Clouds, Circulation, and Climate Sensitivity

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The spread of equilibrium climate sensitivity (ECS) has resisted reduction for decades.

Cloud feedback is one of the leading contributors to the inter-model spread in climate sensitivity.

- What drives the inter-model spread in cloud feedback?
- Can present-day observations provide constraints on ECS?
Subtropical free-tropospheric relative humidity (RH) bears a strong negative correlation with ECS.

Models that are close to the observed RH have relatively high ECS.

(Fasullo and Trenberth, Science, 2012)

Lower Tropospheric Mixing Index (LTMI) = Small-scale mixing (S) + Large-scale mixing (D)

\[
S = \frac{(\Delta R_{700-850}/100\% - \Delta T_{700-850}/9K)}{2} \\
D = <\Delta H(\Delta)H(-\omega_1)>/(-\omega_2 \Delta)H(-\omega_2) >
\]

where

\[
\Delta = \omega_2 - \omega_1
\]

\omega_2 \text{ the average of at 600 hPa, 500 hPa and 400 hPa} \\
\omega_1 \text{ the average of at 850 hPa and 700 hPa}

(Sherwood et al., Nature, 2014)
Changes of the Hadley Circulation, Clouds and Cloud Radiative Effects in the RCP4.5

\[ \Delta = 2074-2098 \text{ in “RCP4.5”} - 1980-2004 \text{ in “historical run”} \]

Multi-model-mean from 15 CMIP5 coupled models
The Equatorial Tropics
(around 5°S to 5°N)

Δ = 2074-2098 in “RCP4.5” – 1980-2004 in “historical run”
The Poleward Flanks of Deep Tropics (around 5° to 15°N/S)

Δ = 2074-2098 in “RCP4.5” – 1980-2004 in “historical run”
Equator-ward side of Descent Zone
(about 15°-30°N/S)

Δ = 2074-2098 in “RCP4.5” –
1980-2004 in “historical run”
Poleward-side of Descent Zone
(about 30°-45°N/S)

\[ \Delta = 2074-2098 \text{ in “RCP4.5”} \quad - \quad 1980-2004 \text{ in “historical run”} \]
Quantifying the Model Differences in Circulation and Relation with Cloud Radiative Effect Changes

- 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 are highly correlated with the inter-model spread in net CRE.

The explained variance by the 1st EOF is 57%.
Normalized Response

Largest Circu. Change

Smallest Circu. Change
Normalized CRE Changes

- **Net CRE**
- **SW CRE**
- **LW CRE**

**Largest Circu. Change**

**Smallest Circu. Change**
Circulation, Cloud Feedback and Climate Sensitivity

Inter-model Spread

Circulation Response

Cloud Feedback

Climate Sensitivity

“Three Cs”
Comparing to Satellite Observations

The Hadley Circulation

CloudSat/CALIPSO Cloud Fraction and AIRS/MLS Relative Humidity
Quantitative Model Performance Metrics to Represent the Hadley Circulation Structure
Quantitative Model Performance Metrics to Represent the Hadley Circulation Structure
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.

• 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).

• Based on the model performance metrics that emphasize the cloud fraction and relative humidity distributions within the entire Hadley Cell, the best estimates of equilibrium climate sensitivity are higher than the multi-model-mean.
Back-up Slides
Equator-ward side of Descent Zone
(about 15°-30°N/S)

Weakening subsidence
Deepening of the boundary layer
Entrainment more free-tropospheric dry air
Decrease of low clouds

Δ = 2074-2098 in “RCP4.5” – 1980-2004 in “historical run”
Weakened Subsidence and the Boundary Layer Drying

![Graph showing normalized principal component of 1st EOF versus normalized RH700-RH850 (\%/K)]
Weakened Subsidence and Boundary Layer Drying

Mixing index $[\text{RH}(700\text{hPa}) - \text{RH}(850\text{hPa})]$, Smallest Norm. Circu.

Mixing index $[\text{RH}(700\text{hPa}) - \text{RH}(850\text{hPa})]$, Largest Norm. Circu.
The best estimates of ECS range from 3.6 to 4.7°C, with a mean of 4.1°C and a standard deviation of 0.3°C, compared to the multi-model-mean of 3.4°C and a standard deviation of 0.9°C.