Examining Cloud Structure and Cloud Radiative Forcing in Large-Scale Regimes

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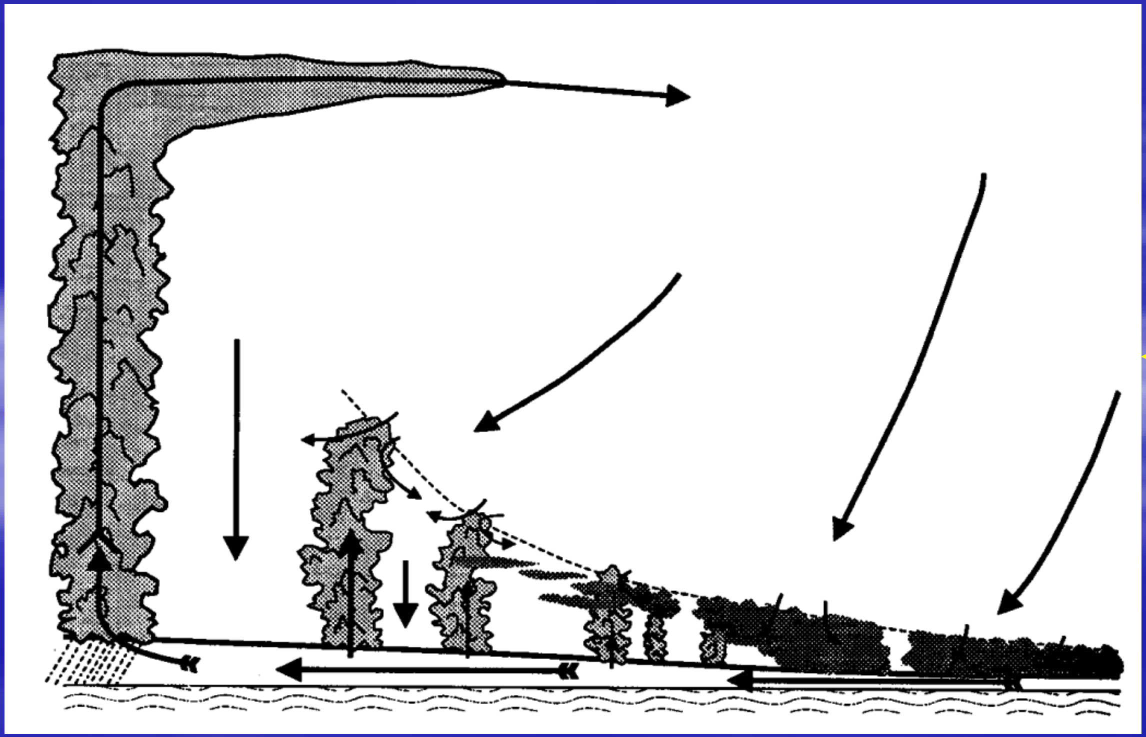
Acknowledgements: Vincent Perun[1]

-Keck Institute for Space Studies Cloud-Climate Feedback Workshop, September 8, 2009-

Background

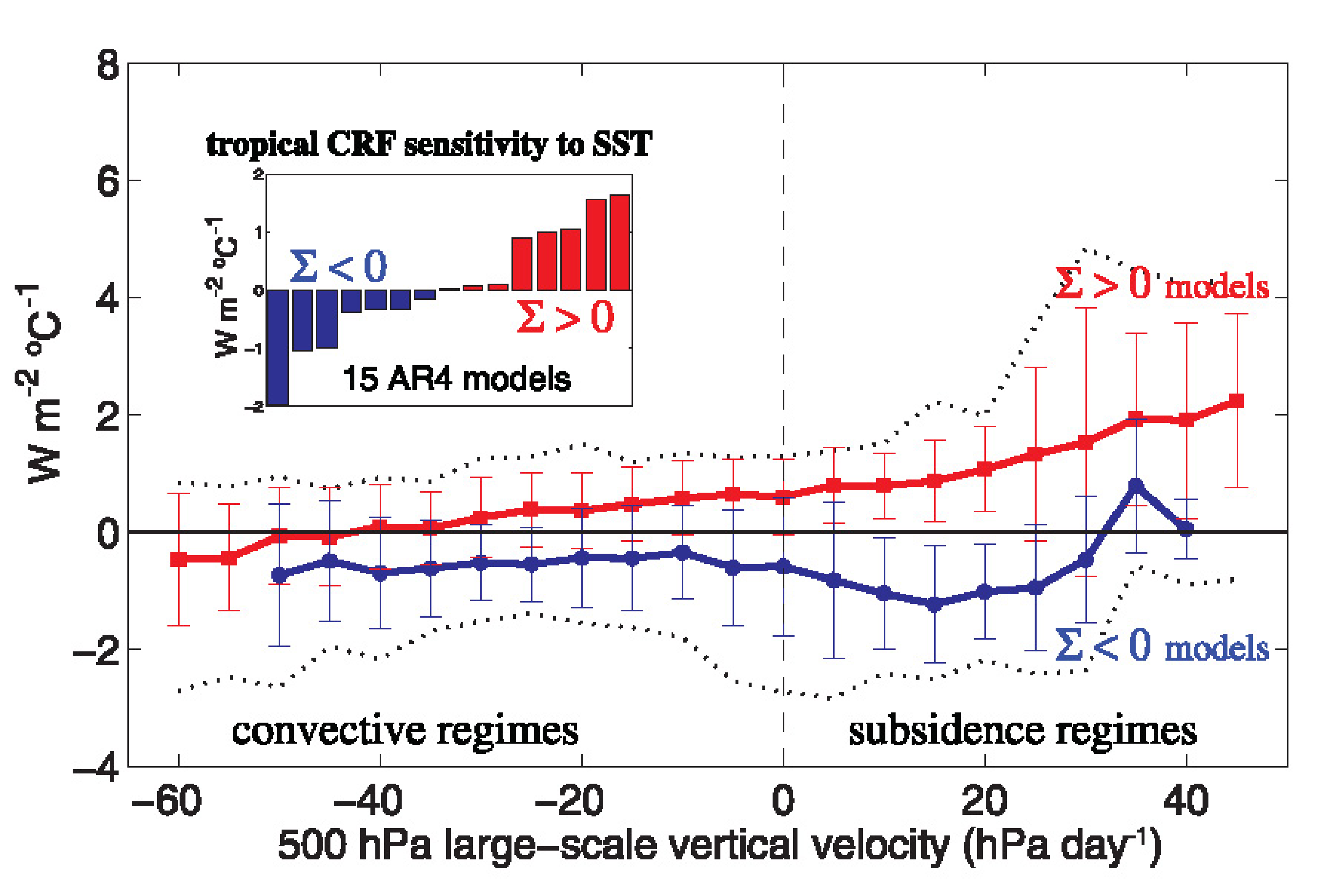
- Clouds are sensitive to large-scale circulation and atmospheric thermodynamic conditions.
- Accurate representation of clouds in large-scale models relies on a better understanding of cloud variations in large-scale regimes.



Quantification of this picture is now possible with new satellite observations.

From Emanuel (1994)

"The Bony-gram"



IPCC AR4, from Bony and Dufresne (2005)

Objective

- Provide a comprehensive view of cloud distributions in large-scale regimes using new satellite observations.

- Evaluate climate model simulations using the observations.

Data and Models

Observations:

- CloudSat ice and liquid water content (CWC=IWC+LWC)
- AMSR-E sea surface temperature (SST) and water vapor path (WVP)
- QuikSCAT surface wind and TRMM precipitation
- AIRS temperature and water vapor (to derive Convective Available Potential Energy (CAPE) and Lower Tropospheric Stability, $\theta_{700hPa} - \theta_{surface}$)

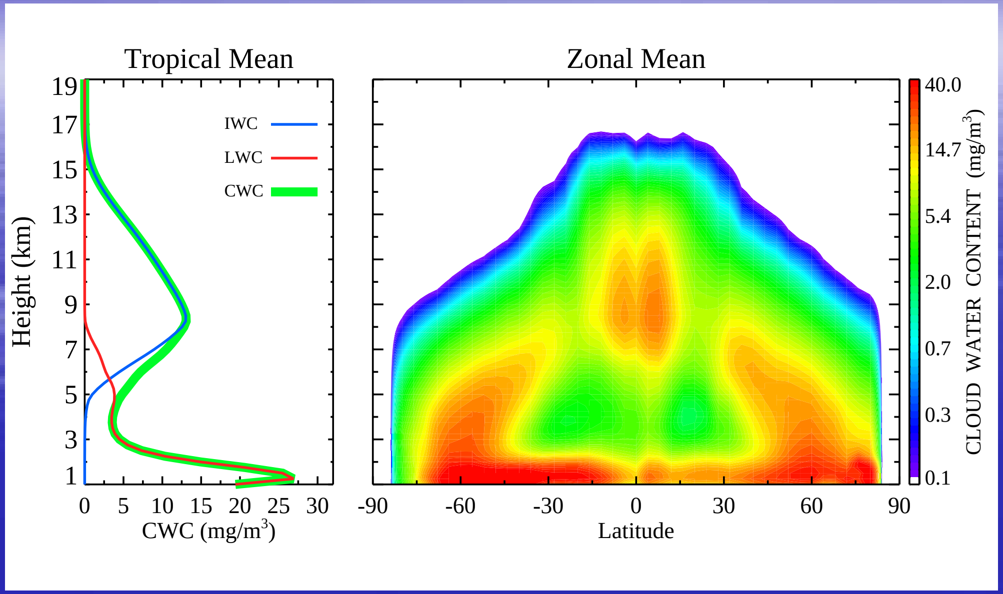
- NCEP/GEOS-5 Analysis of ω_{500hPa}

Models

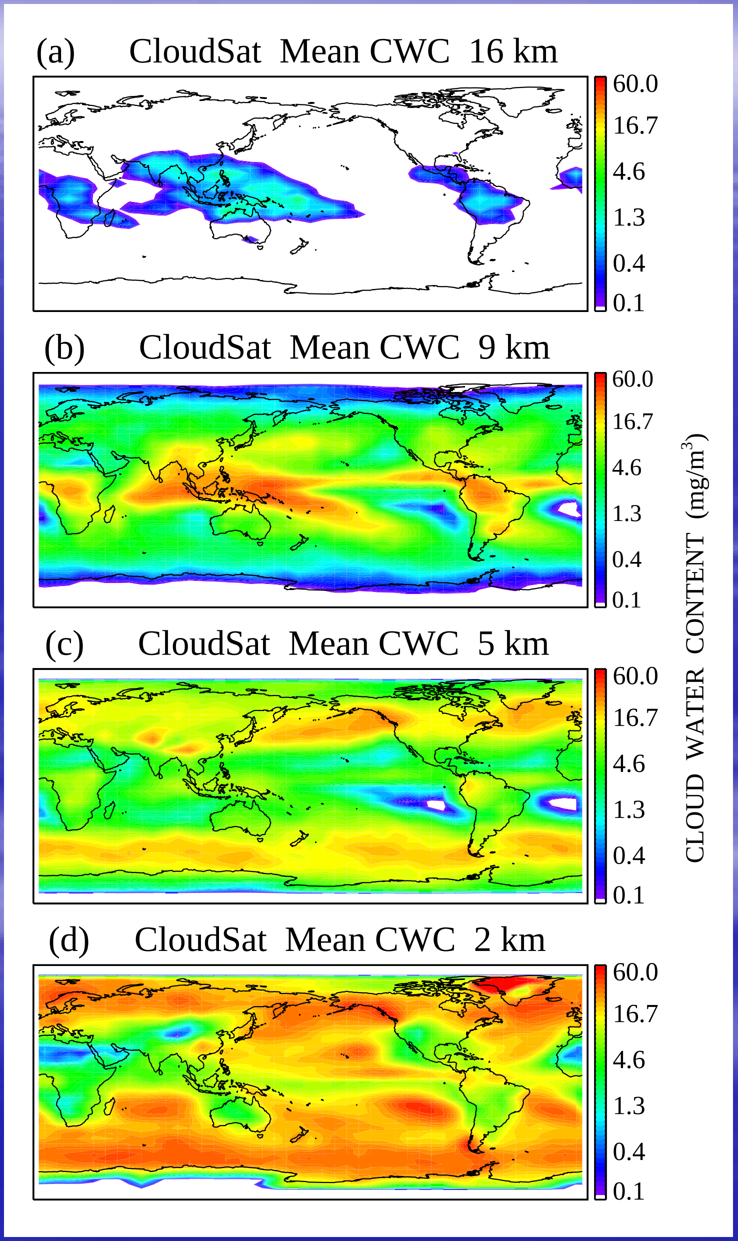
- GMAO GEOS5 analysis
- NCAR CAM 3.5
- GFDL AM2

Major work: Interpolate all variables on CloudSat tracks (over 2 TB of data)

Annual-mean Observed Cloud Water Content

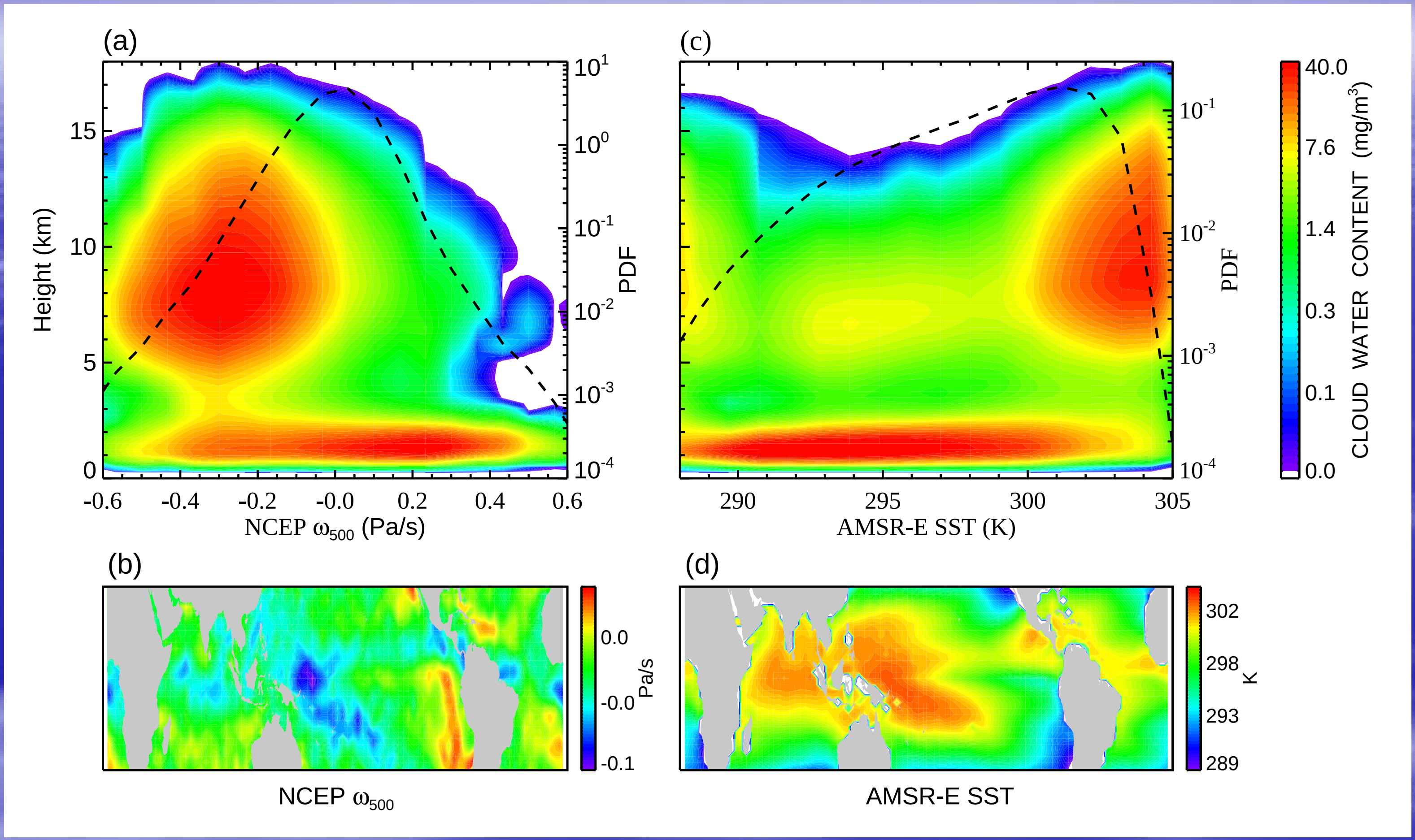


- Double peaks in tropical CWC profile, one at ~8 km (IWC) and the other at ~1.5 km (LWC)
- CWC is high over the mid-latitude storm tracks
- Liquid and ice clouds have different preferred geographical regions.
- Low clouds concentrate over eastern Pacific, south Indian Ocean, North Pacific and Atlantic, and mid-latitude storm tracks.
- High clouds are over western Pacific, Indian Ocean, South America and central Africa.



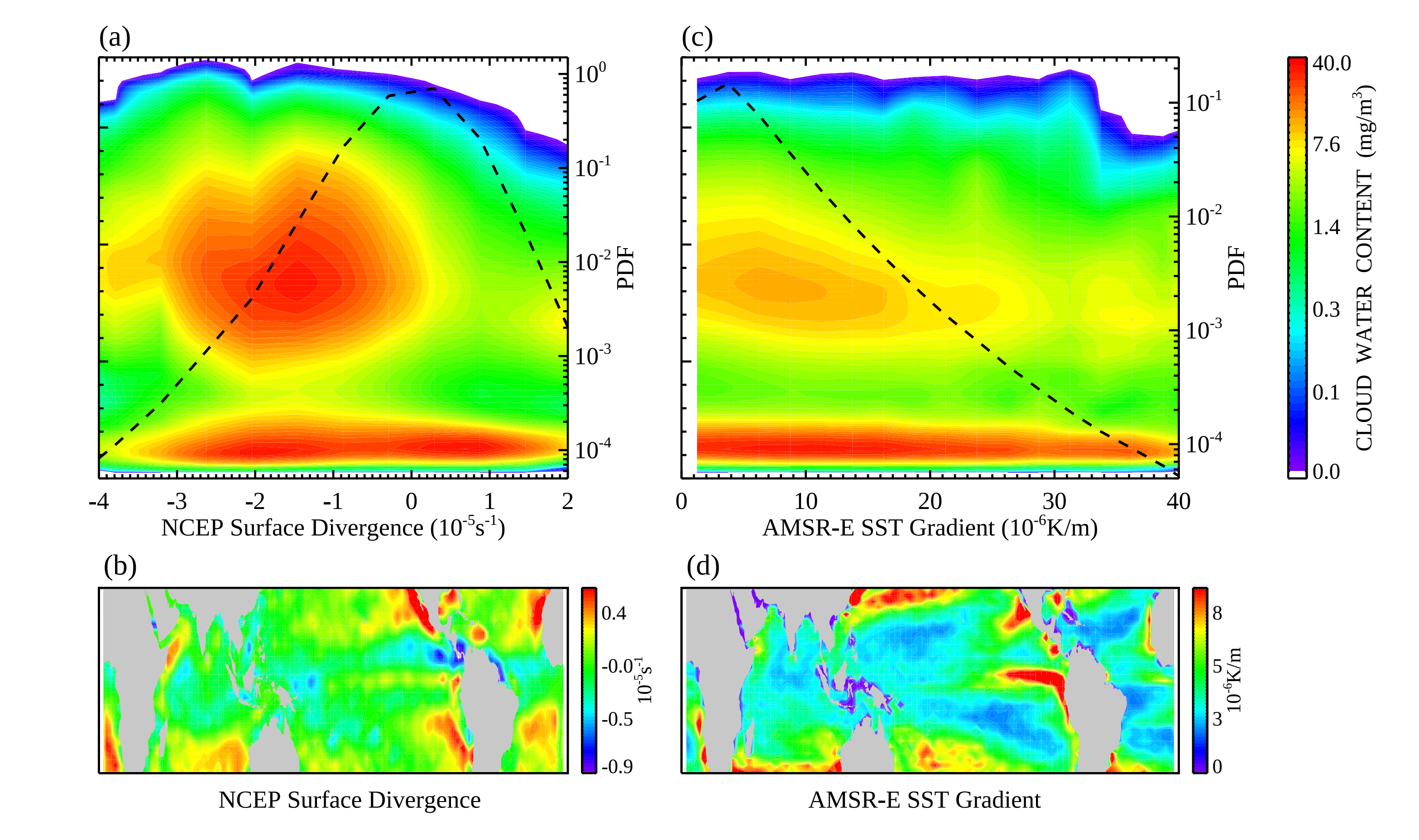
From Su et al (2008, GRL)

CWC Sorted by ω_{500} and SST



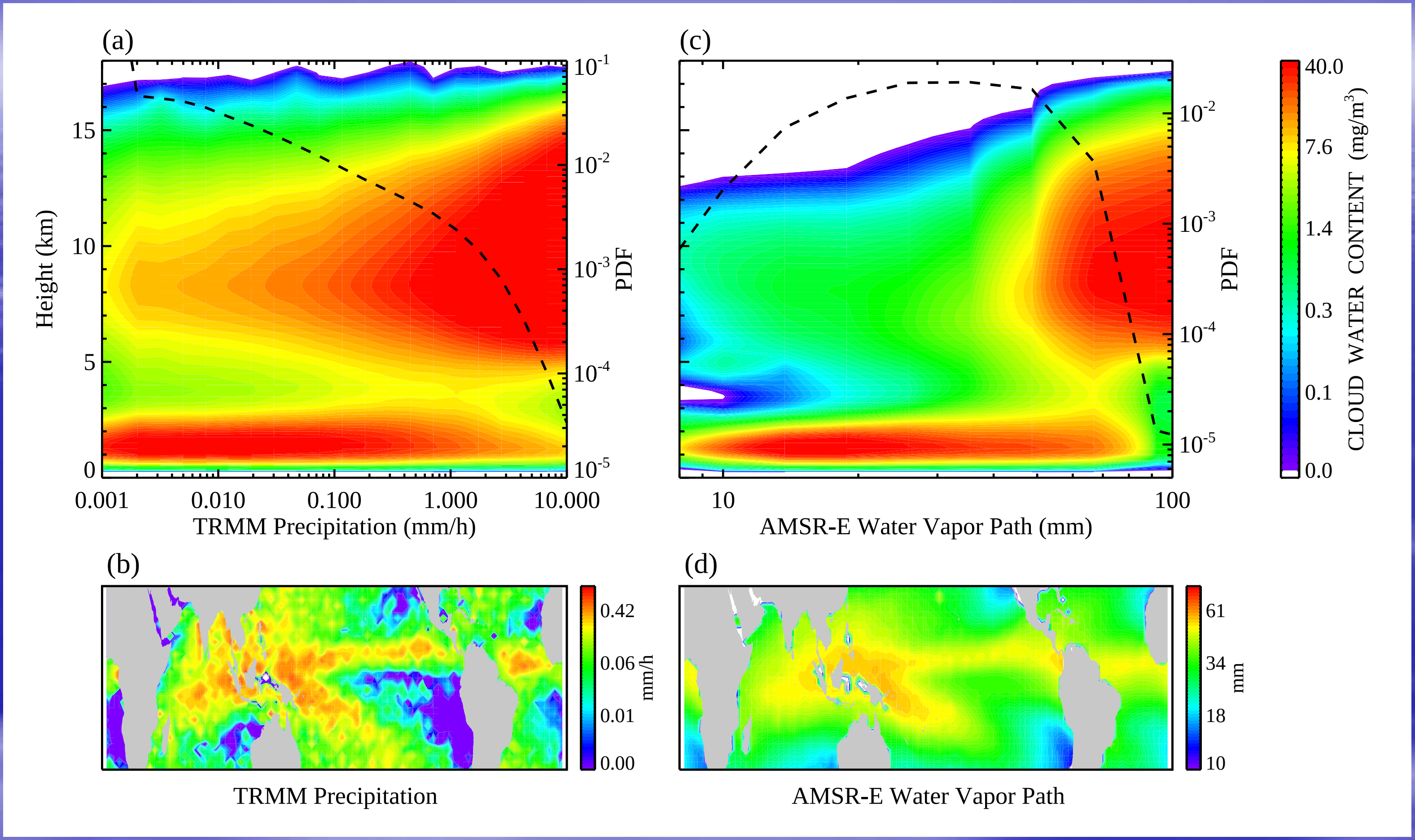
- Deep convective clouds are clustered in large-scale upwelling and high SSTs.
- Shallow clouds are over large-scale subsidence and colder SSTs.
- Infrequent high clouds over colder SSTs may be due to detrainments and the influence of extra-tropical storms.

CWC Sorted by Surface Divergence and SST Gradient



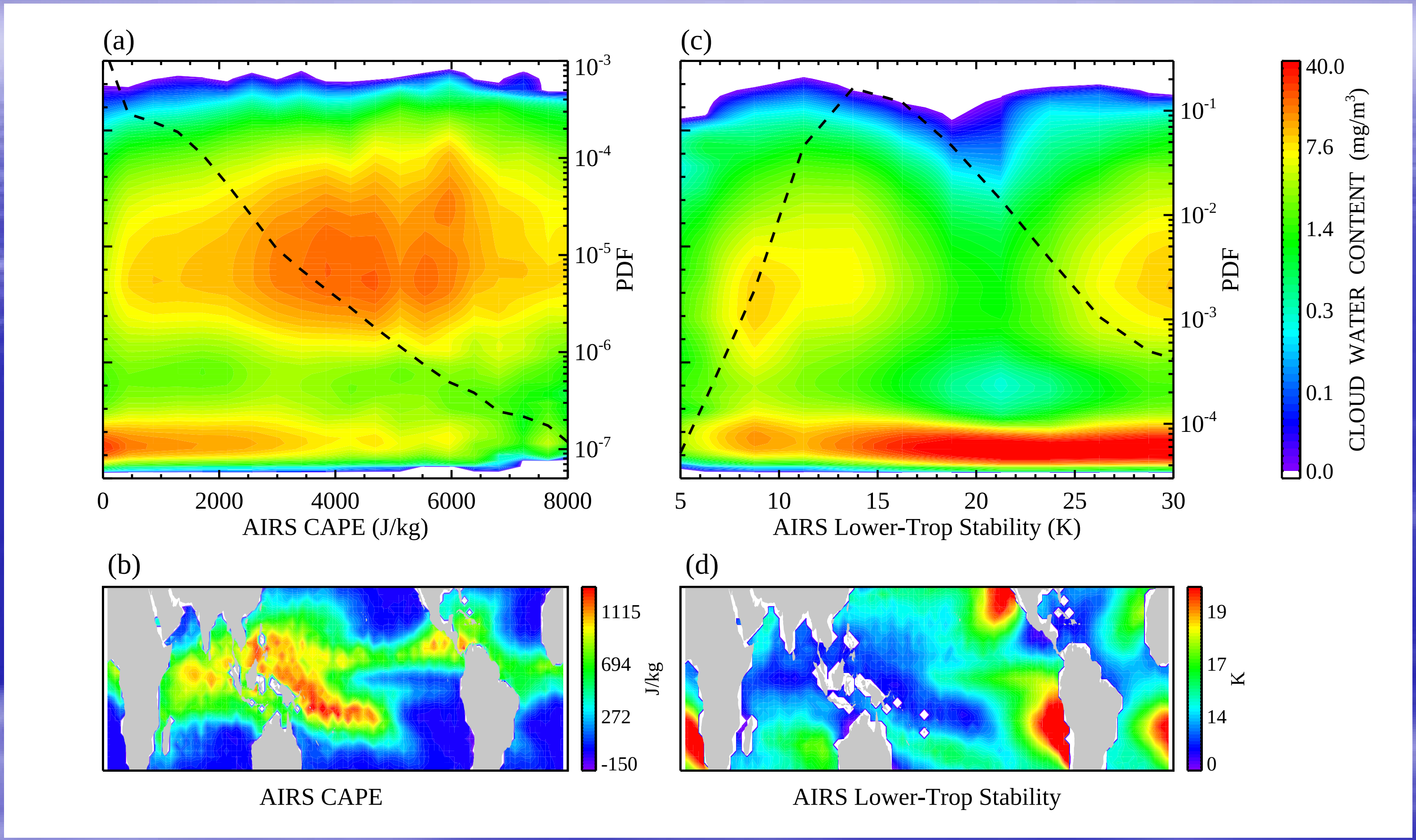
- High clouds are over surface convergent and weak SST gradient regions.
- Low clouds are over surface divergent and strong SST gradient regions.
- Some hints of mid-level clouds over surface divergent and strong SST gradient regions, maybe a result of advection of convective detrainments.

CWC Sorted By Precipitation and Water Vapor Path



- Heavy precipitation is from deep clouds. Only 15% of precipitating clouds have surface rain rates >= 2 mm/h, but they contribute to 55% of tropical rainfall.
- Deep clouds occur in moist air columns while low clouds are associated with drier air. Moist air columns with WVP >= 50 mm have only 0.3% occurrence frequency, but they contain 57% of total precipitable water.

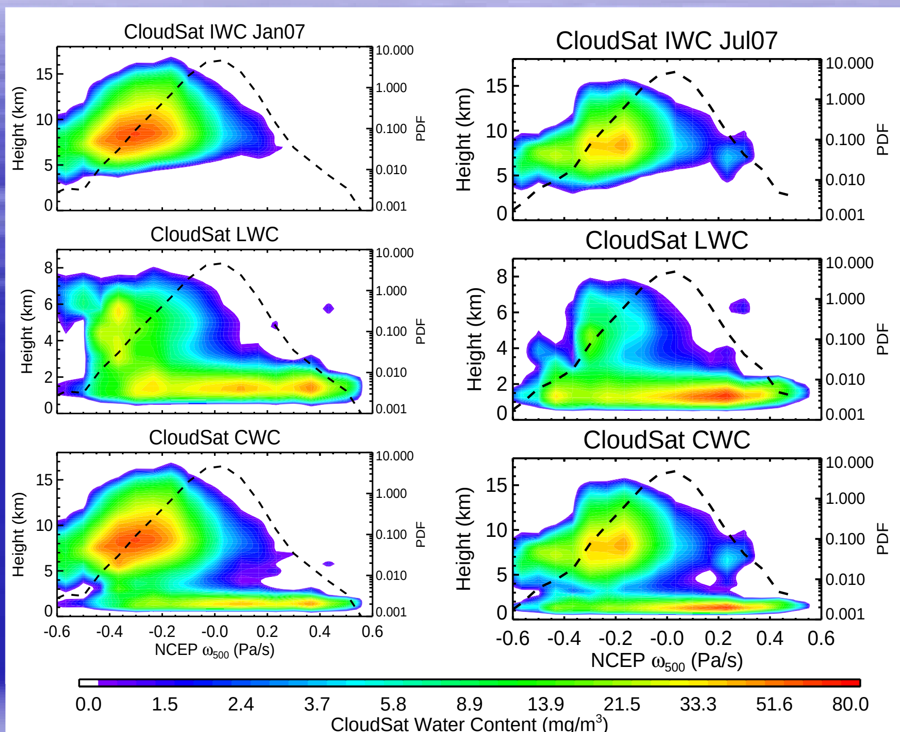
CWC Sorted by CAPE and LTS



- CAPE resembles deep convection pattern. High clouds are over high CAPE regions. Low clouds are more towards the lower CAPE regions.
- LTS is nearly a “complement” of CAPE.
- Shallow clouds are over higher LTS regions than high clouds. Infrequent high clouds exist at very high LTS values.

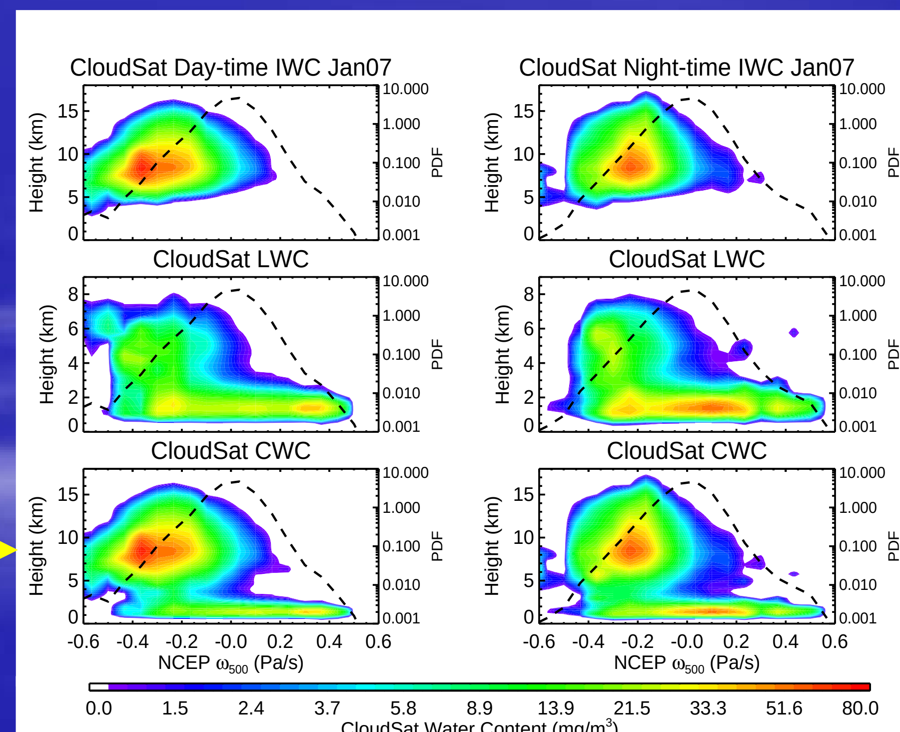
Seasonal and Day-Night Differences

January **July**



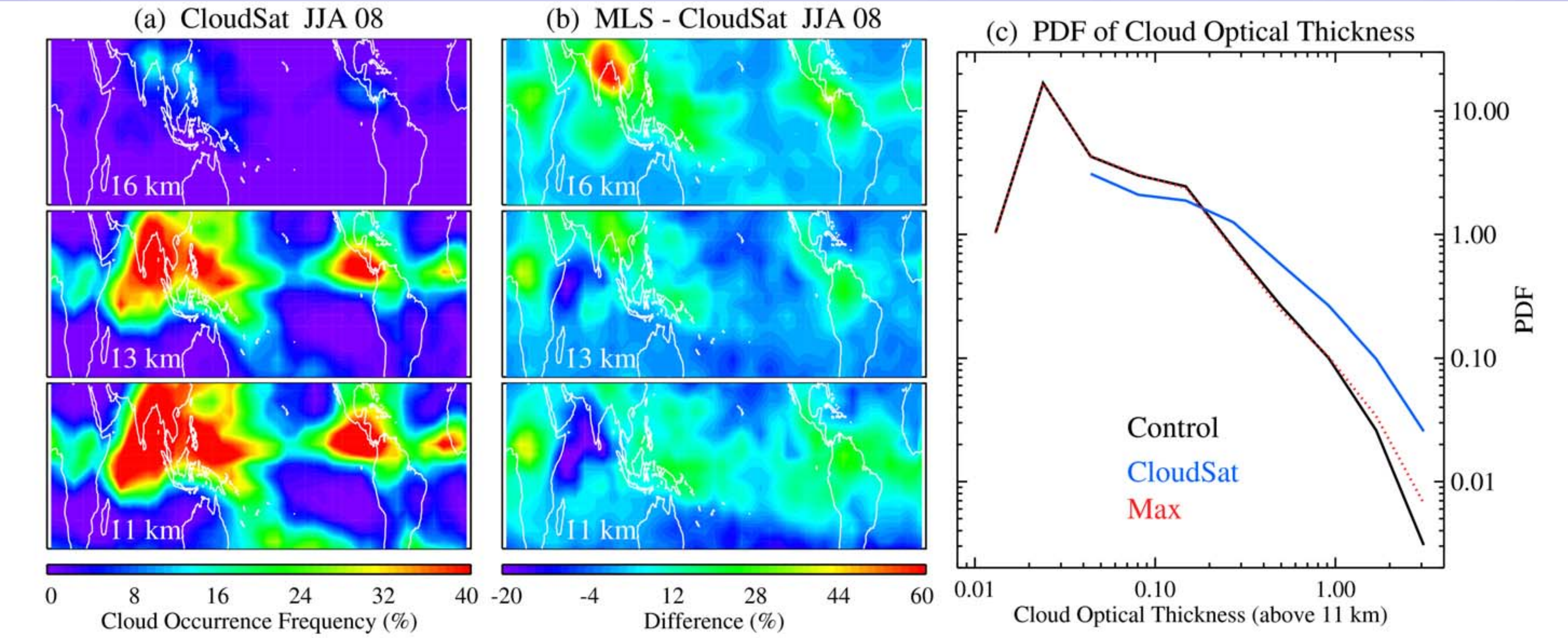
- Larger LWC in July than in January.
- Larger IWC in January than in July.

Day **Night**



- Larger LWC at night than in the day.
- Larger IWC in the day than at night.

Combining Cloud Observations From Multiple Sensors

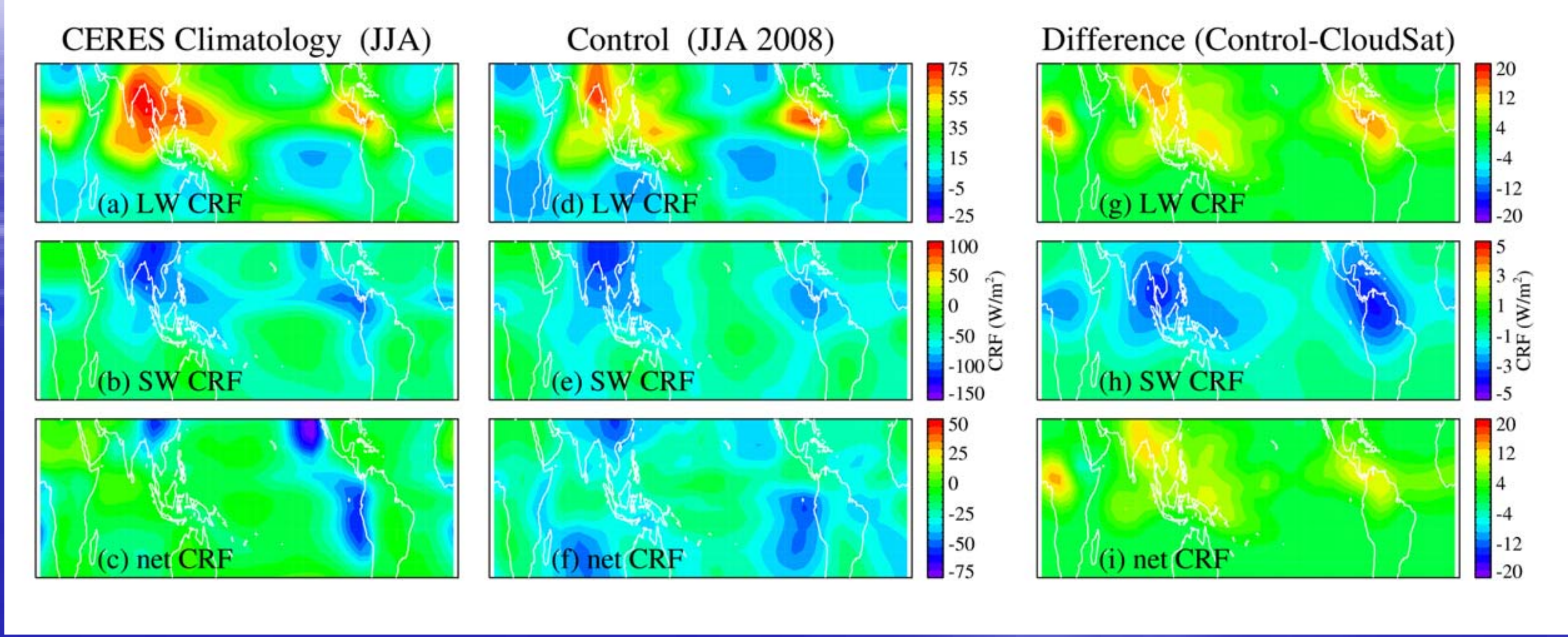


- The cloud occurrence reported by CloudSat is about 10% less than MLS near the tropopause in the tropical average and is about 60% lower in South Asia monsoon region.

- The thin cirrus clouds captured by MLS but missed by CloudSat mostly have visible optical depth ranging from 0.01 to 0.2.

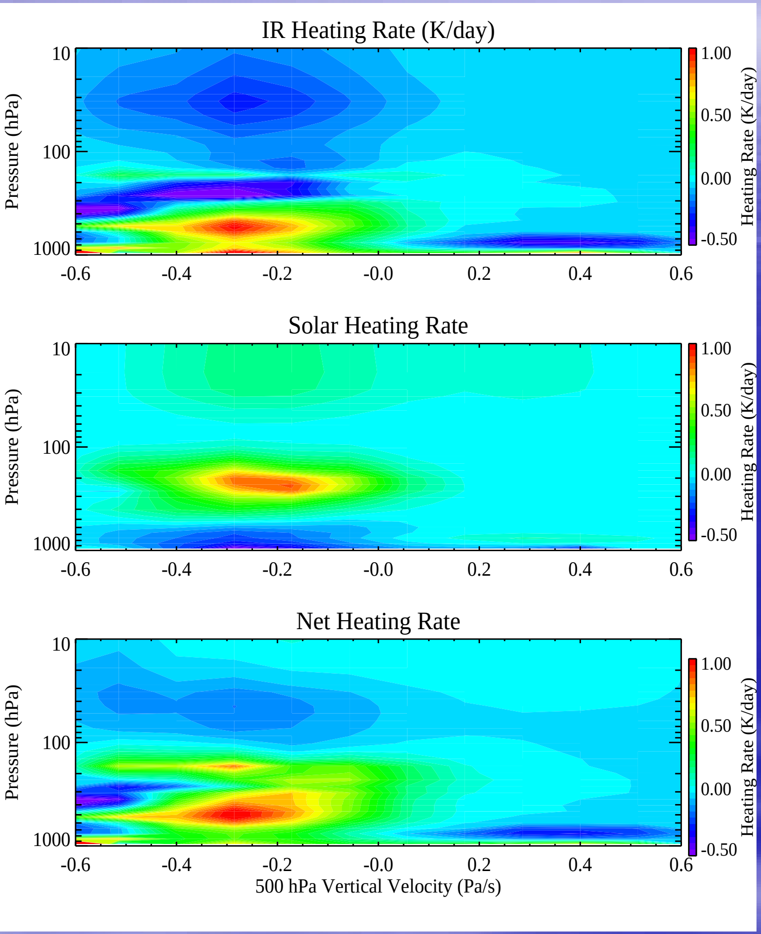
From Su et al. (2009, GRL)

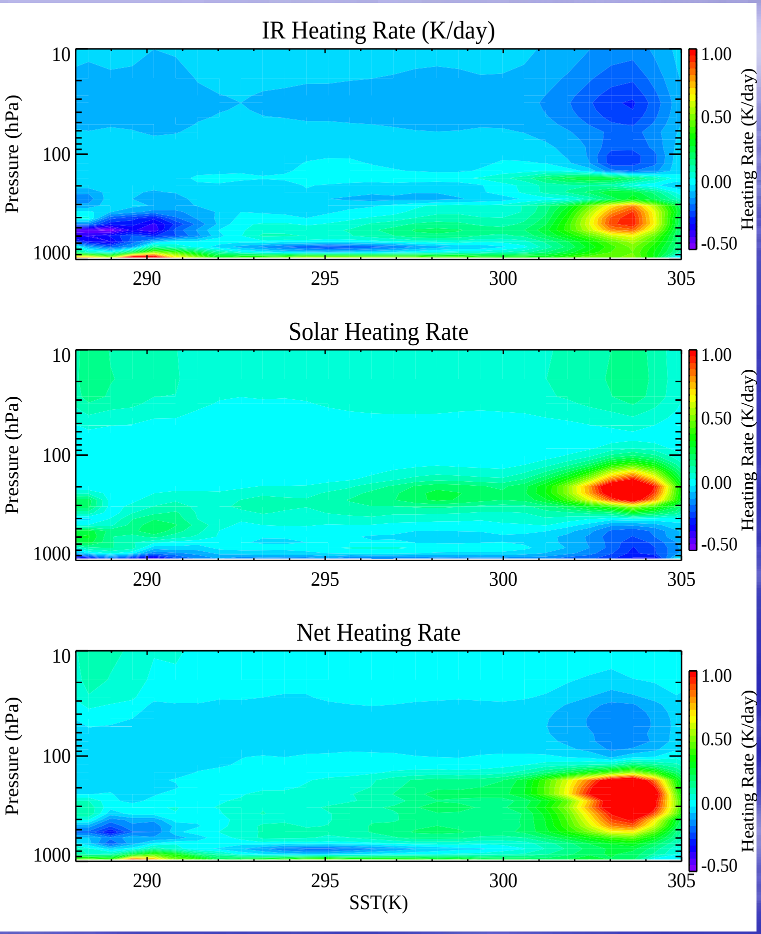
Cloud Forcing Difference Using CloudSat and MLS Cloud Measurements



	Observations (ISCCP)	Control Run (MLS+CloudSat)	CloudSat Only	Max of MLS/CloudSat
TOA-LW	26.6±5.0	21.7	17.0	22.8
TOA-SW	-48.0±5.0	-46.9	-45.7	-47.7
TOA-net	-21.4±10.0	-25.2	-28.7	-24.9
SFC-LW	18.9±10.0	8.3	8.2	8.4
SFC-SW	-50.0±10.0	-51.6	-50.3	-52.6
SFC-net	-31.1±20.0	-43.3	-42.1	-44.2

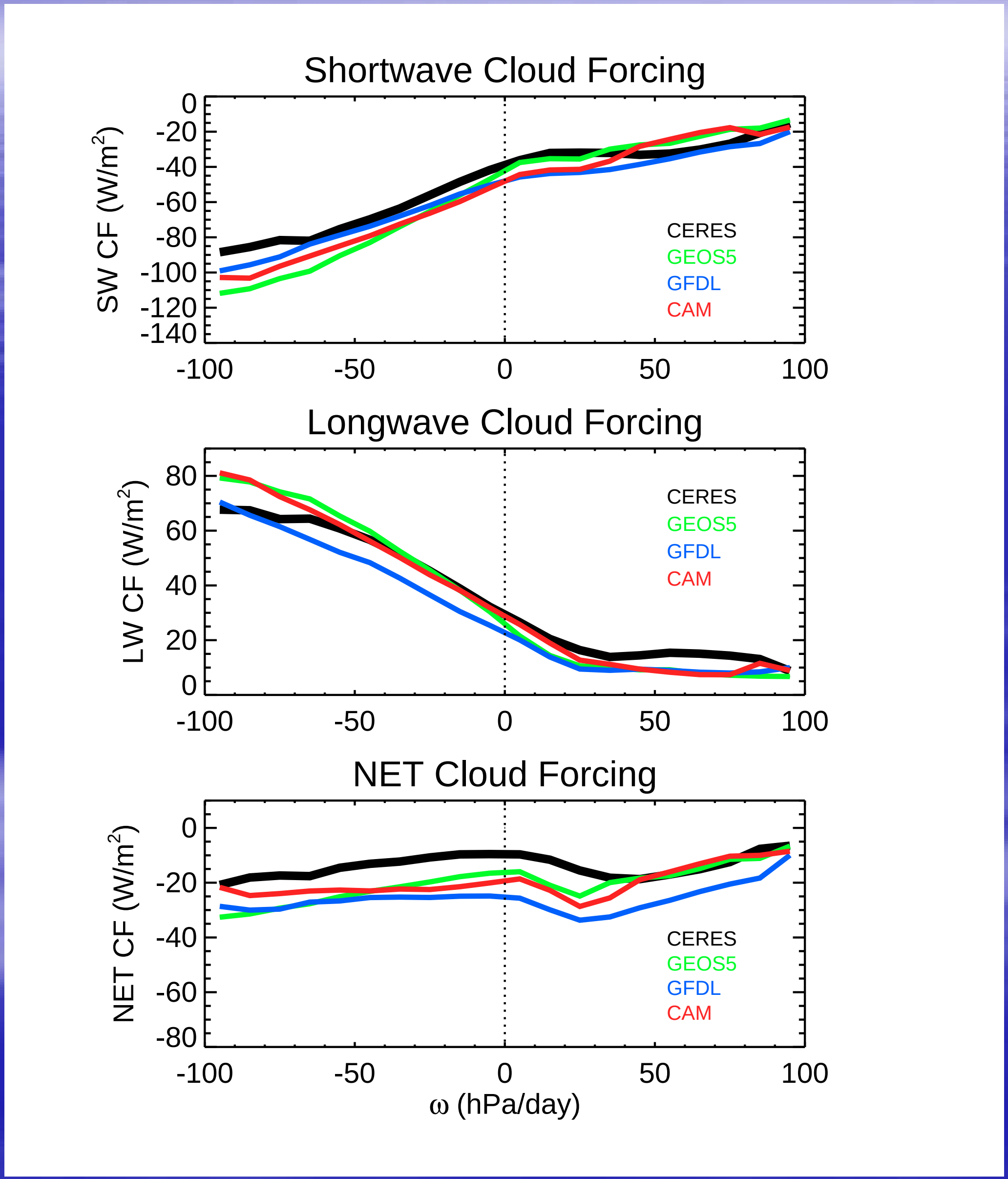
Cloud Heating Rate Variations in Large-scale Regimes





- Over large-scale upwelling and warm SST, a vertical dipole pattern of cloud radiative heating rate dominate.
- Over large-scale subsidence and cold SST, cloud cooling prevails in the atmosphere.
- The cloud radiative heating is particularly important in the tropical tropopause layer.

Comparison to Models – TOA Cloud Forcing

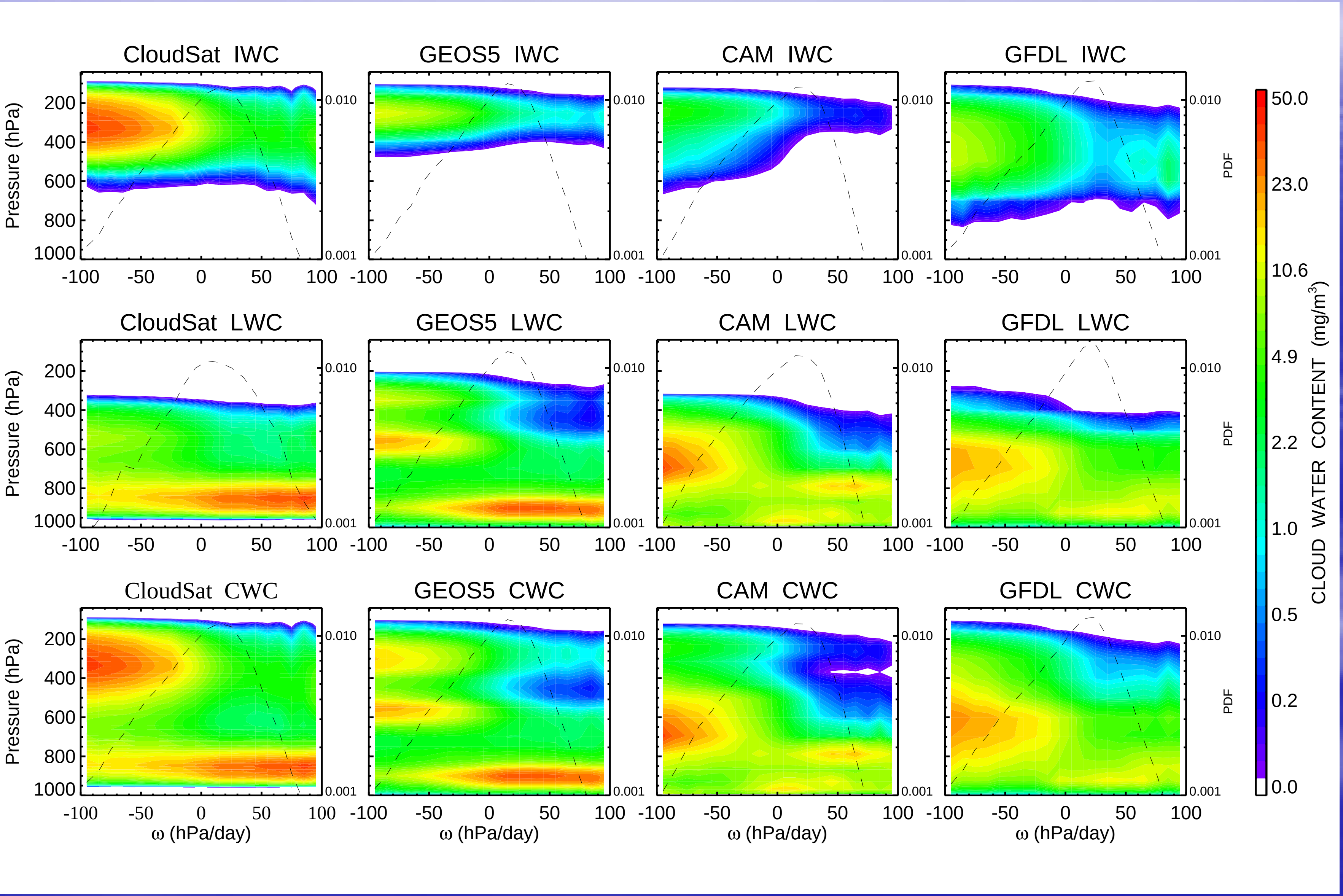


- CERES: 5-year (3/2000-10/2005) climatology EBAF
- GMAO GEOS-5: 2007 analysis
- NCAR CAM3.5: driven by climatological SST
- GFDL AM2: driven by observed SST (10/2006 – 9/2007)

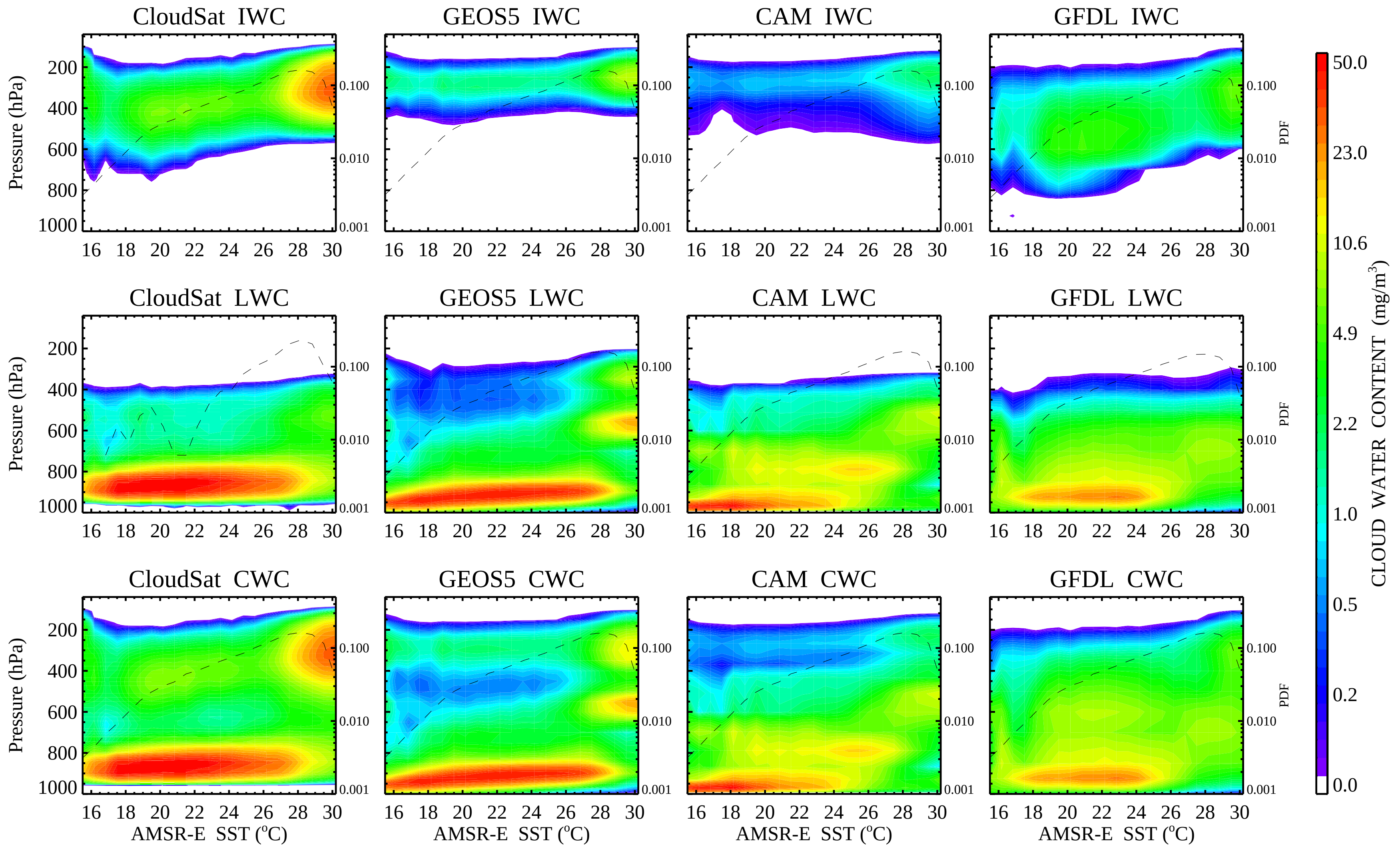
All model results are interpolated on CloudSat tracks and re-gridded on 2.5º (lon) x 2.0º (lat) grids.

✓ They agree fairly well!

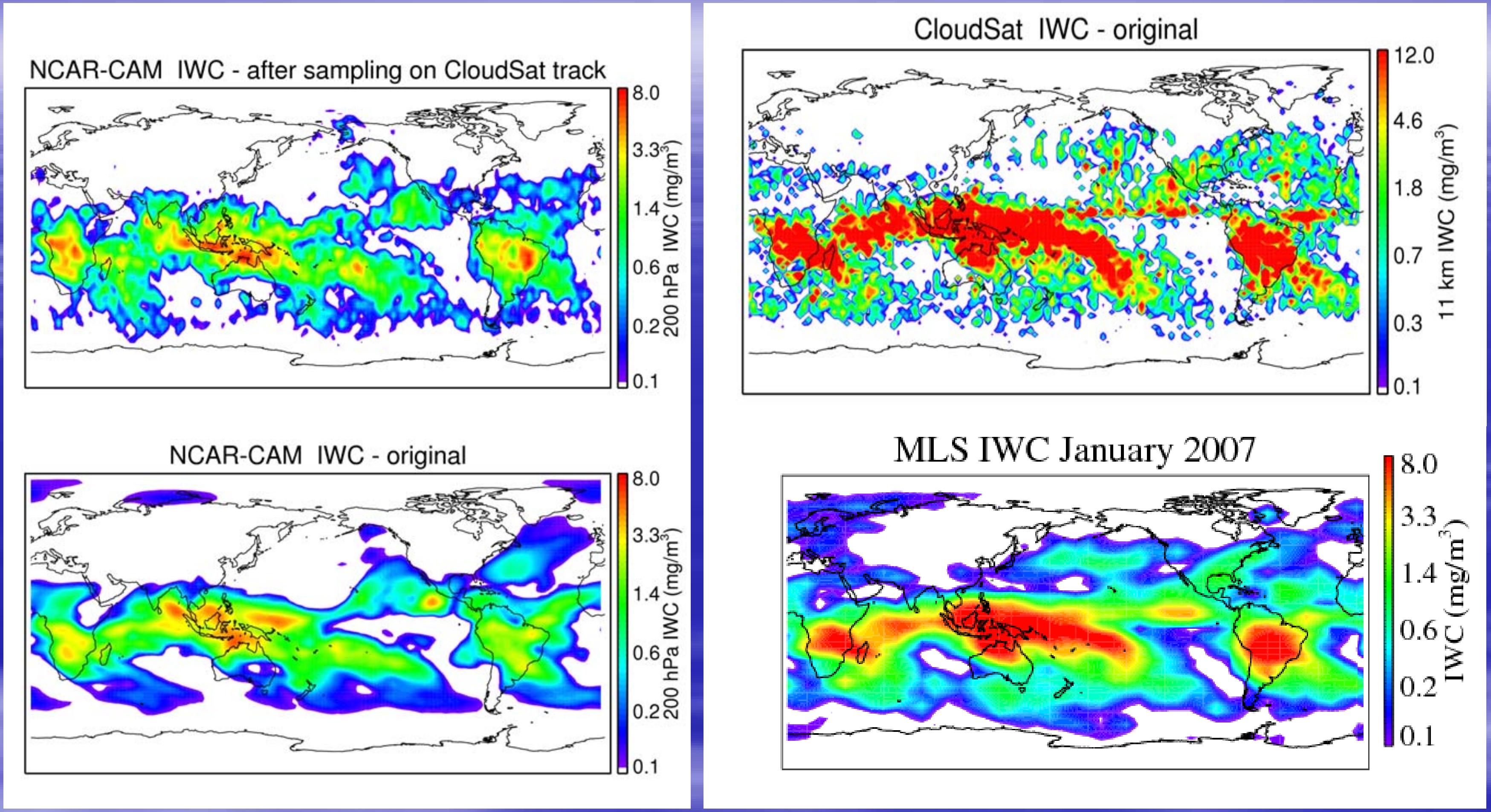
Comparison to Modeled Clouds Sorted by ω_{500}



Comparison to Modeled Clouds Sorted by SST



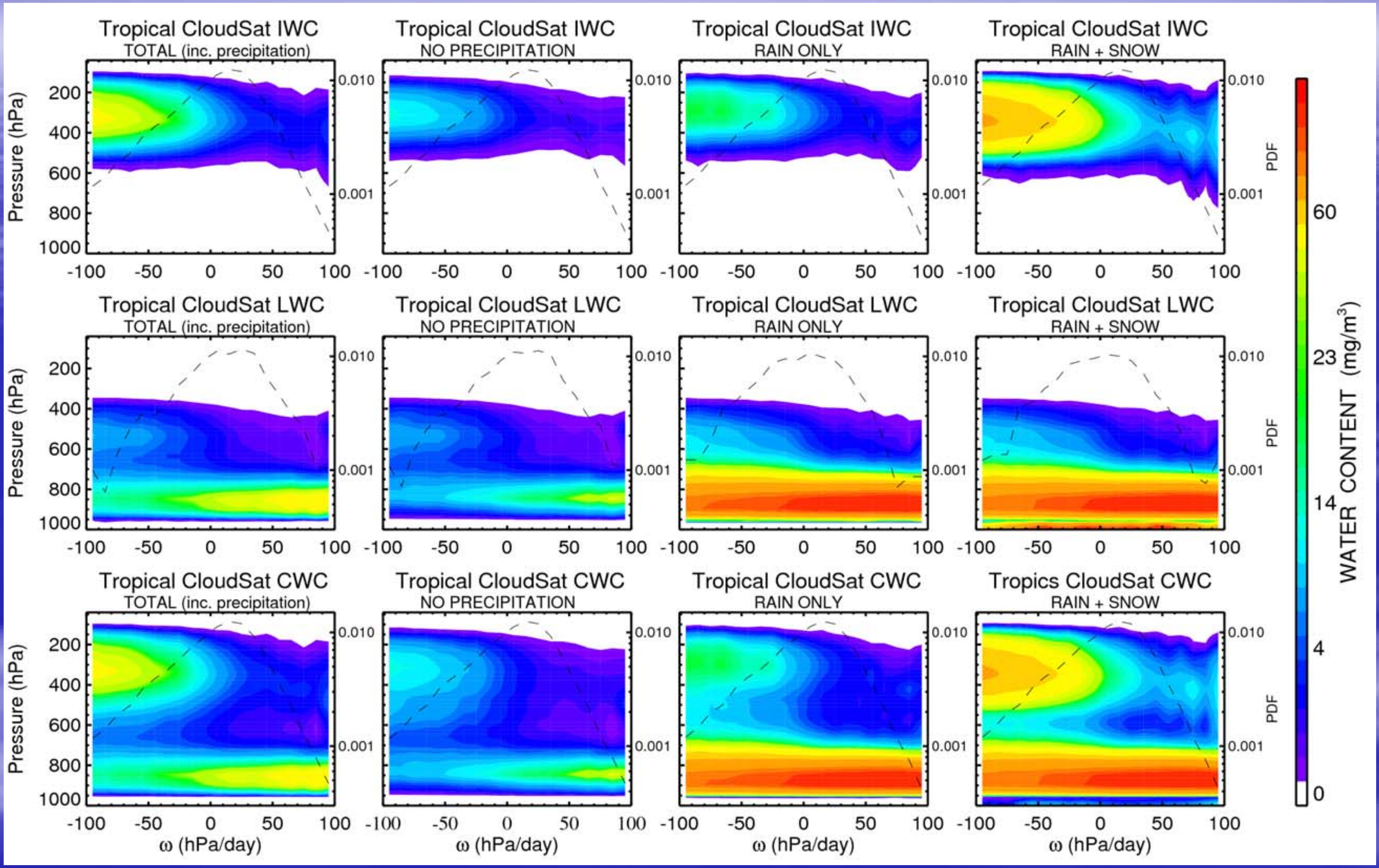
Consistent Spatiotemporal Sampling



- CloudSat observations are twice-a-day, ~1:30am and ~1:30pm. The gap between two ascending/descending orbits is about ~2000 km.

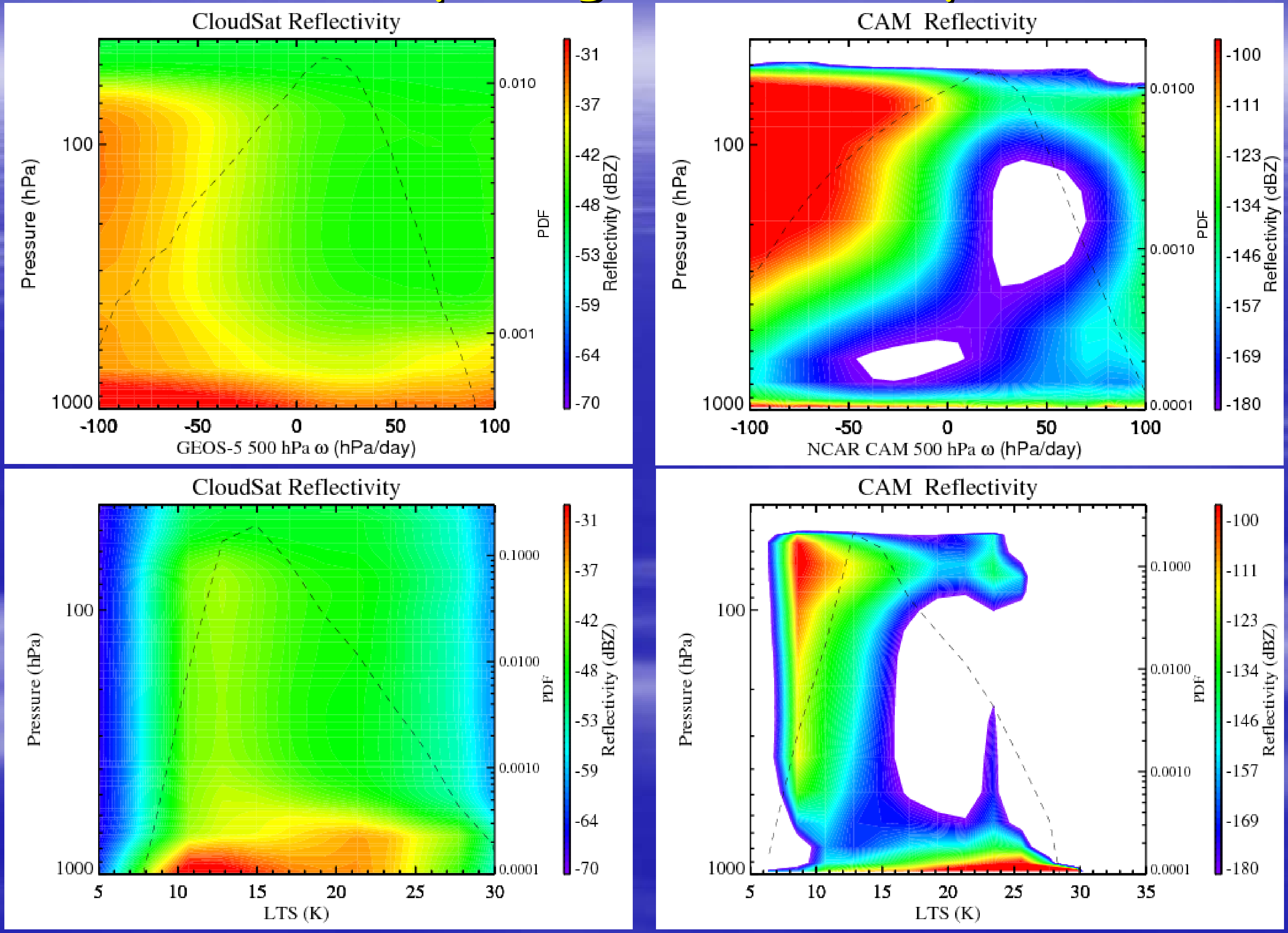
- Sampling models' 6-hourly outputs onto the CloudSat tracks in space/time makes the IWC/LWC over land much stronger – diurnal variability of clouds matters.

Separate Clouds Scenes By Precipitation Phases

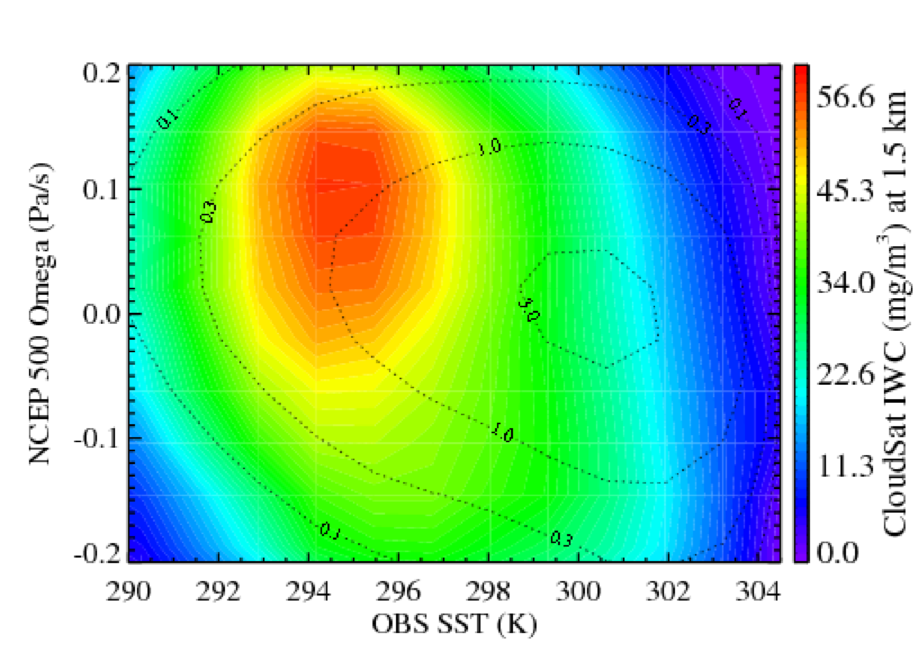


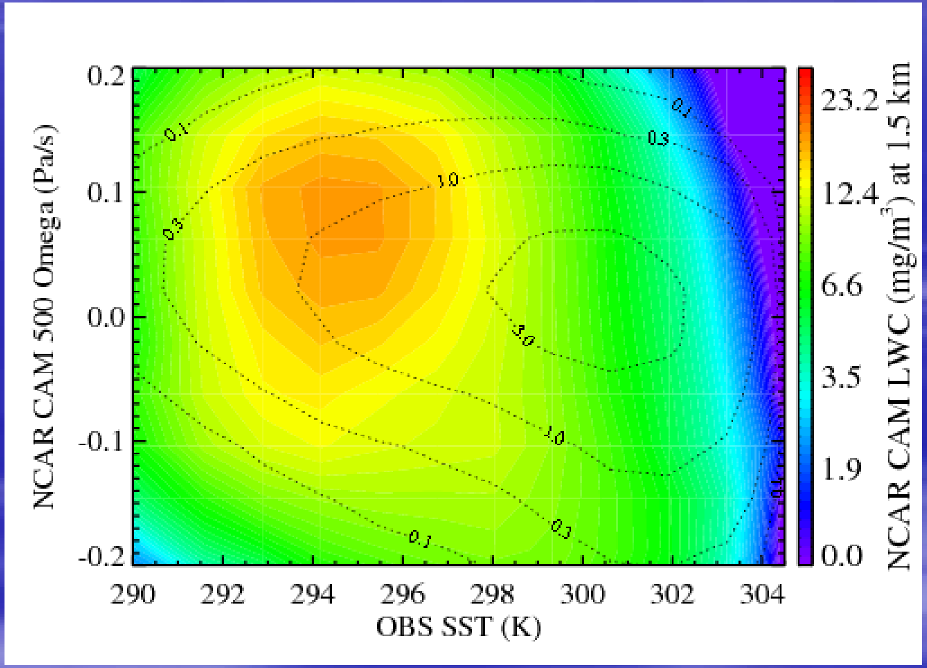
Precipitating clouds are denser than non-precipitating clouds. Separating modeled results similarly may provide additional insights into model-data discrepancies.

Comparing Reflectivity



Clouds as a Function of Joint Distributions of Large-scale Parameters





Using the Bi-Variate Composite (BVC) analysis to identify the coupling among large-scale processes and clouds.

Summary

- Two dominant cloud modes are shown in the retrieved CloudSat IWC and LWC profiles. The high and low clouds are associated with distinctly different large-scale regimes, consistent with existing knowledge of tropical clouds.

- CloudSat detects about 10% less thin cirrus than Aura MLS in the tropical average. These thin cirrus clouds have a net TOA warming of 3-4 W m^{-2} and a net surface cooling of ~1 W m^{-2}.

- The climate model simulations exhibit large discrepancies of cloud structure from CloudSat data. Notably, both IWC in the upper troposphere and LWC in the boundary layer are weaker than the CloudSat retrievals. Maximum CWC is at the different heights from CloudSat data.

- On-going work: use radar reflectivity directly; include precipitating particles (rain and snow) in the modeled LWC/IWC; examine joint distributions; search for "optimal" regime parameters …