A mechanism for zonally asymmetric circulation and precipitation response to global warming in the subtropics

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Zonal asymmetries in precipitation in present-day climate

Zonal asymmetries in precipitation with global warming

GFDL CM3: RCP8.5
$\Delta$: (2091-2100) minus (2006-2015)
Constraints on circulation and precipitation changes with global warming

• CMIP5 models predict an increase in precipitation and a weakening of the time-mean mass flux with global warming. [Held and Soden, 2006; Vecchi and Soden, 2007]

• Stationary circulations in the subtropics (monsoon flows) and deep tropics (Walker cell) weakens with global warming faster than the zonal-mean circulation (Hadley cells). [Vecchi et al., 2006; Douville et al., 2002; Tanaka et al., 2004; Ueda et al., 2006; Cherchi et al., 2011; Ma et Yu, 2014]

• Precipitation and circulation are constrained globally, but no comprehensive theory describes local changes or changes in one of their component (e.g., zonal-mean or stationary). [Mitchell et al., 1987; Knutson and Manabe, 1995; Allen and Ingram, 2002; O’Gorman and Schneider, 2008; Schneider et al., 2010; O’Gorman et al., 2012]
Setting description: “Gill-like” forcing

Global warming experiment with idealized GCM (T85, 30 levels) [O’Gorman and Schneider, 2008]

Surface conditions: Slab ocean, uniform thermal inertia and albedo

Forcing: Uniform insolation

Global warming: Longwave optical depth is varied globally, mimicking increase or decrease in GHG concentration
Hydrologic imbalance

Contours: P-E ≤ -1.5 mm day⁻¹ in cold (Ts=291K, cyan), reference (Ts=302K, green) and warm (Ts=311K, magenta) climates

Wet zones near heating zone, enhanced dryness to the west.
Zonally asymmetric precipitation

Wet zones near heating zone, dryness to the west.

Contours: $P^+ \leq -1.5$ mm day$^{-1}$ in cold (Ts=291K, cyan), reference (Ts=302K, green) and warm (Ts=311K, magenta) climates

Wet zones near heating zone, dryness to the west.
Stationary vertical wind

Contours: $\omega^+ \geq 1.5 \times 10^{-8} \text{ s}^{-1}$ in cold ($T_s=291\text{K}$, cyan), reference ($T_s=302\text{K}$, green) and warm ($T_s=311\text{K}$, magenta) climates

Hydrologic pattern largely consistent with stationary wind
Stationary vertical wind

\[ \omega^* = g^{-1} \int \omega^+ \mathcal{H} (\omega^+(p_b)) \, d\mathcal{A} \quad \text{with } p_b = 850 \text{mbar} \]

Hydrologic pattern largely consistent with stationary wind
Vertical profile of stationary updraft with global warming

Troposphere deepens with global warming
Stationary circulation is non-monotonic with global warming

\[ \omega^* = g^{-1} \int \omega^+ \mathcal{H} (\omega^+(p_b)) \, d\alpha \]
A modal decomposition

- The dynamics in the free troposphere depends on the sensitivity of the dynamics to a subcloud temperature anomaly, and the magnitude of the subcloud-layer temperature anomaly:

\[ \delta \omega \approx \partial_{T_r} \omega \left( \delta T_r \right) \]

\[ \omega_{bc}^* = \hat{\Omega} \omega_r^* \]
Sensitivity of vertical winds to temperature anomalies

\[ \omega^*_{bc} = \hat{\Omega} \omega^*_r \]

Low-level temperature anomalies are communicated to troposphere by convection.

Convective adjustment process is uniform across tropics.

Vertical Wind Mode

\( \sigma \)

\( \Omega \) [none]
Sensitivity of vertical winds to temperature anomalies

Vertical wind mode strengthens with global warming: i.e., winds become more sensitive to LCL temperature anomalies in warm than in cold climates
Thermal forcing on the vertical winds

\[ \omega_{bc}^* = \hat{\Omega} \omega_r^* \]

We assume friction-less Sverdrup balance in the lower troposphere.

Global stationary vertical wind coefficient

\[ \omega_r^* = p_s \frac{\beta r_d}{f^2} (-\partial_x T_r)^* \]

[SV]

Mean Surface Temperature [K]
Thermal forcing on the vertical winds

Vertical wind coefficient decreases, consistent with a weakening of the zonal temperature gradient.
Strength of stationary circulation from modal decomposition

\[ \omega_{bc}^* = \hat{\Omega} \omega_r^* \]

Modal expression captures the behavior of the stationary circulation

Global stationary vertical wind maximum from 1st BC mode

- \((\omega_{bc})_{\text{max}}\)
- \(\beta_o \big/ f_o \ [(v_{bc})_{\text{max}}]\)
- \(\Omega_{\text{max}} \ Q_o \big/ \partial_T q_s\)
Stationary circulation changes with global warming can be described by a scaling that depends only on radiative-convective properties of the atmosphere.
A mechanism for non-monotonicity in strength of stationary circulation

Non-monotonic behavior arises from dynamics being more sensitive to subcloud temperature anomalies, and subcloud temperature anomalies weakening with global warming.
Summary (1)

• We simulate a stationary circulation in an idealized moist GCM with a heat patch.
• Stationary circulation varies non-monotonically with global warming.
• Stationary circulation is non-monotonic because dynamics becomes more sensitive to temperature anomalies with global warming, but temperature anomalies weakens with global warming.
• We have formalized this behavior using a modal decomposition, and relating changes to fundamental properties of the tropical atmosphere.
Stationary precipitation changes with global warming are captured by changes in stationary circulation and zonal-mean moisture.

\[ P^* = \int P^+ \mathcal{H} (P^+) \, d \mathcal{A} \]

Global stationary precipitation from vertical wind

\[ P^* \sim \beta_o r_d \frac{\lambda}{f_o^2} \frac{\Delta Q_o}{\gamma \partial_T q_o} \left|_{s} \int_{p_b}^{p_t} \hat{\Omega} \partial_p q_o \, dp \right. \]

Stationary precipitation changes with global warming are captured by changes in stationary circulation and zonal-mean moisture.
Assuming a climate-invariant ratio of updraft and downdraft in the troposphere provides a simple explanation for the expansion of dry zones with global warming, which is found to scale with global changes in precipitation.
Summary (2)

- Changes in stationary precipitation are captured when combining non-monotonicity of stationary circulation and steady increase of tropospheric moisture.
- Dry zones, as defined by regions of negative stationary precipitation, generally expand with global warming.
- Expansion of dry zones is captured by global changes in precipitation, assuming invariance in areas covered by time-mean subsidence and upwelling.