AI/ML for climate model emulation

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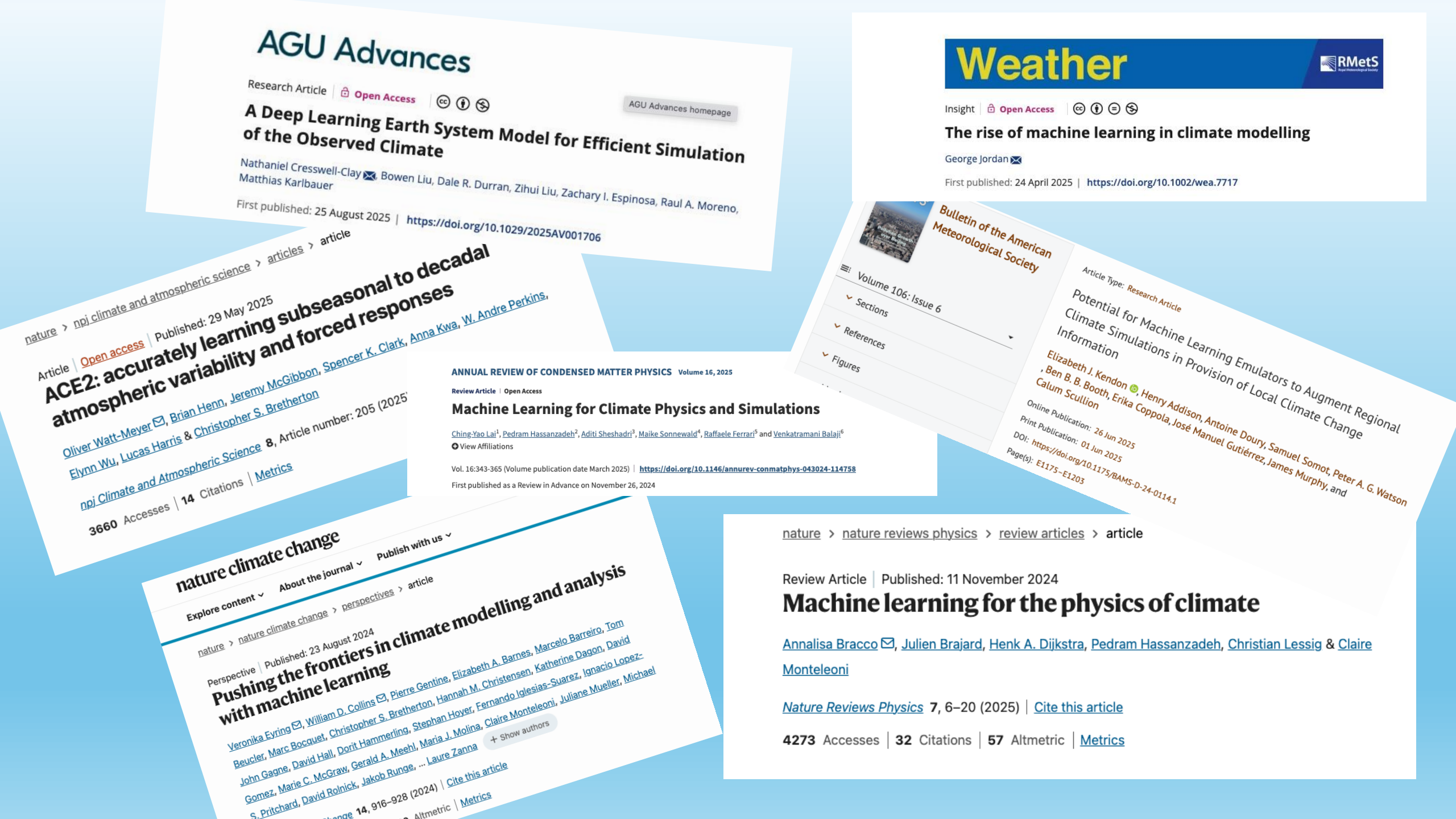

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A Deep Learning Earth System Model for Efficient Simulation of the Observed Climate

Nathaniel Cresswell-Clay, Bowen Liu, Dale R. Durran, Zihui Liu, Zachary I. Espinosa, Raul A. Moreno, Matthias Karlbauer

First published: 25 August 2025 | https://doi.org/10.1029/2025AV001706

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George Jordan

First published: 24 April 2025 | https://doi.org/10.1002/wea.7717

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Oliver Watt-Meyer, Brian Henn, Jeremy McGibbon, Spencer K. Clark, Anna Kwa, W. Andre Perkins, Elynn Wu, Lucas Harris & Christopher S. Bretherton

npj Climate and Atmospheric Science 8, Article number: 205 (2025)

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ANNUAL REVIEW OF CONDENSED MATTER PHYSICS Volume 16, 2025

Review Article | Open Access

Machine Learning for Climate Physics and Simulations

Ching-Yao Lai[1], Pedram Hassanzadeh[2], Aditi Sheshadri[3], Maike Sonnewald[4], Raffaele Ferrari[5] and Venkatramani Balaji[6]

View Affiliations

Vol. 16:343-365 (Volume publication date March 2025) | https://doi.org/10.1146/annurev-conmatphys-043024-114758

First published as a Review in Advance on November 26, 2024

Bulletin of the American Meteorological Society

Volume 106: Issue 6

Sections

References

Figures

Article Type: Research Article

Potential for Machine Learning Emulators to Augment Regional Climate Simulations in Provision of Local Climate Change Information

Elizabeth J. Kendon, Henry Addison, Antoine Doury, Samuel Somot, Peter A. G. Watson, Ben B. B. Booth, Erika Coppola, José Manuel Gutiérrez, James Murphy, and Calum Scullion

Online Publication: 26 Jun 2025

Print Publication: 01 Jun 2025

DOI: https://doi.org/10.1175/BAMS-D-24-0114.1

Page(s): E1175–E1203

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Annalisa Bracco, Julien Brajard, Henk A. Dijkstra, Pedram Hassanzadeh, Christian Lessig & Claire Monteleoni

Nature Reviews Physics 7, 6–20 (2025) | Cite this article

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AI/ML for climate model development and use

- ML is used to develop, refine or substitute for **parameterizations** in climate models.
- ML is used to emulate individual processes or **components** of a climate model.
- ML is used to estimate and provide **initial conditions** to climate models, aiming at accelerate their spin-off period, and/or make their projections (predictions?) more accurate.
- ML is used **on the output** of climate models to correct biases, to downscale model output to higher resolution than the model native grid, to synthesize information from ensembles, identify signals from noise….

AI/ML for climate model development and use (cont'd)

ML is used to **emulate the entire model**, i.e., to build a foundation model that once trained can substitute for the climate model entirely.

ML is used to **create simplified surrogates of climate models for specific purposes** (also emulators):

- Explore the **parameter space** of a model; **Greg's talk**
- Explore the **scenarios space**;
- Explore the **internal variability space**.

AI/ML for climate model development and use (cont'd)

ML is used to **emulate the entire model**, i.e., to build a foundation model that once trained can substitute for the climate model entirely.

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- Explore the **parameter space** of a model;
- Explore the **scenarios space**;
- Explore the **internal variability space**.

The remainder of this talk

Surrogate models/Emulators are developed to explore scenario and internal variability spaces

ANNUAL REVIEW OF ENVIRONMENT AND RESOURCES

Review Article

Emulators of Climate Model Output

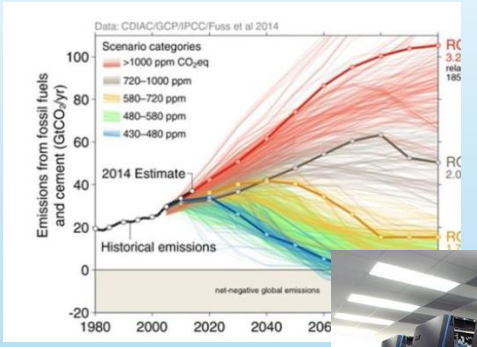
C. Tebaldi[1], N.E. Selin[2,3], R. Ferrari[2] and G. Flierl[2]

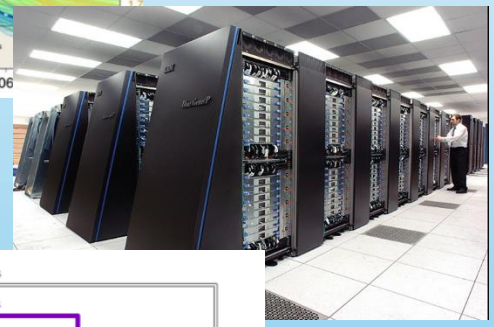
View Affiliations

Vol. 50 | https://doi.org/10.1146/annurev-environ-012125-085838

Review in Advance first posted online on June 06, 2025. (Changes may still occur before final publication.)

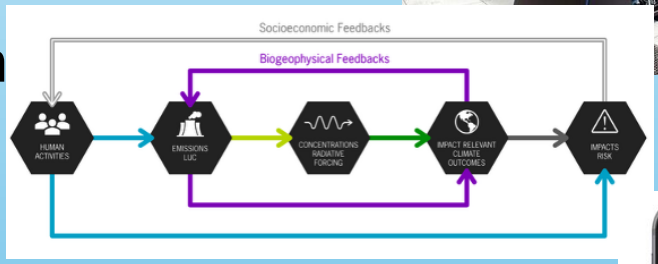
Why use an emulator rather than a climate model?





Provide input/drivers to impact and sustainability research by **exploring more scenarios, generating larger ensembles;**

Support **integrated research and modeling of Earth and Human systems** within the Integrated Assessment Modelin community;



Lighten computational burden of modeling centers esp. as models become more complex and finely resolved;

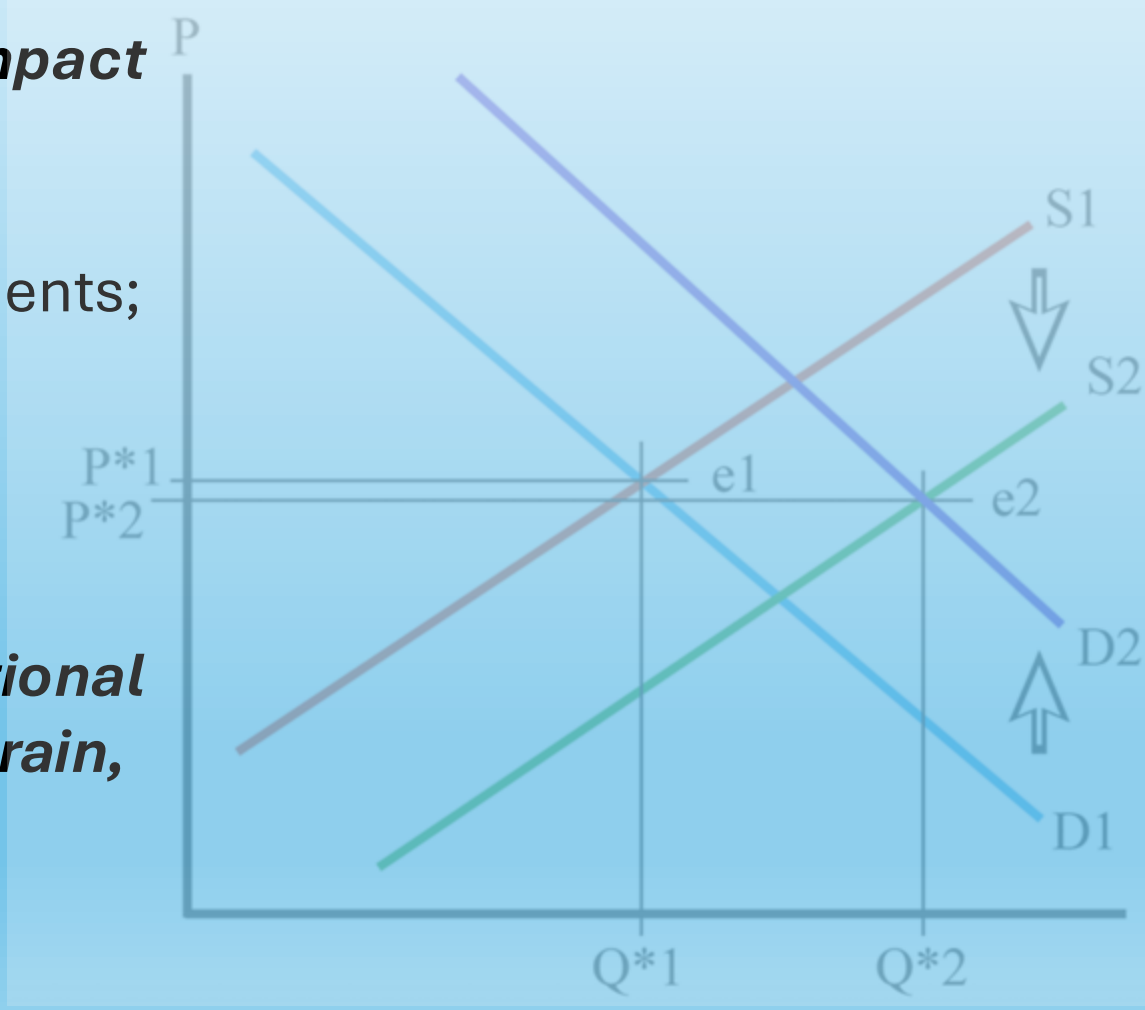
Facilitate **communication/exploration** of alternative futures in support of **policy making/decision making/education**.

Democratization of climate modeling?

Why so much activity in the emulation space now?

Demand side: Need for climate information for ***impact modeling, decision making, policy making, communication*** that goes beyond the handful of scenarios available from full-fledged ESM experiments; climate modeling community focusing on high resolution modeling, needs to supplement those few/short affordable simulations.

Supply side: new and/or more efficient ***computational tools and capacity, large data sets on which to train, data science*** surging in popularity.



What do emulators emulate:

The most common outputs used to be average **temperature and precipitation**, rarely jointly and at most at monthly frequency.

ML emulators are getting *skillful* at emulating **many joint variables, at daily and even sub-daily scales.**

Way forward

More **joint variables** at ***high frequency*** for impact modeling especially of high-impact extremes;

Variables other than atmospheric;

Forcings other than well mixed GHGs;

More rigorous and systematic ***validation*** of emulators, especially to ensure physical consistency, and skill in producing output in the tails of climate and weather variable distribution.

- Can emulators emulate **previously unseen events**?
- Can emulators **overcome ESM shortcomings**?

Way forward (cont'd)

More rigorous and systematic **characterization of data requirements for training emulators, in both quantity and type of experiments.**

More clear and systematic **description** of output and uncertainty sources addressed (scenarios? internal variability? model parameter uncertainty?).

More **coordination with climate modeling projects** in order to organize experiments in support of emulator development.