New Frontiers in the remote sensing of clouds

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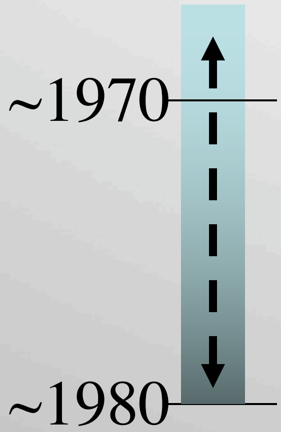
Outline:

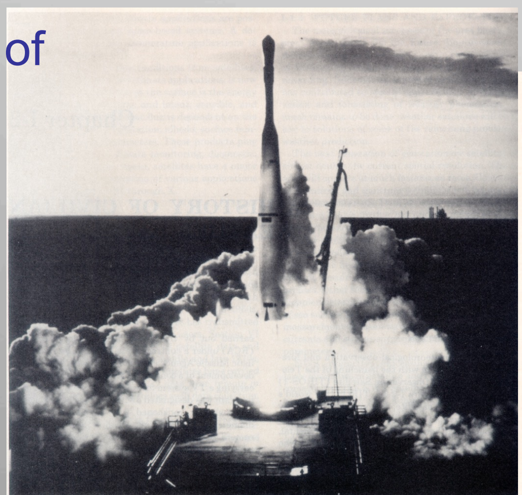
- Reflect on
    - The three eras of cloud remote sensing ➔ why and what I want to observe and some questions posed
    - Remote sensing system ➔ how to observe and typical challenges
    - A-train multi-sensor study of water clouds, ice clouds
    - Observing the warm rain process
    - The next step
- Summary



The first phase: a period of great imagination and some enlightenment

The first 24hr view of global clouds
TIROS-9, February 13, 1965

The launch of TIROS-1, April 1960



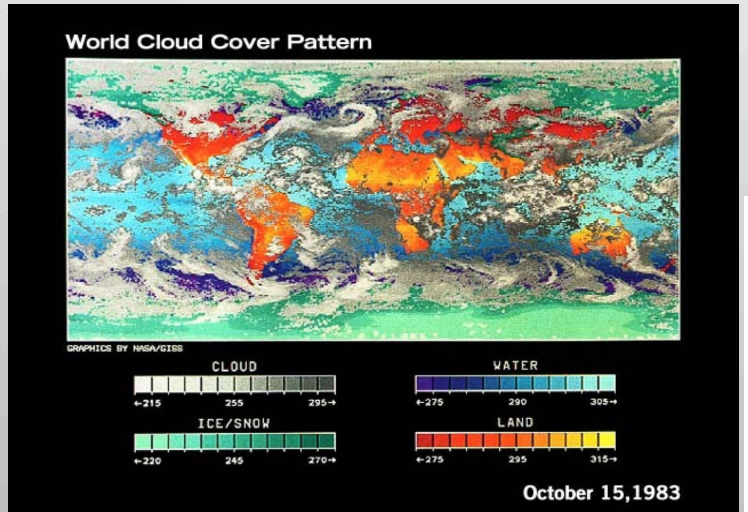
A period when we gathered qualitative data opening new global vistas on clouds - the information content, however, remained low … but this sort of 'imagery' motivated the birth of ISCCP in 1978

1980

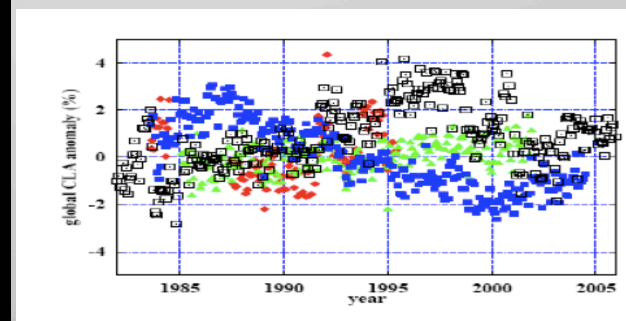
The second phase: information gathering - parameters and techniques

1990

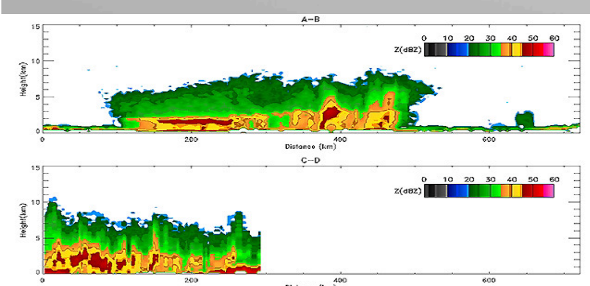
ISCCP



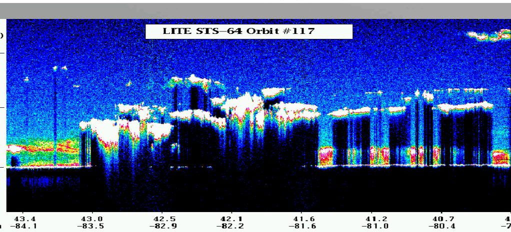
Global climatologies of cloud occurrence*, optical properties, 1983-present



Global CA anomalies from ISCCP (blue), HIRS-NOAA (green), TOVS Path-B (red), and PATMOS-x (grey).

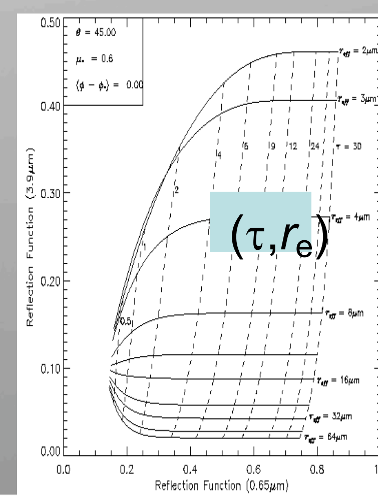


First flight of precipitation radar, TRMM, 1997



First flight of back-scatter lidar, LITE, 1996

CH. 2

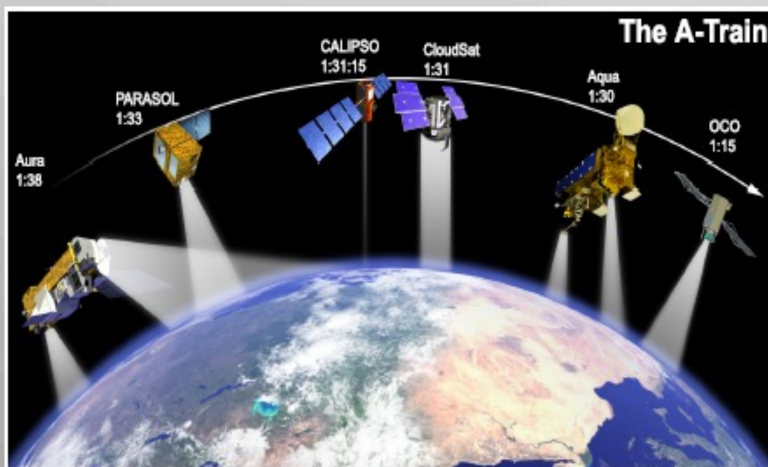


(τ, r_e)

CH. 1

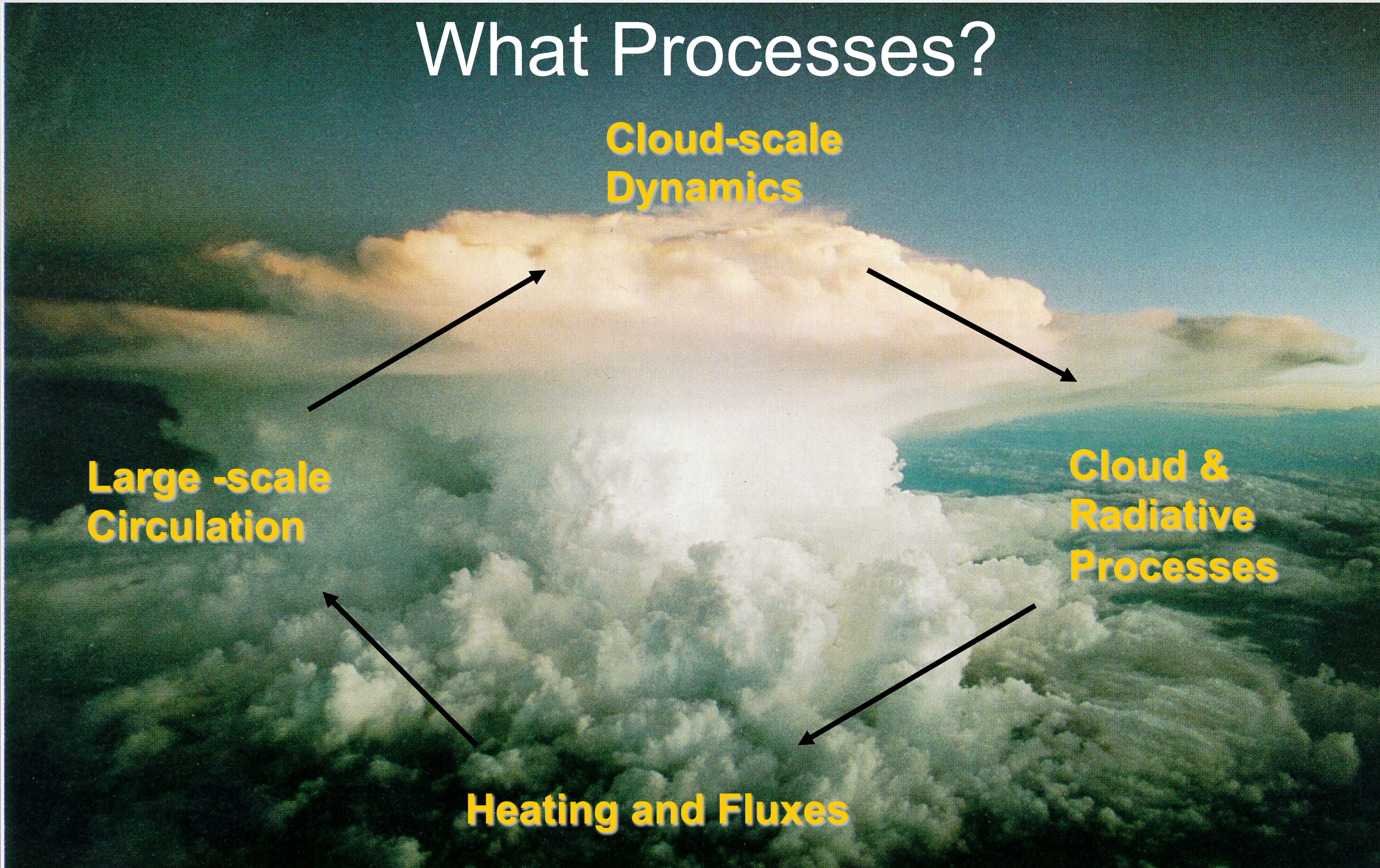
2000

The third phase: grand challenge – integrating information ➔ parameter to process



Since mid 2006, we have access to a wide range of different sensors, active and passive, optical, infrared and microwave, hyper-spectral to coarse band, all approximately viewing Earth at the same time. We are left to pose a strategy that optimally combines these measurements, providing deeper insights on critical ‘water system’ <u>processes</u>.

What Processes?

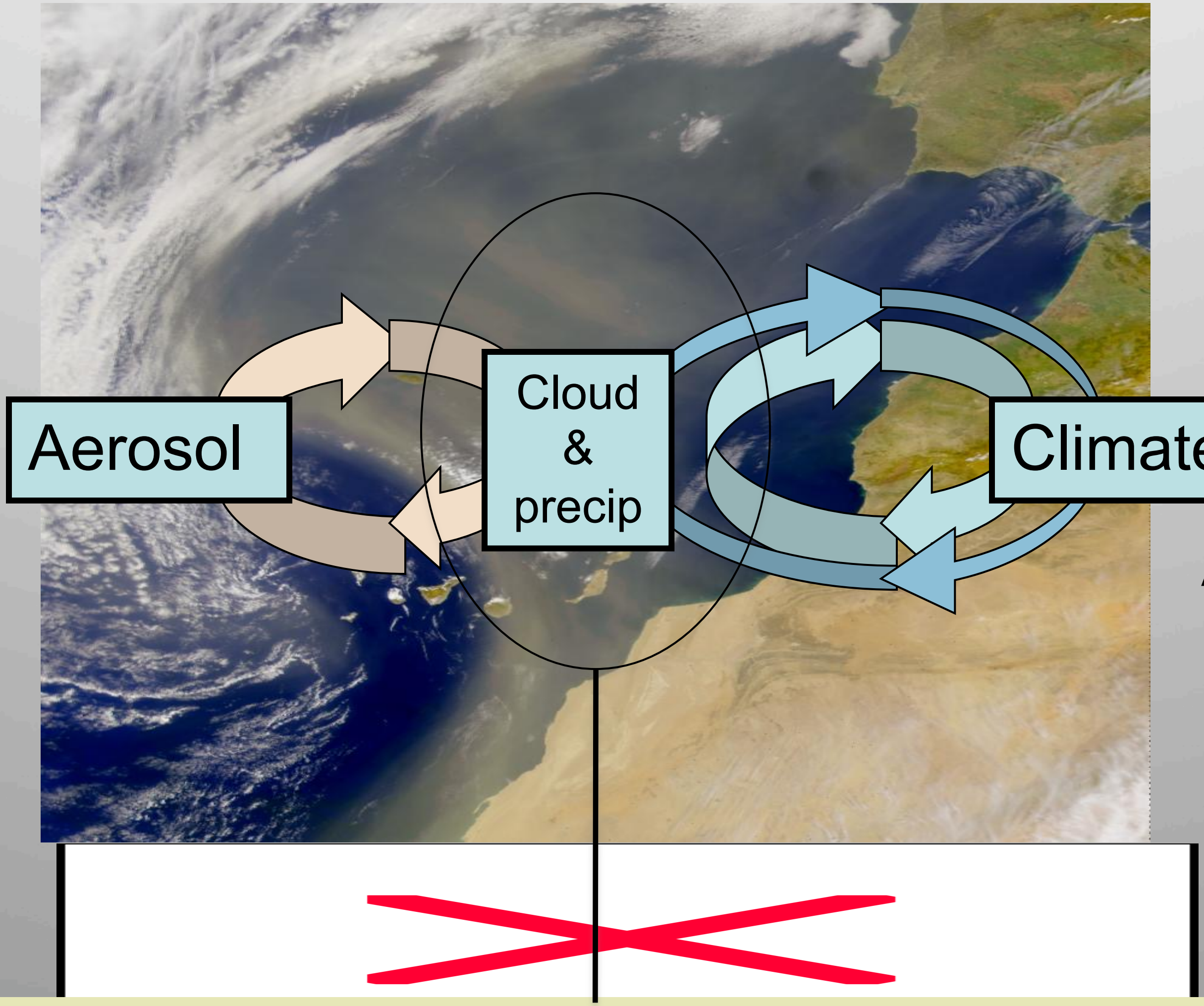


Two pertinent questions to such feedbacks that remote sensing can assist in answering:

Given circulation and clouds, what of fluxes and heating?

Given the heating, what of circulation and clouds?

These feedbacks also involve processes that connect the microphysical scale up to the 'climate' scale



Adapted from Hobbs, 1993.

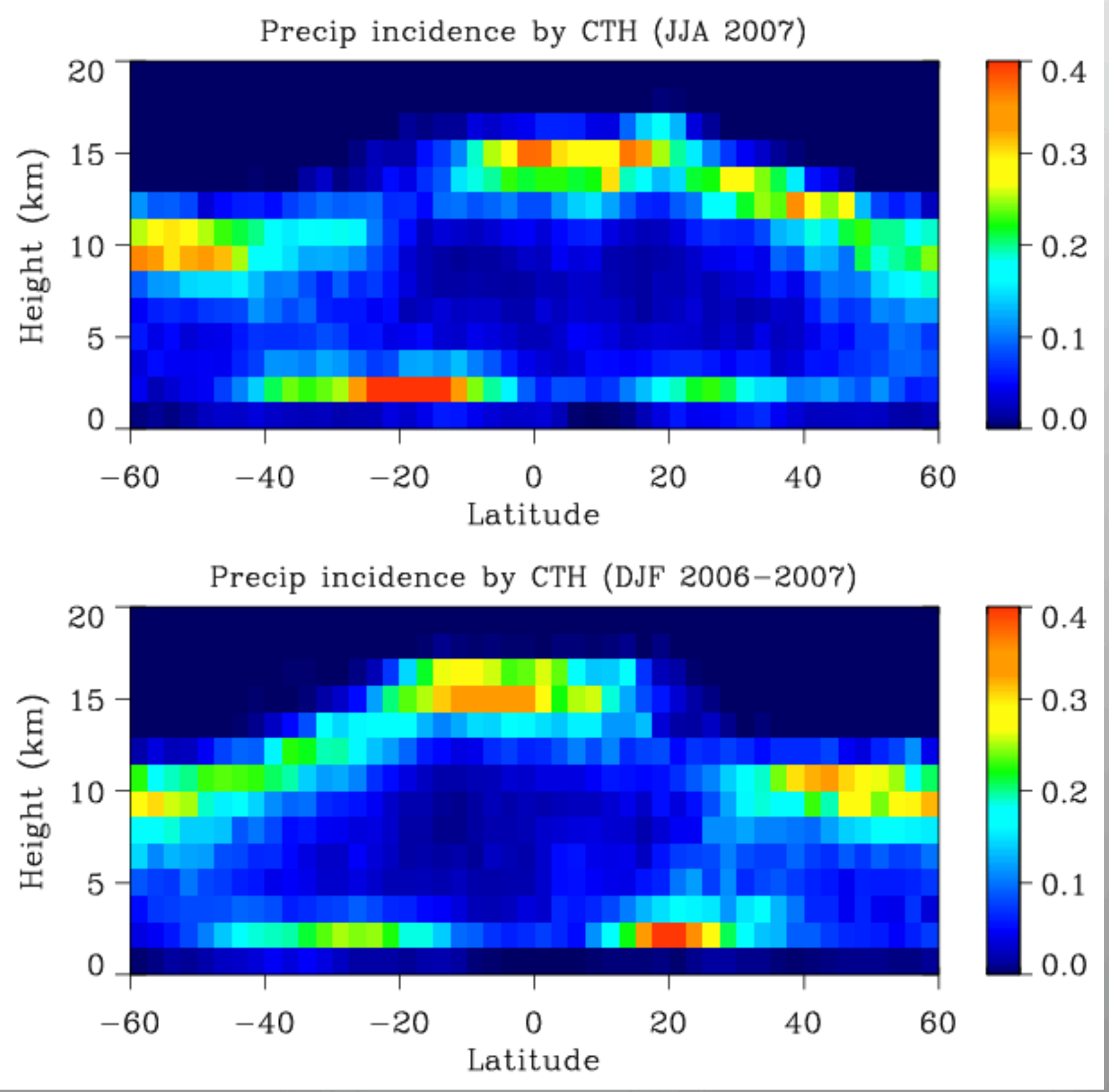
The 'frontiers' lie in developing and using remote sensing tools to study important climate processes

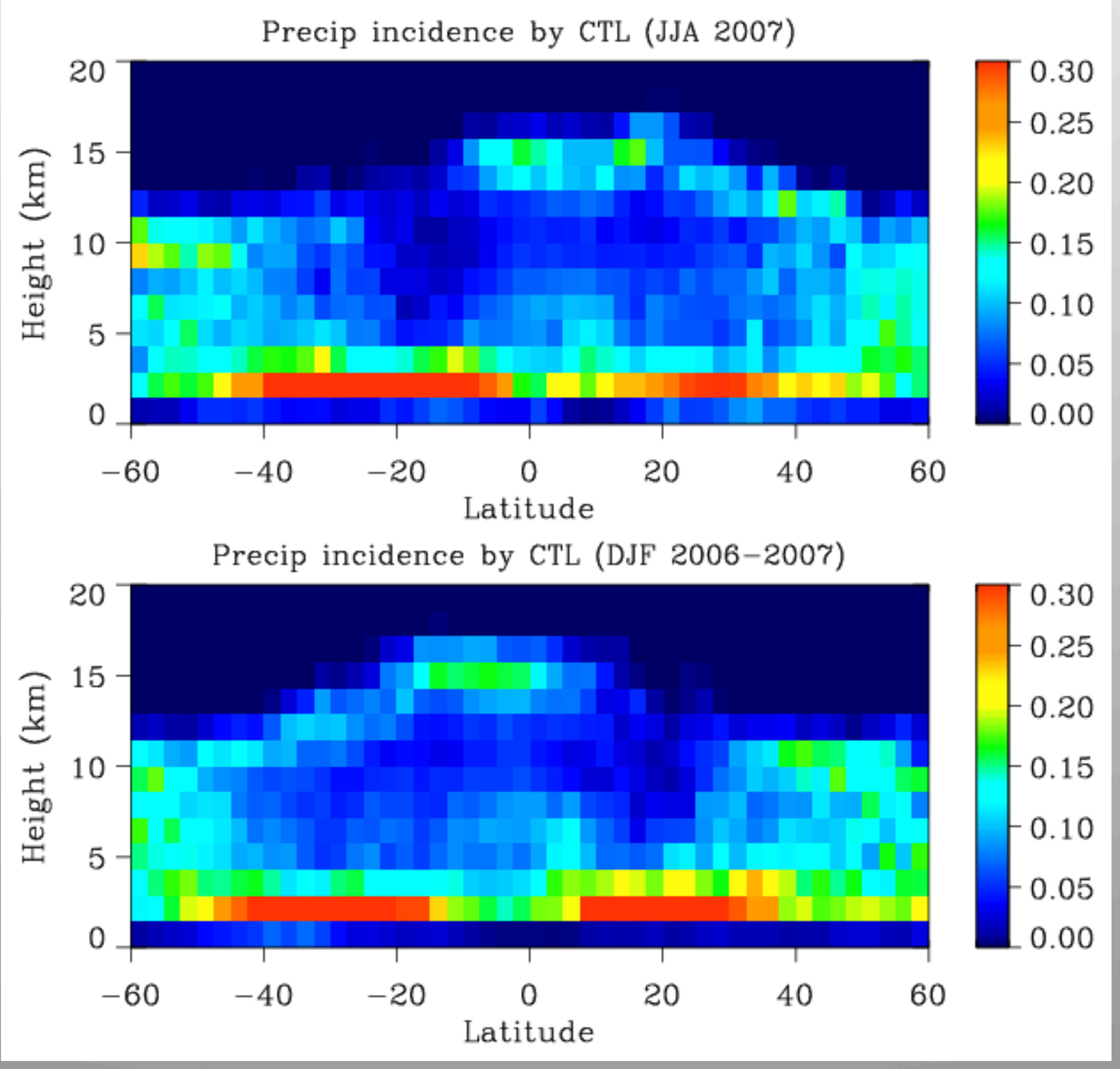
The real frontier

We now consider that clouds and precipitation (and aerosol too??) are part of a continuum of connected processes. Much understanding has been thwarted through a general artificial separation of cloud science and precipitation science. The real opportunities lie in studying/observing processes that lie at the the intersection of the two.

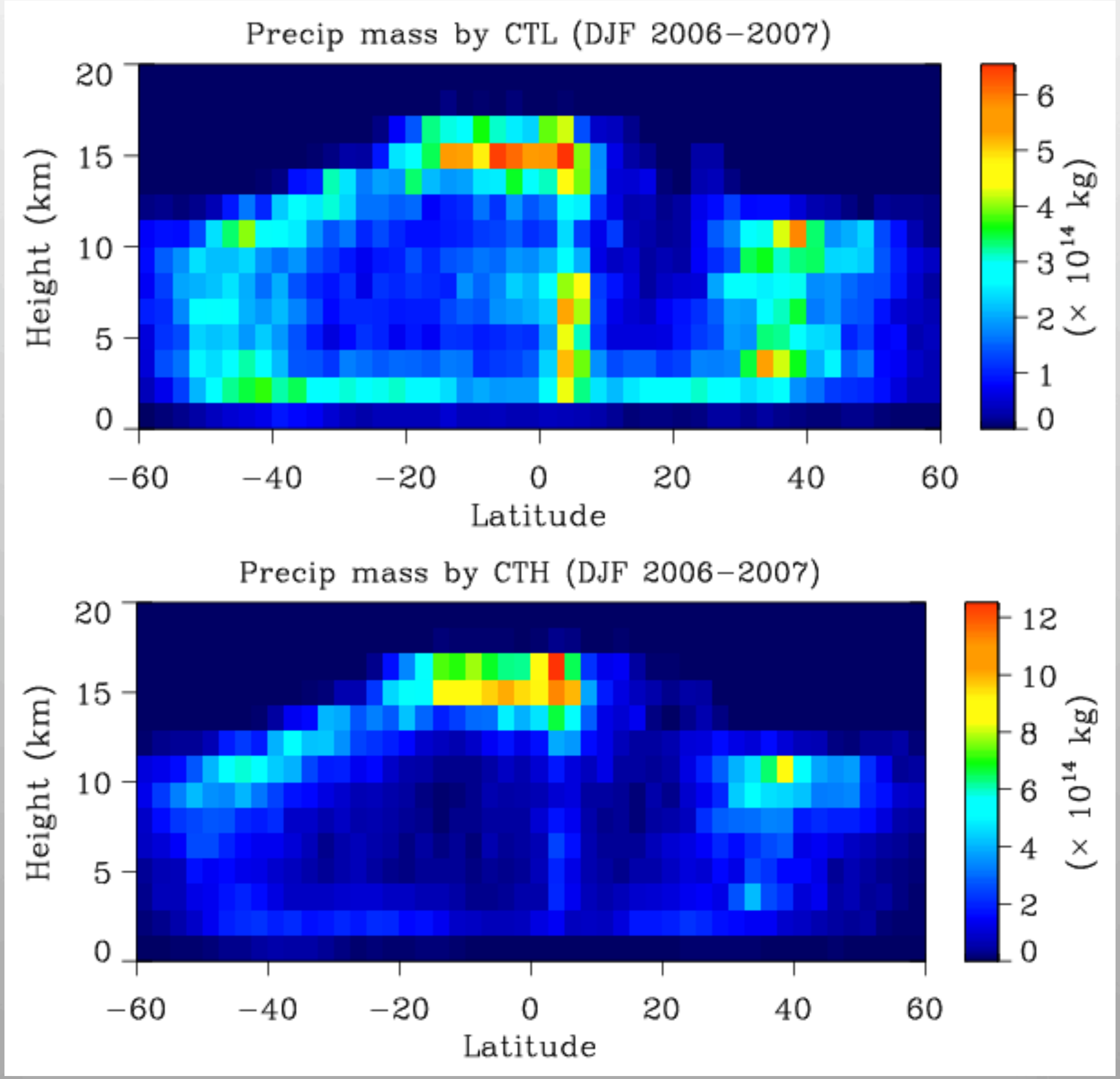
The pathway to improved prediction of precipitation, global and regional, will be through improved prediction of clouds and their evolution.

Cloud and precip structures





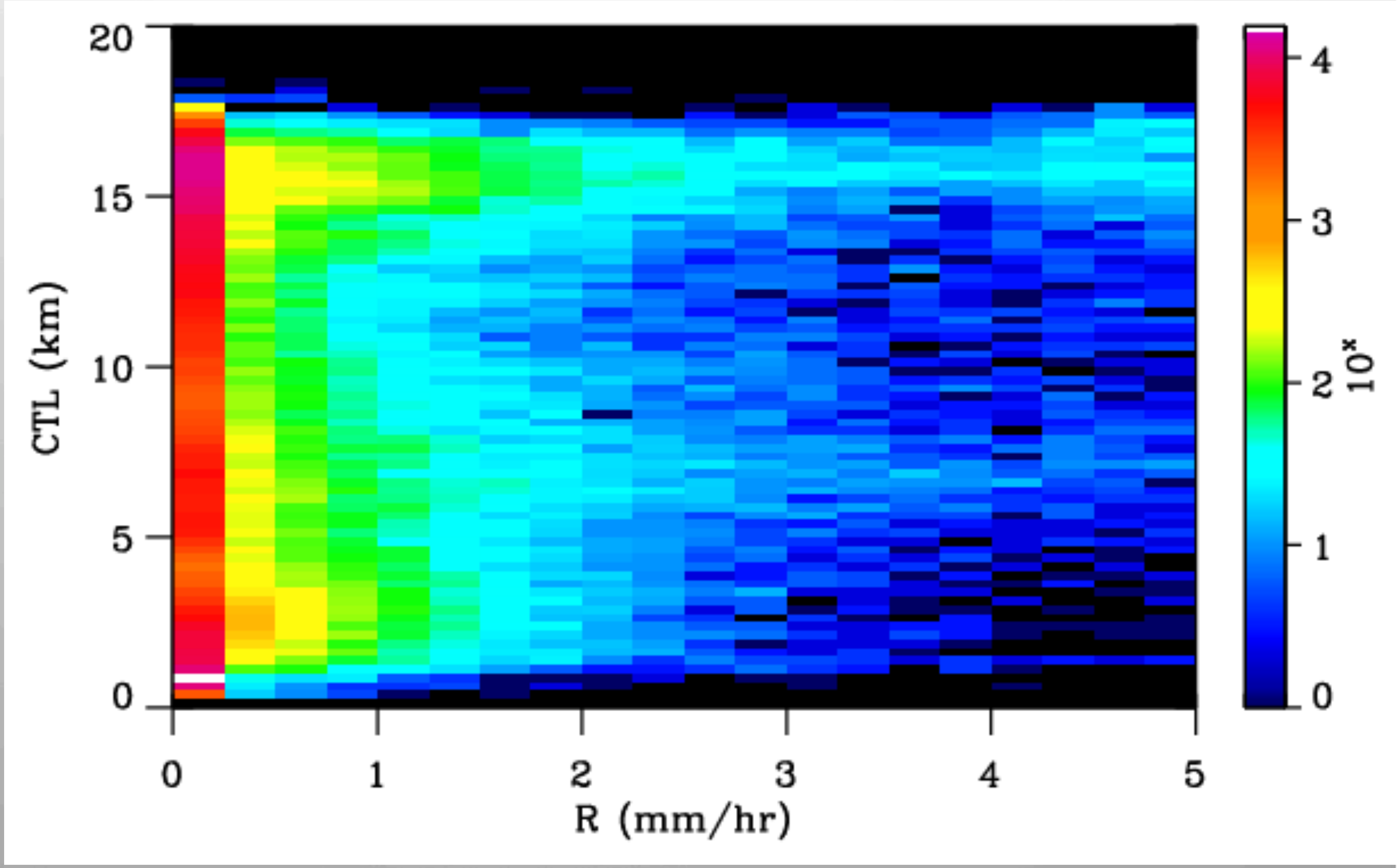
Precip incidence by CTL (JJA 2007)
Height (km)
20
15
10
5
0
−60
−40
−20
0
20
40
60
Latitude
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Precip incidence by CTL (DJF 2006−2007)
Height (km)
Latitude



CloudSat global precipitation products are under construction, - the PIA product illustrated here is describe in Haynes et al., 2008 and is to be released to the sci team b4 the August meeting

Precipitation over global oceans

Top height of precipitating clouds

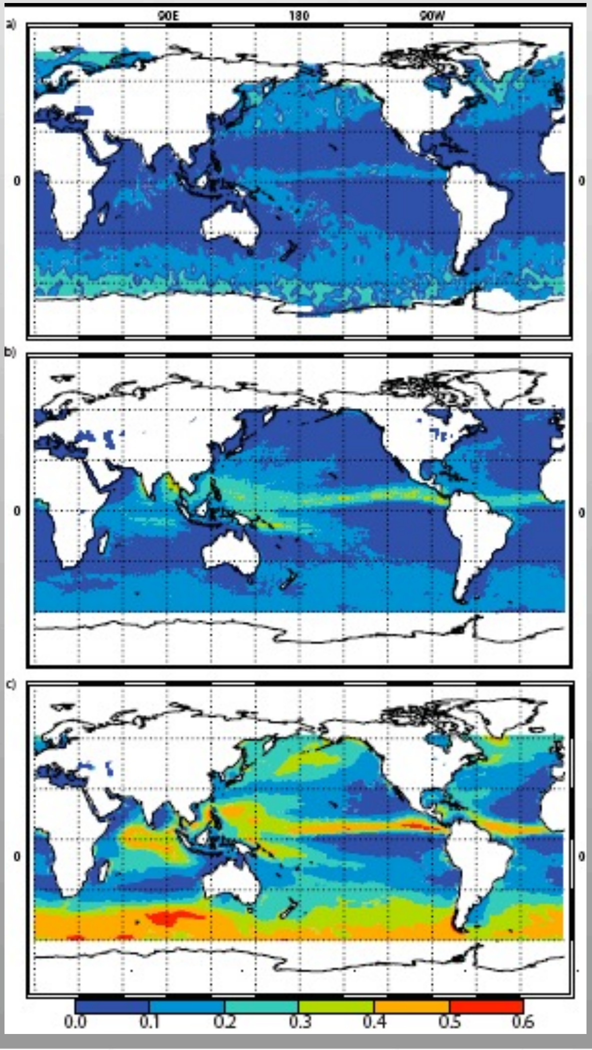


Challenges in representing rainfall…..

CloudSat - 11%

ECMWF – 7.5%

HADGAM – 24.4%

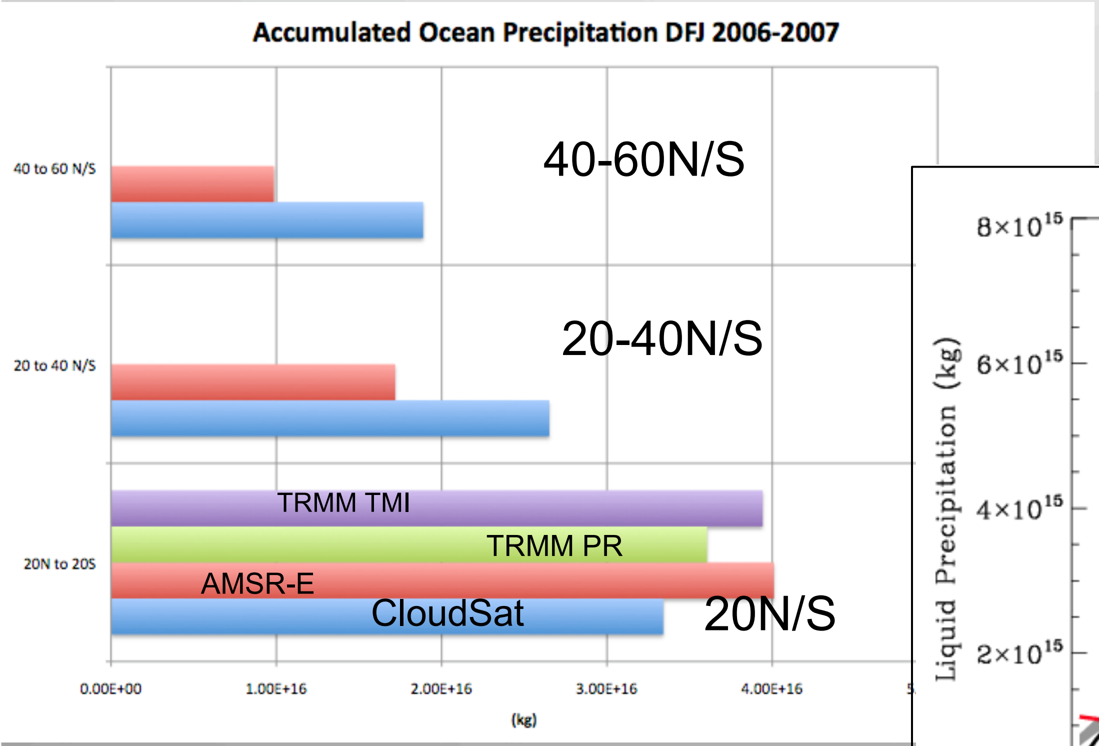


Seasonal JJA precipitation incidence

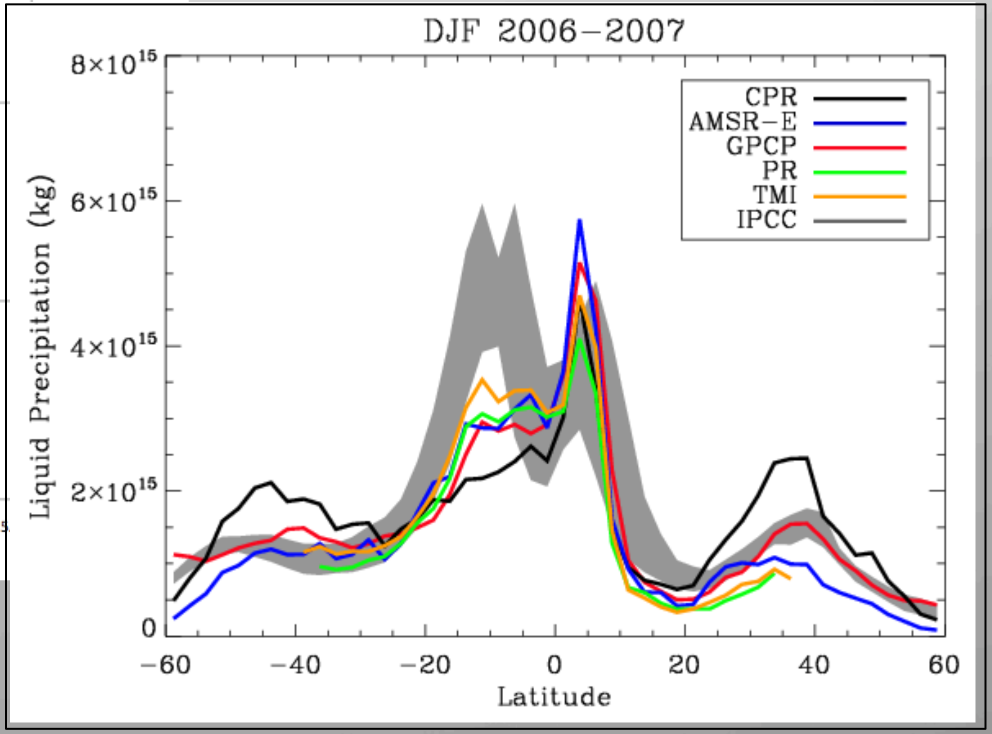
Ellis et al., 2008

Accumulation

accumulation
= incidence X intensity



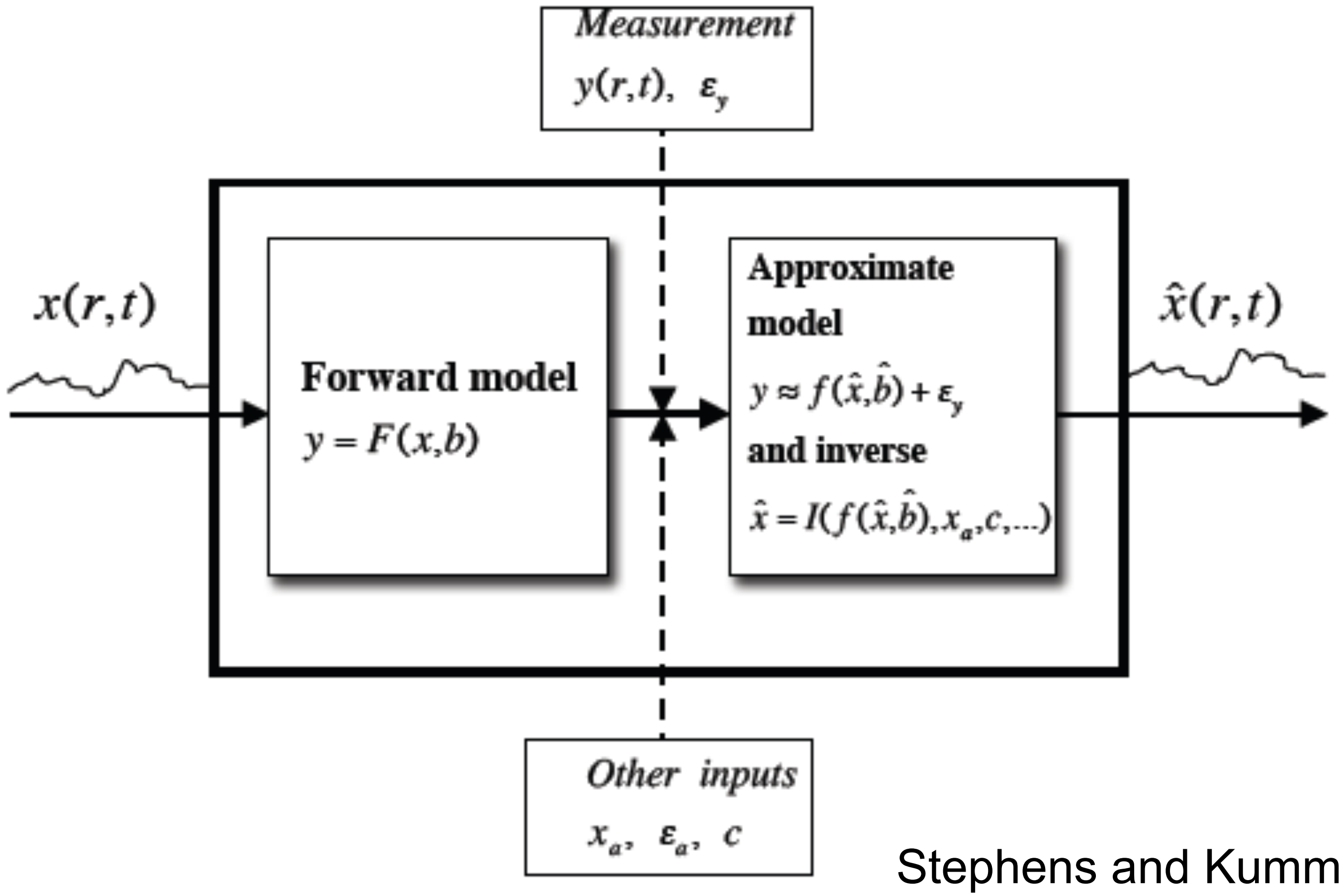
DJF
accumulation



Main elements of a remote sensing observing system

- Platform, determines the representativeness of the observations (e.g. geostationary and the time/space sample as in ISCCP)
- Experimental design - ie the physical basis of the method, the instrument, a priori knowledge data bases, models, etc…

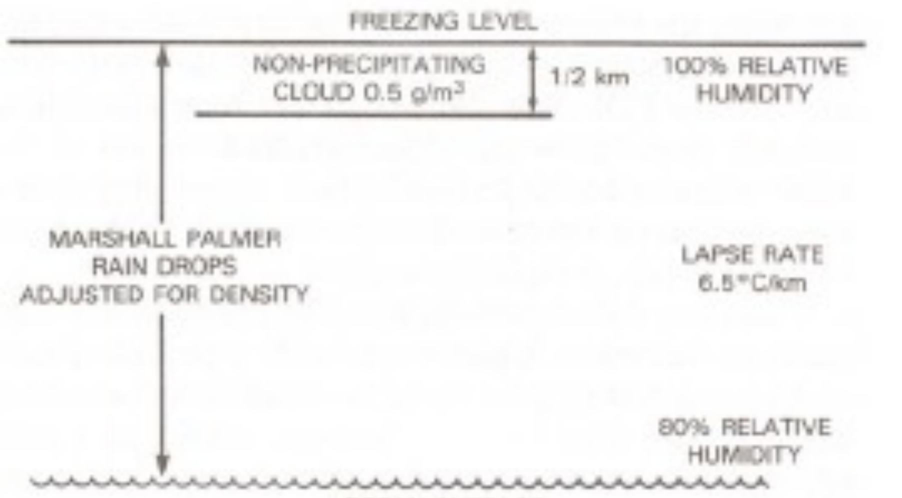
The Remote Sensing Observing System



Stephens and Kummerow, 2008

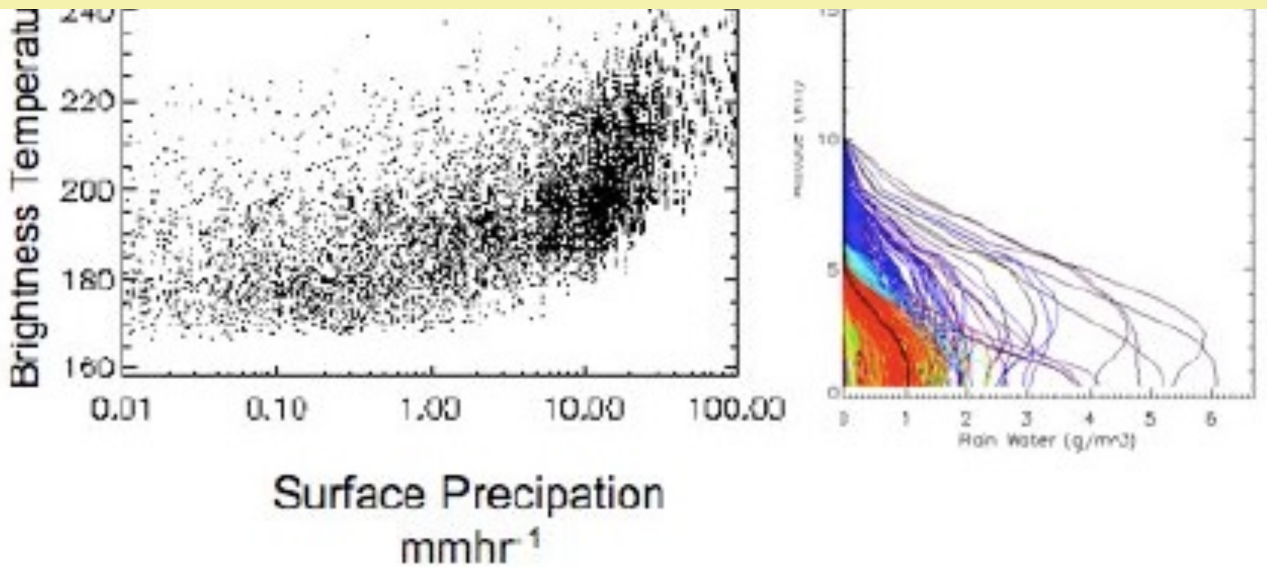
The forward model contains a number elements – a model of the atmosphere, a model of the measurement and an inverse model. The roles of assumptions and parameters involved are often grossly overlooked when assessing the capability of the remote sensing observing system.

The influence of the atmospheric model on the retrieved state is generally overlooked



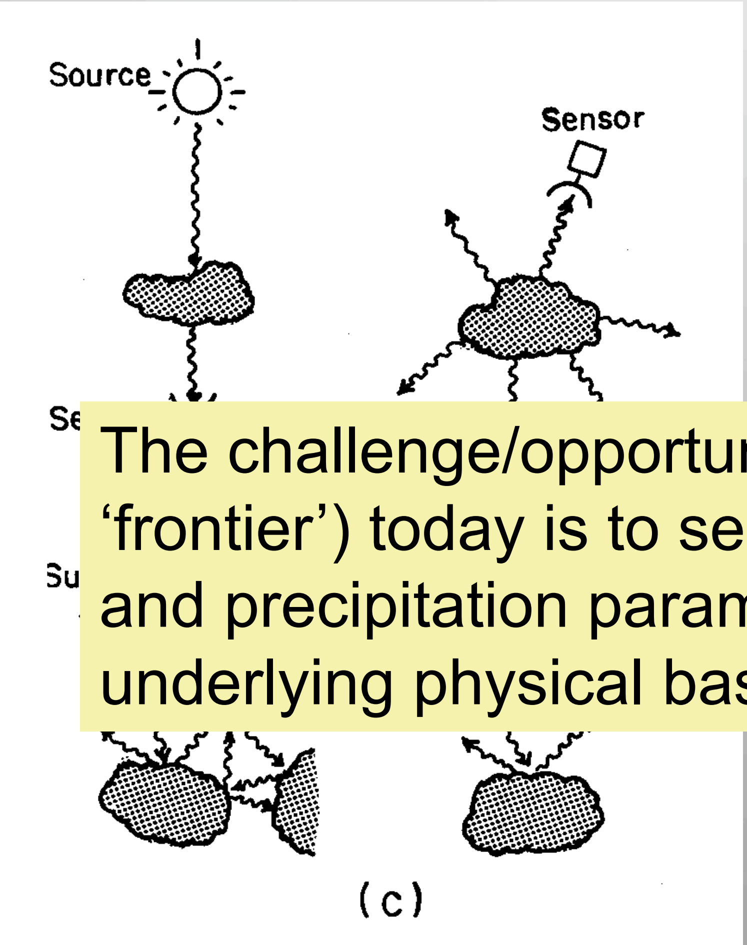
The ‘model’ of Wilheit

So clearly observations that better constrain the ‘atmospheric model’ will potentially provide dramatic improvements to the retrieval problem (eg CloudSat)



Forward Models are typically based on the following types of physics

extinction emission



scattering

Passive (radiometry)

These methods provide primarily path integrated information

bulk water mass

The challenge/opportunity (and perhaps the emerging ‘frontier’) today is to sensibly exploit observations of cloud and precipitation parameters that have different underlying physical bases …

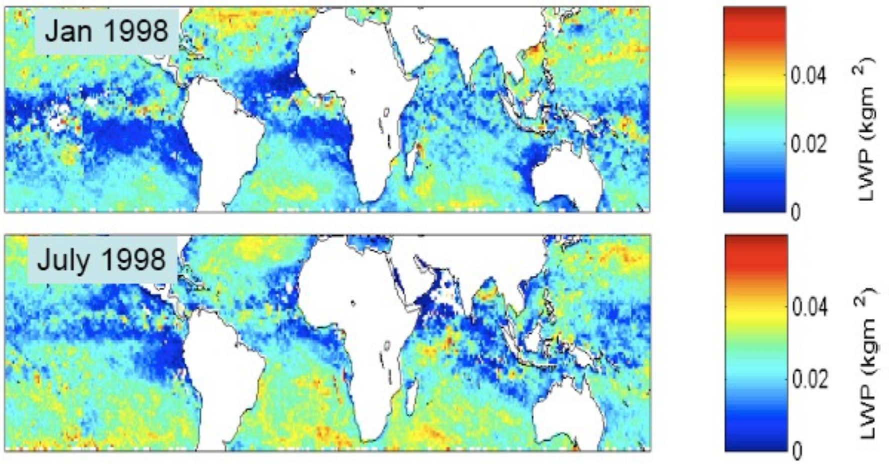
Optimizing multiple sources of ‘similar’ information

Matters to ponder:

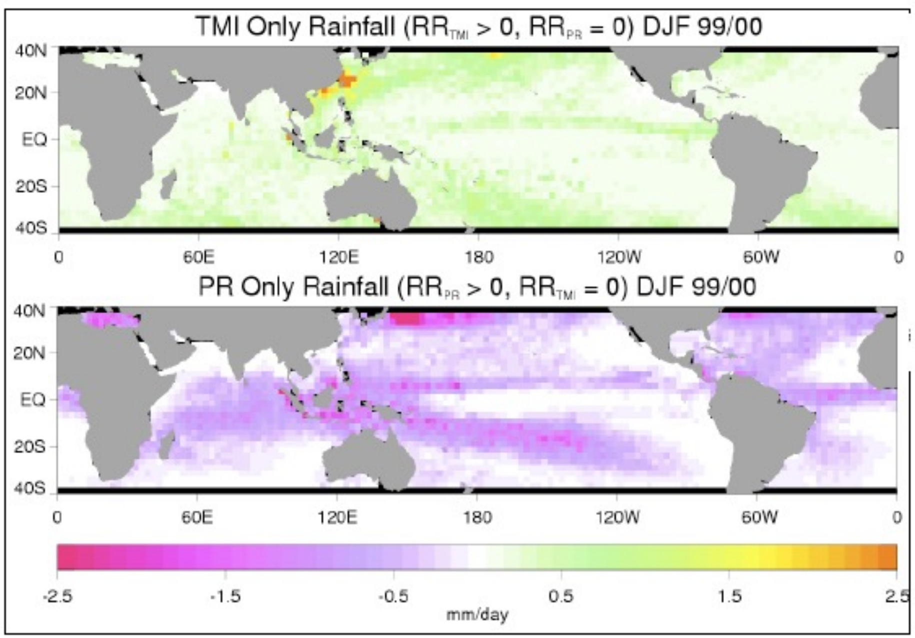
Which of the different approaches (& physics) is optimal?
How accurate is the retrieved information and
What is to be gained in combining different types of measurements ?

Some advantages of multi-sensor data- provides a way of consolidating our understanding:
(i)by providing a way of assessing products and component parts of retrieval approaches through comparison –
(ii)by providing the opportunity to combine into an integrated and physically consistent retrieval approach

The (scene) identification problem



is it cloud or not?

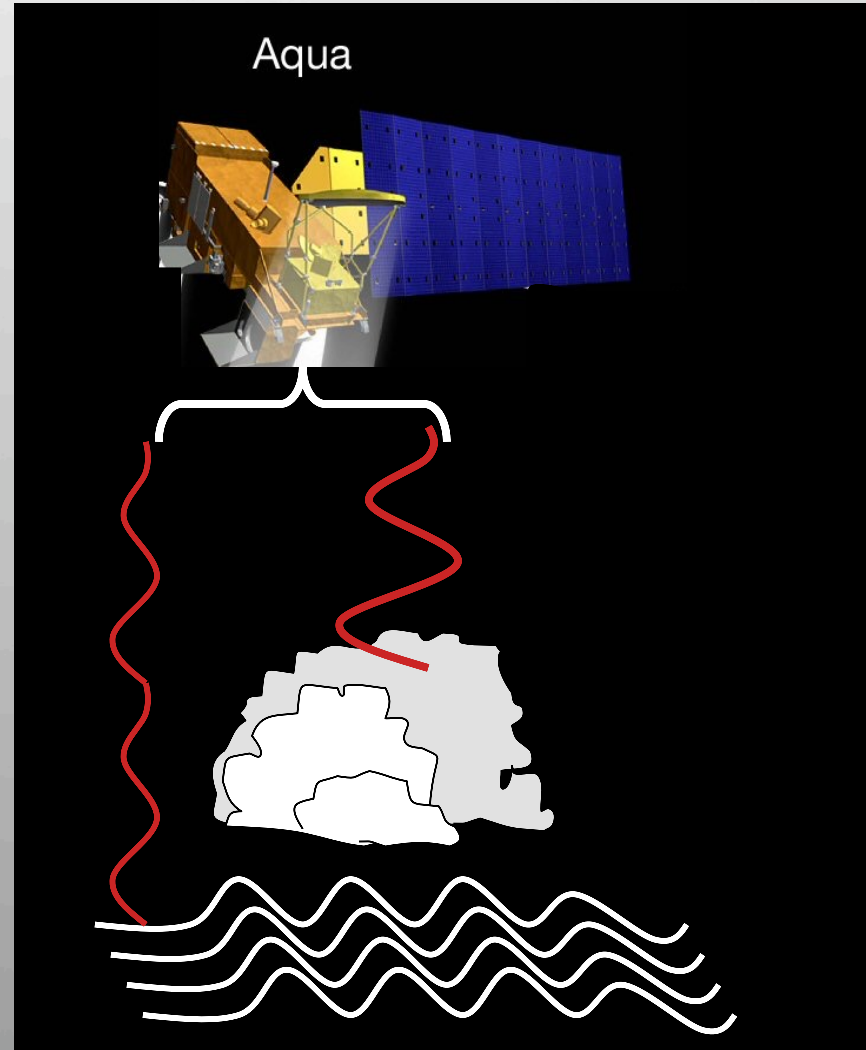


is it cloud or is it rain?

Multi-sensor Example : the water contents of low clouds

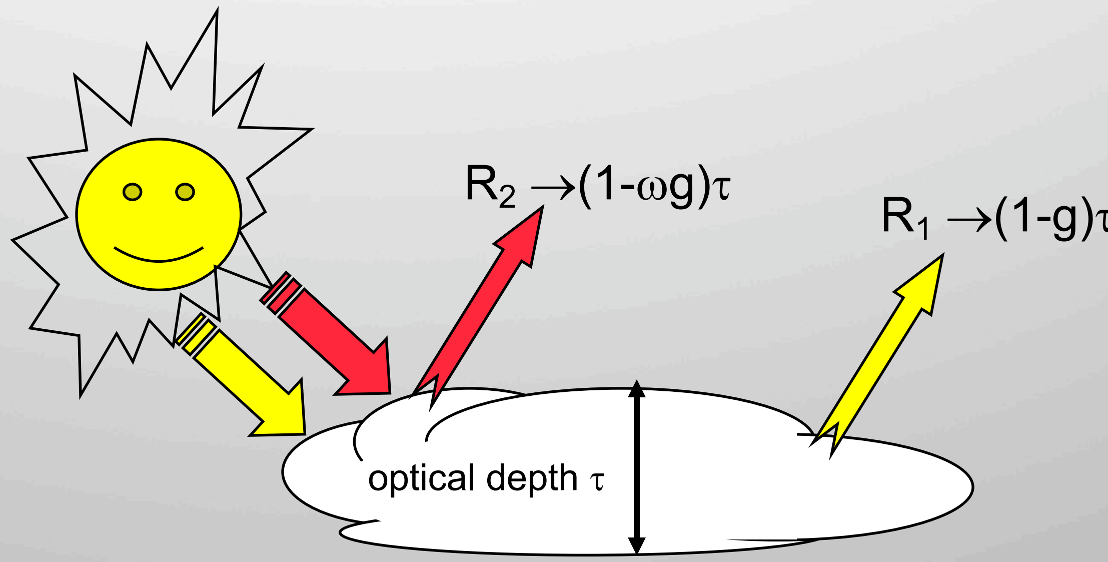
Microwave emission

The difference is related to the absorbing/emitting species along the path - mostly water vapor, cloud liquid water, and precipitation



Scattered sunlight

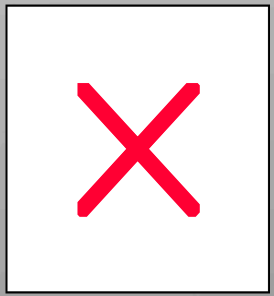
Twomey & Cocks, 1980's
Nakajima & King, 1990s



Visible reflectance (R_1) is a function a combination of parameters, i.e. $R \rightarrow (1-g)\tau$

The reflection in the near-IR (R_2) is a function of optical depth τ and the scattering albedo ω- the latter is a function of particle size r_e.

Measurements of reflection at two wavelengths (or spectral bands) returns the pair of parameters τ and r_e



Do VIS/NIR and PMW estimates of LWP agree?

• Bennartz (2007), Borg & Bennartz (2007), find that, for the NIR observations,

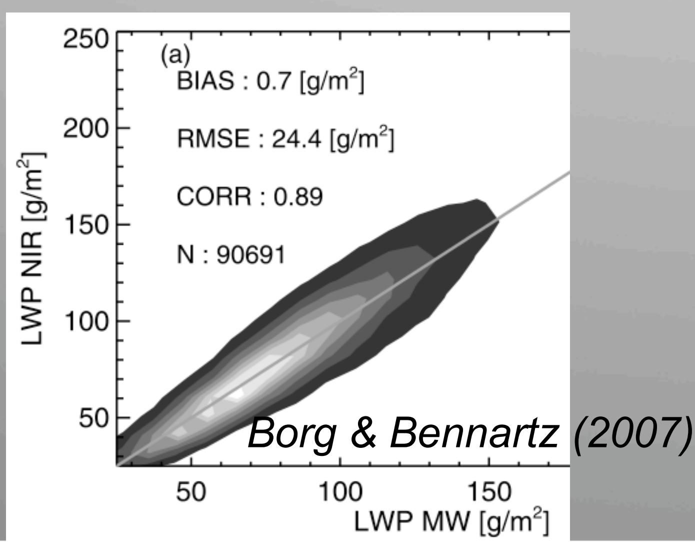
$$LWP = 2/3\ \rho\ \tau R_e \text{ (vertically homogeneous cloud)}$$

be replaced with

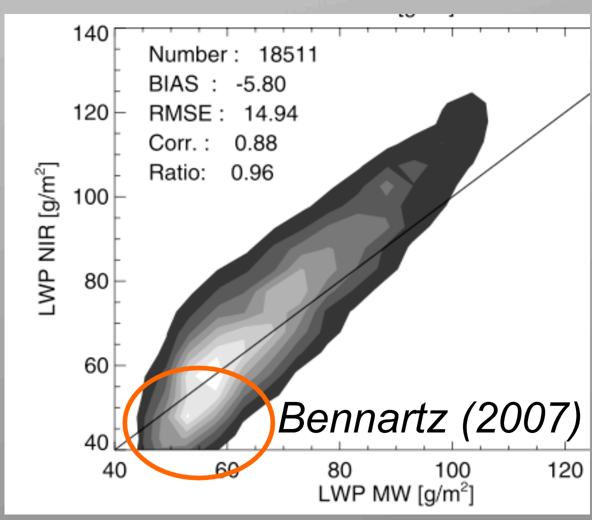
$$LWP = 5/9\ \rho\ \tau R_{e,top} \text{ (adiabatic cloud)}$$

for warm stratocumulus clouds.

This leads to good agreement between NIR & PMW LWP for ***overcast, stratocumulus clouds***:



For **all warm clouds**, however, there is a distinct positive bias in the PMW at the low end of LWP:

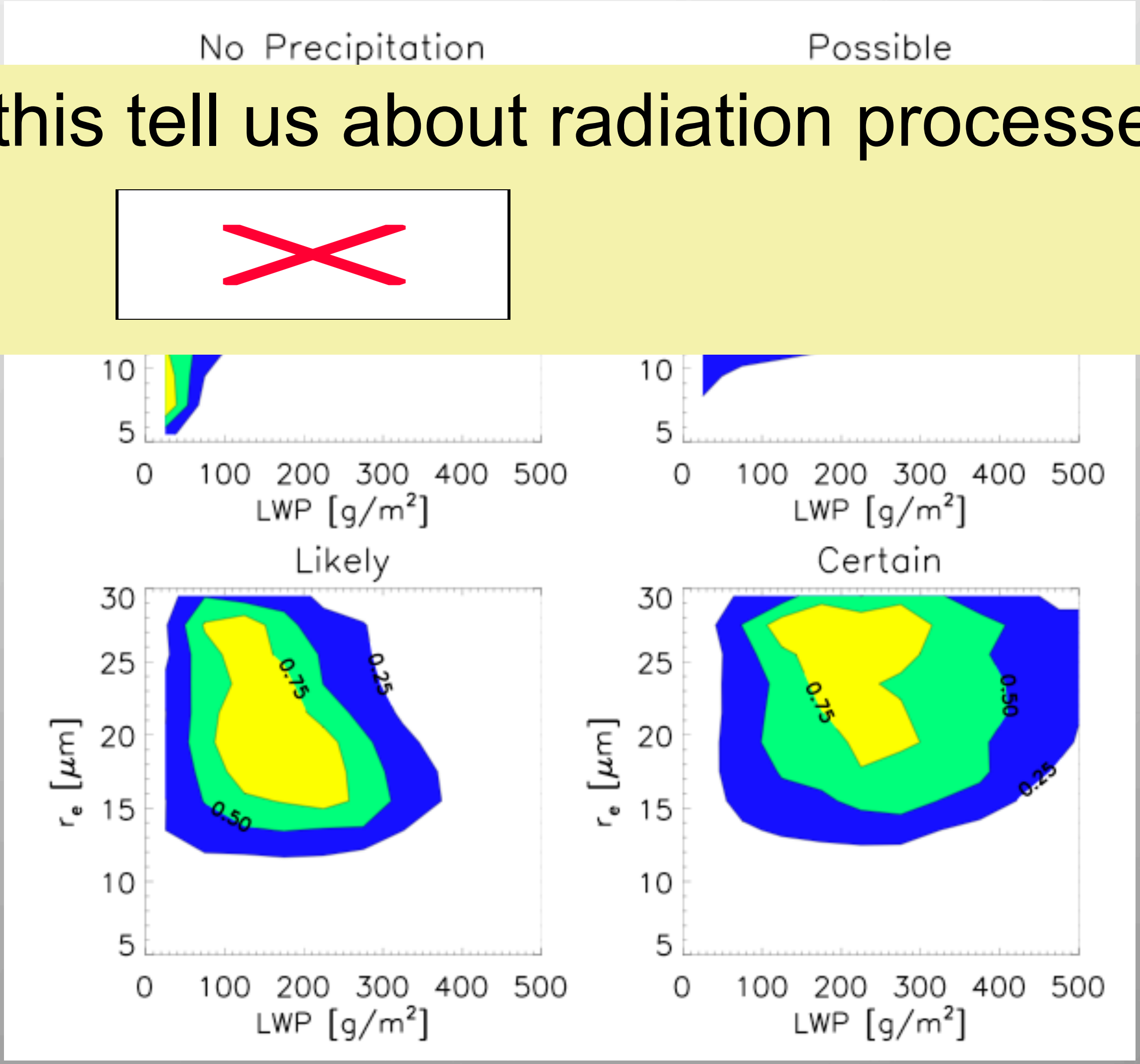


But what about precipitation????

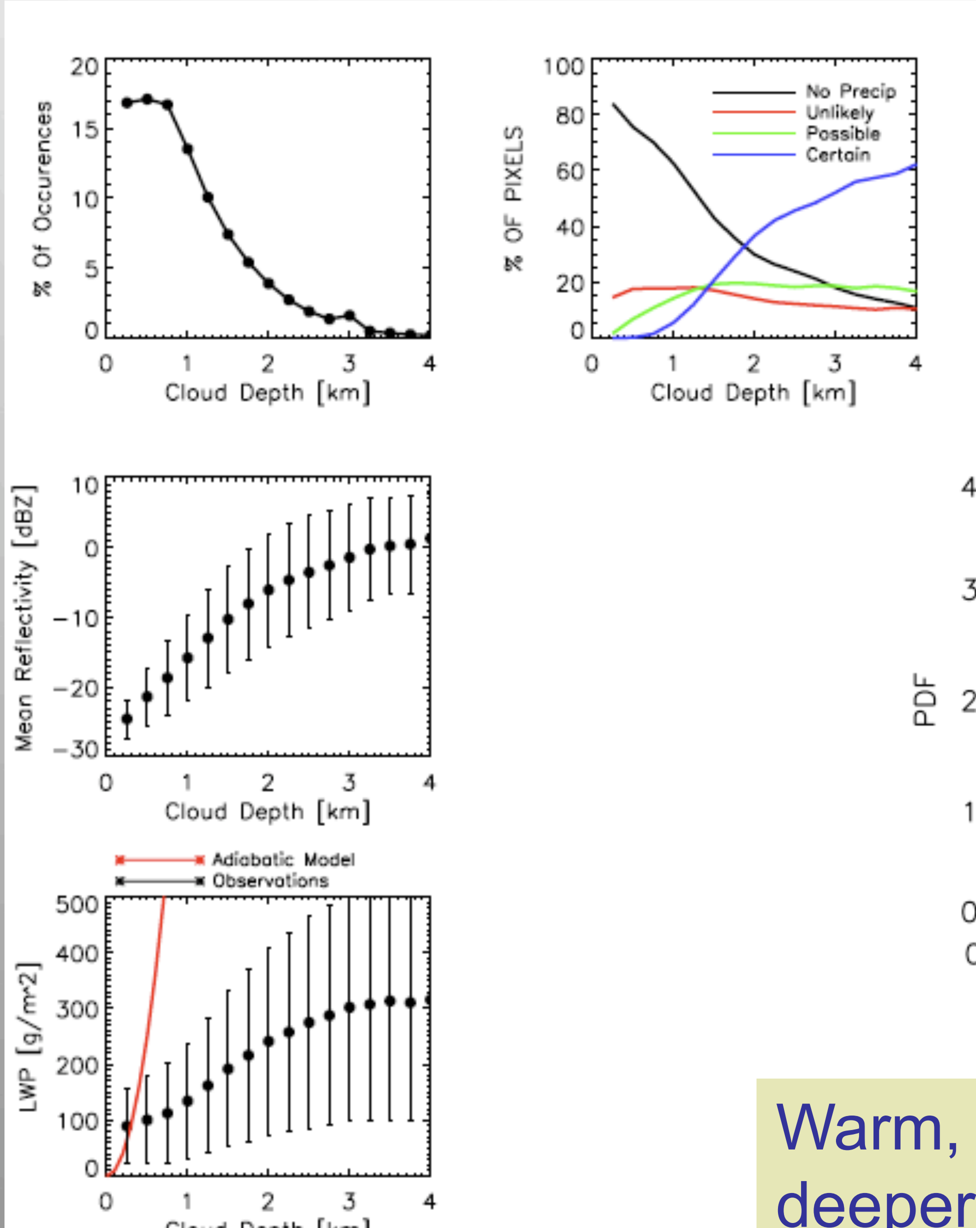
So what might this tell us about radiation processes?

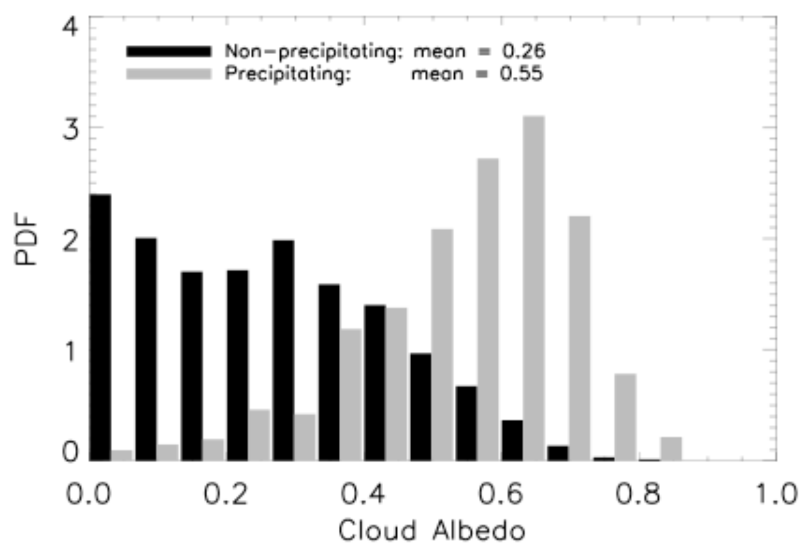
Precipitating clouds are wetter than non-precipitating clouds

The particles are larger but there is no obvious 'threshold' precipitation size

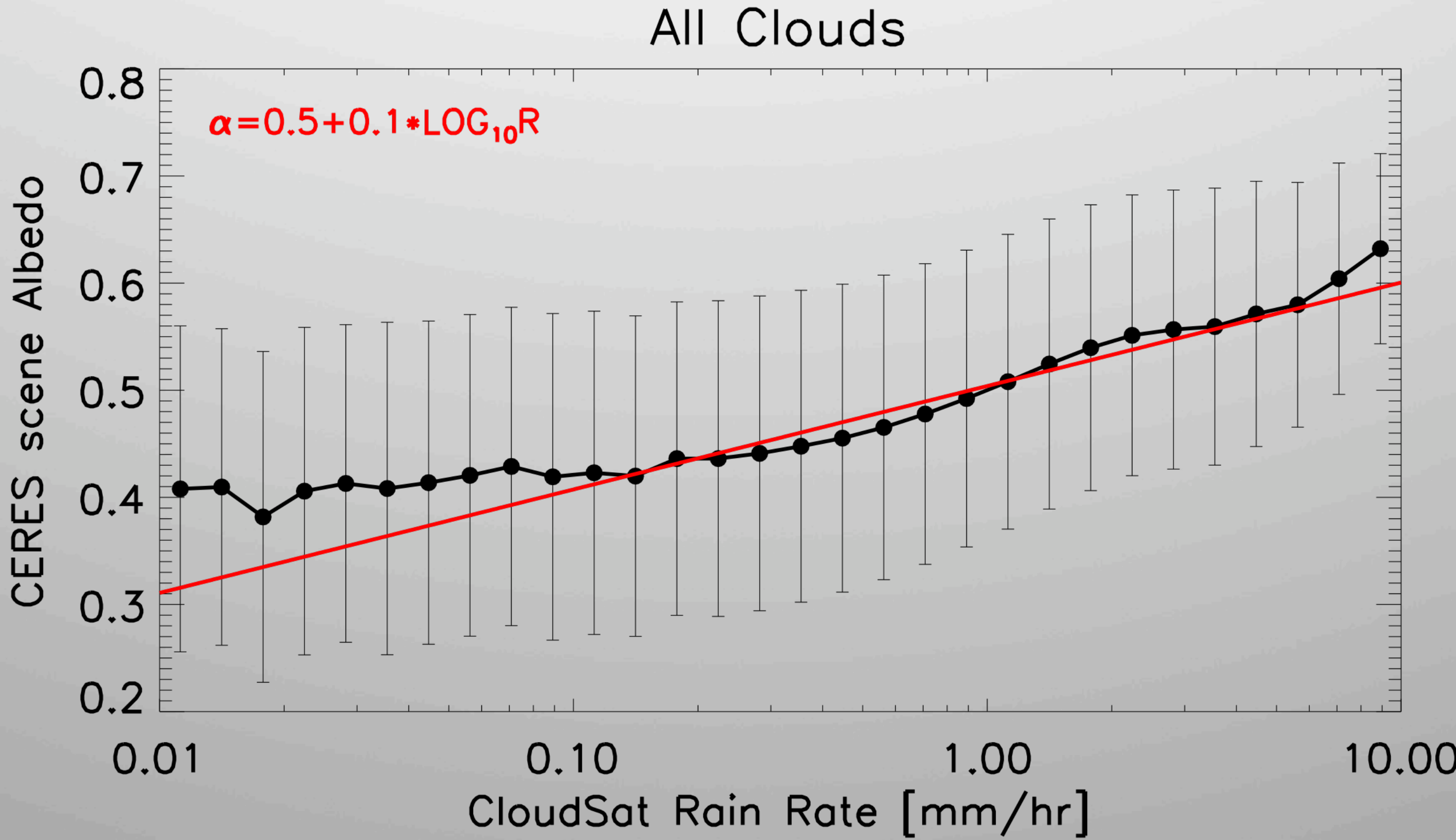


Using MODIS and CloudSat, Stephens et al., 2008





Warm, precipitating clouds are deeper, wetter and brighter than non-raining clouds



All Clouds
α=0.5+0.1*LOG10R
CERES scene Albedo
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.01
0.10
1.00
10.00
CloudSat Rain Rate [mm/hr]

Aerosol indirect effects using A-train obs - Lebsock et al., 2008

Twomey effect?

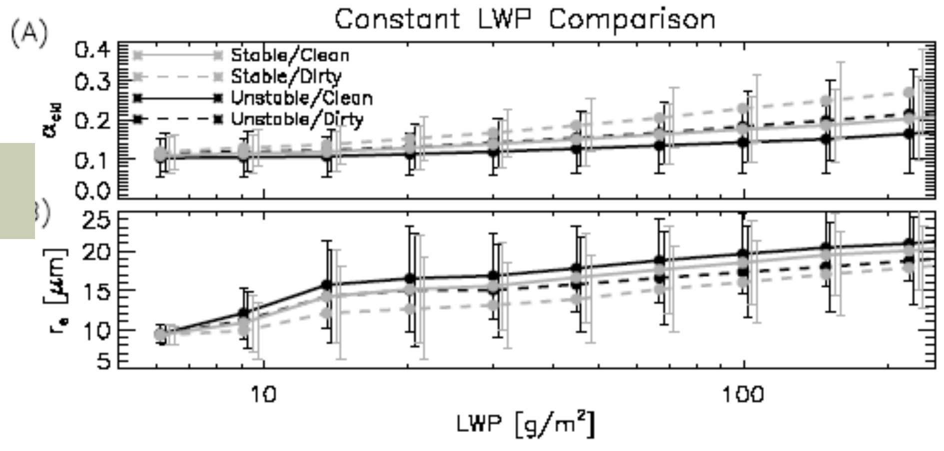
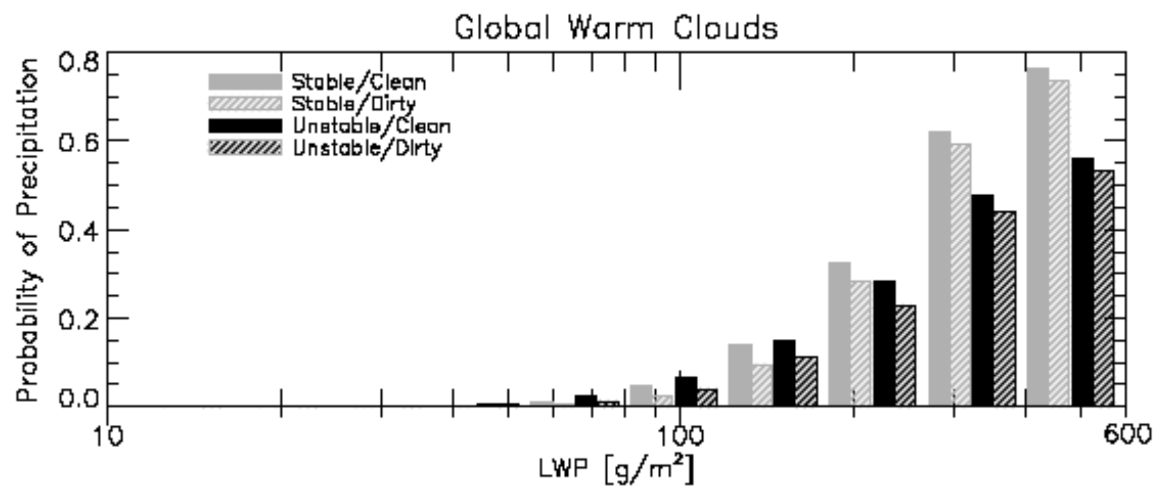


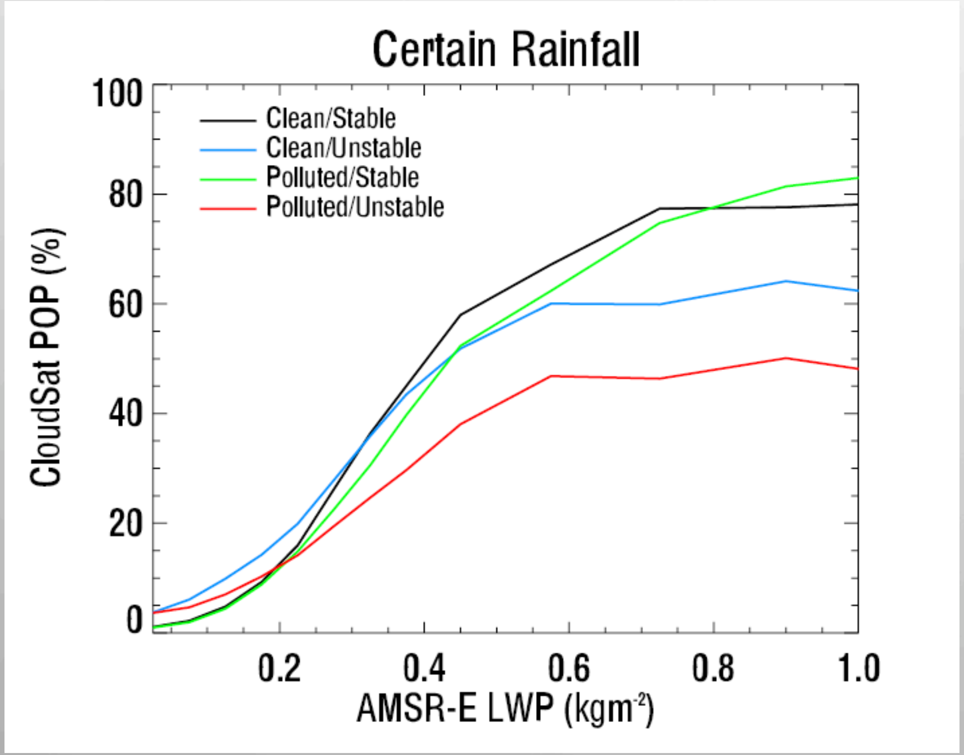
Figure 4. Trends of the cloudy sky albedo and r_e with LWP. The delineation between clean and dirty is given by AI = 0.1. The stable curve represents all LTSS between 18 and 21 K. The unstable curve represents all LTSS between 12 and 15 K.

Warm non-precip

Precipitation



We are able to observe the most important aspects of clouds that affect their albedo - as such we perhaps can say there appears to be a global Twomey effect and a *correlation* between precipitation probability and aerosol

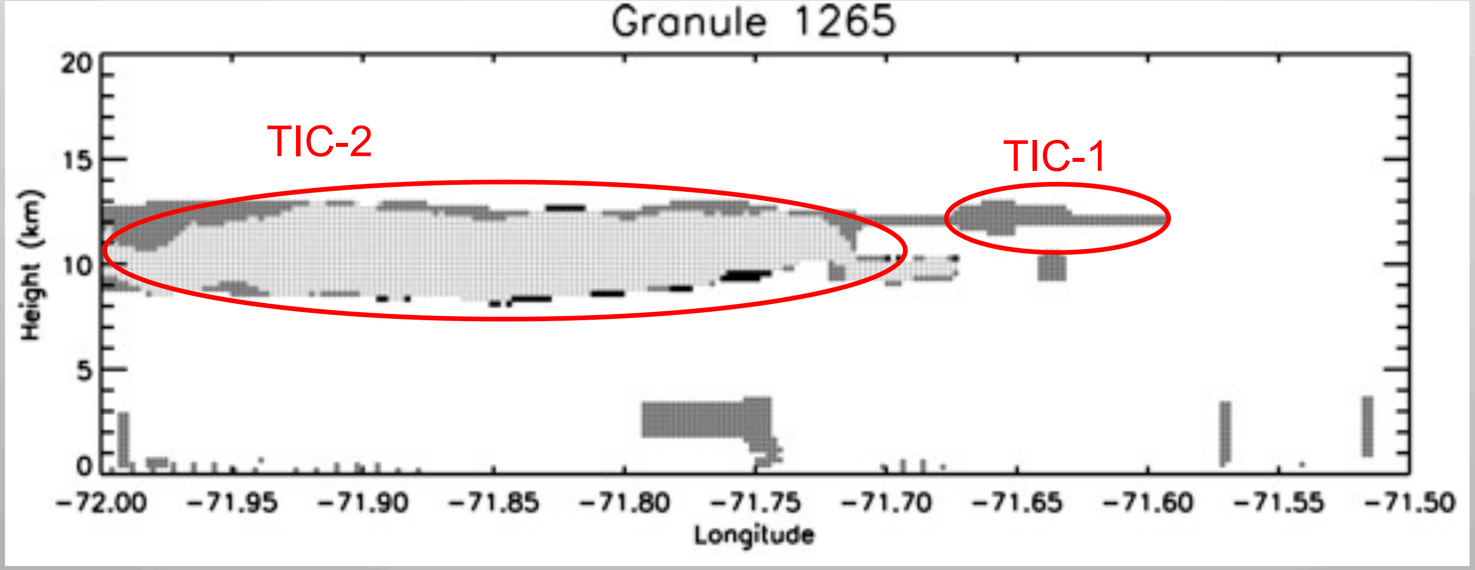


Aerosols appear to have the biggest impact on clouds formed in a more unstable environment. Comparing the blue and red curves suggests that, in a statistical sense, polluted clouds require higher water contents to precipitate.

Example 2: Ice water contents and thin cloud detection

Scattering/transmission by lidar, scattering by mm radar

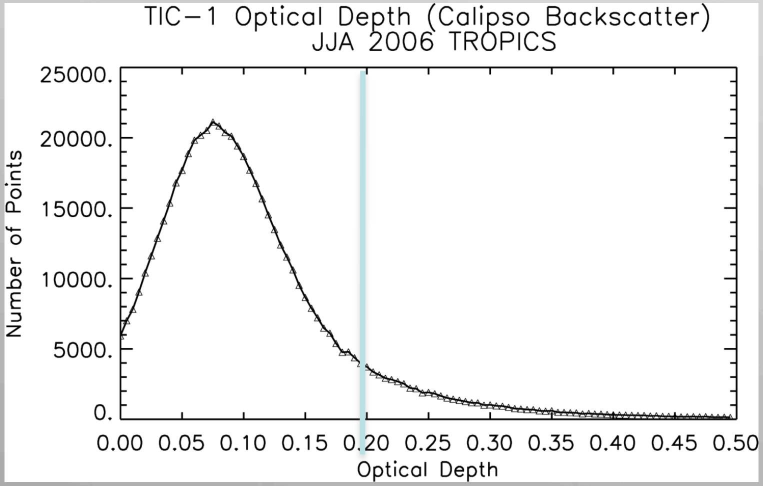
Results from CloudSat & CALIPSO



Thin Ice Cloud (TIC) Type 1 : Only LIDAR can see.
Thin Ice Cloud (TIC) Type 2: Both RADAR and LIDAR can see.

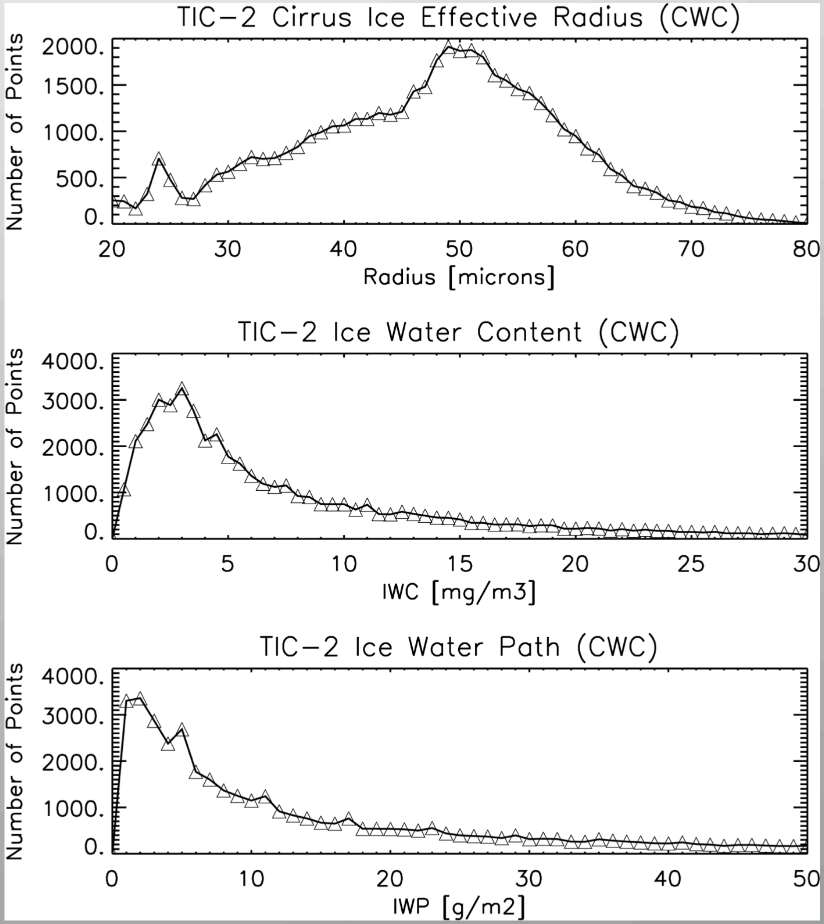
Haladay & Stephens, 2008

CALIPSO ODs for TIC-1

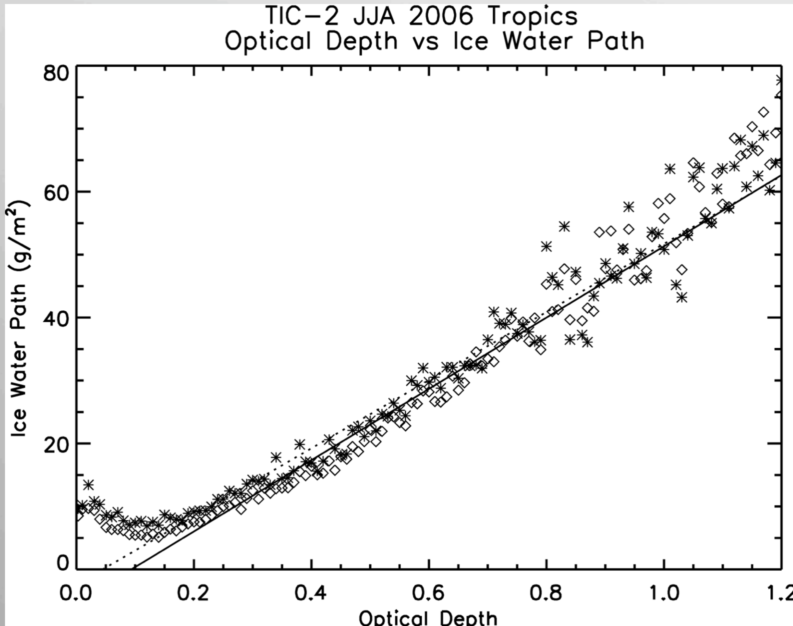


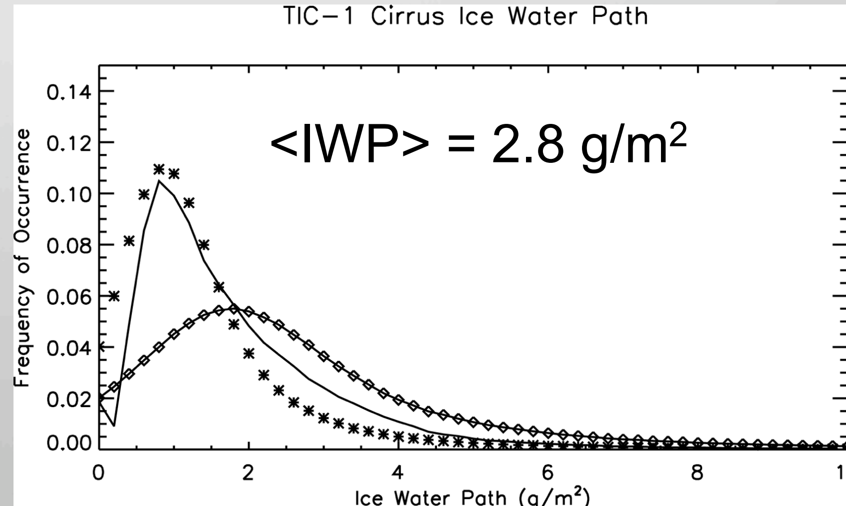
This combination identifies the detection thresholds of one Instrument over the other τ~0.2

CloudSat products for TIC-2



A consistent picture of OD, IWP and particle size



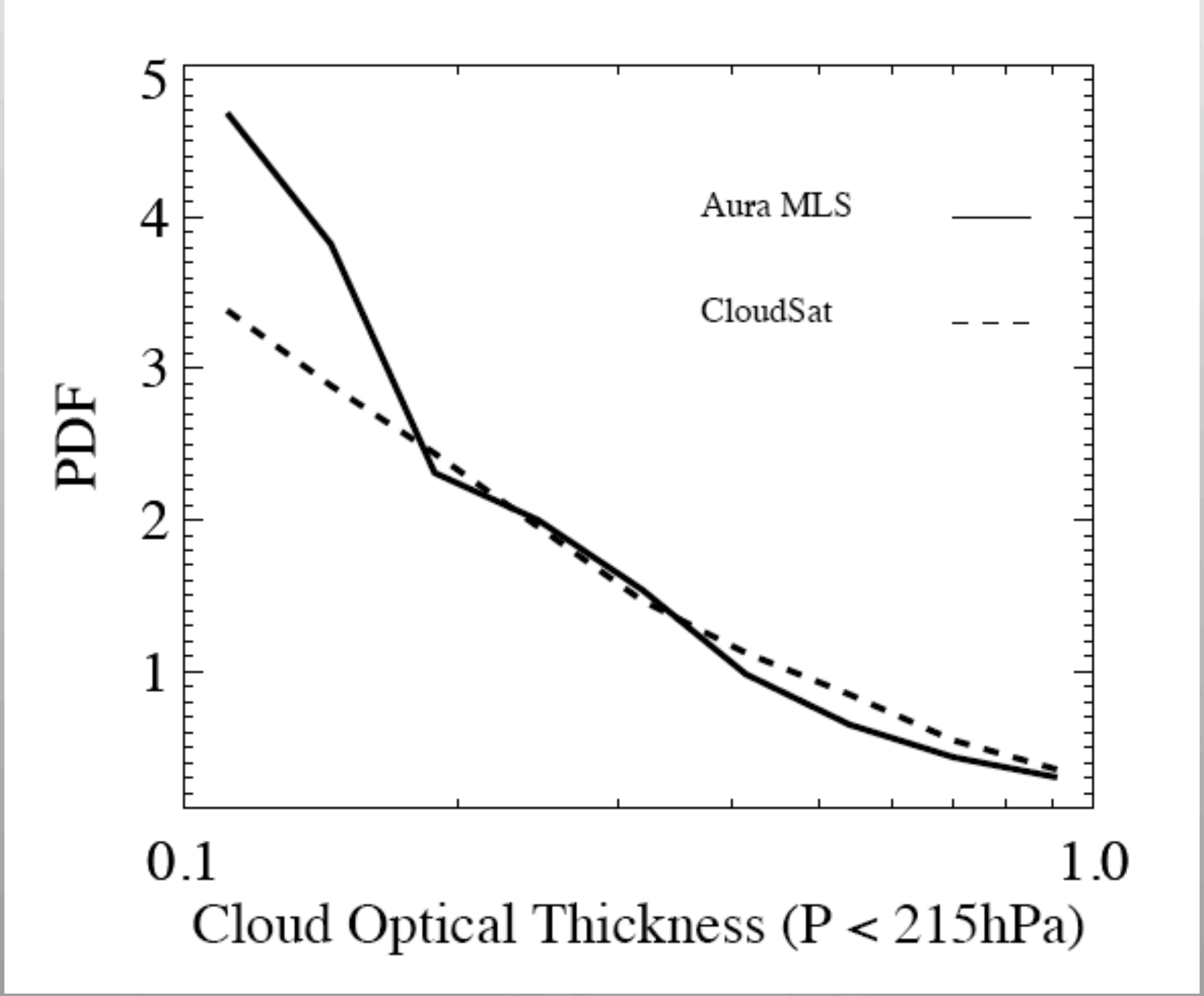


Slope of this curve implies a typical ice effective radius of 40 μm for cirrus.

→

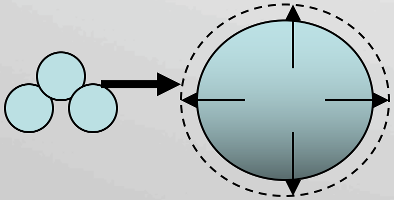
Using 40 μm effective radius, combined with measured Tau yields an estimate of the distribution of IWP of thin cirrus missed by Cloudsat.

MLS and CloudSat IWC comparisons also paint a similar picture

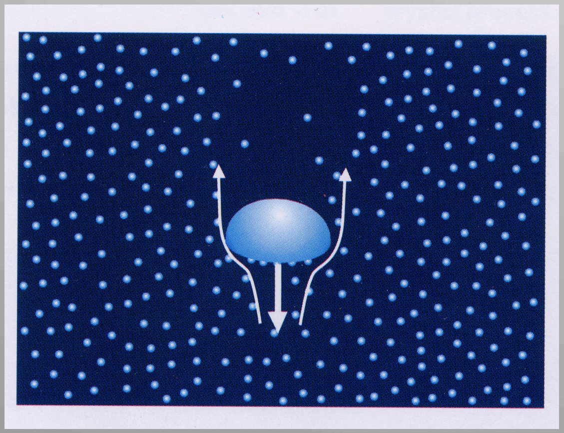


IWC CloudSat and IWC MLS converted to visible extinction using the same Microphysical assumptions. The sensitivities diverge τ ~0.2

Another frontier – probing processes
The example of warm rain



When droplets grow by vapor deposition, the mass increases but not the number concentration



When coalescence occurs, big drops grow by collecting little drops - that is the total droplet number concentration is reduced but the total mass of water doesn't change

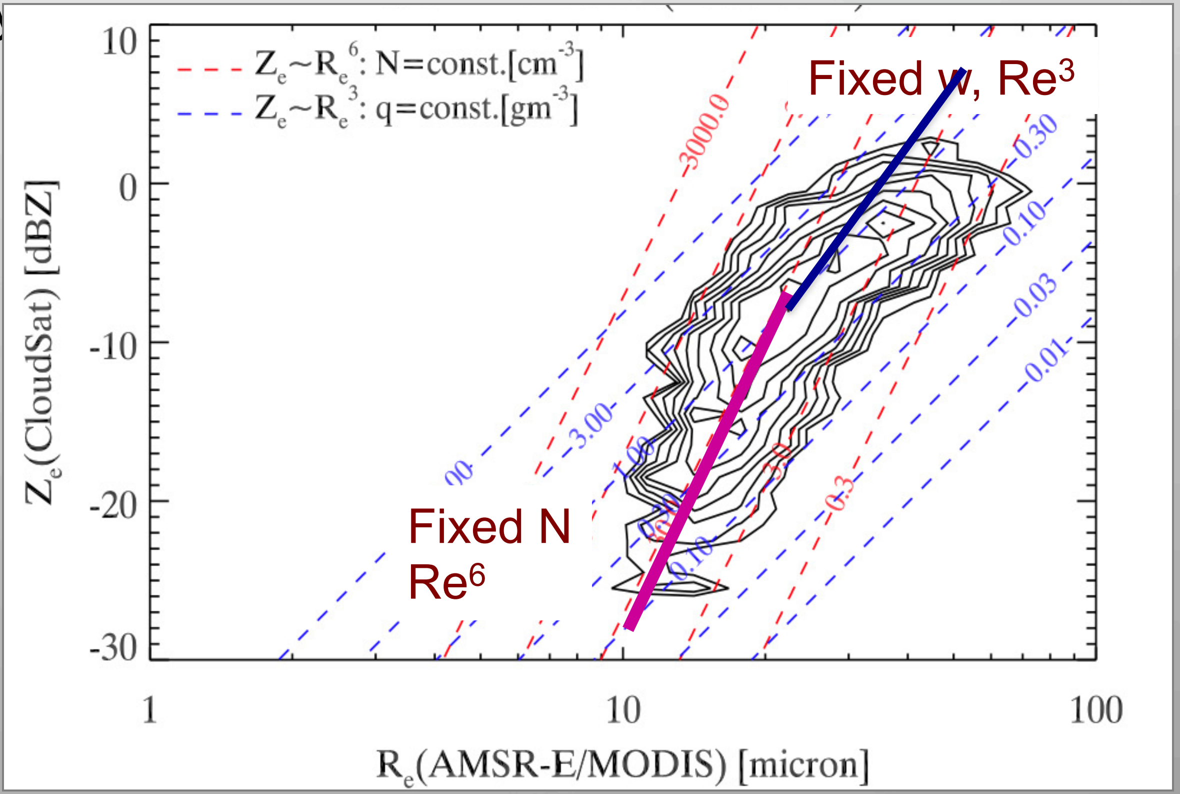
The warm rain coalescence process

The observables

Z_e: layer-mean radar reflectivity

(Masunaga et al., 2002a,b; Matsui et al., 2004)

The relationships

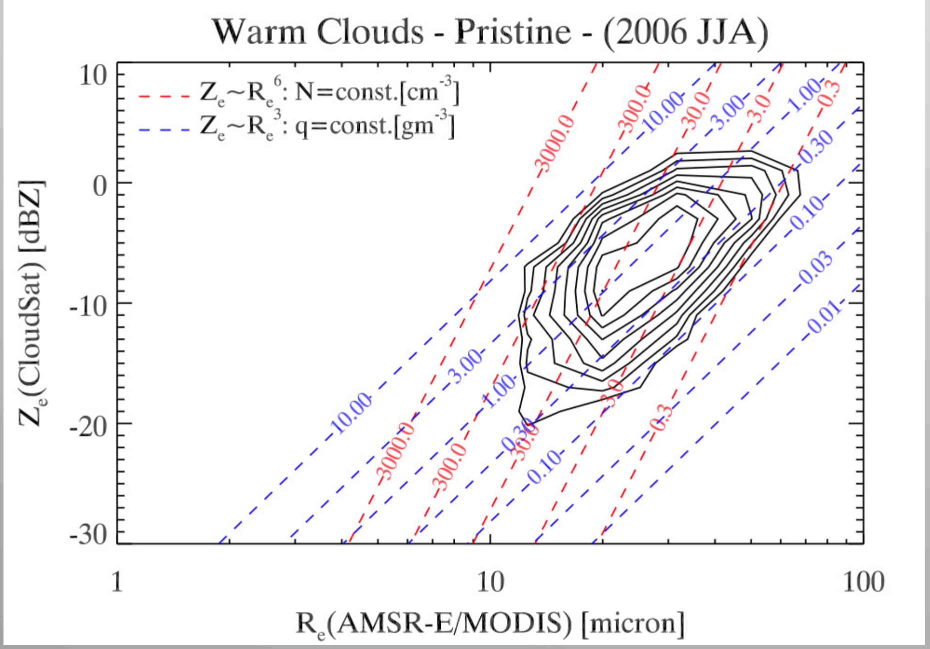


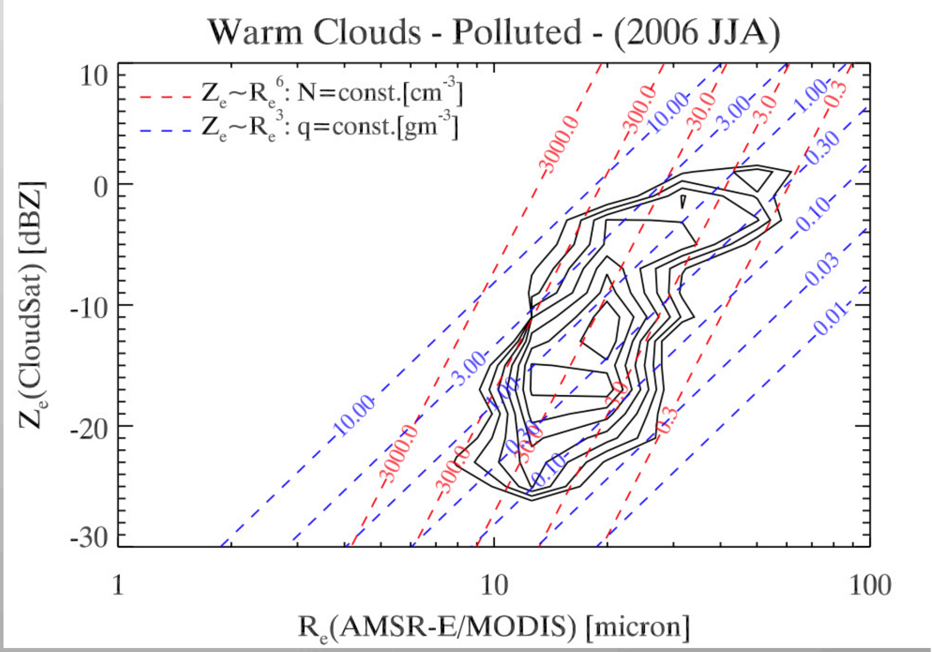
Suzuki and Stephens, 2008

aerosol effects?

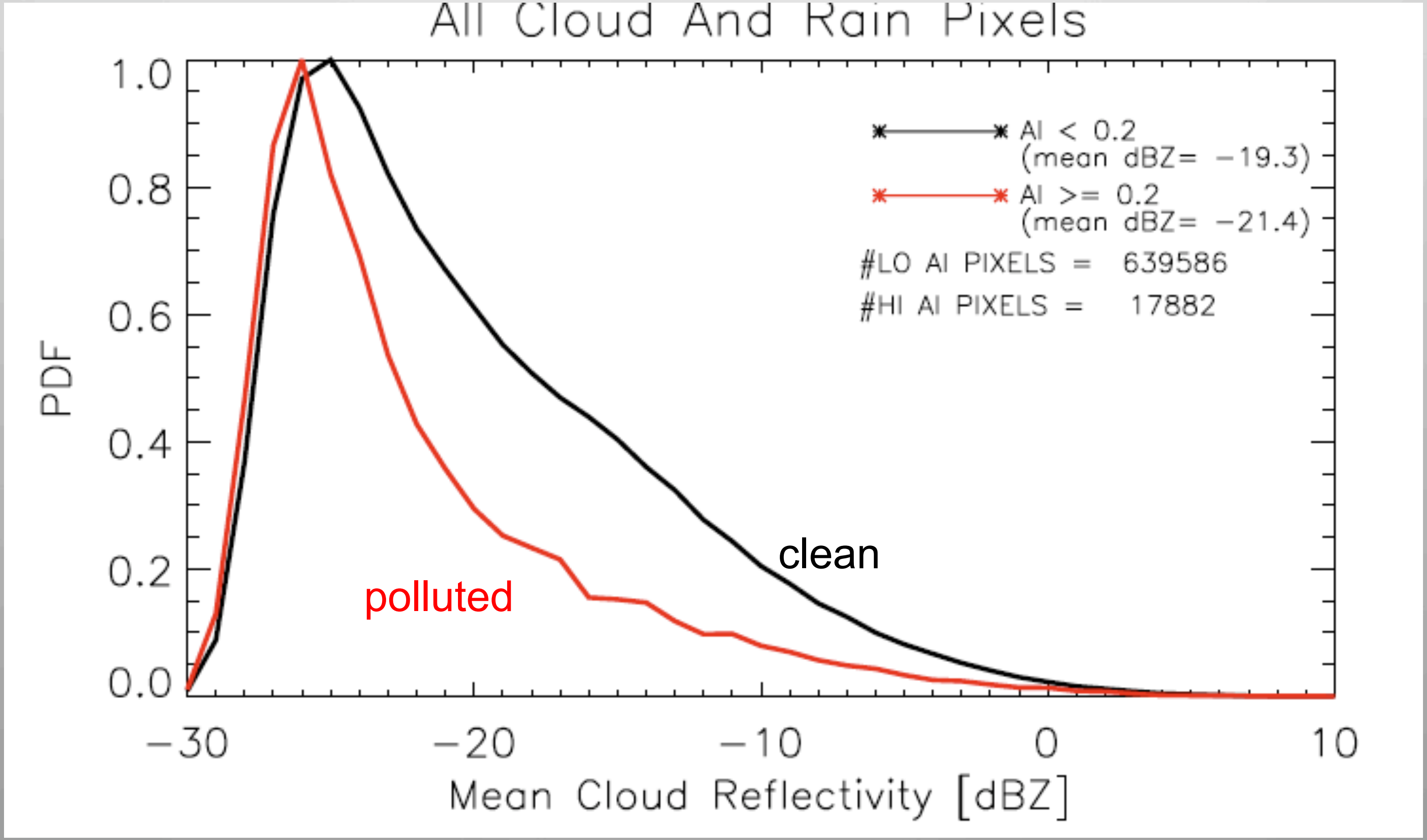
Pristine:
AI < 0.1

Polluted:
AI > 0.1



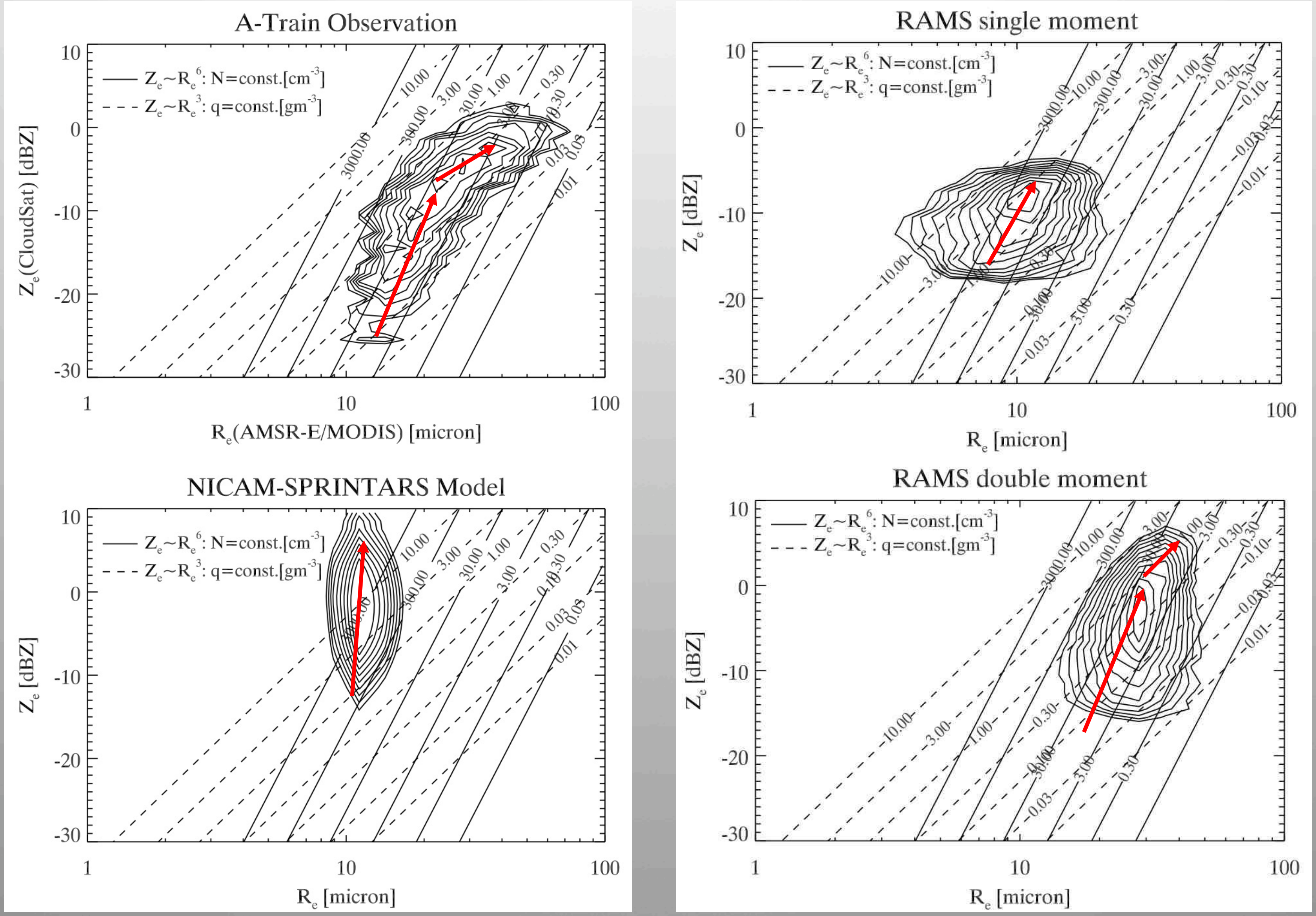


Another way to view these processes



He mean reflectivitiy relates the the rate of coalescence (Stephens and Haynes, 2008)

CRM model performance

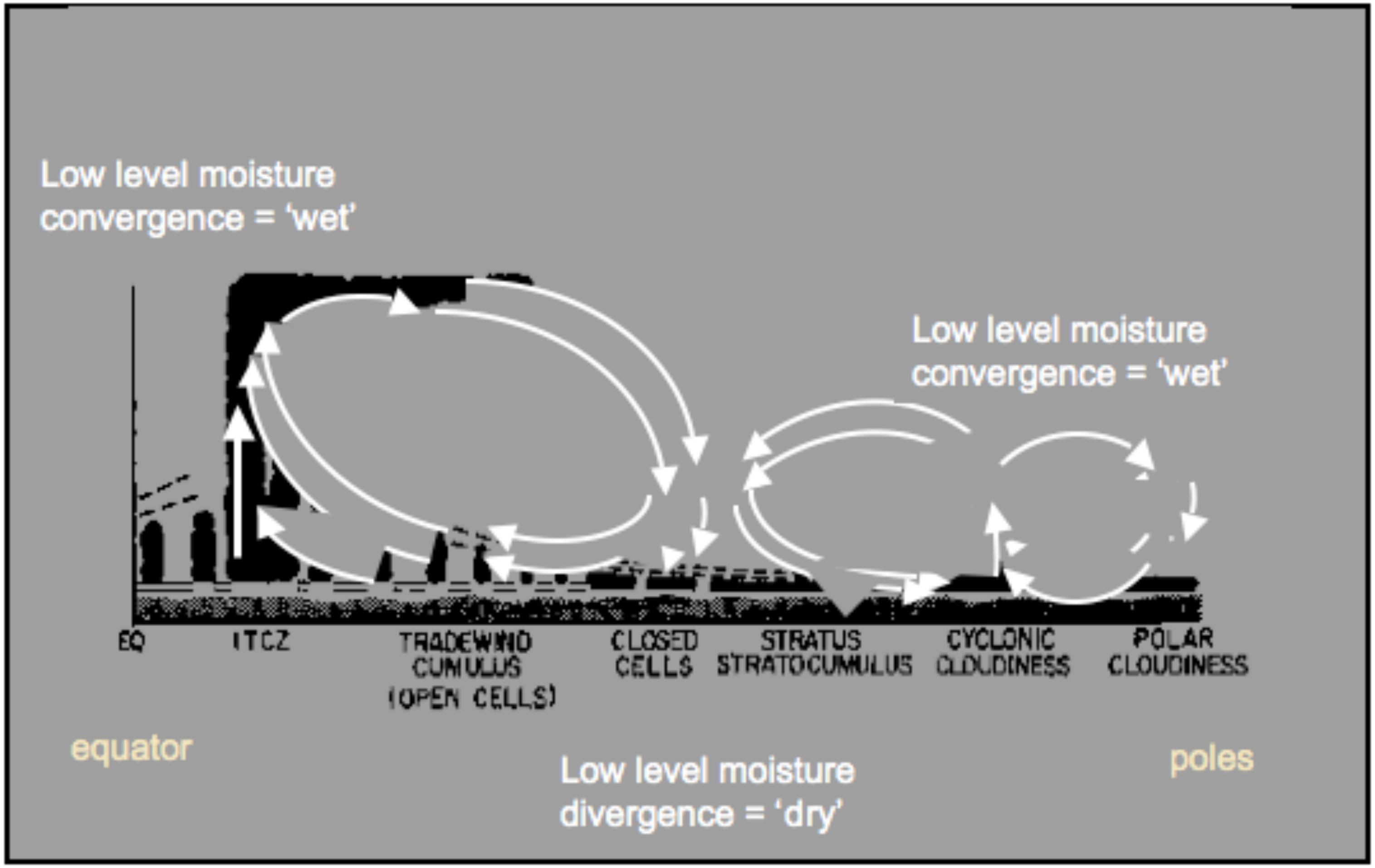


Summary

With the ability now to observe clouds and precipitation jointly and in a variety of different ways, and with an ability to characterize the environment in which clouds form, we are now moving into an era where we may in fact be developing an understanding of how the large-scale environment affects important cloud processes.

This is of central importance to topics like indirect effects, cloud-climate feedbacks .....

The real frontier Tying remotely sensed information to the bigger picture



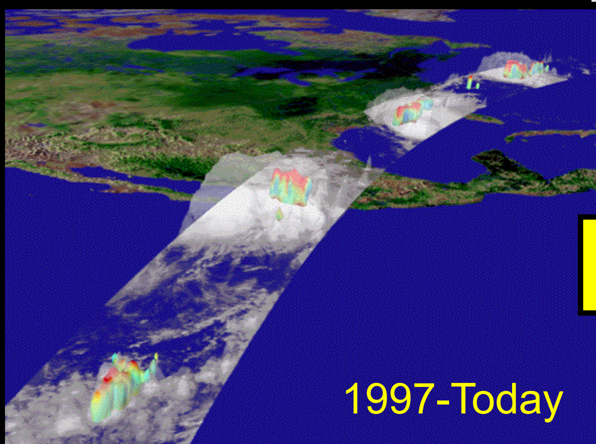
It is in this context that we want to be able to place the cloud properties that we remotely sense

The previous generation was greatly concerned with the dynamics of pressure systems and talked about highs and lows. Today we have not lost interest in these systems but we tend to look upon them as circulation systems. This change in attitude has led to a deeper understanding of their dynamics. Perhaps the next generation will be talking about the dynamics of water systems.

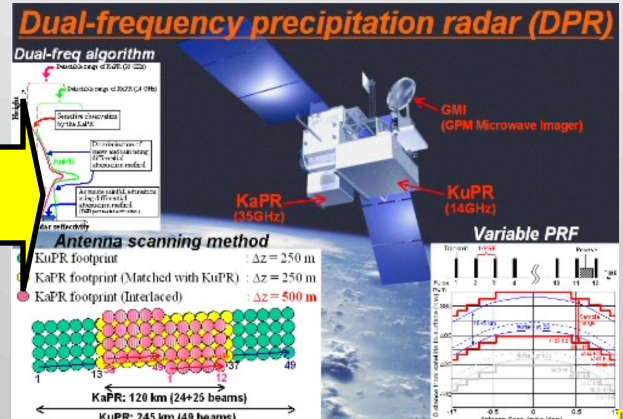
Lorenz, 1970.

Spaceborne Atmospheric Radars

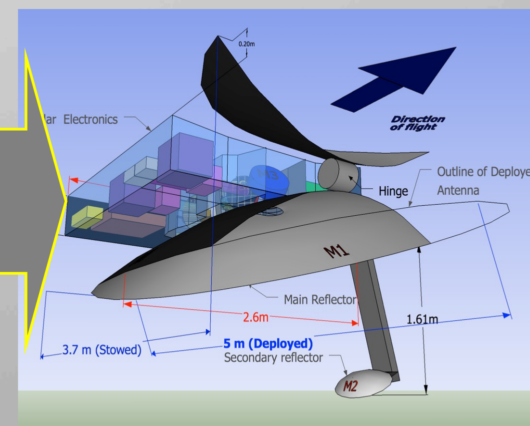
TRMM/PR – NICT/JAXA
Ku, Scanning , Tropical Rain



GPM/DPR – NICT/JAXA
Ku/Ka, Scanning, Precipitation

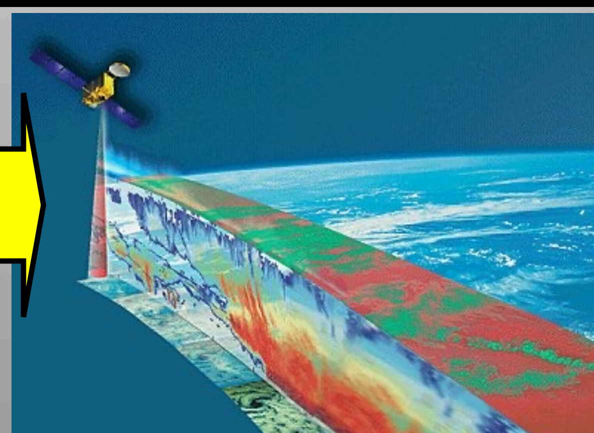


ACE Radar
W/Ka, Scanning,
Doppler



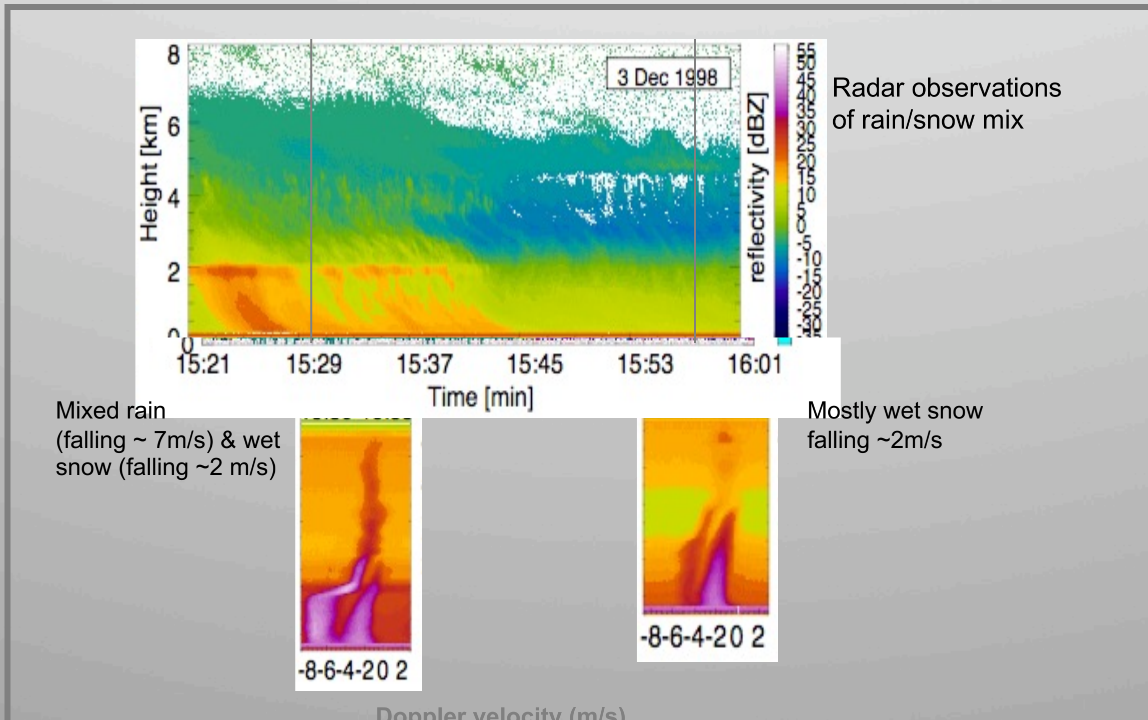
CloudSat/CPR – JPL/NASA
W, -30dBZ , Clouds

EarthCARE/CPR – NICT/JAXA
W, Doppler, Clouds



The next frontier – sustain active and add capability - Doppler

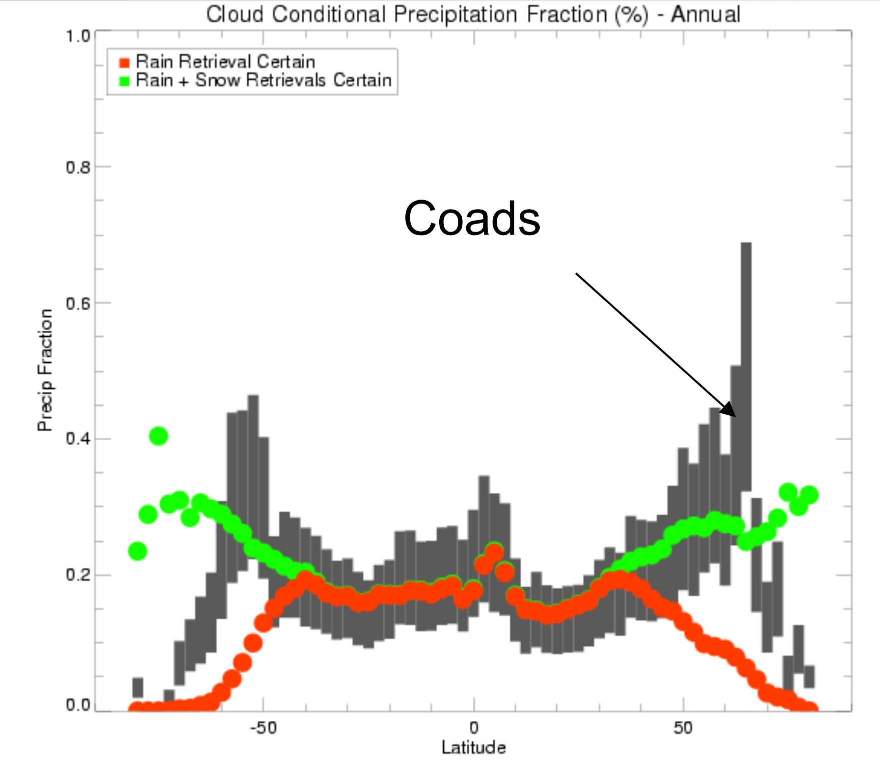
Better way to discriminate/determine microphysics

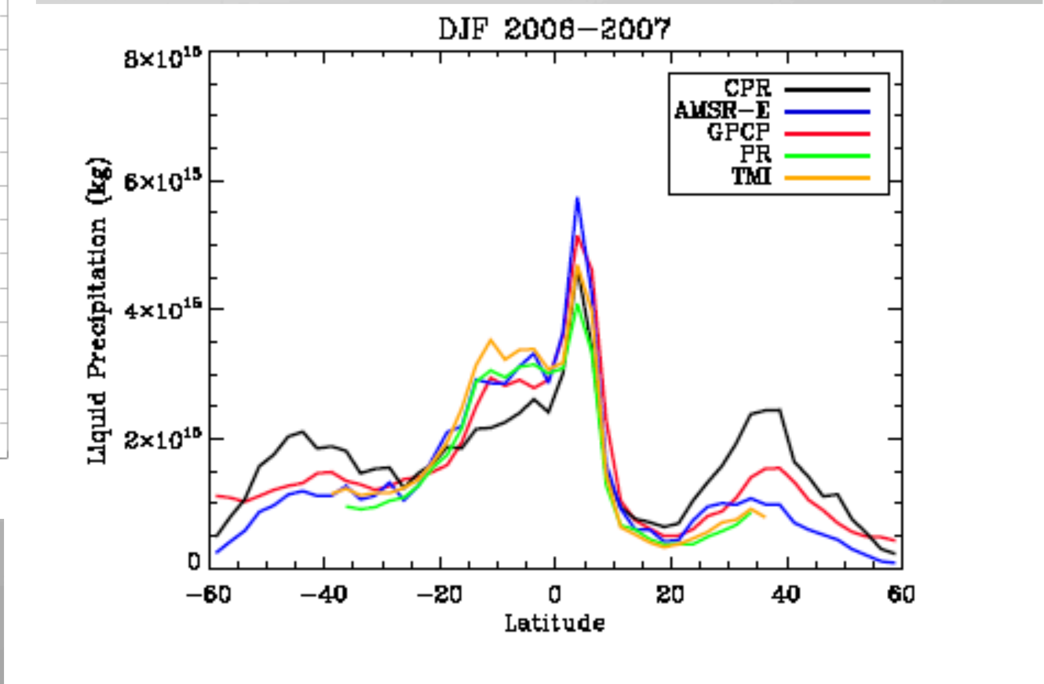


Better way to estimate latent heating

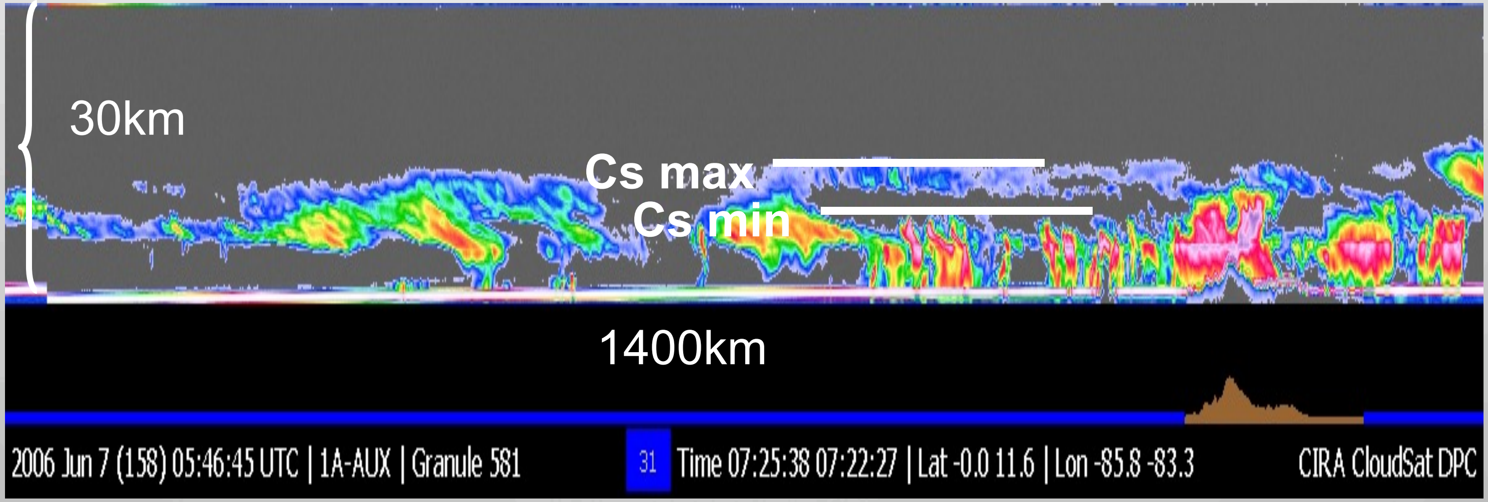
Dynamics of water systems, etc …

Enhanced product - precip incidence & amount





Precipitation as a function of CT height



Any given column may contain multiple cloud layers. We defined two quantities:

- **CTH** - the Cloud Top Height of the Highest Layer

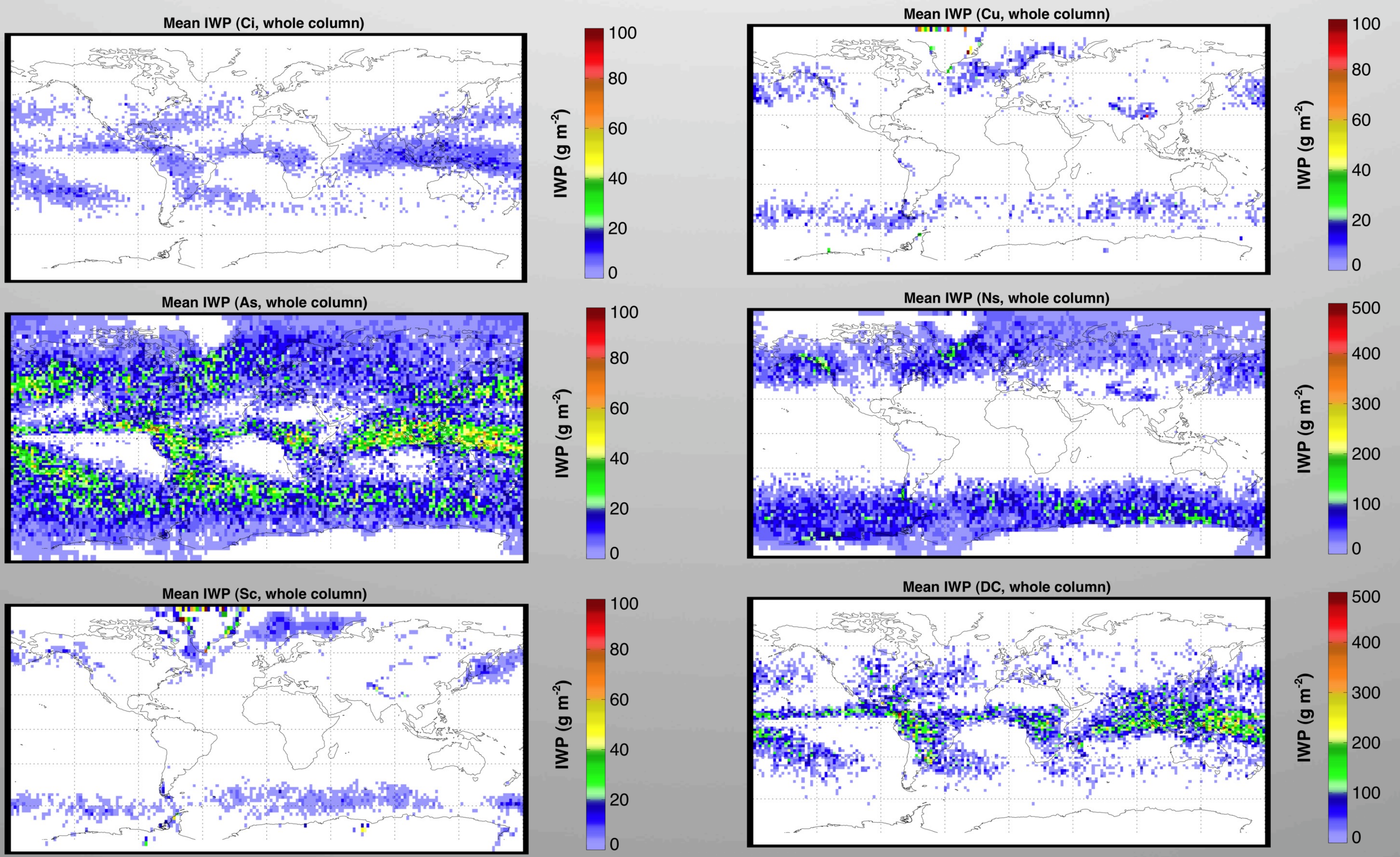
  (close to the traditional CTH observed by IR or passive microwave)

- **CTL** - the Cloud Top Height of the Lowest Layer

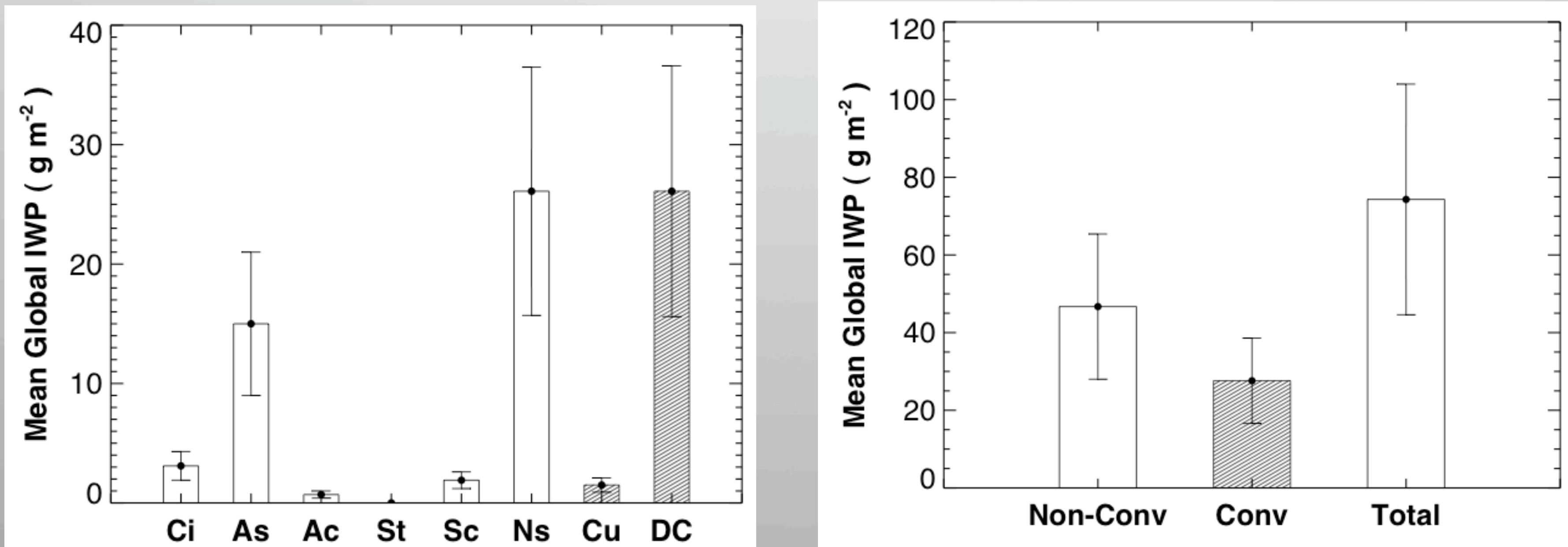
  (closely connected with the height of the physical portion of the cloud system that is associated with precipitation microphysics)

Results from CloudSat, (II):

Global IWP from different cloud types



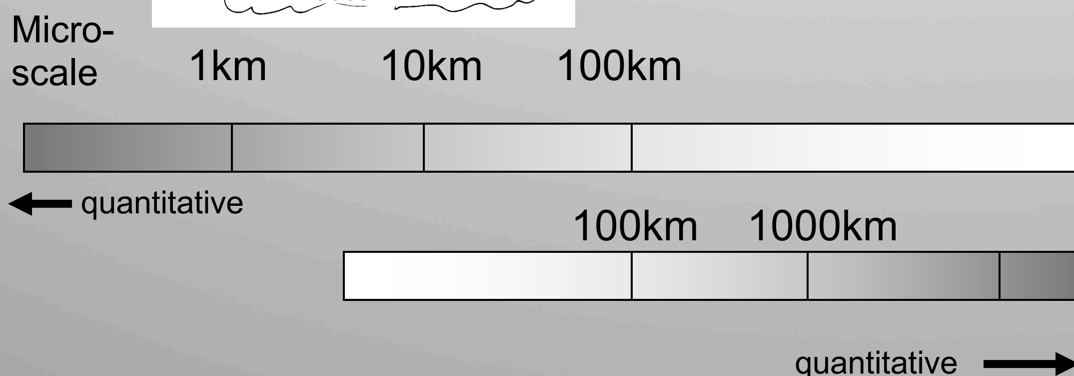
** Austin, Heymsfield, & Stephens, for submission to JGR, 2008*

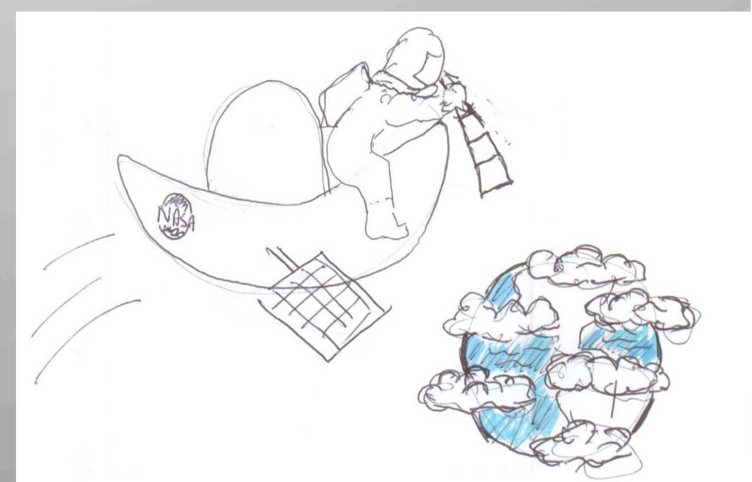


Global Mean IWP from 2B-CWC-RO (version R04), Dec 2006 – Nov 2007. Cloud types from the 2B-CLDCLASS product. Convective cloud types are shaded. Error bars show the estimated systematic uncertainty.

** Austin, Heymsfield, & Stephens, JGR, 2008*

The new frontiers – to bridge the ‘scale gap’

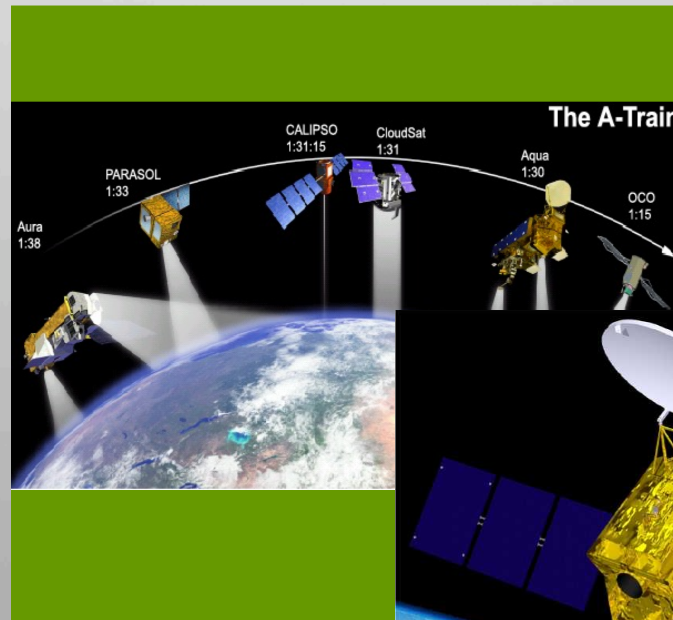




Radar Observations - present capabilities and future challenges/needs for ACE

Graeme Stephens,

Colorado State University



2006-2011

2013-2016?

ACE?

2020?

ACE: What advances over CoudSat and EarthCare?

Radar

- 2 frequency (35/94) Microphysics, precipitation
- Doppler ~0.5m/s conv, 0.3m/s goal - uphysics, dynamics, LH.
- Higher vertical resolution 250m - 4X? oversampled Shallow BL clouds
- Polarization? Phase, ice microphysics
- higher sensitivity ~-35 dBZ (94) & surface clutter filtering - low clouds
- scanning?
- 35/94 GHz radiometry cloud water path, precip; NEDT ~1K??

Lidar

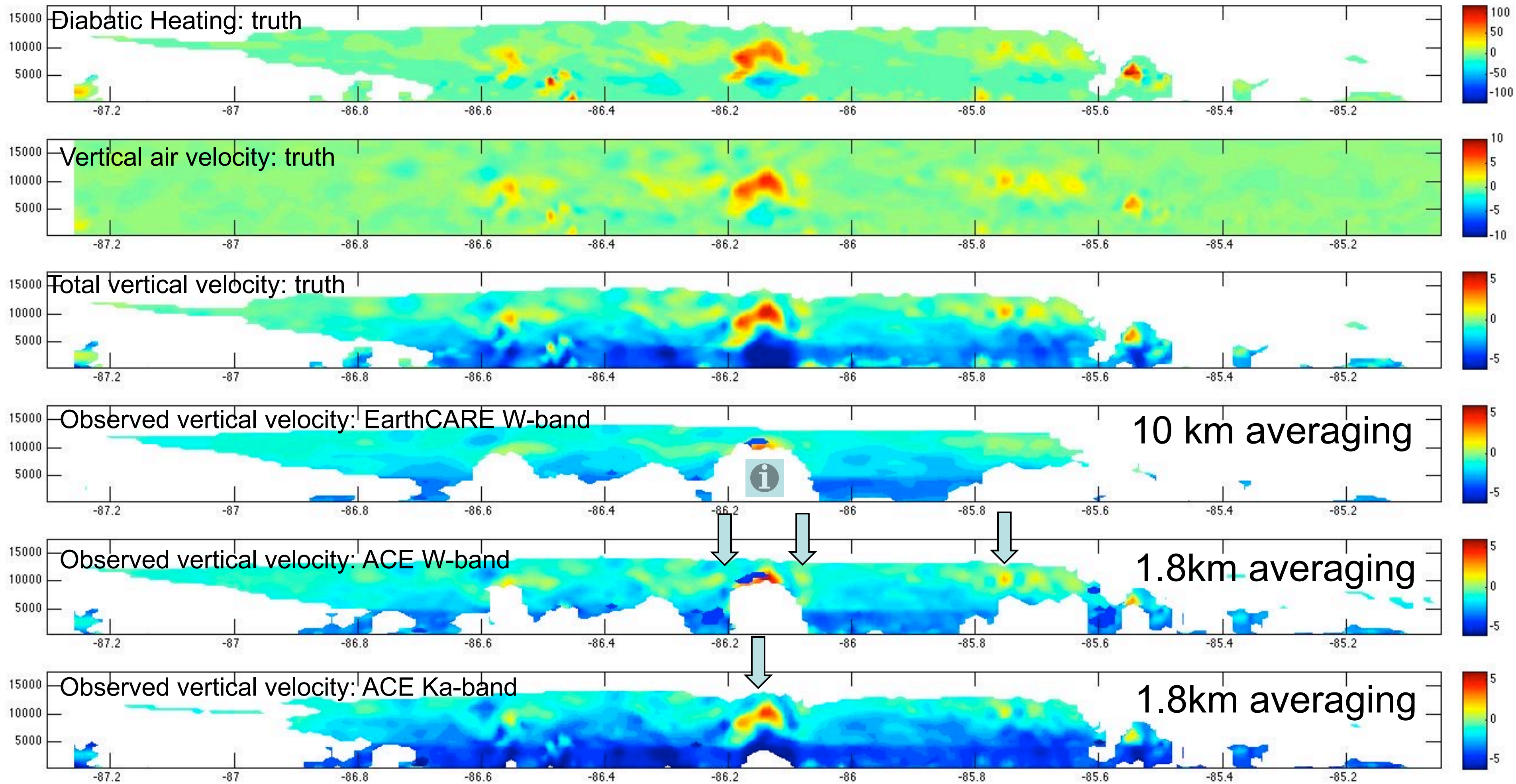
- 2 frequency HSRL — Unambiguous extinction at 2λ's$\rightarrow$ aerosol microphysics

Polarimeter — Aerosol and cloud microphysics, Phase, particle morphology, …

Other sensors ???

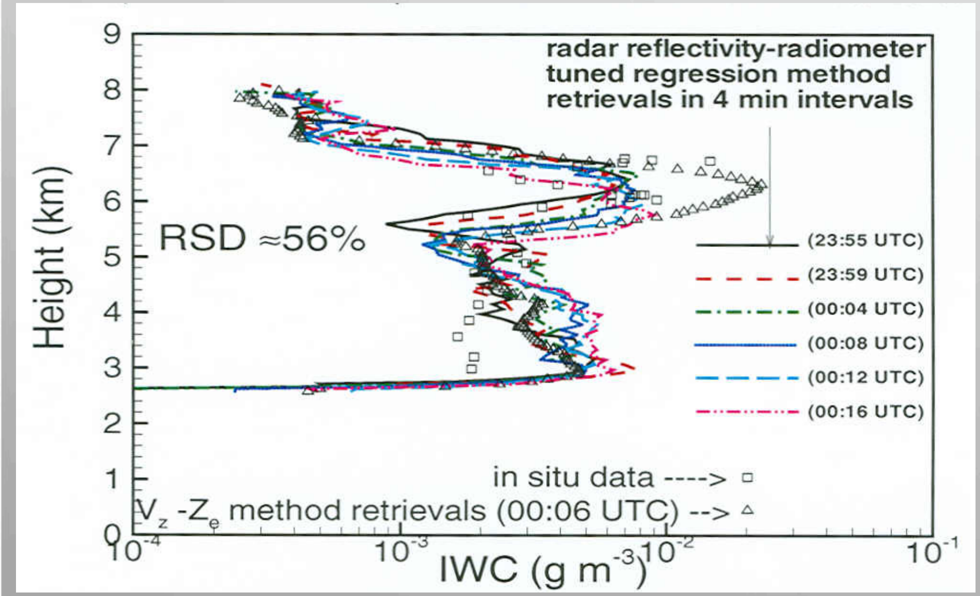
E.g. microwave radiometer, AMSR-E+high frequency

Vertical motion measurement from space



Challenges

5) Much more capability for determining the microphysics of clouds, precipitation and aerosol



The combination of Doppler velocities and radar reflectivity measurements provides a way of measuring profiles of ice cloud microphysics with a capability well beyond that available from space today. Measurement requirement minimum resolution accuracy ~0.2m/sec; scale 1-2km for Z>-15 dBZ

Matrosov et al., 200?

Frontier 2: Using combinations of remotely sensed parameters to characterize processes emphasizing cloud-precip transition

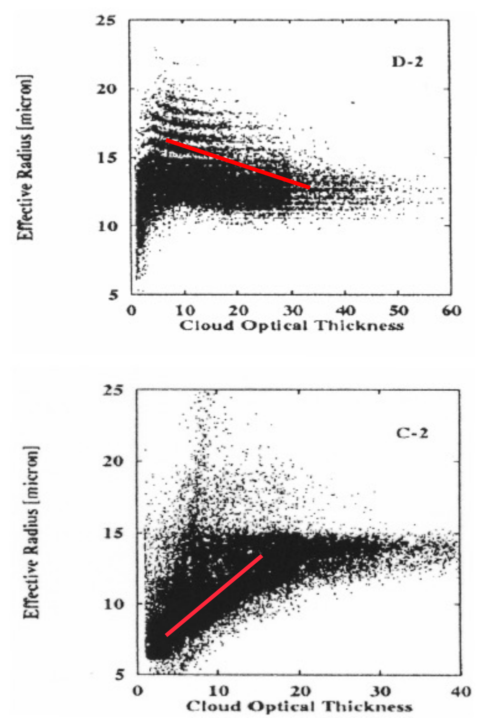
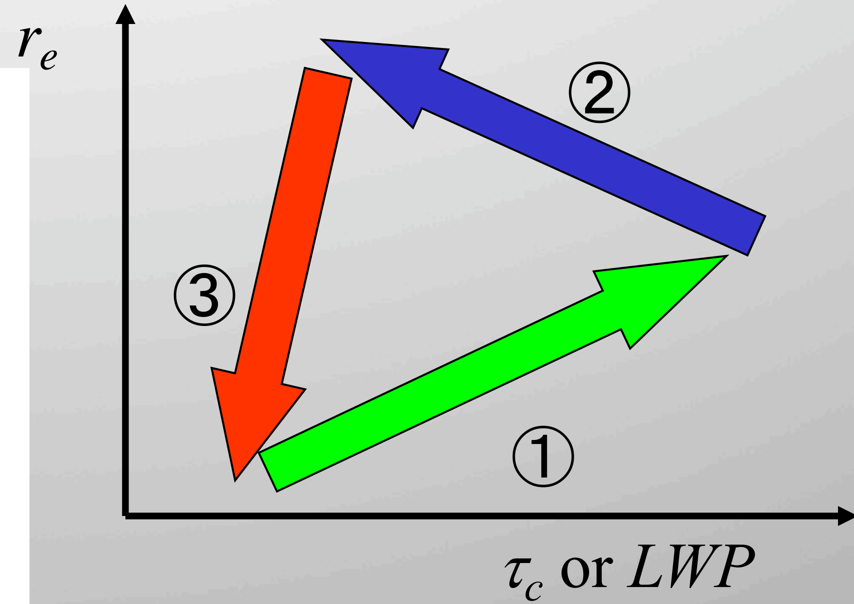


Fig. 1. Scatter plot between effective particle radius and optical thickness obtained from satellite observation over FIRE (upper) and ASTEX (lower) regions (cited from Nakajima and Nakajima 1995)

Nakajima and Nakajima (JAS 1995)



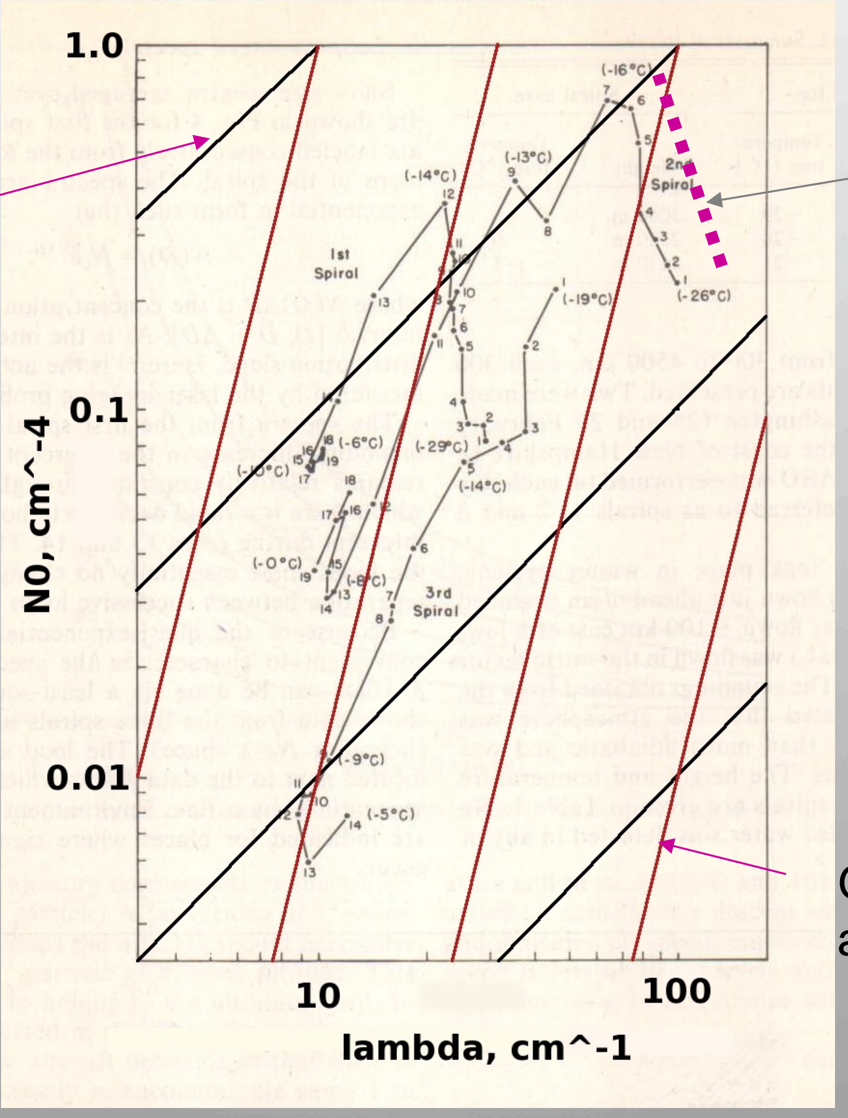
①non-drizzling stage

②drizzling stage

③evaporating stage

Another example - snow

Growth by condensation



Nucleation/growth

Growth by aggregation

1/D

With the new observing systems we have an ability to jointly :

Deduce gross information on cloud optical properties

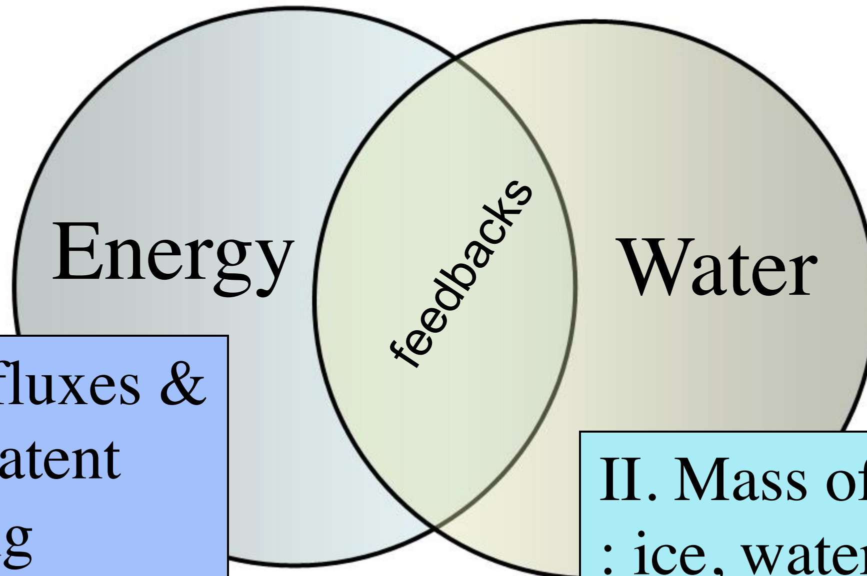
The integrated cloud water I no (& light) rain

The vertical profiles of clouds (thickness, ….)

Precipitation incidence (and amount)

And we can combine these and begin to examine important cloud-scale physical processes set on a much vaster scale than previously studied

The focus is on energy related processes and parameters that affect these and water related processes and parameters that affect these



I. Radiative fluxes & heating, latent heating

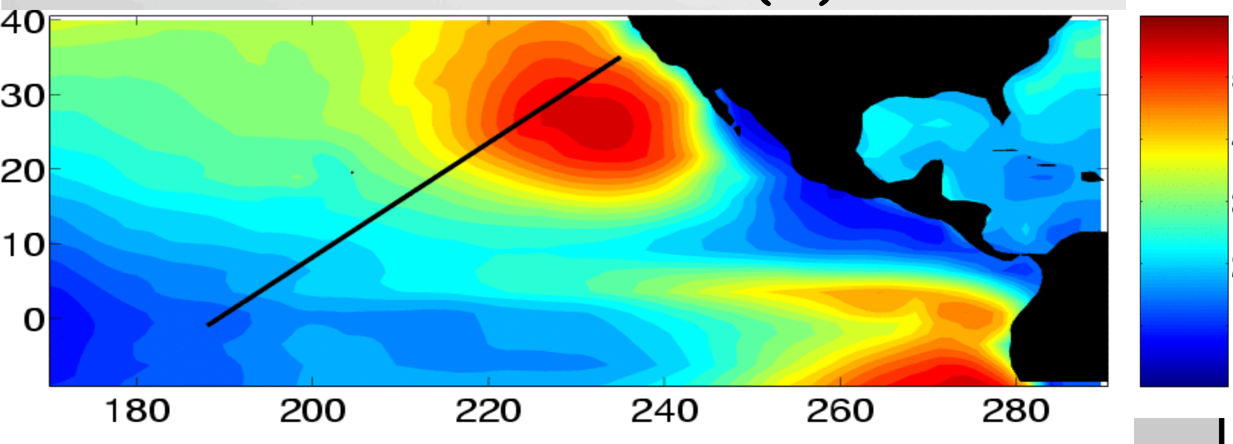
II. Mass of condensed water : ice, water and falling precip)

III. <u>Microphysical</u> & optical properties:

IV. State information, including aerosol and meteorology (motions large & small, thermodynamics …)

GCSS/WGNE Pacific Cross-section Intercomparison (GPCI)

ISCCP Low Cloud Cover (%)



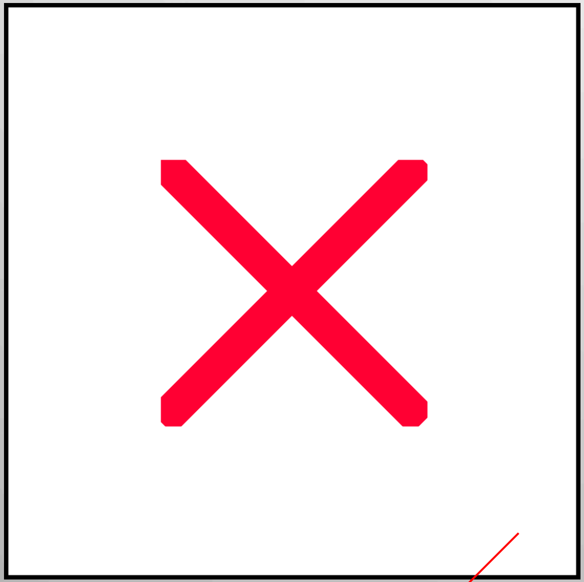
GPCI is a working group of the GEWEX Cloud System Study (GCSS) – funded by the NASA MAP Program

Models and observations are analyzed along a transect from stratocumulus, across shallow cumulus, to deep convection

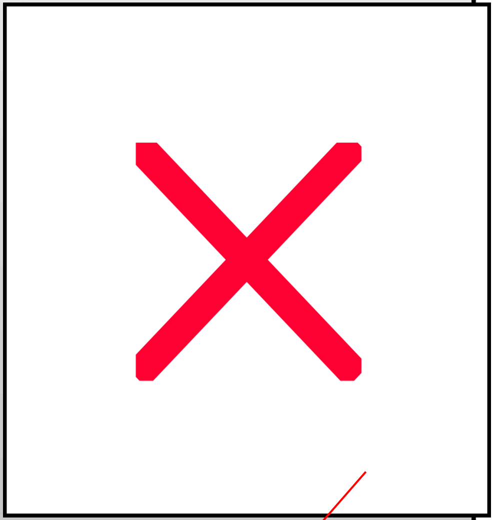
Models: GFDL, NCAR, UKMO, JMA, MF, KNMI, DWD, NCEP, MPI, ECMWF, BMRC, NASA/GISS, UCSD, UQM, LMD, CMC, CSU, GKSS

Mean liquid water content - JJA98

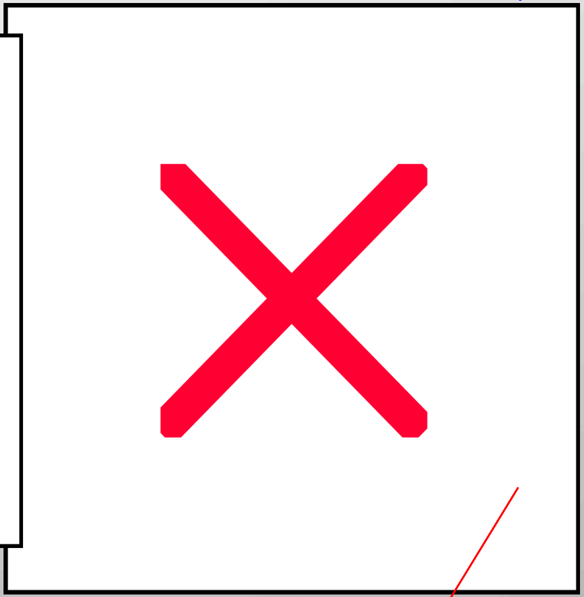
NCAR

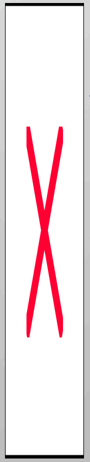


MeteoFrance



UKMO





liquid water

g/kg

Too shallow -> fog

Is this too much liquid water?

How deep should the PBL be..?

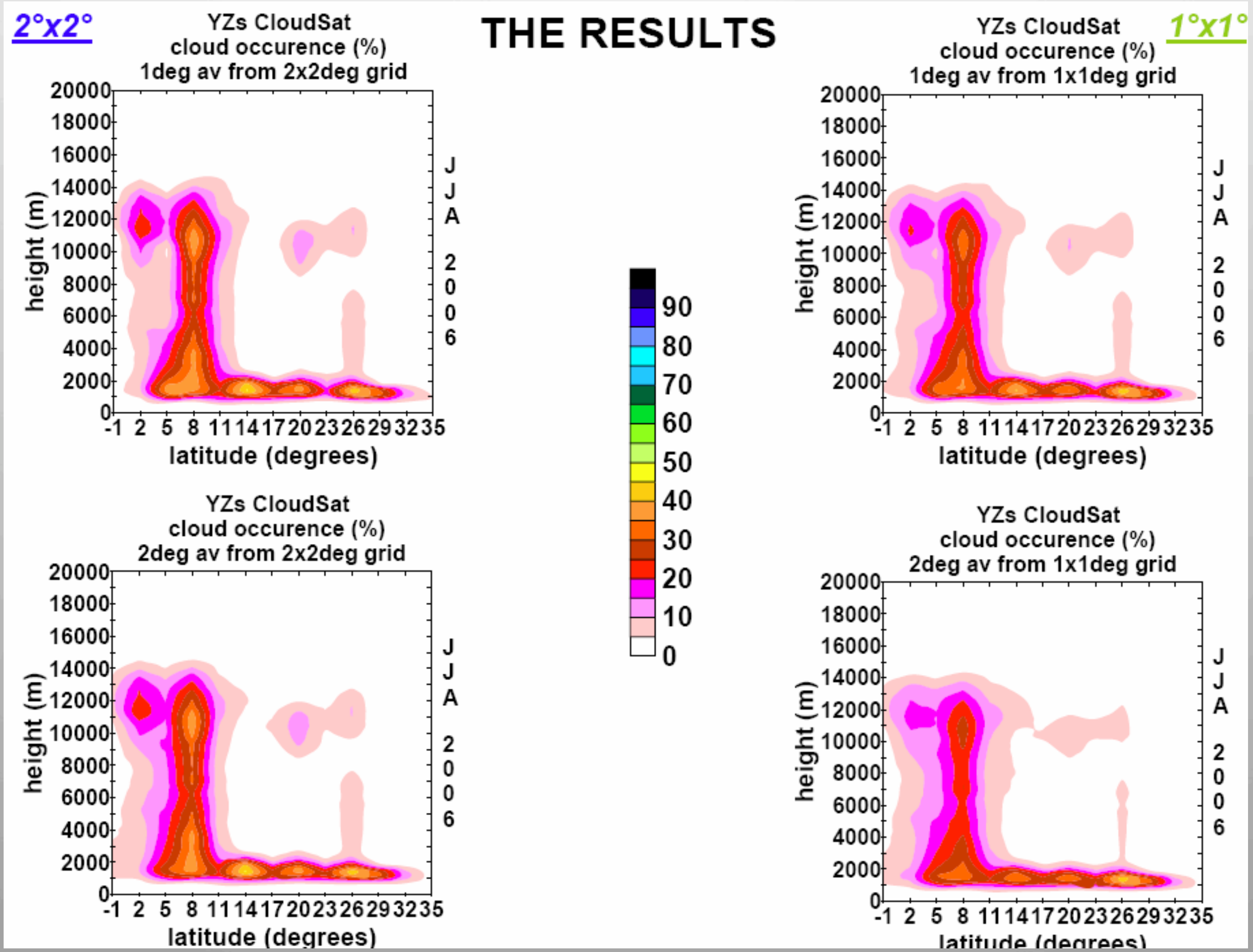
Cloud Cover along GPCI

Deep convection clouds

Boundary layer clouds

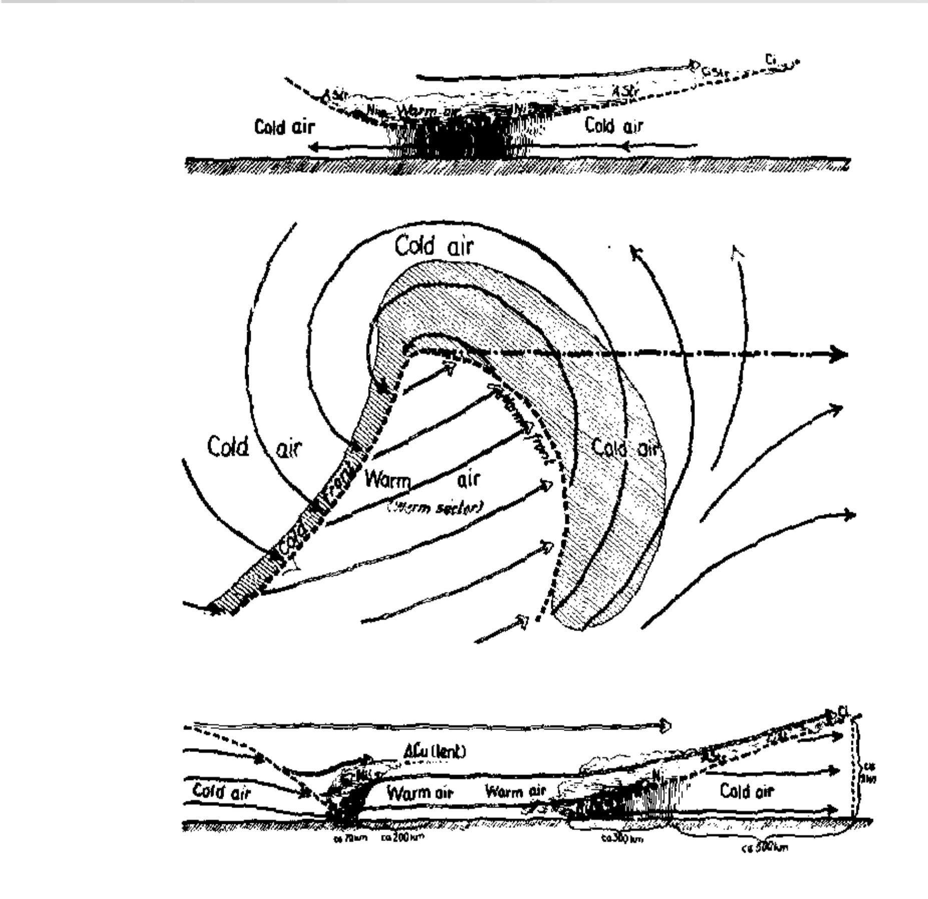
Large differences in clouds between models

CloudSat cloud occurrence along GPCI

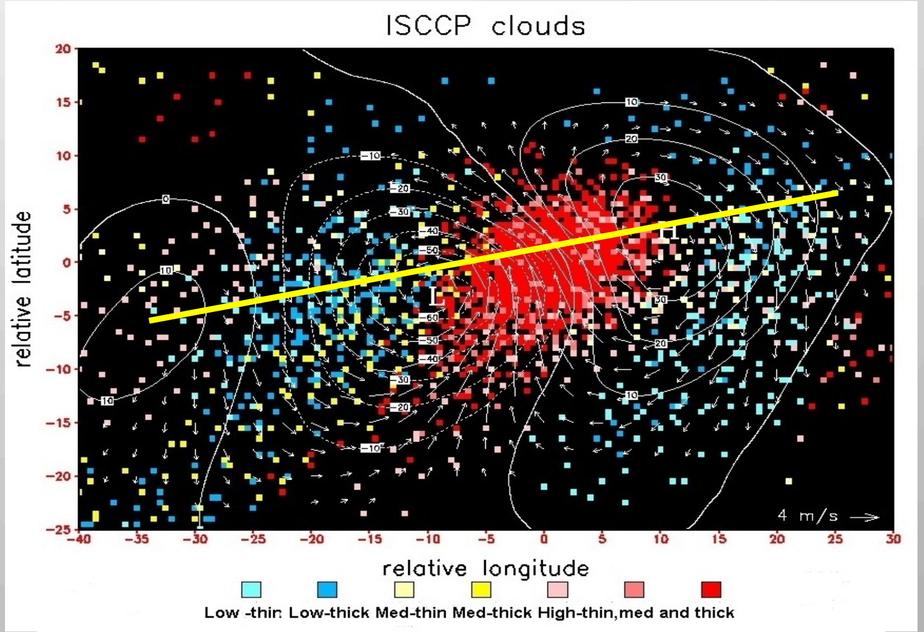


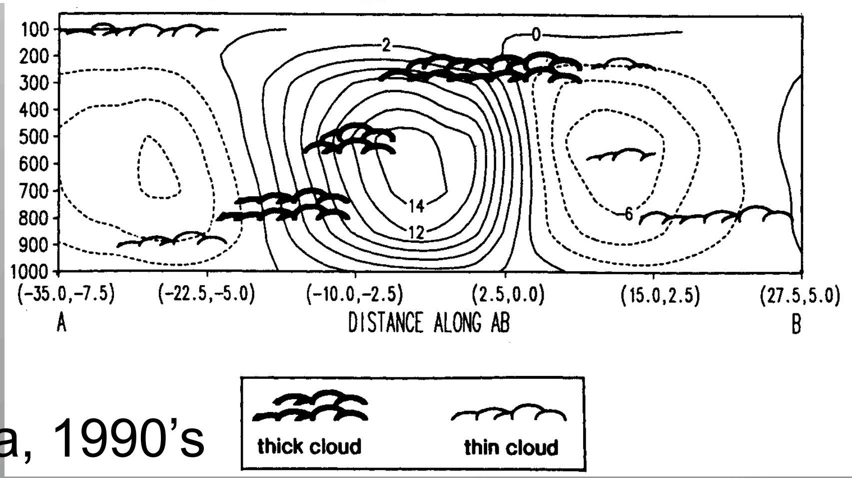
These news obs are being used in quantitative assessment of cloud properties in association with the circulation that defines them

ISCCP and the anatomy of weather systems – the Lau and Crane (1995) example



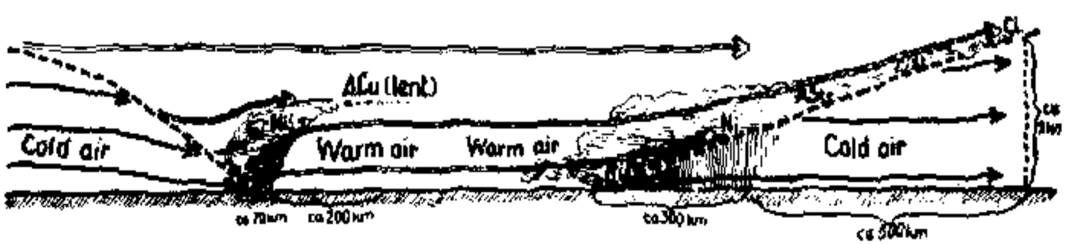
Circa, 1920's - Bjerknes cyclone model

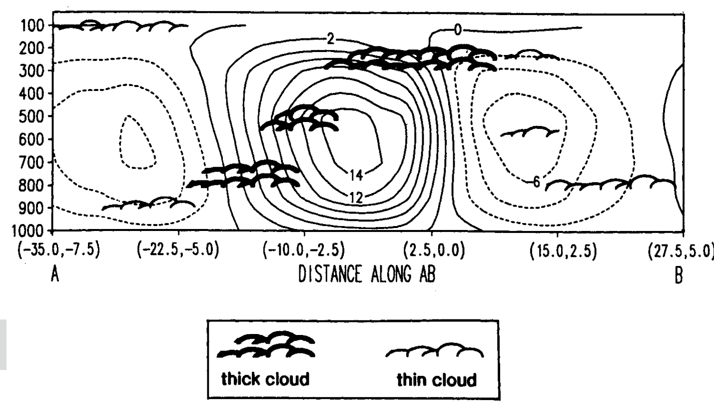


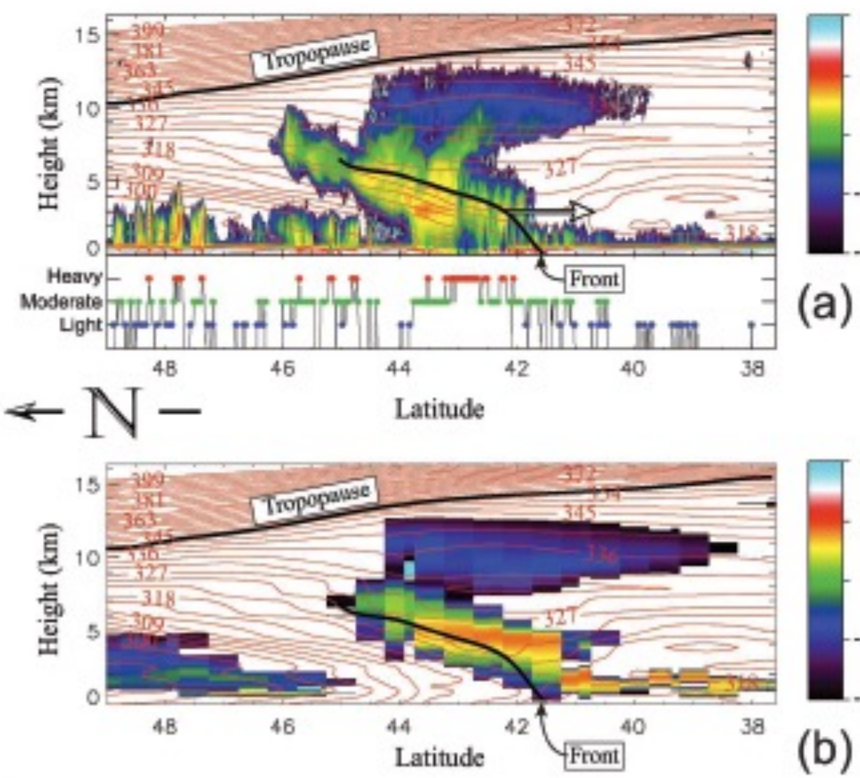


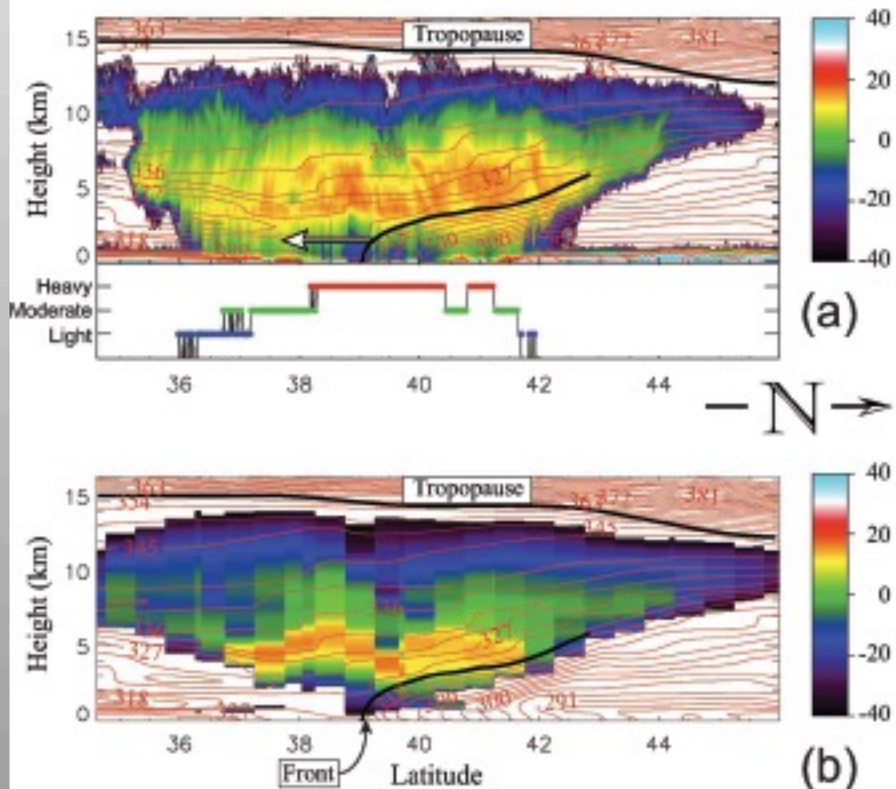
Circa, 1990's
Lau&Crane,1995

Bjerknes to Lau and Crane to Cloudsat







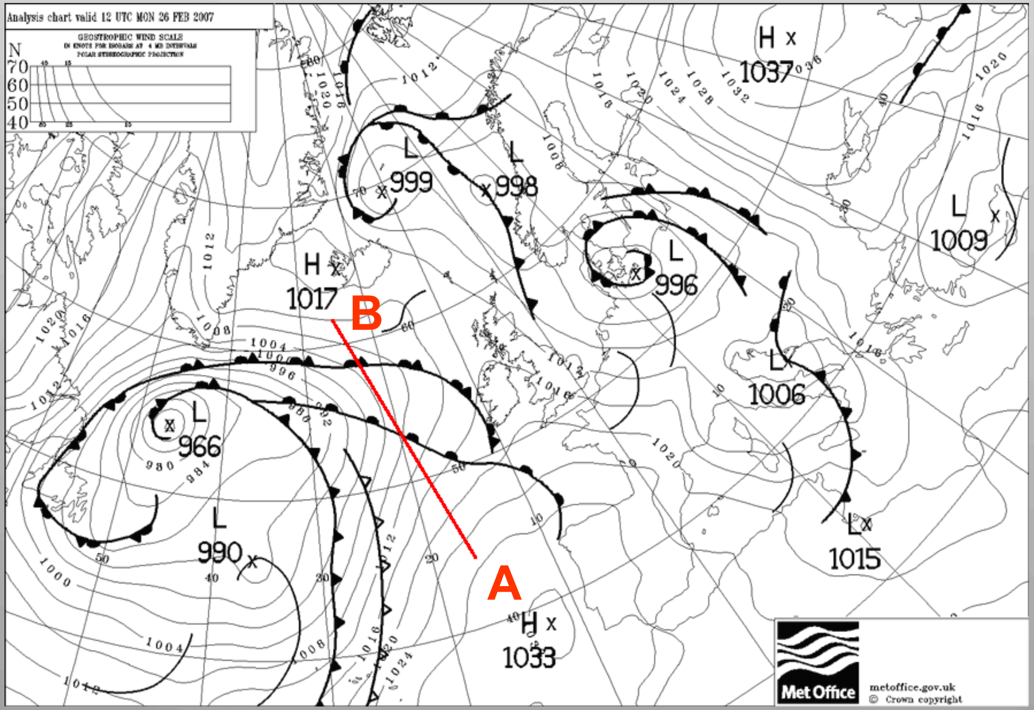


Posselt et al., 2008

FIG. 7. As in Fig. 4, but for a portion of Cloudsat granule 3034, observed at approximately 1730 UTC 22 Nov 2006.

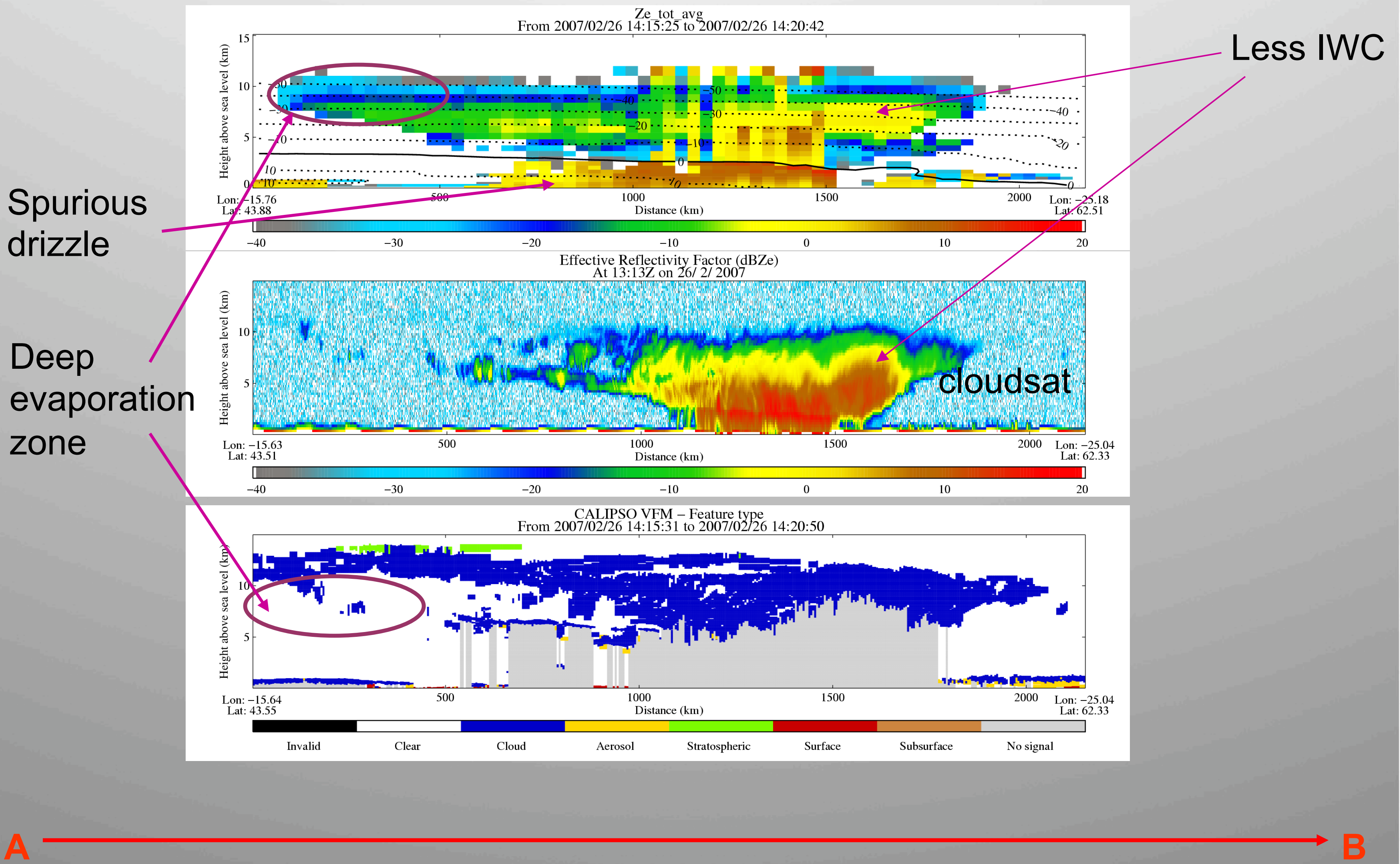
Case study example : 26 February 2007

- Analysis chart valid at 12 UTC
- CloudSat overpass at ~14:15 UTC

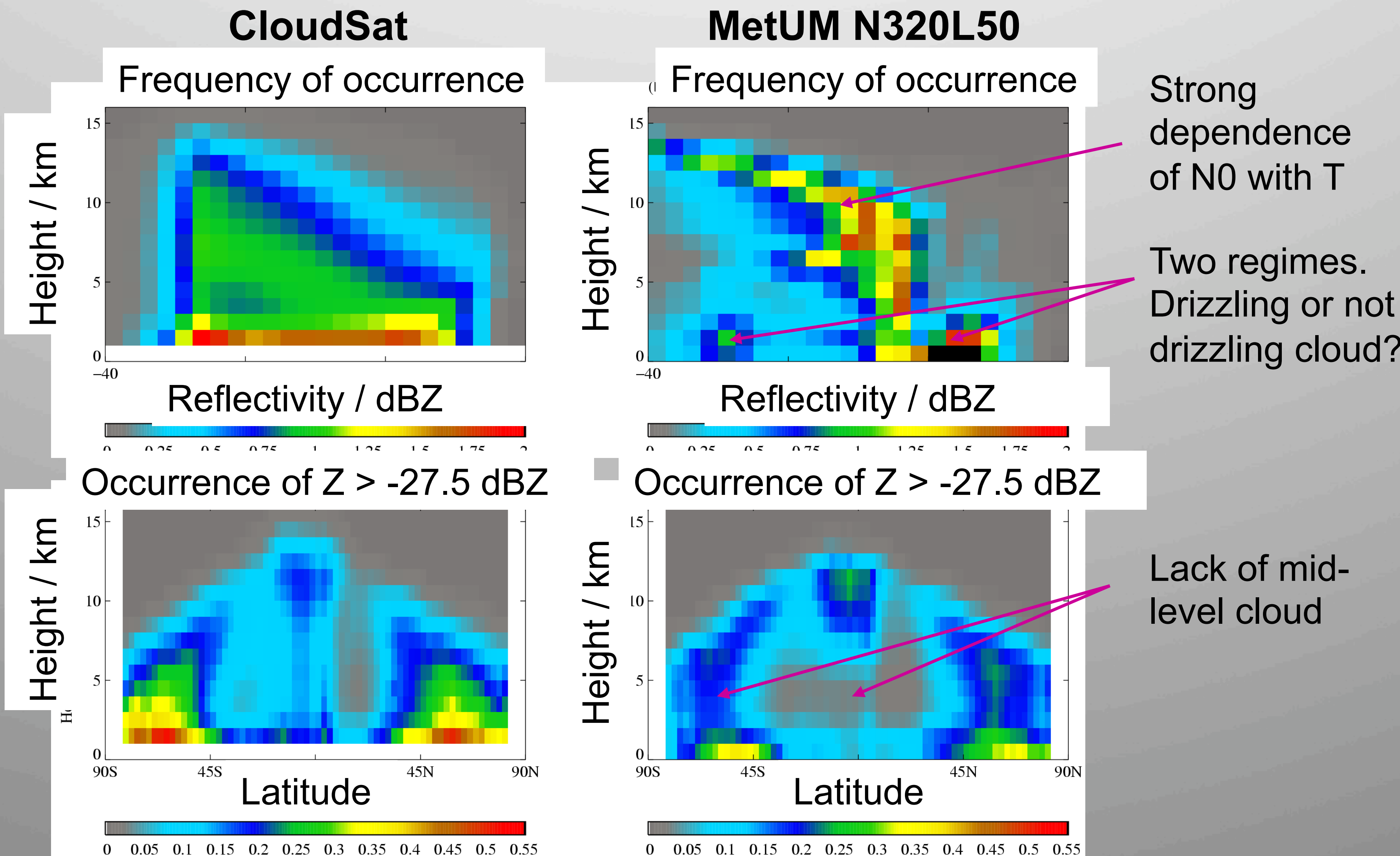


Bodas-Salcedo et al, 2008

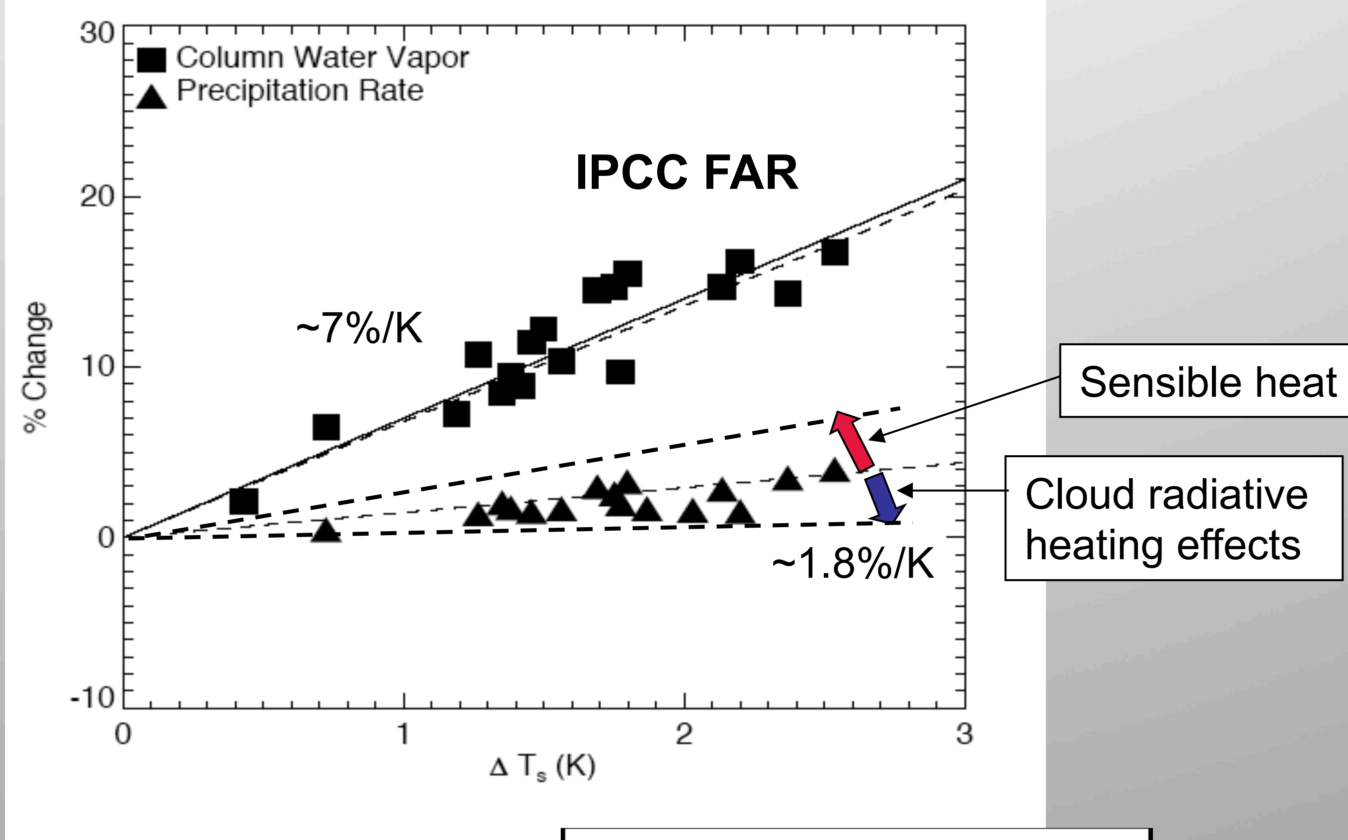
A case study of frontal systems



Simulators of the observing system are being coupled to climate models as part of the CFMIPII activity which is to support the next IPCC assessment

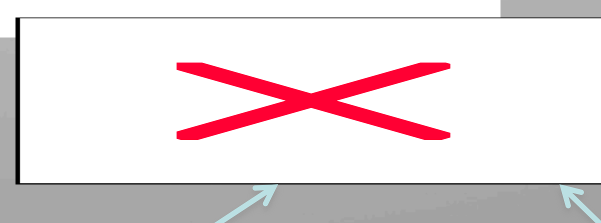


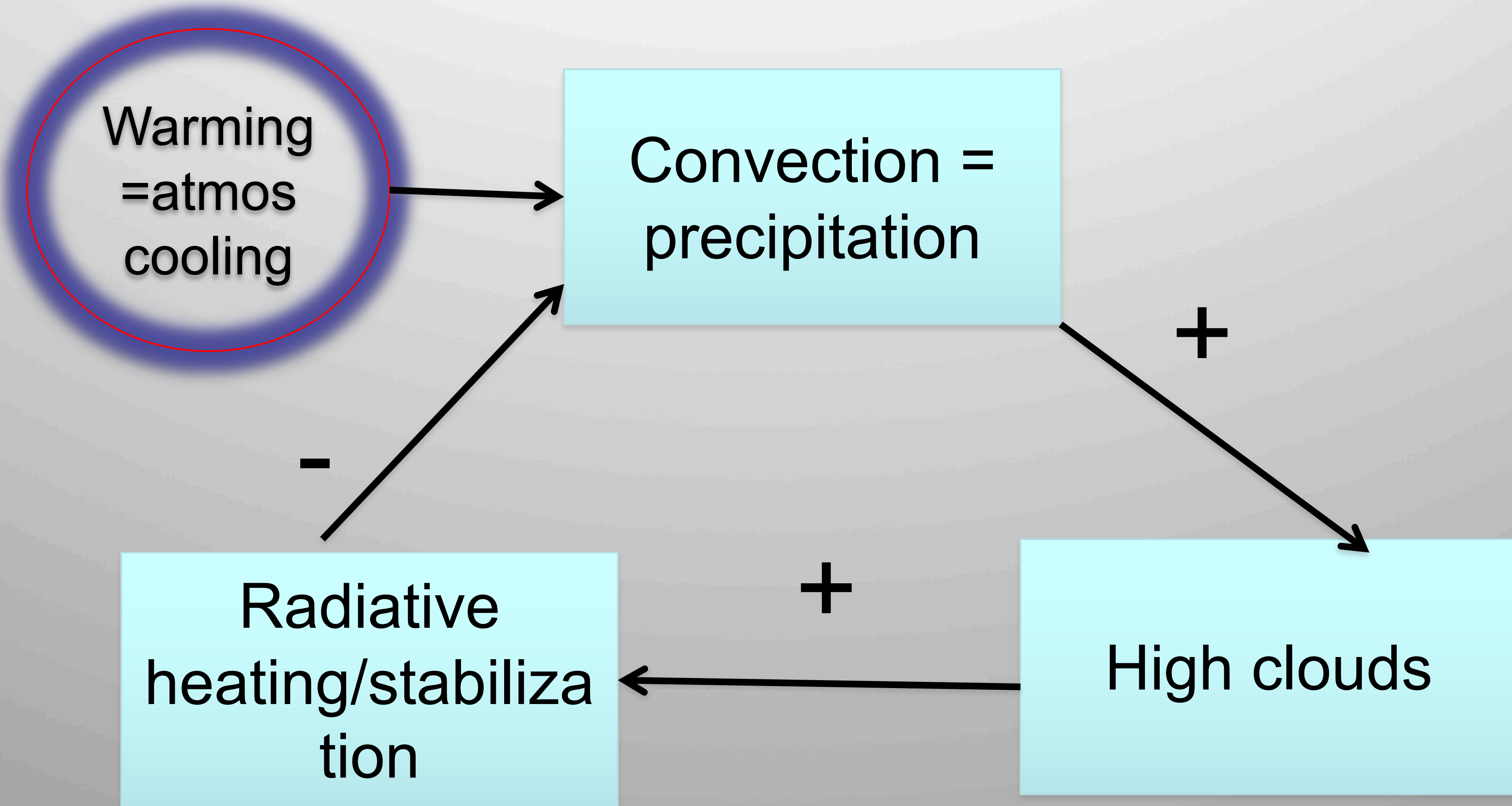
It not just about processes affecting TOA Radiation balance



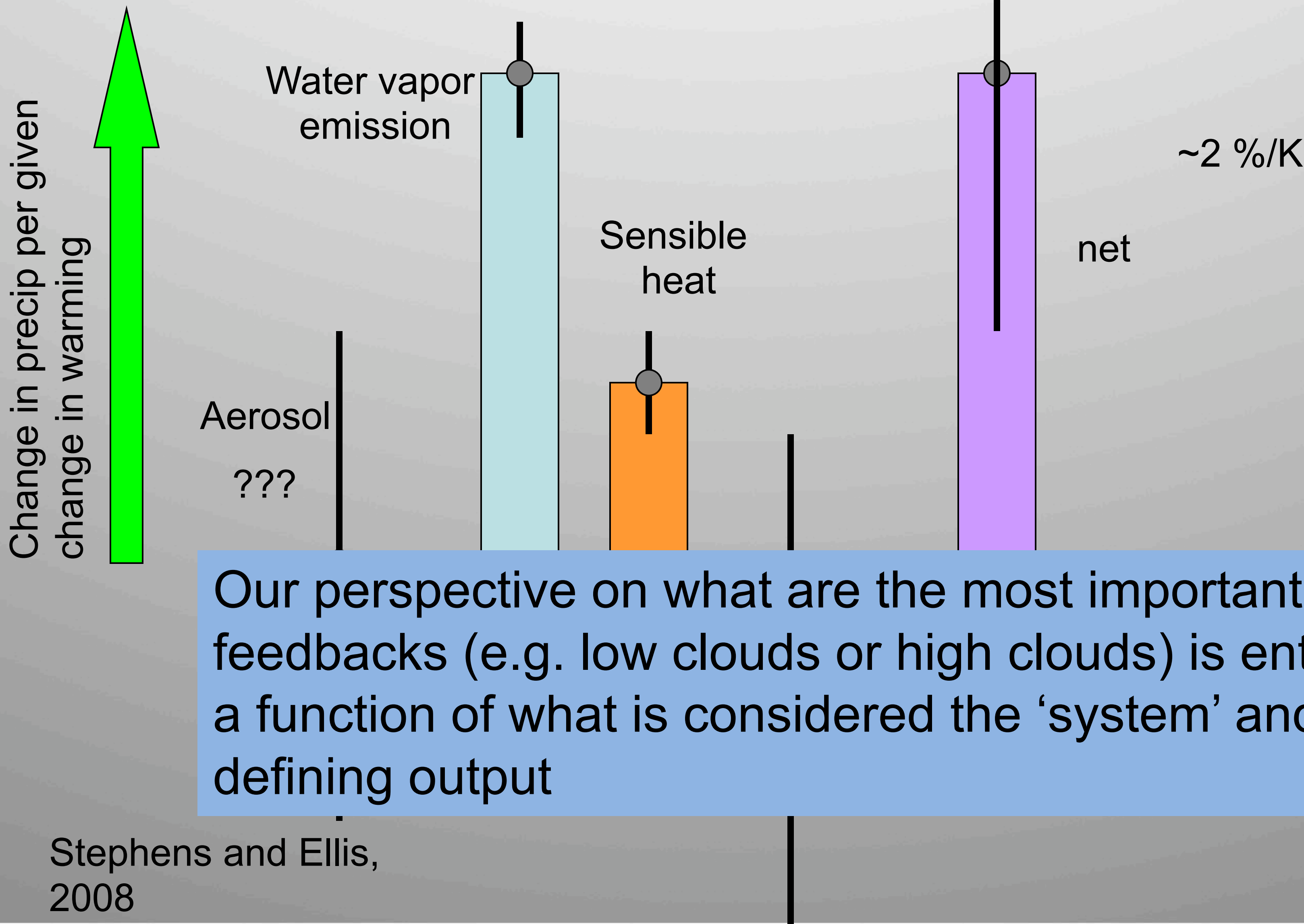
1. The system is the atmospheric energy balance

2. The output is the change in global precipitation ΔP




Warming =atmos cooling
Convection = precipitation
+
High clouds
+
Radiative heating/stabilization
-

…. what establishes global precipitation changes - clouds here also are a major source of uncertainty (and aerosol effects (on clouds) are unknown)

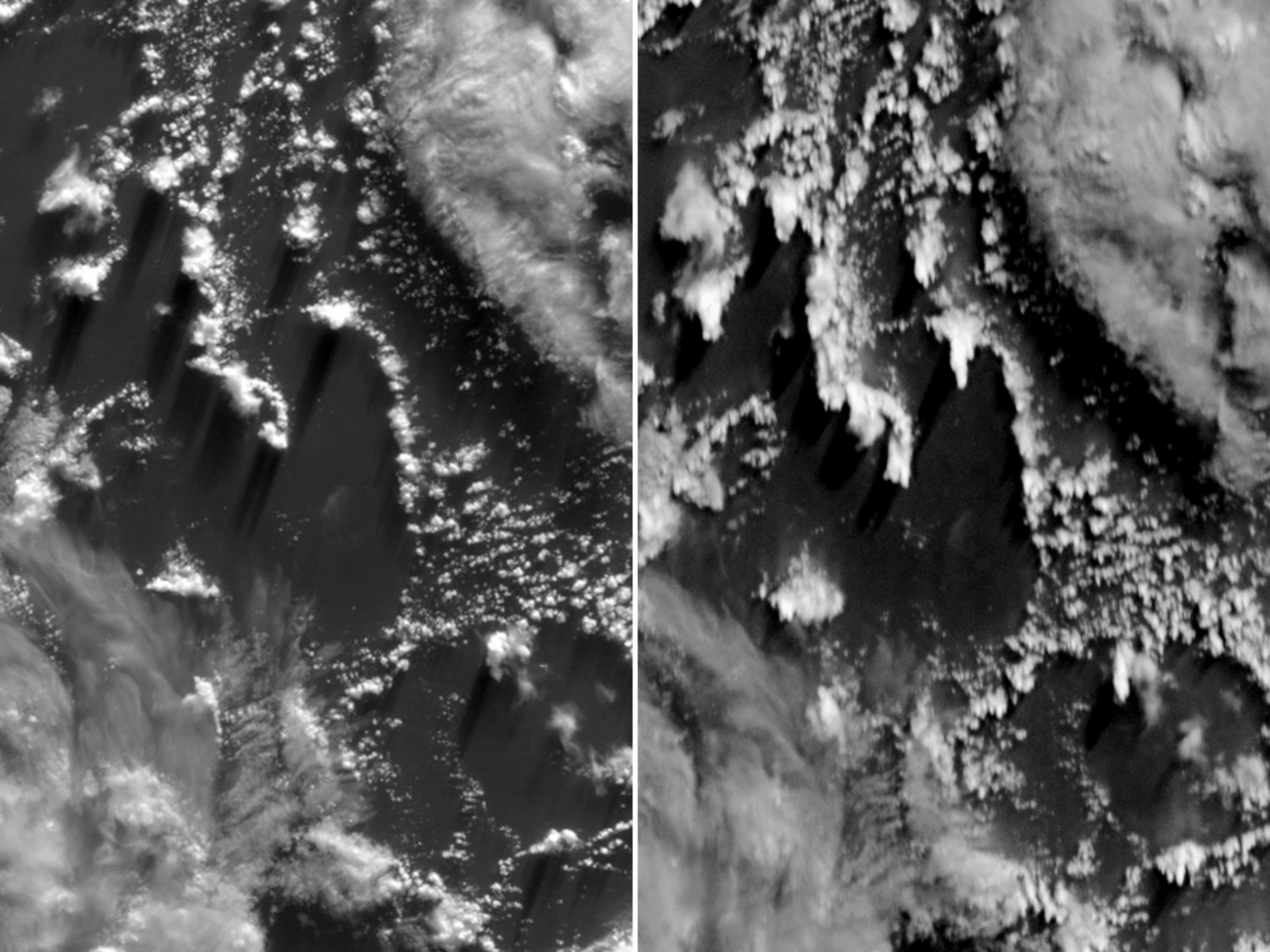


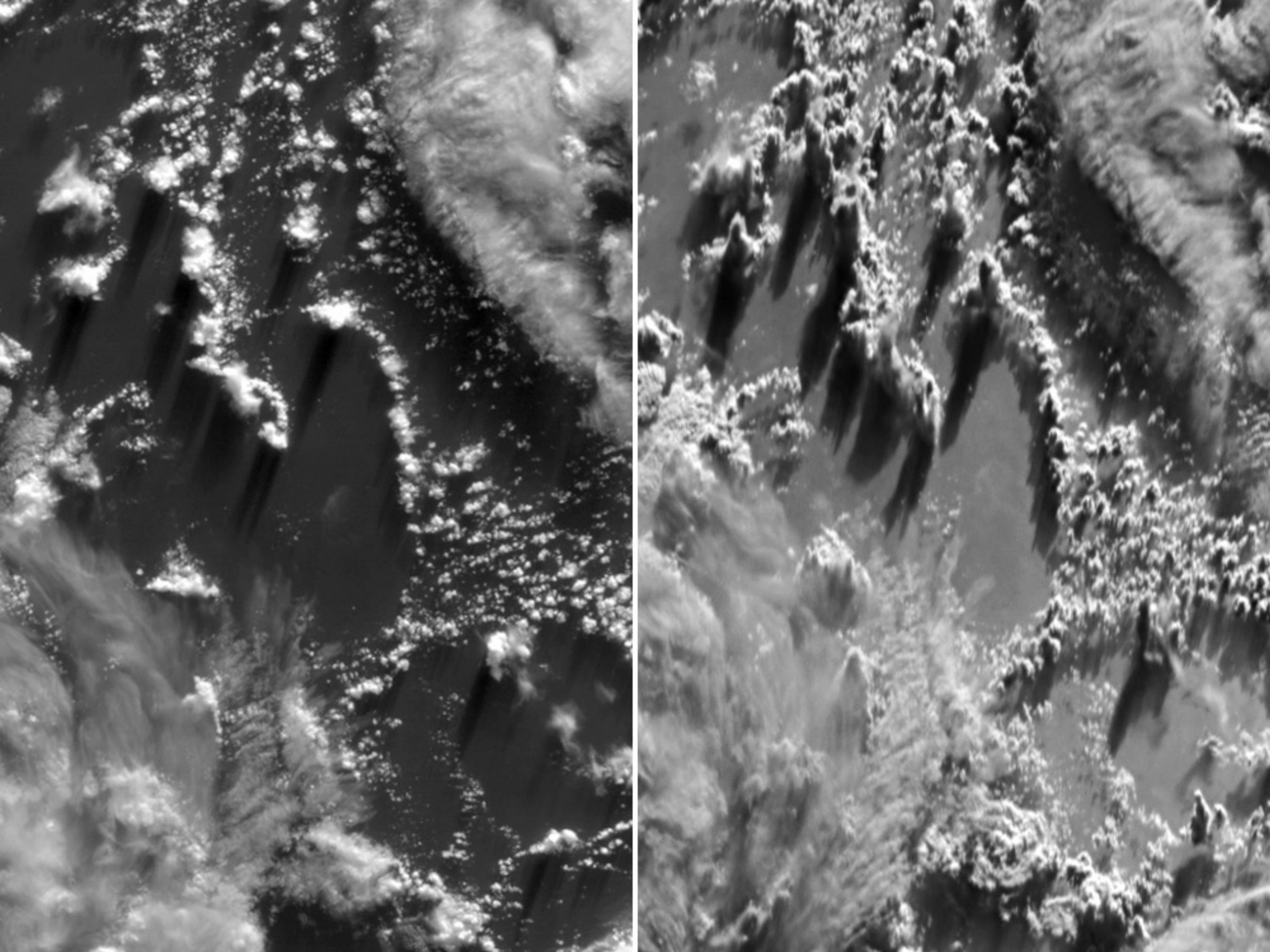
Our perspective on what are the most important feedbacks (e.g. low clouds or high clouds) is entirely a function of what is considered the 'system' and its defining output

Stephens and Ellis, 2008

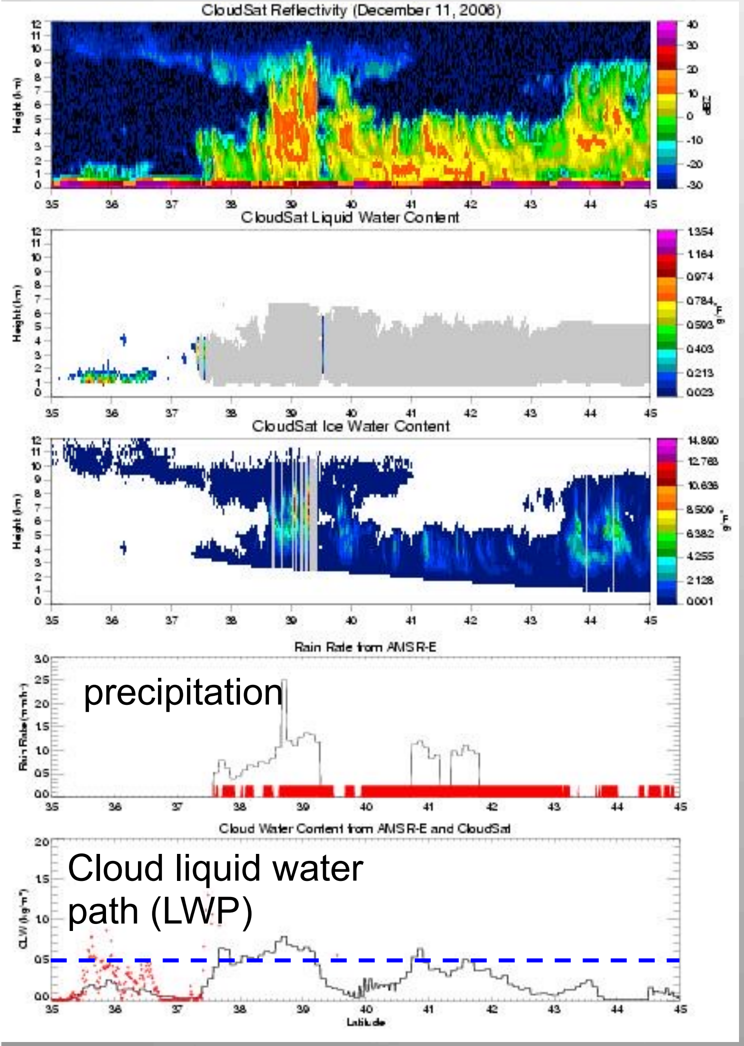
On the what (and why)

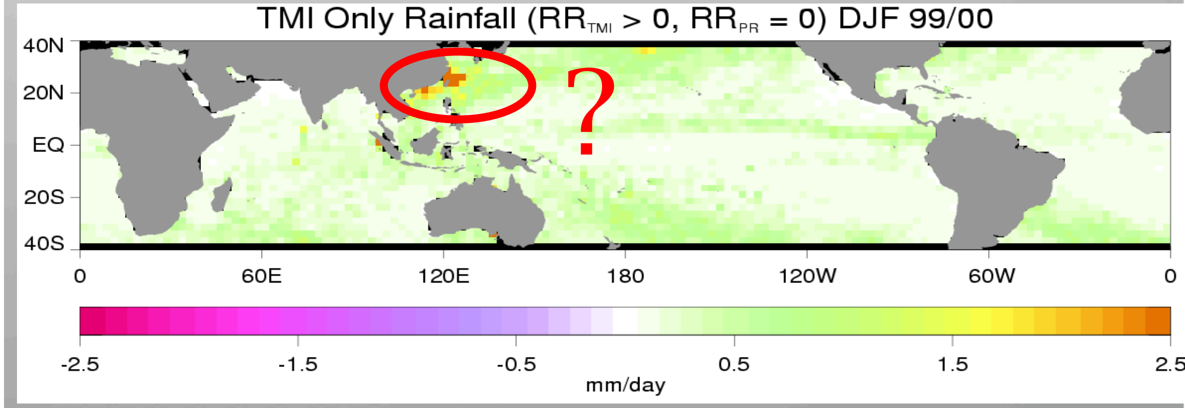
- Quantify the processes that determine where clouds and precipitation form, how they form and how much is formed.
- Provide relevant information about the key parameters of these process





The challenge: is it raining or not?



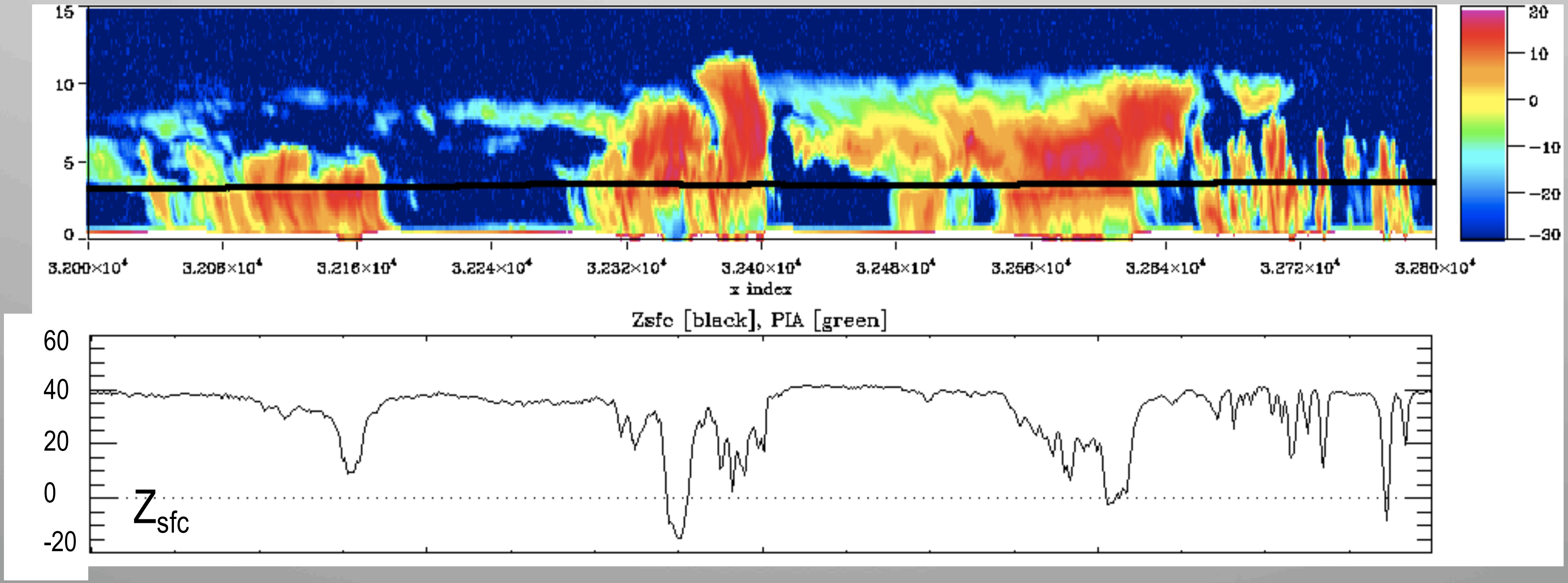


Berg et al., 2006

Precip incidence (and amount) from Path Integrated Attenuation (PIA)

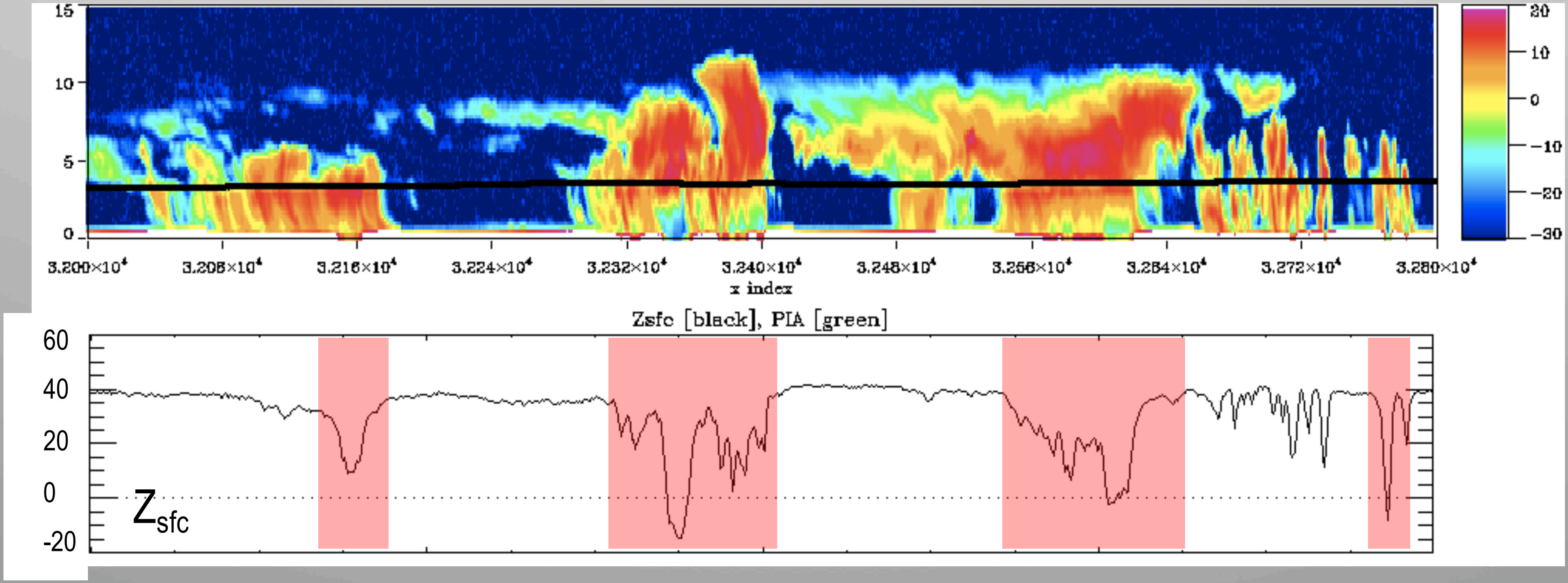
- The PIA within a raining column can be estimated by the decrease in surface reflectivity from the clear sky background value:

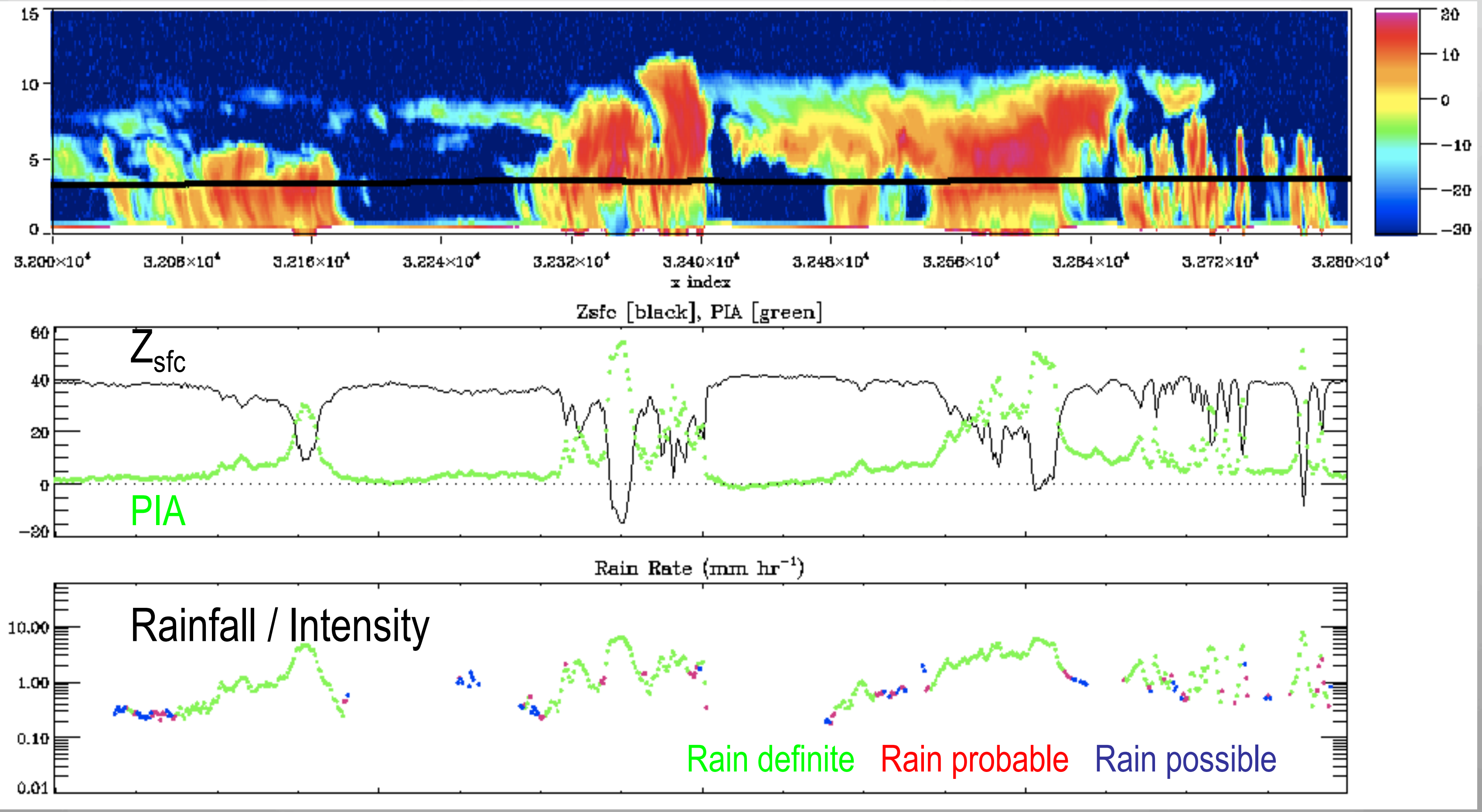
$$PIA = Z_{sfc,clear} - Z_{sfc,obs}$$



$$PIA = Z_{sfc,clear} - Z_{sfc,obs}$$

Surface reflectivity can be 'easily' deduced over oceans

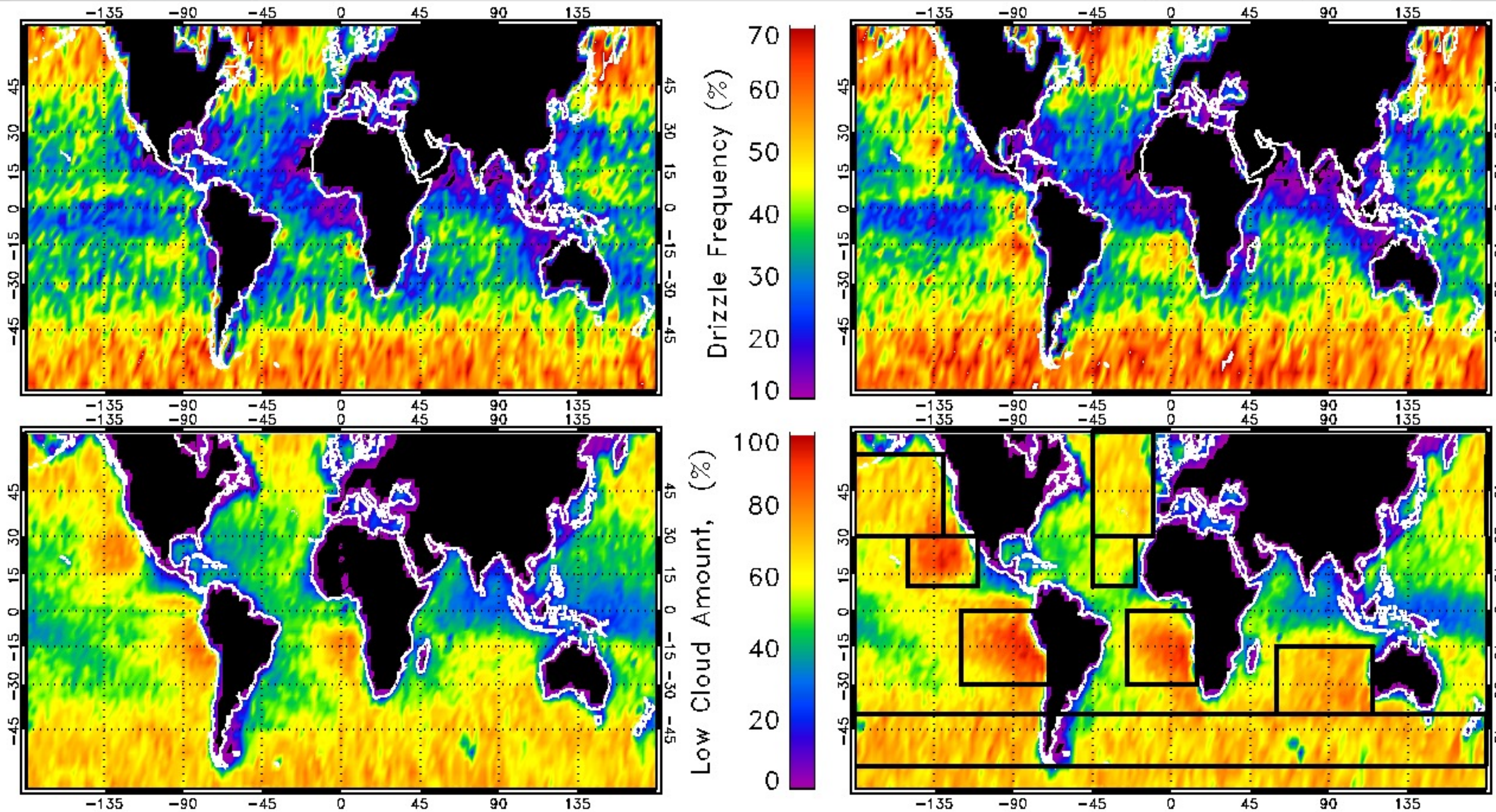




Extremely sensitive detector of rain - ~0.02 mm/hr

Low cloud -drizzle frequency

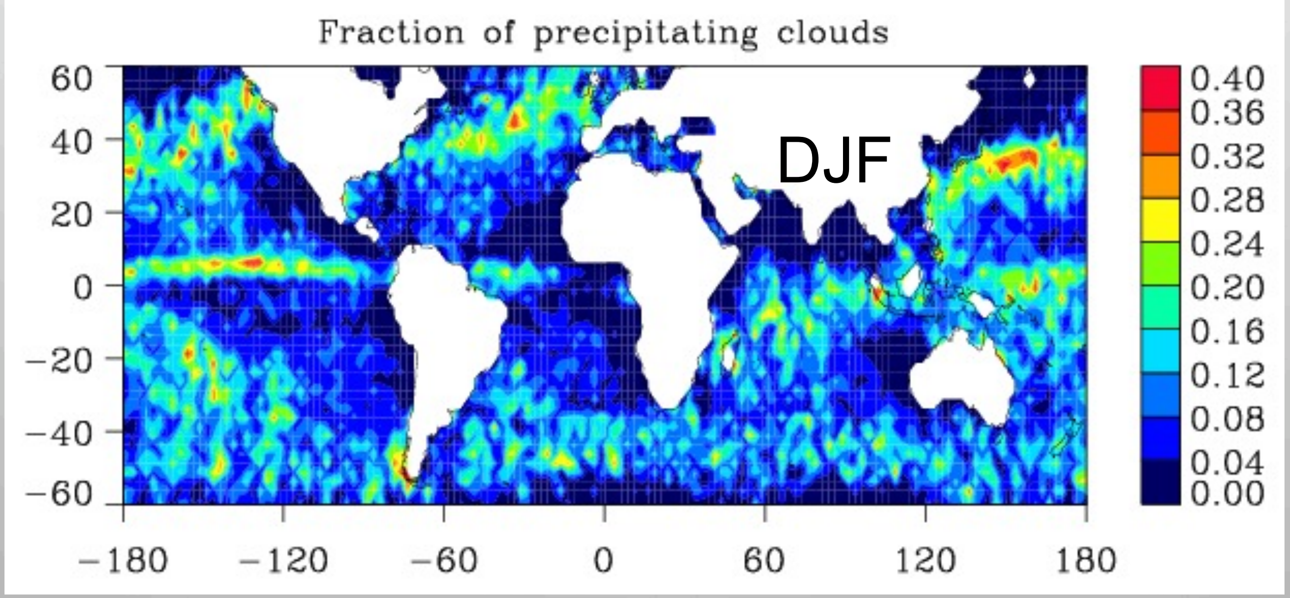
Day Night



Zhien et al., 2008

How Often Does it Rain (Over the Oceans) ?

The Fraction of Oceanic Clouds That Precipitate

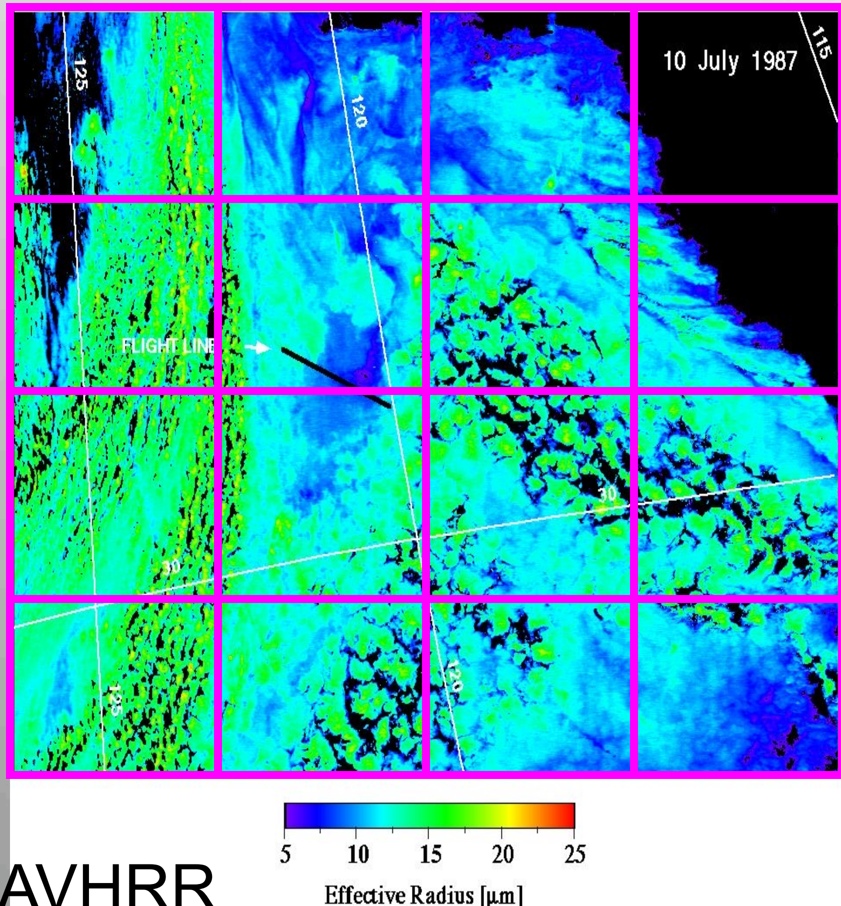


The global mean (oceans) value is ~0.13, i.e., on average, about 13 percent of the clouds observed over our oceans at any time are producing rain.

Stephens et al., 2008

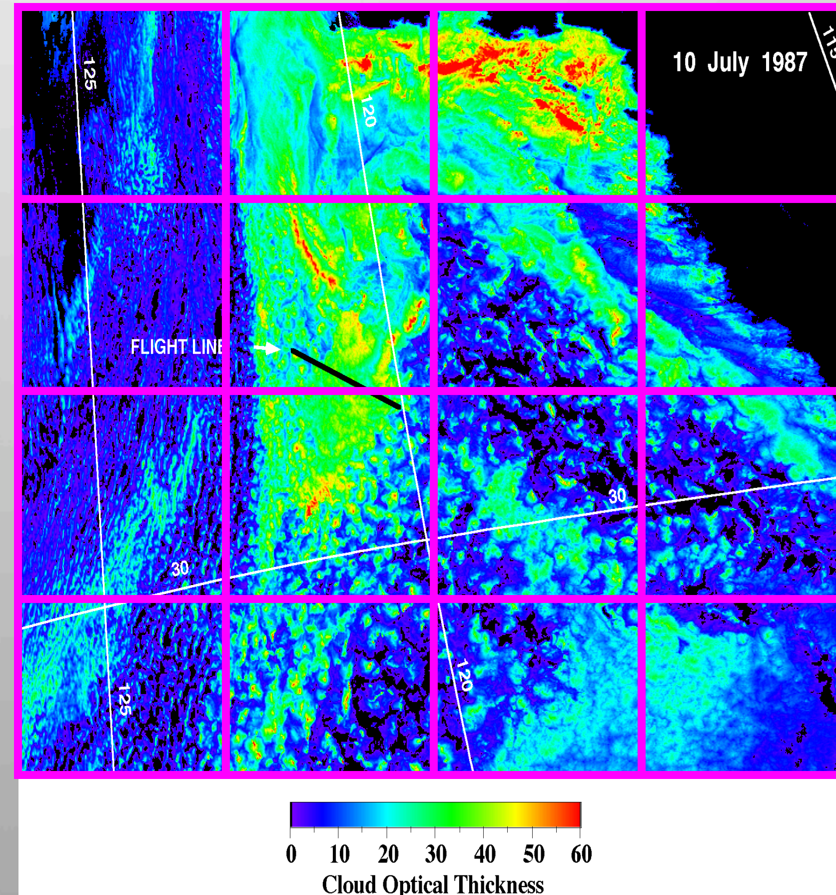
water cloud optical properties

Effective Radius



AVHRR

Optical Thickness

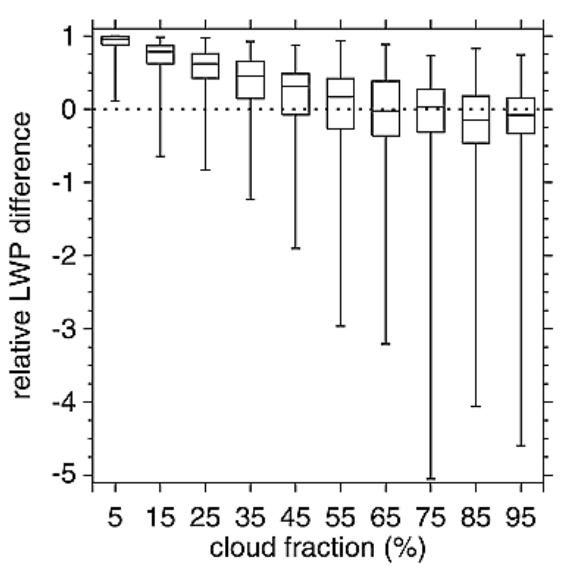


Nakajima and Nakajima (JAS 1995)

Do VIS/NIR and PMW estimates of LWP agree?

• Horvath & Davies (2007) find similar good agreement for TMI LWP versus MODIS (Terra), in general. However, they see a positive bias in the TMI LWP relative to MODIS (Terra) for partially cloudy scenes, that increases with decreasing cloud fraction. For clear scenes, the bias is +15 g/m^2.

• Greenwald et al. (2007) find a smaller positive bias (+ 7 g/m^2) for AMSR-E relative to MODIS (Aqua), that is a strong function of wind speed and water vapor path (worse at lower wind speeds and higher WVPs).



This is possibly due in part to the "beam-filling effect", and will remain in the Wentz product until a beam-filling correction is instituted for non-raining scenes.