

COLORADO STATE UNIVERSITY

ATMOSPHERIC SCIENCE

Distilling machine learning-based climate emulators for physical understanding



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11 June 2025 CESM Workshop



Overview ●○	Green's functions	Evaluating emulators
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- Machine learning-based climate emulators
 - ▶ Replace traditional climate models with ML
 - ▶ Fast & stable on long timescales



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 $\partial R / \partial SST$



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 - "Distillation" model

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Green's functions

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Ai2 Climate Emulator



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Ai2 Climate Emulator

Three versions, trained on:



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Overview	Green's functions	Evaluating emulators
3	Green's function simulations	

 \Leftrightarrow **r** = G**f** General solution

Differential equation (GCM)

GFMIP; Bloch-Johnson et al. (2025)

 \Leftrightarrow *LG* = δ_{f} Response to localized forcing

 $L\mathbf{r} = \mathbf{f}$



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Linearized response of the climate to SST forcing

Evaluating emulators

Global mean, top of the atmosphere, radiation budget

N = F + R

Global mean, top of the atmosphere, radiation budget

incoming energy - outgoing energy 🤶

Radiative imbalance



Global mean, top of the atmosphere, radiation budget

incoming energy - outgoing energy 🦛

Radiative imbalance





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Radiative imbalance



Feedback depends on pattern of surface warming





Global mean, top of the atmosphere, radiation budget





Green's functions

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Evaluating emulators

Climate emulators for scientific discovery

• Probing the "observed" climate system in a new way (e.g. ACE-ERA5)





Evaluating emulators

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 - ▶ Turn off forcing in the real world







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- Fails to capture expected negative trend
 - ► Lack of energy conservation constraint?







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 - ► Turn off forcing in the real world
- Physically realistic sensitivity map
- Fails to capture expected negative trend
 - ► Lack of energy conservation constraint?
- "True" radiation Green's function unknown
 - Direct comparison with GF simulations in GCMs (e.g., Wu et al. 2025, E3SM); CAMulator vs CAM









Green's functions as distillation model

• Climate emulators need systematic testing (e.g., Ullrich et al. 2025)



Green's functions

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- "Distill" the nonlinear, statistical "black box"



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