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Delineating local coupled feedbacks and remote drivers using a Green's function approach in the coupled climate system

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1. Introduction and Motivation

A long tradition exists using linear response theory in climate science. Specifically, utilizing Green's functions in atmospheric general circulation model (AGCM) experiments, by prescribing idealized sea surface temperature (SST) boundary forcing patterns ($\delta\mathbf{T}$), has provided valuable insight into the SST-forced atmospheric response ($\delta\mathbf{y}$; e.g., Branstator, 1985a,b, Barsugli & Sardeshmuk, 2002, Barsugli et al., 2006), including radiative feedbacks (e.g., Zhou et al., 2017, Dong et al., 2019):

$$\delta\mathbf{y} = \mathbf{J}_a^{-1}\delta\mathbf{T} \quad \text{(equation 1)}$$

Recently, this framework has been extended into settings using AGCMs coupled to an aquaplanet (Kang et al., 2017) and to a slab ocean model with realistic continental configuration (Liu et al., 2018a,b,2020).

Building on this work, we have developed a Green's function approach for the coupled climate system, i.e., using an AGCM coupled to a fully dynamical ocean model, to quantify the roles of local coupled feedbacks and remote drivers in determining regional climate change patterns (Stuecker et al., 2018,2020). Among other applications, we used this approach to quantify the physical mechanisms responsible for SST pattern ($\delta\mathbf{T}$) formation in the coupled system in response to radiative forcing ($\delta\mathbf{F}$):

$$\delta\mathbf{T} = \mathbf{J}_b^{-1}\delta\mathbf{F} \quad \text{(equation 2)}$$

[K] [K W^{-1} m^2] [W m^{-2}]

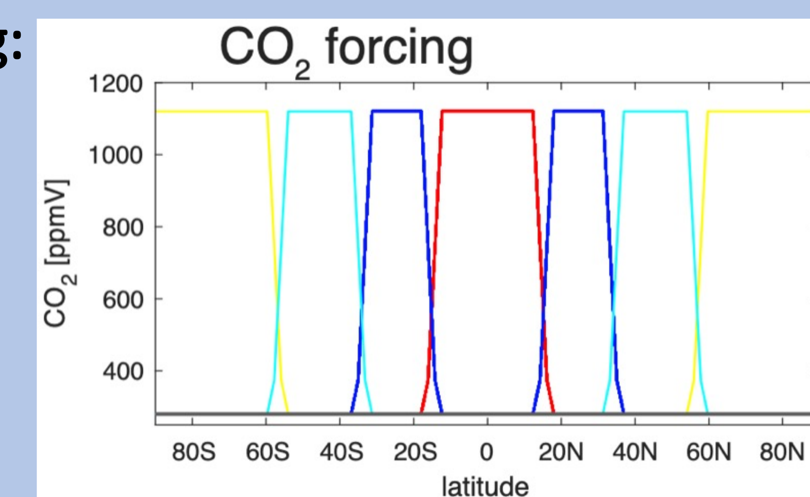
So far, this approach has been proved successful in quantifying the physical processes leading to polar amplification (Stuecker et al., 2018), the tropical warming pattern (Stuecker et al., 2020), as well as Hadley circulation changes in response to warming (Kim et al., in review).

2. Experiments

i) Standard coupled GCM global control and 4xCO_2 experiments. Surface temperature response: $\delta\mathbf{T}$ (LHS of equation 2)

ii) Conduct coupled GCM experiments with only regionally perturbed CO_2 forcing:

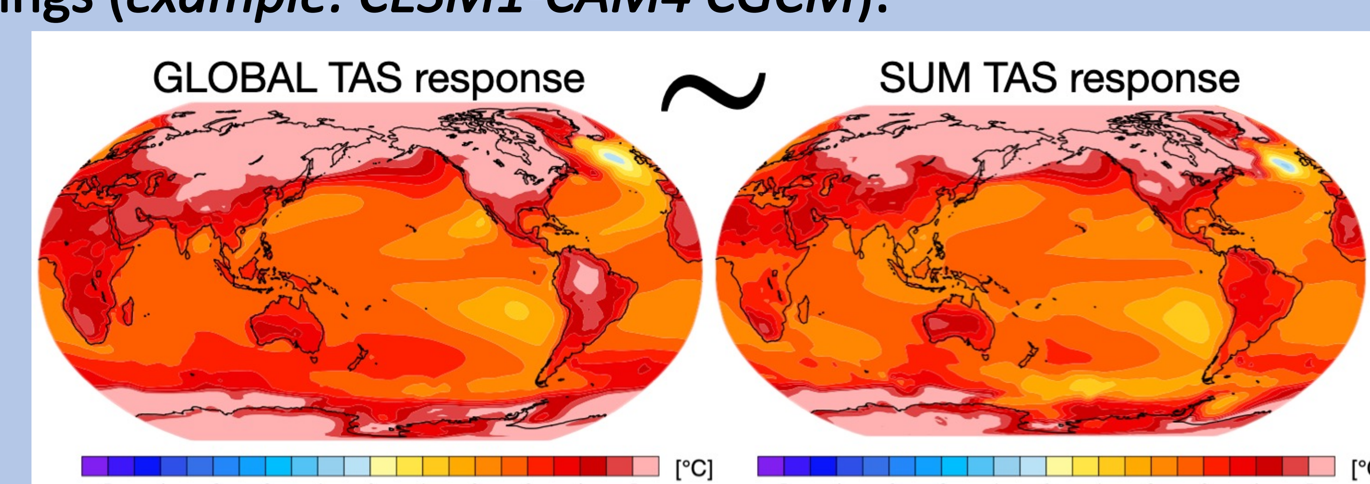
Note: we only conducted meridionally symmetric forcing experiments so far due to computational limitations



(Stuecker et al. 2020)

iii) Conduct equivalent AGCM experiments with the same perturbed CO_2 forcing structures to translate the regionally CO_2 quadrupling to a radiative forcing in units [W m^{-2}]

iv) Compare the coupled climate response to GLOBAL 4xCO_2 forcing to the SUM of the climate response to the REGIONAL 4xCO_2 forcings (*example: CESM1-CAM4 CGCM*):



(Stuecker et al. 2020)

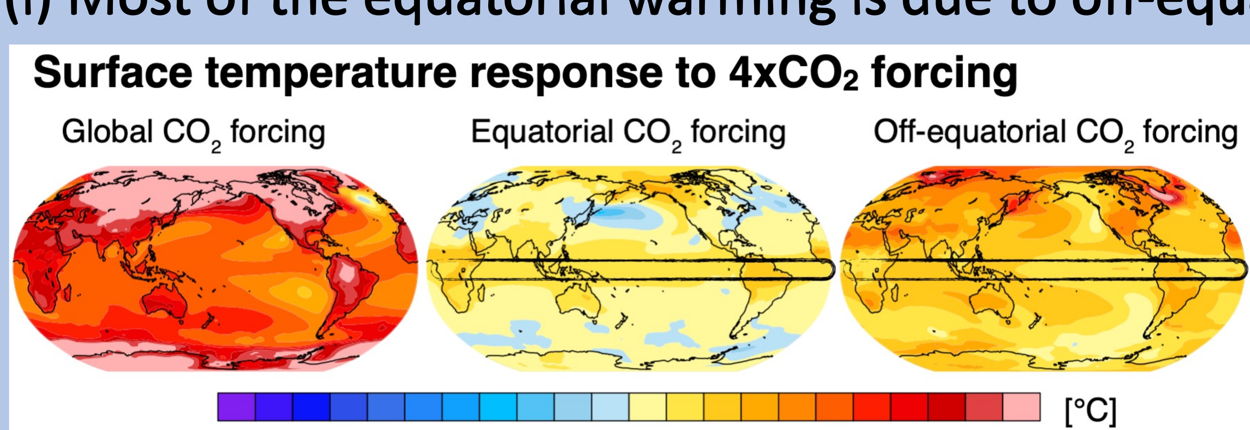
$$\delta\mathbf{T} \sim \mathbf{J}_b^{-1}\delta\mathbf{F}$$

Linearity holds!

3. Example Application

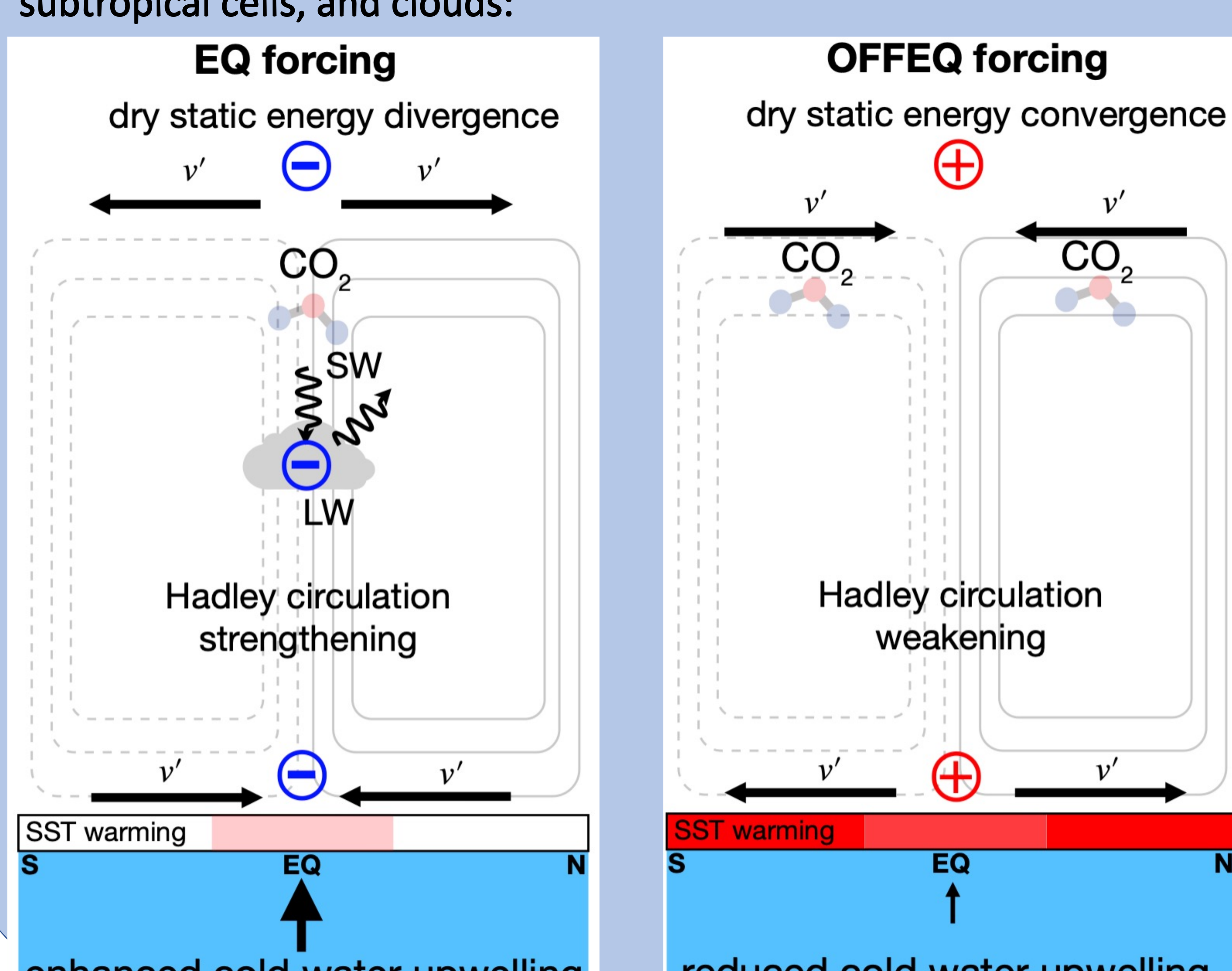
What processes determine the amount of equatorial warming in response to greenhouse gas forcing?

(i) Most of the equatorial warming is due to off-equatorial forcing:



(Stuecker et al. 2020)

(ii) Mechanism: Strong coupling between Hadley circulation, oceanic subtropical cells, and clouds:



(Stuecker et al. 2020)

4. Model Intercomparison Project (MIP)

Goal: quantify uncertainties in the mechanisms identified so far as well as investigate the dynamics of transient warming patterns

In planning: different tiers of experiments in addition to the standard setup shown in section 2 above

Models participating so far:
CESM1-CAM4 (*results shown here*), CESM1-CAM5, CESM2-CAM6, MIROC6, AWI-CM3 (FESOM2 + OpenIFS)

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5. References

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nature climate change LETTERS https://doi.org/10.1038/s41558-019-0667-6

Strong remote control of future equatorial warming by off-equatorial forcing

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Weak future Hadley cell intensity changes due to compensating effects of tropical and extratropical radiative forcing

(*under review*)

Doyeon Kim[1+], Hanjun Kim[1+], Sarah M. Kang[1*], Malte F. Stuecker[2], Timothy M. Merlis[3]

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