Carbon dioxide's direct weakening of the tropical circulation: from comprehensive climate models to axisymmetric Hadley cell theory

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Key point

The spatial structure of radiative forcing provokes tropical circulation changes…

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… & these *direct* circulation changes are more robust than temperature-dependent ones

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:

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

Direct tropical circulation weakening robustly simulated in CMIP5 GCMs

Bony et al. (2013)

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… & these *direct* circulation changes are more robust than temperature dependent ones

IPCC AR5: 45+ figures of structure of radiative forcing

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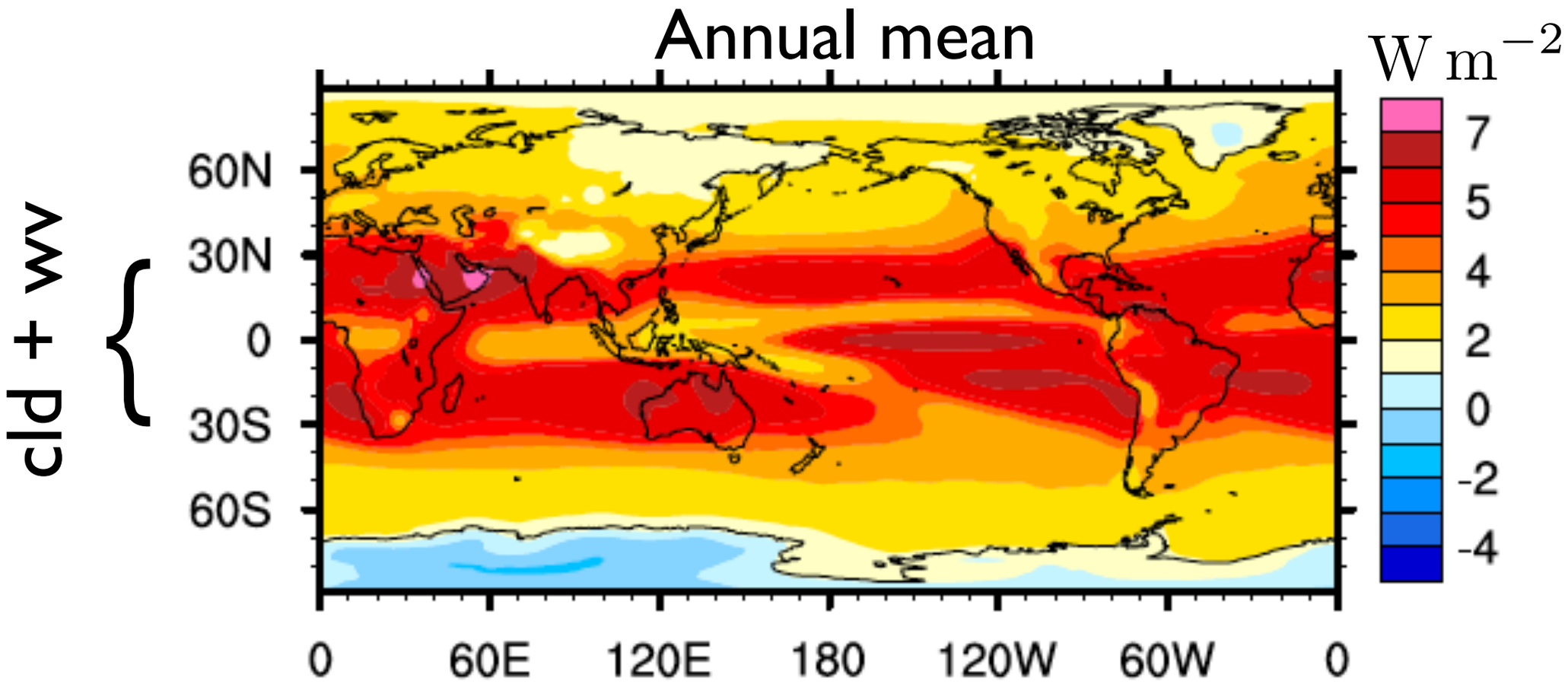
… & these *direct* circulation changes are more robust than temperature dependent ones

IPCC AR5: 45+ figures of *aerosol* radiative forcing, but 0 of carbon dioxide's structure

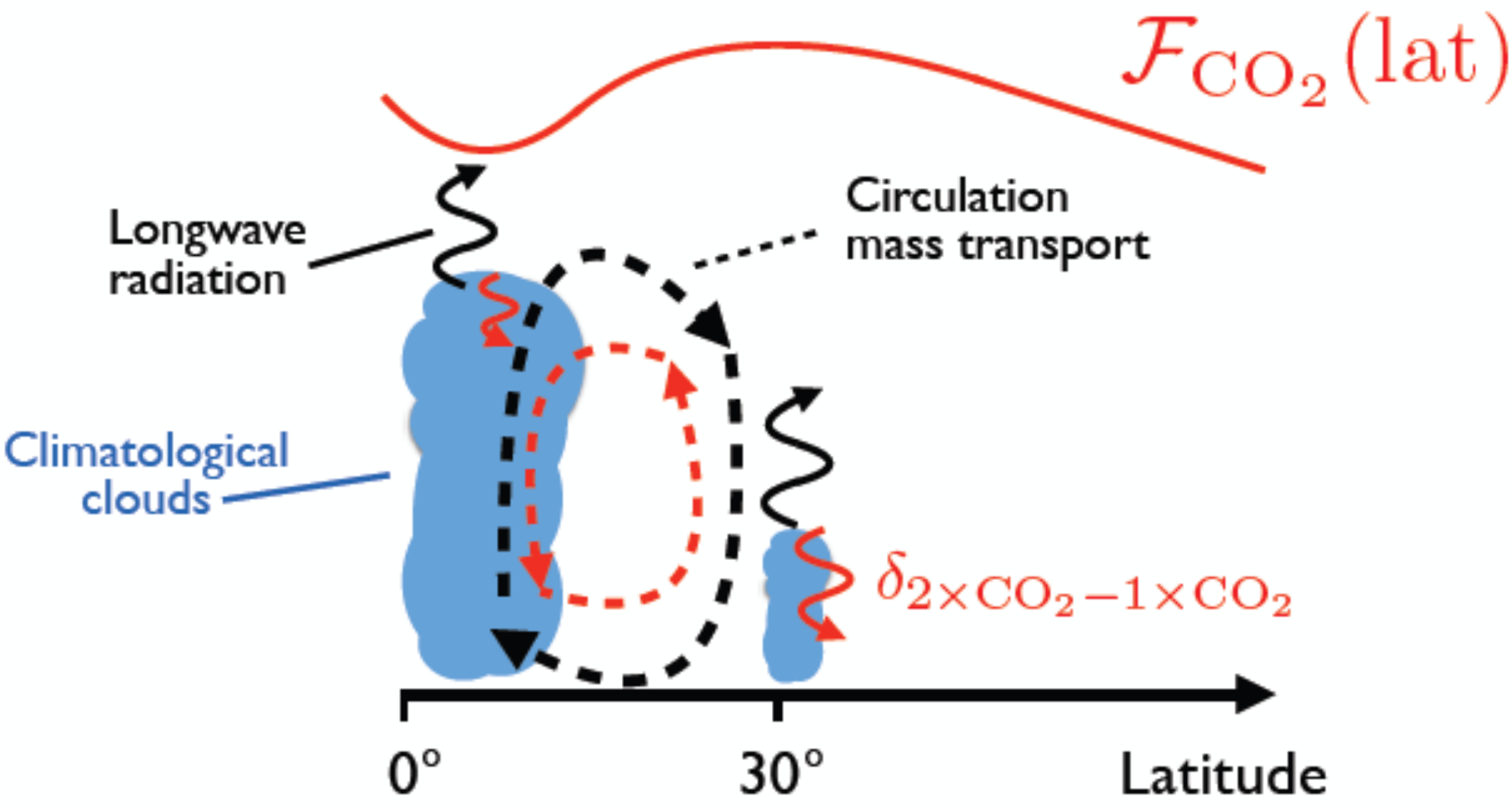
Spatial structure of CO_2 radiative forcing



Zhang & Huang (2014)

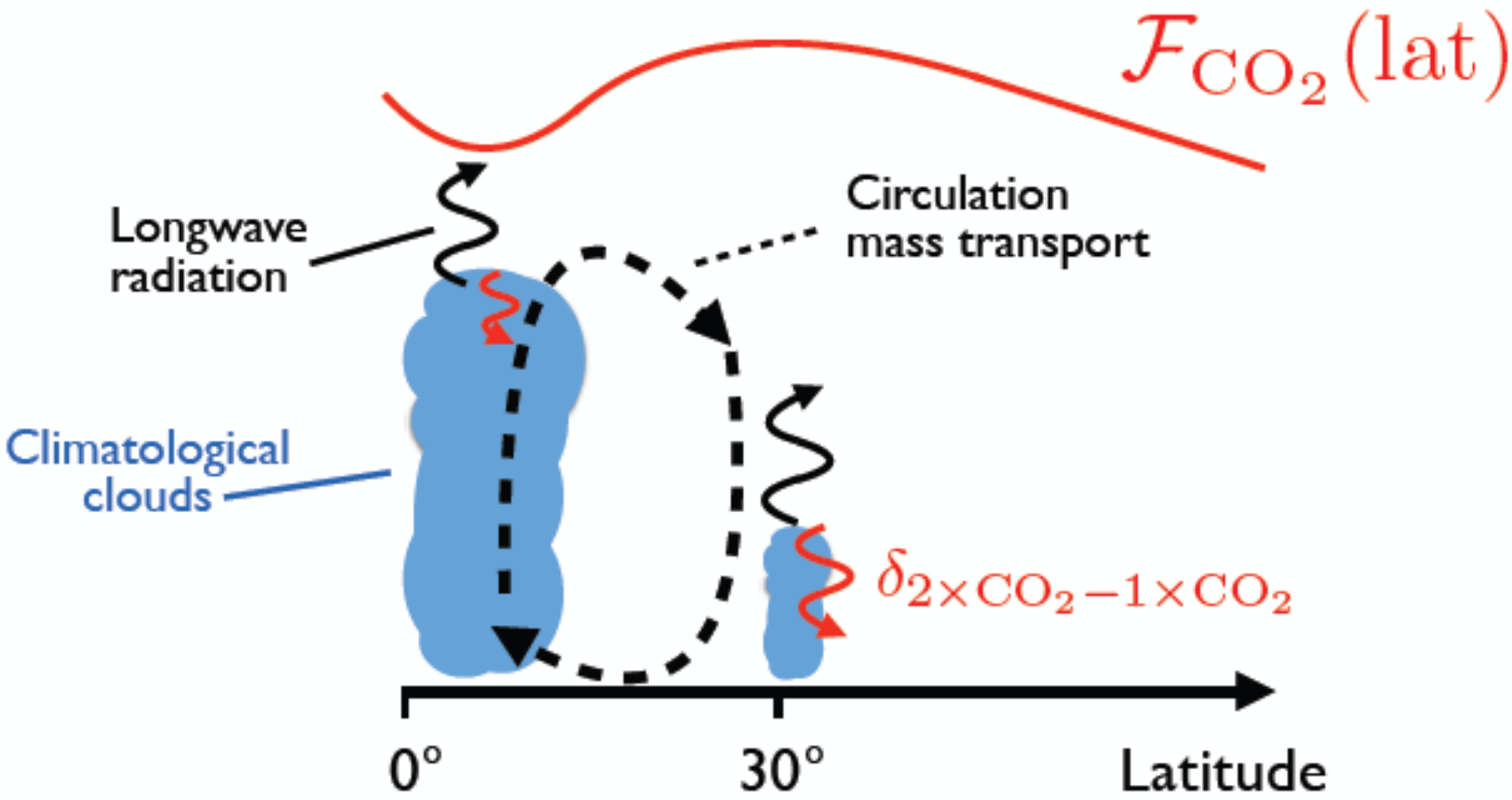
The climatological cloud and w.v. distribution "masks" (=reduces) the CO_2 radiative forcing in regions of mean ascent.

CO_2 radiative forcing is spatially inhomogeneous!



Required atmospheric energy transport of mean tropical circulations decreases.

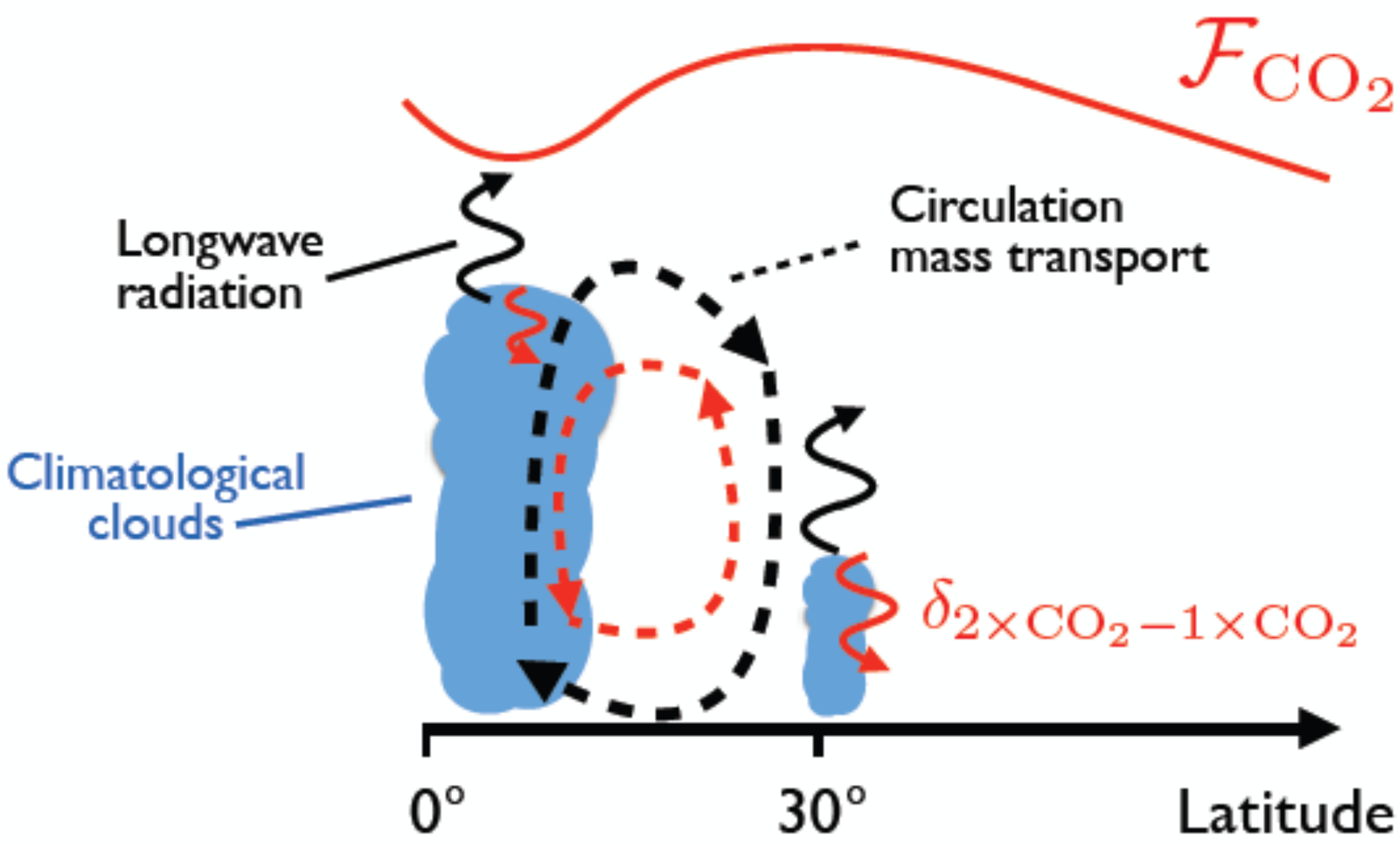
Sketch of cloud masking of CO_2 radiative forcing



Surface radiation & fluxes also affect circulation energetics…
key for land-sea circulation changes

Shaw & Voigt (2016)

CO_2 radiative forcing is spatially inhomogeneous!



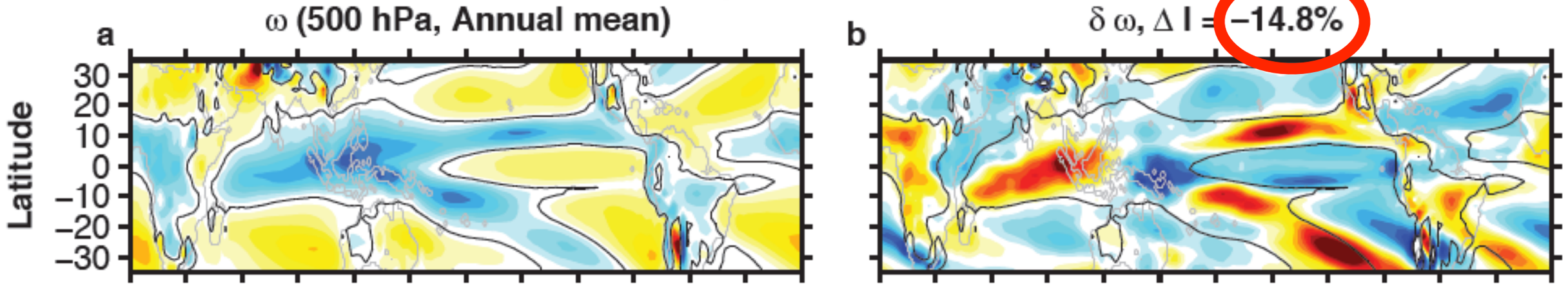
Merlis (2015): Direct weakening of tropical circulations from masked CO_2 radiative forcing. PNAS

Tropical circulation response to 4×CO_2

$$I = \overline{\omega}^{\downarrow} - \overline{\omega}^{\uparrow}, \ \Delta I / I$$

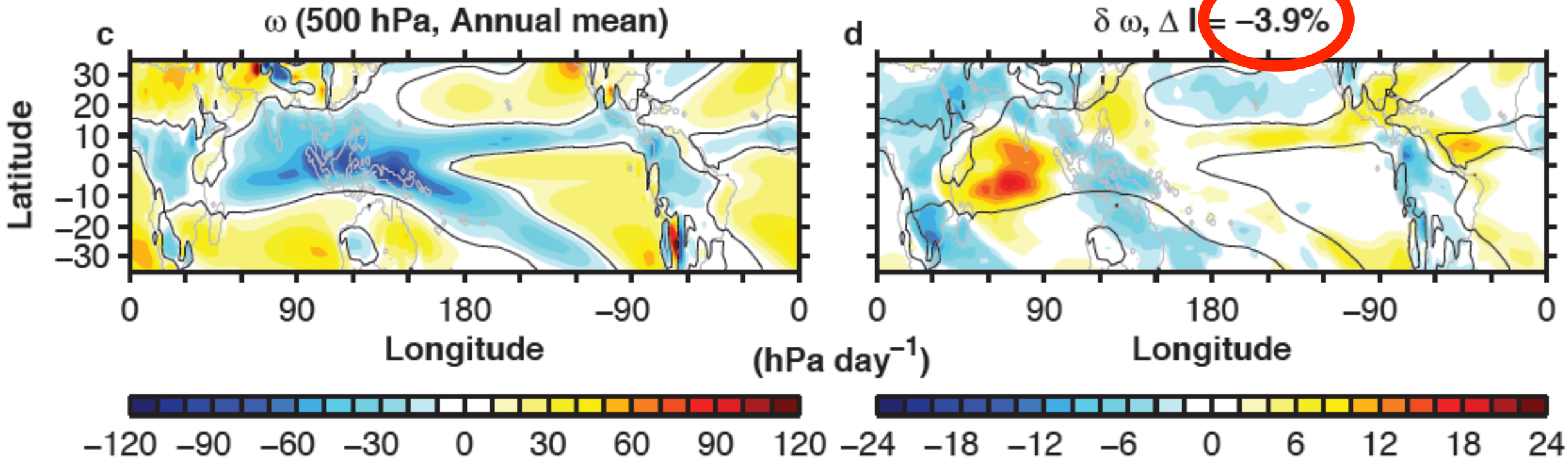
GFDL ESM2M

Coupled Simulations



GFDL AM2.1

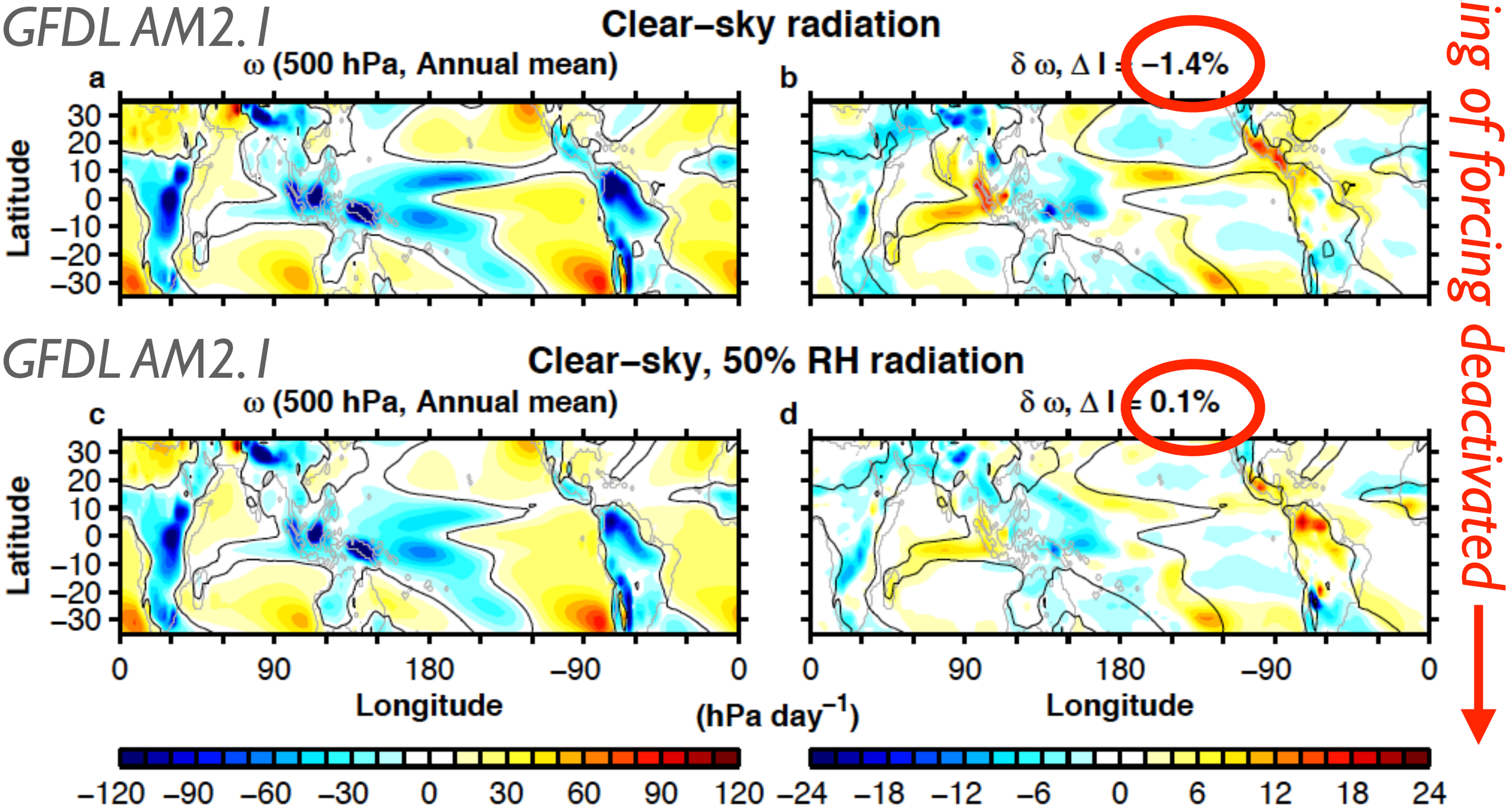
Prescribed–SST Atmospheric Simulations



~15-25% of century-scale weakening is a direct CO_2 weakening

Removing masking by altering radiative transfer

GFDL AM2.1

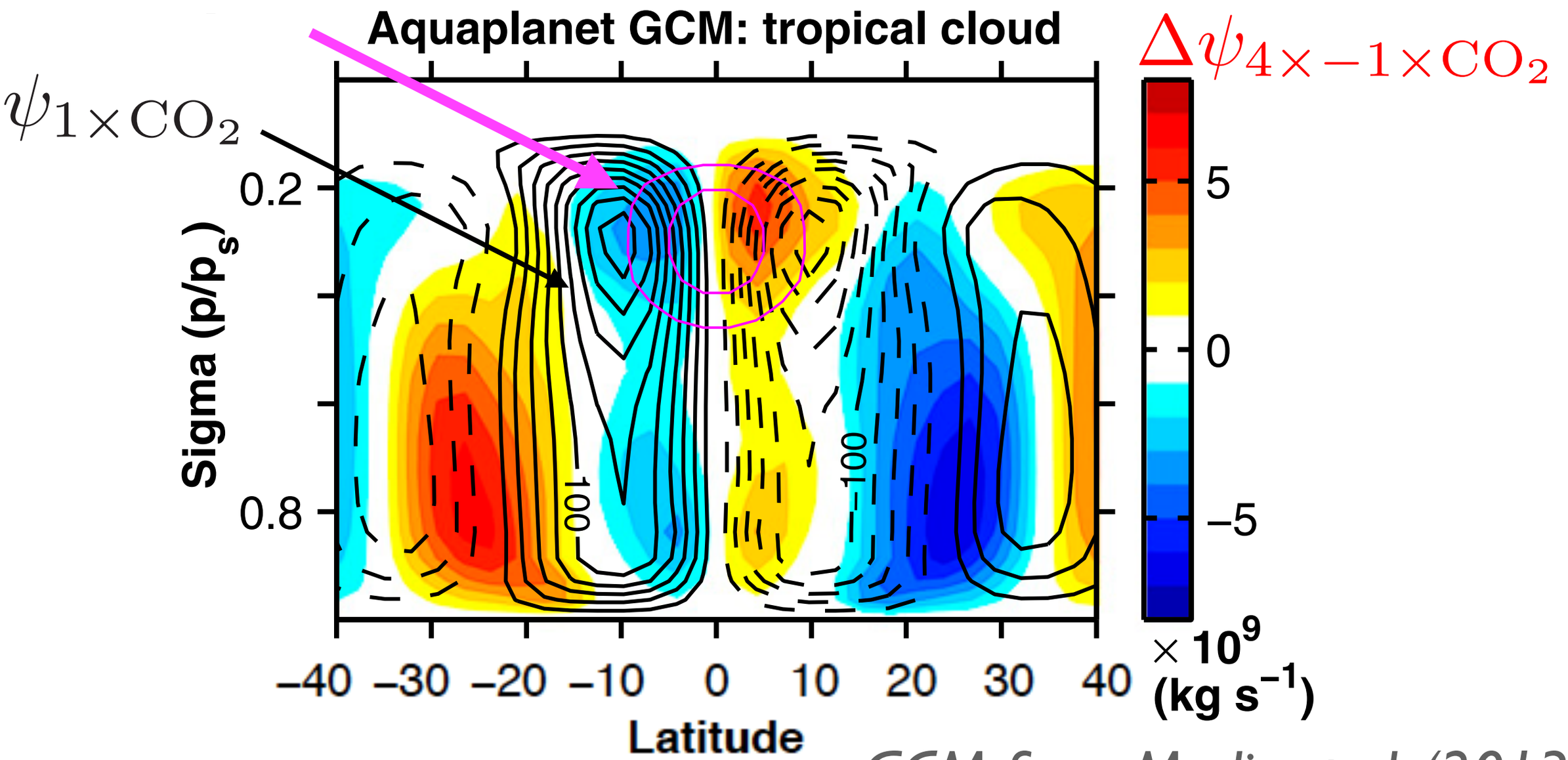


Masking of forcing deactivated

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

Idealized Models: Aquaplanet & One-layer

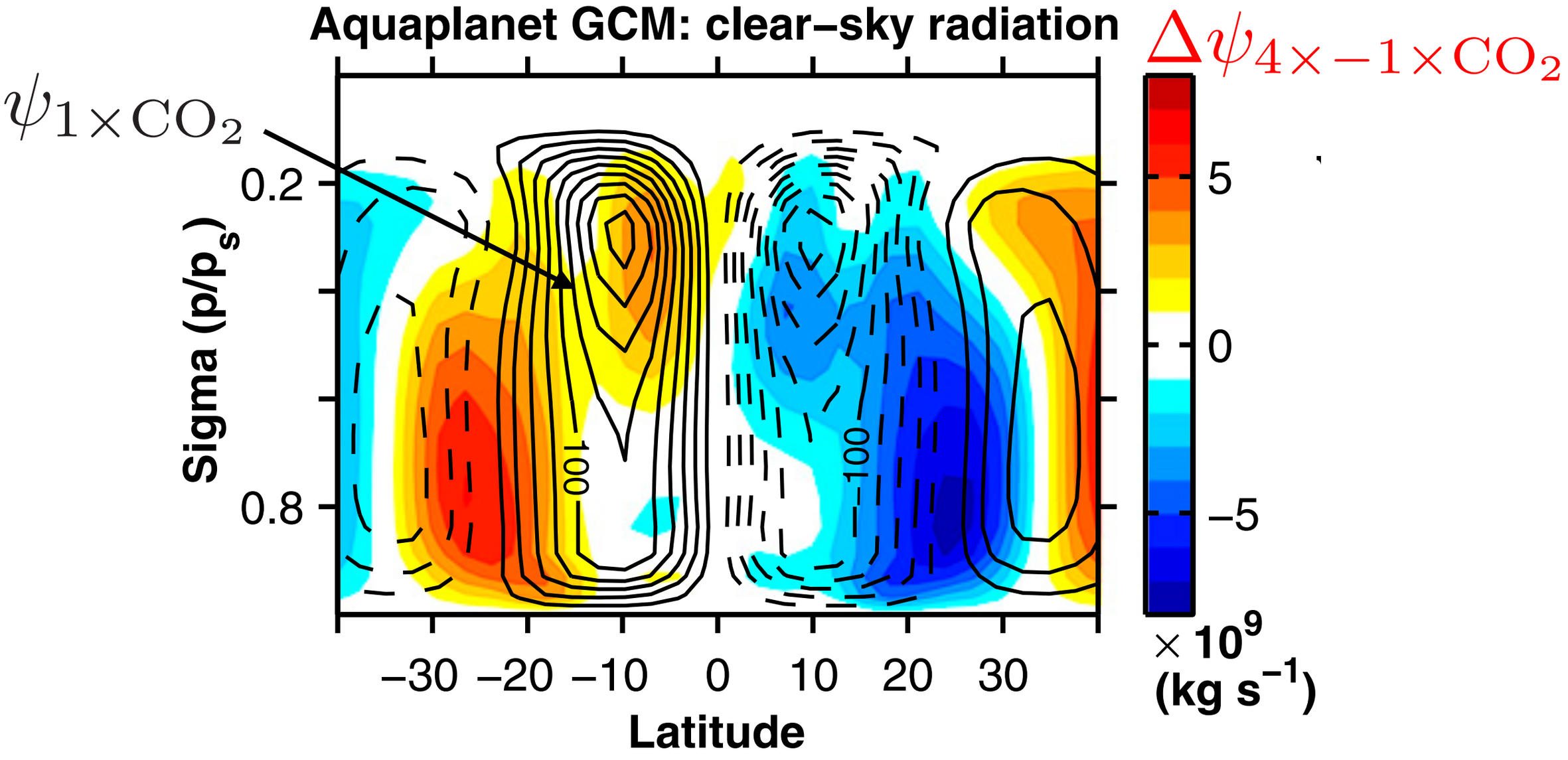
Prescribed cloud



GCM from Merlis et al. (2013)

~2% direct weakening like comprehensive BC GCMs

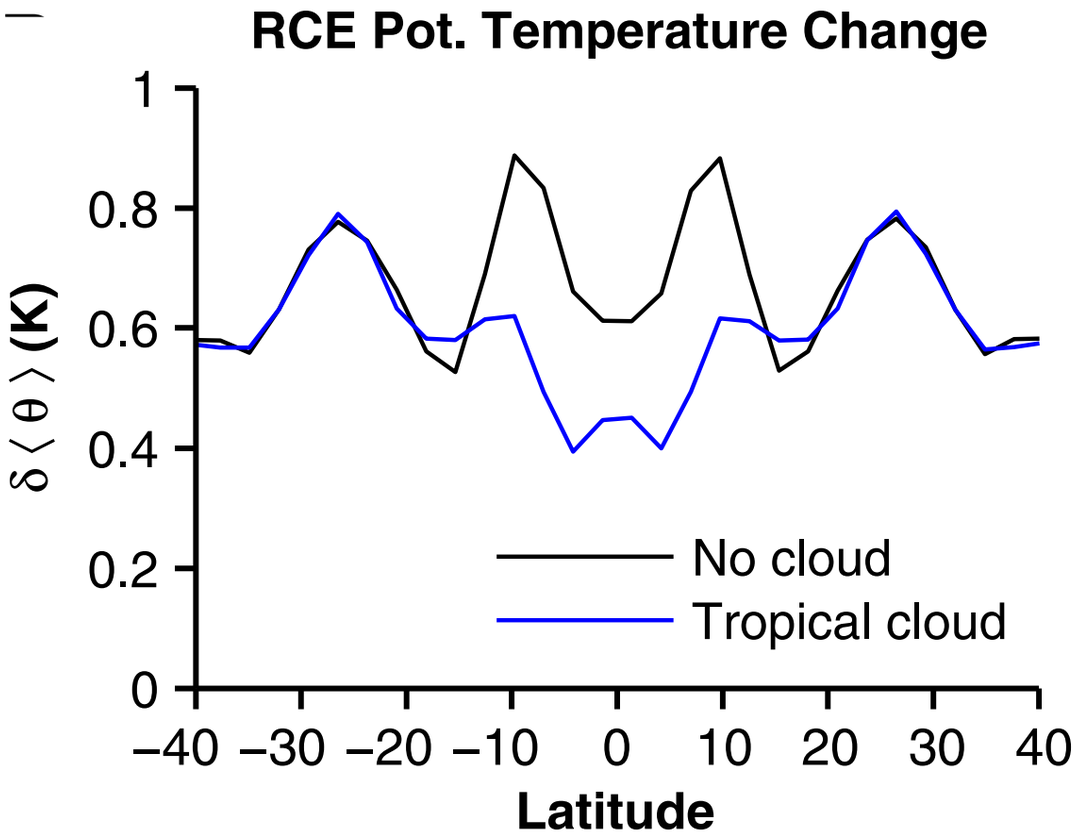
Idealized Models: Aquaplanet & One-layer

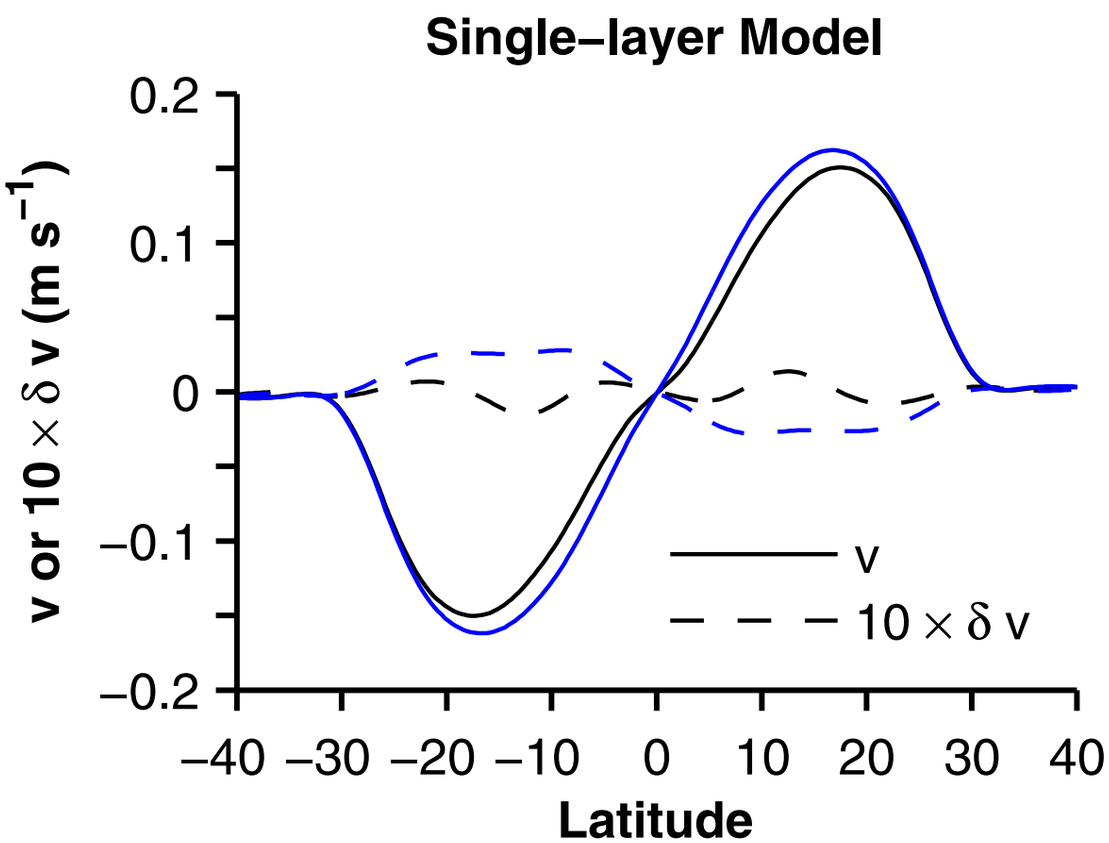


Remove cloud ⟹ remove direct CO2 weakening

Idealized Models: Aquaplanet & One-layer

This mechanism is based on energetic Hadley cell theory (Held & Hou, 1980) $\Longrightarrow$ axisymmetric models with appropriate thermal forcing will simulate it

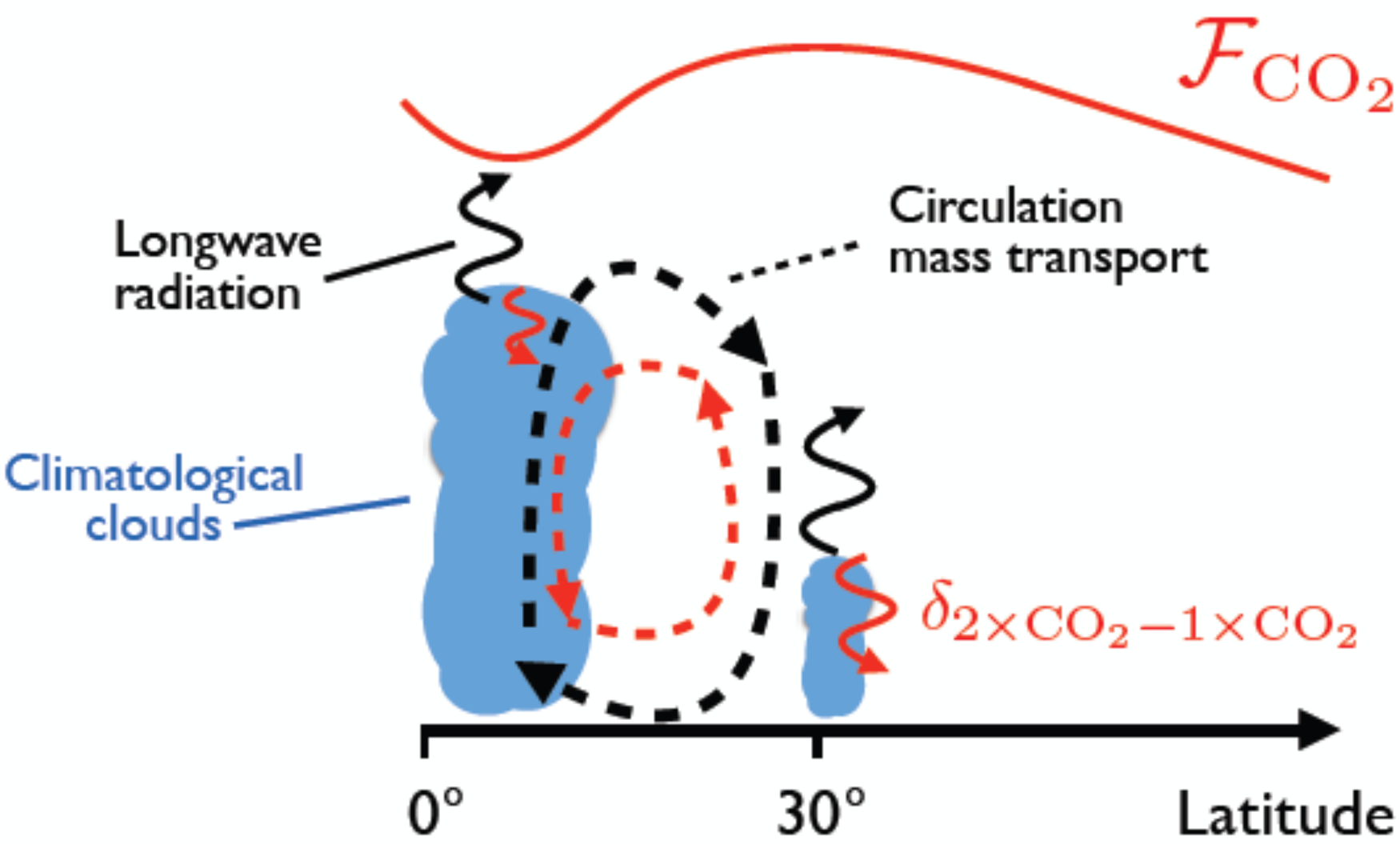




SLM from Sobel & Schneider (2009) implemented by Tim Cronin

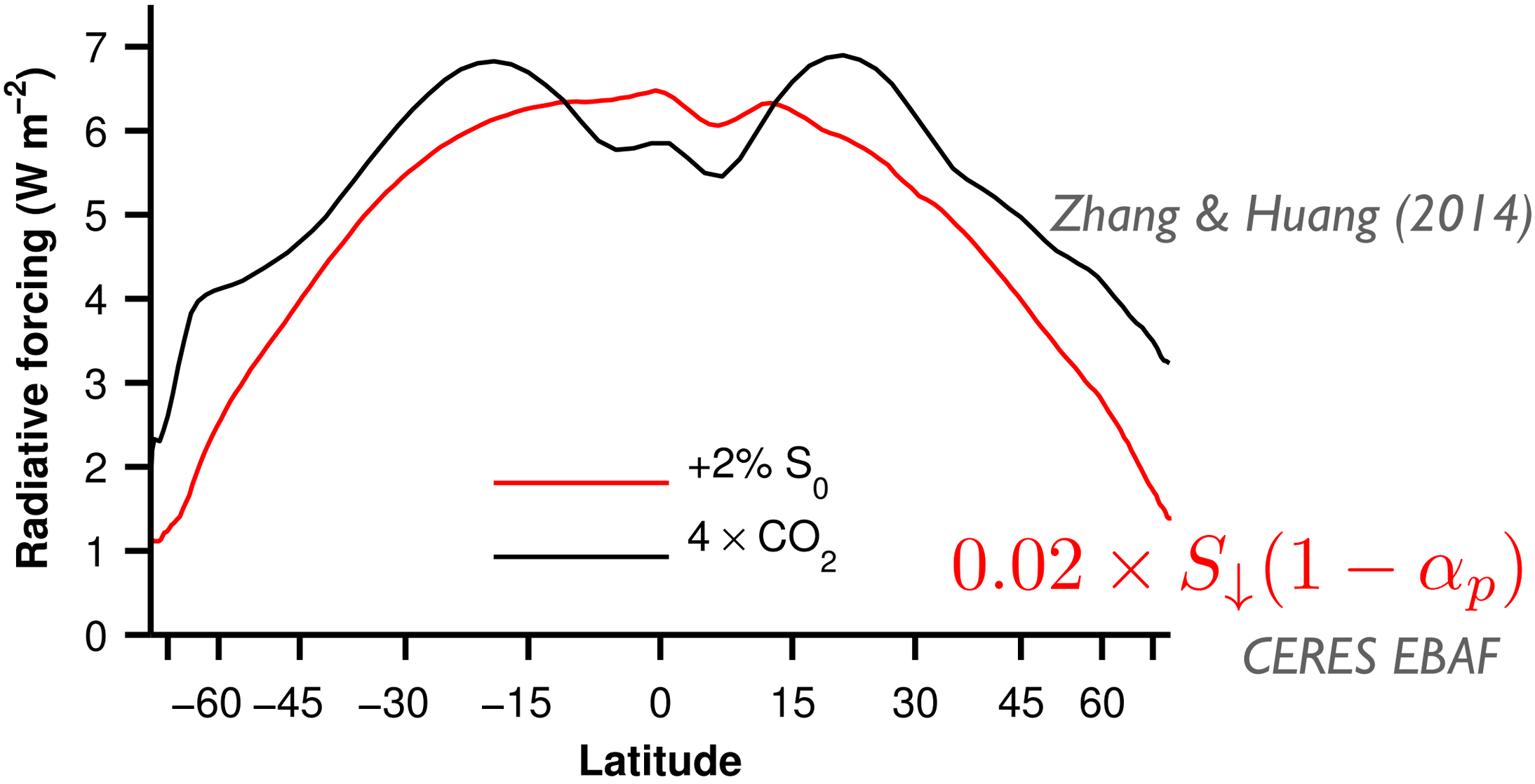
~2% direct weakening across model hierarchy

CO_2 radiative forcing is spatially inhomogeneous!



Low clouds: little impact on longwave & big impact on shortwave

Differences in spatial structure of radiation forcing



Zhang & Huang (2014)

$$0.02 \times S_{\downarrow}(1 - \alpha_p)$$

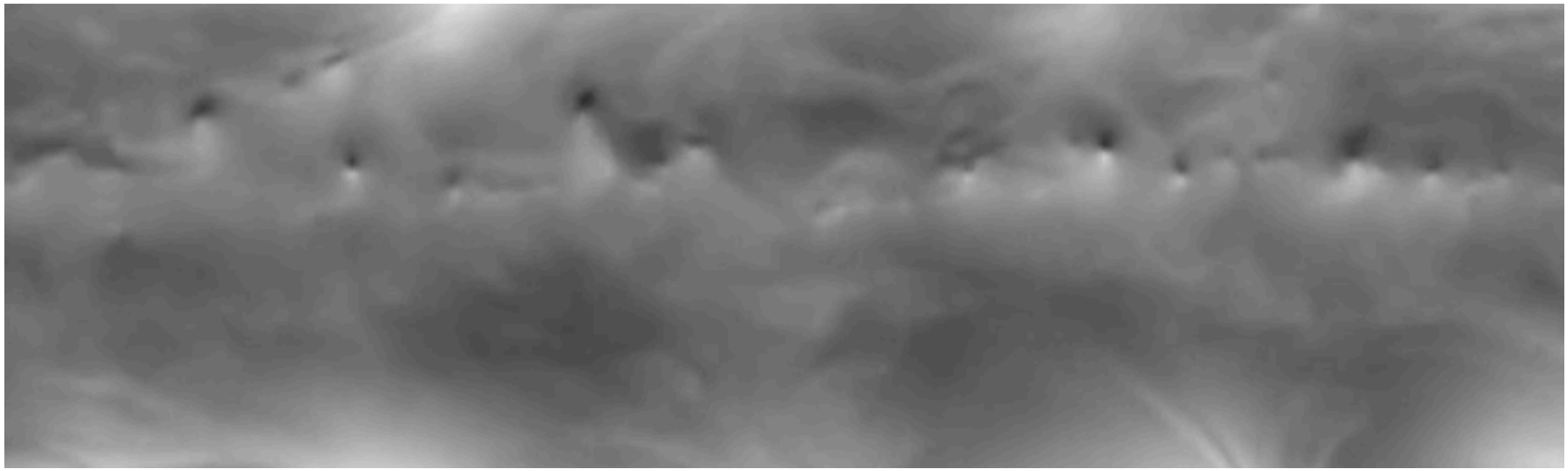
CERES EBAF

Expect differences in circulation change
($\Longrightarrow$ P & TC) from affect on moist energetics!

Direct circulation response to CO_2, solar forcing

fixed SST, altered forcing

In aquaplanet version of GFDL's HiRAM 50-km GCM



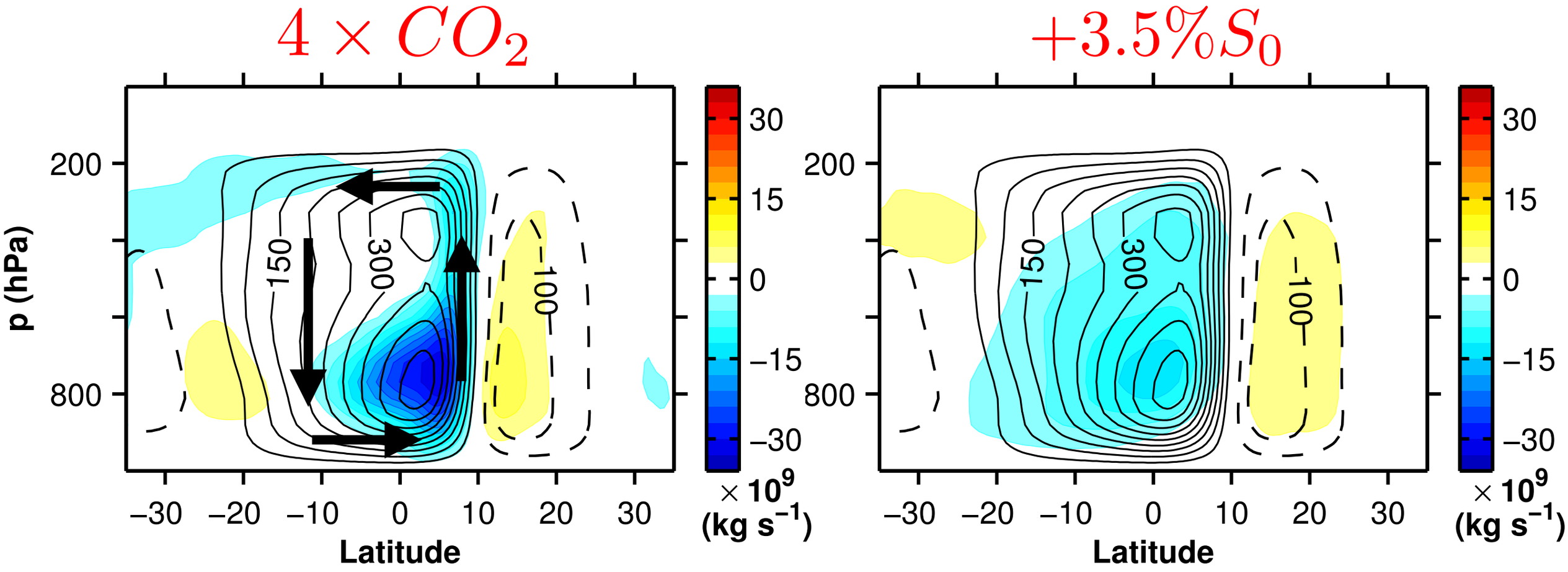
Merlis et al. (2013b)

Comprehensive BC GFDL AM2.1 also has forcing dependent direct mean circulation response

Direct circulation response to CO_2, solar forcing

fixed SST, altered forcing

In aquaplanet version of GFDL's HiRAM 50-km GCM



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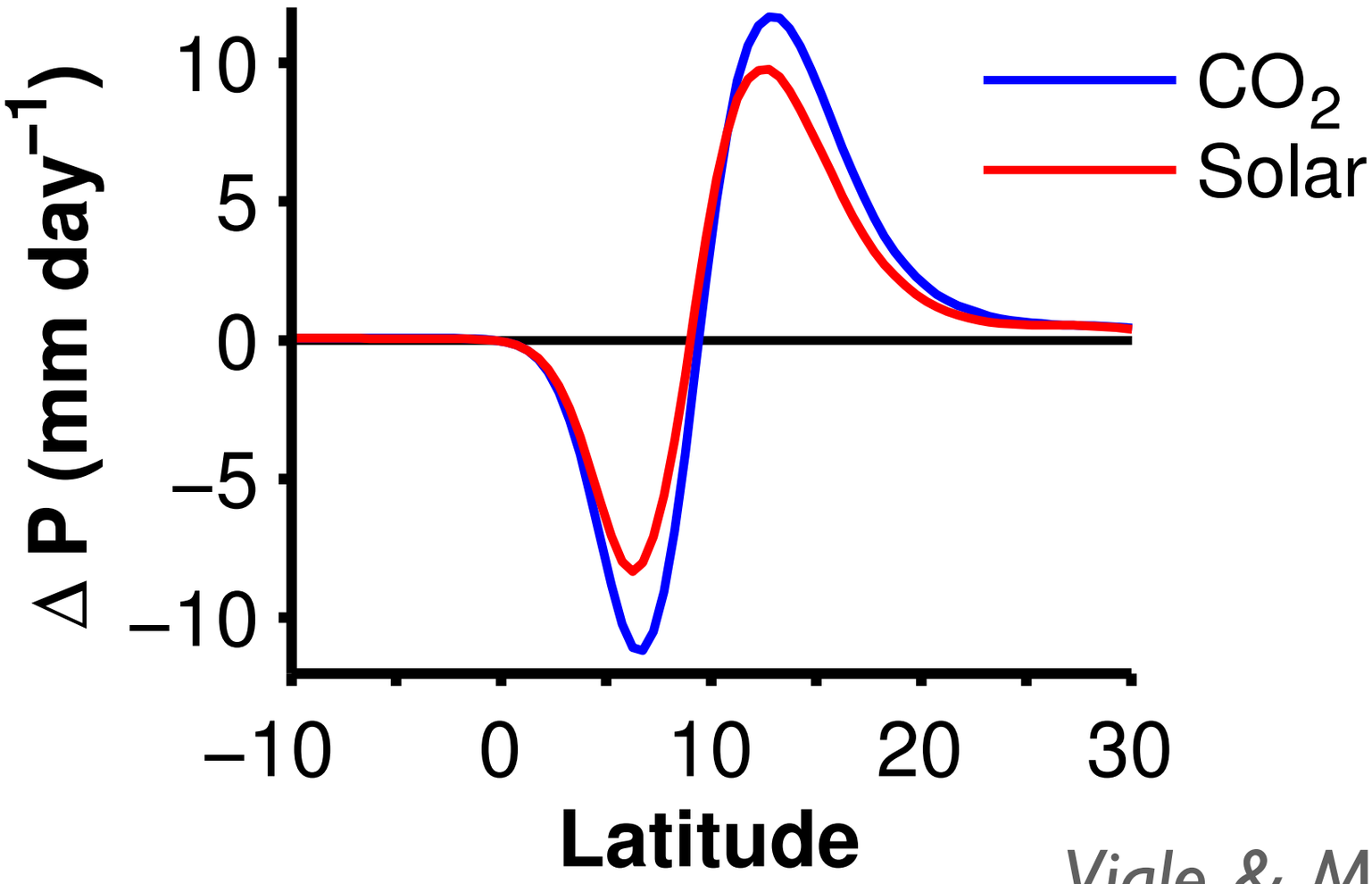
CO_2 forces larger ITCZ shifts than comparable S_0 increase

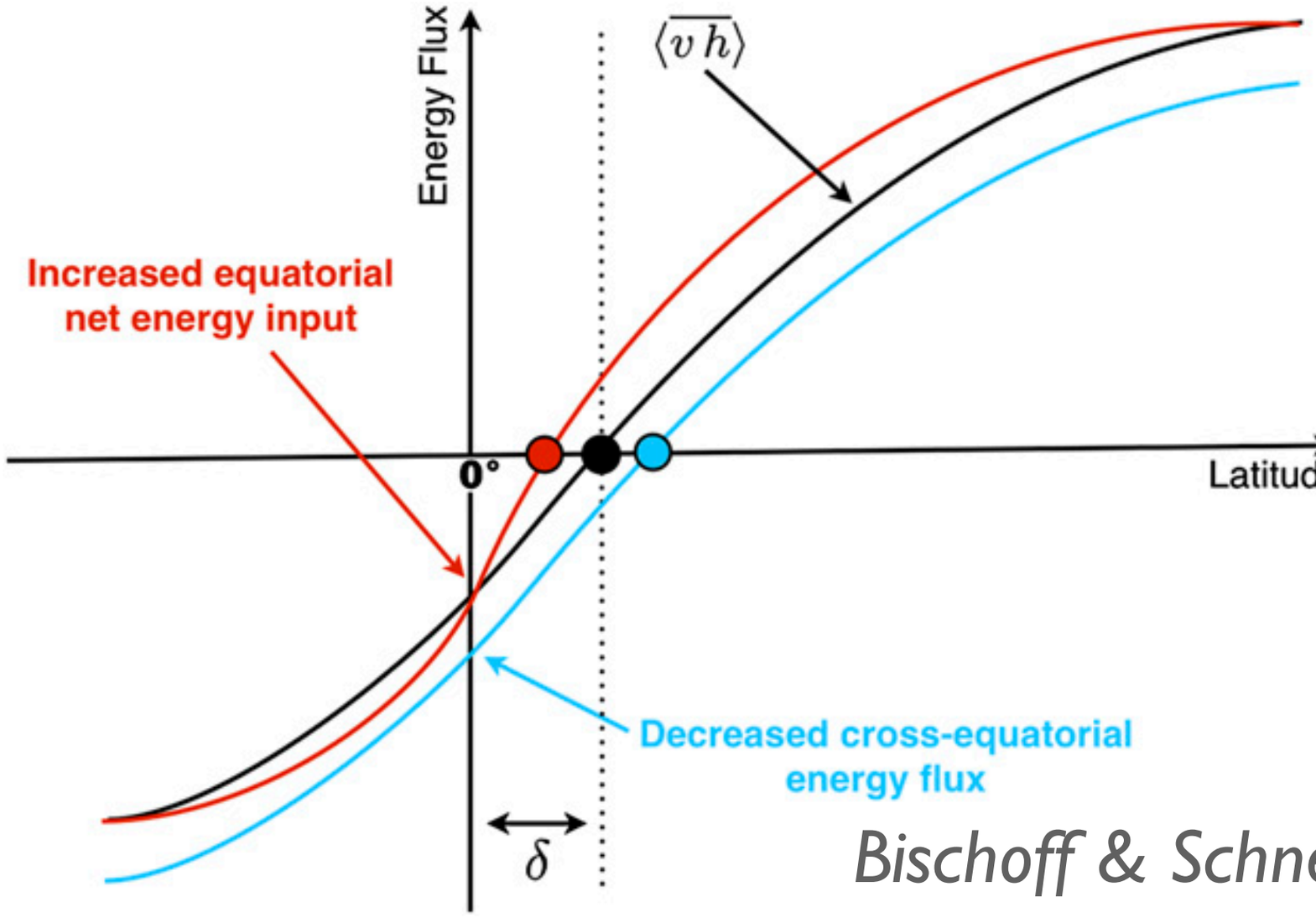
These shifts are *temperature-dependent* (not direct) changes



Viale & Merlis (submitted)

3° shift vs. 2.5° shift of latitude of maximum P with same *global-mean* radiative forcing

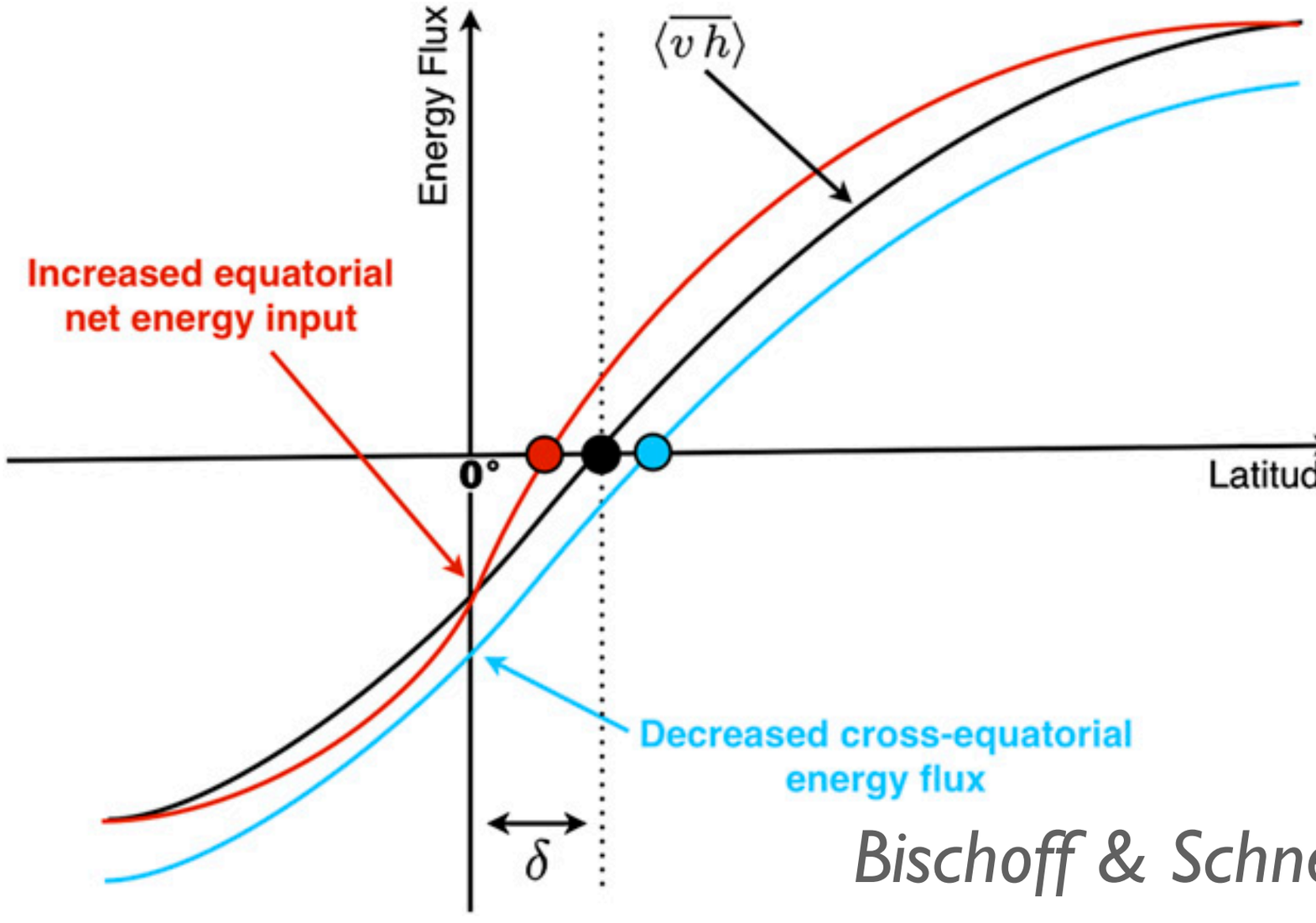
CO_2 forces larger ITCZ shifts than comparable S_0 increase



Bischoff & Schneider (2014)

Solar forcing provokes an increase in tropical energy input because it is larger in the tropical mean than CO_2 forcing

CO_2 forces larger ITCZ shifts than comparable S_0 increase



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Thank you!

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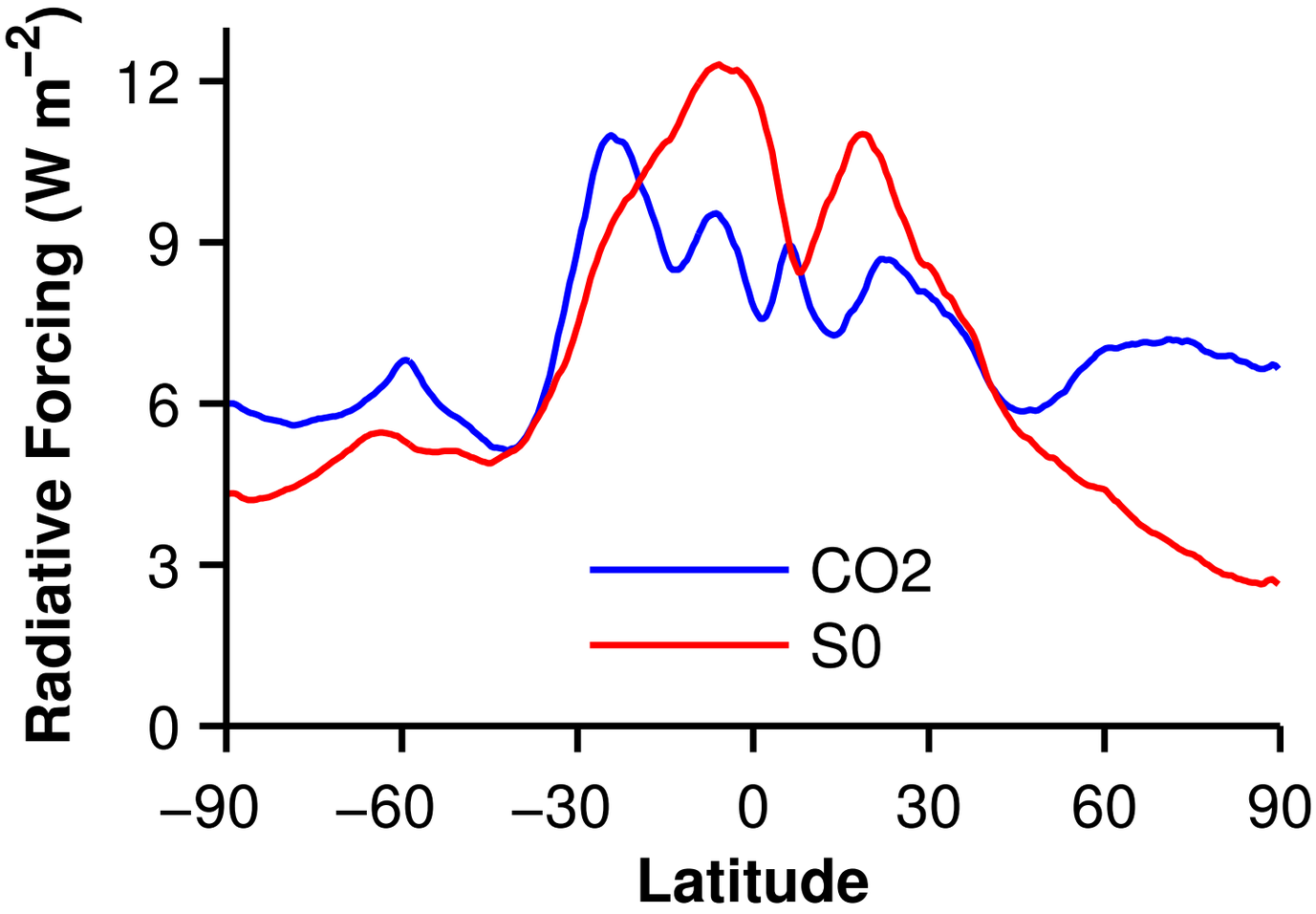

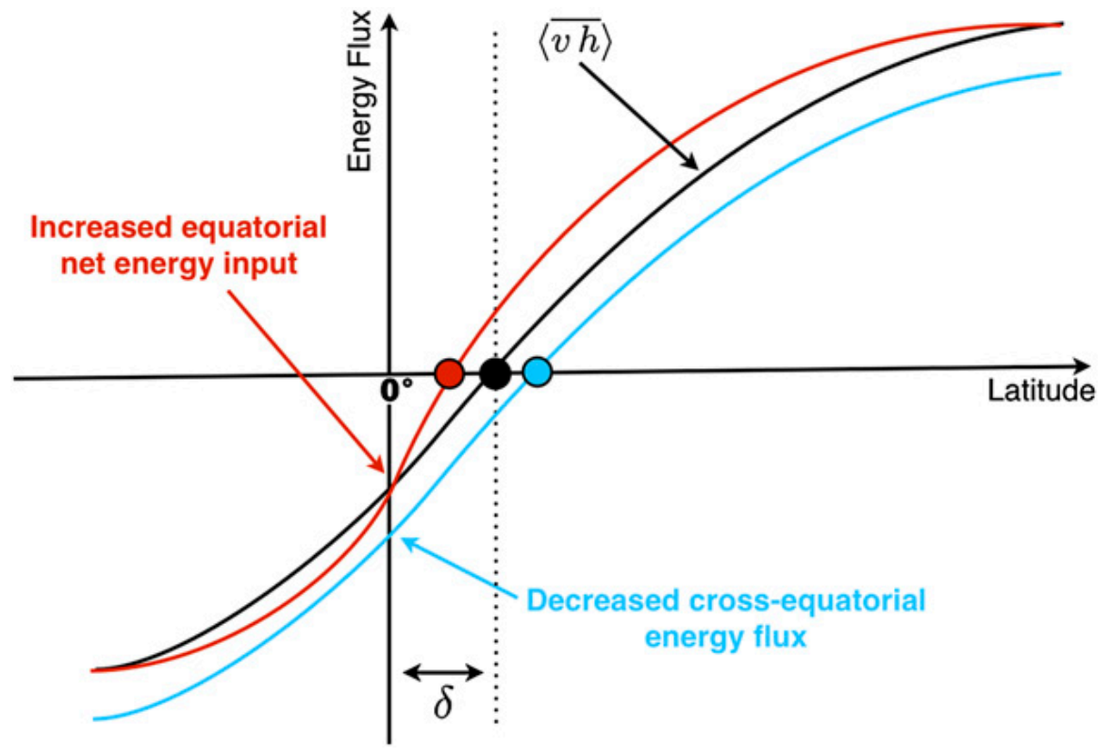

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