Accounting for Uncertainty of Projected Sea Surface Temperature Patterns in Coupled Global Circulation Models

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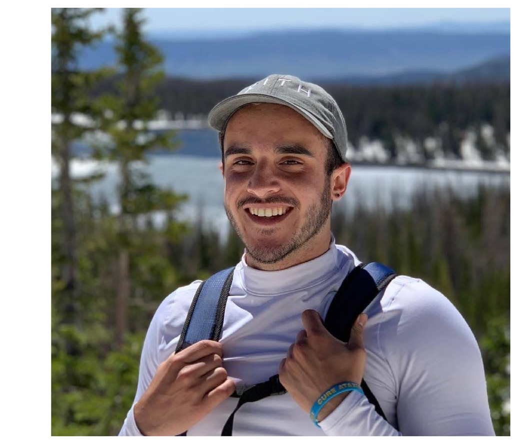
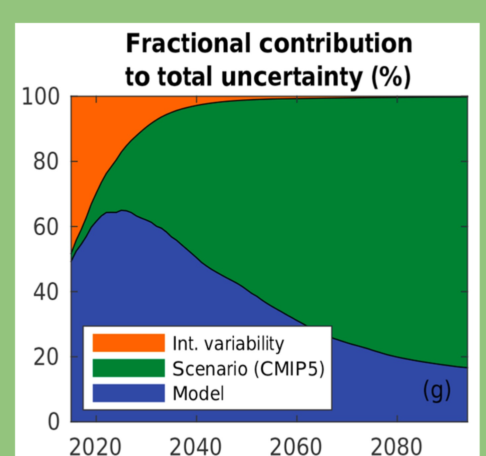


Motivation

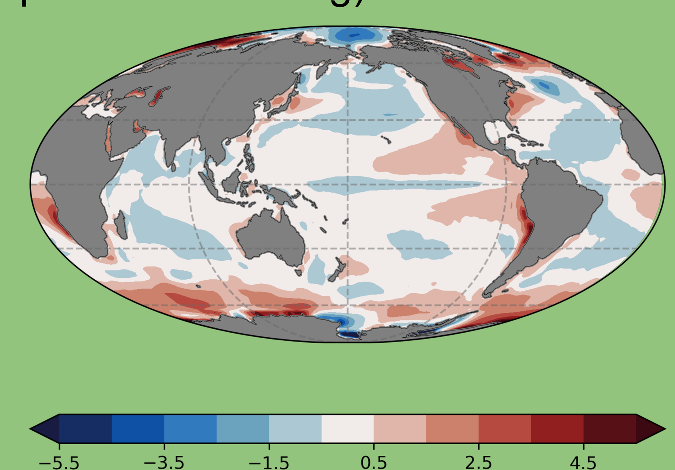
Global political, economic, and jurisdictional decision making rely on projections from fully-coupled atmosphere-ocean global circulation models (AOGCMs).

AOGCMs disagree on climate projections due to three uncertainties: scenario uncertainty (forcing), internal variability, and model (structural) uncertainty.



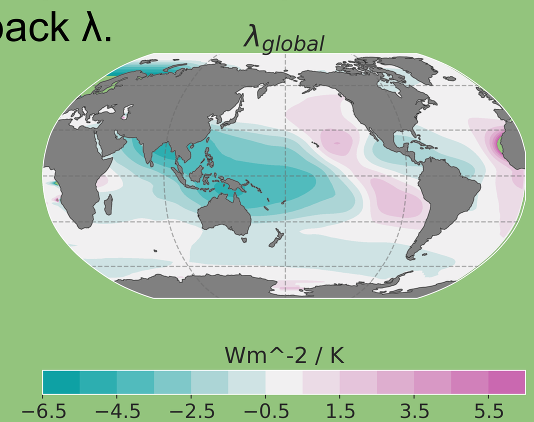
Fractional contribution of individual sources to toto uncertainty for single-model initial-condition large ensemble projections (Lehner et al., 2020).

AOGCMs also share two common problems, which we refer to as **SST pattern uncertainty**: models fail to reproduce observed SST patterns due to deficiencies in modeled ocean-atmosphere interaction (Gregory et al., 2020; Seager et al., 2019), which can **produce mean state biases and/or trend biases** (inability of the model to reproduce the correct SST pattern in response to a forcing).



Surface temperature biases (°C) over ocean between historical simulations (2000-2020) of four representative CMIP5 models and HadCRUT observations

Compounding this issue further is the **pattern effect**, which states that the evolution of the spatial structure of surface warming affects the global mean radiative feedback λ.



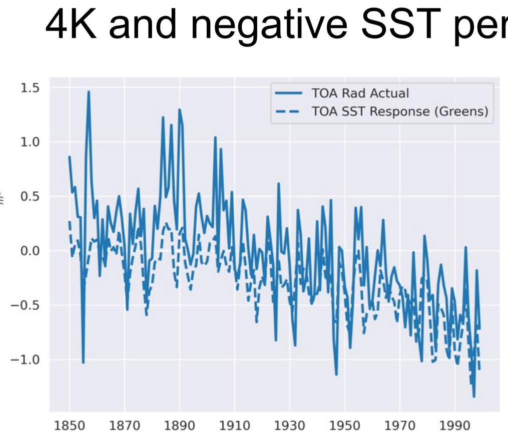
Annual- and global-mean λ response per SST warming in each grid box developed from radiative response and temperature Green's Functions (GF).

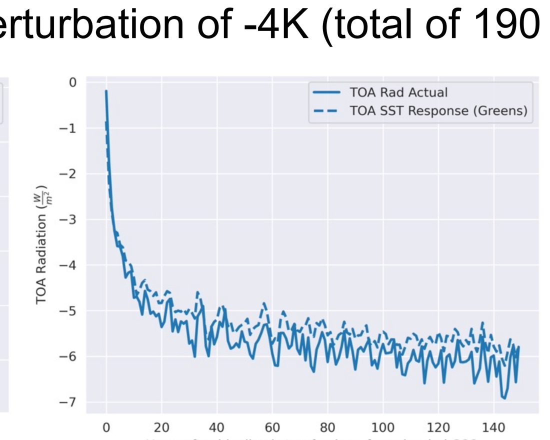
Question: The impact of modeled ocean-atmosphere deficiencies on climate change projections is an inchoate uncertainty that has received little attention. What is the impact of SST pattern uncertainty for projections of lambda and temperature?

Method

GF Setup and validation

- We develop a Green's Function (GF) for surface temperature, TOA radiative response, and Charney feedbacks (with PRP) using the Max Planck Institute atmospheric model ECHAM version 6
- We run 95 equal-area fixed-SST patch simulations for a positive SST perturbation of 4K and negative SST perturbation of -4K (total of 190 simulations)





Cosine squared patches of equal area were used to develop the GF (not shown). Historical (left) and abrupt-4xCO_2 (right) radiative response output from the fully coupled MPI-ESM GCM (solid) and the GF convoled with the SST pattern evolution from that same coupled MPI-ESM GCM (dashed). The radiative response from MPI-ESM is calculated by subtracting the modeled forcing from the modeled net TOA radiative imbalance.

Green's Functions as linearization of the climate system

Some linear differential equation → $Lu = f$ ← Some climate system forcing (e.g., SST)

Some climate system response (e.g., TOA radiative response)

1. Integrate the linear differential operator

$$u = Gf$$

Green's Function

2. Get the 1st order Taylor Series expansion

$$\Delta \mathrm{u_i} = \sum_{j=1}^{n} \frac{\partial u_i}{\partial f_j} \Delta \mathrm{f_j} + \epsilon_X$$

e.g., TOA radiative response

Our forcing is SST perturbations (in the form of a patch)

Projections Scenarios

What if the RCP8.5 mean projected SST pattern is wrong in regions of poor AOGCM performance historically?

To create global mean temperature projections, we divide our TOA radiative response GF by our surface temperature GF, both forced with SST patterns derived from MPI-ESM's coupled model output for RCP8.5. We alter these SST patterns based on known deficiencies (see Table). To calculate global-mean temperature, we use the energy balance model equation:

$$\Delta T = \frac{N - F}{\lambda}$$

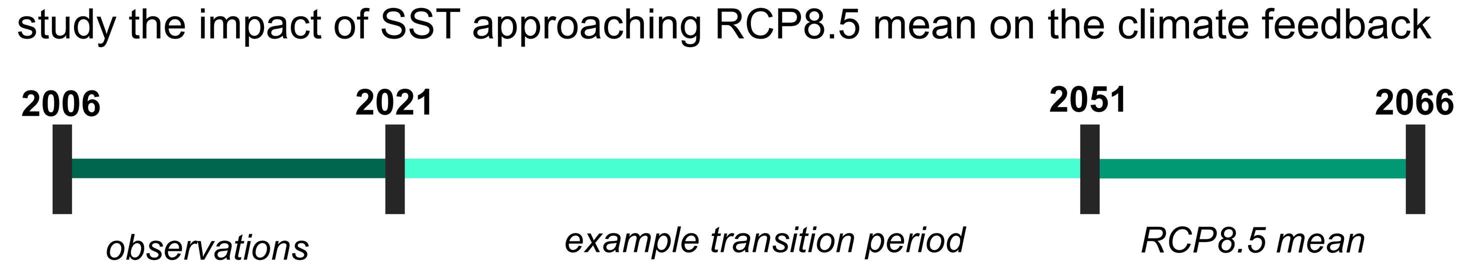
N from model output and F from calculated model forcing

Calculated by plugging in SST pattern to "λ GF"

	Scenario	Motivation
1	North Atlantic	Mean state bias
2	East Pacific/Cold Tongue	Mean state bias/erroneous model response (Seager et al., 2019)
3	West Pacific	Uncertain model response

What if today's observed SST pattern returns to RCP8.5 mean over the course of the next 30-70 years? What if some regions continue following the observed trends?

We interpolate the SST pattern from the end of observations (2021) to a given year of the RCP8.5 mean (e.g., 2051; 30-year transition period) to study the impact of SST approaching RCP8.5 mean on the climate feedback

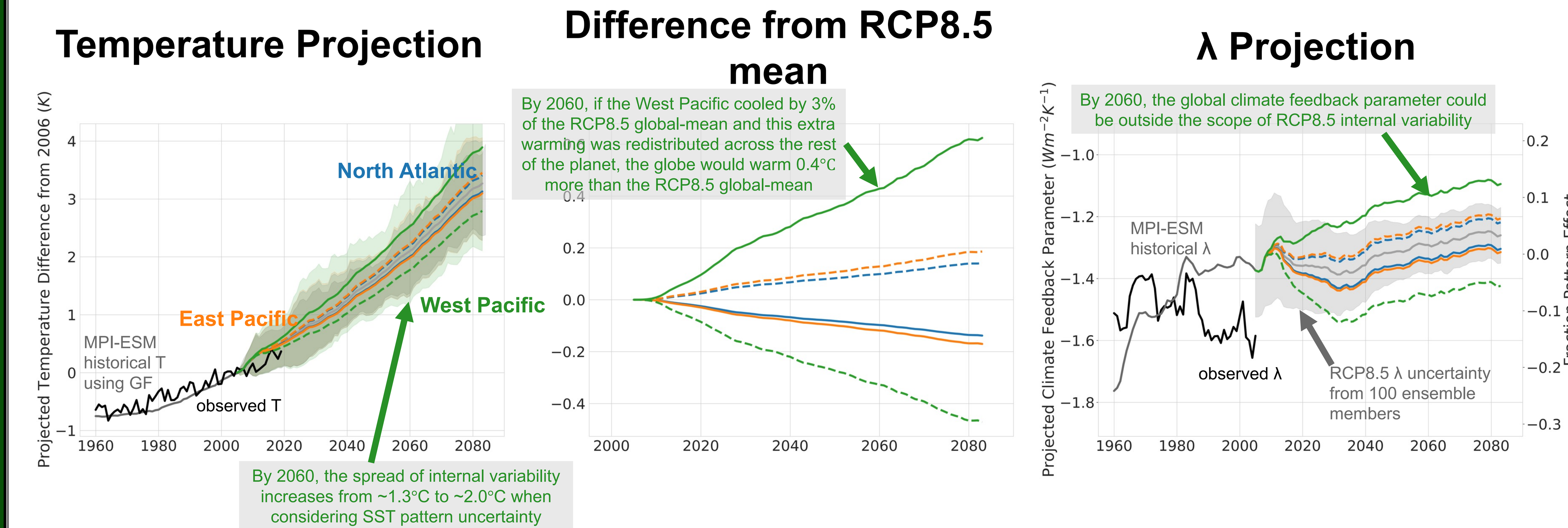


Throughout this study, λ is calculated using a 30-year sliding window of global-mean R and T from the SST pattern plugged into the GF, so two examples would be:

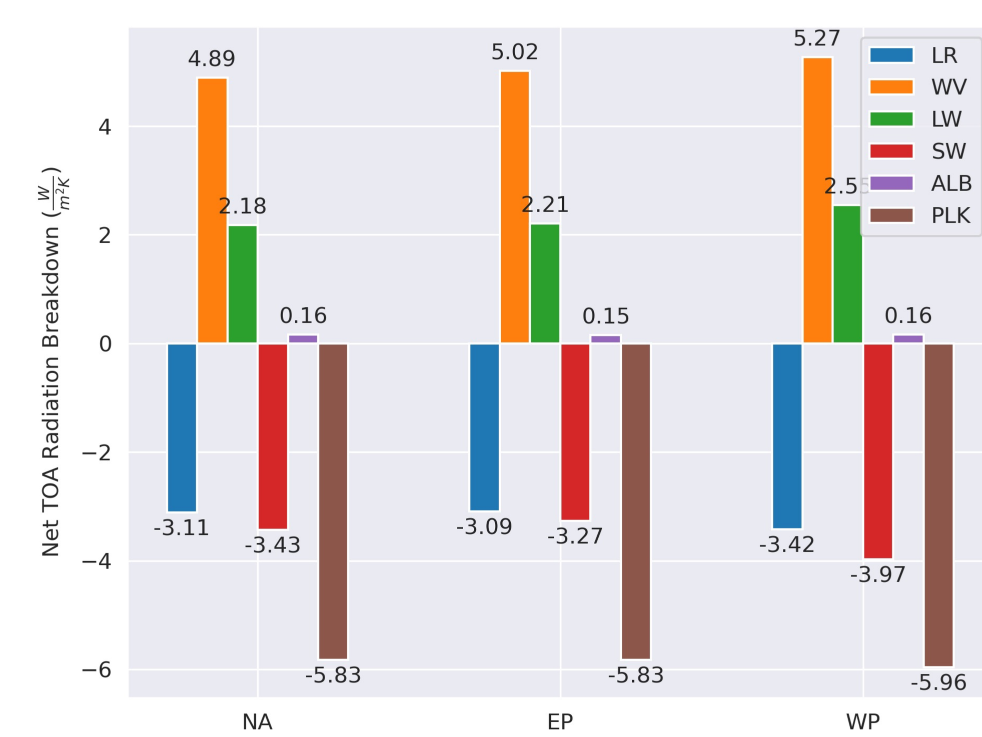
λ in 2021: 15 years of SST observations and 15 years of transitional SST.

λ in 2045: 21 years of transitional SST and 9 years of RCP8.5 mean SST.

Results

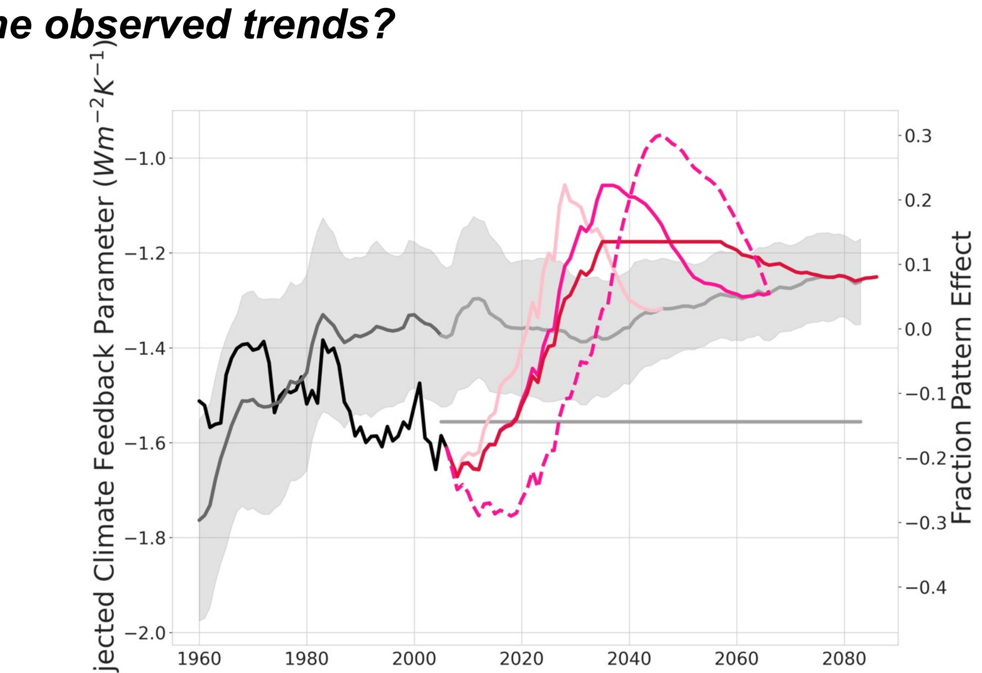


Global-mean radiative feedback (right) and temperature (left) between 1960 and 2020 simulated by the GF forced with SSTs from the coupled climate model (gray) and with HadISST observations (black). Feedback and temperature projections of the GF forced with SSTs from the coupled climate RCP8.5 simulations (gray) and adjusted SSTs inspired by SST pattern uncertainty (colors). The shaded regions represent the spread of 100 MPI-ESM ensemble members. For these plots, we first identify 3% of the global SST anomaly. This anomaly is then subtracted from the scenario region (area-weighted) and redistributed to the rest of the world (solid). We also added this anomaly to the scenario region and subtracted it from the rest of the world (dashed). Shaded regions indicate internal variability from 100 MPI-ESM ensemble members.



What is driving the differences in radiative feedback between different regions (using PRP)? For the West Pacific scenario, there is a slight decrease in Planck's feedback, but most of the difference between the West Pacific scenario and the others is change in the SW cloud feedback.

What if today's observed SST pattern returns to the RCP8.5 SST pattern mean over the course of the next 30-70 years? What if some regions continue following the observed trends?



The SST is interpolated at each grid point from observations to RCP8.5 mean for a 10-year period (light pink), 30-year period (pink; see methods example), and 50-year period (red). The global-mean radiative feedback during the transitional period overshoots the RCP8.5 radiative feedback for all scenarios. This is due to most of the warming occurring in regions with a positive λ response per SST warming.

Conclusions

- **There is an impact of altered SST patterns on temperature projections**. While the WP is the most relevant region in terms of strengthening the pattern effect, altered SST patterns of equal area in the EP and NA change temperature projections.
- According to analysis of Charney feedbacks using PRP, most of the change in the climate feedback parameter between regions is due to the longwave and shortwave cloud fedbacks.
- The pattern effect of model biases and deficiencies adds uncertainty to projections that is on the **same order of magnitude of internal variability**, which is represented by the ensemble spread.
- **RCP scenario uncertainty widens** when considering SST pattern uncertainty, so that the lowest and highest temperature projections for RCP8.5 and RCP4.5 respectively overlap for a longer period than before (not shown).

Acknowledgments

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