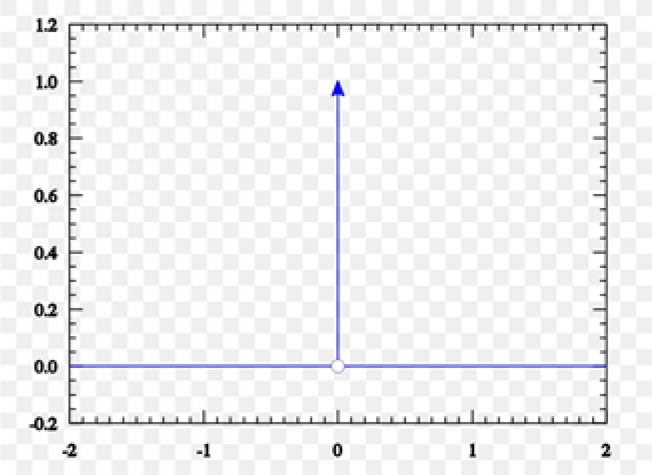
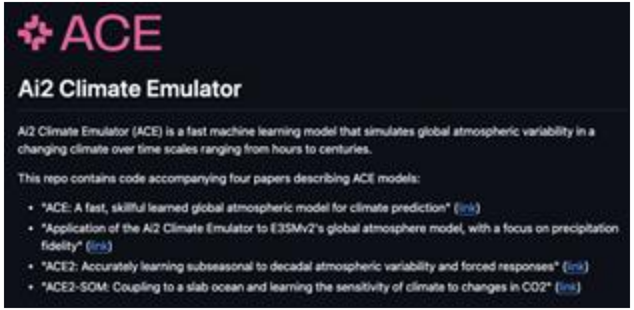
Reanalysis-based Global Radiative Response to Sea Surface Temperature Patterns: Evaluating the Ai2 Climate Emulator

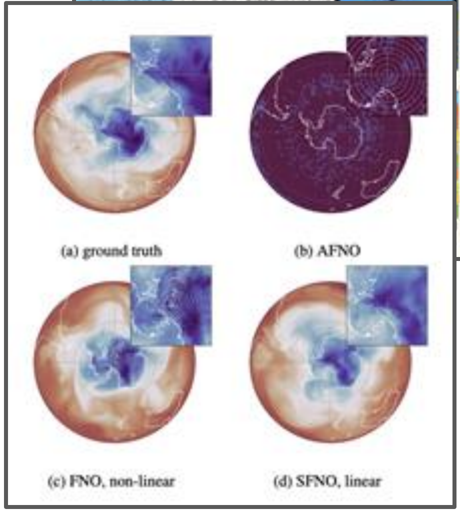




Zihui(Andy) Liu

Overview

- ACE
  - 3 versions
  - SFNO
- Green’s Function Experiment
  - Response on perturbations
  - ~~Well, let’s guess everything is linear~~
- GFMIP setups
  - Emulator testing framework



Function

Motivation (Section 1.1)

- Understanding Climate Feedback → GCMs
    - But…… Lots of parametrizations
    - And…… Slow
    - So…… Machine learning → Emulators!!
    - Emmm…… Are they good?
    - ¯_(ツ)_/¯… I don’t know…… but they are definitely fast…
    - ………… …
    - Emmmmmm… I mean, they parametrized EVERYTHING. What do you expect…
    - (╯°□°)╯︵ ┻━┻
- What if we want to analyze climate emulators like GCMs?

Green’s Function Experiment

Before that, Let’s quickly cover the ML basics →

AI2 Climate Emulator (ACE) (Section 2.1)

- Based on Spherical Fourier Neural Operators
  - (Bonev et al., 2023; Yik 2025, UW Atmos MLJC)
- Autoregressive
  - input T, output T+6hr
- 3 Versions
  - ACE-VF3 ← GFS
  - ACE-EAM ← E3SM
  - ACE2-ERA5 ←ERA5
    - Also forced by CO2

SFNO

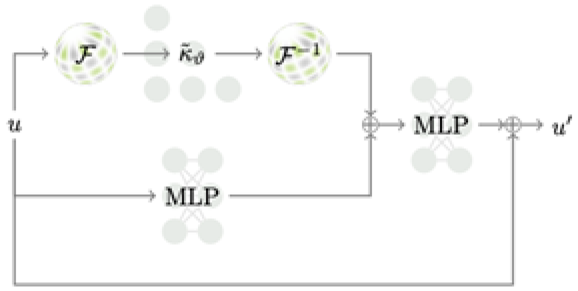


Figure 2 from Bonev et al., 2023

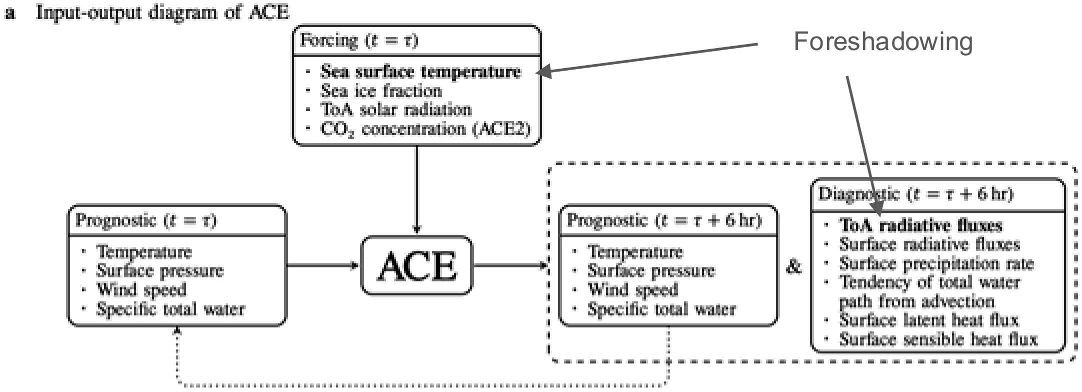


Figure 1a

Thank you.

That’s all I am going to say about Machine Learning in this meeting.

Thanks for listening, and enjoy your pizza…

（ ^_^）o自自o（^_^ ）

Now, back to Green’s function→

Green's Function (Section 1.2)

- How the dynamical systems behave under point-perturbation
  - Idealized situation
- Response to local perturbation
  - Note: No time-dependence. We are more interested in long-term response, i.e. the new equilibrium. We don't need the transient response.
  - Perturbation is like a constant source, and the sink is the ambient whatever
- Representing the causal response
  - Because we literally poke the system, observe its response, and compare against control.

-log()

Green’s Function Experiment (Section 2.2)

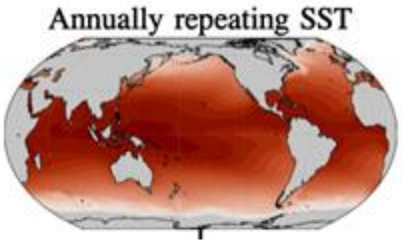
Main Quest: (Finish all side quests to unlock this one)

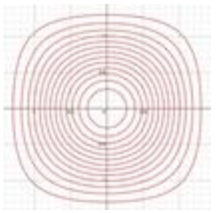
🔒 **Find the TOA response R given local perturbation in SST**

Side Quest:

1. Control Run, 20 years
2. Apply the SST perturbation
3. Run the new system for 2 + 10 year
4. REPEAT 3 for each patch
5. Calculate feedback using this equation
6. HAHA, Repeat 1-5 for each ACE

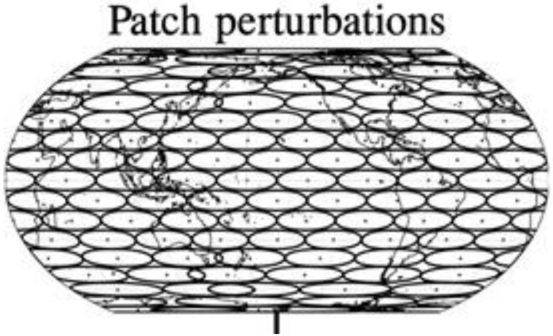
ACE-VF3 ACE-EAM ACE2-ERA5





$f(x, y) = (\cos(x))^2 (\cos(y))^2$

$$T_p(\varphi, \vartheta) = \begin{cases} A\cos^2\left(\pi\frac{\varphi-\varphi_p}{\delta\varphi_p}\right)\cos^2\left(\pi\frac{\vartheta-\vartheta_p}{\delta\vartheta_p}\right) & \begin{cases}\varphi-\varphi_p \in [-\delta\varphi_p, \delta\varphi_p] \\ \vartheta-\vartheta_p \in [-\delta\vartheta_p, \delta\vartheta_p]\end{cases} . \\ 0 & \text{elsewhere} \end{cases} \quad (1)$$



$$\frac{\partial R}{\partial^* T_j} = \frac{1}{\sum_p T_{p,j}} \sum_p \frac{T_{p,j}}{\langle T_p \rangle} \Delta_p R \quad (2)$$

* Please don’t ask me any questions about this equation. It broke me

Green’s Function Experiment

JAMES Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1029/2023MS003700

The Green's Function Model Intercomparison Project (GFMIP) Protocol

Jonah Bloch-Johnson[1], Maria A. A. Rugenstein[2], Marc J. Alessi[2], Cristian Proistosescu[3], Ming Zhao[4], Bosong Zhang[5], Andrew I. L. Williams[5], Jonathan M. Gregory[1,6], Jason Cole[7], Yue Dong[8], Margaret L. Duffy[9], Sarah M. Kang[10], and Chen Zhou[11]

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- Previous procedure is from
  - Green’s Function Model Intercomparison Project (GFMIP; Bloch-Johnson et al. 2023)
  - Protocol for GCMs
  - How models response to pattern effect.
  - GCM doesn’t respond consistently
    - No “***Ground Truth***”

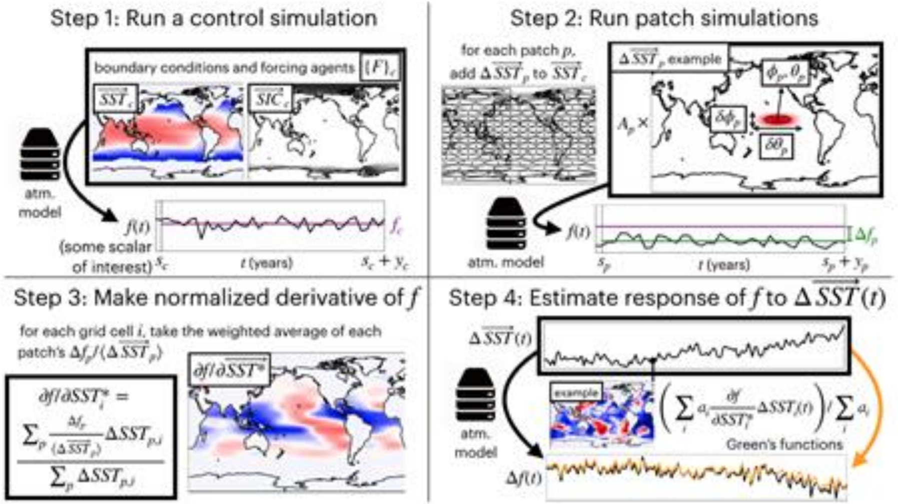

Figure 2 from B-J et al. 2023

Green’s Function Experiment (Section 3.1)

Control

- ACE2-ERA5
  - Reproduce some features
  - Amplitude is low
- ACE-EAM
  - Good!
- ACE-FV3
  - Bad
  - (possible reason) Numerical Weather Prediction model is not energetically closed

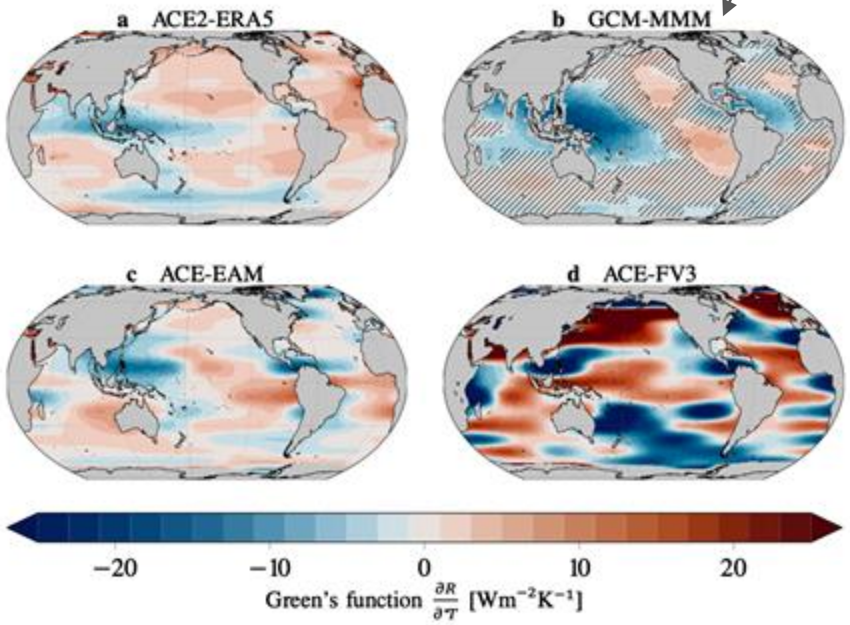

Figure 2. Green’s functions of (**a**) ACE2-ERA5, (**b**) Multi-model mean (MMM) of 5 GCMs (Bloch-Johnson et al., 2024), (**c**) ACE-EAM, and (**d**) ACE-FV3. Note that the the resolution of ACE is $1^\circ \times 1^\circ$, while the GCMs are on a $3.75^\circ \times 2.5^\circ$ grid. Hatching in **b** indicates regions where at least one GCM disagrees on the sign of the Green’s function.

Green’s Function Experiment (Section 3.2)

- Historical Reconstruction using ACE Green’s Function
- The reconstruction is not linear.

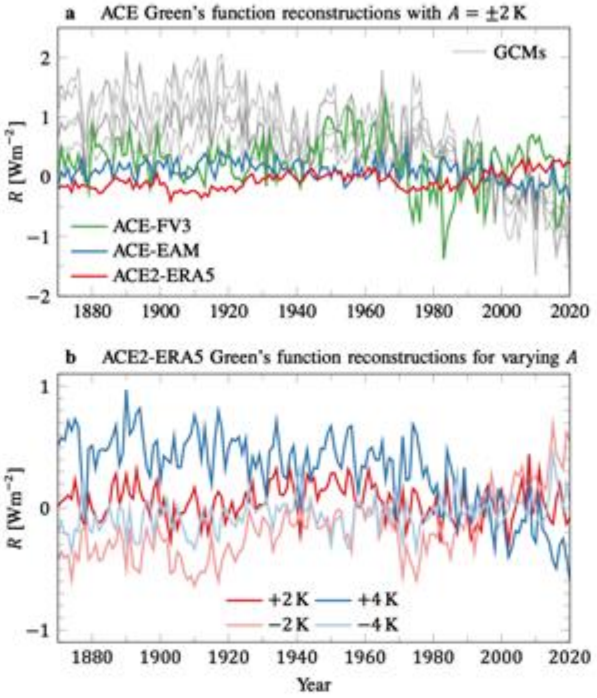

Figure 3. Historical reconstruction of the net ToA radiation R, formed by convolving the Green's functions with AMIP sea surface temperature anomalies with respect to 1971-2020.

Discussion (Section 4)

- **[Potential Problem]** Observation is to short to see response. We have to rely on GCMs currently.
- ACE2-ERA5 have fixed CO2 during the Green's function experiment.
- **[Problem]** ACE2-ERA5 biased toward the observation, and have hard time extrapolate prediction
- **[Potential Fix]** physical constrain the ACE2 model
- **[Benefit]** Investigate nonlinear feedback using emulator.
- Emulator is doing poorly in green's function experiment.
    - Turn the bug into feature: green's function experiment is a good benchmark for emulator!