Historical and Future Changes of Tropical Rain Belts: Cloud and Aerosol Processes

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WCRP Grand Challenge 2\textsuperscript{nd} Meeting on Monsoons and Tropical Rain Belts
July 2-5, Trieste, Italy
Outline

• Atmospheric energy constraint on global-mean precipitation
• Moist static energy (MSE) framework for tropical circulation
• Observations of tropical rain belt change
Atmospheric Energy Constraint on Global-mean Precipitation

\[ L_v P = LWC - SWA - SH \]

Allen and Ingram (2002, Nature)

DeAngelis et al. (2015, Nature)
Clear-sky Longwave Radiation

Allan (2009, J. Clim)

$LW_c$ here is clear-sky longwave radiative cooling
Inter-model Spread in Clear-sky Shortwave Absorption

Pendergrass and Hartmann (2012, GRL)

DeAngelis et al. (2015, Nature)
Changes of Hadley Circulation, Cloud Radiative Effects and Precipitation

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

(Multi-model mean from 15 CMIP5 coupled models)

(Su et al., 2014, JGR)

“The Wet Get Wetter, The Dry Get Drier”
Tightening of Tropical Ascent and High Clouds Key to Precipitation Change in a Warmer Climate

Su et al. (2017, Nature Comm.)
ITCZ Narrowing Linked to High Cloud Reduction

(a) Interannual tropical $\frac{dF_\omega}{dT_s}$ vs. $\frac{dF}{dT}$ (%/K)

(b) Centennial tropical $\frac{dF_\omega}{dT_s}$ vs. $\frac{dF}{dT}$ (%/K)

- Correlation = 0.51
- Correlation = 0.65

Su et al. (2017, Nature Comm.)
Longwave Effect of High Cloud Reduction

(a) Interannual tropical \(\frac{d\sigma_{\text{CF}}}{dT_s}\) (W/m\(^2\)/K)

(b) Centennial tropical \(\frac{d\sigma_{\text{CF}}}{dT_s}\) (W/m\(^2\)/K)

Correlation = -0.77

Su et al. (2017, Nature Comm.)
Observational Constraint on Hydrological Sensitivity

- Observation-based Interannual $dP/dTs : 2.1\%/K$ to $3.0\%/K$
- Observation-constrained hydrological sensitivity: $2.6\%/K$ to $2.9\%/K$
- The multi-model-mean of the 21 models is $2.6\%/K$

Su et al. (2017, Nature Comm.)
Moisture Static Energy Budget

\[ \partial_t \langle T \rangle + \langle \mathbf{v} \cdot \nabla T \rangle + \langle \omega \partial_p s \rangle = \frac{g}{p_T} \left( P + R + H \right) \]

\[ \partial_t \langle q \rangle + \langle \mathbf{v} \cdot \nabla q \rangle + \langle \omega \partial_p q \rangle = -\frac{g}{p_T} \left( P - E \right) \]

\[
P = E - \frac{p_T}{g} \langle \mathbf{v} \cdot \nabla q \rangle - \frac{p_T}{g} \langle \omega \partial_p q \rangle
\]

\[
\Delta P_{dyn} \approx -\frac{p_T}{g} \langle \Delta \omega \partial_p q \rangle
\]

\[
\Delta P_{therm} \approx -\frac{p_T}{g} \langle \omega \partial_p \Delta q \rangle
\]


\[ \Delta P_{dyn} \propto \Delta \omega \]
Moisture Static Energy Budget

\[ \partial_t (q + T) + \langle \mathbf{v} \cdot \nabla (q + T) \rangle + \langle \omega \partial_p h \rangle = \frac{g}{p_T} F_{\text{net}} \]

\[ h = T + \phi + q = s + q \]

\[ F_{\text{net}} = R + E + H = (S^\dagger_t - S_t^\dagger - L_t^\dagger) + (S_s^\dagger - S_s^\dagger + L_s^\dagger - L_s^\dagger) + E + H \]

\[ \omega(x, y, p, t) = -\Omega_1(p) \omega_1 \quad GMS = \langle \Omega_1(-\partial_p h) \rangle \]

\[ \omega_1 \approx \frac{g}{p_T} \frac{F_{\text{net}}}{GMS} \]

\[ \Delta \omega_1 \propto \Delta F_{\text{net}} \]
Radiative Changes of Clouds and Water Vapor

Voigt and Shaw (2015, Nature Geo.)
Inter-model Spread of Circulation and Precipitation Changes

\[ \Delta P \propto \Delta \omega_1 \]
Energetic Constraint of Tropical Circulation Change

\[ R = 0.74 \]

\[ \Delta \omega_1 \propto \Delta F_{net} \]
Longwave Cloud Radiative Effect

- Less longwave loss at TOA leads to a stronger ascent
Clear-sky Shortwave Absorption

• Greater clear-sky shortwave absorption leads to a stronger ascent
The Role of Absorbing Aerosols

\[ \frac{\mathrm{d}F_{\text{SW, clr}}}{\mathrm{d}T_s} \left( \% K^{-1} \right) \]

\[ \frac{1}{F_{\text{net}}} \frac{\mathrm{d}F_{\text{SW}}}{\mathrm{d}T_s} \left( \% K^{-1} \right) \]

\[ R = 0.51 \]

Historical
Observed Narrowing of the ITCZ

Wodzicki and Rapp (2016, JGR)
Observed Narrowing of the ITCZ

Su et al. (2018, in prep)
CMIP5 Simulations of the Narrowing

Su et al. (2018, in prep)
Summary

• The changes of the ITCZ intensity and area are strongly constrained by atmospheric energy budget.

• Model diversity in the radiative effects of tropical high clouds and absorbing aerosols contributes significantly to the inter-model spread in the ITCZ intensity and area changes in the past decades.

• Observational evidence of the narrowing of ITCZ is robust.