Impacts of Sea Surface Temperature Patterns on Global Radiative Response

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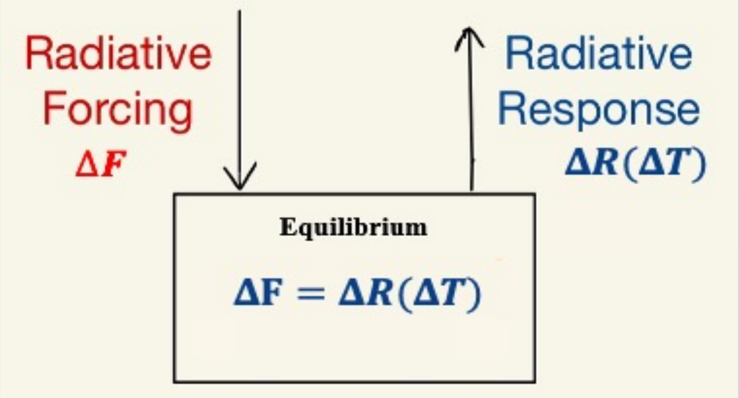
Abstract

Variations in sea surface temperature (SST) patterns significantly impact radiative fluxes at the top of the atmosphere (TOA). In this work, we explore the sensitivity of radiative feedbacks to SST patterns in idealized aquaplanet simulations using Community Atmospheric Model version 5 (CAM5), part of Community Earth System Model (CESM 1.2.1). We use a Green's function approach where we prescribe delta function-like perturbations in SST in latitude bands, with SSTs kept fixed at climatological values everywhere else. We use 37 equidistant '2K' warming patches in both hemisphere. We find that the radiative response is primarily driven by warming at the equator, primarily due to an increase in off-equatorial low clouds. Tropical surface warming spreads significantly both horizontally and vertically whereas extra-tropical warming leads to temperature responses confined within the lower tropospheric column. An interesting result is that the response to imposing multiple patches is strongly non-linear, except for near-equatorial patches. This test demonstrates that Green's function responses in the model are strongly linear only in the Intertropical Convergence Zone (ITCZ). These findings reveal significant nonlocal effects of SST variations on radiative feedback, a strong dominance of equatorial SSTs in moderating Earth's energy budget, and a surprising degree of non-linearity.

BACKGROUND

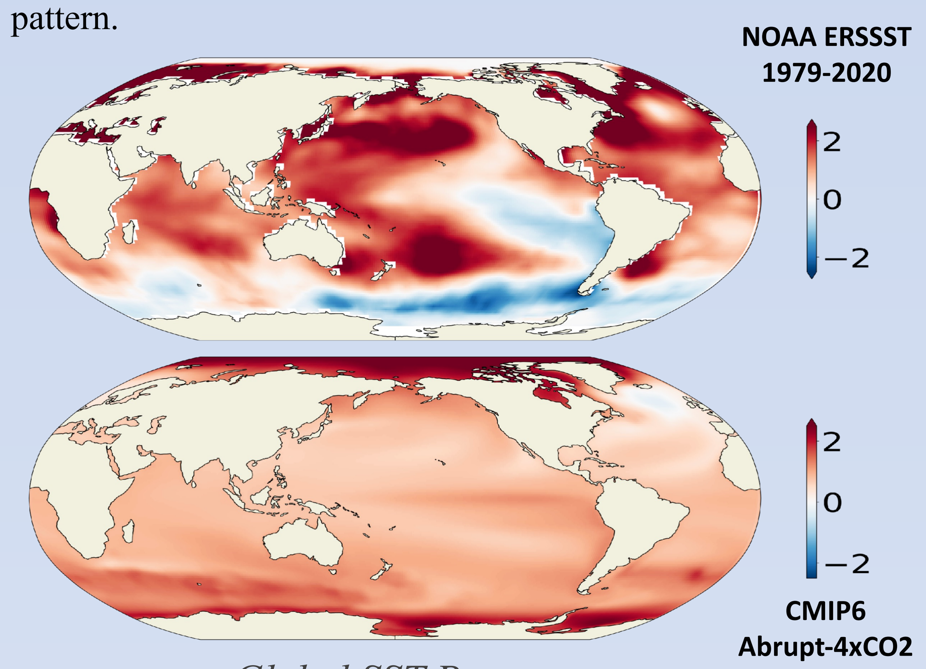
- What determines how much the Earth warms if we increase greenhouse gases.
  - If we increase GHG, more energy trapped in the climate system
- The Earth will warm until the radiative response balances the forcing.
  - We know the radiative forcing of CO2 well



Radiative Equilibrium

The big research question is **"how much does the Earth Radiate out when it warms"**

The standard assumption in the field has been to assume that the radiative response only depends on global temperature changes. However, there is a significant disparity between observed and model simulated SST pattern.



Global SST Patterns

- Observed warming pattern from NOAA:
  - Eastern Pacific cooling
  - Western Pacific warming
  - Northern Atlantic warming
  - Southern Atlantic warming
  - Southern ocean cooling
- Long-term warming pattern from Climate Model simulation (CMIP6):
  - More uniform

So, it is important to understand the radiative responses for verity of spatial pattern of SST.

METHODOLOGY

Change of global radiative response

$$\Delta R(\Delta T(\phi_i)) = \sum_{\phi_i} \frac{\partial R}{\partial \Delta T(\phi_i)} \Delta T(\phi_i) + \epsilon$$

Where ϵ is the higher order and due to the limited computational resource, we considered only the first term according to previous studies (Zhou et al., 2017; Barsugli and Sardeshmukh, 2002; Dong et al., 2019). It is possible to get the change of global radiative response $\Delta R(\Delta T(\phi_i))$ due to the change of SST ($\Delta T(\phi_i)$) by using local change of radiative response for the perturbation of local temperature i.e., $\partial R / \partial \Delta T(\phi_i)$. To calculate the global radiative response, we considered one dimensional delta like SST patches along the latitude.

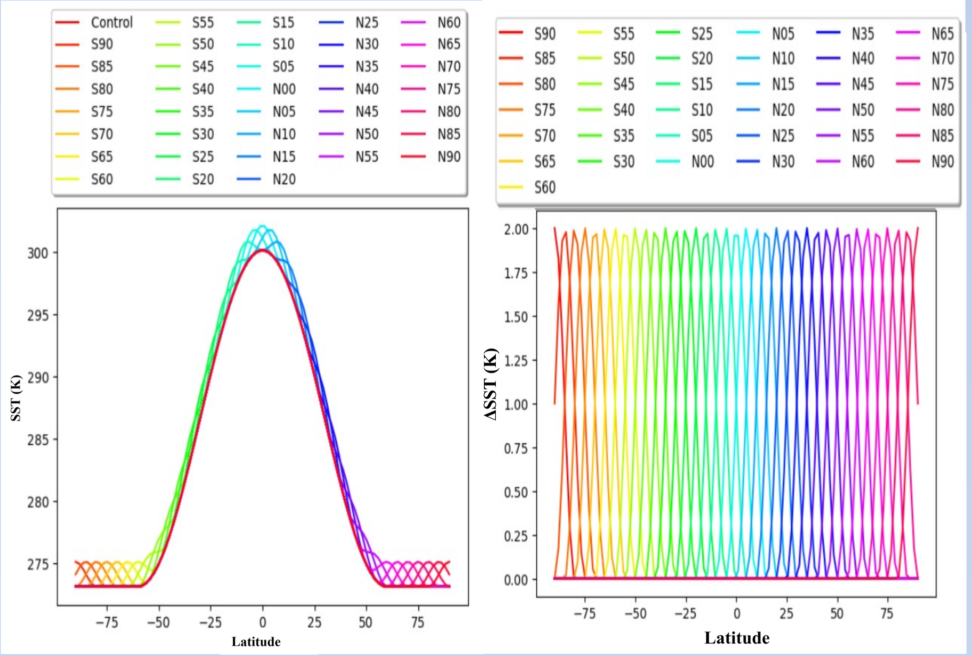
The control simulation was run with a prescribed SST of monthly climatology. Then we formed +2K warming 37 latitude band from 90S to 90N where each patch center was 5 degrees apart and the band width of each patch was 20 degrees. We call these 37 patches as experiment and for every experiment we used a delta like function that is called green's function (Barsugli and Sardeshmukh, 2000; Zhou et al., 2017; Kang et al., 2017).

Community Atmospheric Model version 5 (CAM5) part of Community Earth System Model (CESM 1.2.1)	
Compset	Aquaplanet (Idealized)
Grid Size	$1.1^0 \times 2.5^0$
No. of vertical level	32
Run year	20

METHODOLOGY (cont.)

$$\Delta T(\phi) = A\cos^2\left\{\frac{\pi(\phi - \phi_c)}{2\phi_c}\right\}$$

Here, A=2K is the peak amplitude of SST (T) anomaly, ϕ is the latitude and subscript c is for center of the patch. Apart from the patch band width, we considered the monthly climatological SST everywhere in each experiment.

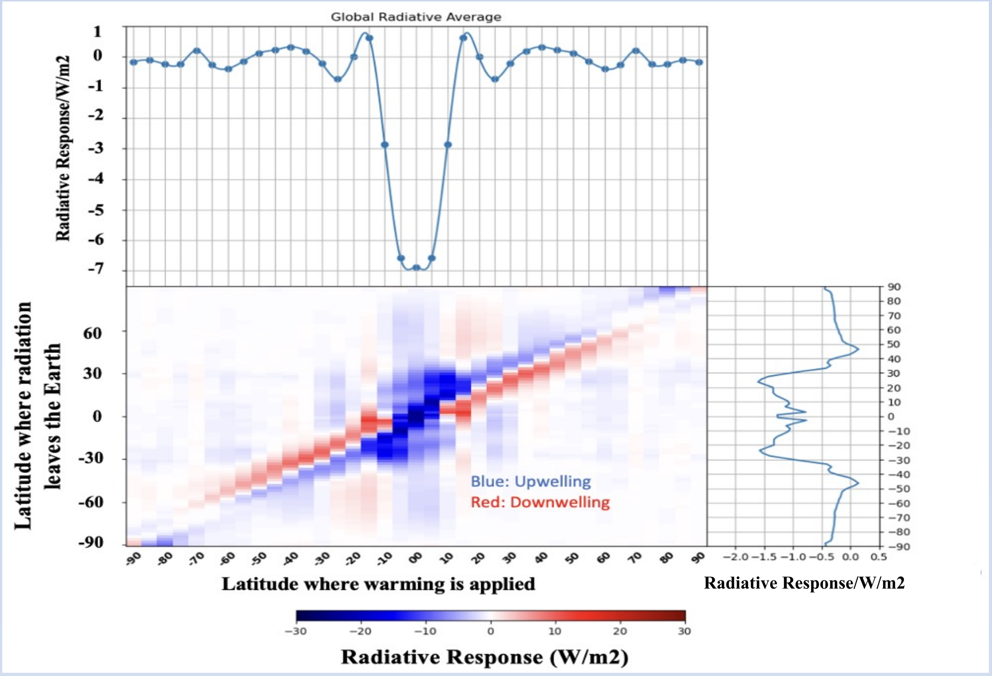


Prescribed Zonal Mean SST Profiles

Control and experiments (left), Difference between prescribed zonal mean SST profiles of control and experiments i.e., patch band width(right) (Narrow patch: 20-degree width)

- The total sum of SST ($\Delta T(\phi)$) for all the experiment is equivalent to +4K warming in all latitude. Thus, we run a case +4K warming everywhere and compare with the sum of all experiments to find out the non-linearity of the system.
- To check the non-linearity into further degree, we also considered experiment with the 100 degrees band width, and each patch center was 25 degrees apart (wide patches shown in the supplementary document).
- We considered the wider patches to understand the impacts of global circulations such as Hadley cell (HC), Inter tropical convergence zone (ITCZ) in the non-linearity of radiative response.

RESULTS

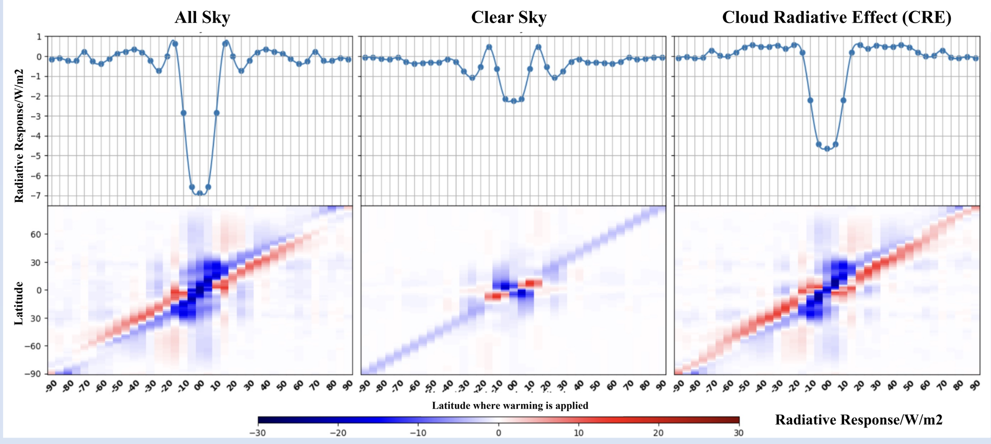


Spatial Sensitivity Map of Radiative Responses with SST ($\frac{\Delta R_i}{\Delta T_i}$)

Horizontal axis in the color plots is warming patches by latitude and vertical axis is the latitude. Blue means upwelling and red means downwelling radiation in the color plots. The right line plot shows where the radiation leaves the atmosphere as a function of latitude. The top line plot shows global radiative response as a function of where warming is applied.

- Global radiative response as a function of where warming is applied (top):
  - The radiative response is primarily driven by warming right the equator.
  - Global radiative responses are largely unaffected by the warming near the pole.
- Where radiation leaves the atmosphere (right)
  - Radiation leaves the Earth primarily from subtropical region.

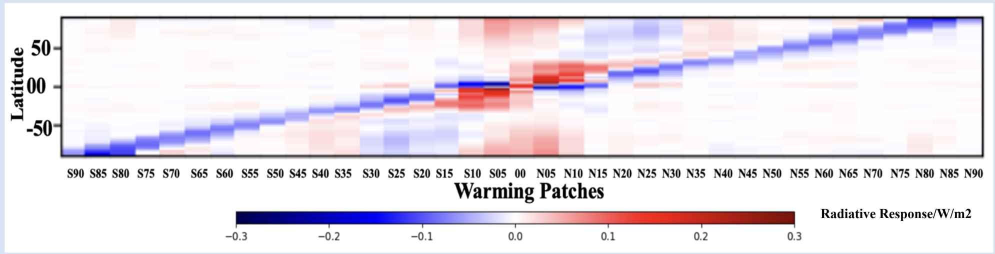
Radiative response occurs broadly in the tropics, but primarily controlled by the amount of equatorial warming!



Spatial Sensitivity Map of Radiative Responses

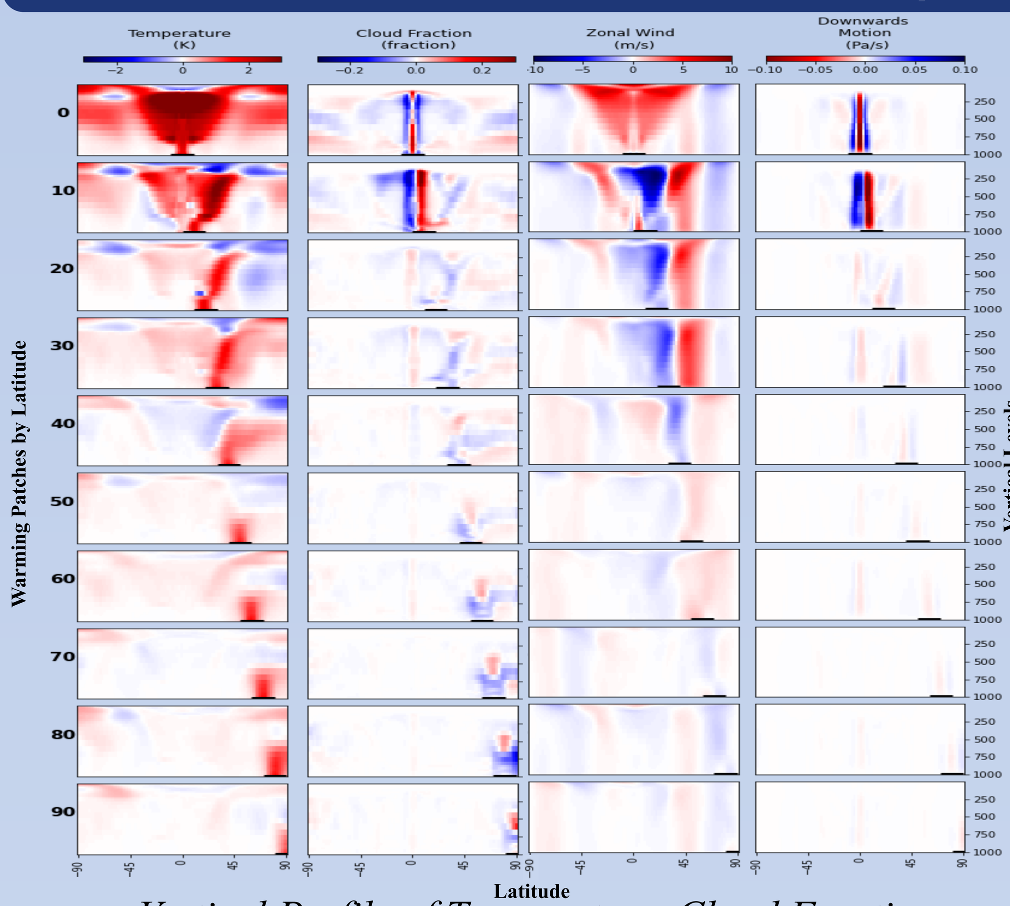
All sky (left), Clear sky (middle), CRE (right)

- In clear sky radiative response ~ -2 W/m^2 found from the equator warming. On the other hand, radiative responses ~ -5 W/m^2 for cloudy sky.
- It is evident that most of the responses are due to cloud—specifically low cloud.
- A positive low cloud fraction is produced everywhere by warming near the equator.
- A negative cloud fraction is produced at the patch center and positive elsewhere in all the other latitude patches. For this dipole characteristics, we got nearly zero TOA radiative responses.



Vertically integrated zonally mean low cloud fraction

RESULTS (cont.)



Vertical Profile of Temperature, Cloud Fraction, Zonal Wind & Downward Motion

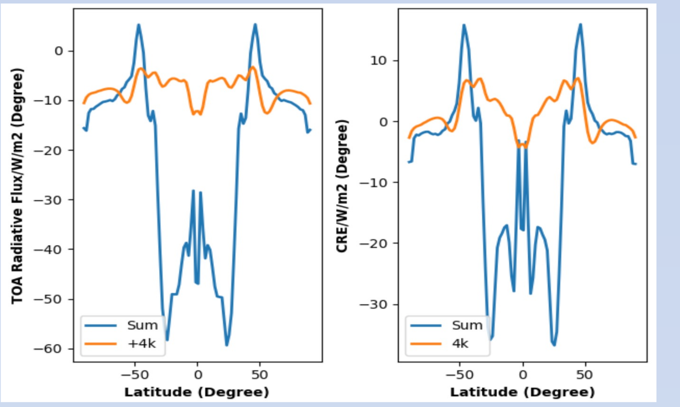
Since there is no anti-symmetry in the model, we are simply displaying the NH patches here, and the responses in the SH are identical to NH.

- In response to equator warming, the temperature response spreads significantly horizontally in the upper troposphere and vertically near the equator (Kang et al., 2017).
- Warming near extratropical region and pole constraint the temperature in the lower troposphere.
  - This is why we found the decrease of low cloud at high latitude
- Cloud fraction and downward wind increases at the center of the equator patch and decreases nearby i.e., Hadley cell contraction.
  - A clear indication of Hadley cell shift for 5N warming
- Warming at the equator and nearby induces vertically upwelling and eastward motion.

Non-linearity:

- There is a surprising degree of non-linearity between the sum of all narrow patches experiment (blue line) and their equivalent +4K warming (orange line) in both TOA radiative flux and CRE.
- The responses are linear near equatorial patches (supplementary document).
- This same comparison for wide patch experiments has less non-linearity then narrow patch experiments (supplementary document).

The width of wide and narrow patch experiments are 100^0 and 20^0 respectively. Thus, our hypothesis for this non-linearity is related to the disturbance of general circulation. Because the contraction and shift of Hadley cell is less significant for wide patch experiment than the narrow patch experiment.



Zonal Mean TOA Radiative flux and CRE

CONCLUSIONS & FUTURE WORK

Conclusions:

- The radiative response is primarily driven by warming at the equator, primarily due to an increase in off-equatorial low clouds.
- The equator warming spreads temperature significantly in upper troposphere whereas extra-tropical and pole warming leads to temperature responses confined within the lower tropospheric column.
- The surprising degree of non-linearity in global radiative responses are mainly due to the disturbance of general circulation for local warming.

These findings reveal significant nonlocal effects of SST variations on radiative feedback, a strong dominance of equatorial SSTs in moderating Earth's energy budget.

Future Work:

- Quantitative analysis of global circulation disturbances like the Hadley cell and ITCZ due to local warming may eventually disclose intriguing features of the Earth energy budget projection.
- Even though it is computationally complex, taking into account an actual warming scenario rather than the idealistic analysis would be an interesting analysis as well for future.

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For supplementary document and additional details please visit https://github.com/PappuP/AQUAPLANET.git or scan