Tropical Circulation Changes Across Forcing Agents

Timothy M. Merlis
McGill University

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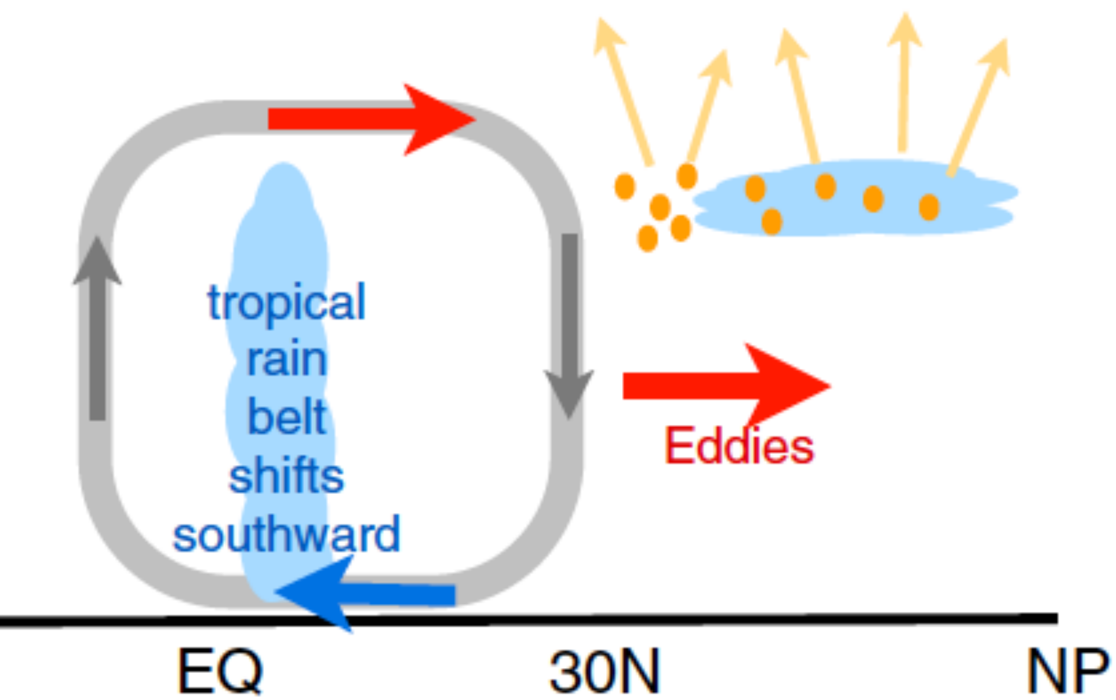
New mechanism for direct CO_2 circulation weakening posits a key role for spatial pattern of forcing

ITCZ Energetic Framework

Energetic perspective: ITCZ in hemisphere exporting energy

Kang et al. (2009)



Hwang et al. (2013)

Recipe:

1) Take annual-mean forcing/feedback

2) Diffuse energy in atmos to determine annual-mean δcirculation

3) Compute annual-mean change in water vapor flux to determine P shift

Frierson & Hwang (2012), Hwang et al. (2013), Bischoff & Schneider (2014)

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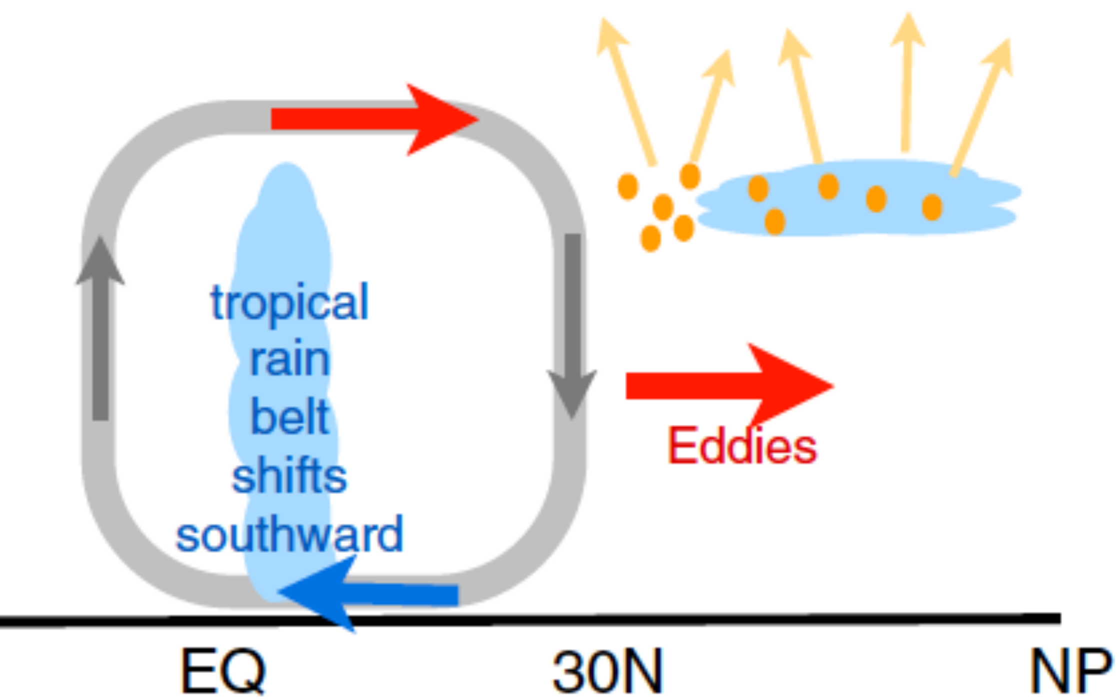

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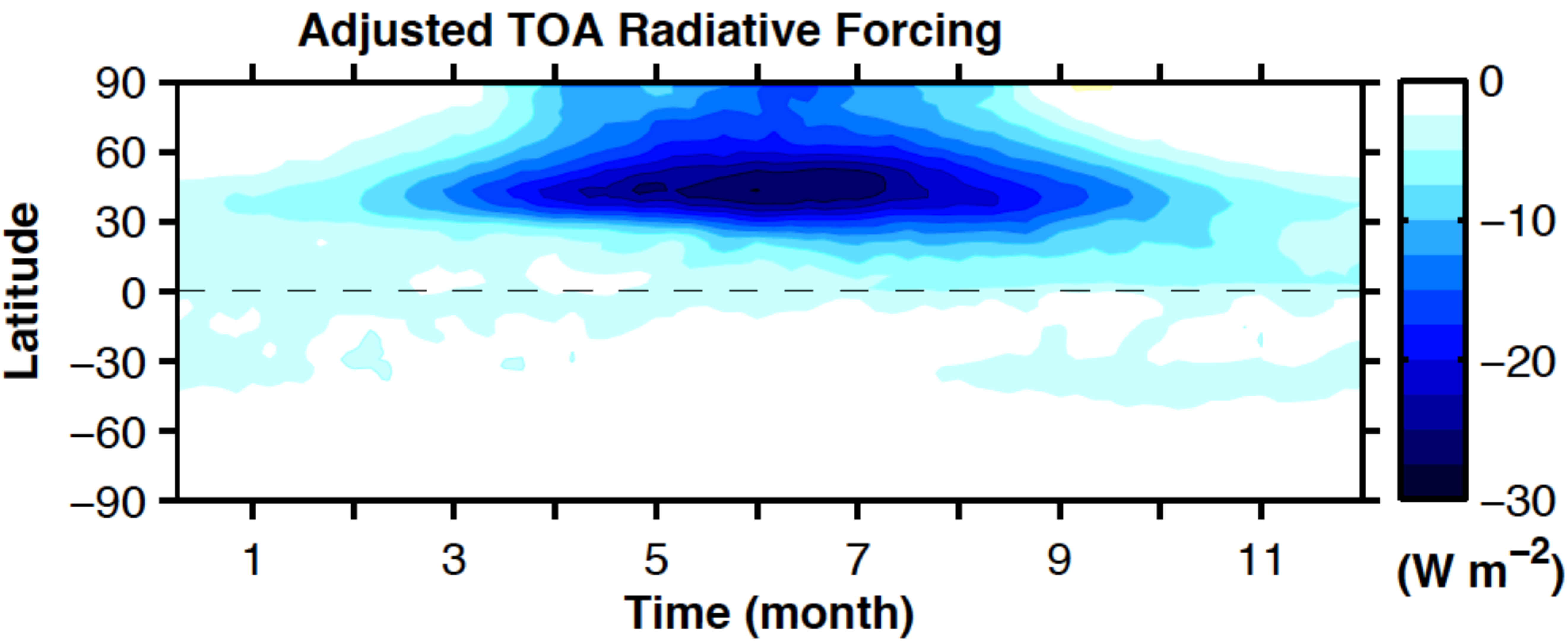
Should we worry about the often unstated '*annual-means*'?

Sulfate Aerosol Forcing

…in an aquaplanet GCM! *Merlis et al. (2013a)*



2.2x anthropogenic perturbation *Yoshimori & Broccoli (2008)*

Sulfate Aerosol Forcing

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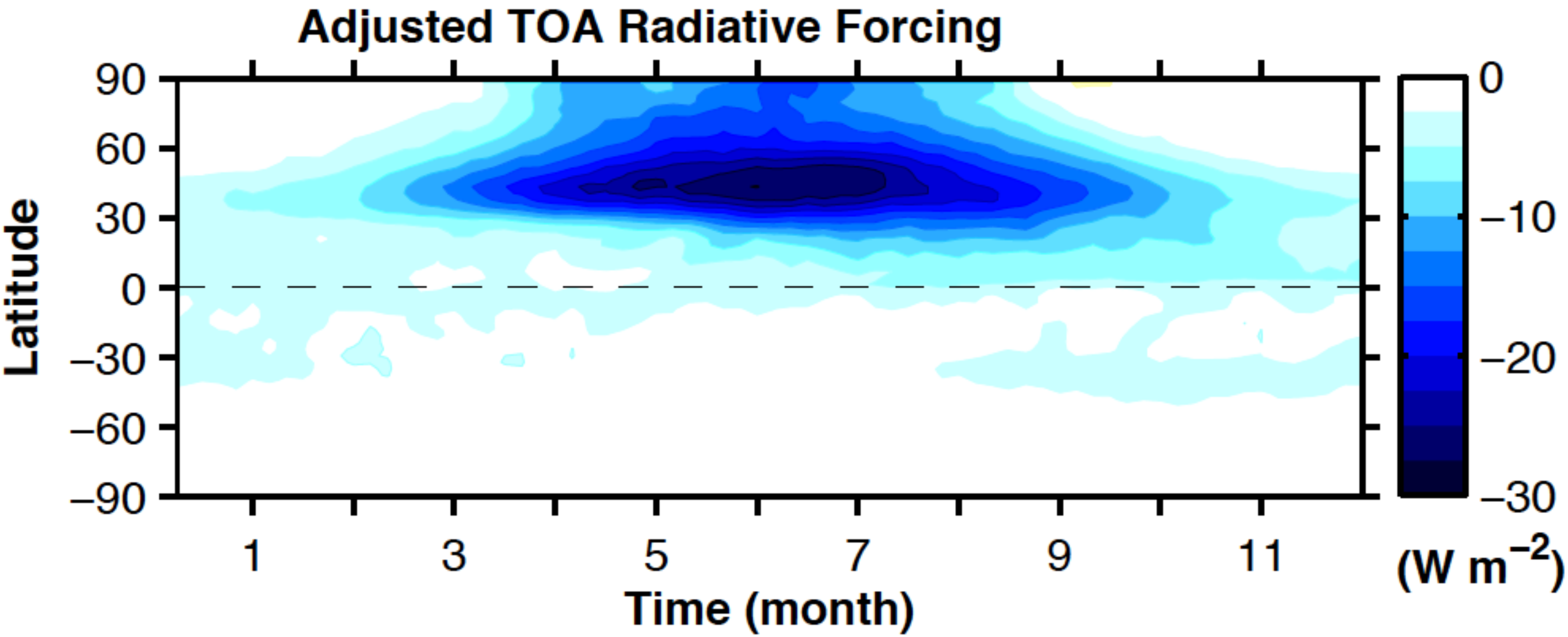
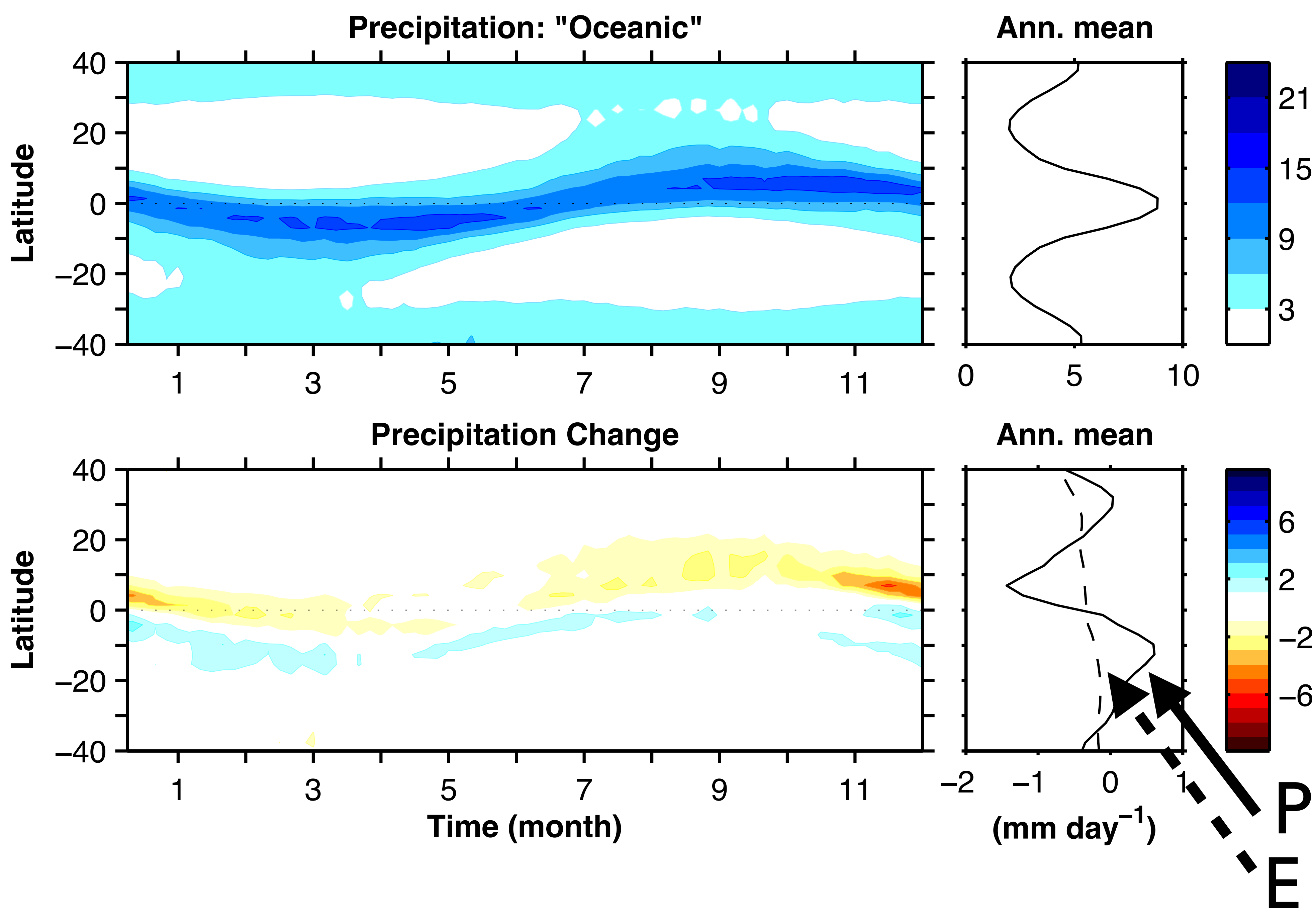


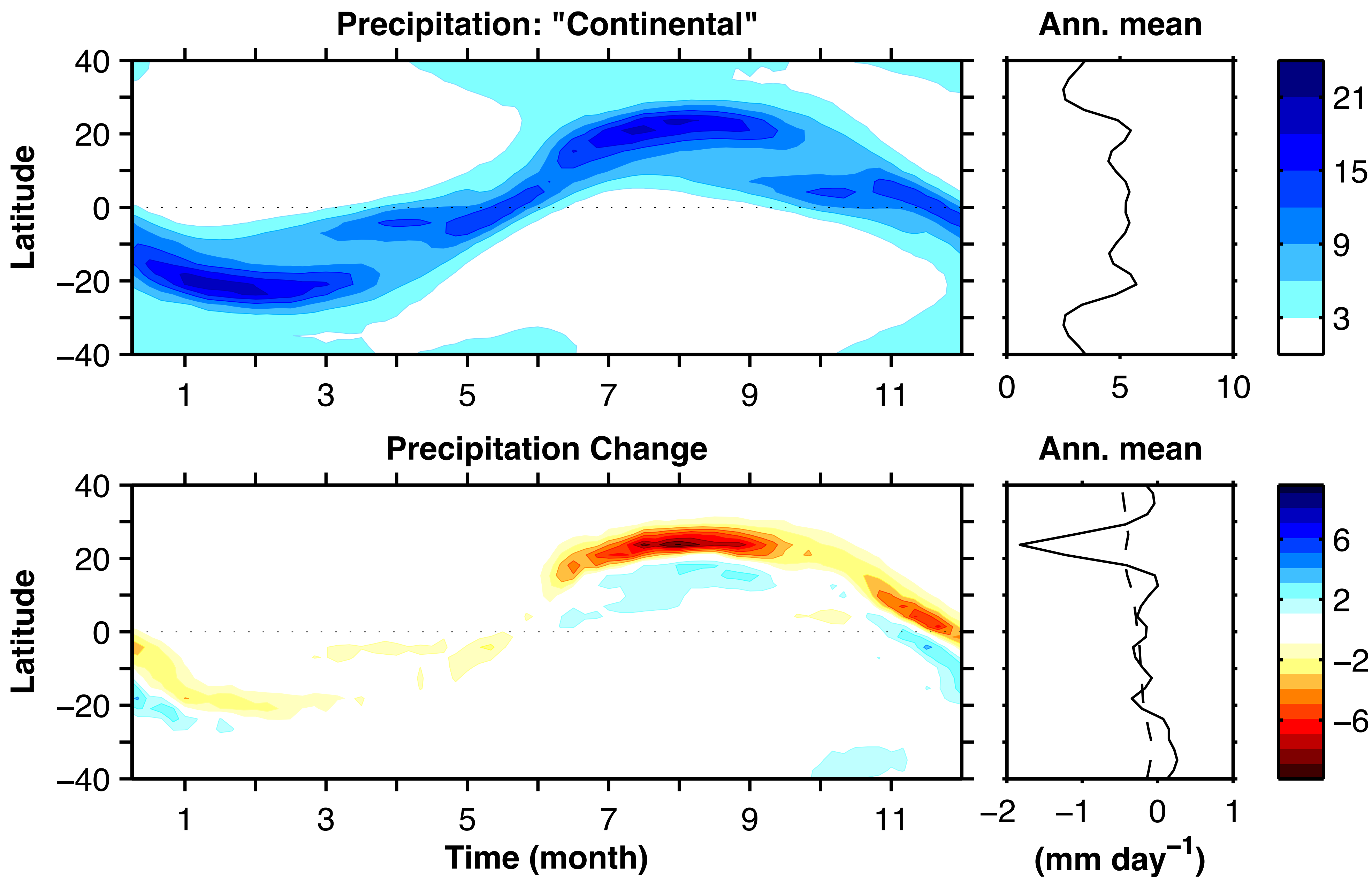
"Continental": 5m slab ocean
"Oceanic": 20m slab ocean
} infinite reservoir for evaporation

“Oceanic” Precipitation



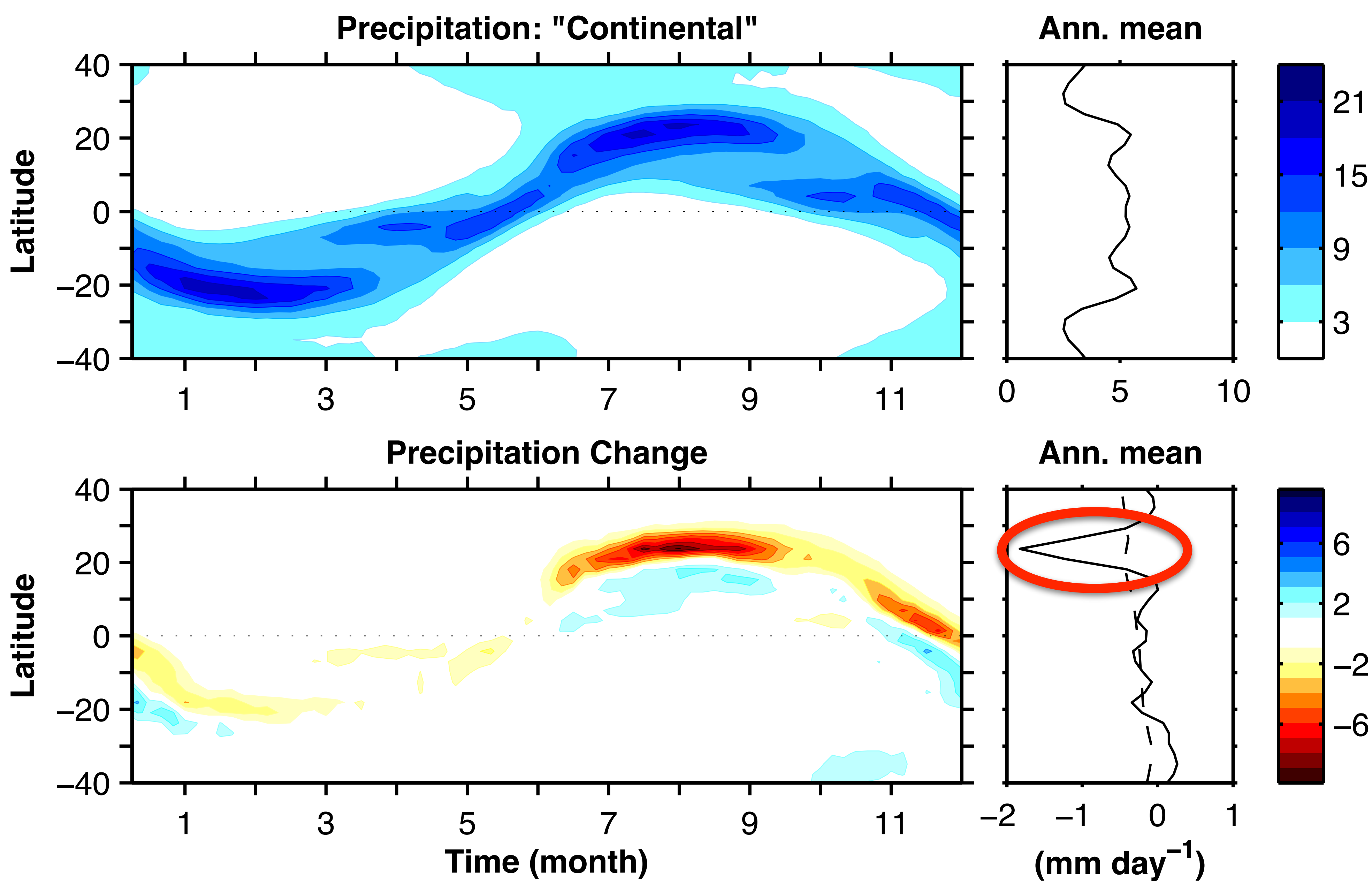
Southward shift throughout seasonal cycle

“Continental” Precipitation



Southward shift strong in NH summer & annual-mean response reflects this.

“Continental” Precipitation



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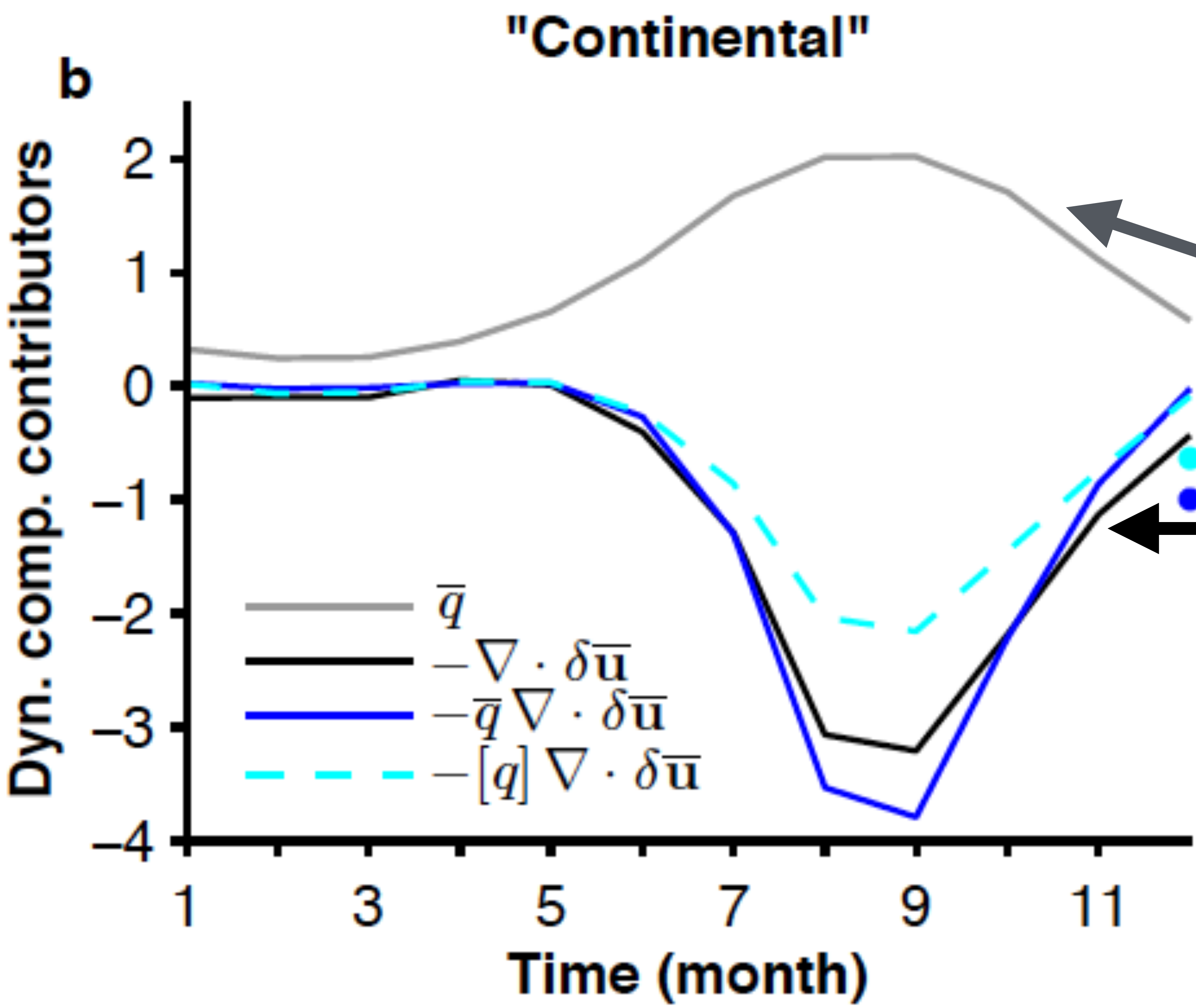
'Dynamic' P-E change

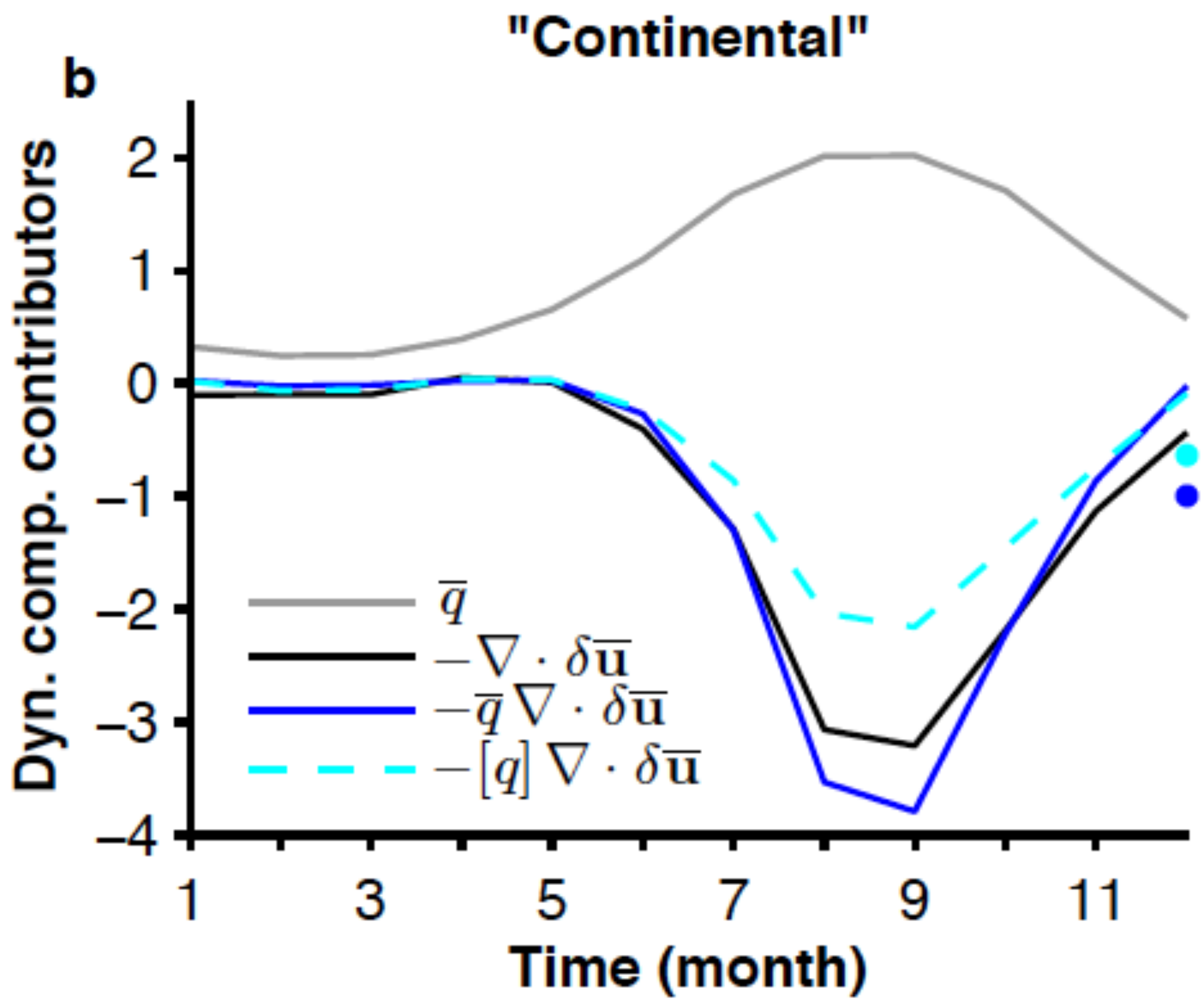


Normalized by ann. mean

$\propto \delta\overline{\omega}$

Seasonal change in circulation (summer maximum) correlated with climatological time of high humidity.

‘Dynamic’ P-E change



This is a rectification mechanism similar in spirit to ‘thermodynamic’ precession mechanism: *Merlis et al. (2013c)*

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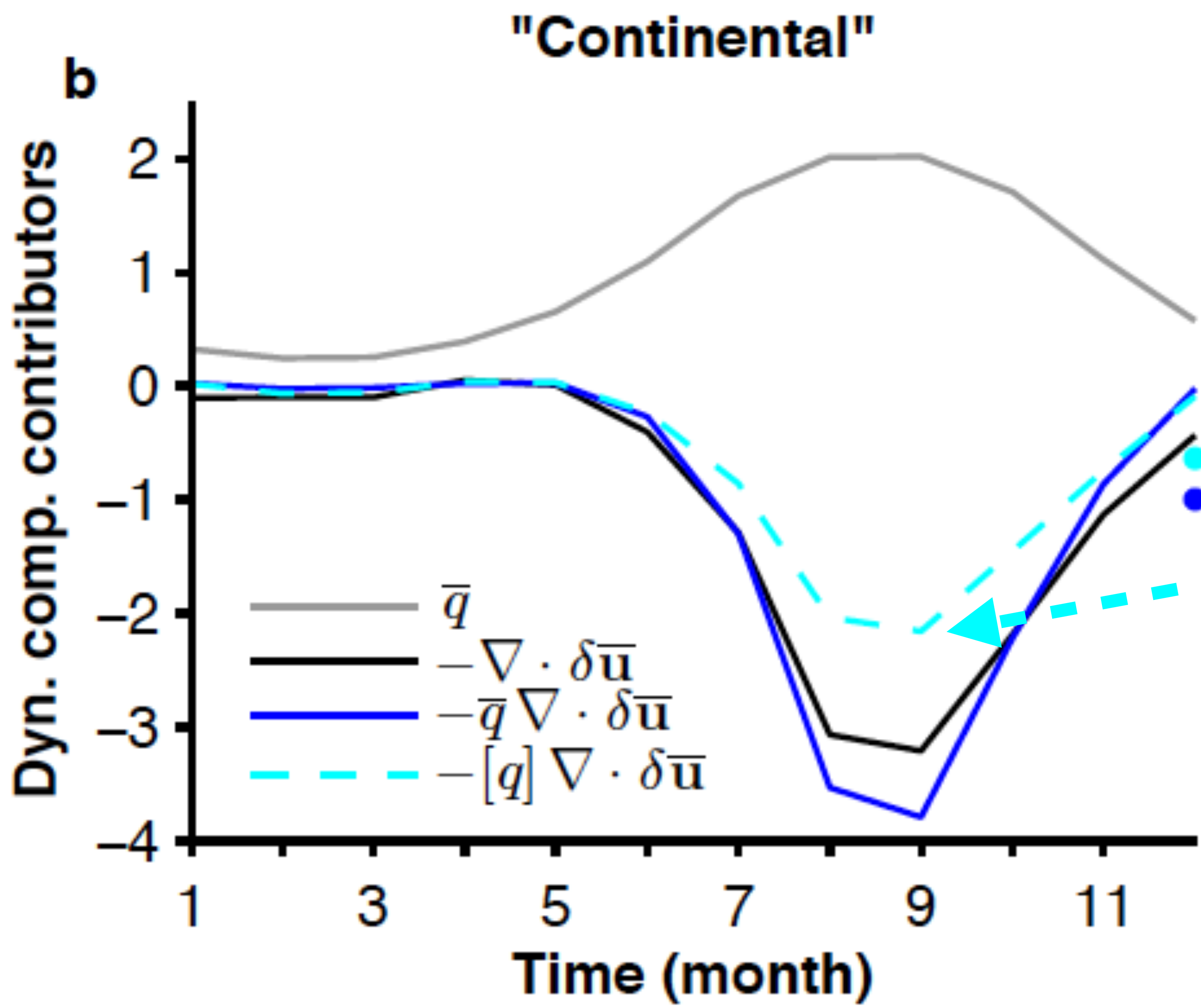
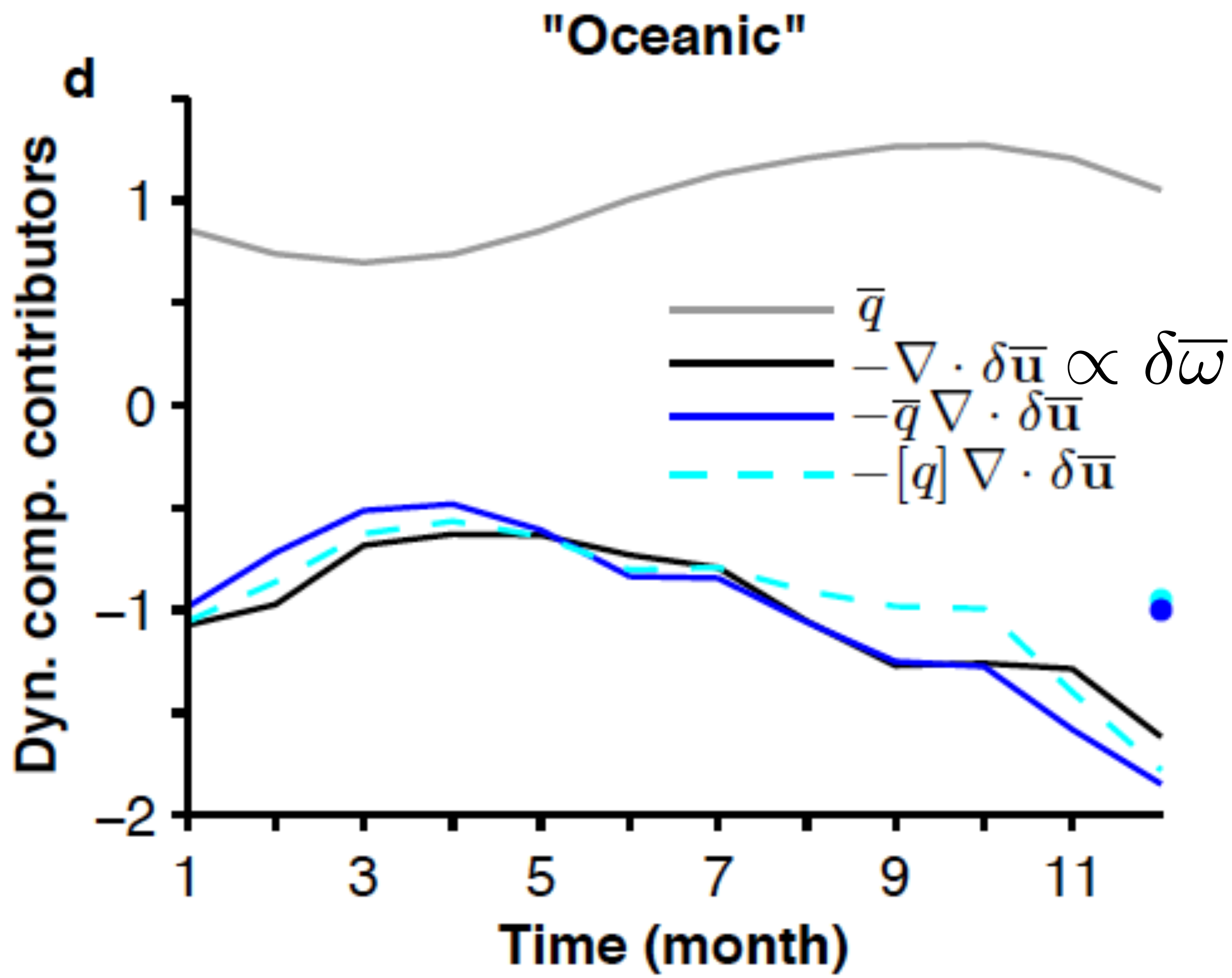


Neglecting climatological seasonality of humidity

~40% underestimate of annual-mean change

‘Dynamic’ P-E change



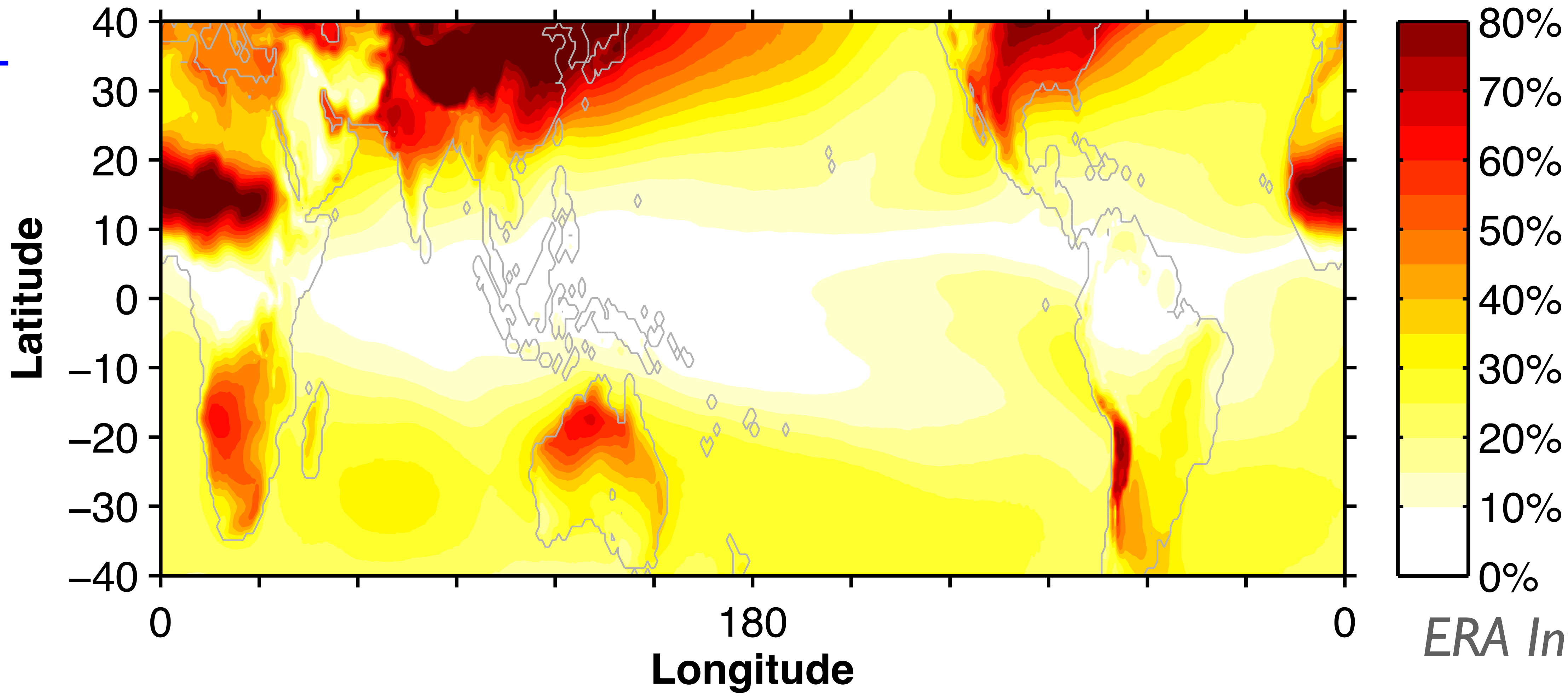
Neglecting seasonality minimally underestimates annual-mean P-E change in “oceanic” regime

Seasonality of Earth's humidity

Magnitude of seasonal cycle relative to annual mean:

$$\overline{q}(t) \approx [q] + q' \cos(2\pi t \, \mathrm{yr}^{-1} + \phi)$$

$$\frac{q'}{[q]}$$

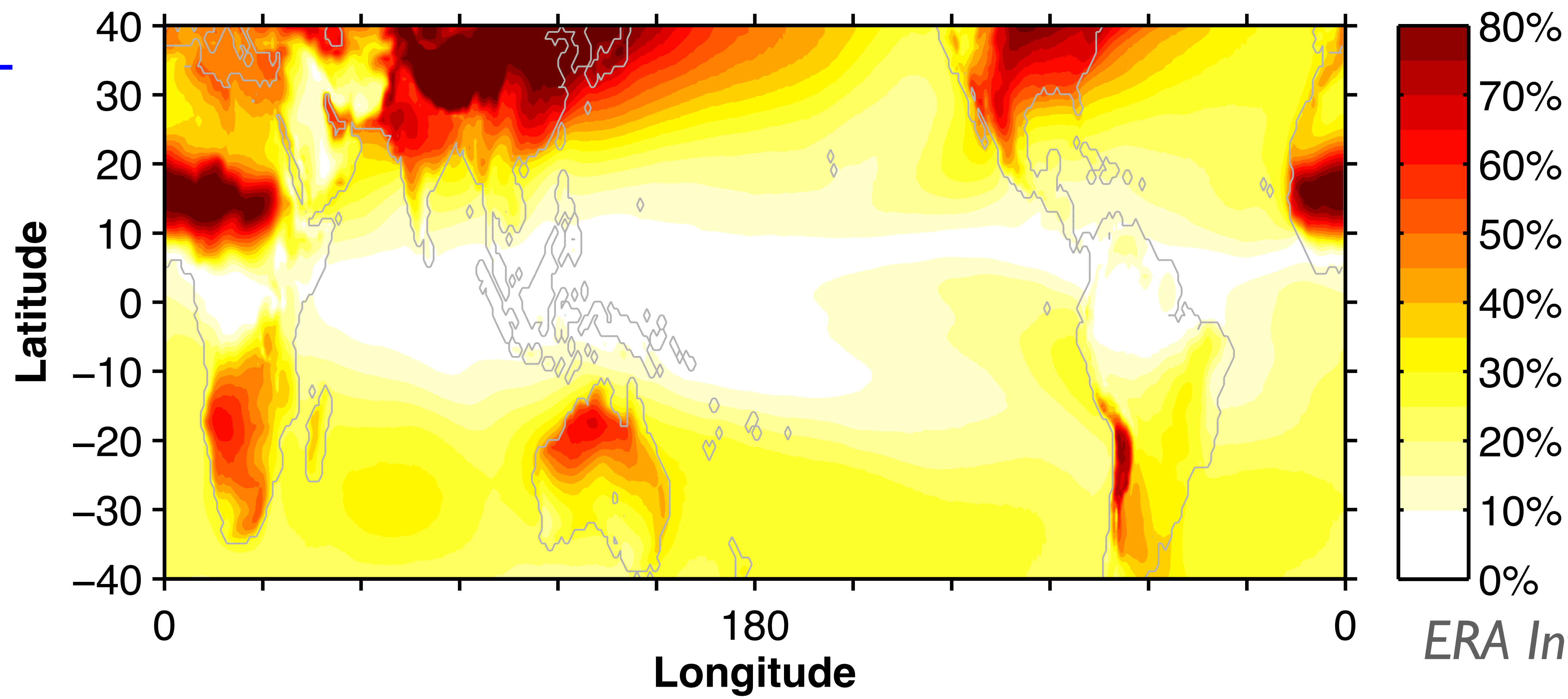


ERA Interim

Seasonality of Earth's humidity

If circulation change has a similar magnitude seasonality: $\frac{\delta\omega'}{\delta[\omega]} \sim \frac{q'}{[q]}$

$\frac{q'}{[q]}$



Error

~50%

~25%

~5%

ERA Interim

- We cannot straightforwardly apply the energetic ITCZ framework to monsoons.

Seasonality is important for precip response to sulfate aerosol forcing in "continental" regime

N.B. Energetics of seasonal circulation changes is a useful perspective, though energy storage is important: *Chou & Neelin (2003), Merlis et al. (2013b), Chamales et al. (2015)*

'Recipe' TBD…

Direct vs. Temperature Mediated Climate Changes

Many climate changes are proportional to the amount of global warming:

$$\frac{dX}{dCO_2} \approx \frac{\partial X}{\partial \langle T_s \rangle} \frac{\partial \langle T_s \rangle}{\partial CO_2}$$

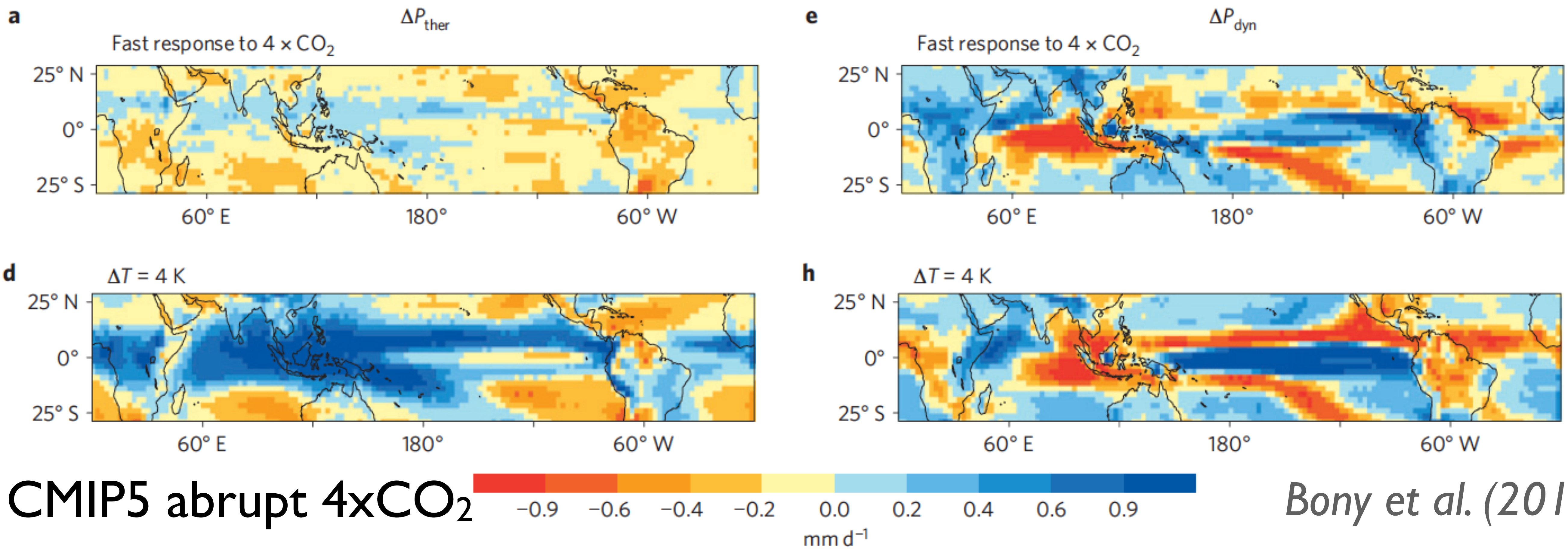
Direct vs. Temperature Mediated Climate Changes

But radiative forcing agents can also *directly* change aspects of climate:

$$\frac{dX}{dCO_2} \approx \frac{\partial X}{\partial \langle T_s \rangle} \frac{\partial \langle T_s \rangle}{\partial CO_2} + \frac{\partial X}{\partial CO_2}$$

Tropical precipitation change

Thermodynamic $\mathbf{u}_0 \, \delta q$ Dynamic $\delta \mathbf{u} \, q_0$



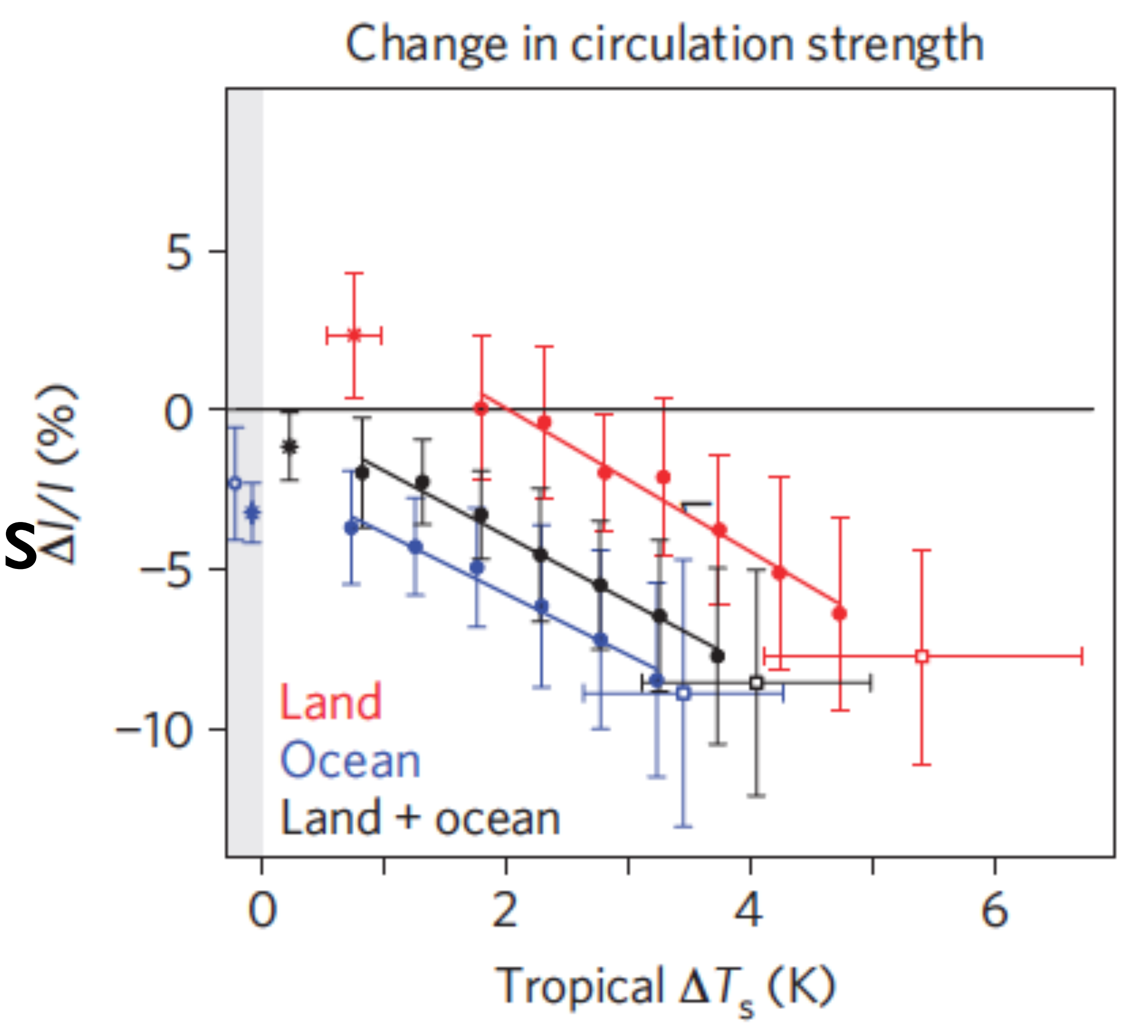
CMIP5 abrupt $4xCO_2$

Bony et al. (2013)

Increased CO_2 "directly" weakens tropical circulations.

Circulation changes in fixed-SST simulations

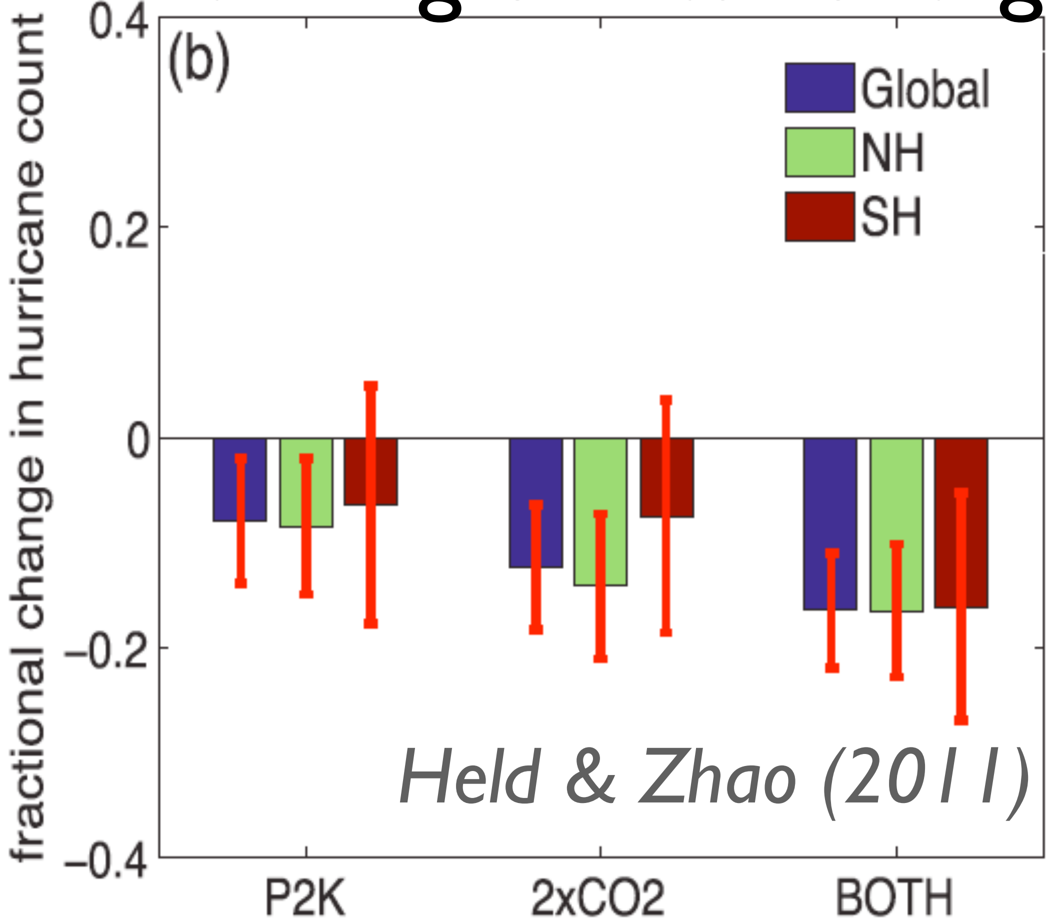
- Fixed-SST aGCM circulations weaken when CO_2 is increased.
- CMIP5 aquaplanet circulations also weaken (land-sea effects *modulate* rather than cause the changes).



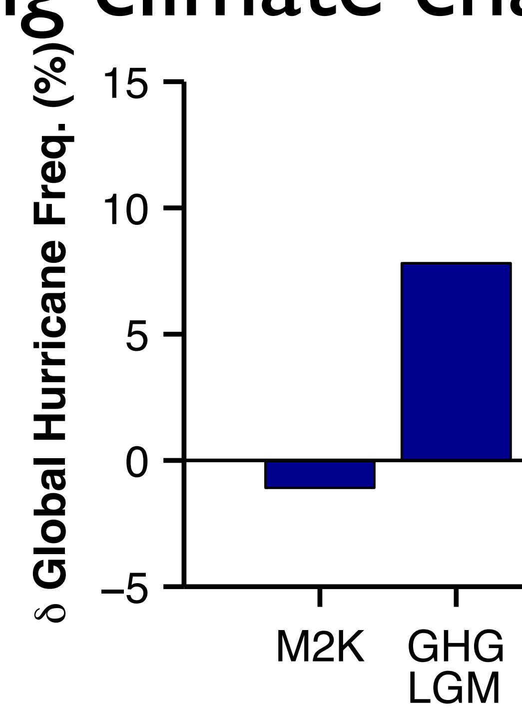
Bony et al. (2013)

Global hurricane (TC) frequency response from direct GHG circulation change

Warming climate changes



Cooling climate changes (LGM)



Merlis (2015, in prep.)

Direct GHG change in hurricane frequency is robust and ~50% of the total change.

Moist energetics of direct response of tropical circulations to CO_2

Analysis of moist static energy:

- Allows the circulation to be related to the energy sources & sinks (e.g., radiation) without explicit consideration of latent heating.
- Efficiency of circulation energy transport (gross moist stability) may change.

Held & Hou (1980), Neelin & Held (1987), Held (2001), Merlis et al. (2013a,b)

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Quiz!

What is the radiative forcing of doubling CO_2?

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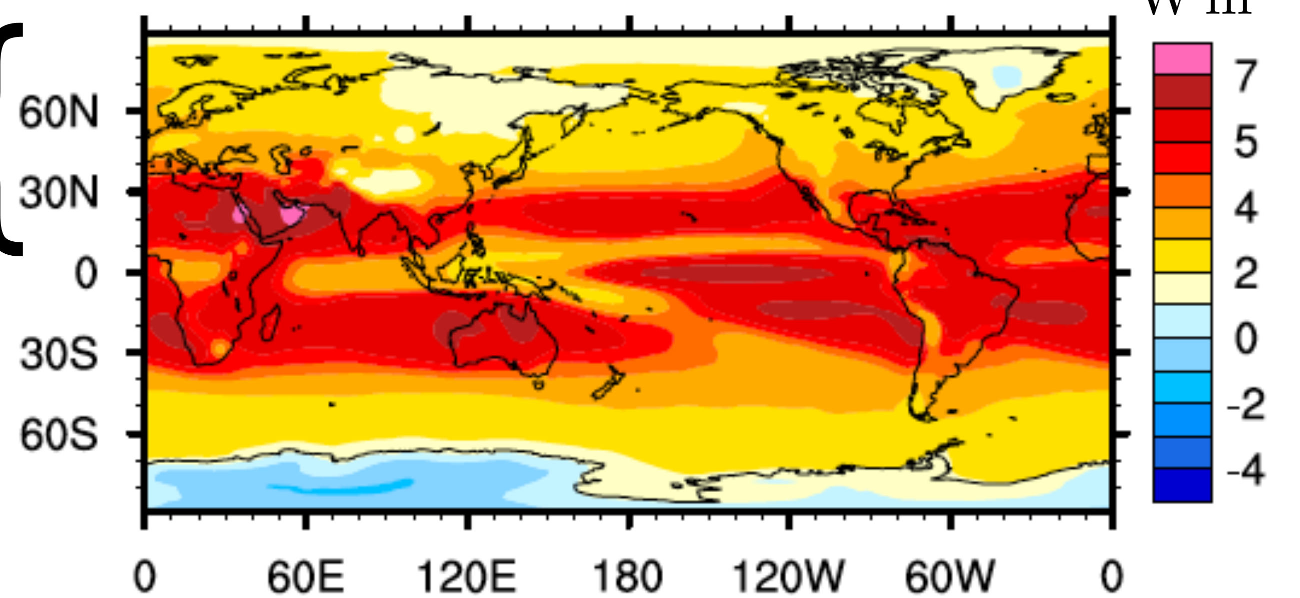
Conclusion from moist energetics:

The spatial structure of CO_2 radiative forcing (often ignored) leads to direct weakening of tropical circulations.

Spatial structure of CO_2 radiative forcing

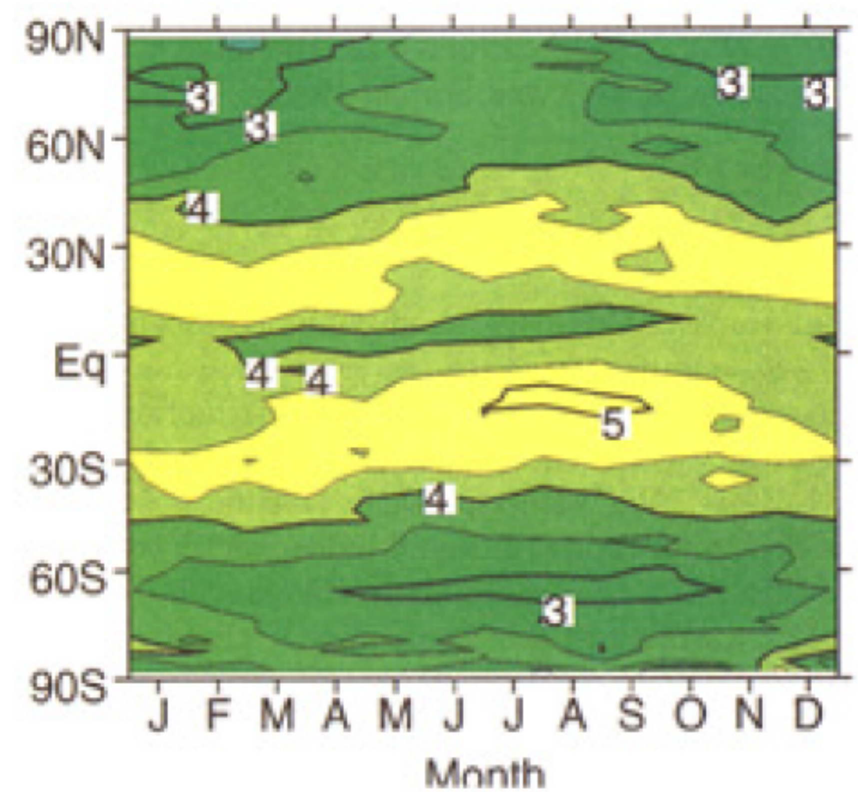
Annual mean

$\propto T$



Zhang & Huang (2014)

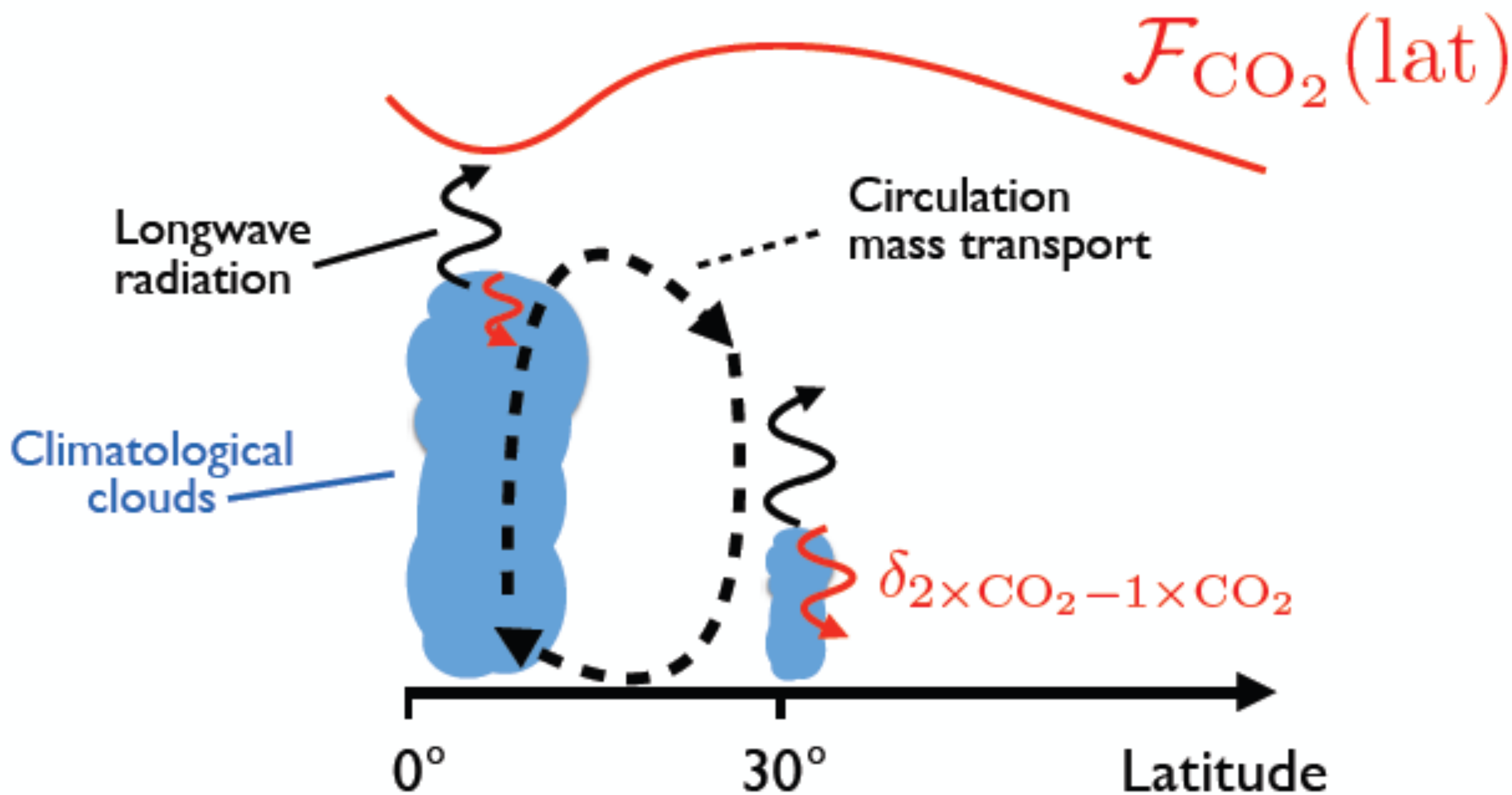
Zonal mean $\mathrm{W\,m^{-2}}$



Govindasamy & Caldeira (2000)

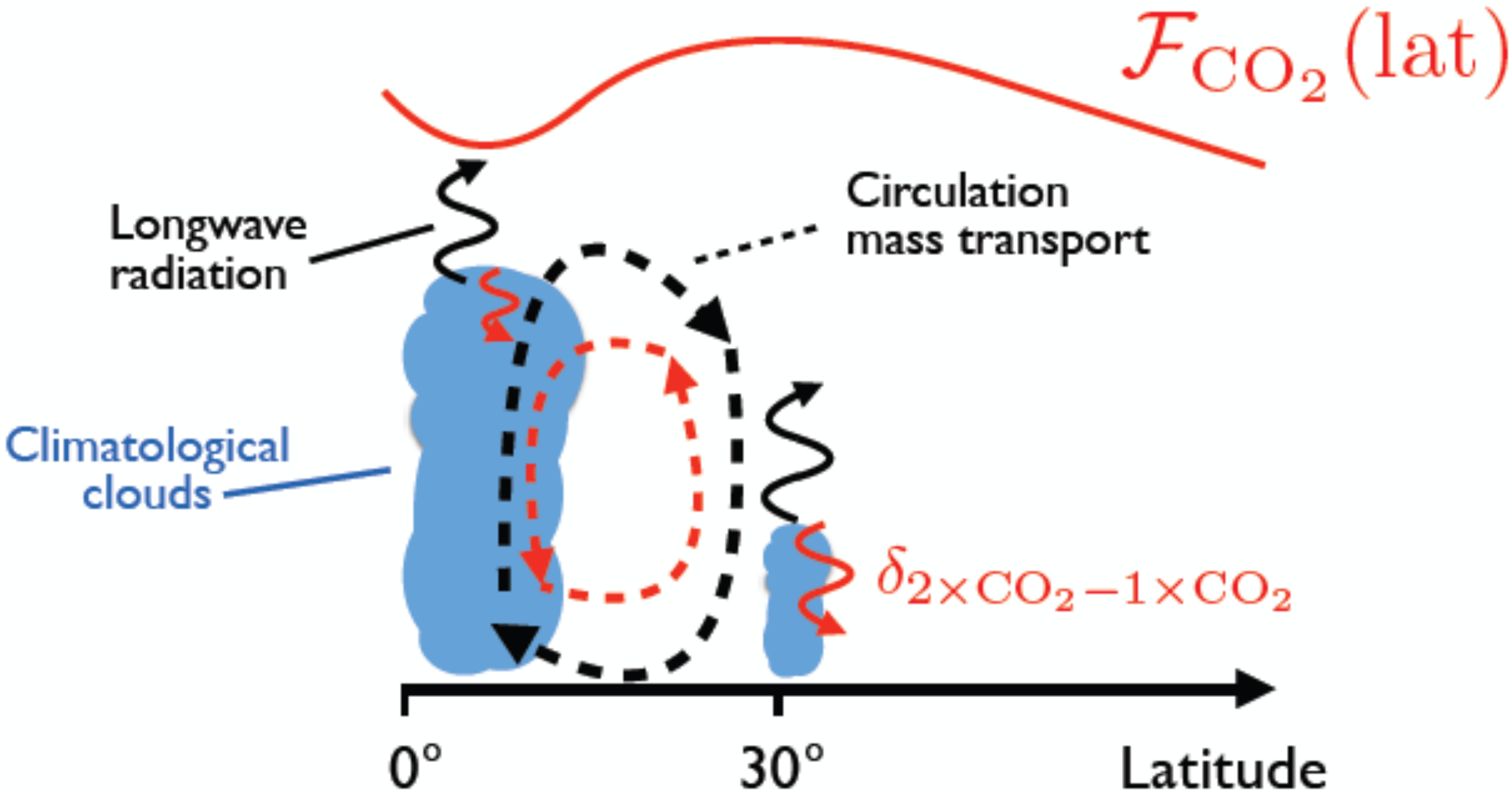
The climatological cloud distribution masks the CO_2 radiative forcing in regions of mean ascent.

Sketch of cloud masking of CO_2 radiative forcing



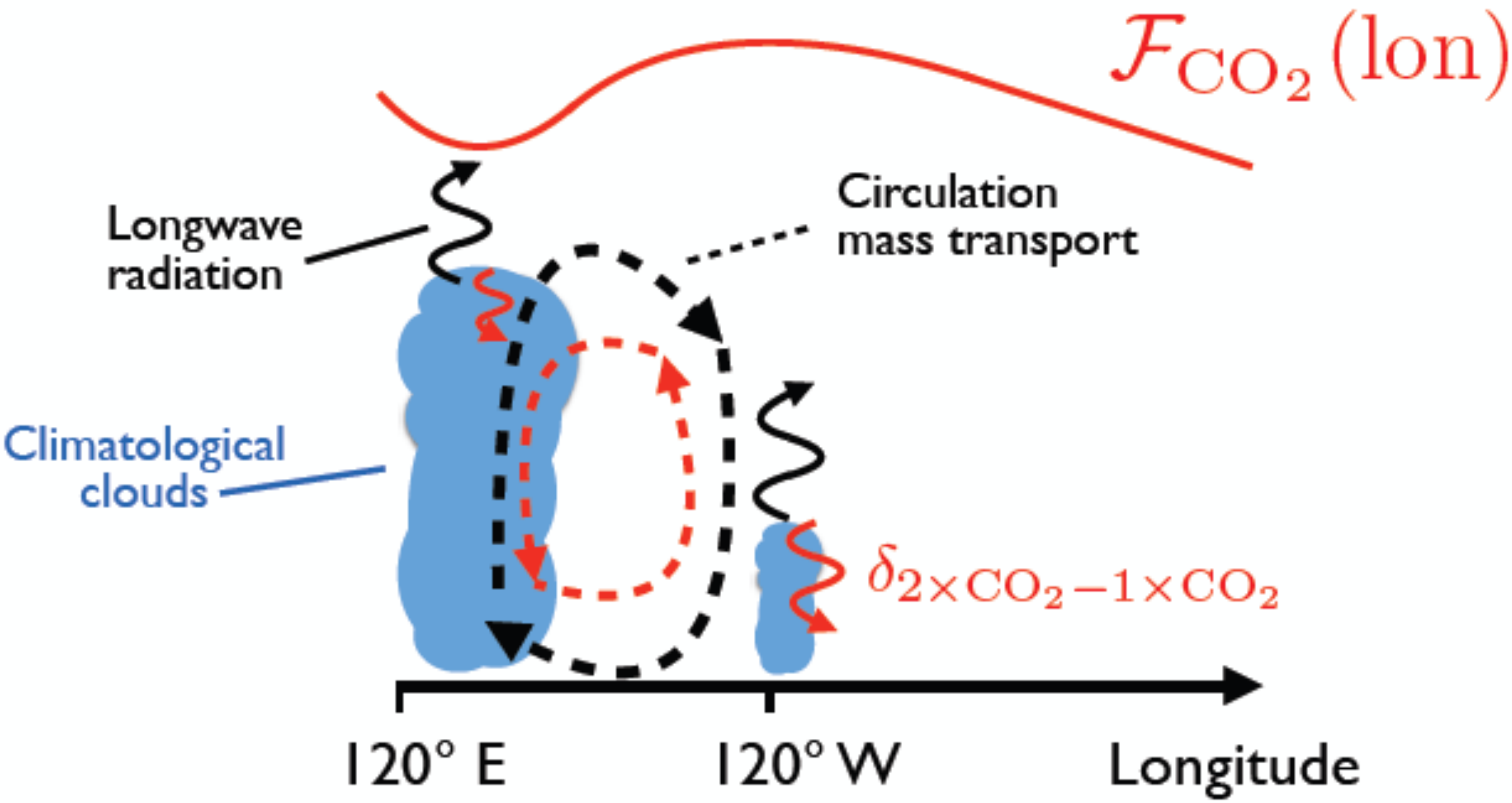
Surface radiation & fluxes also affect circulation energetics.

Sketch of cloud masking of CO_2 radiative forcing



Required atmospheric energy transport decreases.

Sketch of cloud masking of CO_2 radiative forcing

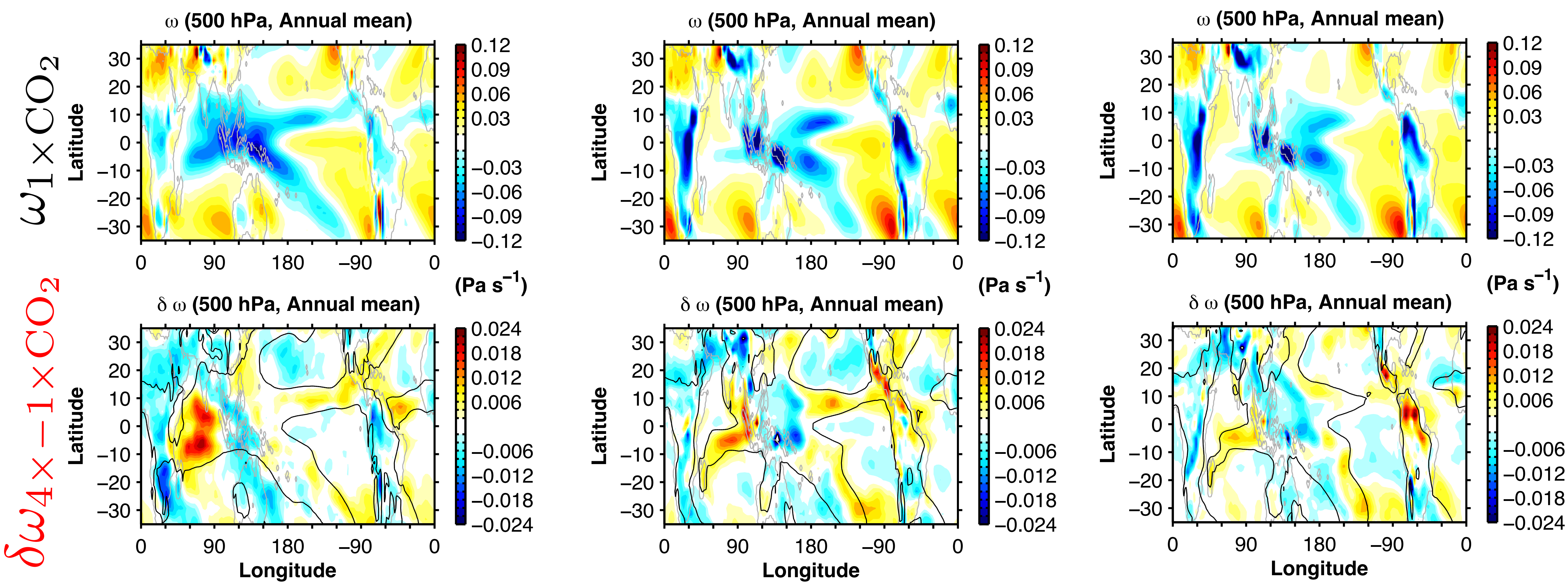


Forcing gradient also acts to oppose Walker circulation.

GFDL's AM2.1 direct circulation response to 4×CO_2

Masking of forcing deactivated →

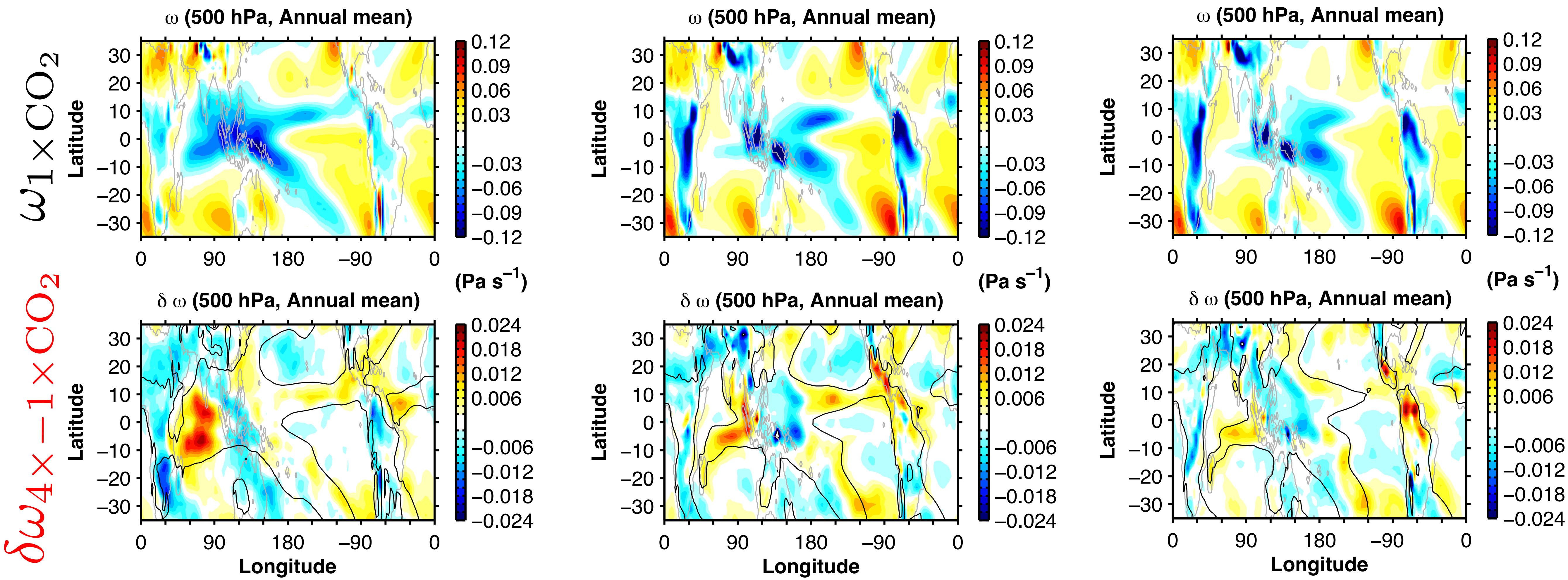
Comprehensive rad: "Cloud off" rad: "Fixed RH" rad:



$I = \overline{\omega}^{\downarrow} - \overline{\omega}^{\uparrow},\ \Delta I / I:$ -3.9% -1.4% +0.1%

GFDL's AM2.1 direct circulation response to 4×CO_2

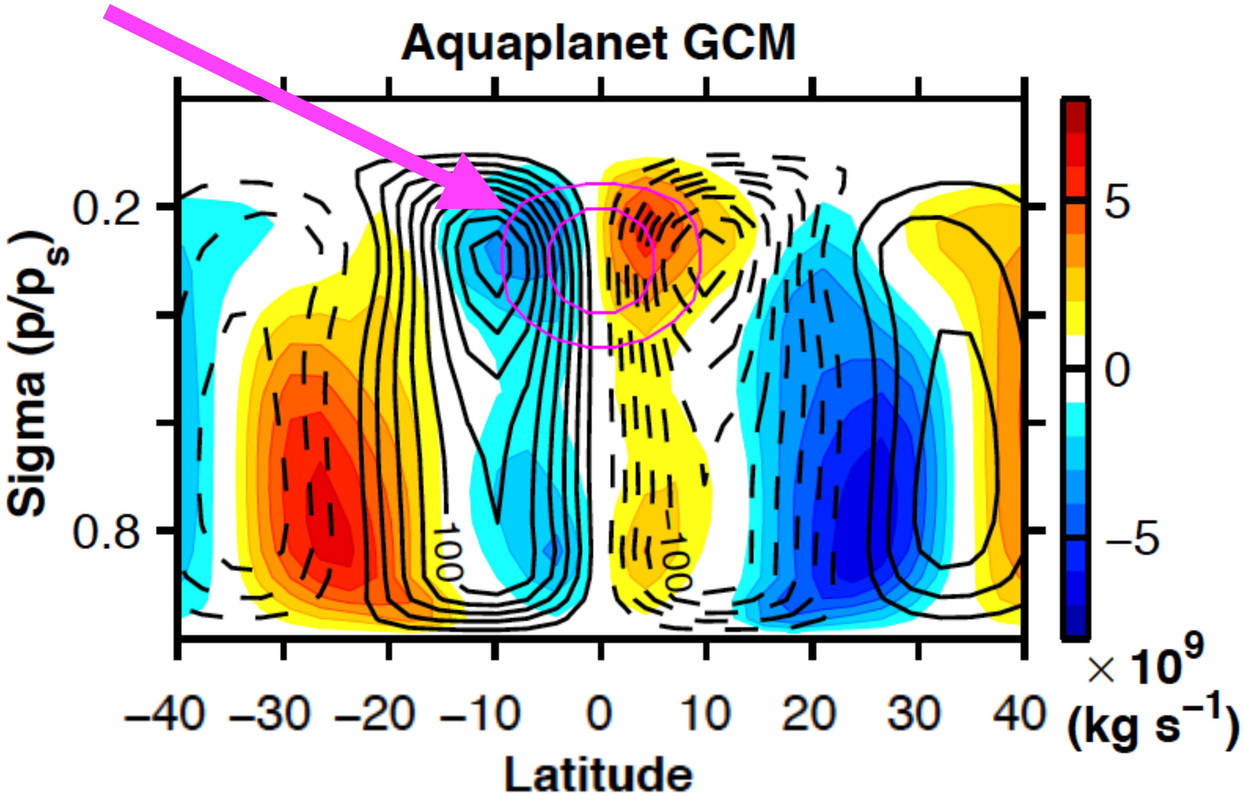
Comprehensive rad: “Cloud off” rad: “Fixed RH” rad:



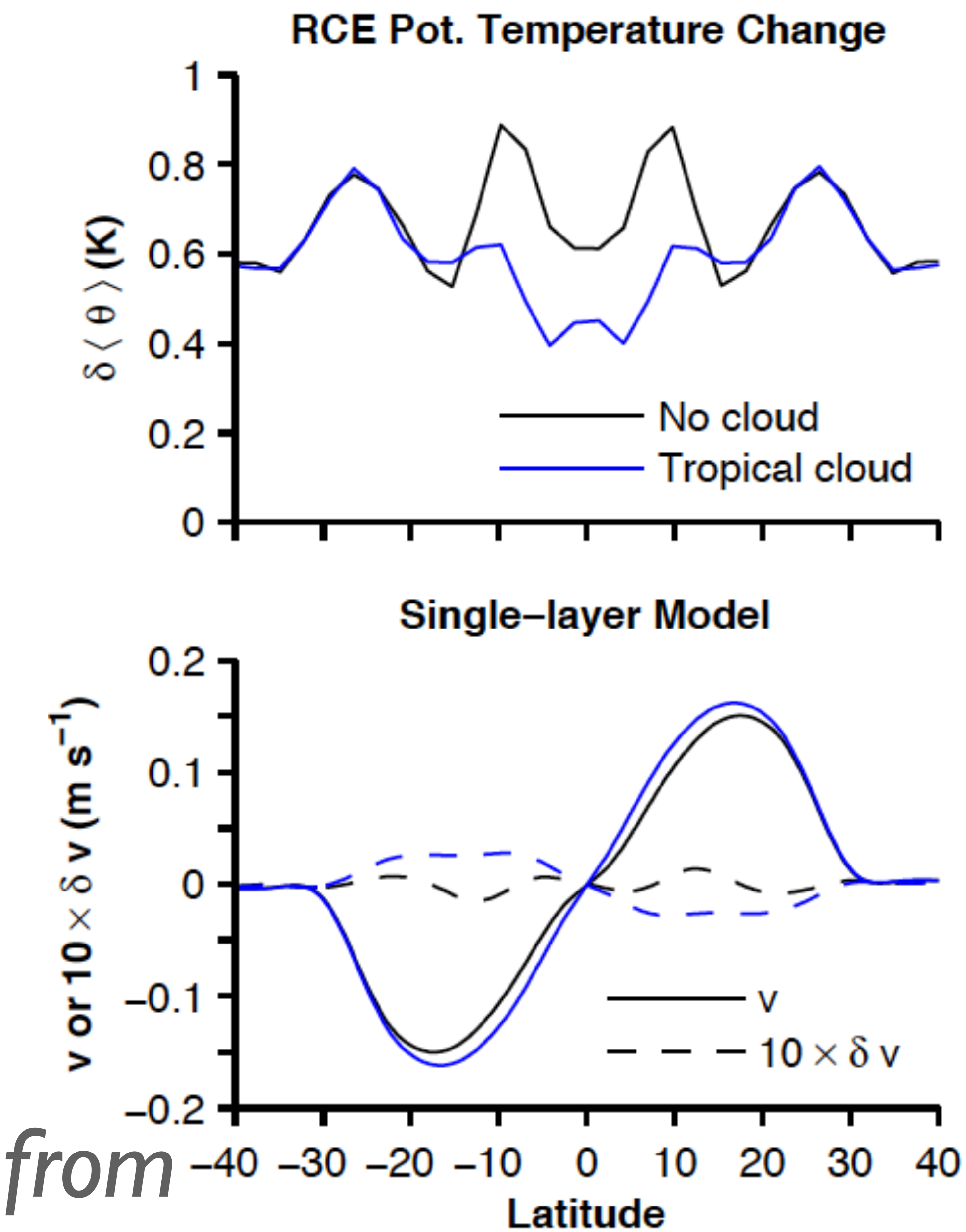
Direct CO_2 weakening of tropical circulations decreases as masking is deactivated!

Idealized Models

Prescribed cloud



GCM from Merlis et al. (2013)



SLM from Sobel & Schneider (2009)

~2% direct weakening across model hierarchy

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New mechanism for direct CO_2 circulation weakening posits a key role for spatial pattern of forcing