

Hadley Circulation, Cloud Feedback, Humidity and Climate Sensitivity

Hui Su¹

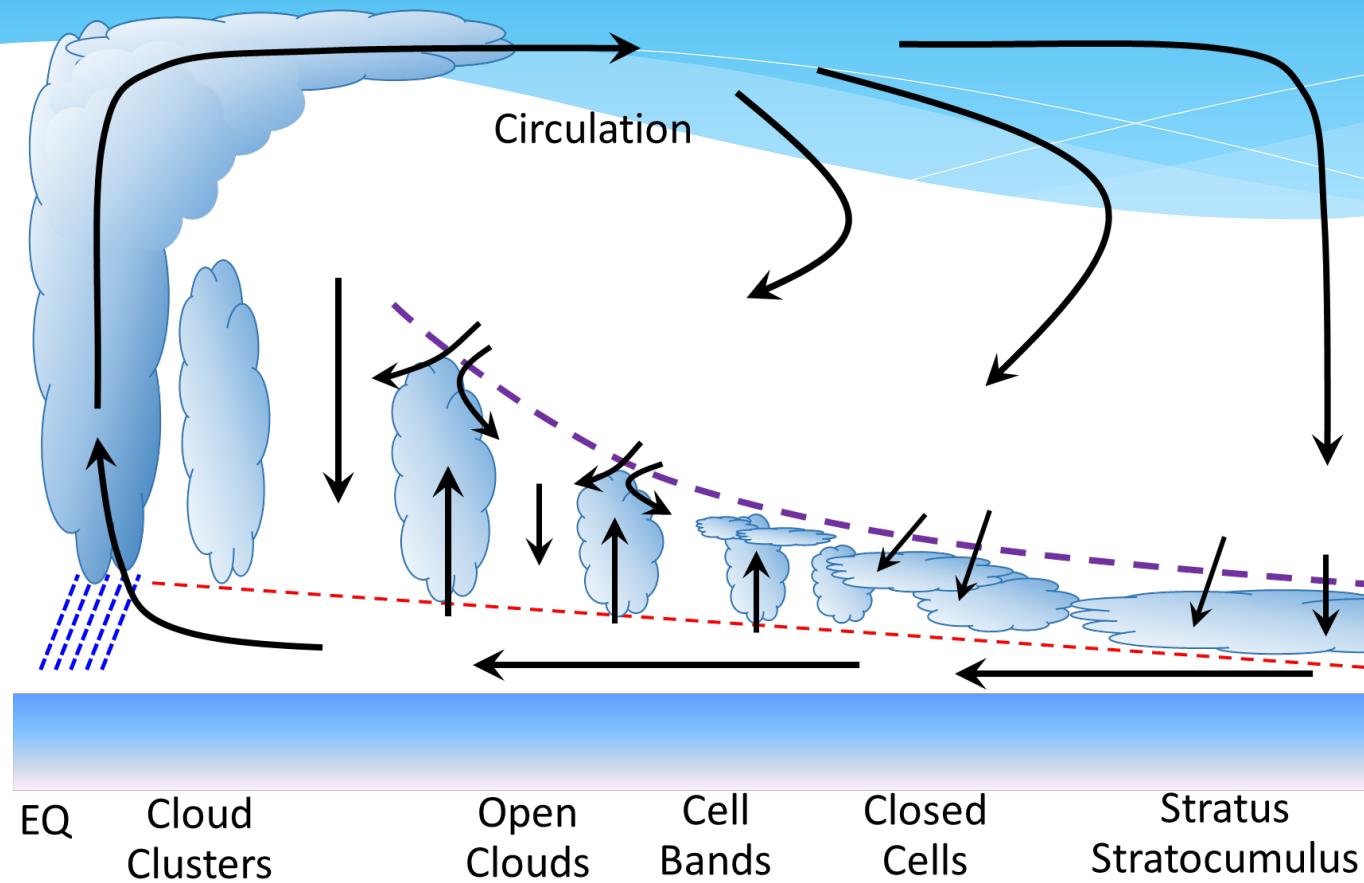
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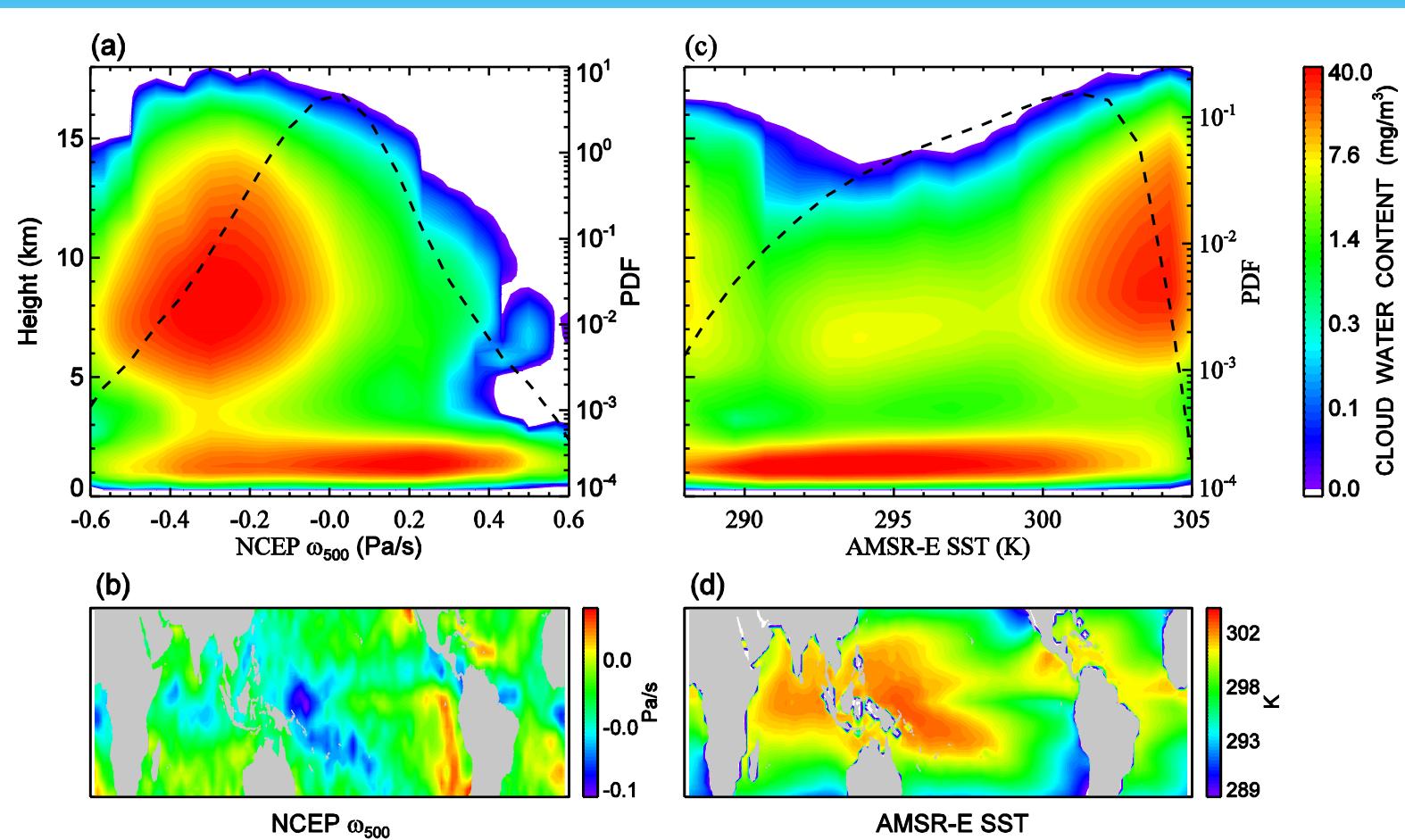
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Large-scale Circulation and Clouds



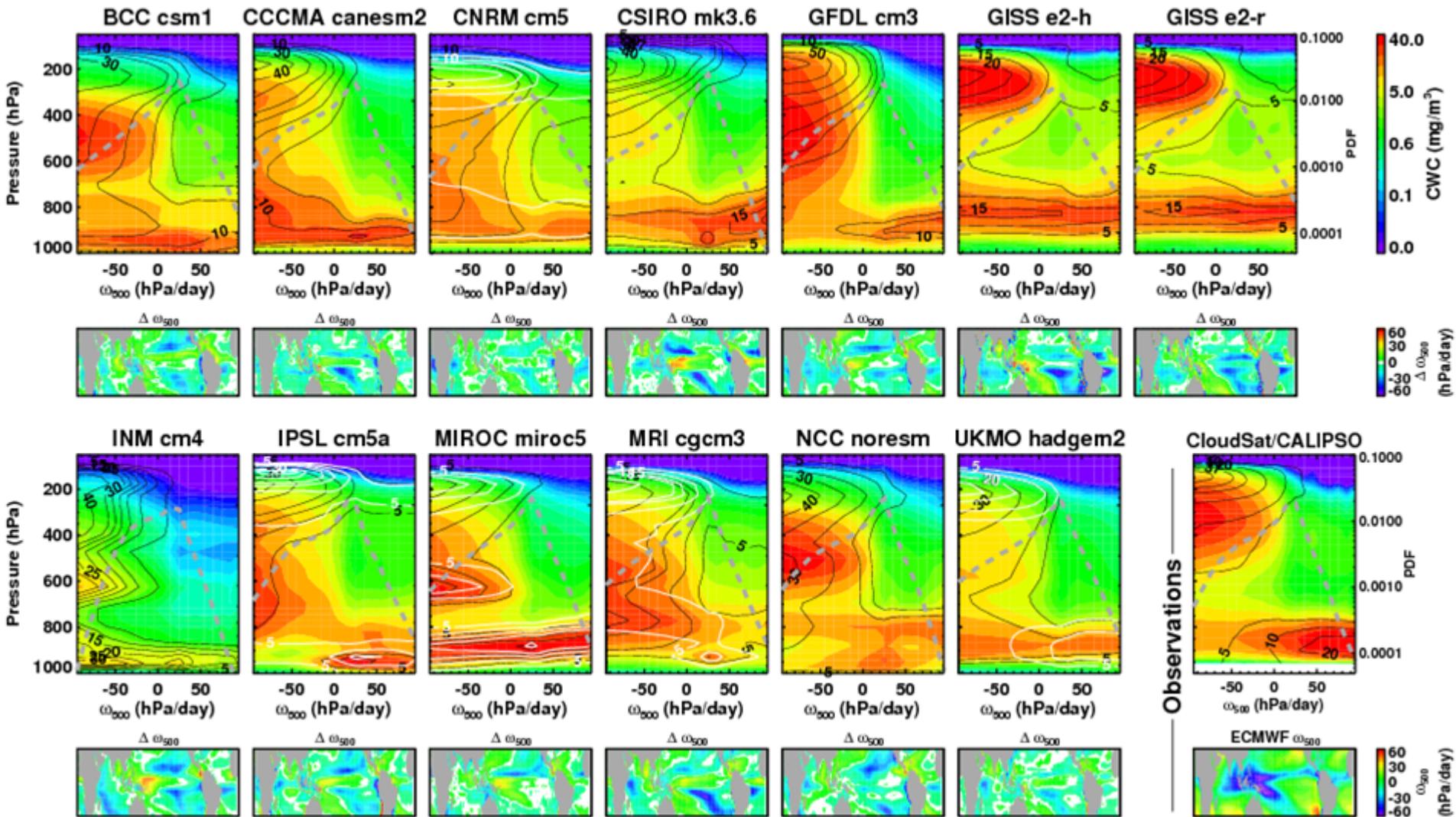
(Emanuel, 1994)

Observed Clouds in Large-scale Regimes



(Su et al., GRL, 2008)

CMIP5 Simulated Clouds Sorted by ω_{500}



(Su et al., JGR, 2013)

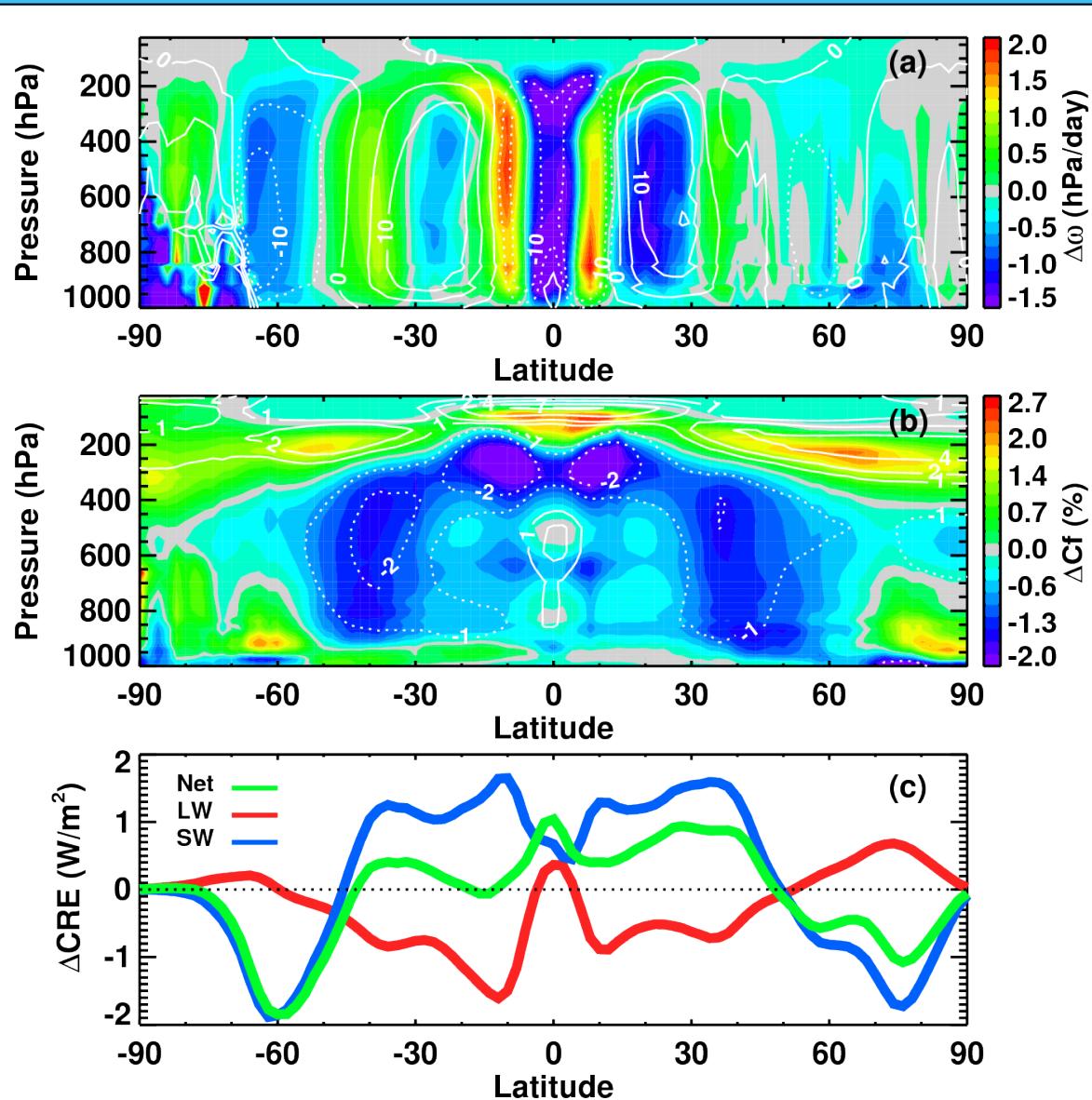
Motivation

- Cloud feedback is one of the leading contributors to the inter-model spread in climate sensitivity (e.g., Cess et al. 1989; Stephens 2005)
- What processes drive the inter-model spread in cloud feedbacks to increasing CO₂?



- How can we use observations to constrain model simulations of cloud feedbacks in order to constrain climate sensitivity?

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

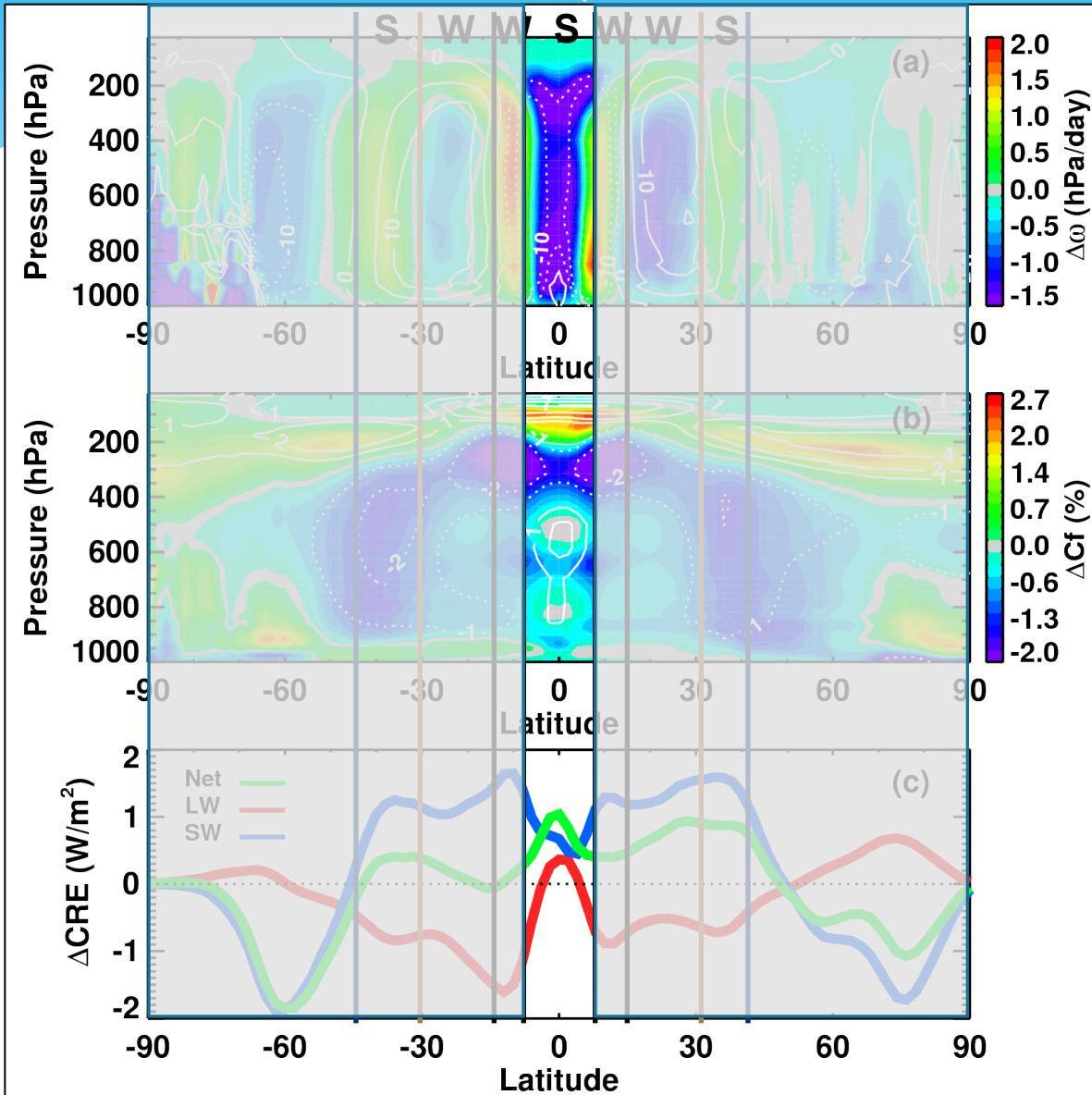


(Su et al., JGR, 2014)

Multi-model-mean from
15 CMIP5 coupled models

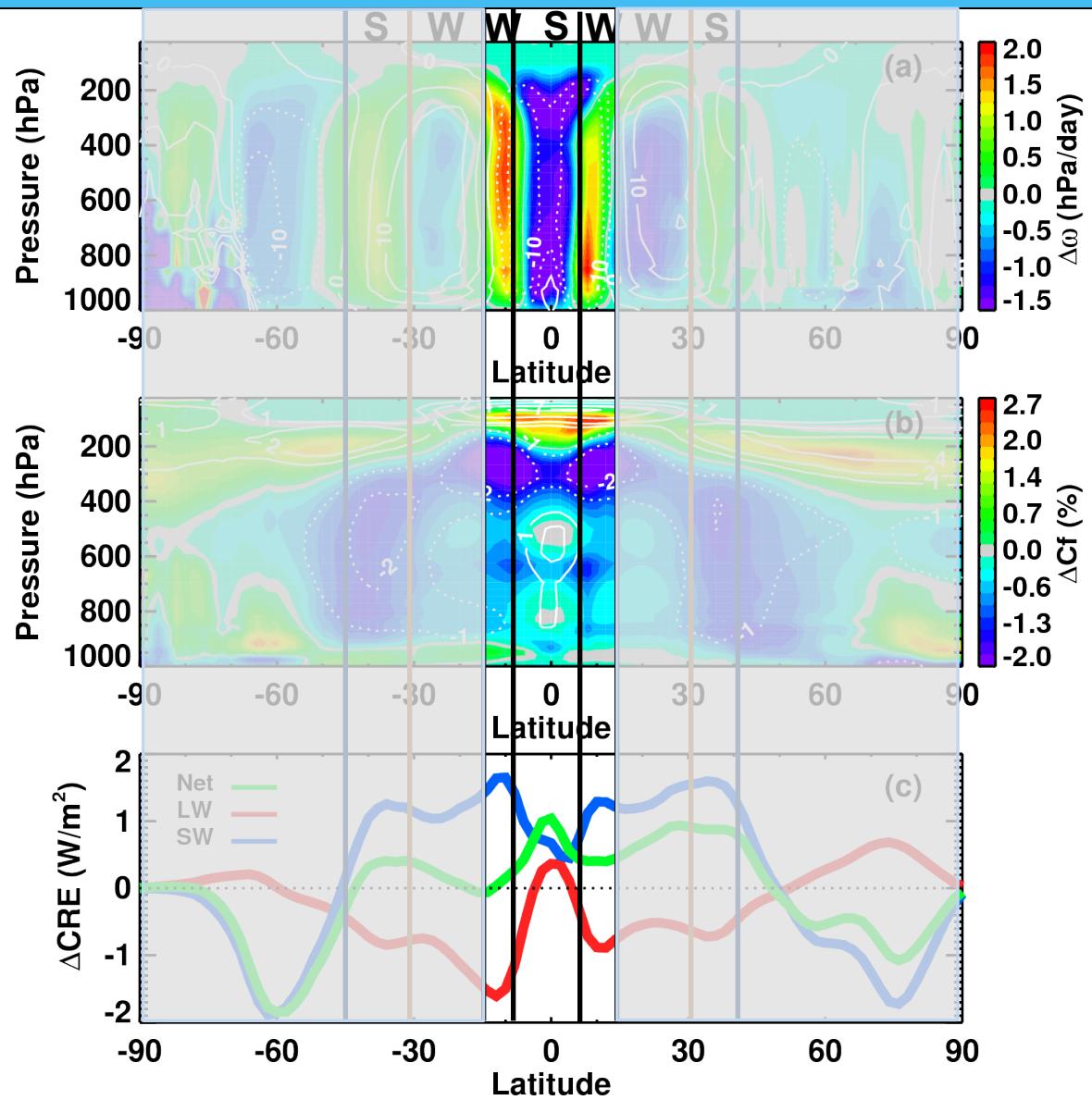
$\Delta = \text{2074-2098 in "RCP4.5"} - \text{1980-2004 in "historical run"}$

The Equatorial Tropics (around 5°S to 5°N)



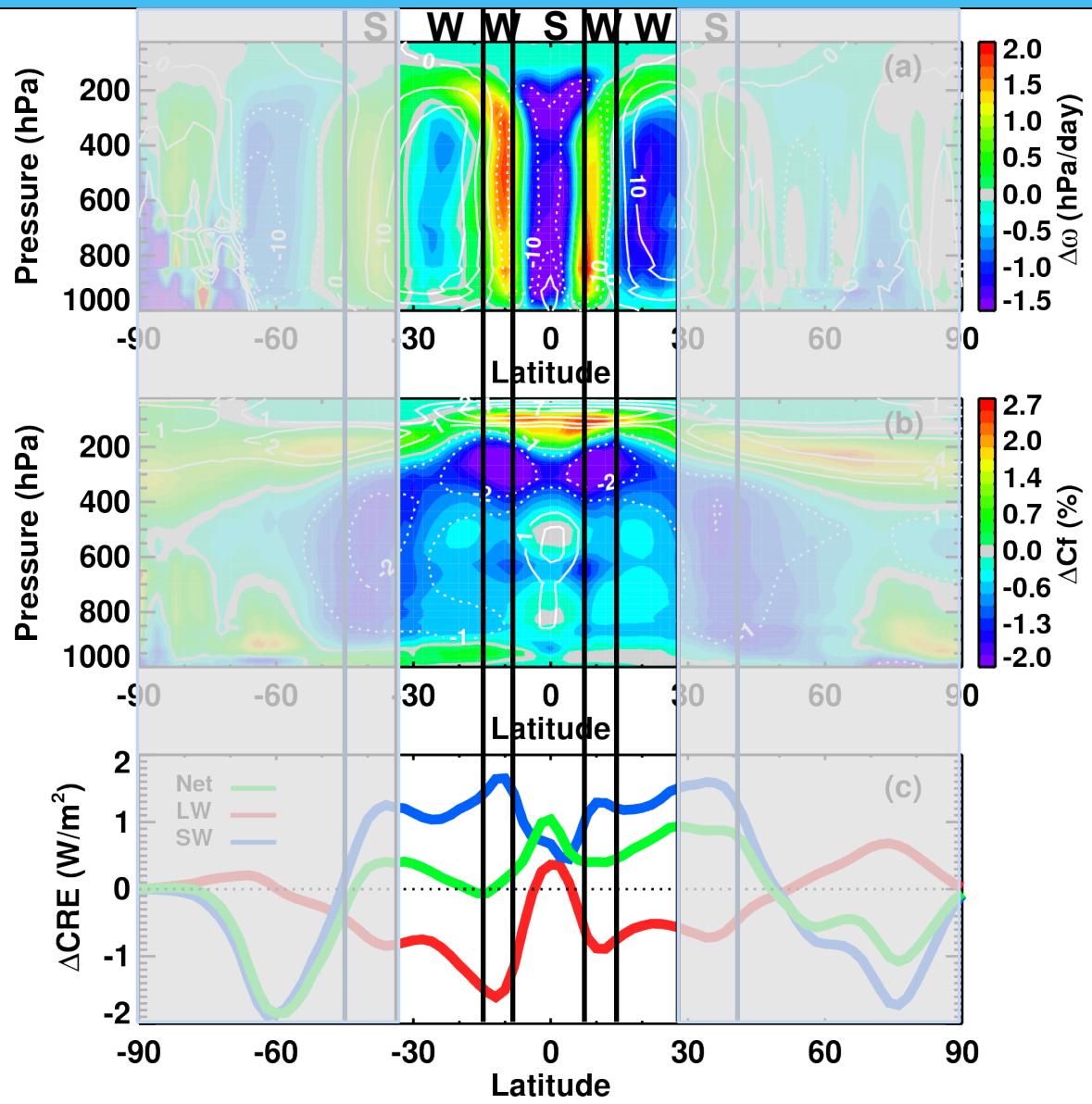
$\Delta = \text{2074-2098 in "RCP4.5"} - \text{1980-2004 in "historical run"}$

The Poleward Flanks of Deep Tropics (around 5° to 15°N/S)



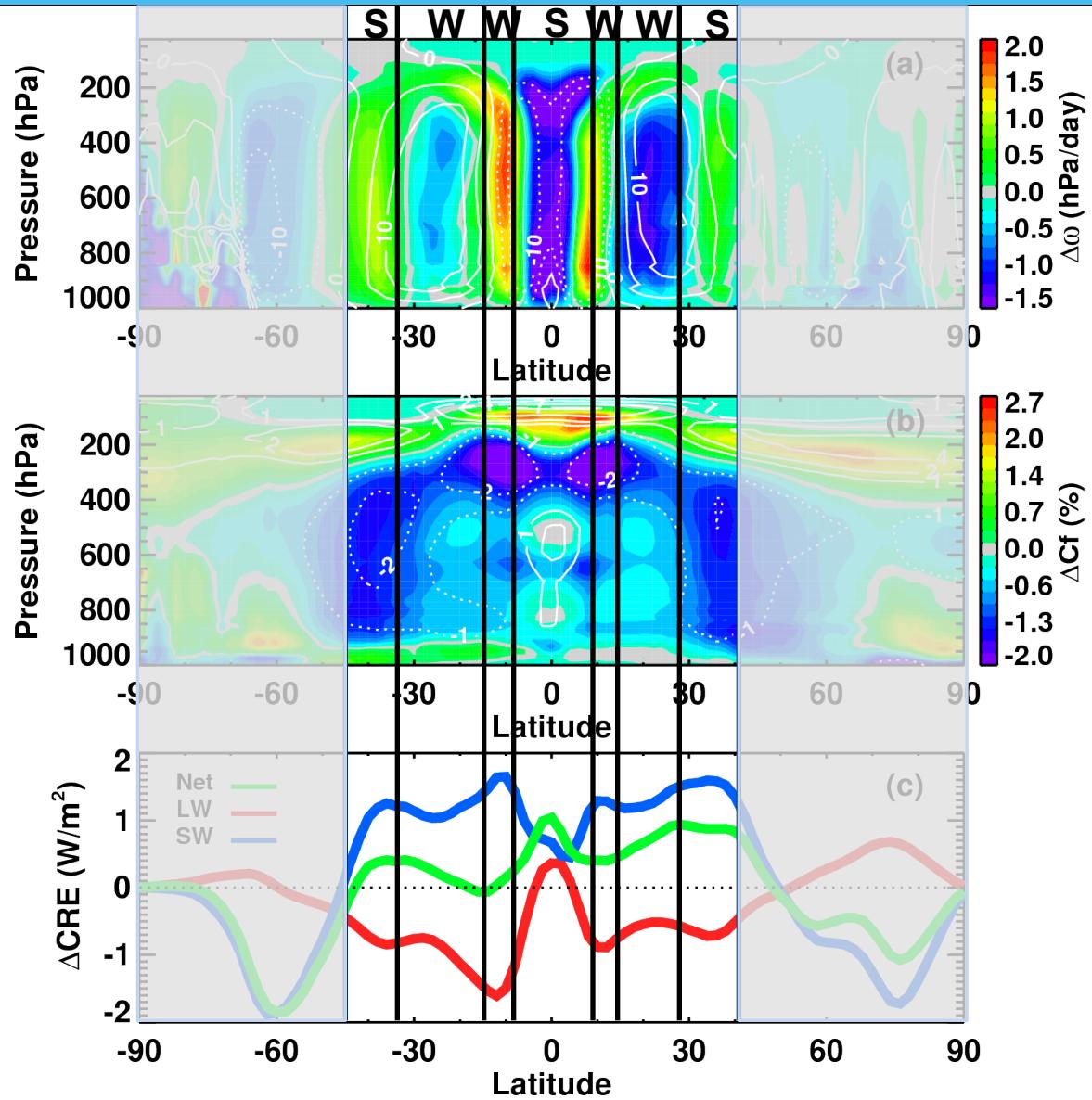
$\Delta = 2074-2098$ in “RCP4.5” –
 $1980-2004$ in “historical run”

Equator-ward side of Descent Zone (about 15°-30°N/S)



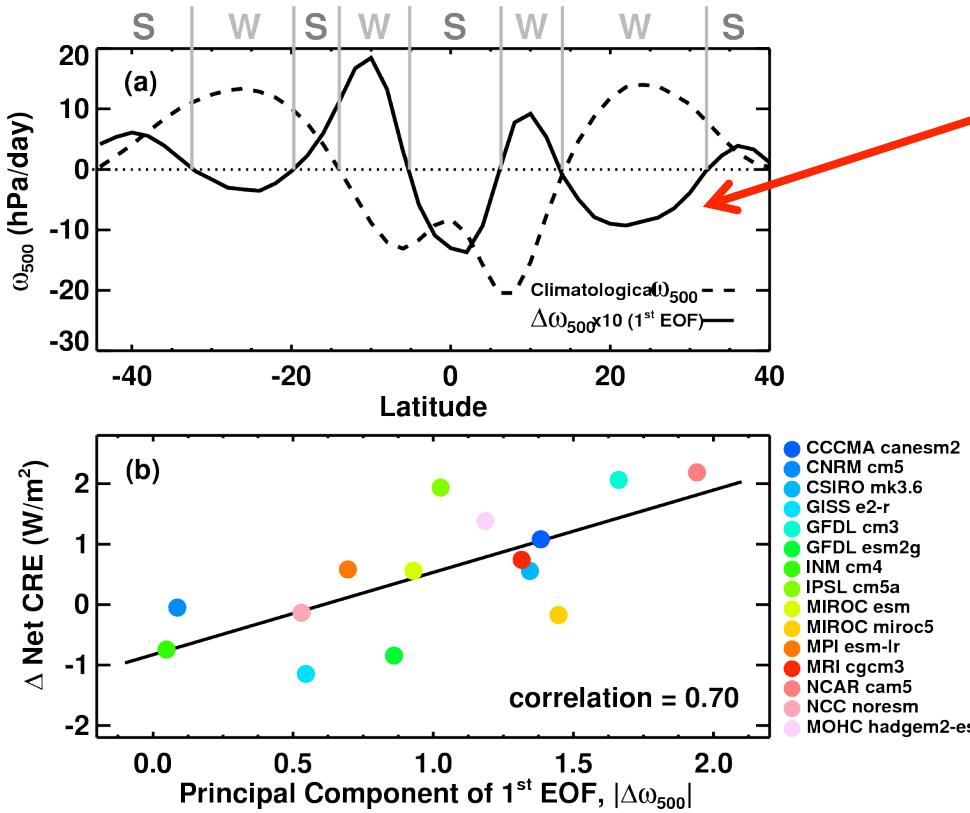
$\Delta = \text{2074-2098 in "RCP4.5"} - \text{1980-2004 in "historical run"}$

Poleward-side of Descent Zone (about 30°-45°N/S)



$\Delta = \text{2074-2098 in "RCP4.5"} - \text{1980-2004 in "historical run"}$

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

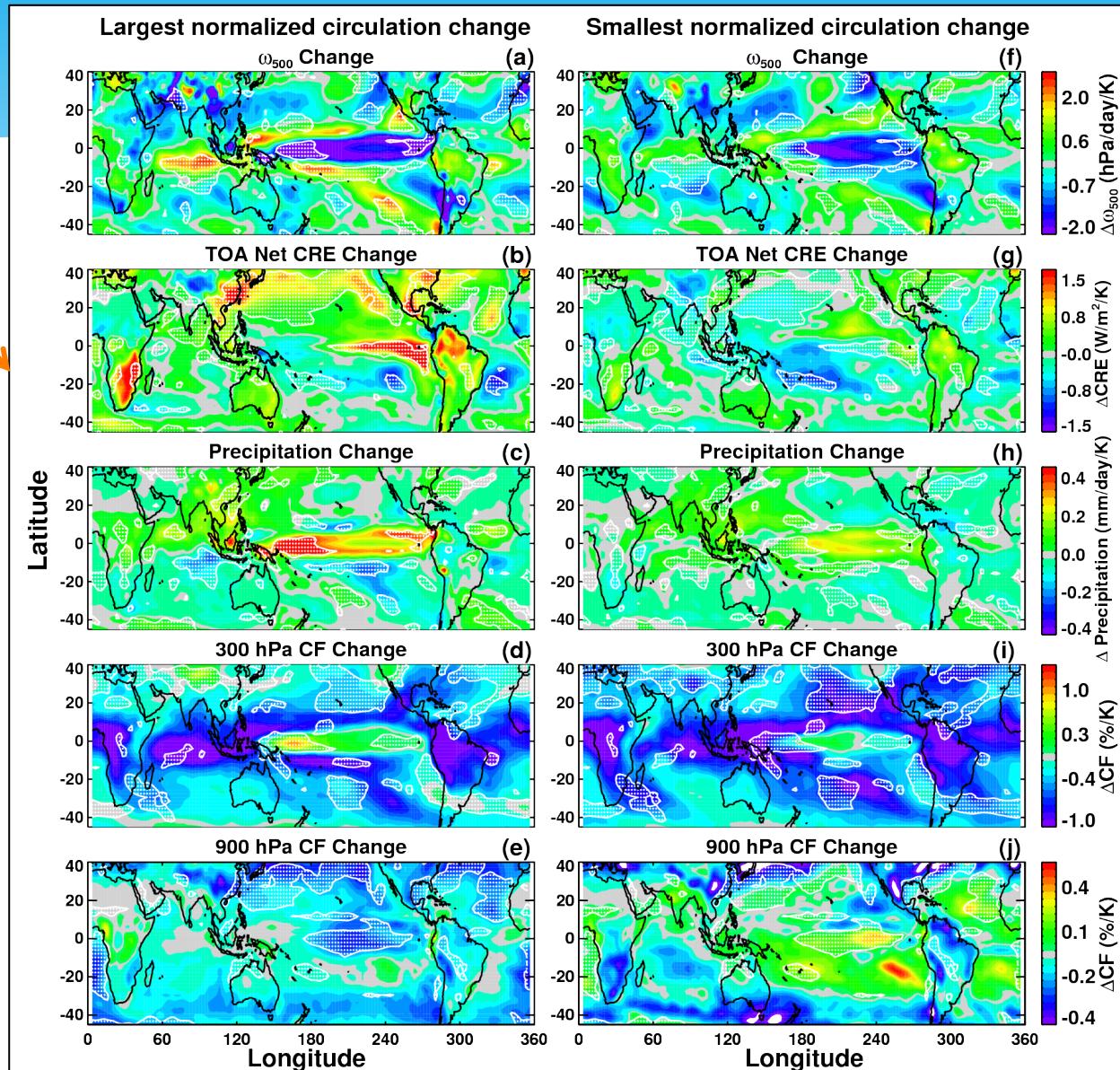


The explained variance by the 1st EOF is
57%

- ✓ 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

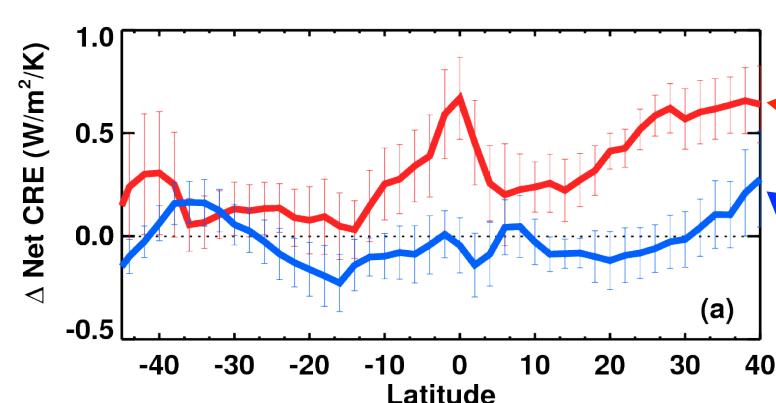
Largest
Circu.
Change



Smallest
Circu.
Change

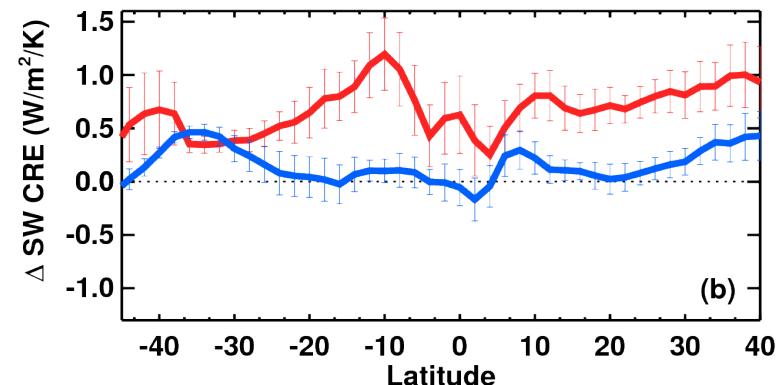
Normalized CRE Changes

Net CRE



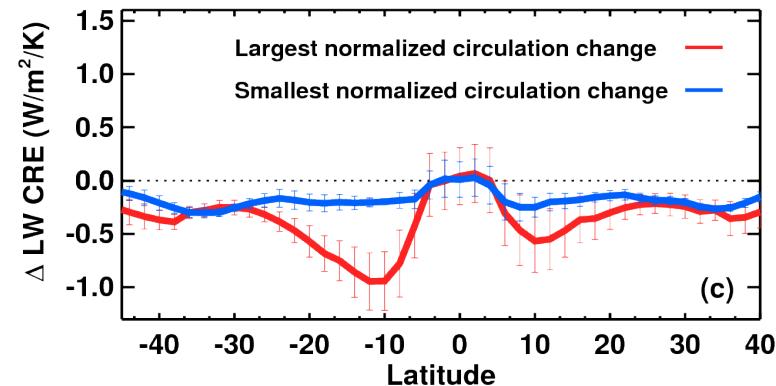
Largest
Circu.
Change

SW CRE

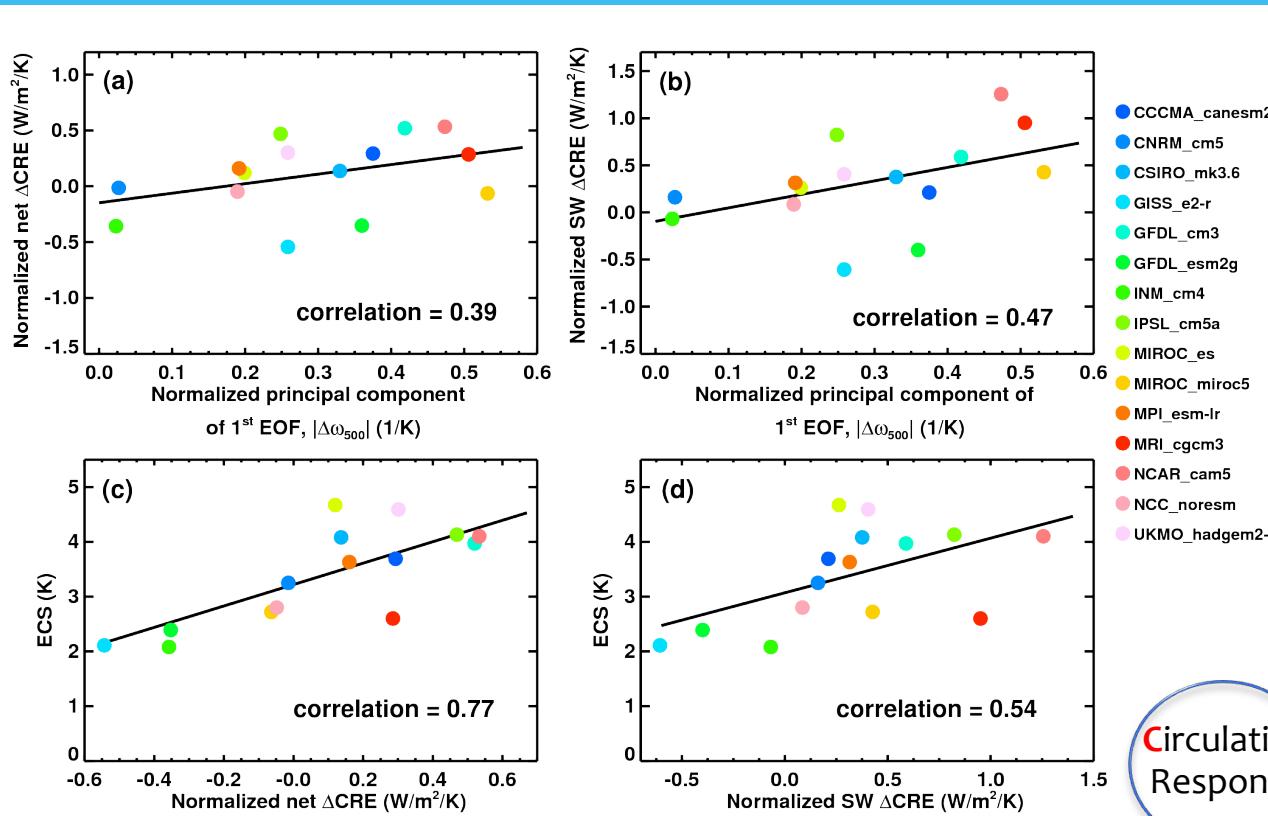


Smallest
Circu.
Change

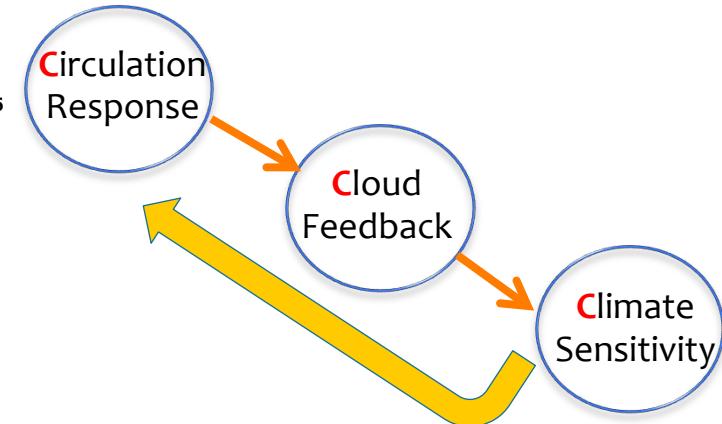
LW CRE



Circulation, Cloud Feedback and Climate Sensitivity

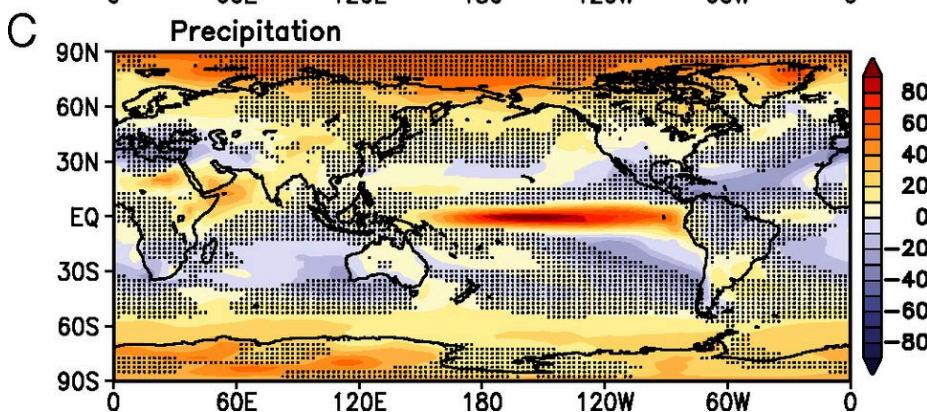
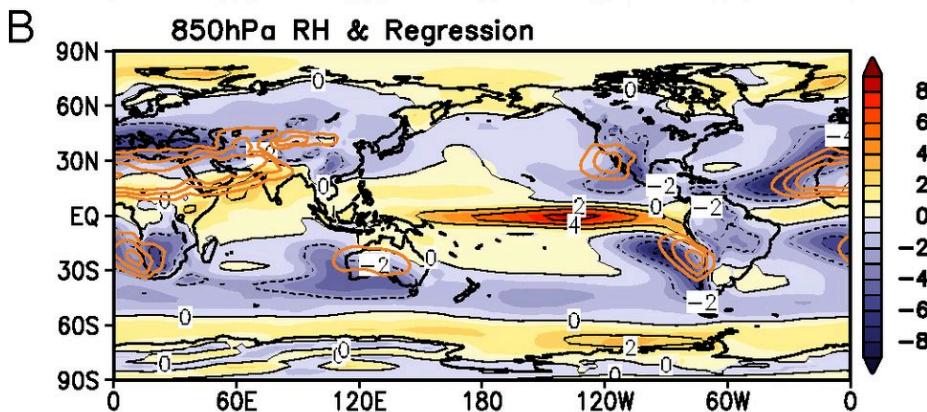
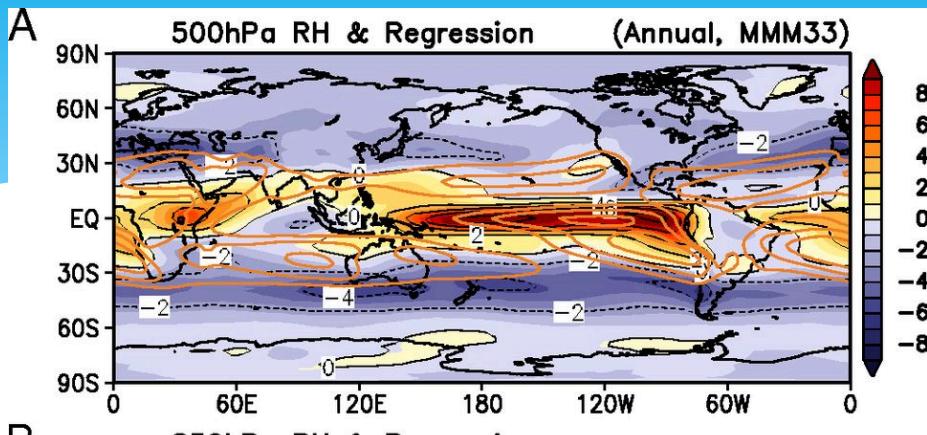


Inter-model Spread



“Three Cs”

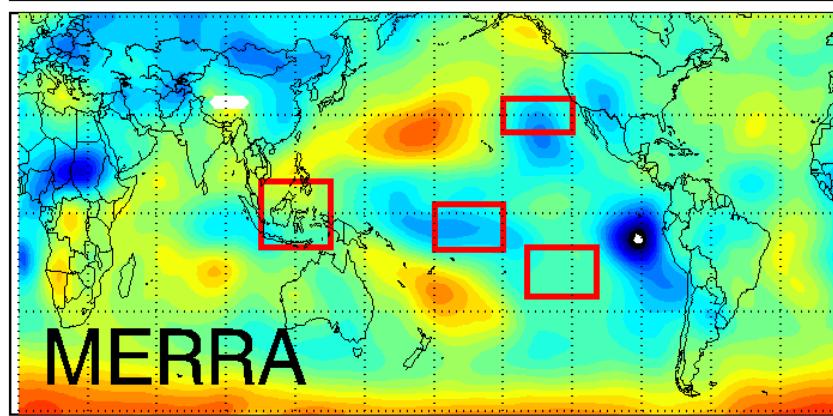
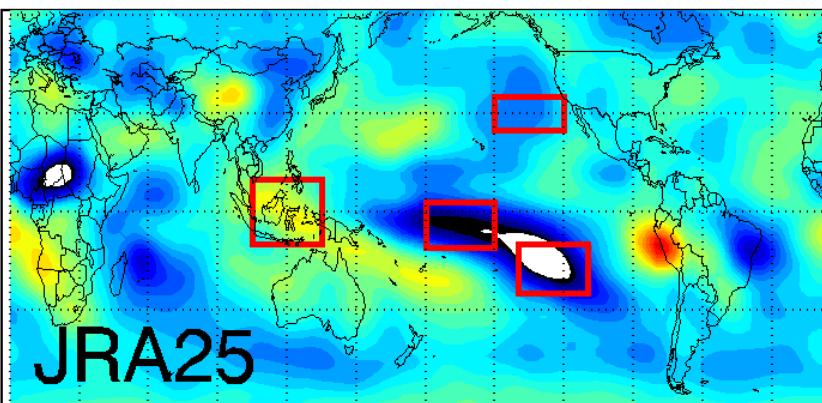
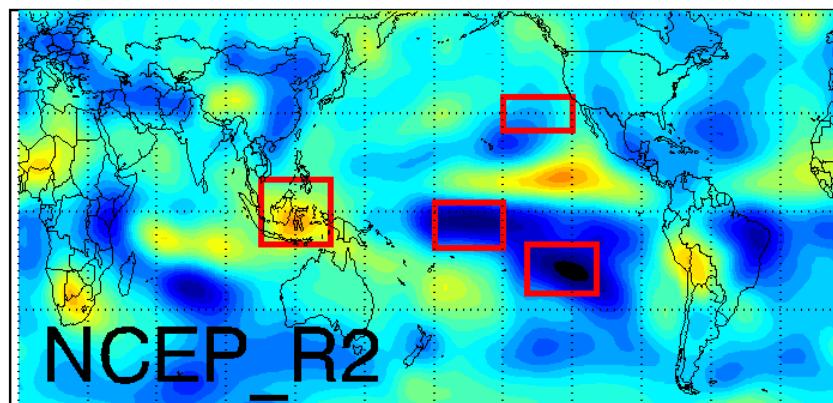
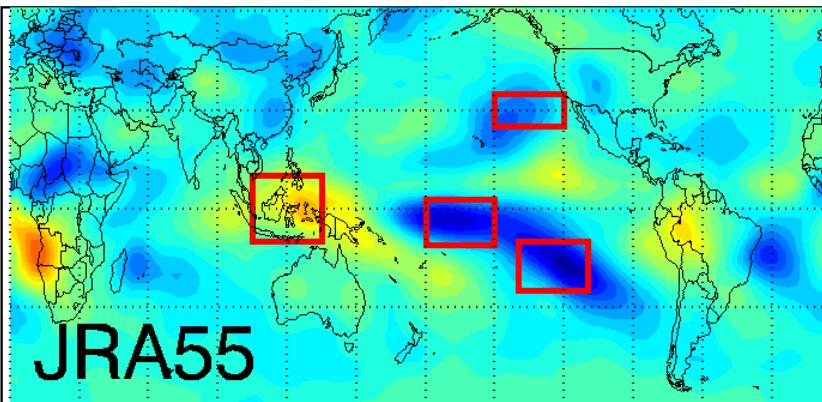
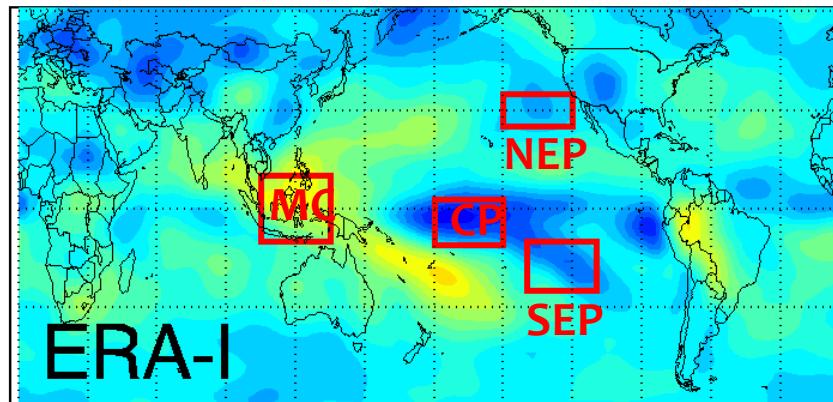
Circulation Change and Global Dryness



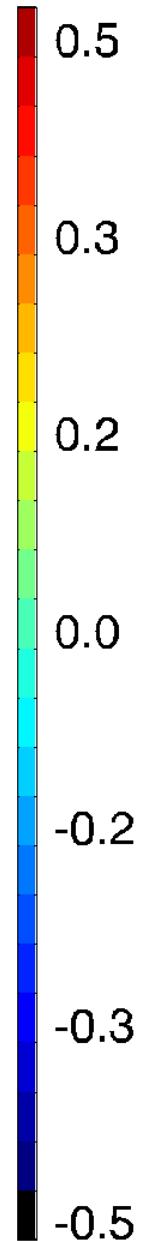
(Lau and Kim, PNAS, 2015)

“.....greenhouse warming is likely to contribute to the observed prolonged worldwide droughts in recent decades.”

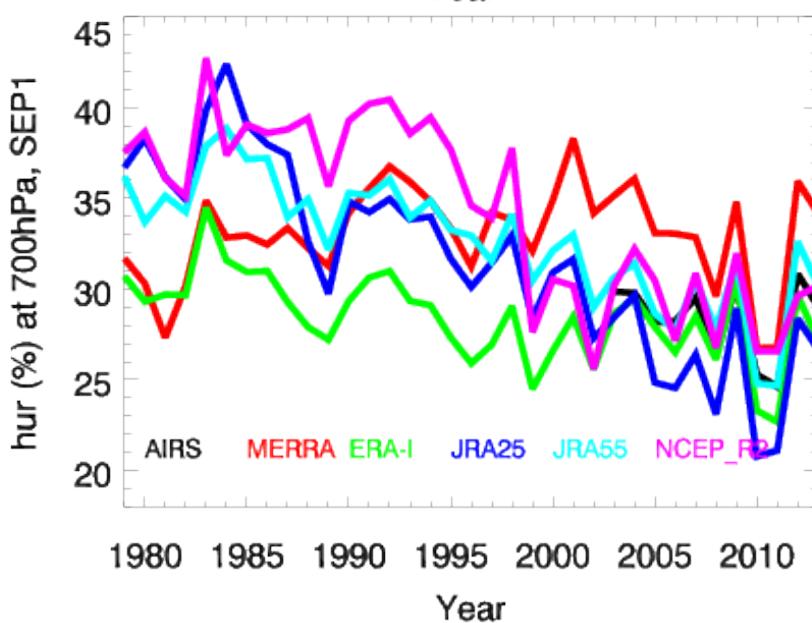
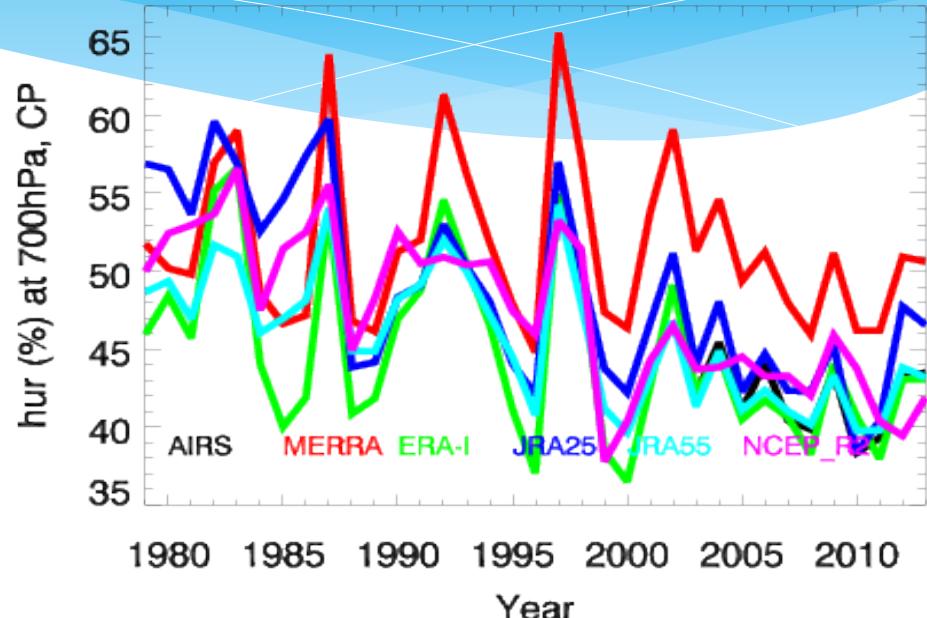
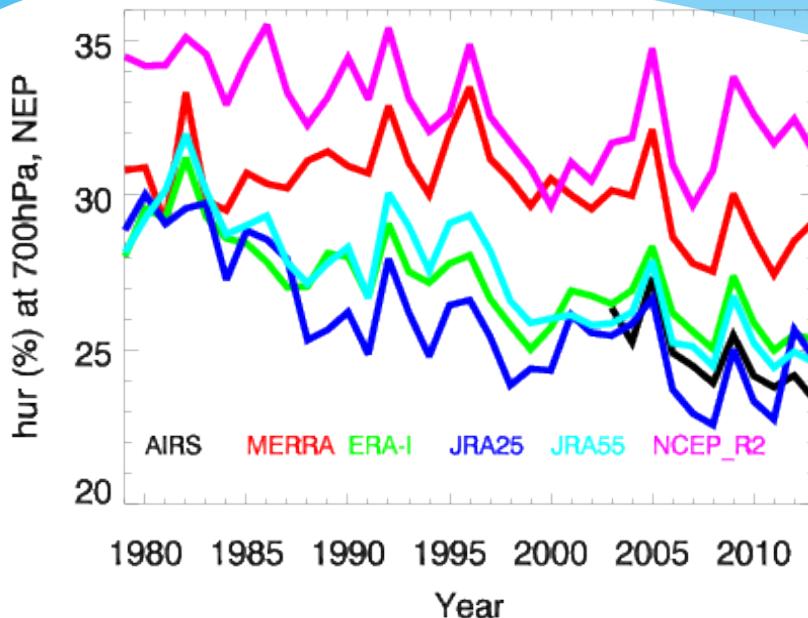
700 hPa Relative Humidity Trend (1979-2013)



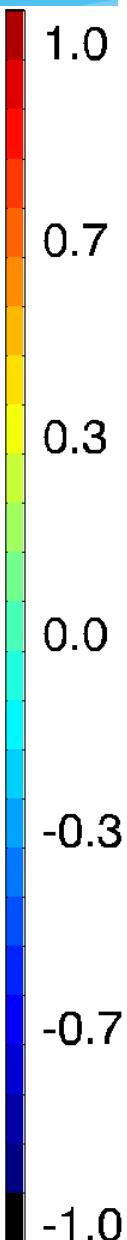
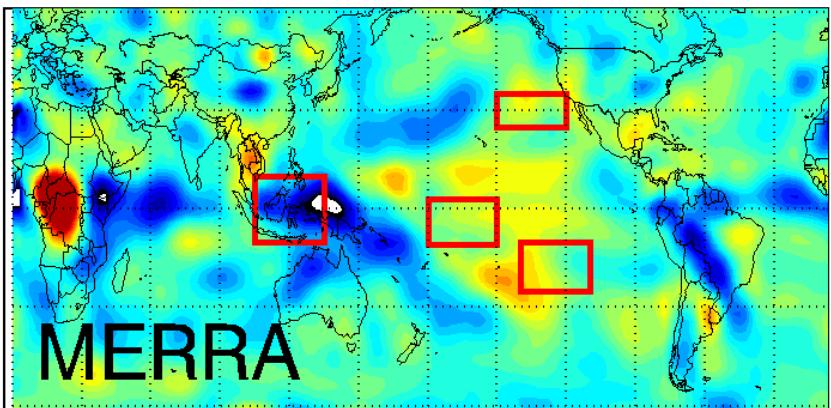
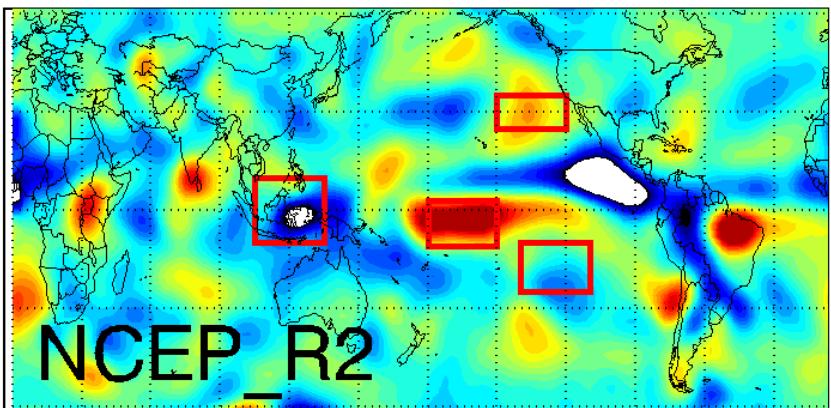
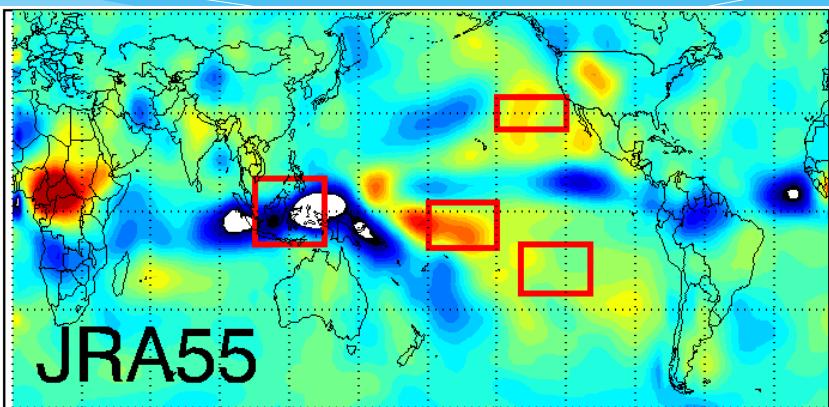
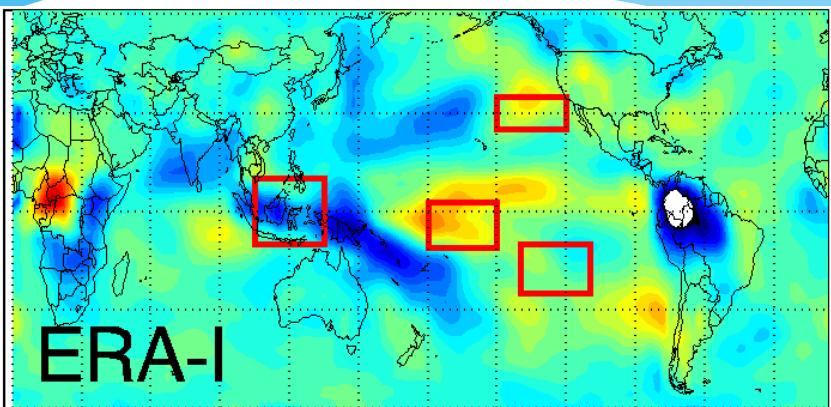
(Su et al., in prep)



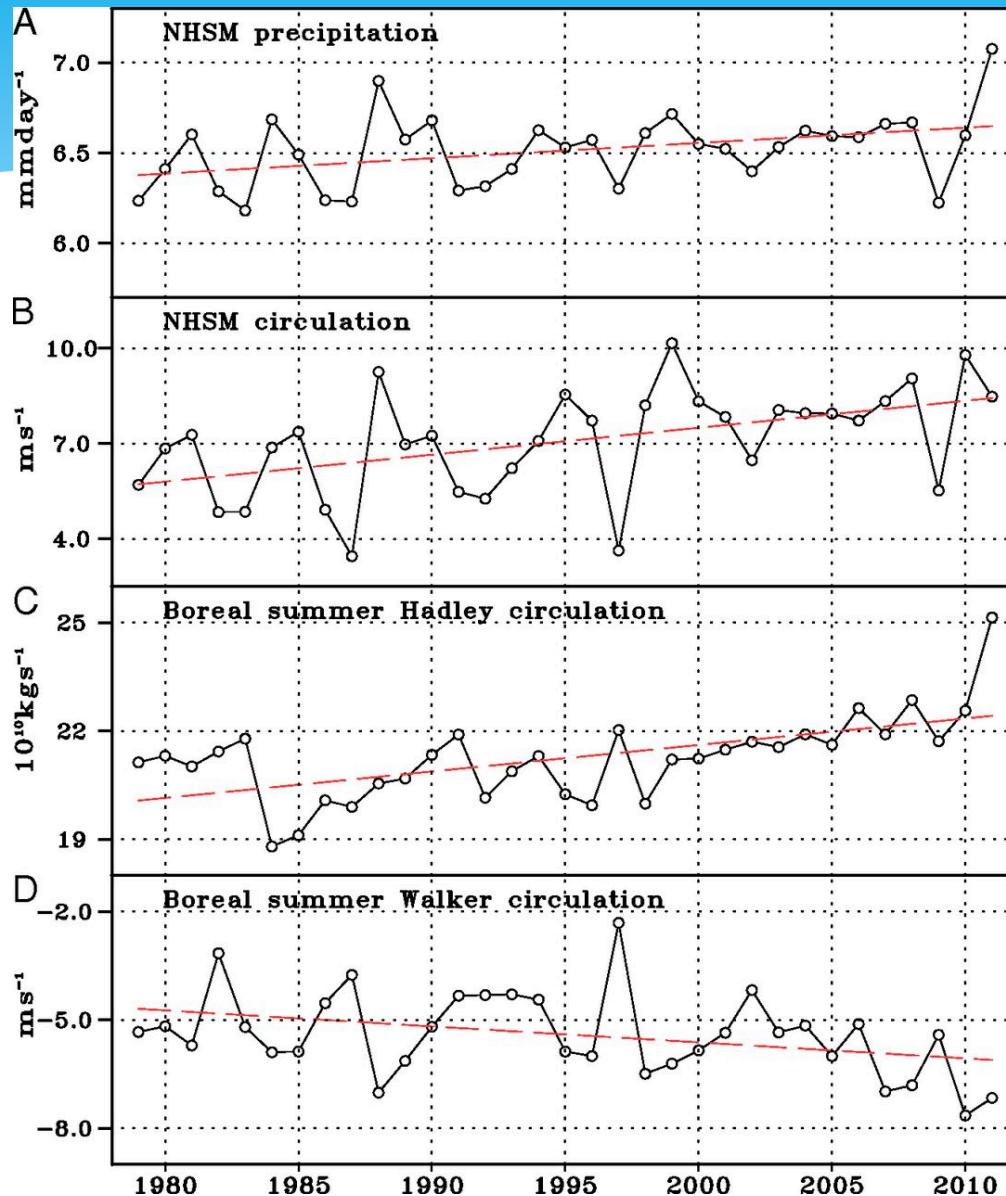
Observed RH at 700 hPa (1979-2013)



Trend in ω_{500} (10^{-3} Pa s $^{-1}$ /year)

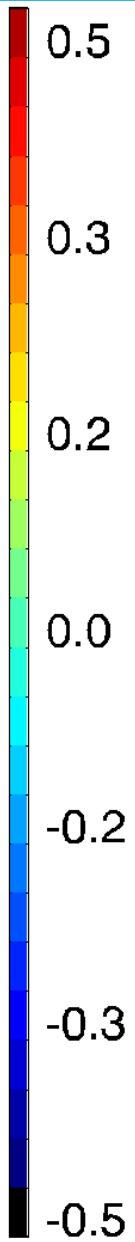
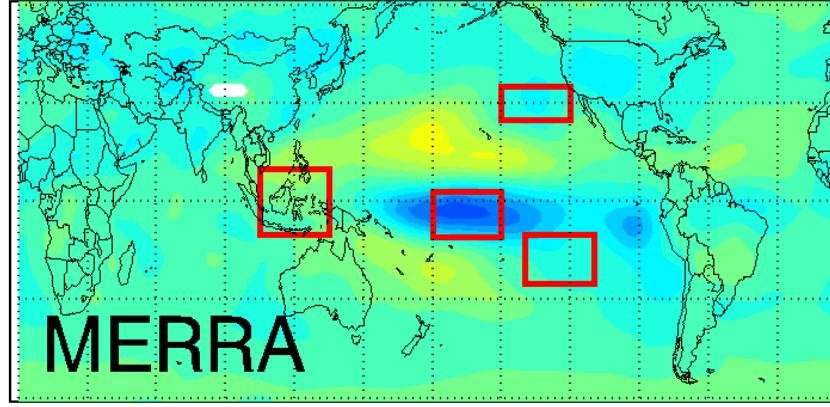
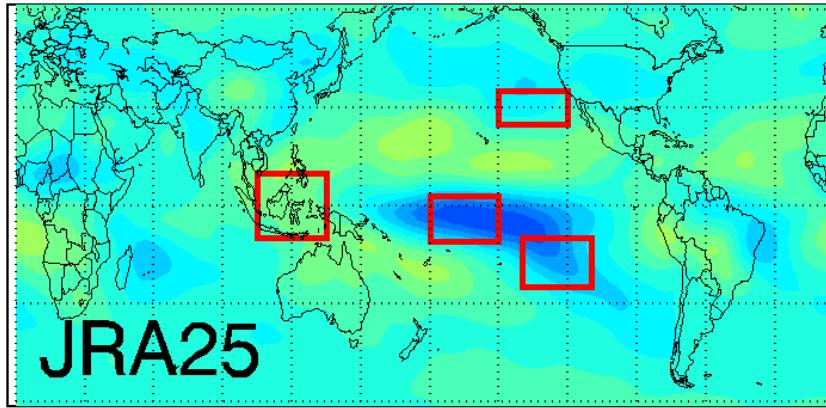
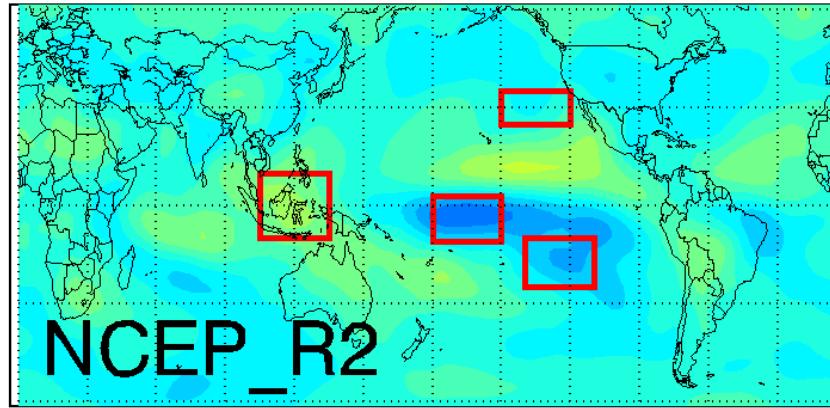
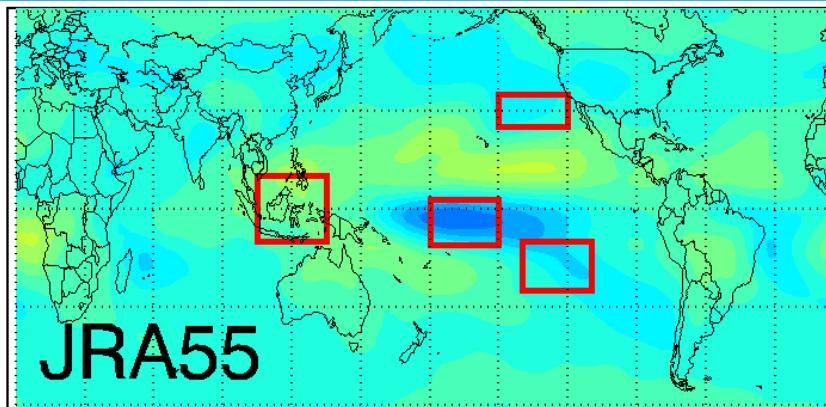
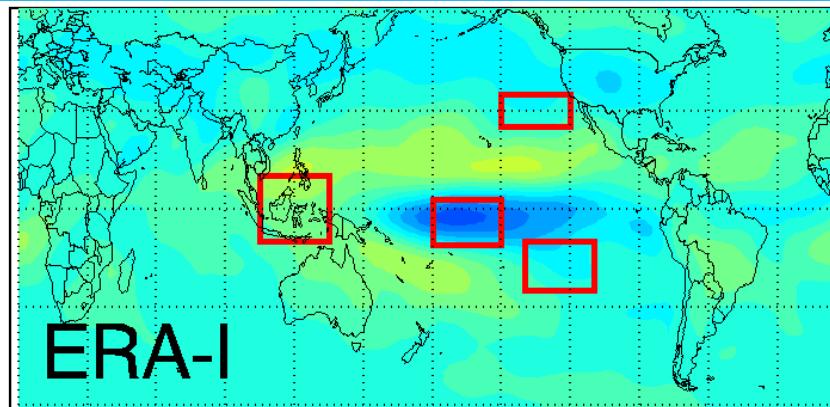


Circulation Trend in the Past 30 years

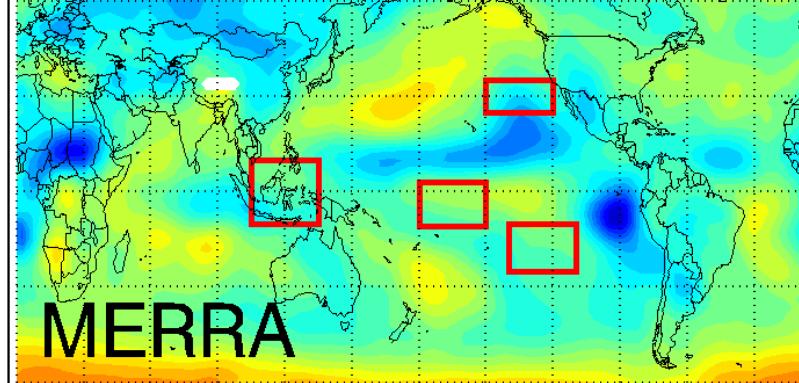
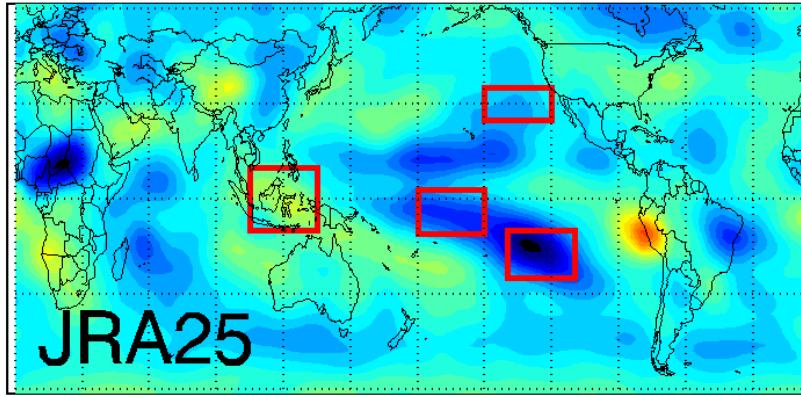
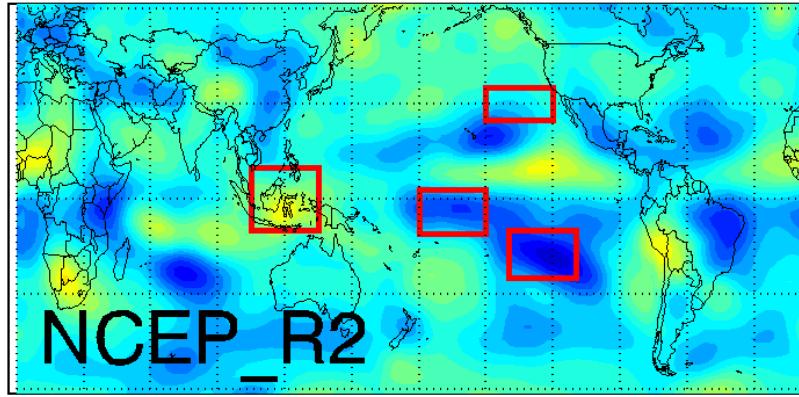
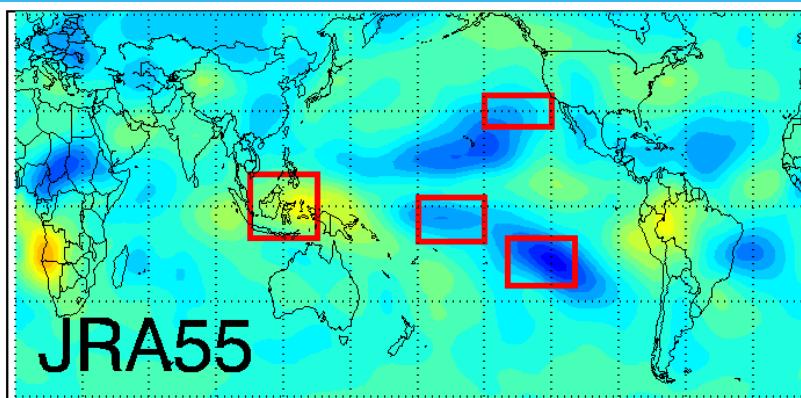
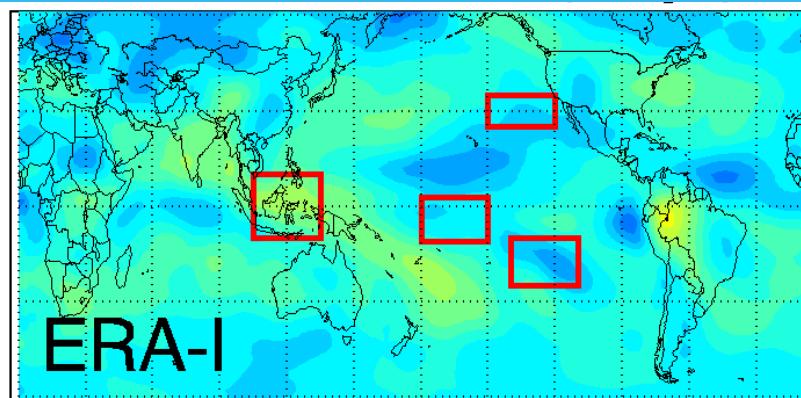


(Wang et al., PNAS 2013)

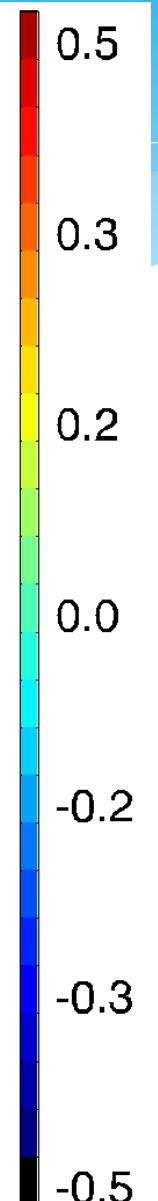
PDO Driven Trends in 700 hPa RH



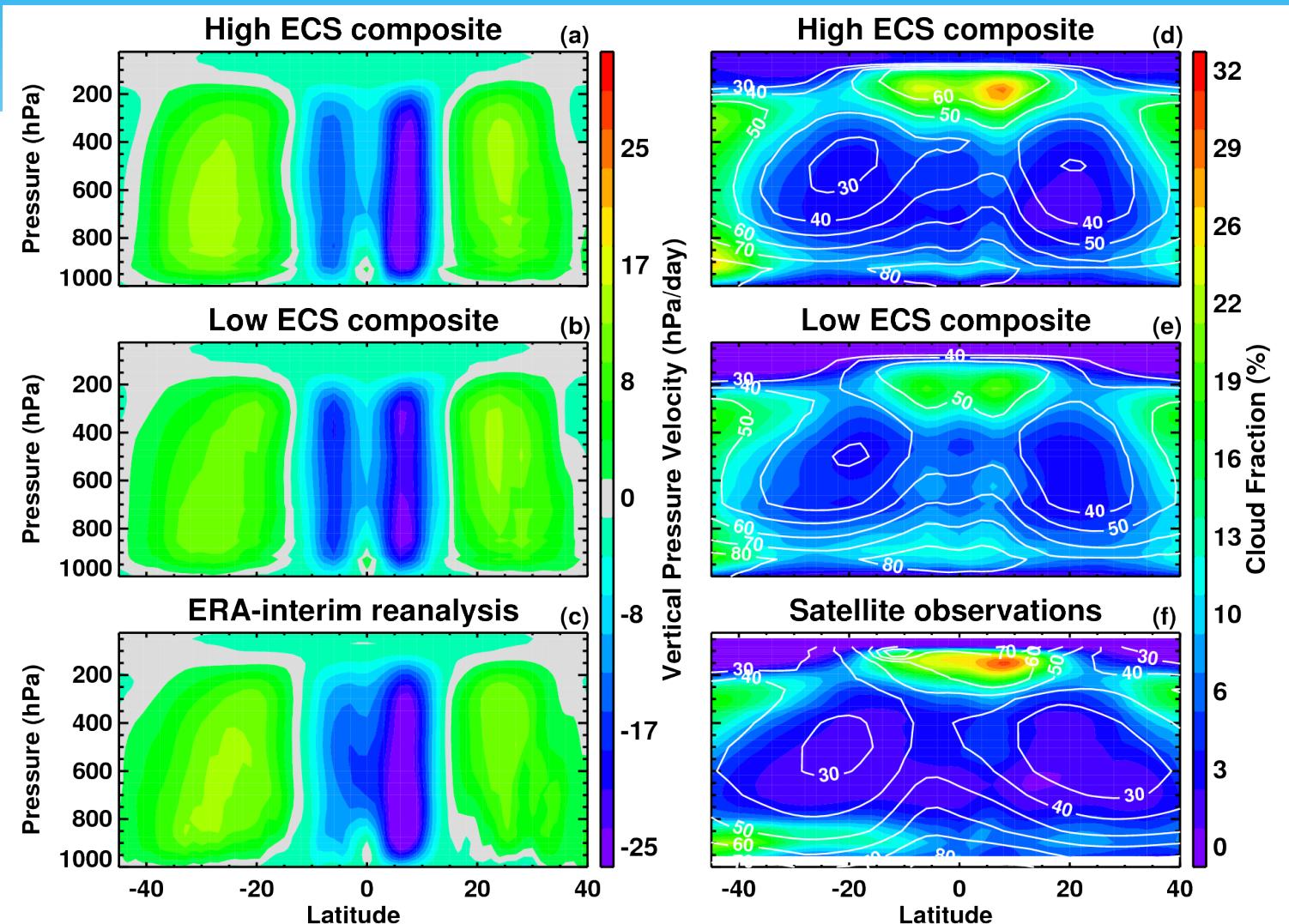
Non-PDO Trends in 700 hPa RH



	NEP	SEP	CP	MC
By PDO	32%	30%	65%	52%



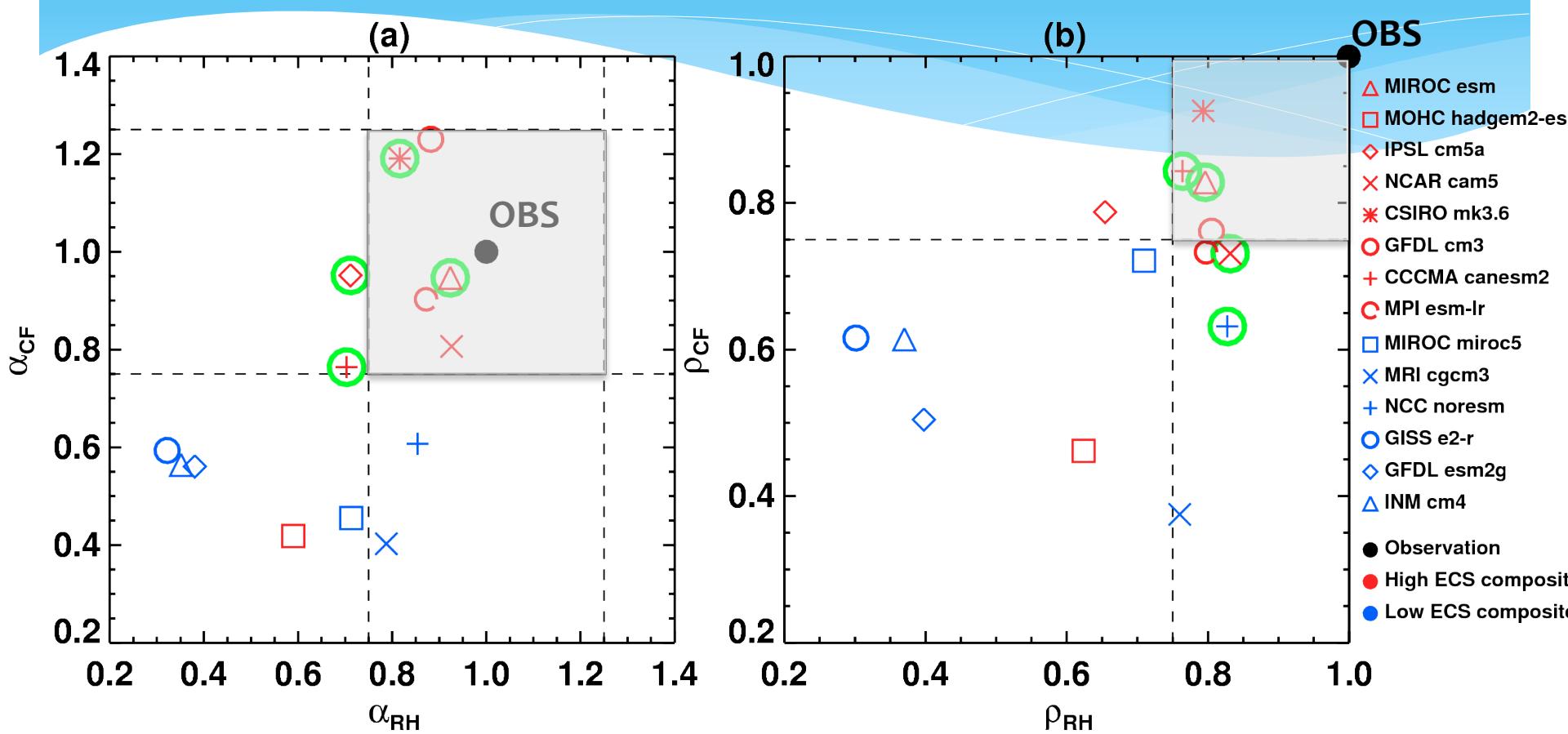
Emergent Constraint on Climate Sensitivity



The Hadley Circulation

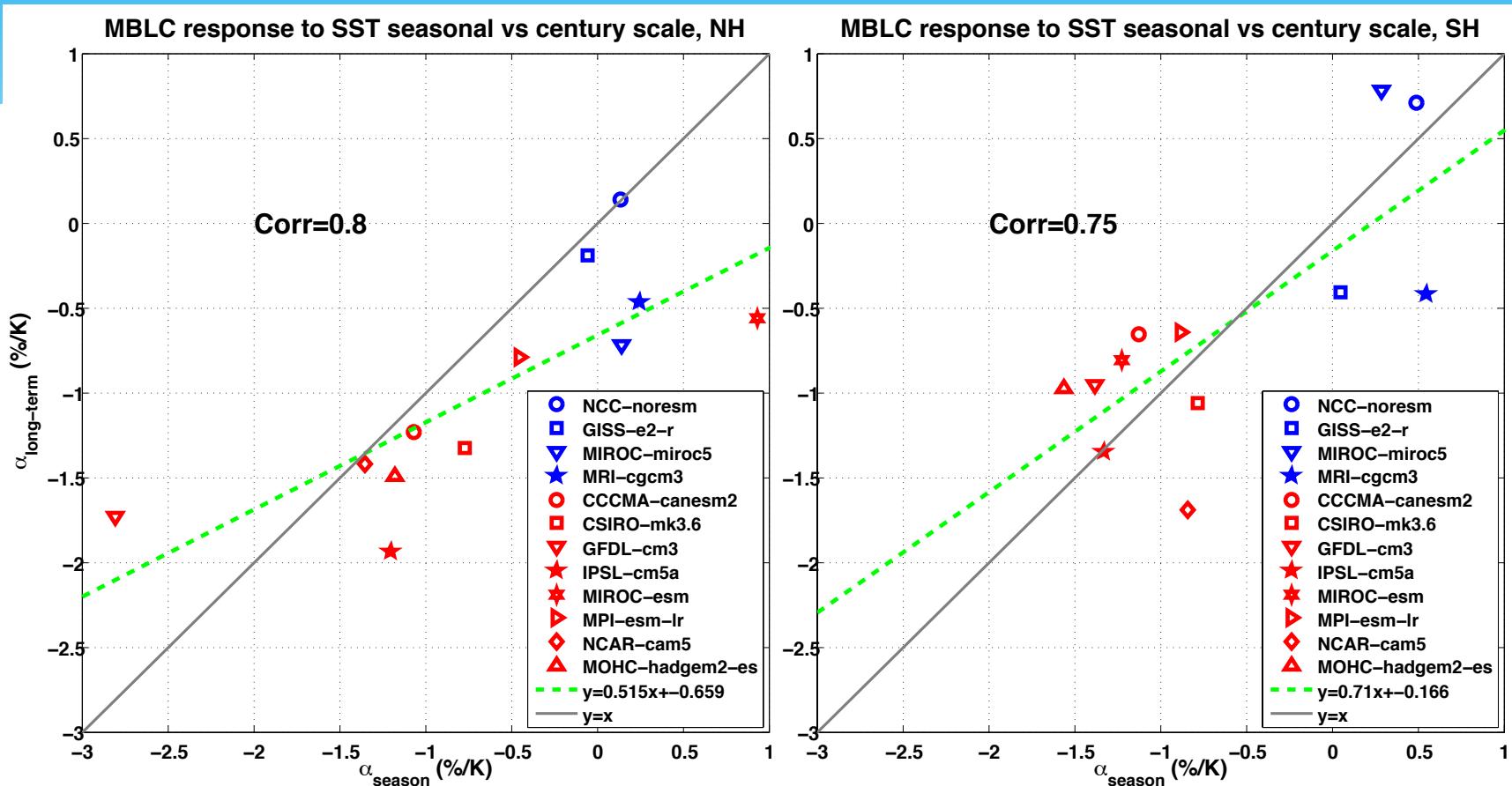
CloudSat/CALIPSO Cloud Fraction and
AIRS/MLS Relative Humidity

Hadley Circulation Structure Suggests High Climate Sensitivity



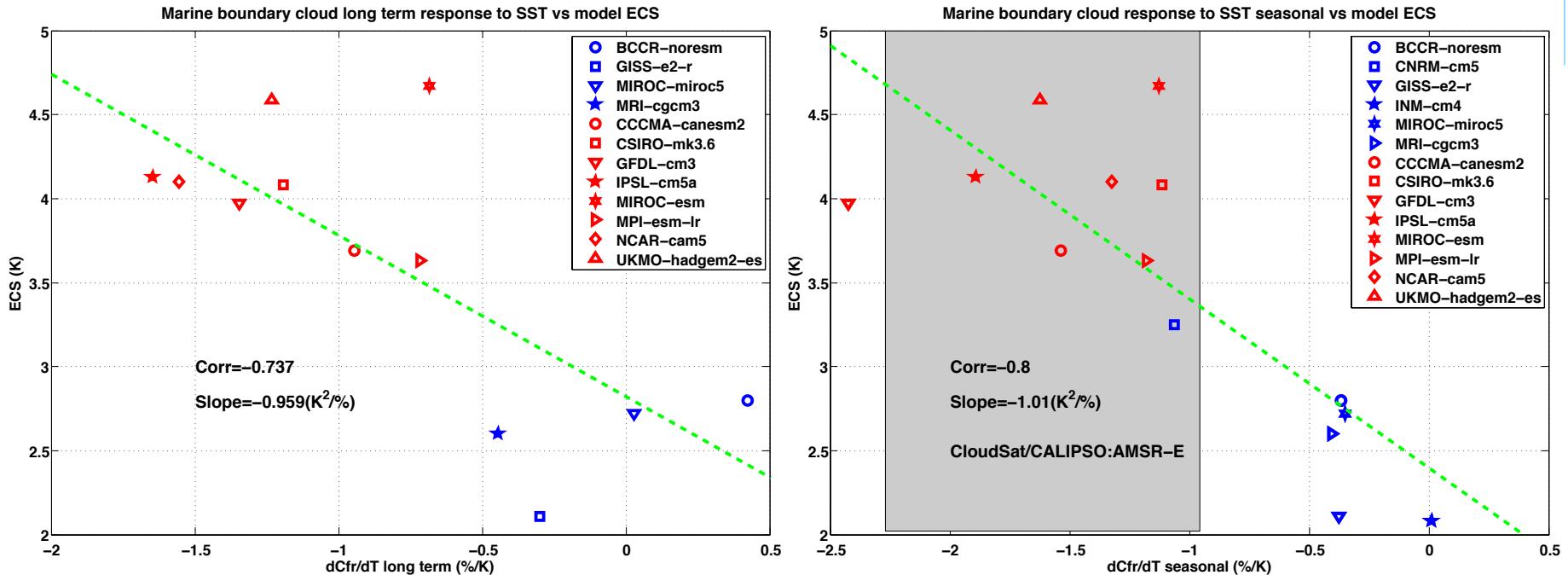
(Su et al., JGR, 2014)

Long-term Cloud Change imprinted in Seasonal Variation



(Zhai, Jiang and Su, GRL, in review)

Another Evidence of High Climate Sensitivity



(Zhai, Jiang and Su, GRL, in review)

Conclusions

- Changes of the Hadley Circulation exhibit latitudinally alternating weakening and strengthening structures, with nearly equal contributions by the weakening or strengthening segments to the integrated cloud radiative effect changes within the Hadley Cell.
- Model differences in circulation change is correlated with cloud feedback strength and explains about 15-20% of the inter-model spread in cloud radiative effect changes.
- In the past 30 years, enhanced Hadley Circulation is associated with increased subtropical dryness, 30% of which can be explained by PDO. The Walker Circulation is also strengthened, largely related to PDO.
- High sensitivity models simulate better the spatial variations of clouds and relative humidity in association with the Hadley Circulation than the low sensitivity models, consistent with previous studies (Fasullo and Trenberth, 2012; Klein et al., 2013; Sherwood et al., 2014; Su et al., 2014; Tian et al., 2015).

Conclusions (Cont.)

- **Inter-model spread in the variation of marine boundary layer cloud (MBLC) fraction with surface warming on the seasonal time scale is strongly correlated with that on the centennial time scales.**
- **Satellite observations of seasonal cycle of MBLC provides another evidence of high climate sensitivity.**