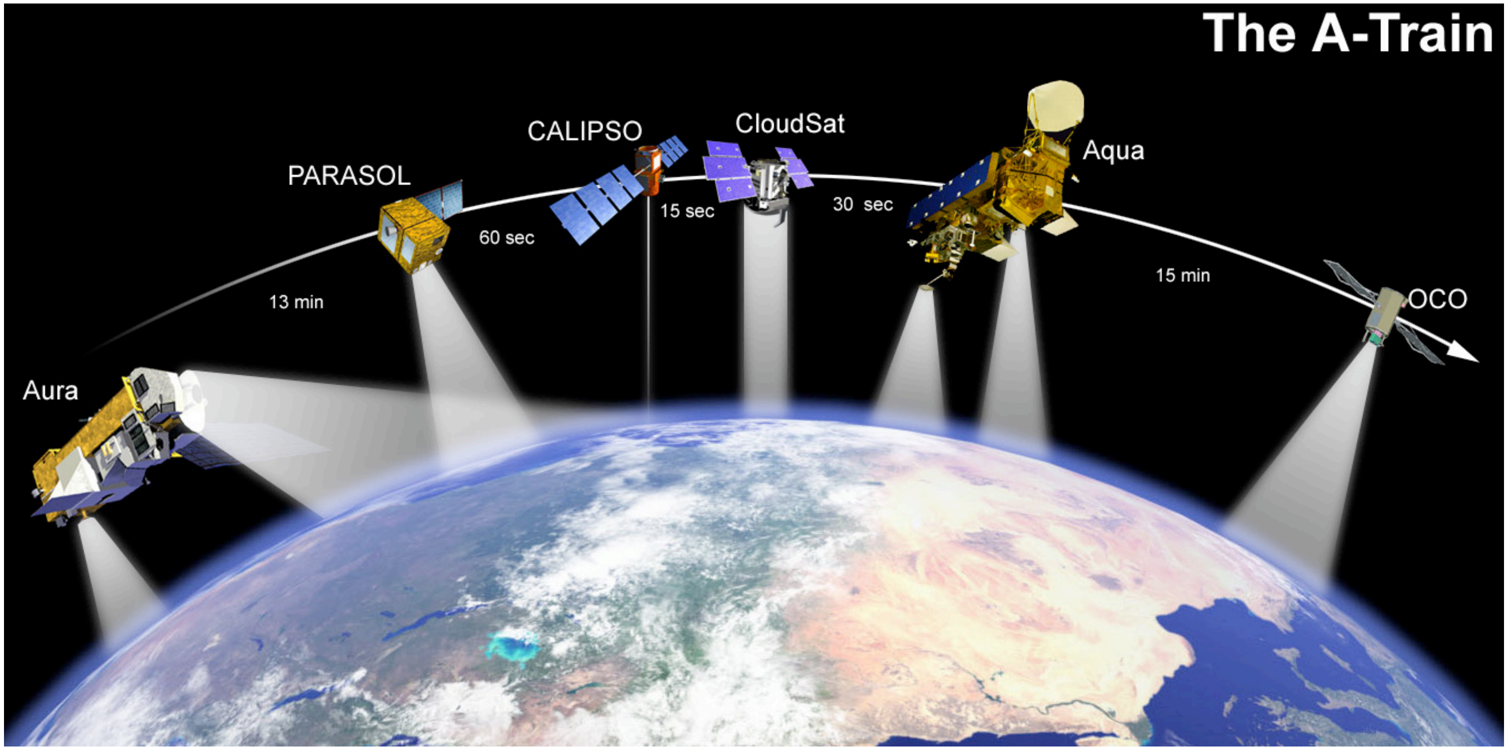
Multiple sensors, often similar quantities:

- **Temperature from AIRS, MLS, TES, MODIS.**
- **Water vapor from AIRS, AMSR-E, TES and MODIS.**
- **Clouds from CloudSat/CALIPSO, MODIS, AIRS and AMSR-E.**



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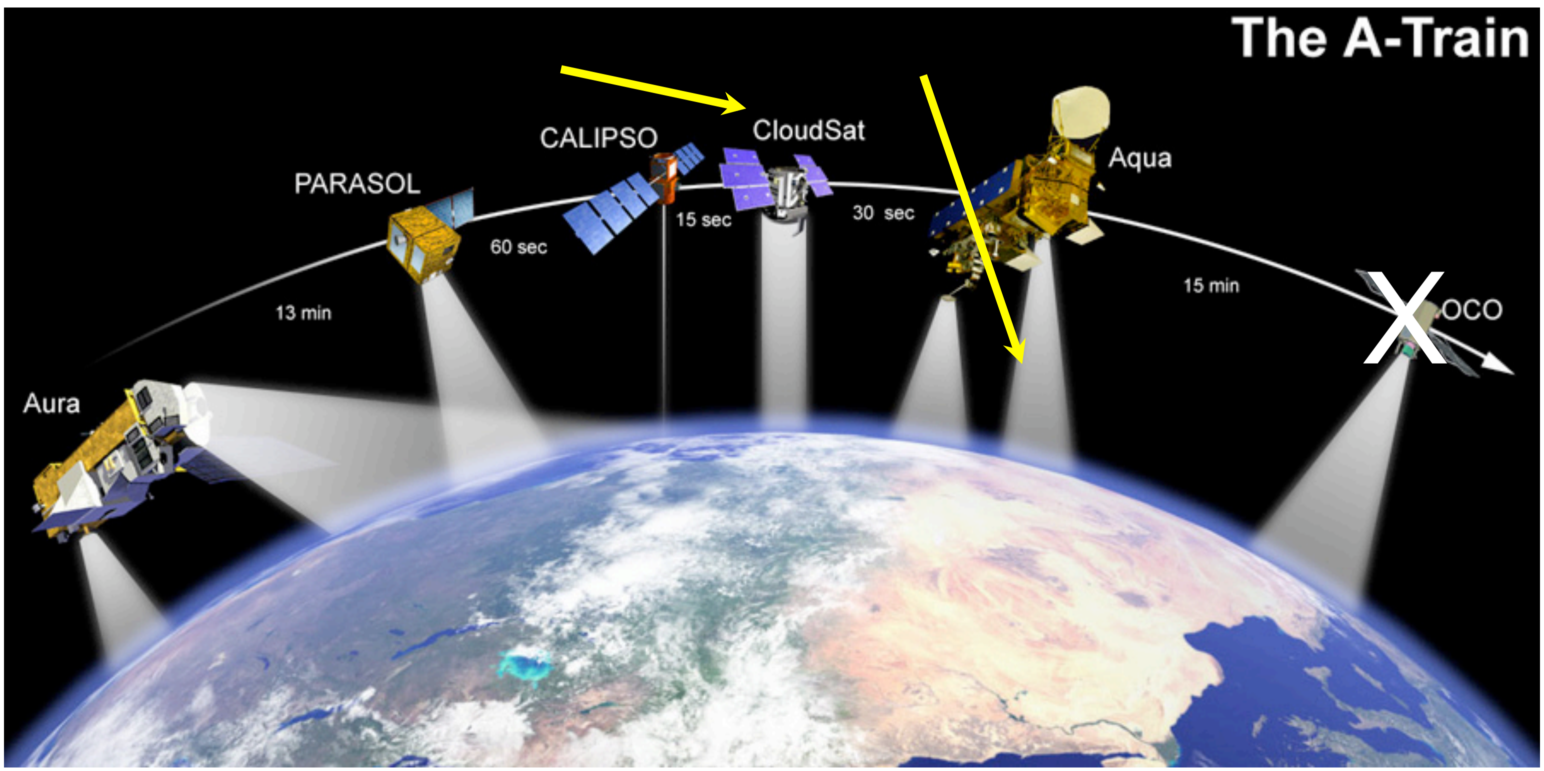
Showing Data from Two *Independent* Instruments

1. **AIRS water vapor profiles.**
2. **CloudSat cloud classes overlie AIRS near nadir.**



14

Collocated AIRS and CloudSat Datasets

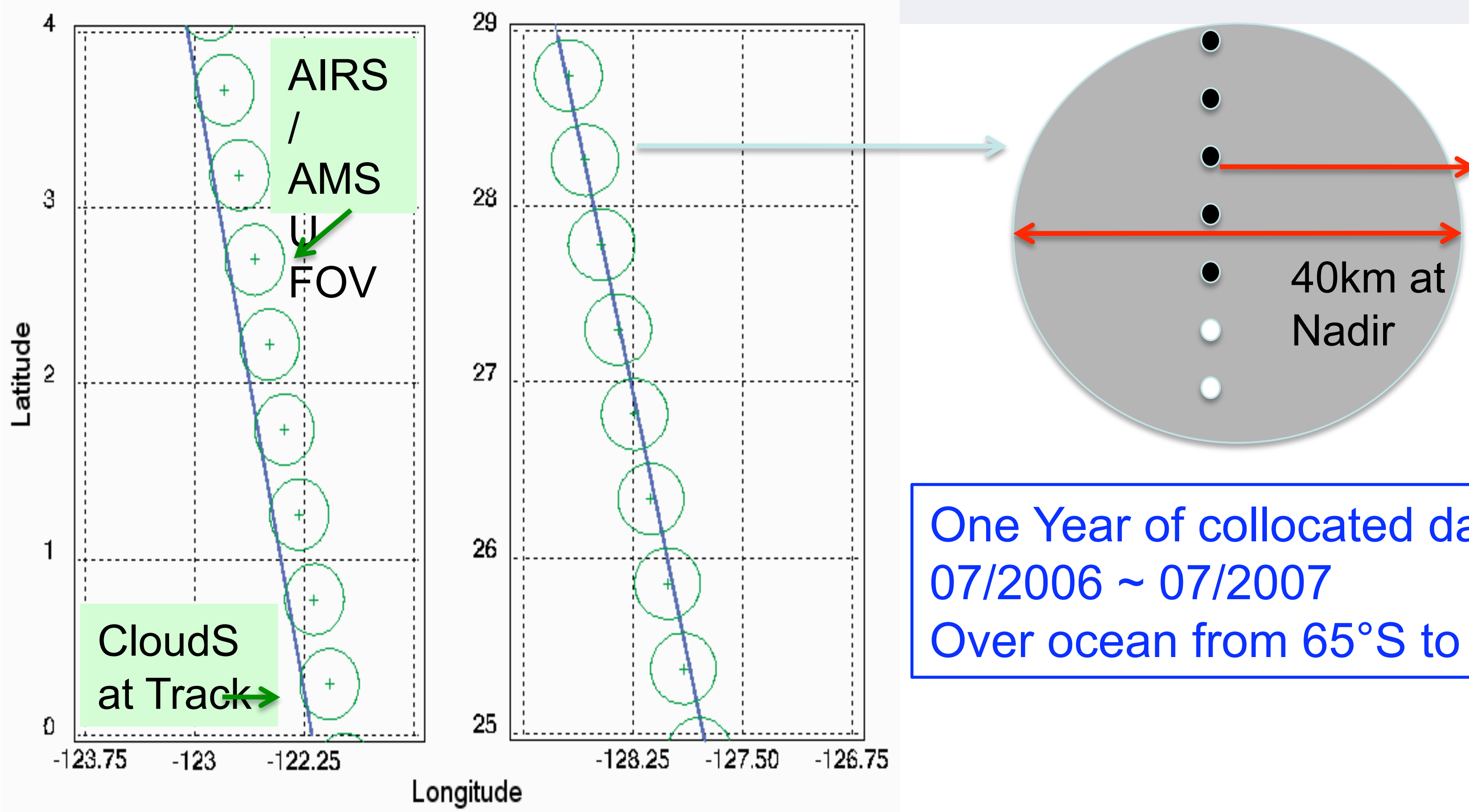


Figure from NASA/GES DISC, A-Train Data Depot

One Year of collocated data:
07/2006 ~ 07/2007
Over ocean from 65°S to 65°N

- **Huge difference in the spatial resolution of these instruments.**

Thanks to Qing Yue

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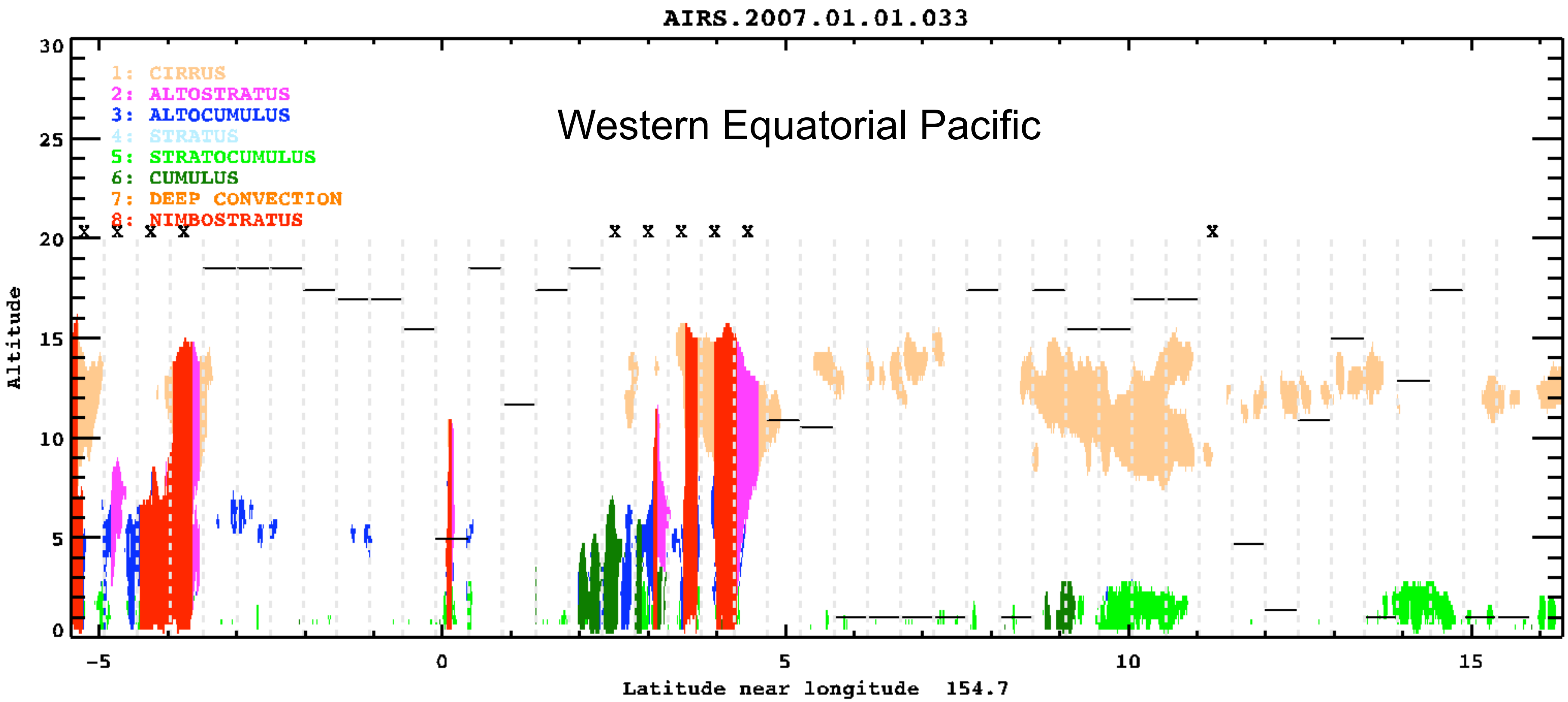
AIRS-CloudSat Matched Data

Color fill = CloudSat Class (Sassen and Wang, 2008, GRL)



Black lines: AIRS 'best' retrieval altitude
X: no AIRS tropospheric profiling.

16

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AIRS Mean Water Vapor by *CloudSat* Classes

January 2007, 15S-15N, Ocean only

1) Shallow Clouds

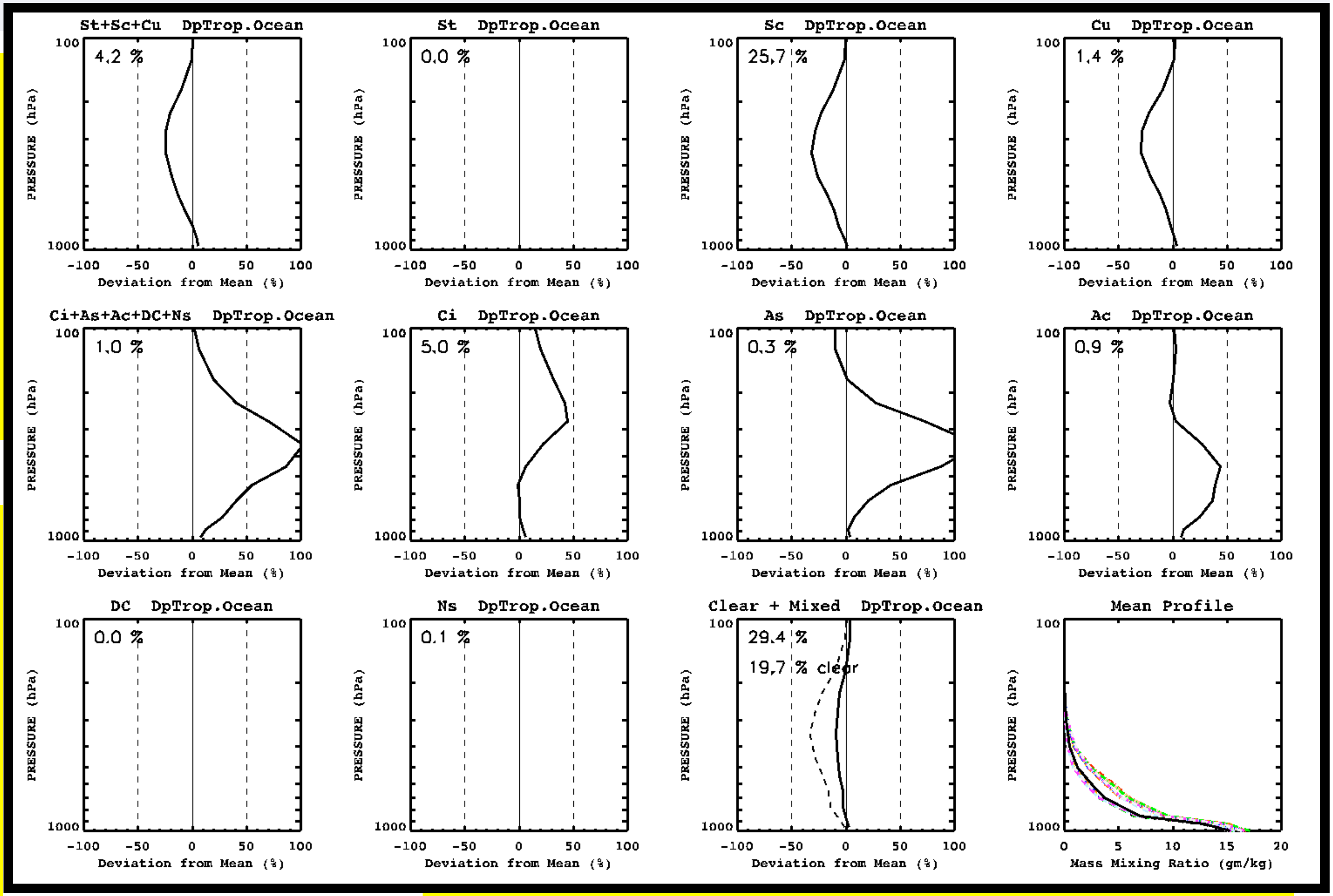
40% of all scenes

Yields are ~80%.

2) Deep Clouds

17% of all scenes

Yields are ~2 to 63%.



3) Clear & Mixed; ~43% of scenes; Yield is 68%.

No Universal Water Vapor Profile by Cloud State

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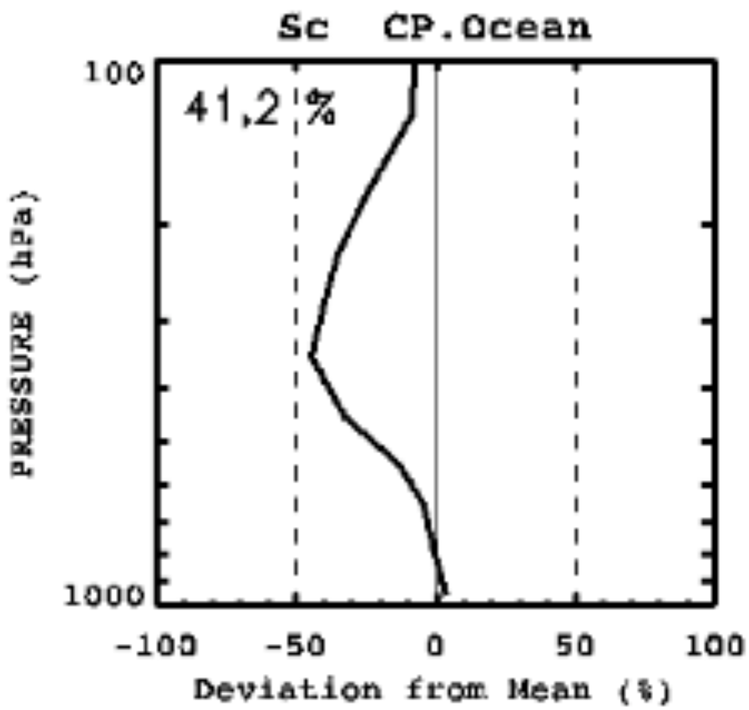
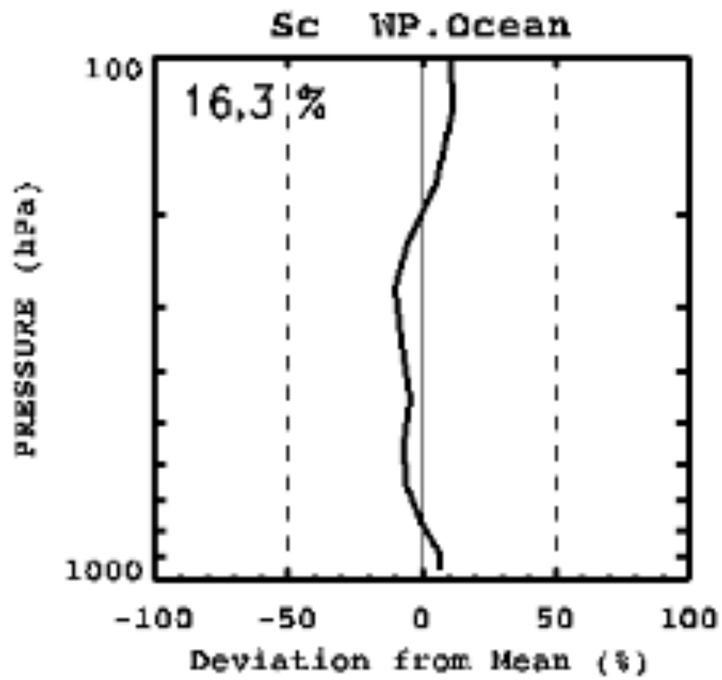
Mean AIRS water vapor profiles for CloudSat Stratocumulus class, relative to the tropical mean



E. Pacific Cool Pool



W. Pacific Warm Pool

18

Fraction of *CloudSat* Shallow Oceanic Clouds Events and *AIRS* Yields

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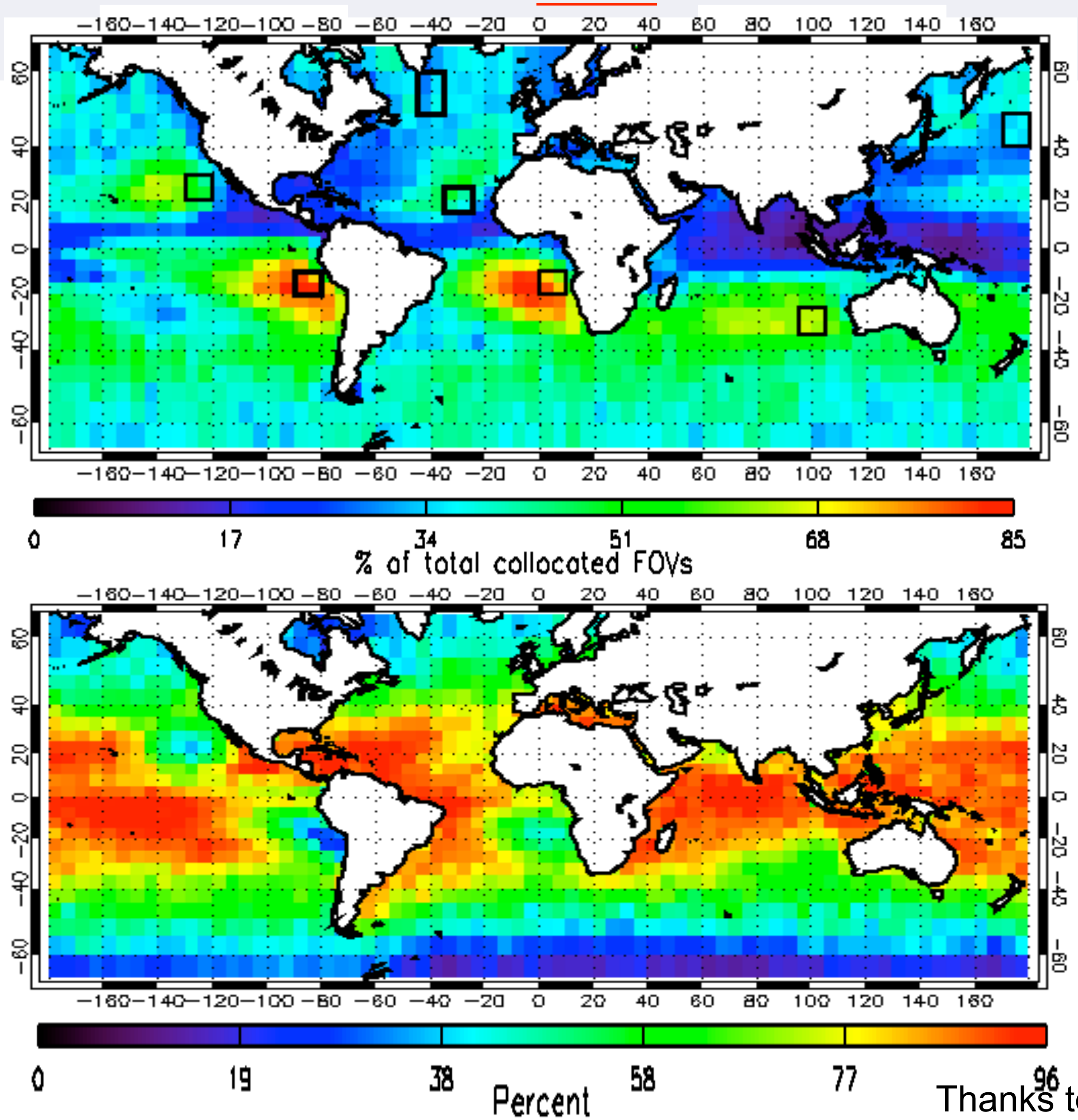

Thanks to Qing Yue

Collocated AIRS and CloudSat Datasets

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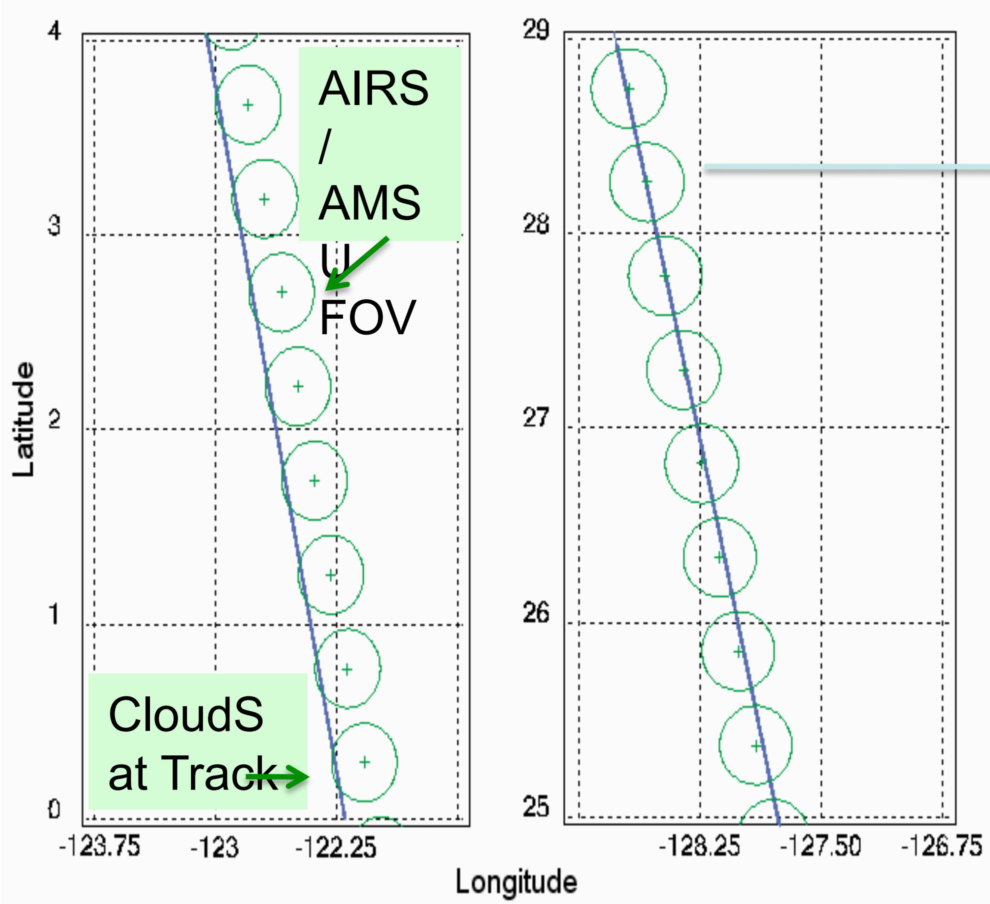
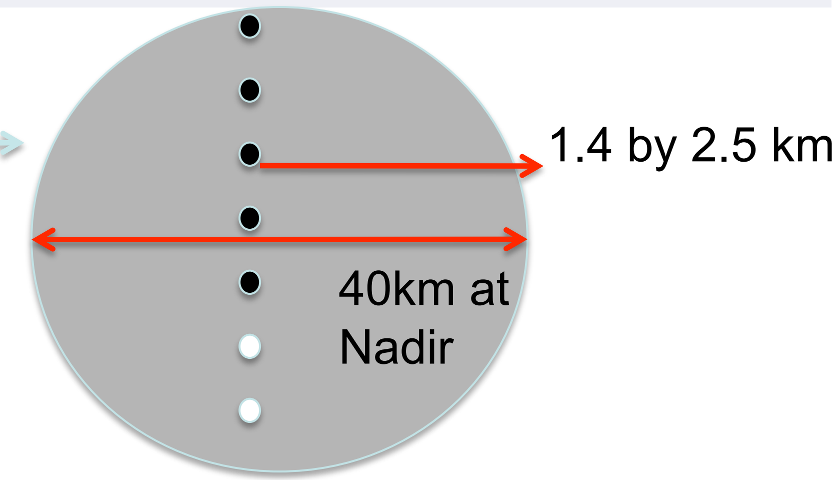


Figure from NASA/GES DISC, A-Train Data Depot



One Year of collocated data:
07/2006 ~ 07/2007
Over ocean from 65°S to 65°N

- **Huge difference in the spatial resolution of these instruments.**

Thanks to Qing Yue

A basic question in our analyses:
What combined CloudSat cloud top classes are found in AIRS footprints?

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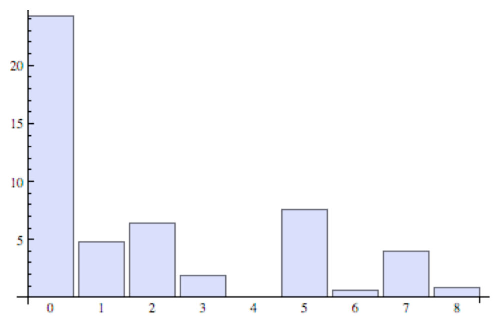
1- Consider topmost matched CloudSat classes in an AIRS fields of view.

2- Transform each histogram into a scenario (binary list):



{1,1,1,1,0,1,1,1,1}

0	1	2	3	4	5	6	7	8
No cloud	Cirrus	Altostrastus	Altocumulus	St	Sc	Cumulus	Ns	Deep convection

Level 2 Cloud Scenario Classification Product Process Description and Interface Control Document

3- Identify and count each scenario occurrence in the bit list. There are 2^9=512 ways to write a 9 list with 2 digits. For instance, the previous scenario can be coded to 495.

Data shown today: August 2006

Thanks to Alex Guillaume

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Dominant CloudSat Cloud Classes *in AIRS Scenes*

scene code	count	proportion [%]	scene
264	1057776	27.14	{"nc", "Sc"}
256	703439	18.05	{"nc"}
384	258885	6.64	{"nc", "ci"}
320	217153	5.57	{"nc", "AlSt"}
296	179918	4.62	{"nc", "Alcu", "Sc"}
392	128973	3.31	{"nc", "ci", "Sc"}
268	124975	3.21	{"nc", "Sc", "Cu"}
448	104261	2.68	{"nc", "ci", "AlSt"}
258	92868	2.38	{"nc", "Ns"}
288	70978	1.82	{"nc", "Alcu"}
64	56502	1.45	{"AlSt"}
328	51229	1.31	{"nc", "AlSt", "Sc"}
322	50914	1.31	{"nc", "AlSt", "Ns"}
300	44125	1.13	{"nc", "Alcu", "Sc", "Cu"}

- **Only 327 combinations exist (of 512 possible).**
- **Fourteen scene types in this table explain 80.6% of scenes GLOBALLY for August 2006.**
- **Some classes will have very few AIRS soundings.**

Clear and Sc are 45% of all scenes, where AIRS yields are generally high (except true stratus west of continents).

Thanks to Alex Guillaume

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Theme 3: Better vertical resolution through improved IR retrievals.

Background:

- High spectral resolution and signal-to noise-ratio => more vertical structure. However:
  - Effects of spectral resolution and S/N are not fully understood.
    - TES: Higher spectral resolution, lower S/N.
    - AIRS: Missing bands, lower resolution, higher S/N.
- *Another tradeoff:* Higher vertical resolution in the IR, but clouds reduce sampling (and resolution)
  - This trade space is not fully understood.
  - Not an issue in the *hyperspectral* microwave.

23
Thanks to John Worden

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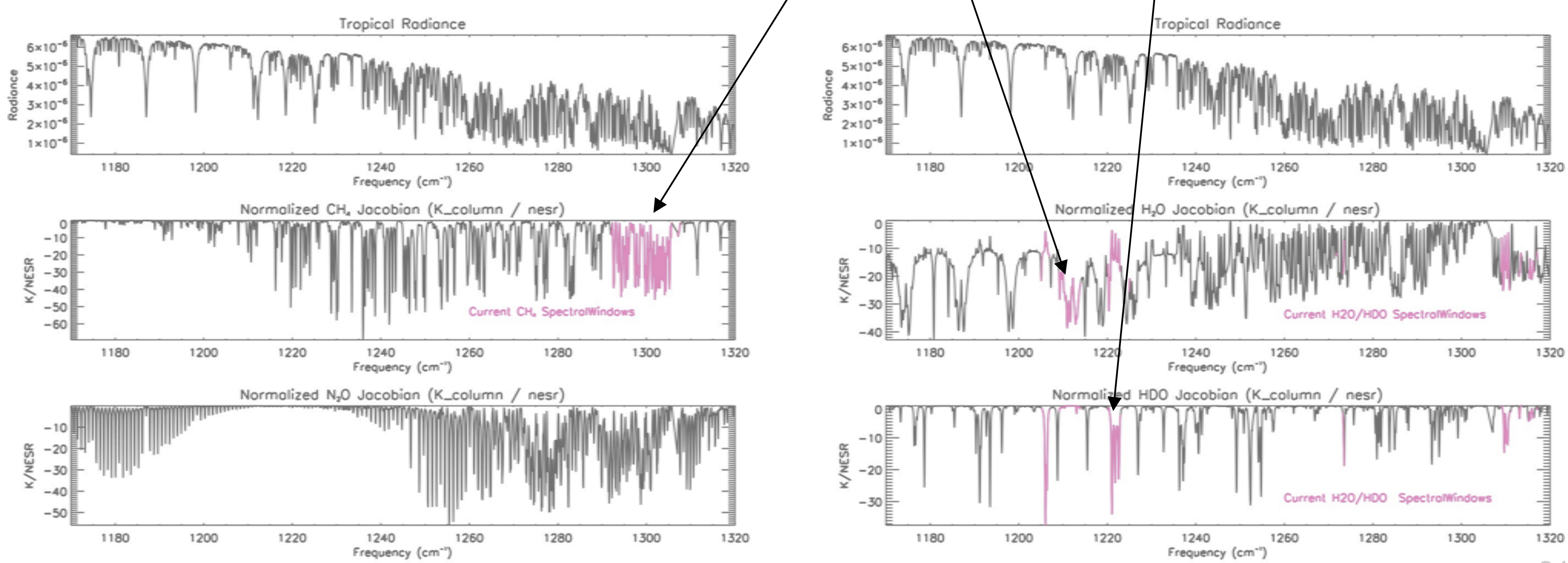
Current TES Retrieval Approach:

•CH_4, HDO, and H_2O tropospheric concentrations are estimated from spectral radiances between 1200 cm^{-1} and 1310 cm^{-1}

•Gases treated as radiative interfering with each other, resulting in the use of "micro-windows" for estimating these species to reduce interference error
(Worden, Kulawik et al., 2004 JGR; Worden, Bowman, Noone et al., 2006, JGR)

Current spectral windows used for CH_4, H_2O, and HDO retrievals



Thanks to John Worden

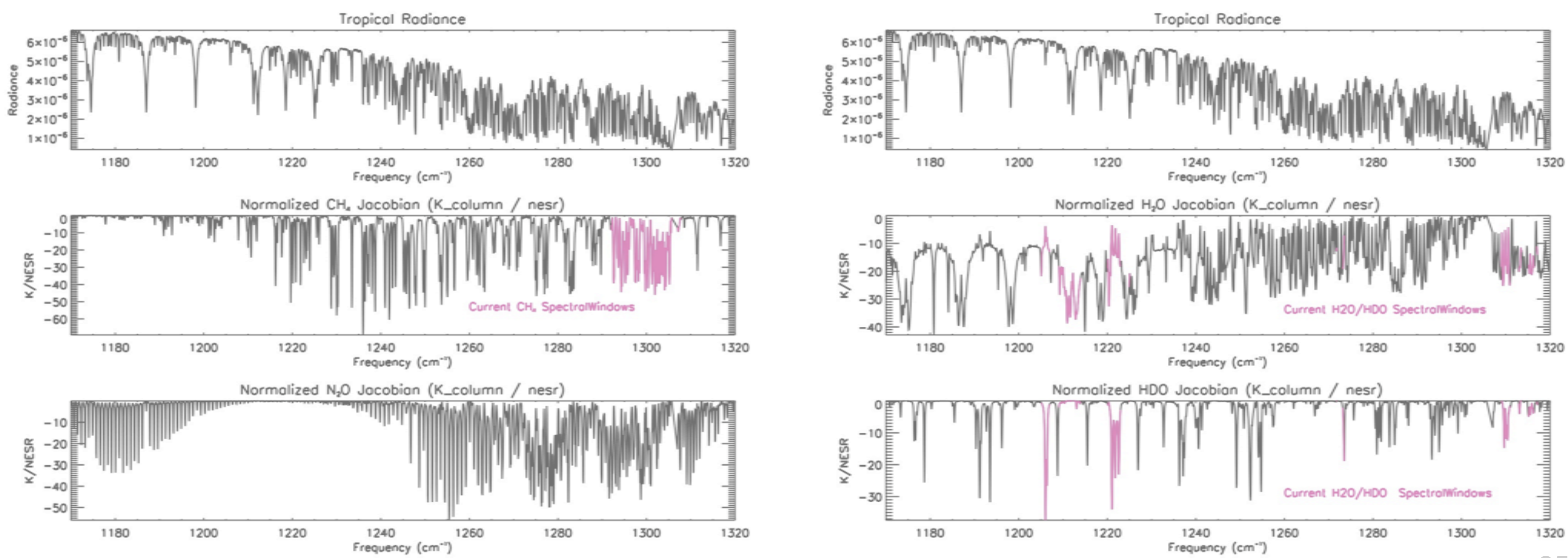
New Approach with TES (in testing)

•Simultaneous profile retrieval estimate of CH_4, H_2O, HDO/H_2O ratio, and N_2O using (nearly) entire radiance from 1170 cm^{-1} to 1320 cm^{-1}

•Increases CH_4 lower troposphere retrieval sensitivity by using weak absorption lines near 1240 cm^{-1} where surface-to-space transmittance is higher

•H_2O and HDO retrieval sensitivity increased by using more spectral regions

•Simultaneous profile retrieval minimizes interference error



Thanks to John Worden

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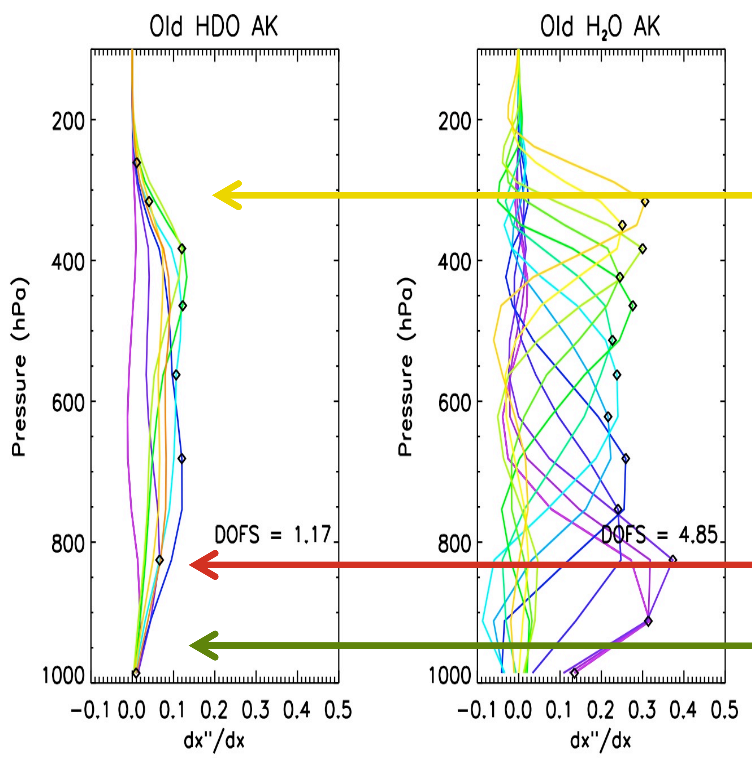
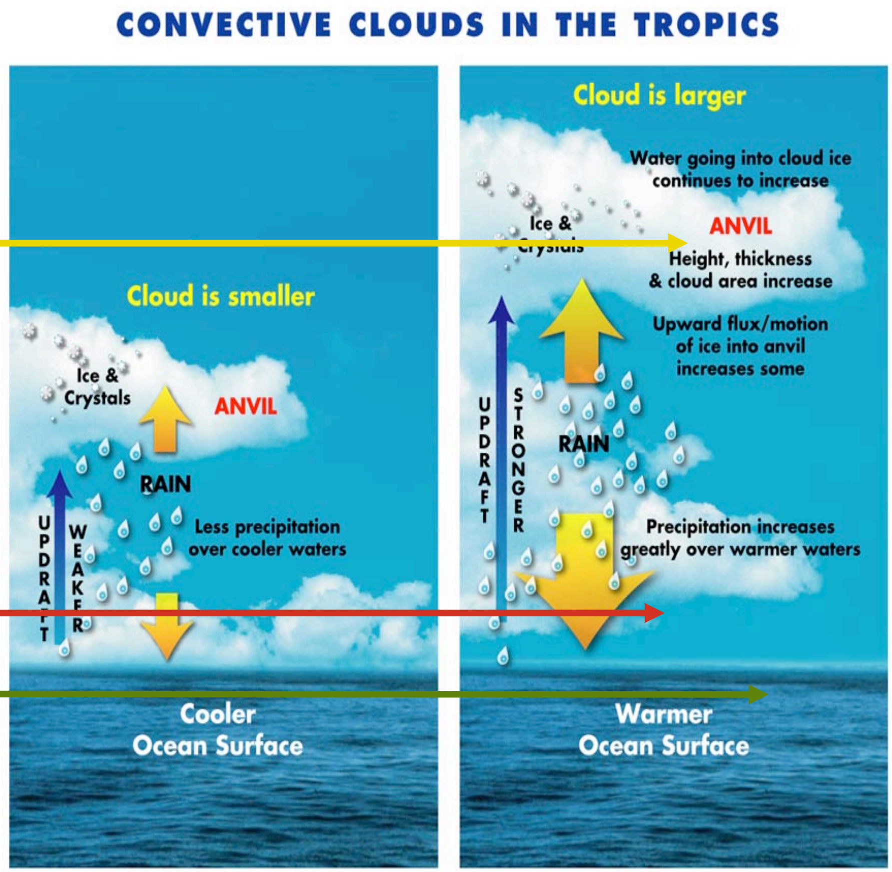
Older method: Limited vertical resolution of HDO/H_2O ratio and H_2O reduces capability to distinguish lower and upper tropospheric cloud processes





Del Genio et al., J. of Climate 2002

Thanks to John Worden

New method: vertical resolution can now distinguish cloud processes in the middle/upper troposphere from lower troposphere (at least in the tropics)

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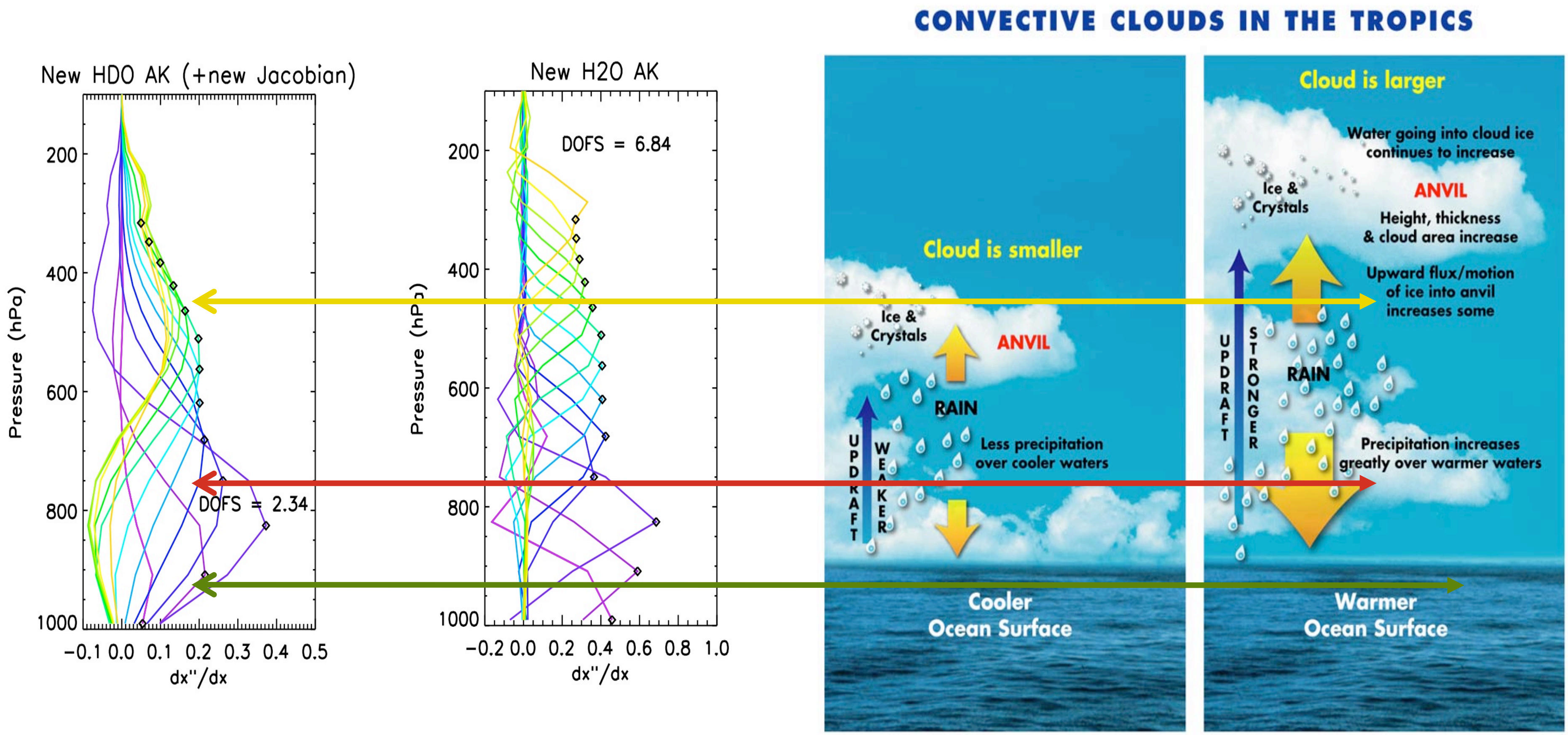

Del Genio et al., J. of Climate 2002

Thanks to John Worden

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Summarizing
Improving Current Instruments and Data Sets

- **Information content not fully exploited. Need:**
  - **New retrieval methods.**
  - **Possible regime-based analyses**
    - **e.g., we know AIRS works well in trade Cu.**
- **Better use of multi-sensor observations**
  - **Careful bookkeeping of matched *<u>AIRS-CloudSat</u>* data sets gives important climate insights.**
  - **NASA recognizes value, <u>but only for existing retrieved products</u>**
    - **Currently little support for multi-sensor retrievals**
      - **For example, no merged AIRS-TES retrievals.**

Thanks to Tom Pagano

28

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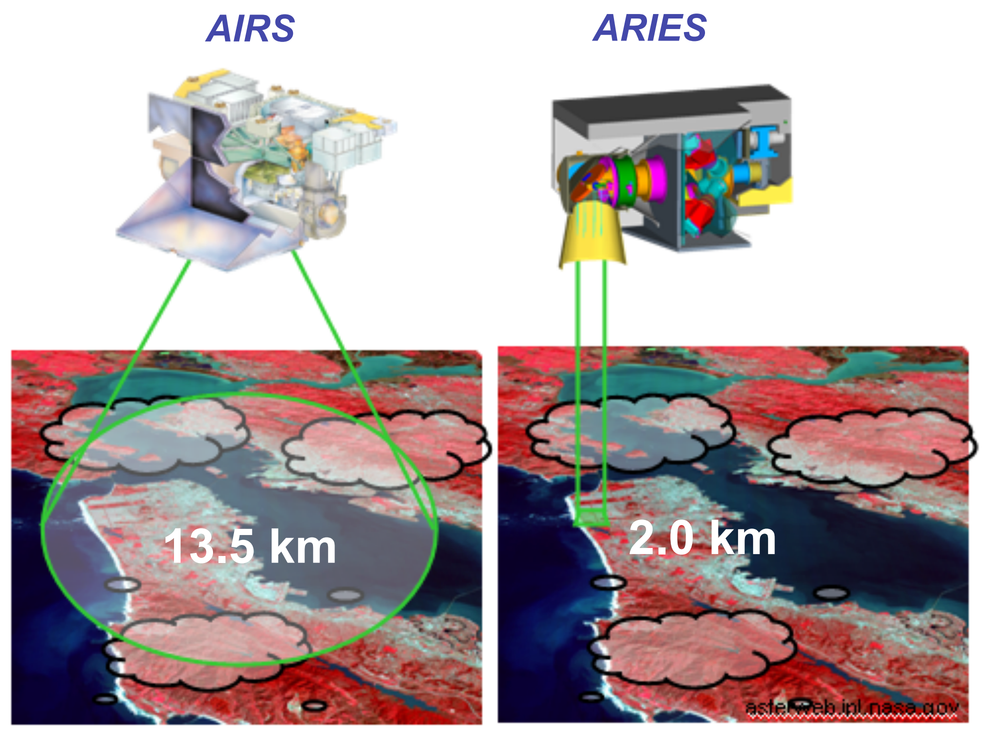
Theme 4. The Future: Imaging in the Hyperspectral IR

More Channels and Higher Spatial Resolution

Advanced Remote Sensing Imaging Emission Sounder (ARIES)

Requirements:
- 3.4 – 15.4 μm
- Hyperspectral: Over 4000 Channels (AIRS has 2378)
- 2 km Horizontal Resolution
- Global Daily Coverage (±55° Swath)

Features
- Higher Spectral Resolution
    - Resolves Boundary Layer
    - Improves Vertical Resolution
- Higher Spatial Resolution
    - Improves Cloud Clearing Yield
    - Improves Surface Spectral Emissivity
    - Improves CO2 Yield and Accuracy



Band	Spectral Range	Spectral Resolution	No. Channels
MW1	2100 - 2950 cm^{-1}	1.0 cm^{-1}	1024
MW2	1150 - 1613 cm^{-1}	0.5 cm^{-1}	1024
LW1	880 - 1150 cm^{-1}	0.5 cm^{-1}	1024
LW2	650 - 880 cm^{-1}	0.4 cm^{-1}	1024

Thanks to Tom Pagano

29

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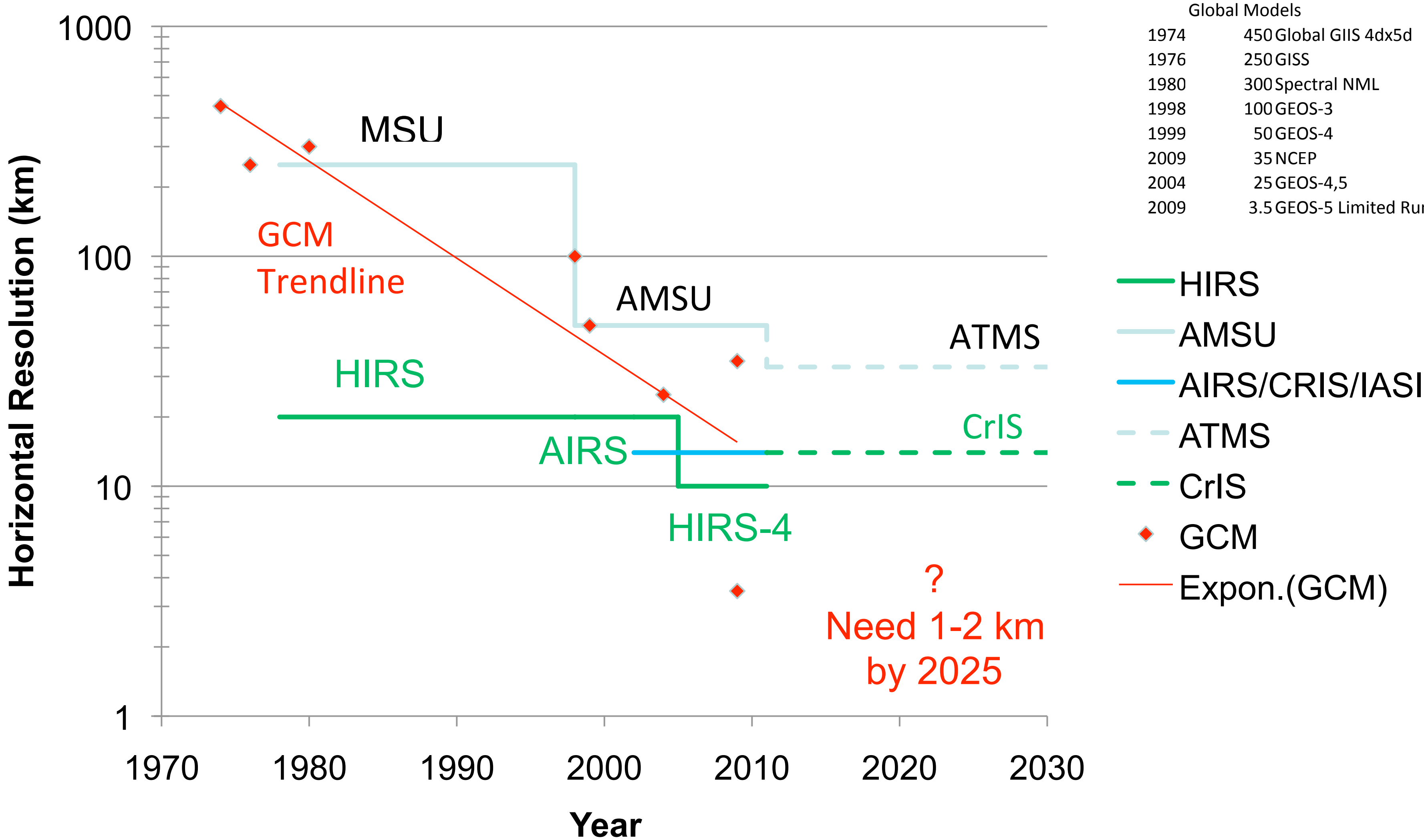
Higher Resolution Sounders Needed to Initialize and Validate Next-Gen GCM's

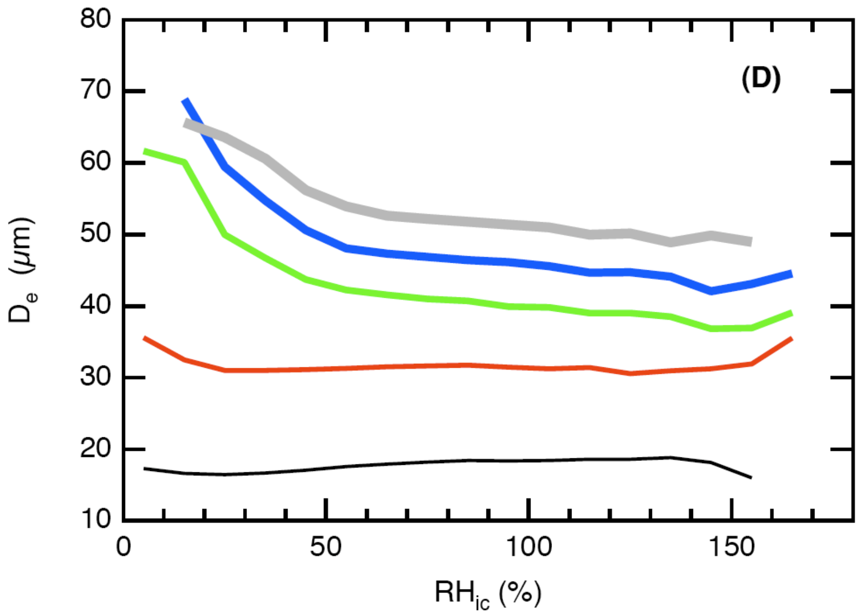


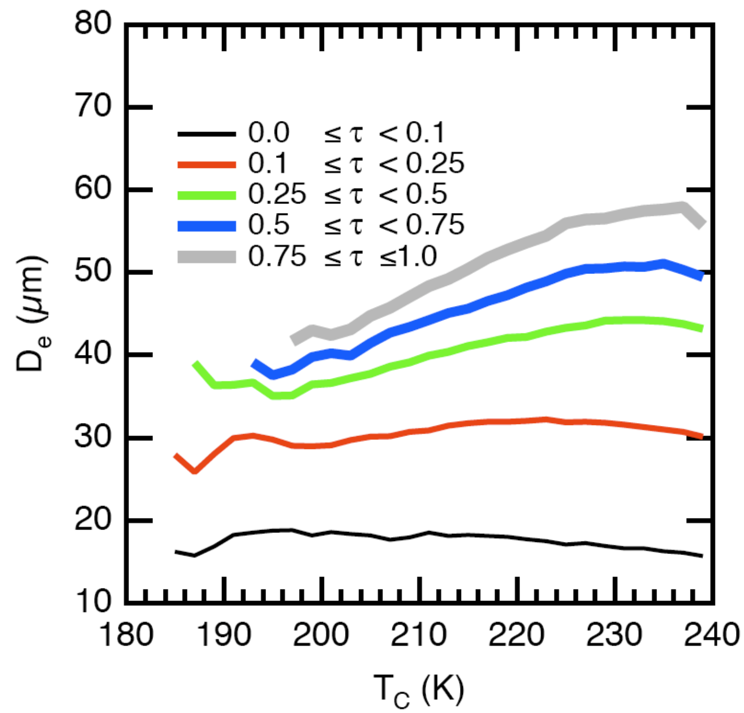
Global Models

1974	450	Global GIIS 4dx5d
1976	250	GISS
1980	300	Spectral NML
1998	100	GEOS-3
1999	50	GEOS-4
2009	35	NCEP
2004	25	GEOS-4,5
2009	3.5	GEOS-5 Limited Run

Need Cloud-Resolving *Observations* for Microphysics Retrievals

AIRS Provides Ice Microphysics Simultaneously With Relative Humidity and Temperature





These are in addition to existing products for cloud height and fraction

Kahn et al. 2008, Atmos. Chem. Phys.

Thanks to Tom Pagano

Higher Spatial Resolution Will Improve Process Studies of Clouds and Water Vapor

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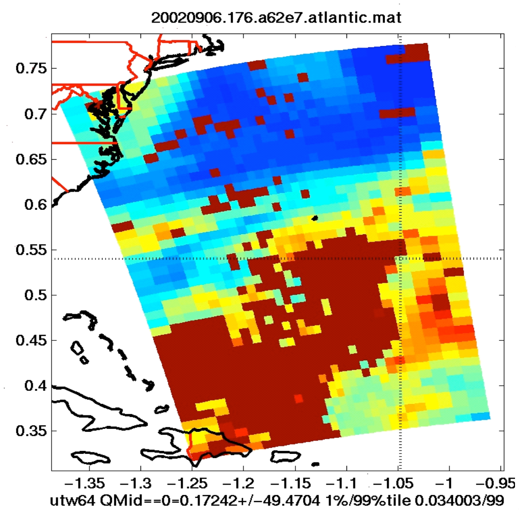
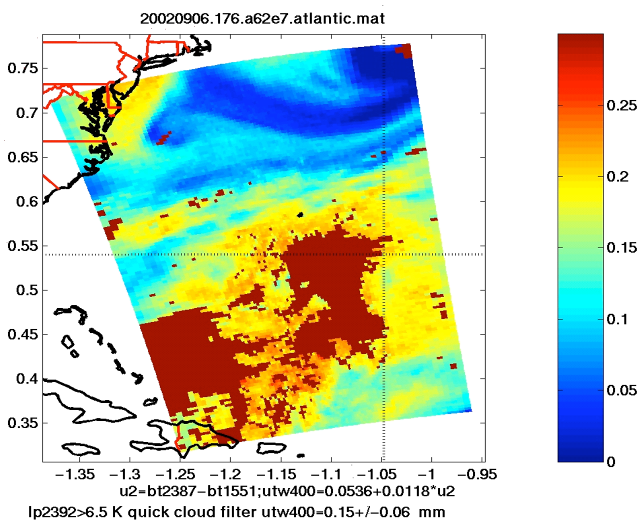
Water Vapor

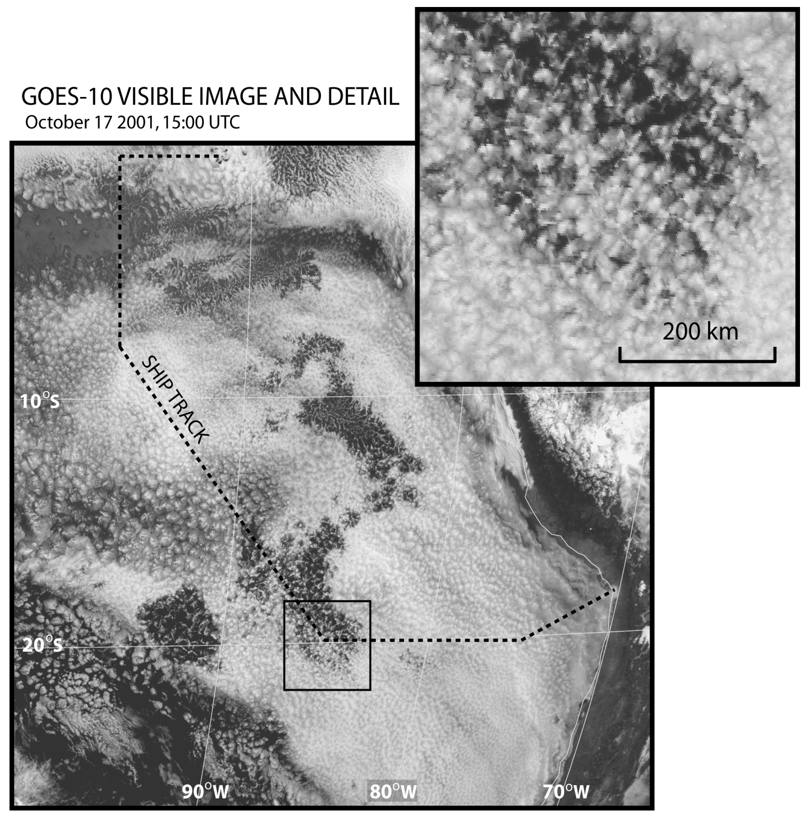
Current (AIRS) 50 km



15 km



Sub Gridscale Resolution Needed to Constrain Cloud Physics Parameterization



Bretherton et al (2004)

Thanks to Tom Pagano

Expect Improvements in Emissivity — and Boundary Layer Accuracy and Yield — from Higher Spatial Resolution IR Sounder

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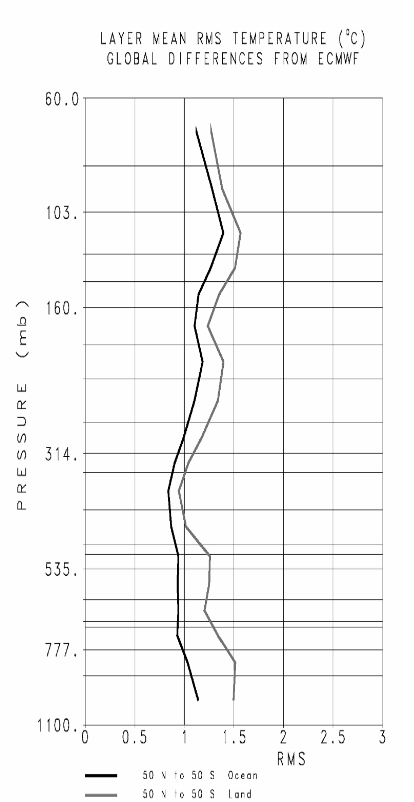
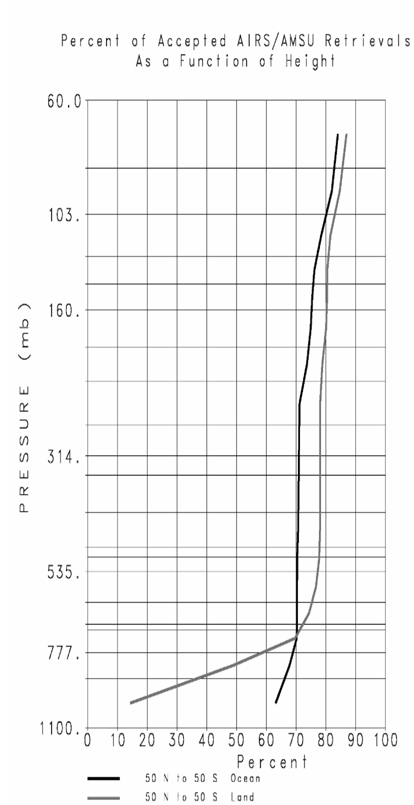
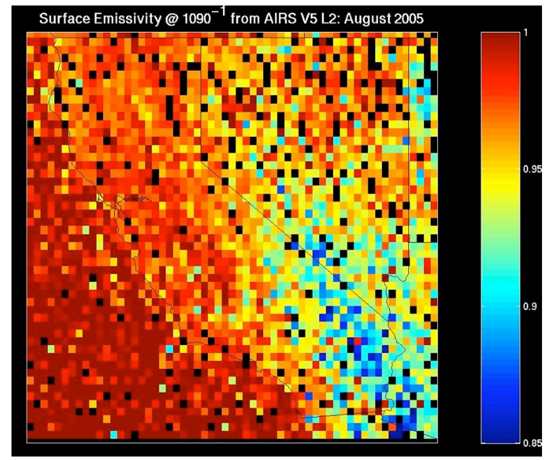
AIRS Yield and Accuracy Degrade Near Land Surface





Land cases limited by inadequate surface emissivity knowledge.



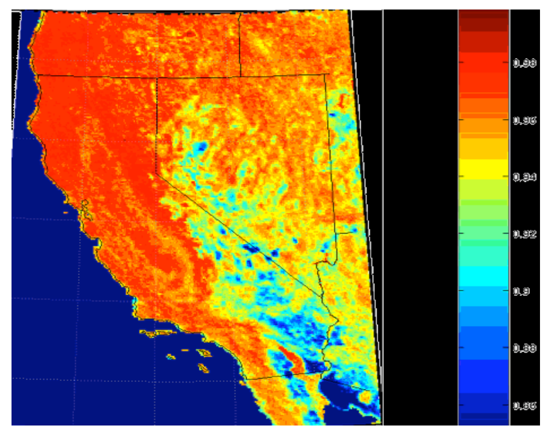
T. Pagano (JPL)

AIRS (Hyperspectral)

One Month
August 2005
Cloud-cleared

50x50 km

v = 1095 cm^{-1}



S. Hook (JPL)

MODIS (Broadband)

One Month August
August 2003
Cloud-Free Scenes

5x5 km

v = 1205 cm^{-1}

Joel Susskind, 2008

Thanks to Tom Pagano

33

Conclusions for Next Steps

- **High resolution IR sounding will address increasing demands for fine scale observations to**
  - **Match next generation of GCM's.**
  - **Address small-scale climate processes involving clouds and water vapor. Largest uncertain player in climate change.**
  - **Trace gas observations**

- ***How do we continue (or improve on) the A-Train?***
  - ***Details about cloud processes may be best met by***
    - ***Imaging visible and hyperspectral IR instruments.***
    - **A collocated cloud radar.**
    - **A collocated MW sounder.**