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

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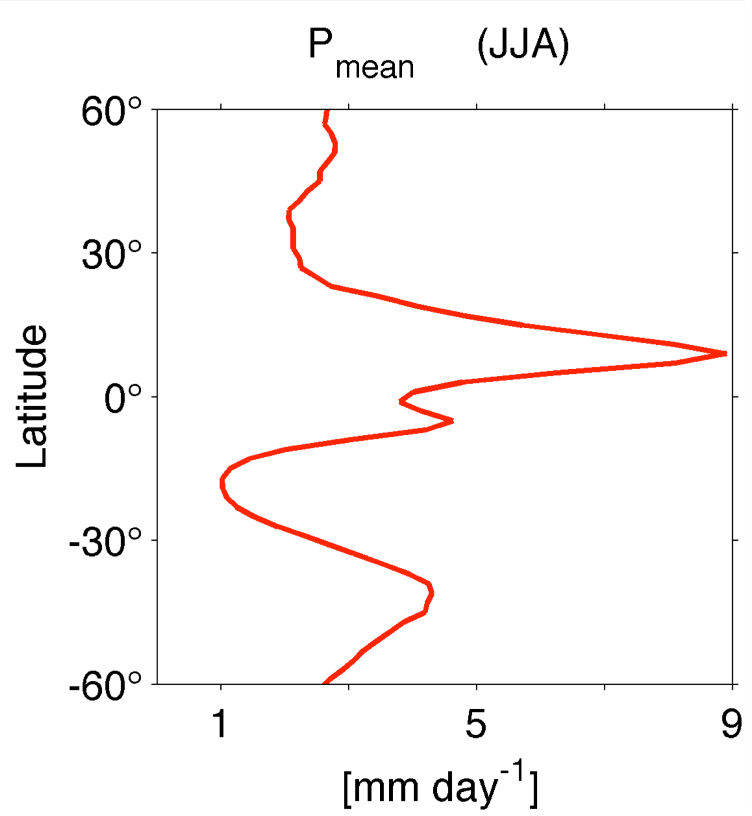
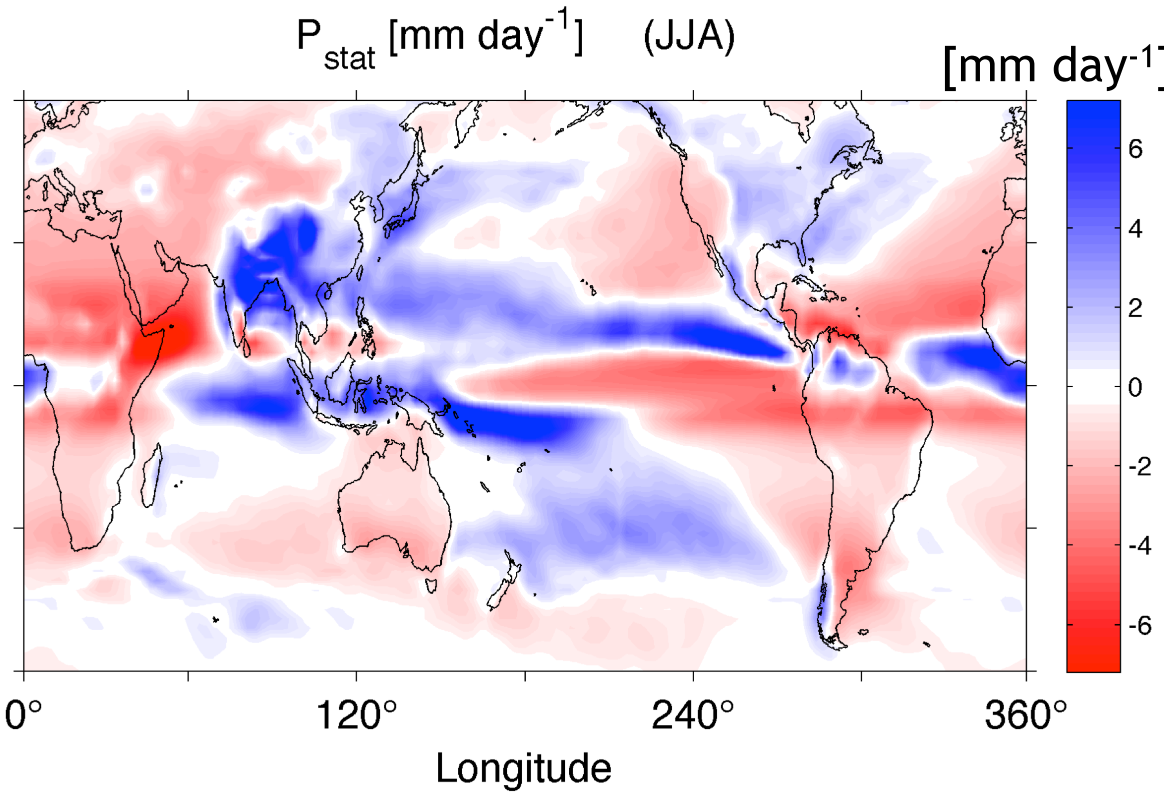
Zonal asymmetries in precipitation in present-day climate



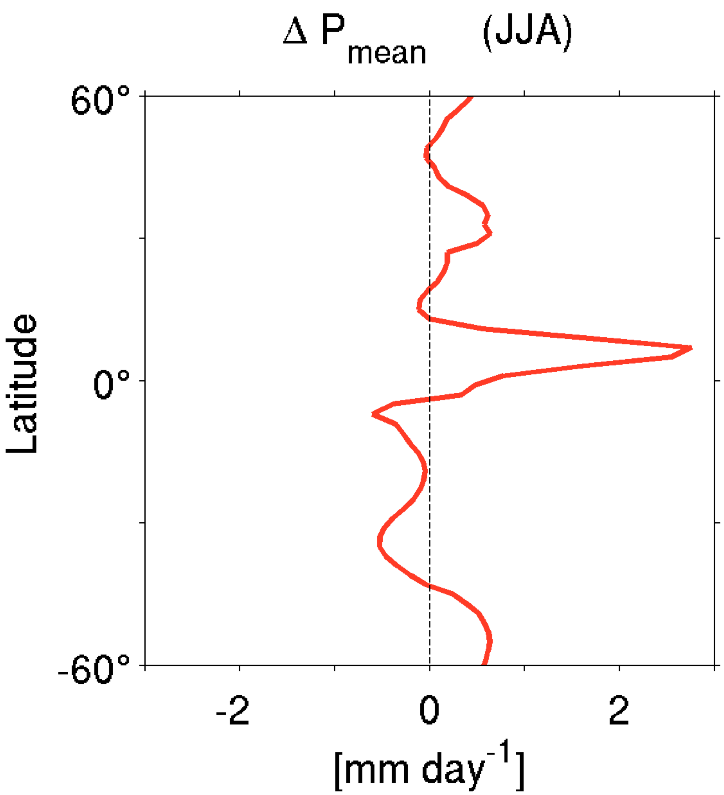
Zonal-Mean



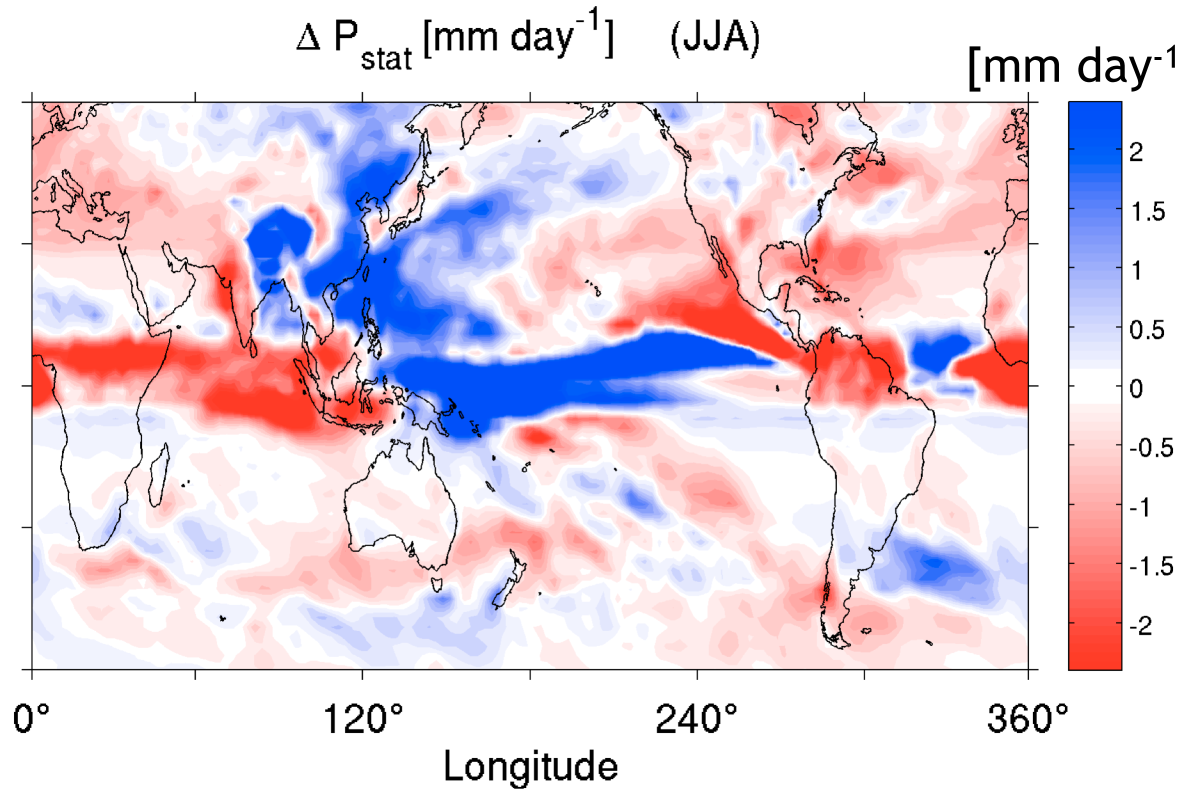
Stationary:
Time-mean, zonal asymmetries

GFDL CM3: RCP8.5
(2006-2015)

Zonal asymmetries in precipitation with global warming



Zonal-Mean



Stationary:
Time-mean, zonal asymmetries

GFDL CM3: RCP8.5
Δ: (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 at., 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]

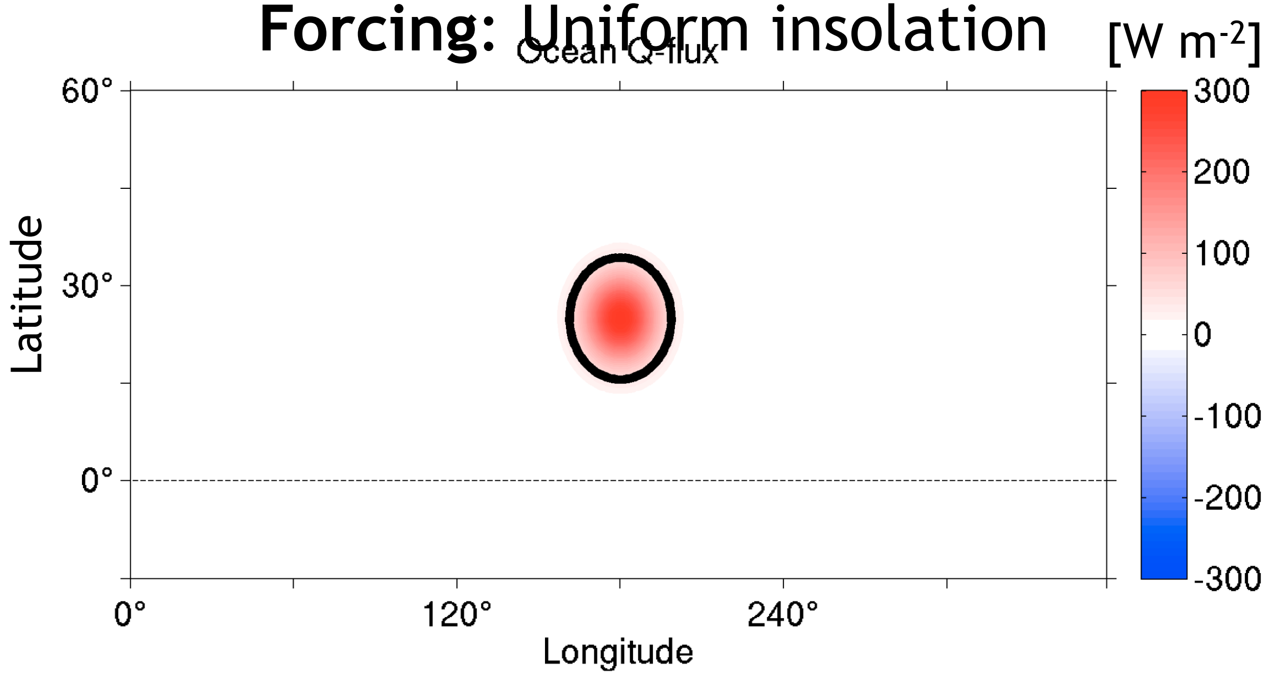
Setting description: "Gill-like" forcing

Global warming experiment with idealized GCM (T85, 30 levels)

[O'Gorman and Schneider, 2008]

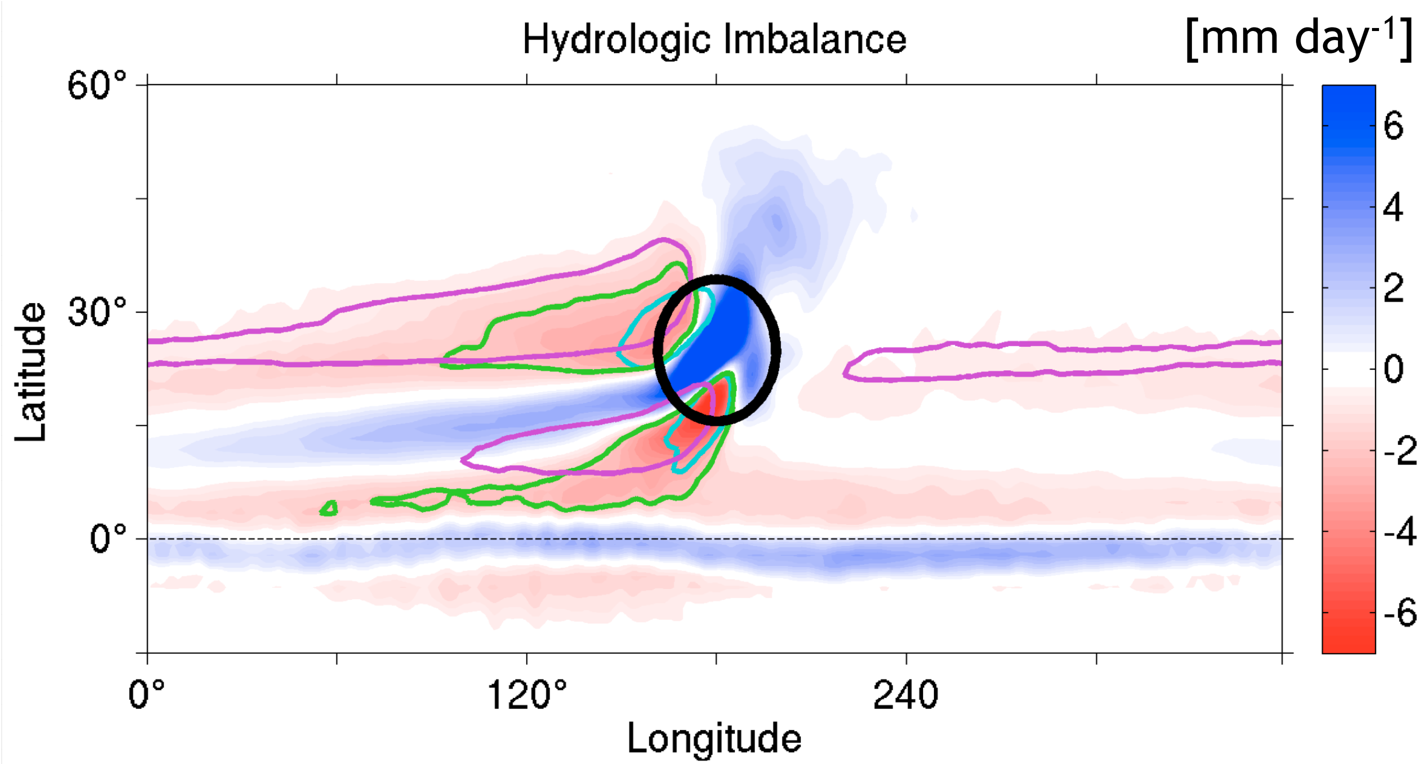
Surface conditions: Slab ocean, uniform thermal inertia and albedo

Forcing: Uniform insolation



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

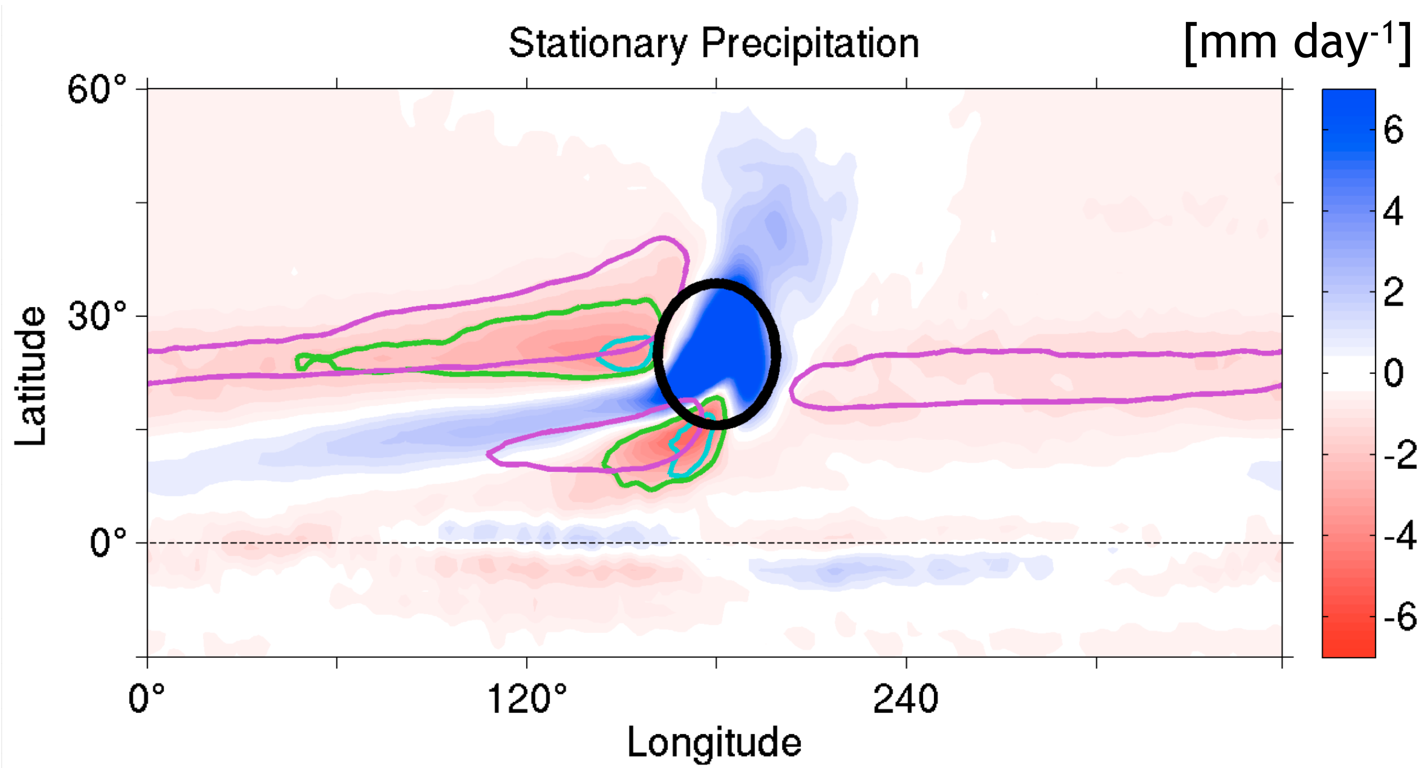
Hydrologic imbalance



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.

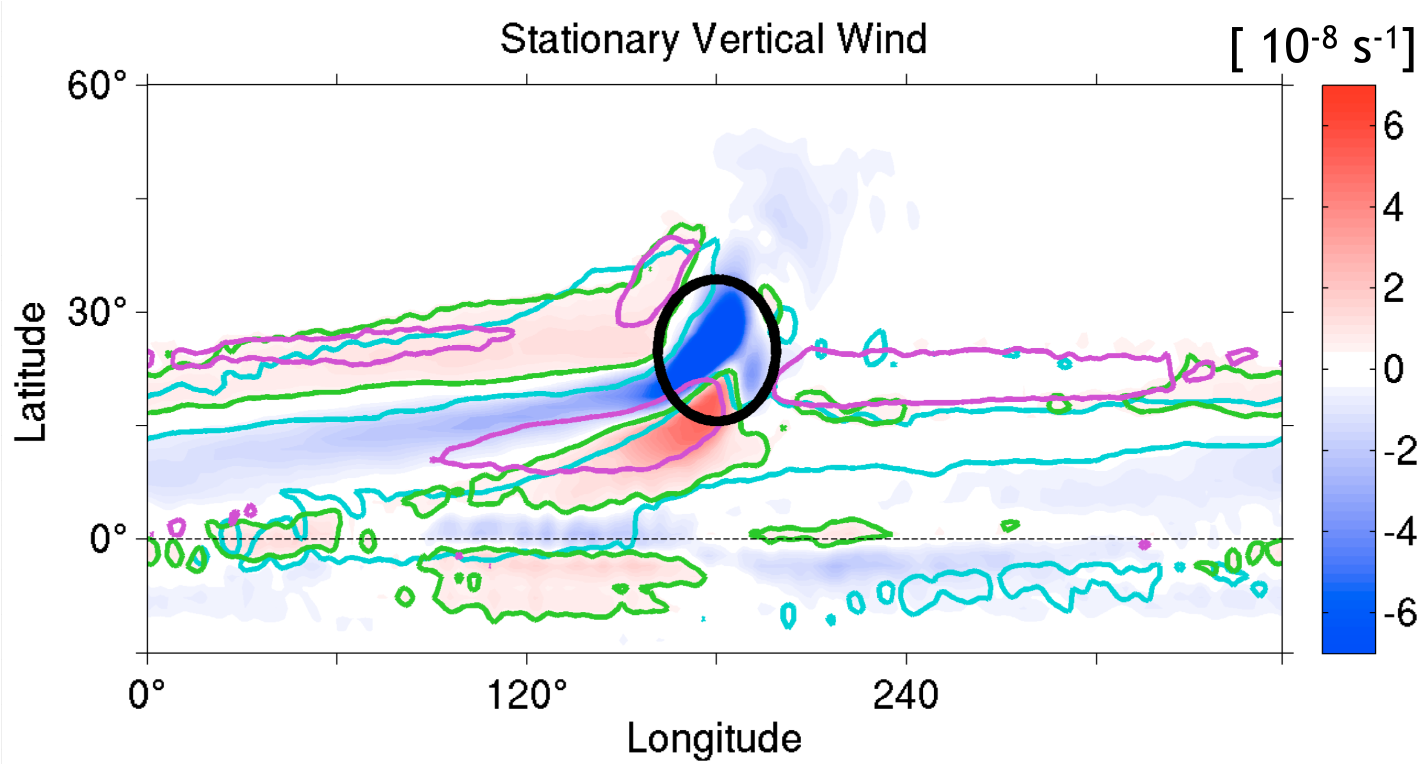
Zonally asymmetric precipitation



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.

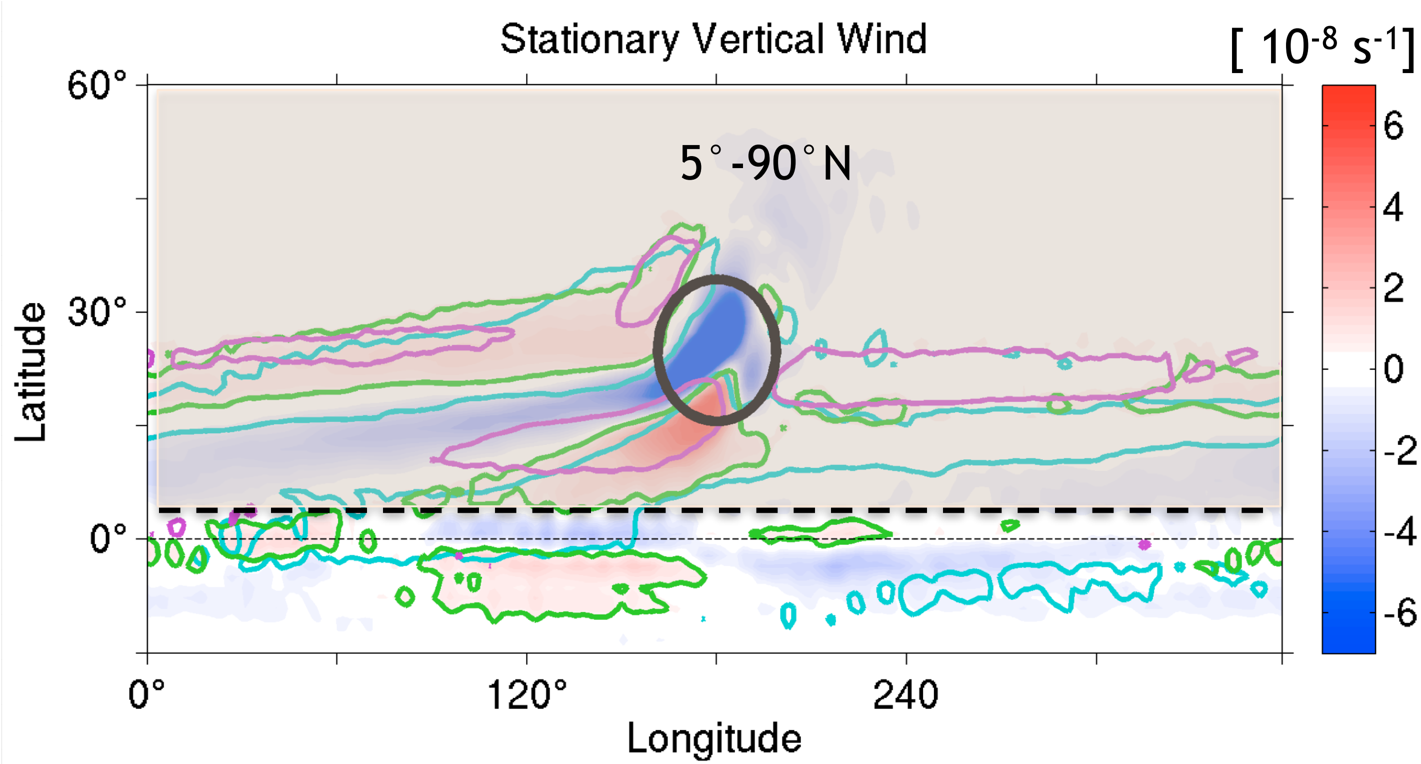
Stationary vertical wind



Contours: $\omega^{+} \geq 1.5\times10^{-8}$ s^{-1} in cold (Ts=291K, cyan), reference (Ts=302K, green) and warm (Ts=311K, magenta) climates

Hydrologic pattern largely consistent with stationary wind

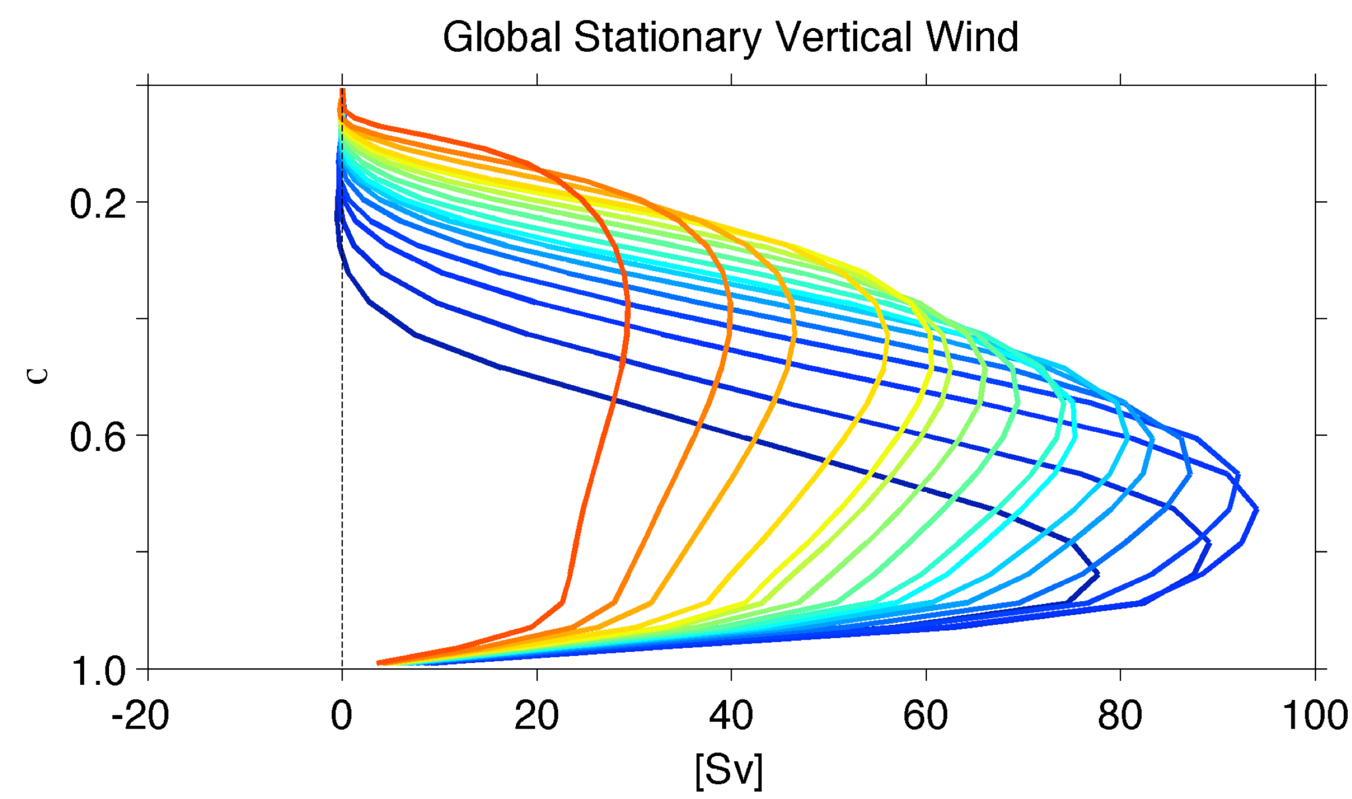
Stationary vertical wind



$$\omega^* = g^{-1} \oint \omega^+ \mathscr{H}\left(\omega^+(p_b)\right) \mathrm{d}\mathscr{A}$$ with p_b=850mbar

Hydrologic pattern largely consistent with stationary wind

Vertical profile of stationary updraft with global warming



$$\omega^* = g^{-1} \oint \omega^+ \mathscr{H}\left(\omega^+(p_b)\right) \mathrm{d}\mathscr{A}$$

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

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:

$$\delta\omega \simeq \partial_{T_r}\omega\,(\delta T_r)$$

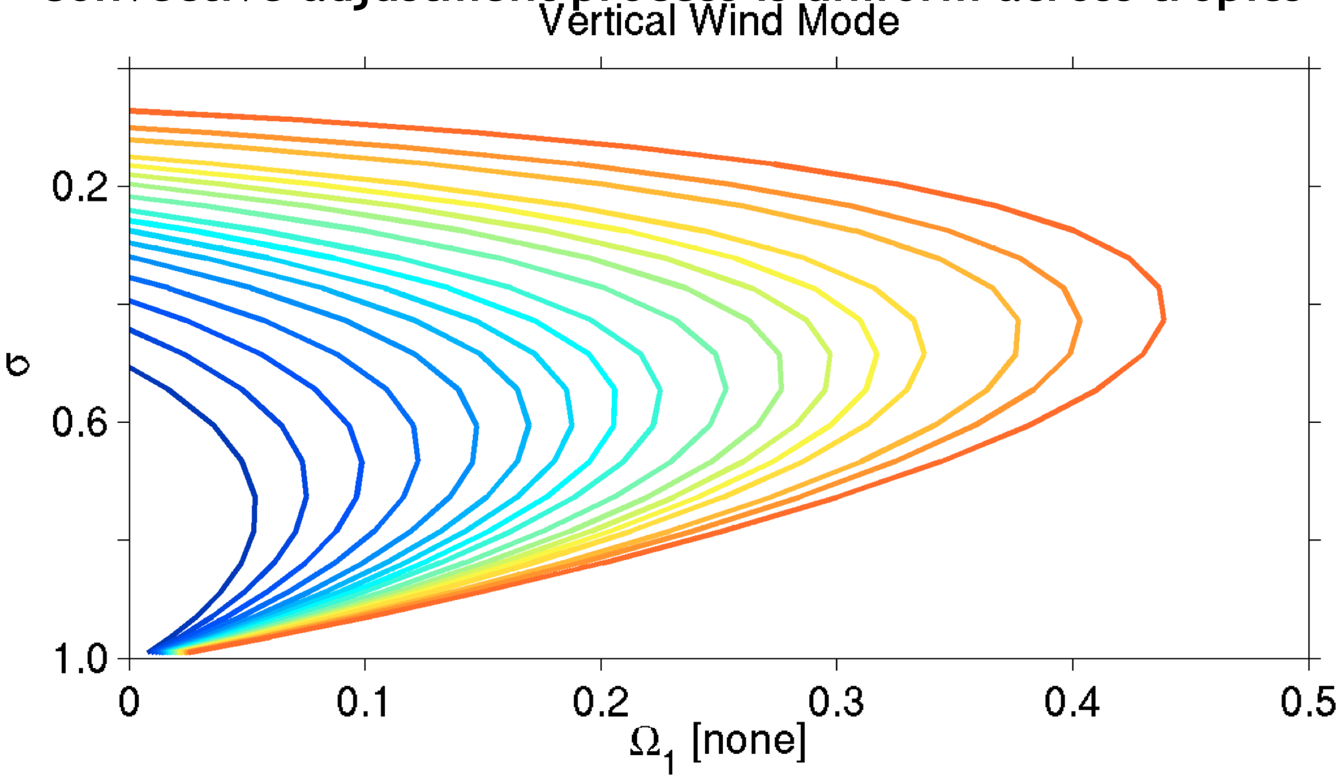
$$\omega_{bc}^{*} = \hat{\Omega}\omega_{r}^{*}$$

Sensitivity of vertical winds to temperature anomalies

$$\omega_{bc}^{*} = \hat{\Omega}\omega_{r}^{*}$$

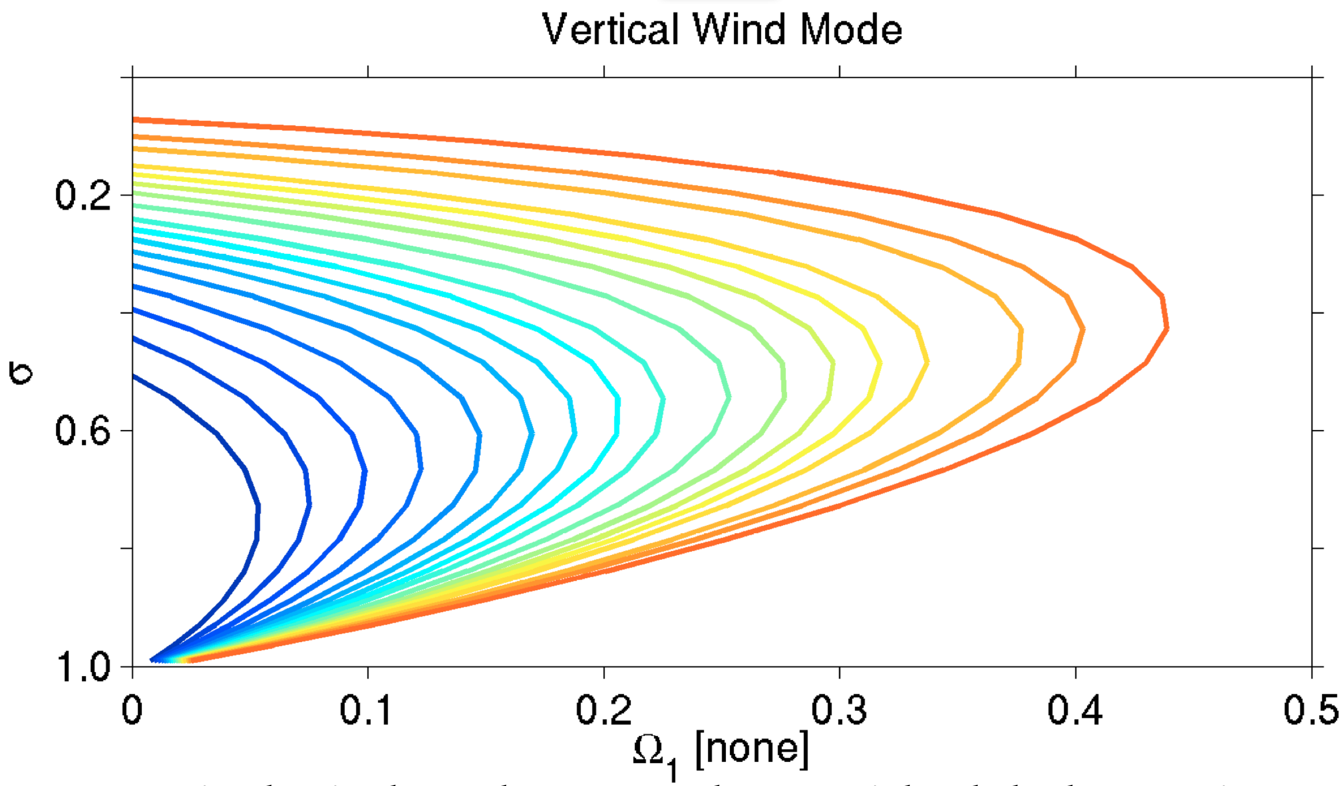
Low-level temperature anomalies are communicated to troposphere by convection

Convective adjustment process is uniform across tropics



Sensitivity of vertical winds to temperature anomalies

$$\omega_{bc}^{*} = \hat{\Omega}\,\omega_{r}^{*}$$

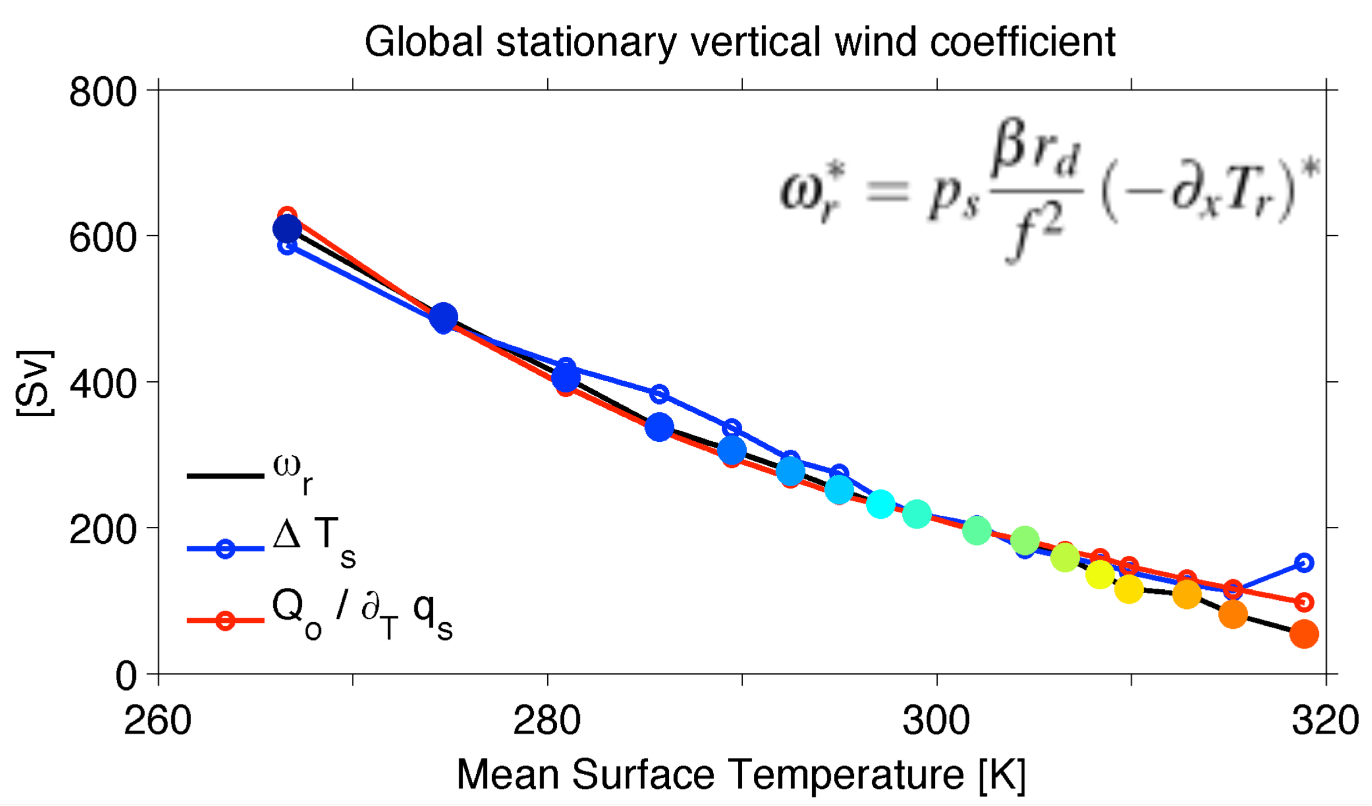


Vertical wind mode strengthens with global warming: i.e., winds become more sensitive to LCL temperature anomalies in warm than in cold climates

Thermal forcing on the vertical winds

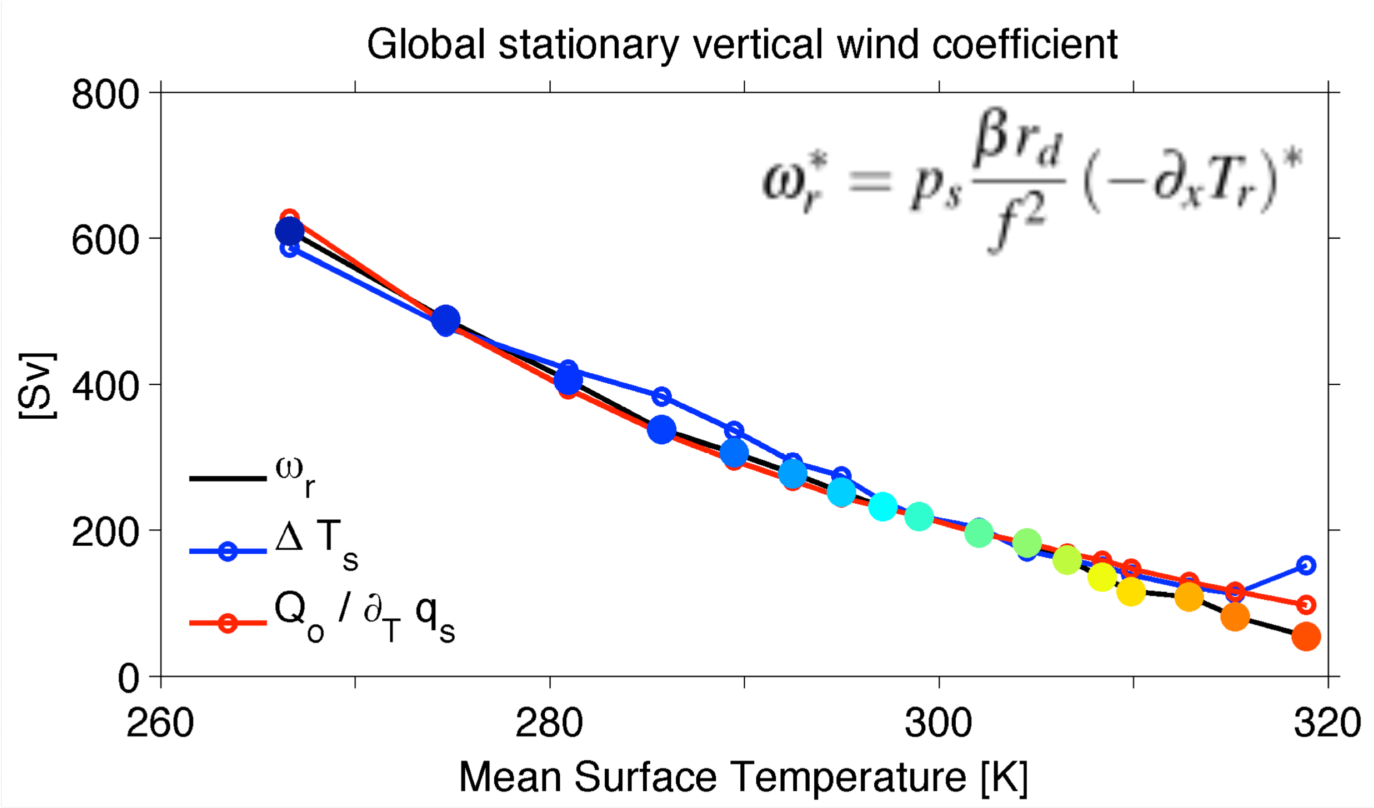
$$\omega_{bc}^{*} = \hat{\Omega}\,\omega_r^{*}$$

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



Thermal forcing on the vertical winds

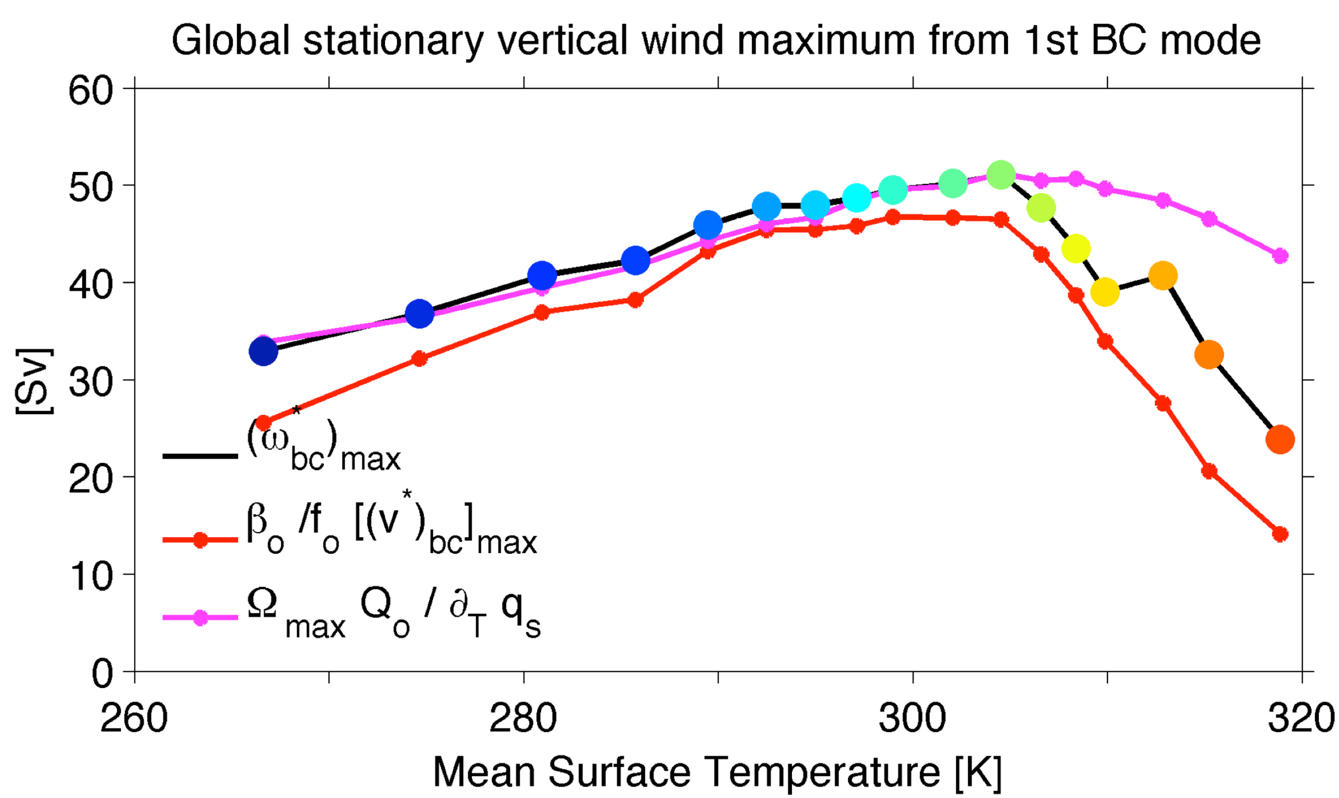
$$\omega^*_{bc} = \hat{\Omega}\,\omega^*_r$$



Vertical wind coefficient decreases, consistent with a weakening of the zonal temperature gradient

Strength of stationary circulation from modal decomposition

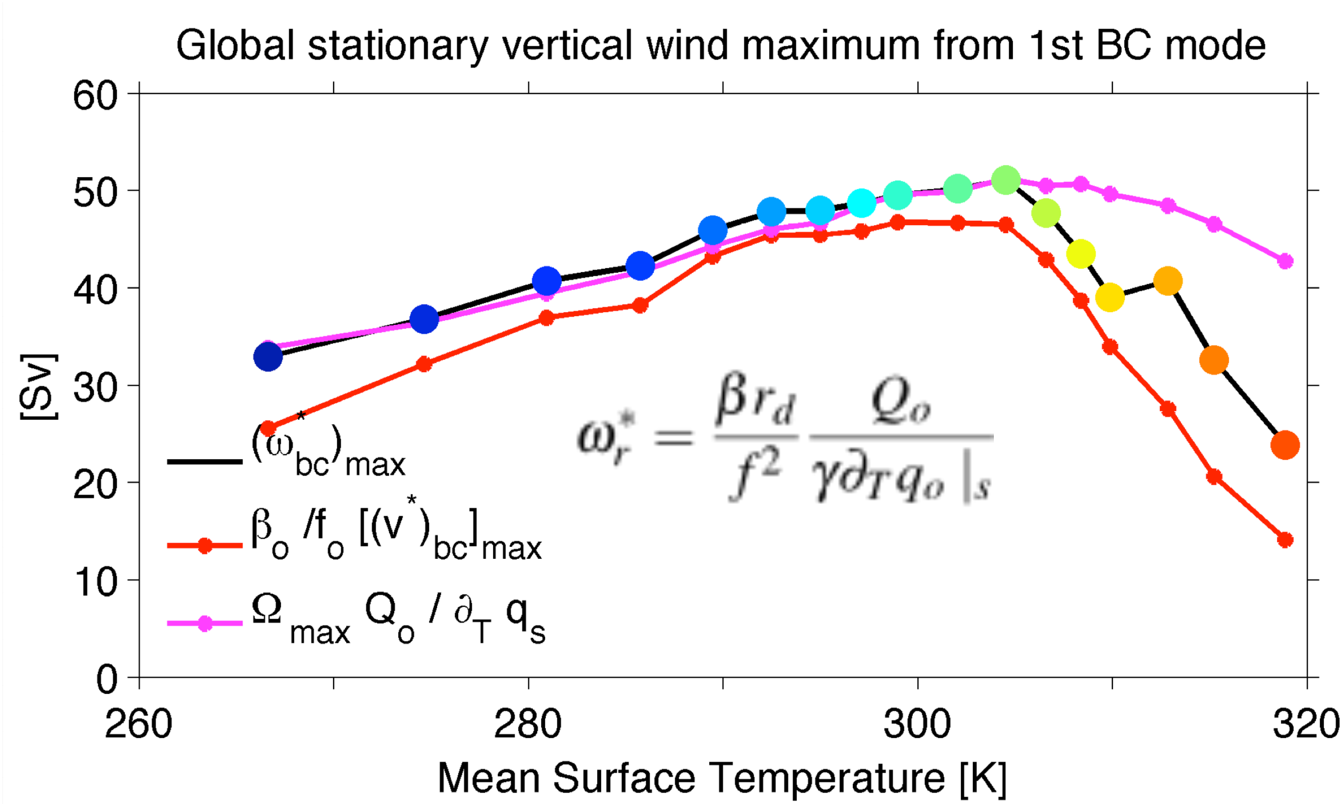
$$\omega^*_{bc} = \boxed{\hat{\Omega}\omega^*_r}$$



Modal expression captures the behavior of the stationary circulation

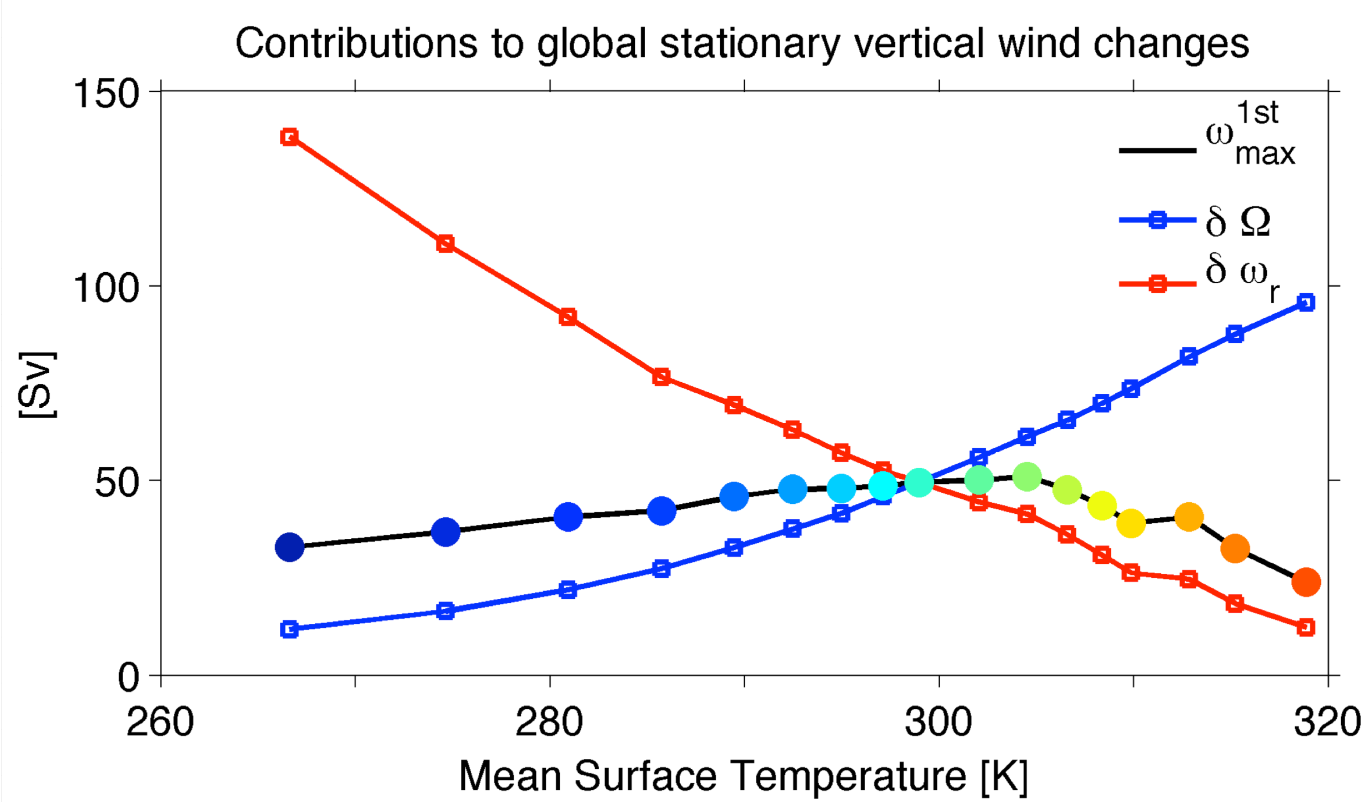
Strength of stationary circulation

$$\omega_{bc}^{*} = \hat{\Omega}\omega_{r}^{*}$$



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



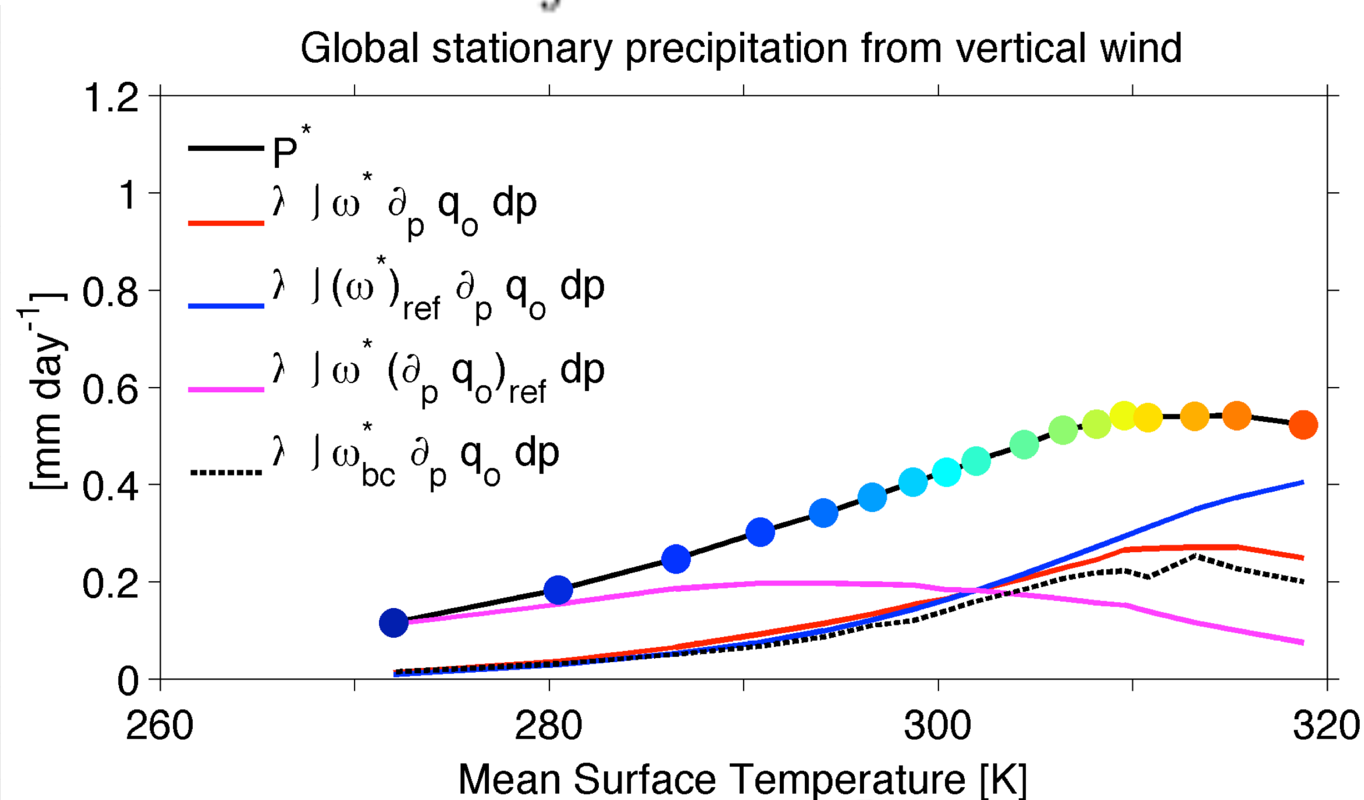
Non-monotonic behavior arises from dynamics being more sensitive to subcloud temperature anomalies, and subcloud temperature anomalies weakening with global warming

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

$$P^* = \oint P^+ \mathscr{H}\left(P^+\right) \mathrm{d}\mathscr{A}$$

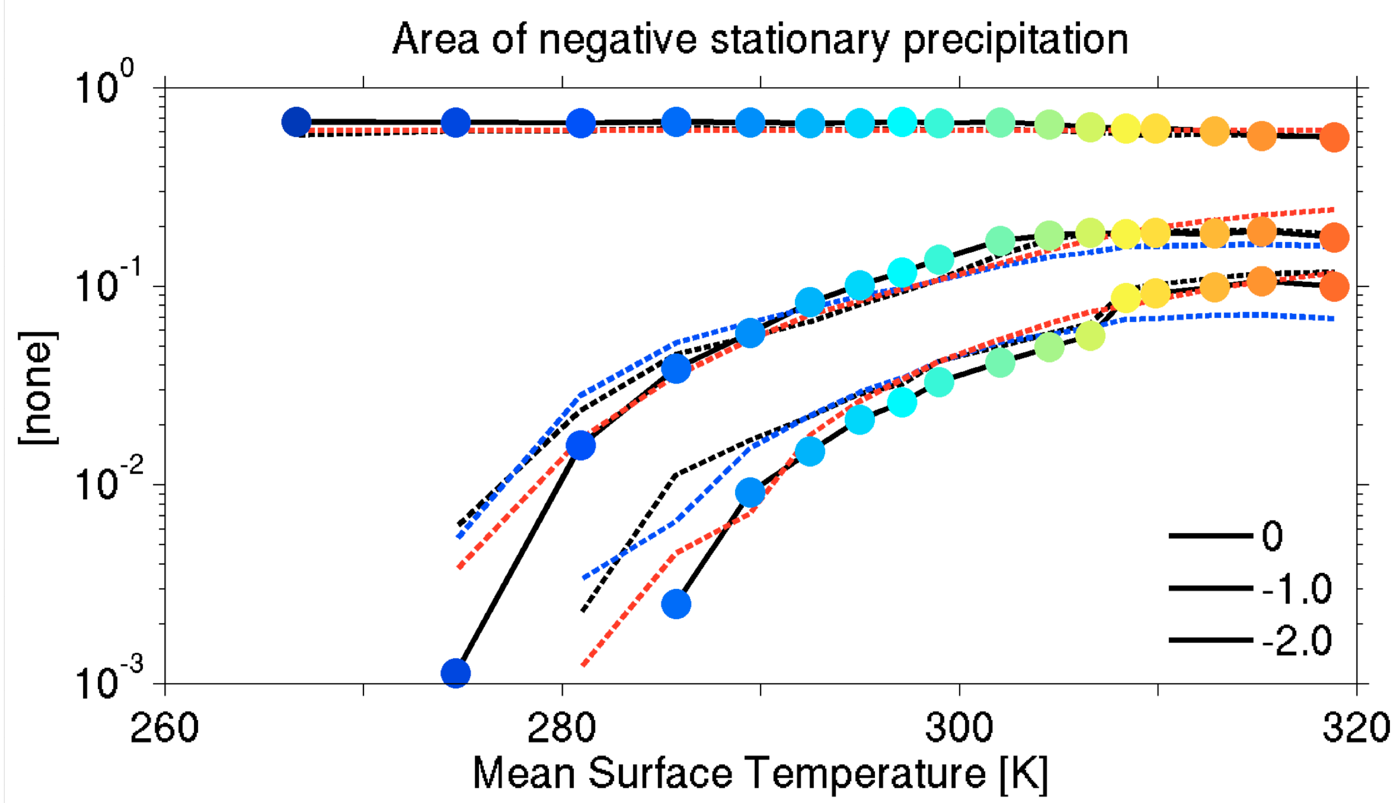


$$P^* \simeq \frac{\beta_o r_d}{f_o^2} \lambda \frac{\Delta Q_o}{\gamma \partial_T q_o|_s} \int_{p_b}^{p_t} \hat{\Omega} \partial_p q_o \frac{\mathrm{d}p}{g}$$

Stationary precipitation changes with global warming are captured by changes in stationary circulation and zonal-mean moisture

Area of dry zones

$$\mathscr{A}_d = \oint \mathscr{H}\left(-P^+ - P_d\right) \mathrm{d}\mathscr{A}$$



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.