Changes of the Hadley Circulation Under Global Warming and Their Linkage with Climate Sensitivity and Hydrological Sensitivity

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Large Spread in Climate Sensitivity and Hydrological Sensitivity

Equilibrium Climate Sensitivity: 2 K – 4.5 K

Temperature-mediated dP/dT_s: 2%/K – 3%/K
Changes of the Hadley Circulation, Clouds and Precipitation Under Global Warming

Multi-model-mean from 15 CMIP5 coupled models

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

“Wet Get Wetter, Dry Get Drier”

(Su et al., JGR, 2014)
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% (Su et al., JGR, 2014)
Normalized Response

Largest Circulation Change

Smallest Circulation Change
Stronger circulation change is associated with greater boundary layer drying.
Circulation Change and Lower Tropospheric Mixing

• Stronger circulation change is associated with stronger boundary layer drying
Circulation, Cloud Feedback and Climate Sensitivity

(Su et al., JGR, 2014)
Circulation, High Cloud and Precipitation Changes

(a) ω_{500} Change

(c) Precipitation Change

(d) 300 hPa CF Change
Tightening of Hadley Ascent Links to High Cloud Cover Reduction

Interannual

dF_ω/dT_s: the fractional change of tropical ascending area per unit surface warming
dCF/dT_s: the tropical-mean high cloud fraction change per unit surface warming

Centennial

Su et al. (2017, Nature Comm.)
High Cloud Shrinkage Leads to Enhanced Longwave Radiative Cooling

Su et al. (2017, Nature Comm.)
• Unconstrained hydrological sensitivity: 2.1%/K to 3.2%/K
• Observation-constrained hydrological sensitivity: 2.6%/K to 2.9%/K

Su et al. (2017, Nature Comm.)
Interaction between Circulation, Clouds and Precipitation

- Stronger Hadley Circulation Change
- Greater subtropical boundary layer drying
- Greater decrease of subtropical low clouds
- Reduced shortwave cloud cooling effect
- High climate sensitivity

INCREASED OLR
- Radiator Fin Expansion
- dry & clear
- RADIATIVE COOLING

DECREASED OLR
- IRIS Shrinkage
- moist & cloudy
- STRENGTHENED ASCENT
- TIGHTENING OF HADLEY ASCENT
- LATENT HEATING
- Enhanced atmospheric longwave cooling
- Reduced cloud longwave warming effect

INCREASED OLR
- Radiator Fin Expansion
- dry & clear

Tightening of Hadley ascent
- Narrowing of ITCZ

Decrease of tropical high clouds
- Expansion of dry and clear area

High climate sensitivity

Higher $dP/dT_s$; Wet Get Wetter and Narrower
Conclusions

• Changes of the Hadley Circulation exhibit latitudinally alternating weakening and strengthening structures.

• Stronger Hadley Circulation change is associated with greater boundary layer drying, which may contribute to the greater decrease of subtropical low cloud fraction and thus higher climate sensitivity.

• The tightening of the ascending branch of the Hadley Circulation is strongly coupled with the decrease of tropical-mean high cloud fraction, which contributes primarily to the inter-model spread in the rates of longwave radiative loss to space and therefore the spread in global-mean precipitation change per unit surface warming.

• Understanding the interactions between circulation, clouds, and precipitation is central to reducing uncertainties of climate sensitivity and hydrological sensitivity.
Atmospheric Energy Constraint on Precipitation

\[ L_vP = LWC - SWA - SH \]

DeAngelis et al. (2015, Nature)
Implications for Extreme Precipitation

Centennial

Global $L_v \cdot dP / dT_s$ (W m$^{-2}$K$^{-1}$)

-0.65

Tropical $dF_\omega / dT_s$ (% K$^{-1}$)

-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4

Wet-area $L_v \cdot dP_{wet} / dT_s$ correlation = -0.52

Su et al. (2017, Nature Comm.)
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 Wet Get Wetter, The Dry Get Drier” (Su et al., JGR, 2014)
Normalized CRE Changes

Net CRE

SW CRE

LW CRE

Largest Circu. Change

Smallest Circu. Change