Tropical Cloud Structure and Large Scale Circulation

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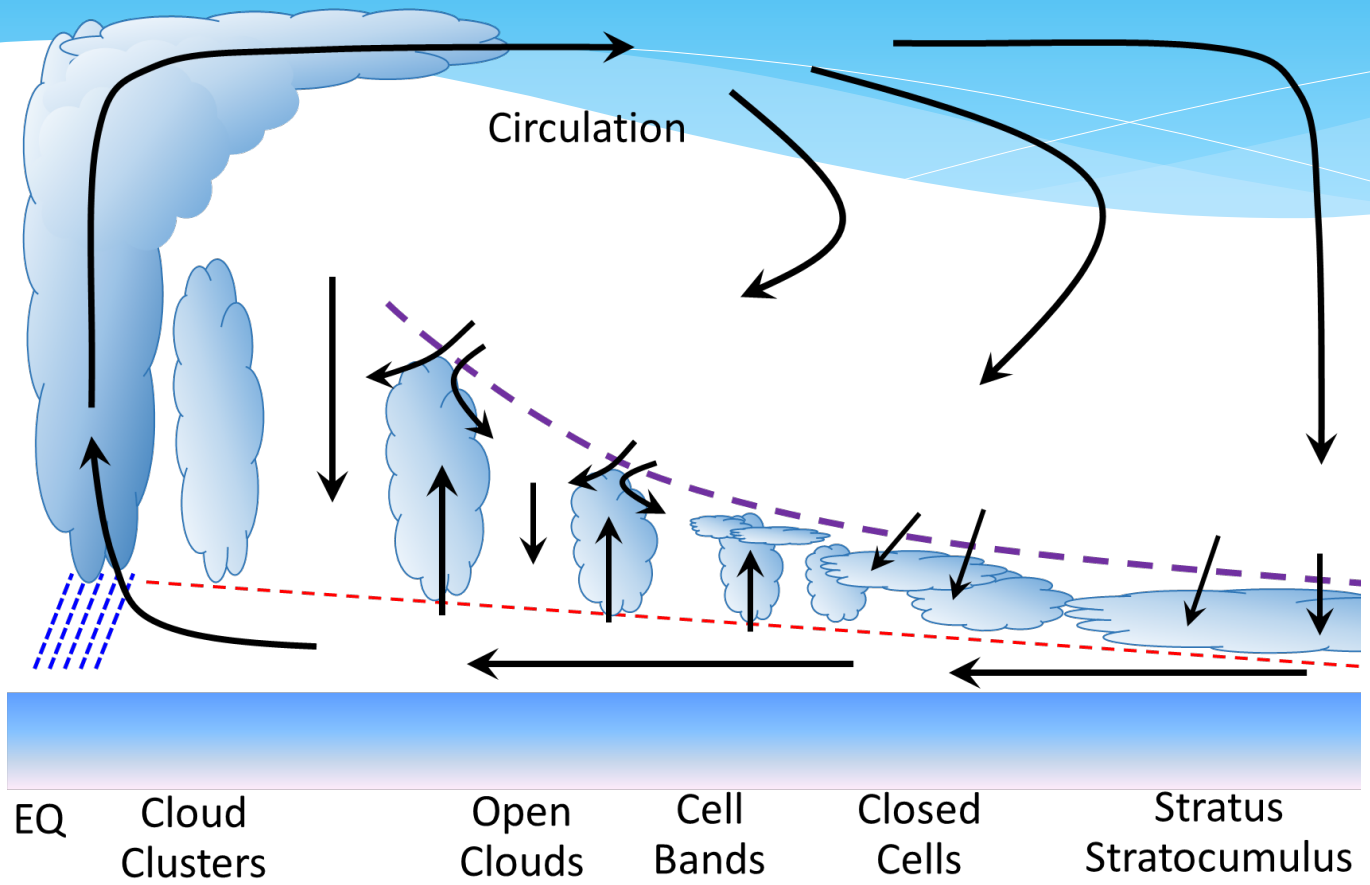
Large-scale Circulation and Clouds



(Emanuel, 1994)

Outline

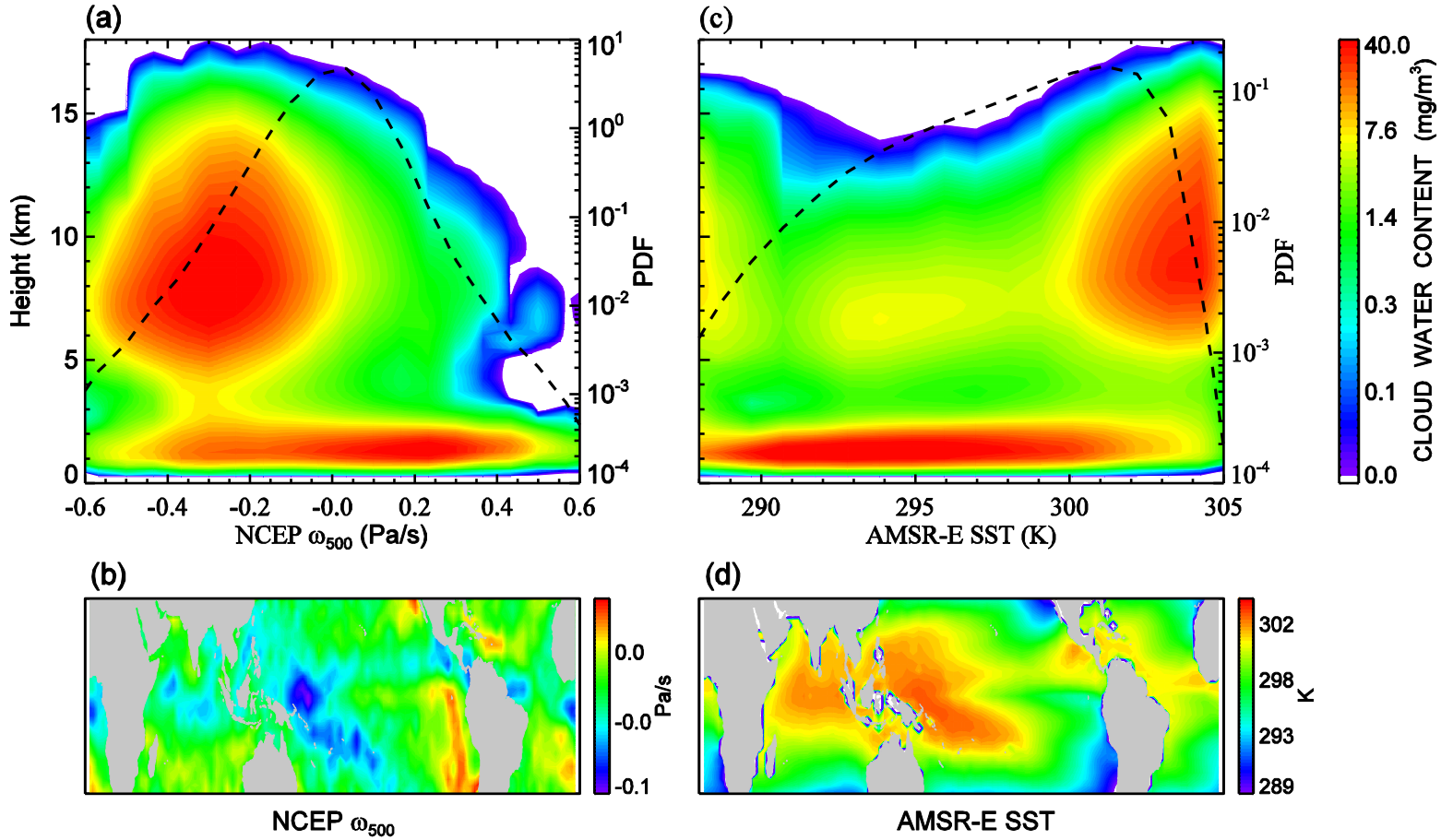
1. "Conditional Sampling" of Cloud Profiles

2. Cloud and Circulation Responses to El Niño

3. Cloud Structure as "Emergent Constraint" on Climate Sensitivity

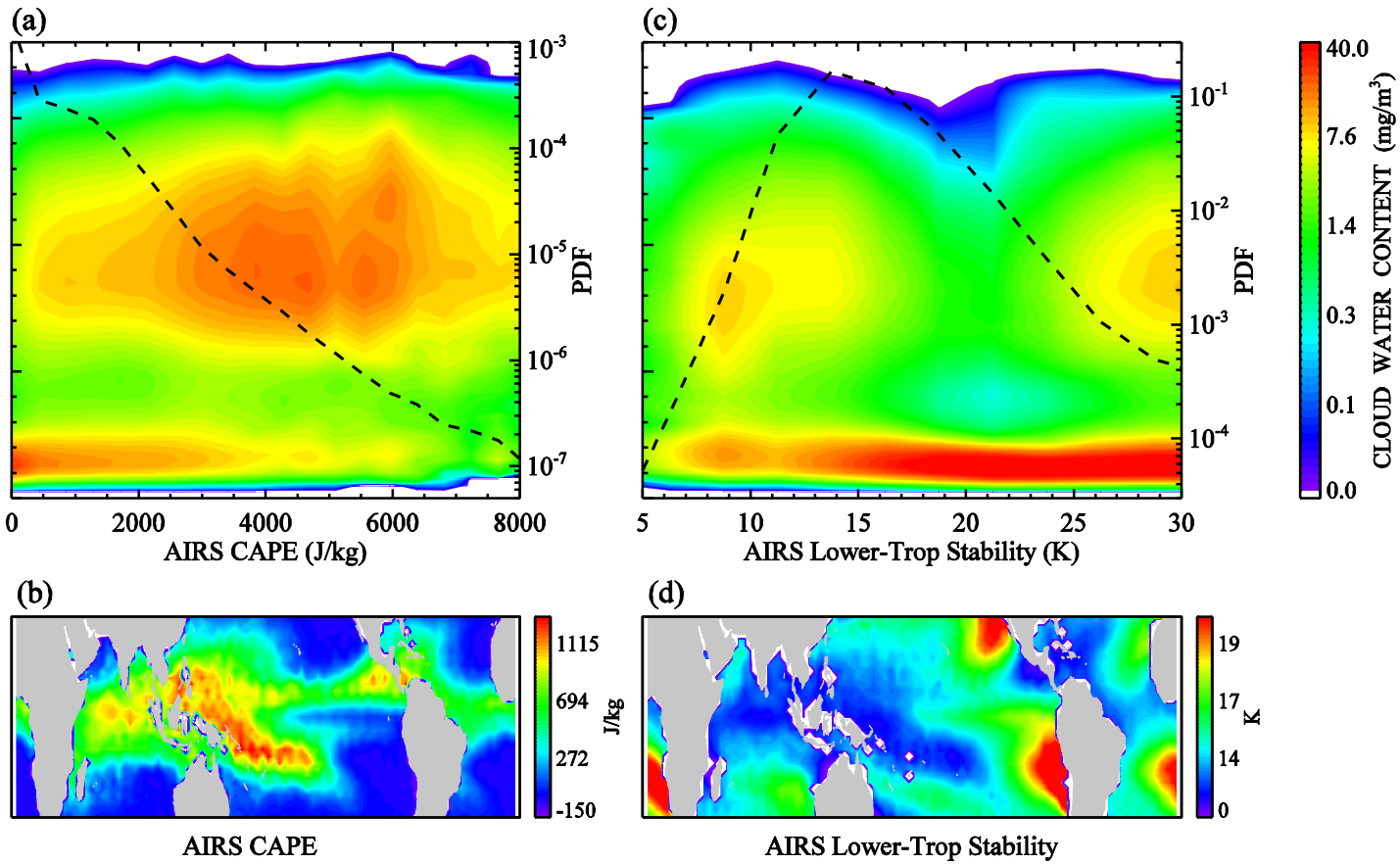
Part I
“Conditional Sampling” of Cloud Profiles

Observed Clouds in Large-scale Regimes



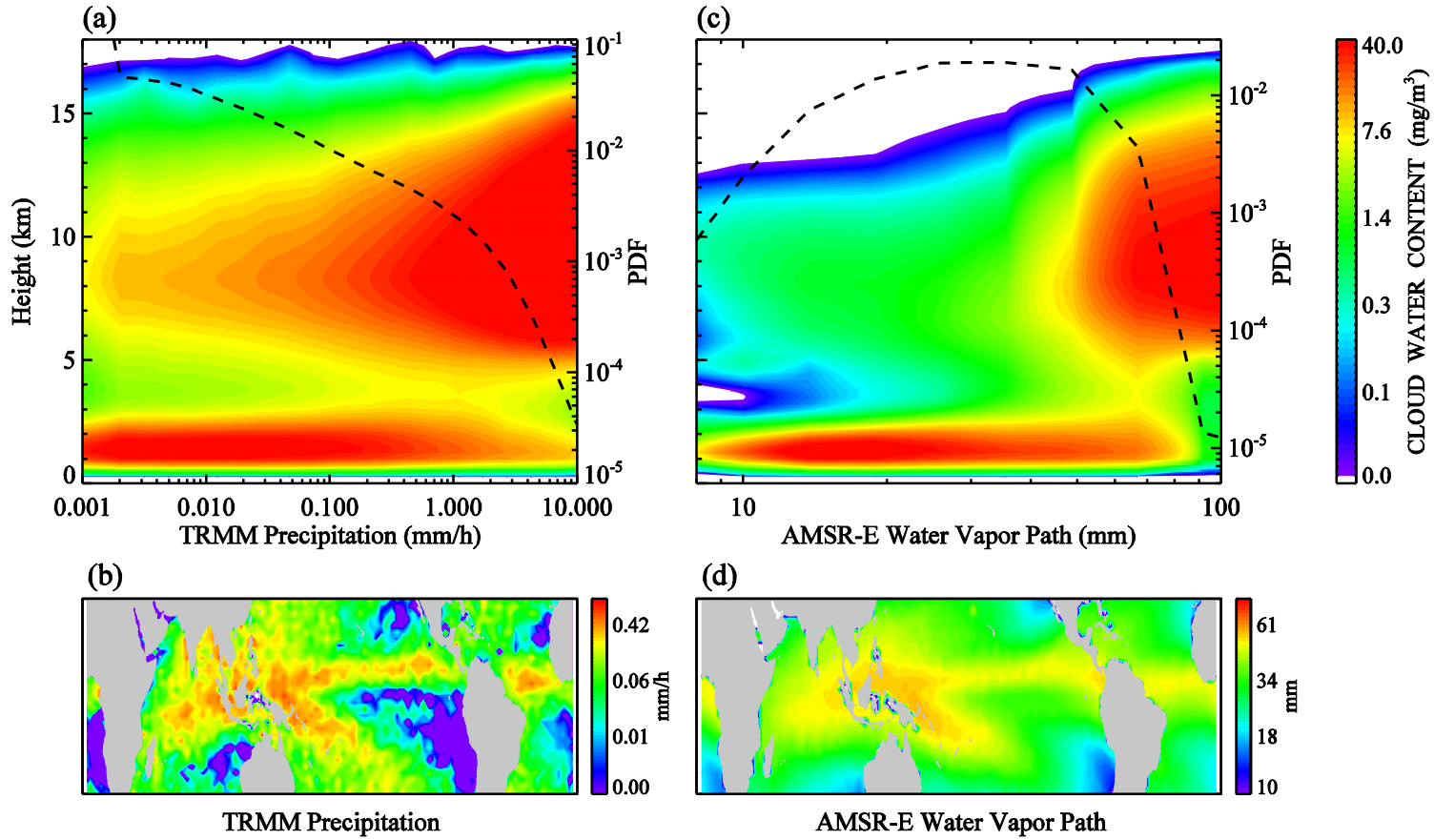
(Su et al., GRL, 2008)

CWC Sorted by CAPE and LTS



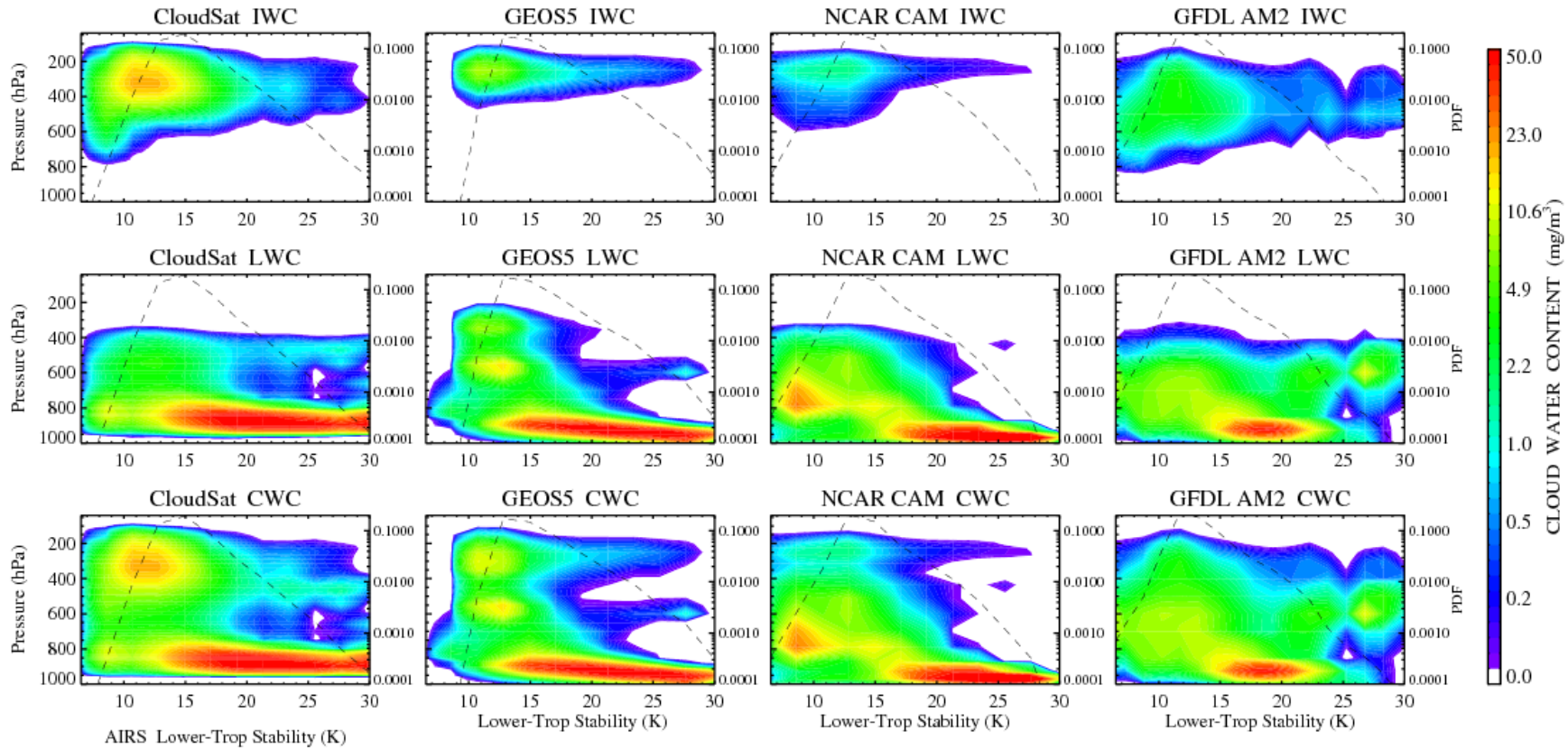
- CAPE resembles deep convection pattern. High clouds are over high CAPE regions. Low clouds are more towards the lower CAPE regions.
- LTS is nearly a "complement" of CAPE.
- Shallow clouds are over higher LTS regions than high clouds. Infrequent high clouds exist at very high LTS values.

CWC Sorted By Precipitation and Water Vapor Path



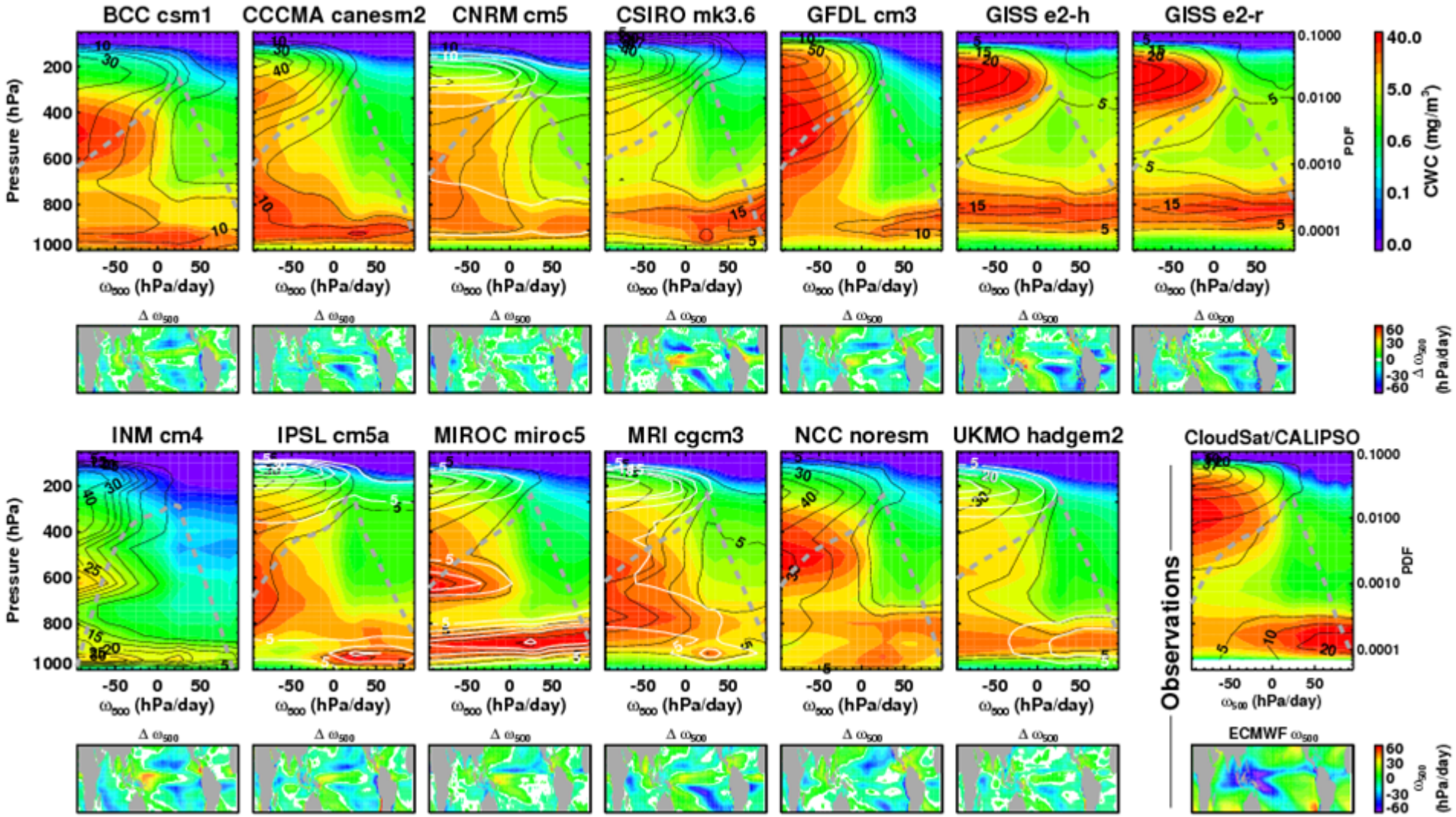
- Heavy precipitation is from deep clouds. Only 15% of precipitating clouds have surface rain rates >= 2 mm/h, but they contribute to 55% of tropical rainfall.
- Deep clouds occur in moist air columns while low clouds are associated with drier air. Moist air columns with WVP >= 50 mm have only 0.3% occurrence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

Comparison to Models and Analyses



(Su et al. JGR, 2011)

CMIP5 Simulated Clouds Sorted by ω_{500}



(Su et al., JGR, 2013)

Diagnostic Framework

C_v Cloudiness in a given large-scale regime (V)

P_v Probability density function of a large-scale regime (V)

$$\int P_v dV = 1$$

$< C >$ Tropical-mean cloudiness

$$< C > = \int P_v \, C_v dV$$

$\delta P_v = P_v^{\,m} - P_v^{\,o}$ Difference between modeled and observed pdf of Regime V

$\delta C_v = C_v^{\,m} - C_v^{\,o}$ Difference between modeled and observed cloudiness in Regime V

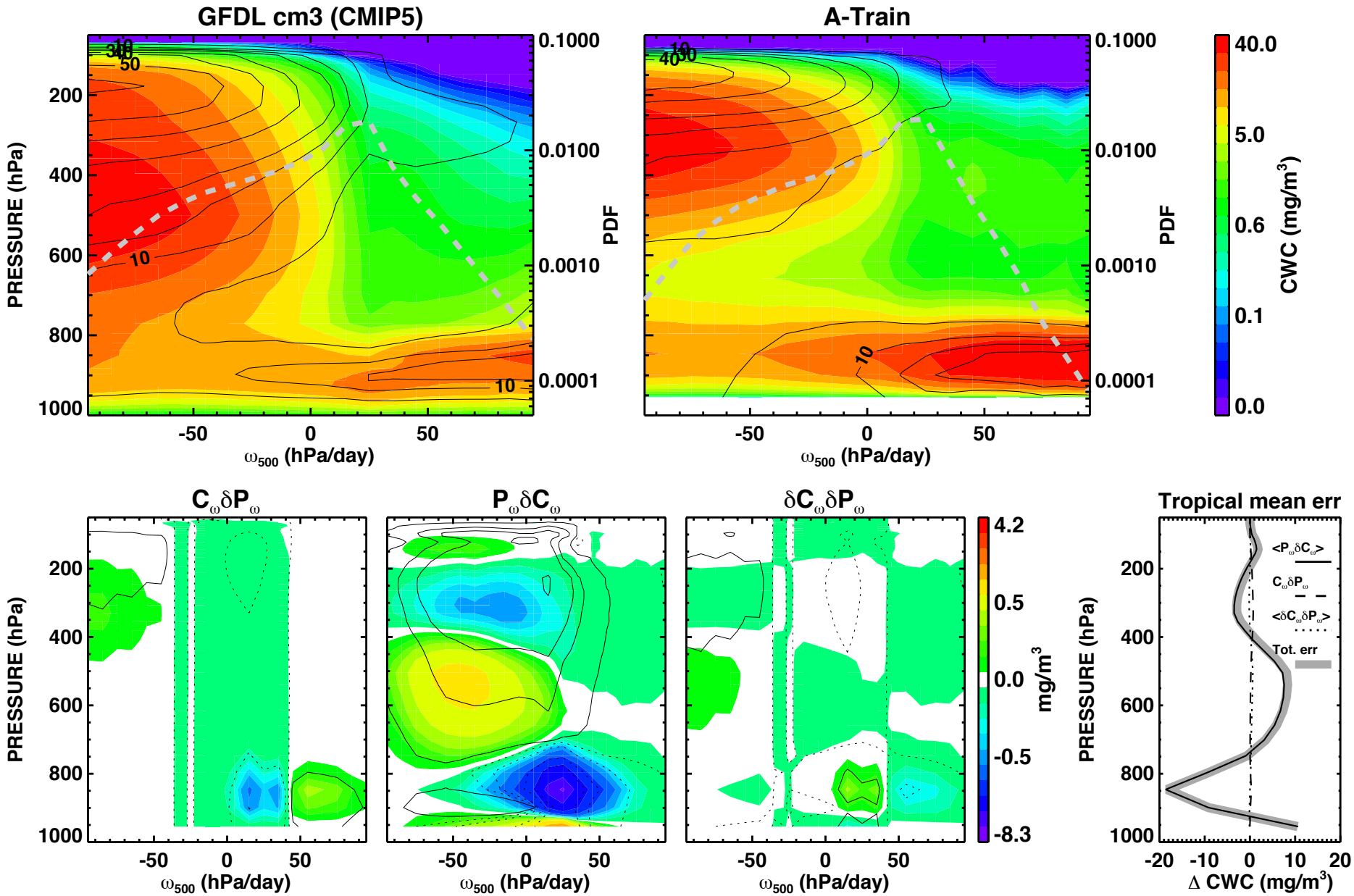
$$< \delta C > = \int C_v^{\,o} \delta P_v dV + \int P_v^{o} \delta C_v dV + \int \delta P_v \delta C_v dV$$

Large-scale error

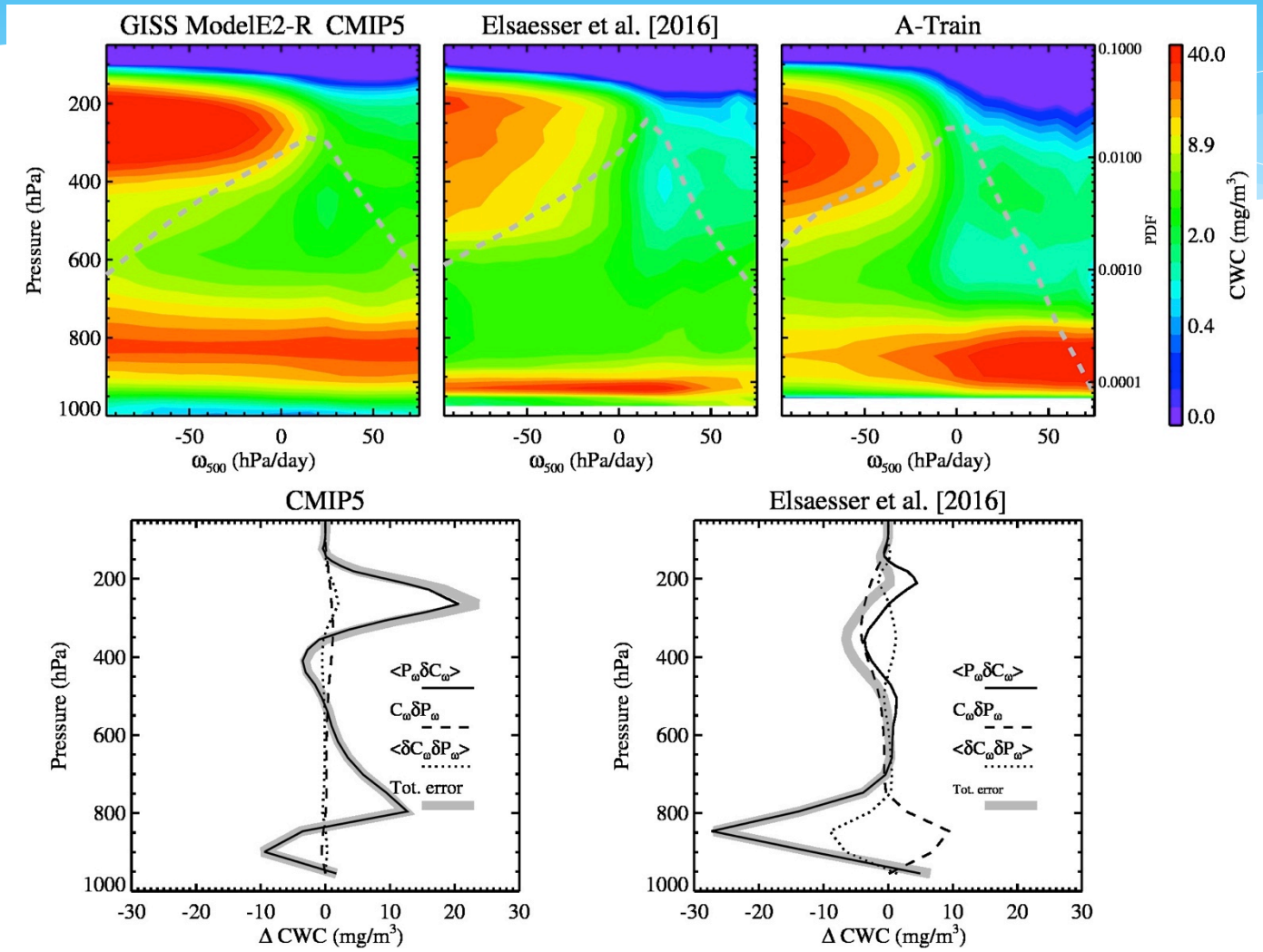
Parameterization error

Co-variation error

GFDL CM3 Clouds Sorted by ω_{500}

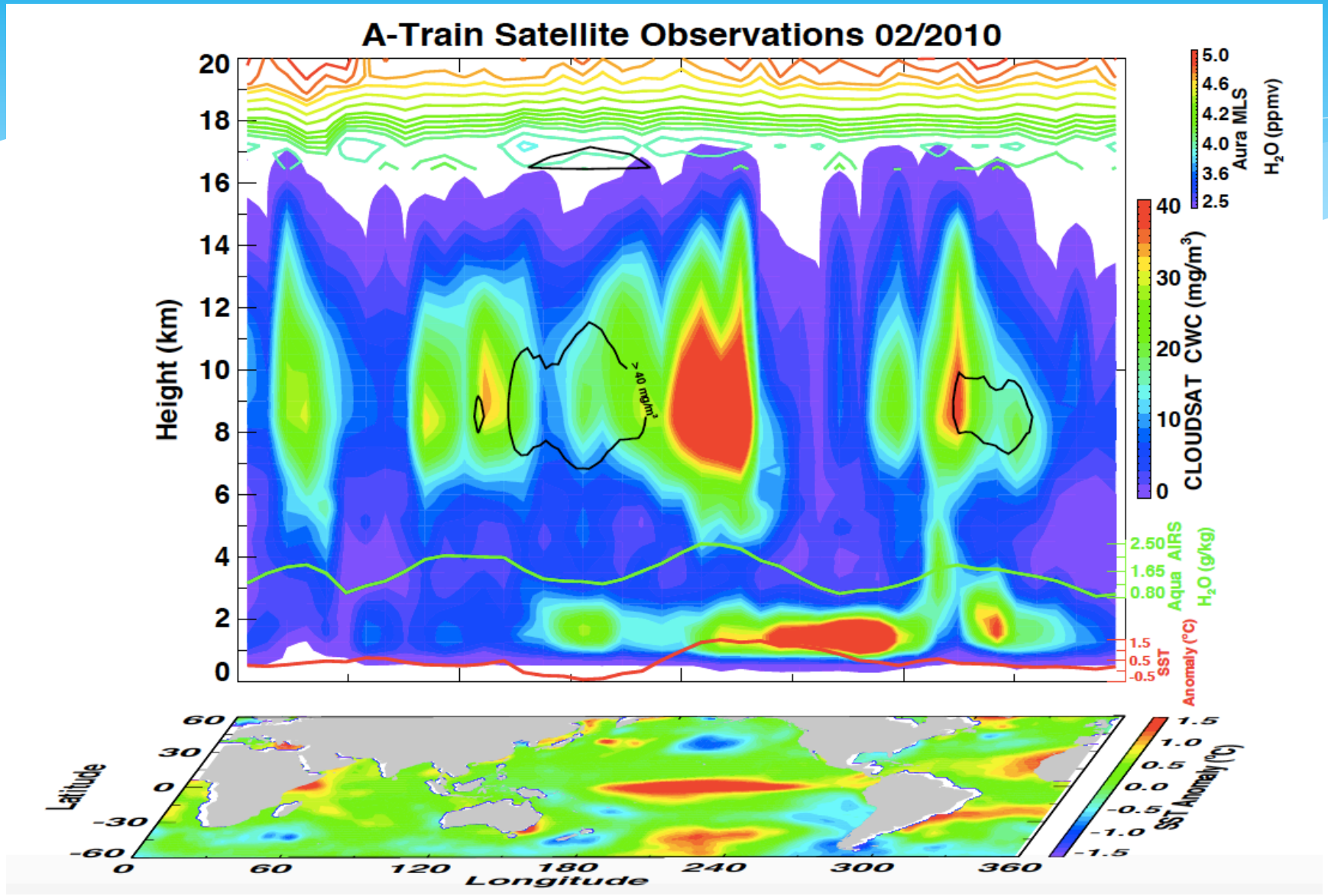


GISS Model Improvements



Part II
Cloud and Circulation Responses to El Niño

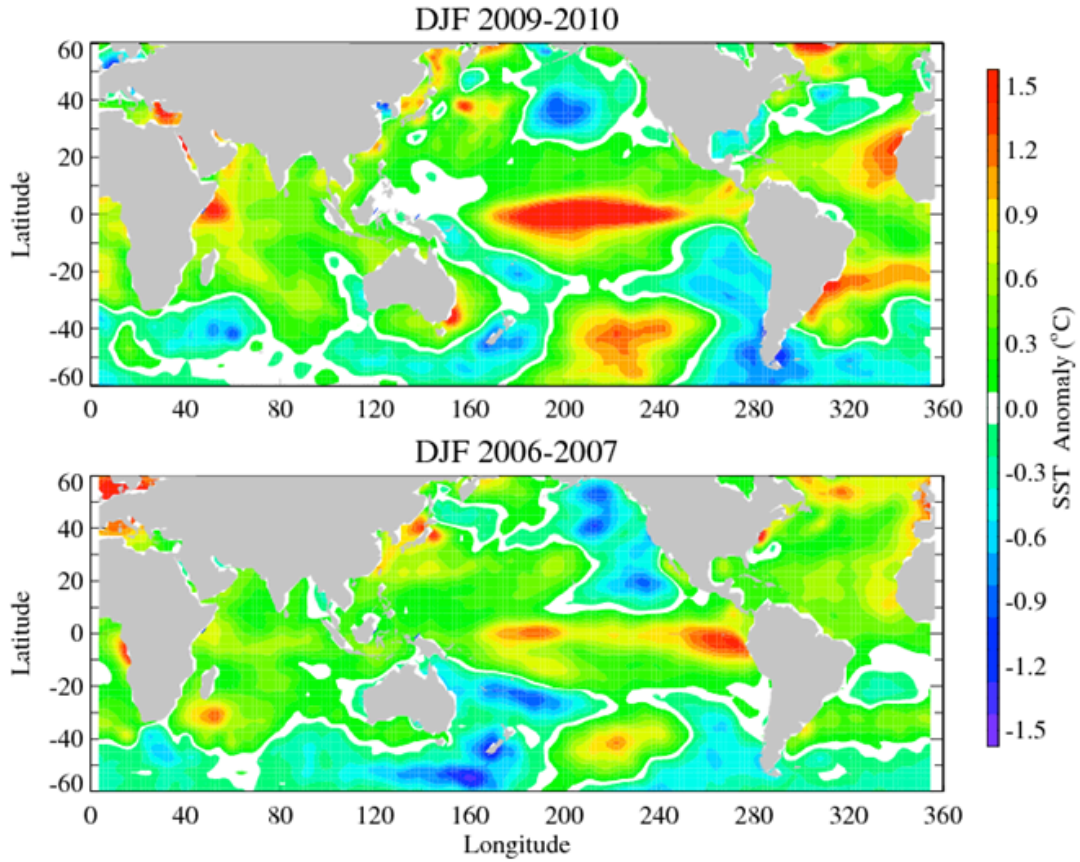
A-Train View of El Niño



Two Types of El Niños

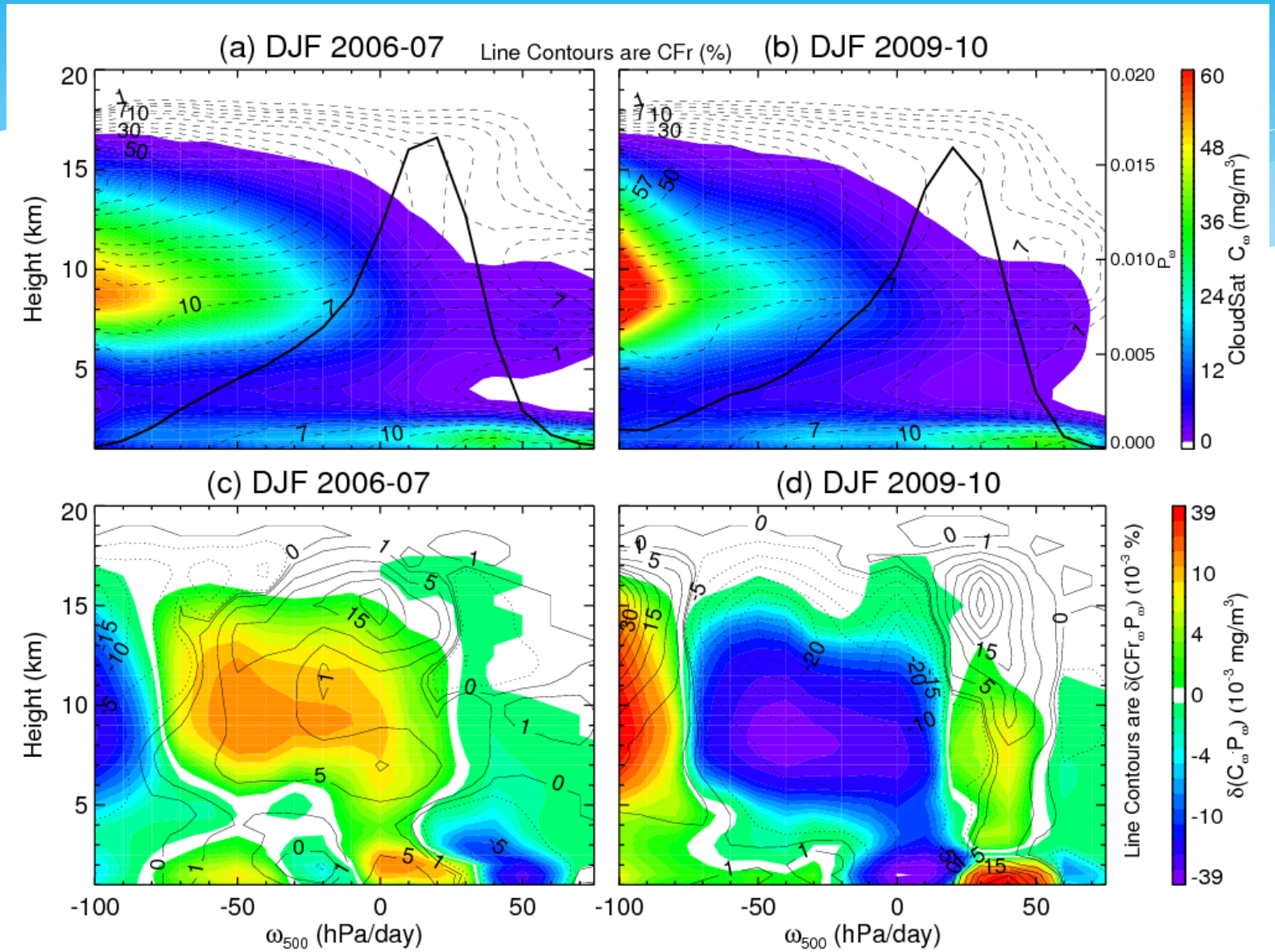
Strong CP-El Niño
(Modoki)
2009-10 DJF

Moderate EP-El Niño
2006-07 DJF

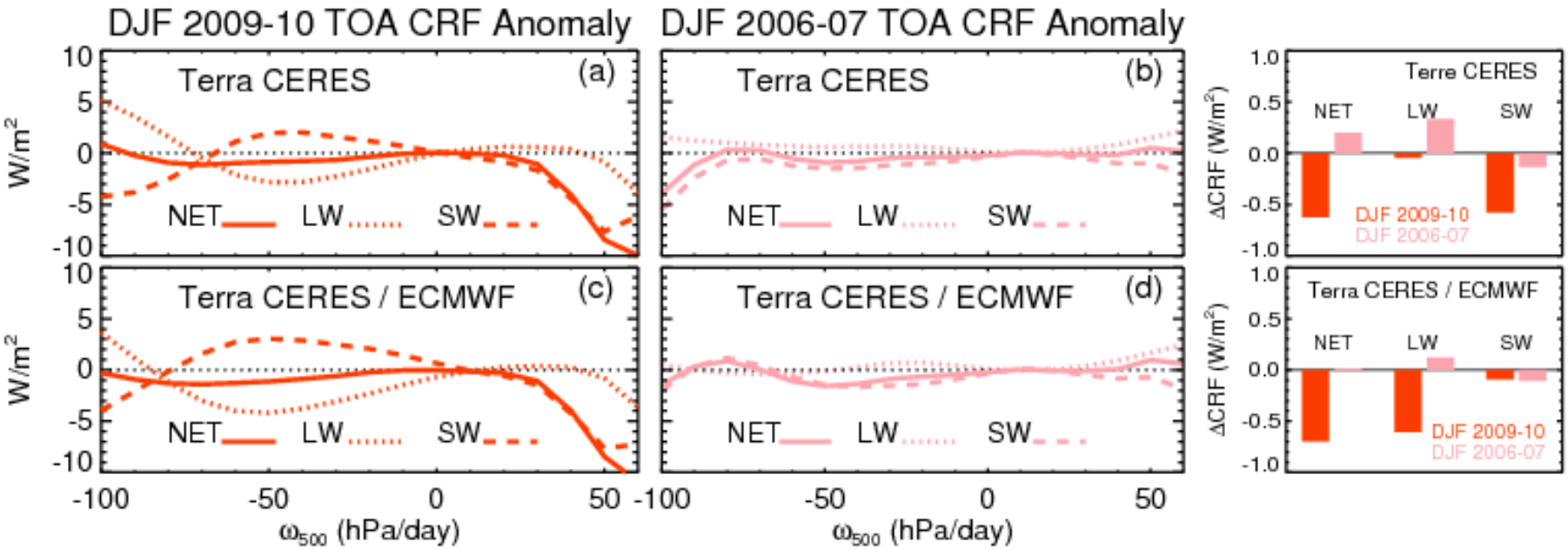


(Su and Jiang, J. Clim, 2013)

Decompose the Dynamic and Thermodynamic Cloud Changes



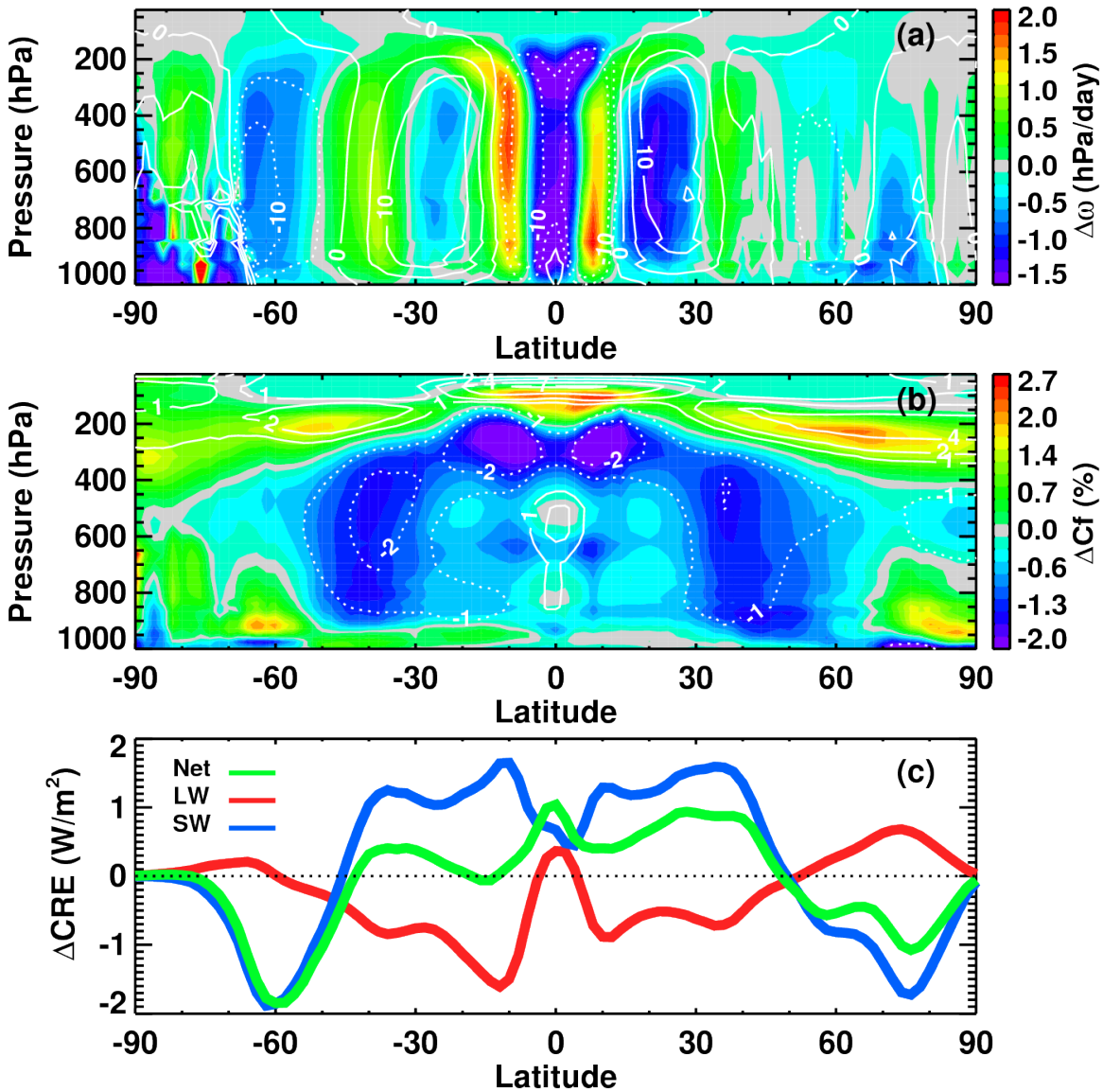
TOA Cloud Radiative Forcing Changes



(Su and Jiang, J. Clim, 2013)

Part III
Cloud Structure as “Emergent Constraint” on Climate Sensitivity

Changes of the Hadley Circulation, Clouds and Cloud Radiative Effects in the RCP4.5

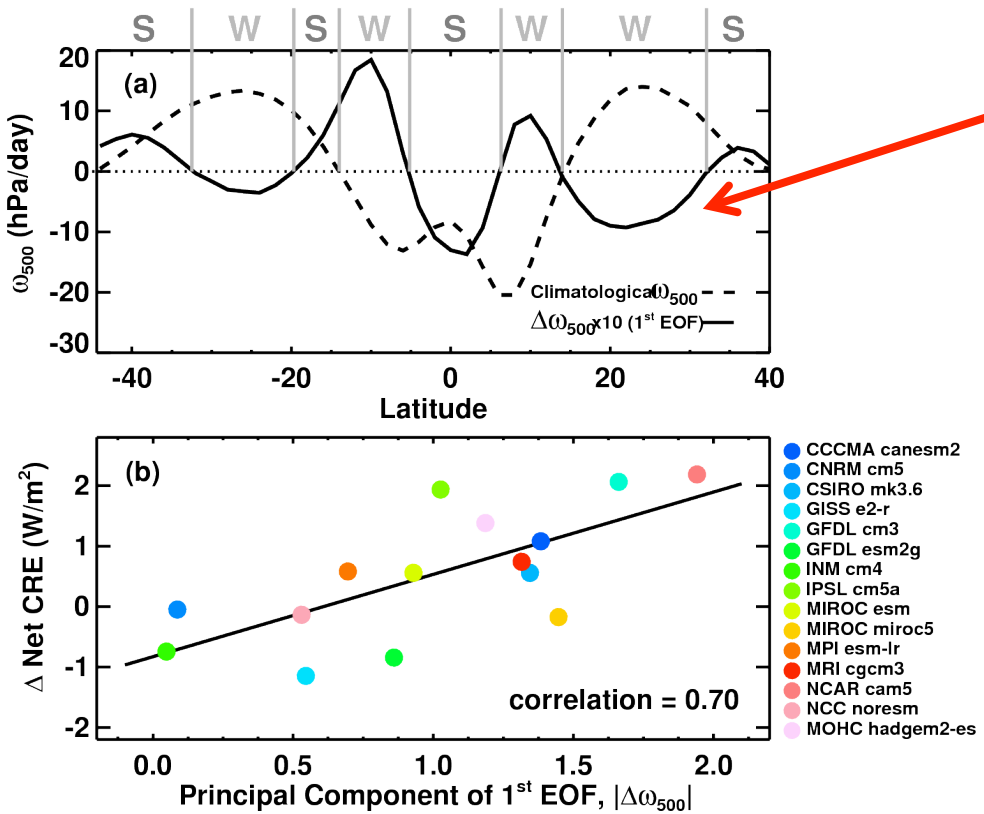


(Su et al., JGR, 2014)

Multi-model-mean from 15 CMIP5 coupled models

Δ = 2074-2098 in "RCP4.5" – 1980-2004 in "historical run"

Quantifying the Model Differences in Circulation and Relation with Cloud Radiative Effect Changes

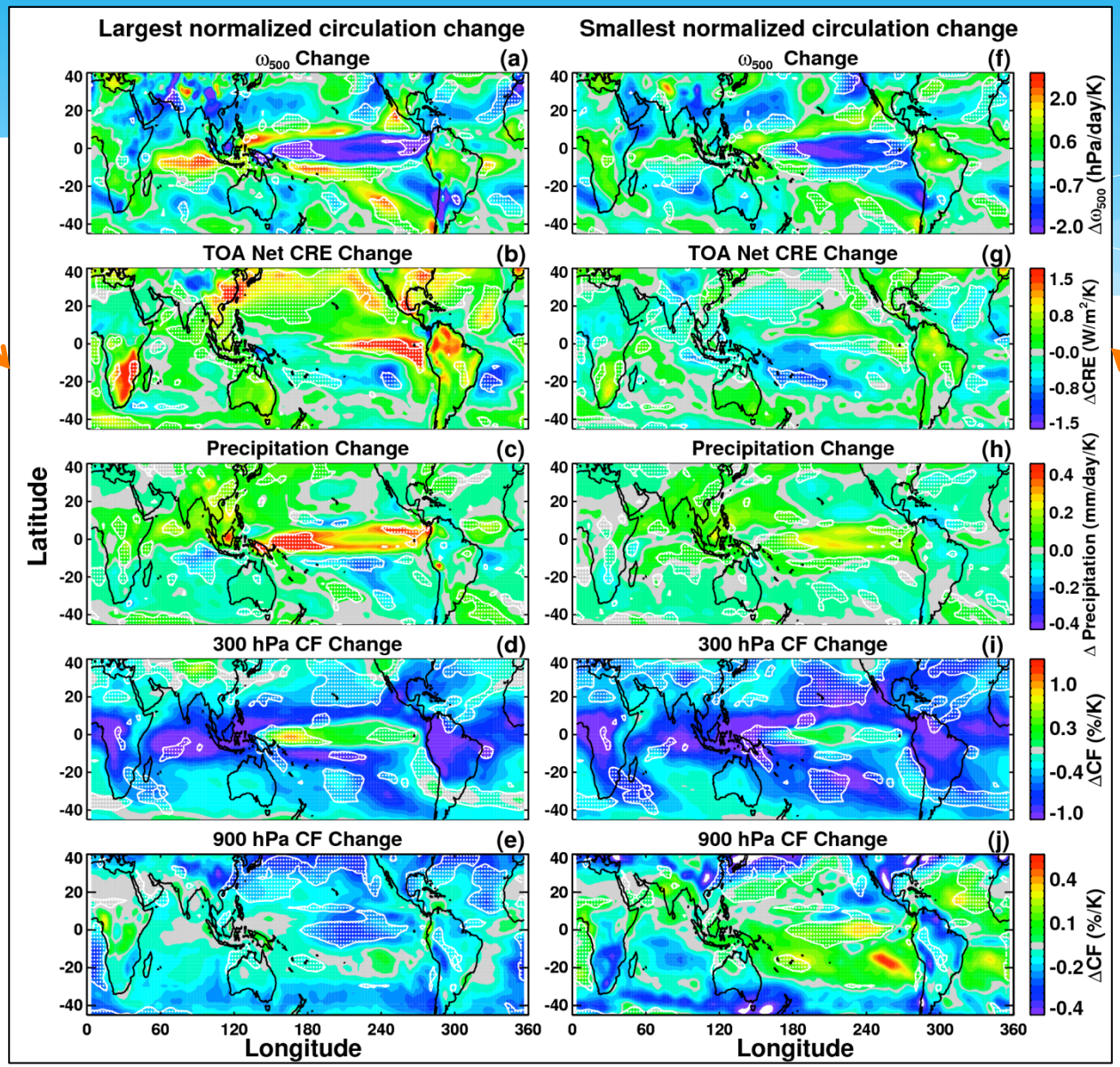


The explained variance by the 1st EOF is **57%**

- ✓ **Area-weighted CRE changes for the weakening and strengthening segments account for 54% and 46% of the total CRE change within the HC.**
- ✓ **The amplitudes of the 1st EOF mode differ by two orders of magnitude in models.**
- ✓ **Differences in the Hadley Circulation changes are highly correlated with the inter-model spread in net CRE changes.**

Normalized Response

Largest Circu. Change



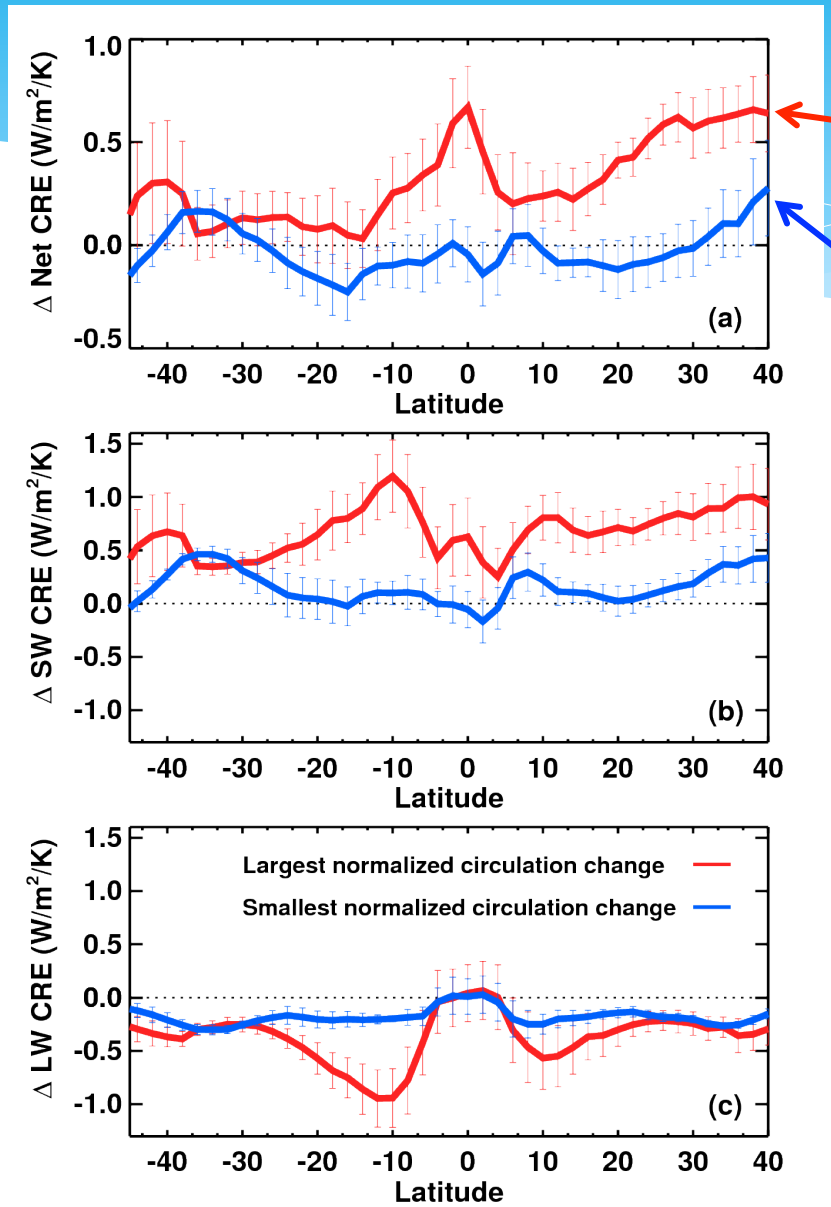
Smallest Circu. Change

Normalized CRE Changes

Net CRE

SW CRE

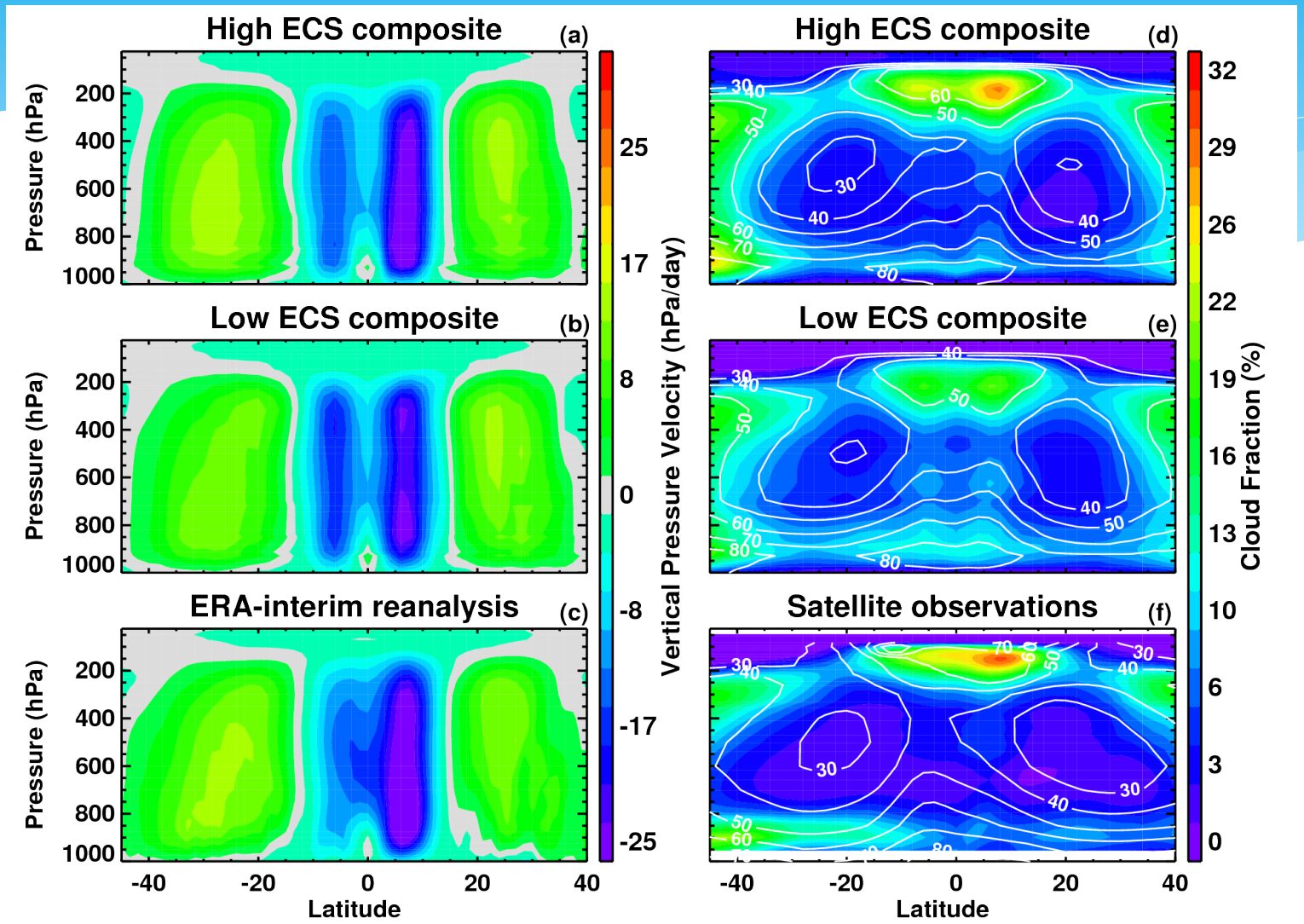
LW CRE



Largest Circu. Change

Smallest Circu. Change

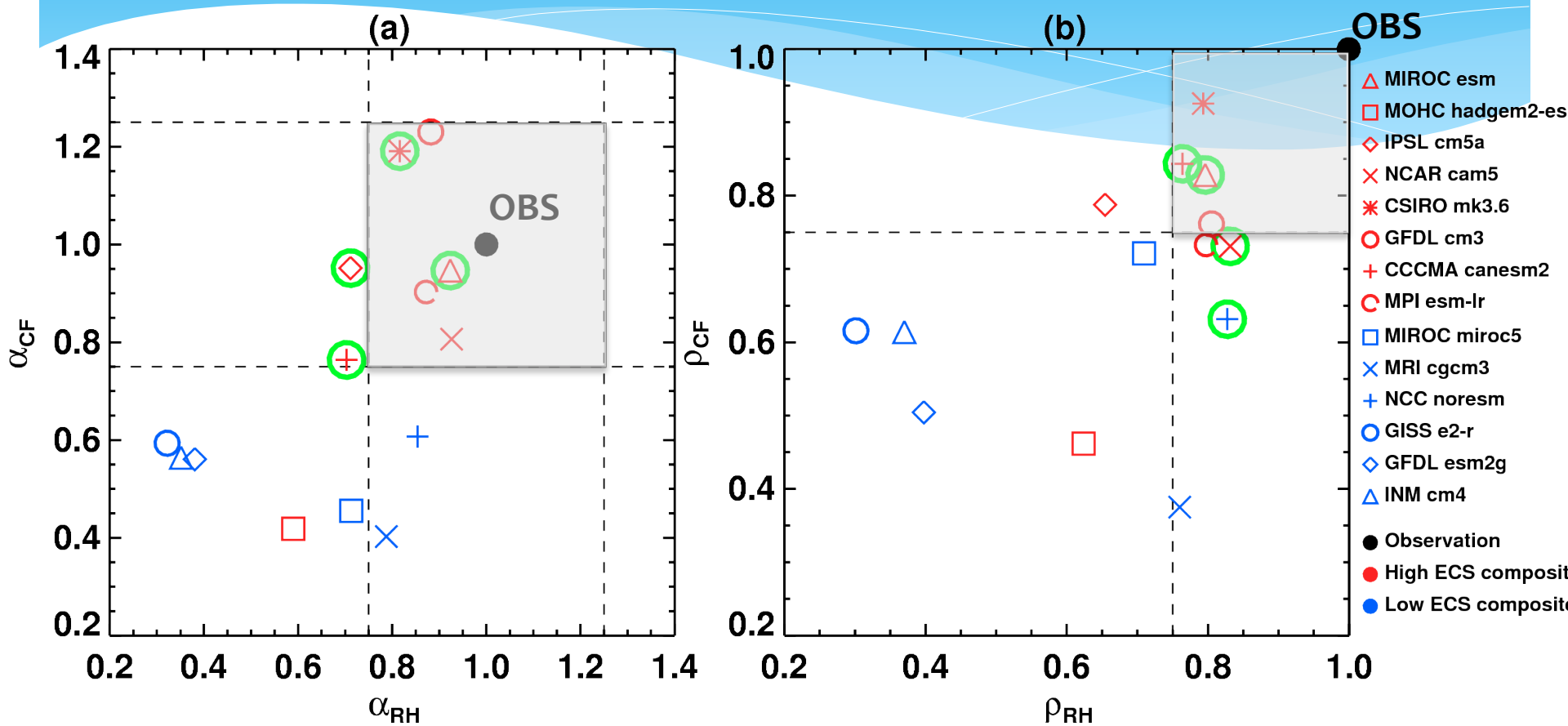
Emergent Constraint on Climate Sensitivity



The Hadley Circulation

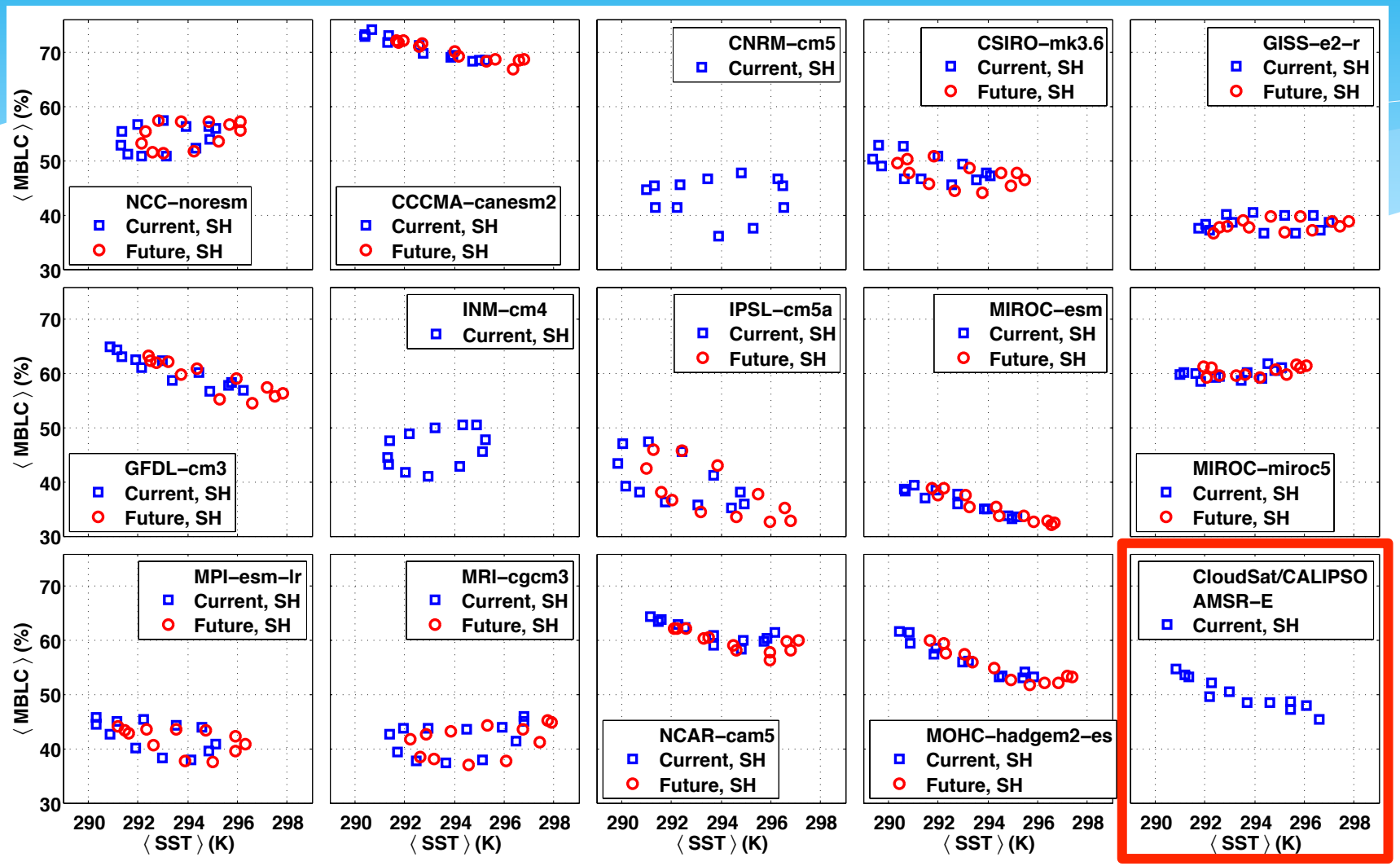
CloudSat/CALIPSO Cloud Fraction and AIRS/MLS Relative Humidity

Hadley Circulation Structure Suggests High Climate Sensitivity



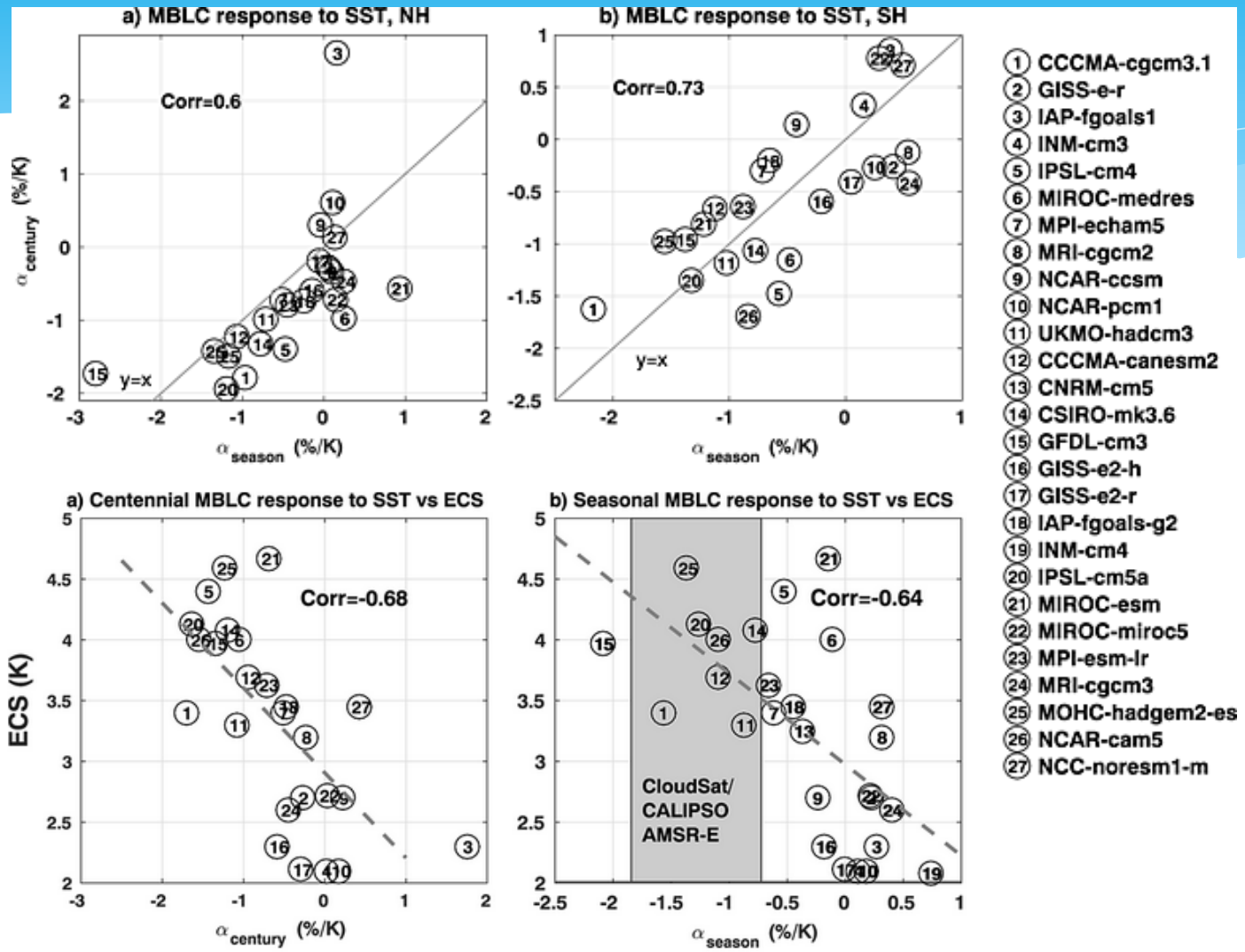
(Su et al., JGR, 2014)

MBLC Seasonal Variation, 20°S – 40°S



(Zhai et al., GRL, 2015)

MBLC Sensitivity to SST at Seasonal and Centennial Time Scales



Satellite observations of MBLC seasonal cycle suggest that the best estimate of ECS ranges from 3.6 to 4.6 K, with a mean of 4.1 K and a standard deviation of 0.3 K.

Summary

- **Cloud vertical structure observed by CloudSat/CALIPSO displays close couplings with large-scale circulation, serving as important metrics for climate model evaluations and improvements.**

- **Multi-year CloudSat/CALIPSO observations have revealed the profound impacts of El Niño on cloud distributions and cloud radiative effects.**

- **Observed cloud structures and seasonal variations serve as useful "emergent constraints" on climate sensitivity.**