AI-guided climate model ensembles for refining future projections

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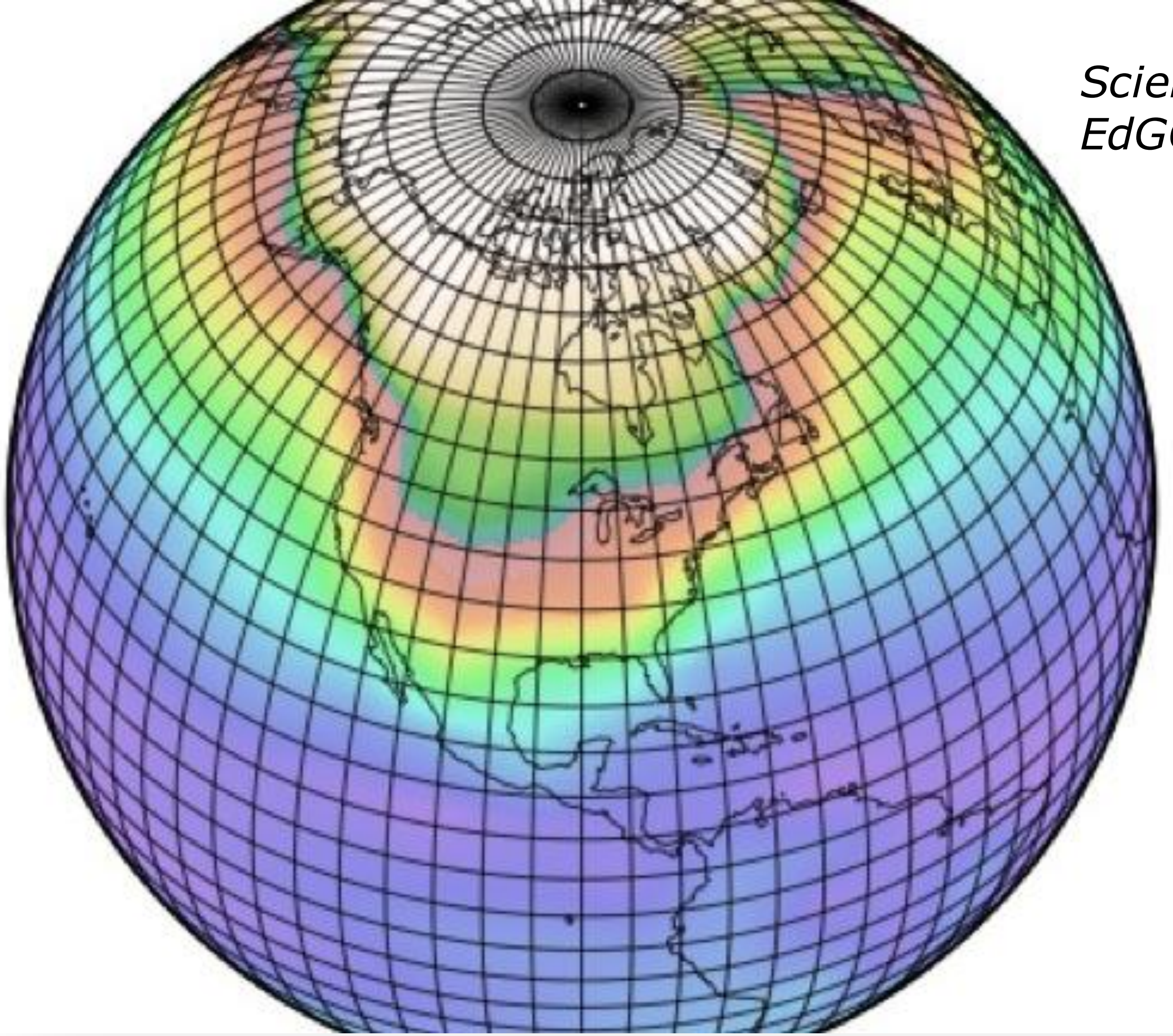
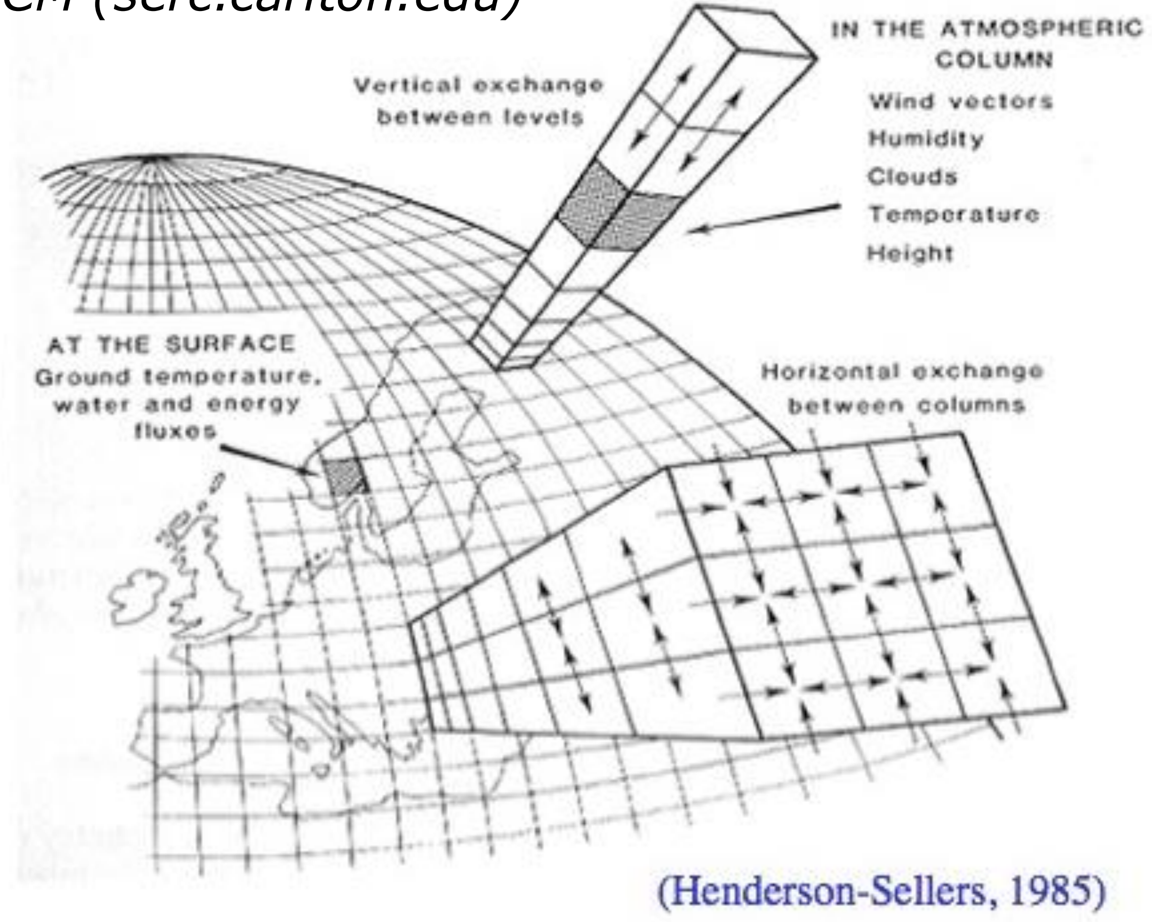
Marcus van Lier-Walqui (GISS/CU)
Jingbo Wu (GISS/CU), Qingyuan Yang (LEAP/CU), Kait Loftus (LEAP/GISS/CU)
NASA/GISS Clouds Group, NSF-STC Learning the Earth with AI and Physics (LEAP)

National Academies Roundtable on AI & Climate Change Webinar 1, 23 September 2025

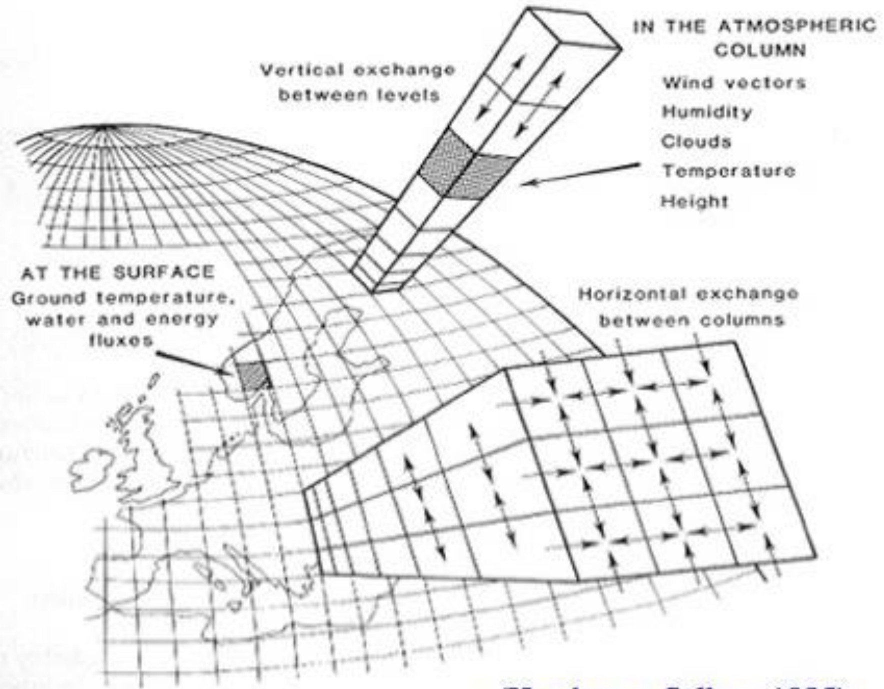
The Earth System from space

Science Education Resource Center (SERC), EdGCM (serc.carlton.edu)





From the satellite view to developing models



(Henderson-Sellers, 1985)

Within each grid cell, math equations **('physics')** exist for computing key variables in the Earth system (atmos. example below)…

- Temperature (T)
- Pressure (P)
- Winds (U, V)
- Humidity (Q)

- Conservation of momentum

$$\frac{\partial \vec{V}}{\partial t} = -(\vec{V}\cdot\nabla)\vec{V} - \frac{1}{\rho}\nabla p - \vec{g} - 2\vec{\Omega}\times\vec{V} + \nabla\cdot(k_m\nabla\vec{V}) - \vec{F}_d$$

- Conservation of energy

$$\rho c_{\vec{v}}\frac{\partial T}{\partial t} = -\rho c_{\vec{v}}(\vec{V}\cdot\nabla)T - \nabla\cdot\vec{R} + \nabla\cdot(k_T\nabla T) + C + S$$

- Conservation of mass

$$\frac{\partial \rho}{\partial t} = -(\vec{V}\cdot\nabla)\rho - \rho(\nabla\cdot\vec{V})$$

- Conservation of H_2O (vapor, liquid, solid)

$$\frac{\partial q}{\partial t} = -(\vec{V}\cdot\nabla)q + \nabla\cdot(k_q\nabla q) + S_q + E$$

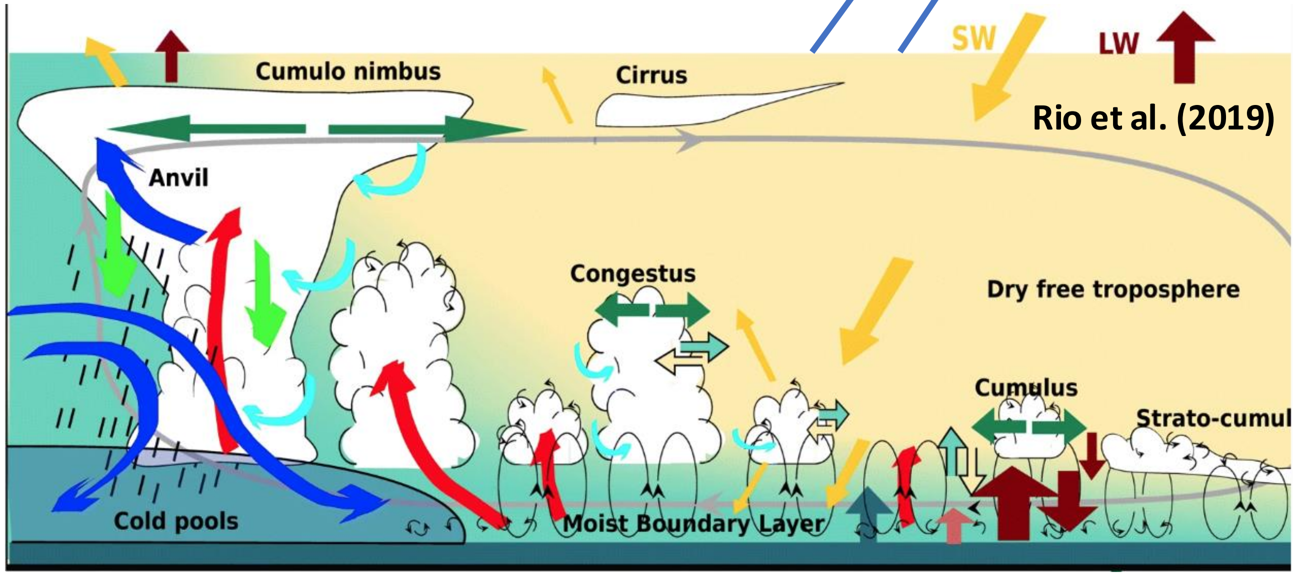
- Equation of state

$$p = \rho R_d T$$

Models are complicated, but understandable!

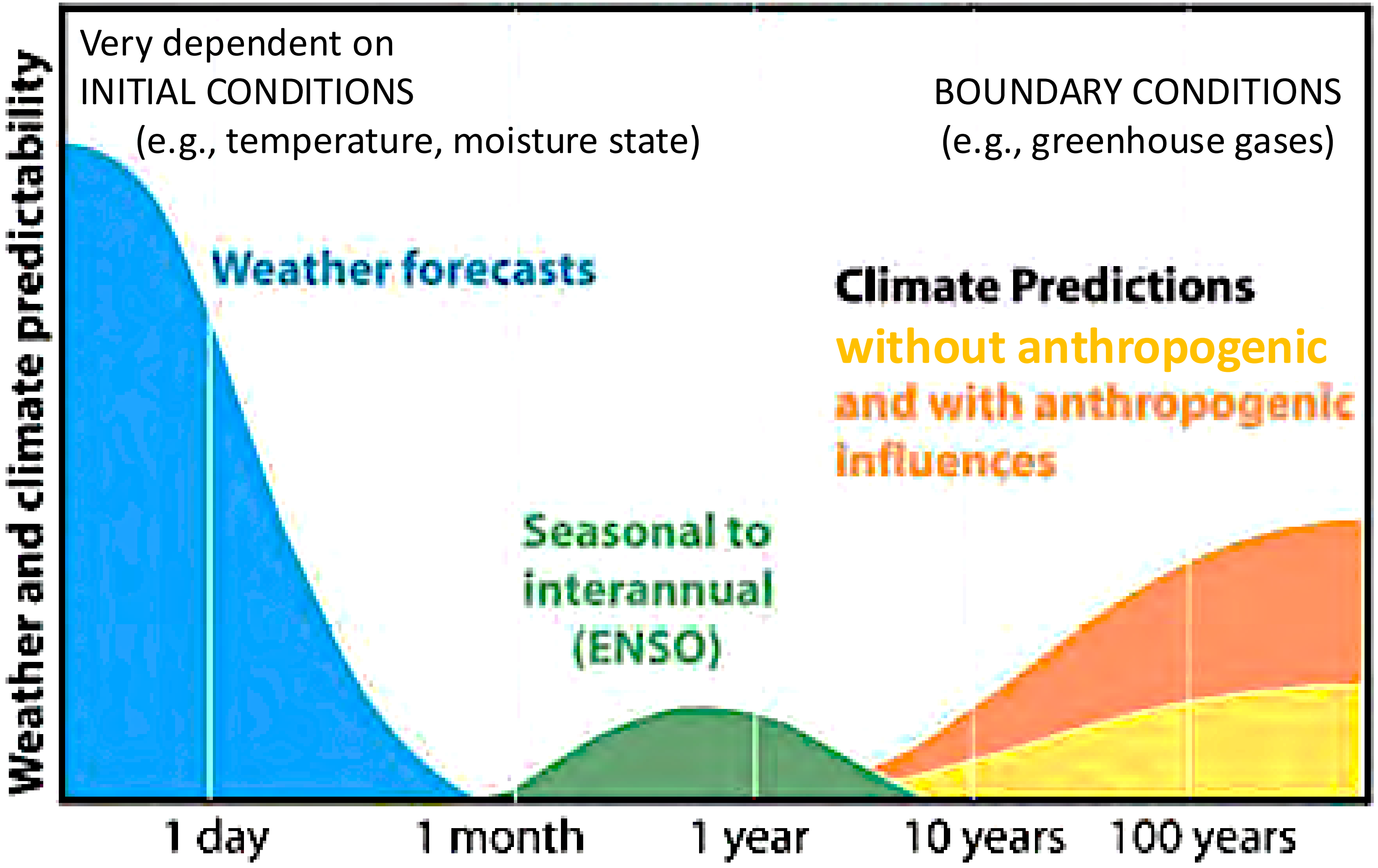
Subset of phenomena represented in a cell:
Cloud, thunderstorms, precipitation processes (*C, S, S_q, & E variables in top/right grey boxes*).

At this point, we use the model to step forward in time (i.e., prediction).



Underneath this, a dynamic ocean, cryosphere (ice), land…

Predictability of weather and climate



H. Simon, T. Zacharia, R. Stevens DOE Modeling, Town Hall Report; Figure courtesy of Kevin Trenberth
https://cseweb.ucsd.edu/classes/wi13/cse245-b/slides/exascale.pdf

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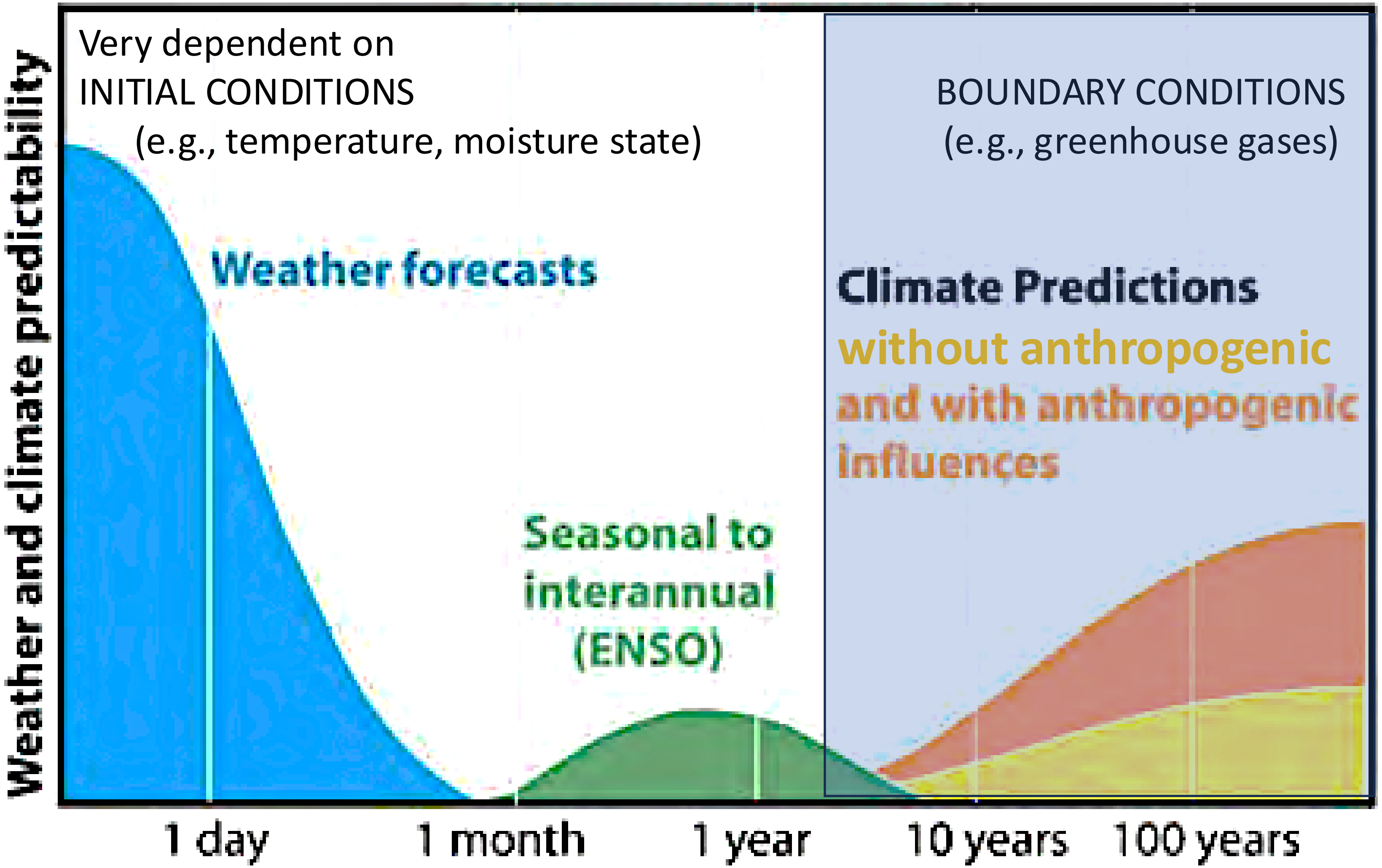

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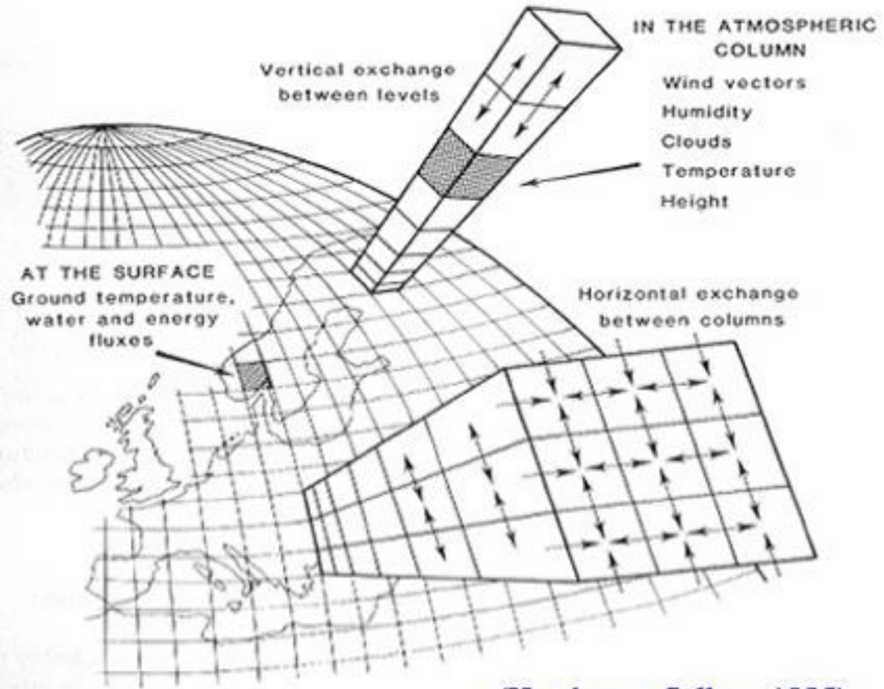

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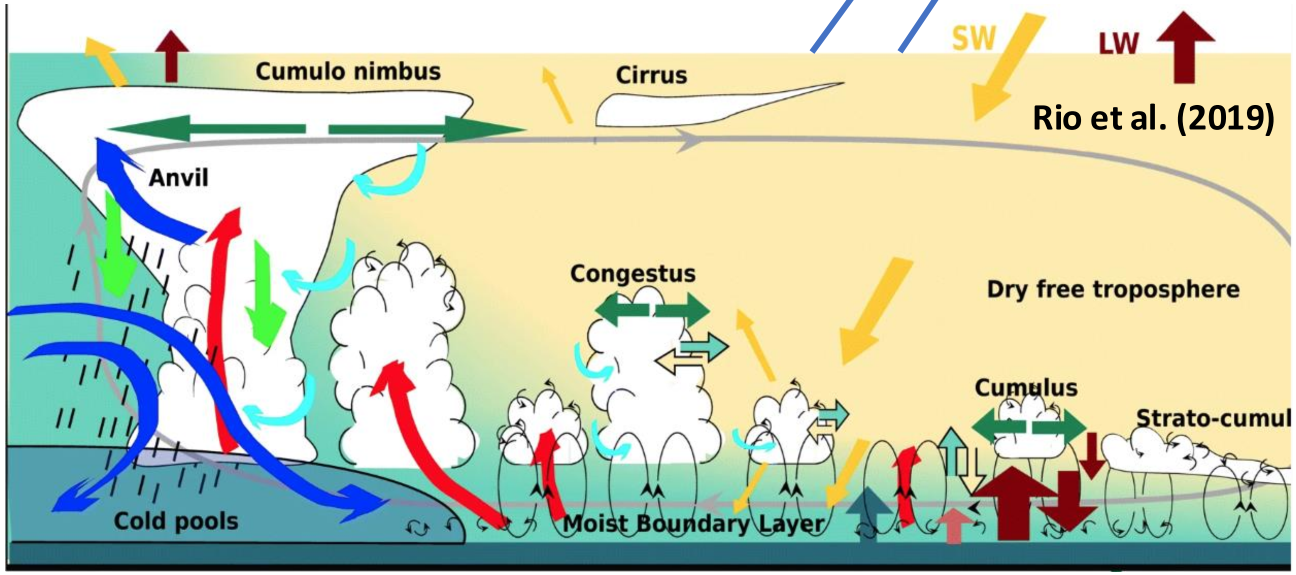


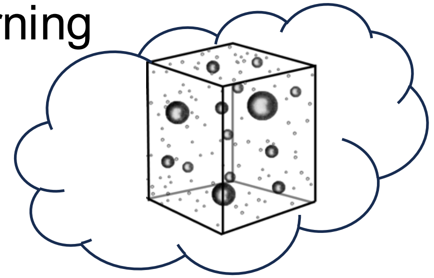
Underneath this, a dynamic ocean, cryosphere (ice), land…

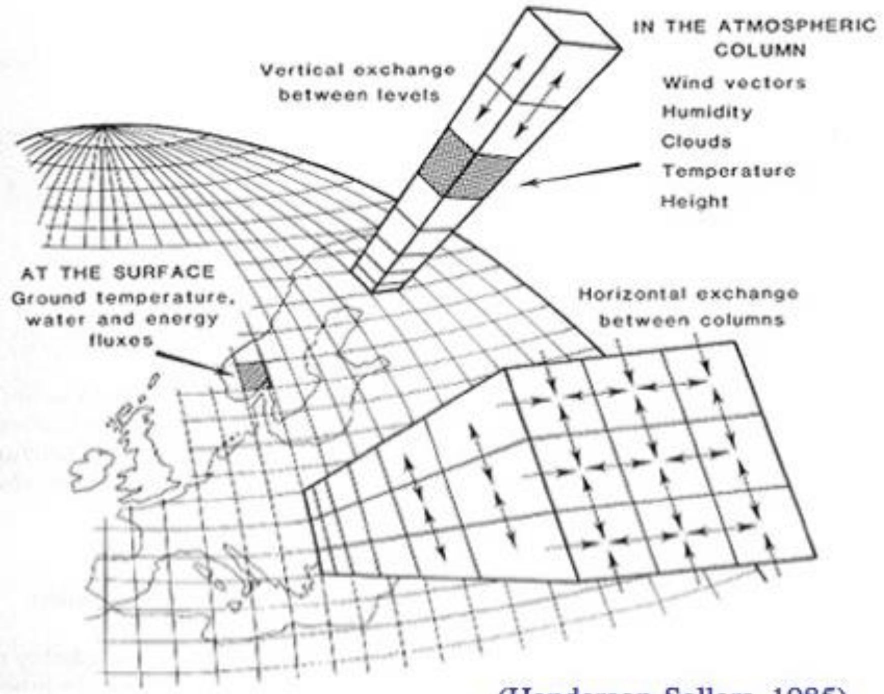
Grey Boxes → In these are 100s of math equations that have unknown numbers attached. **(we call these 'physics parameters')**

Examples

Known: gravitational constant (g); R_d

Not-known: parameters governing how quickly cloud drops become raindrops.





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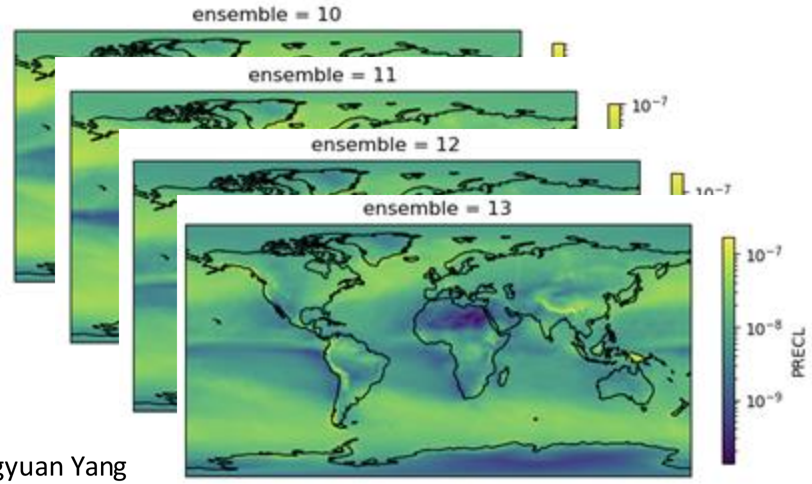
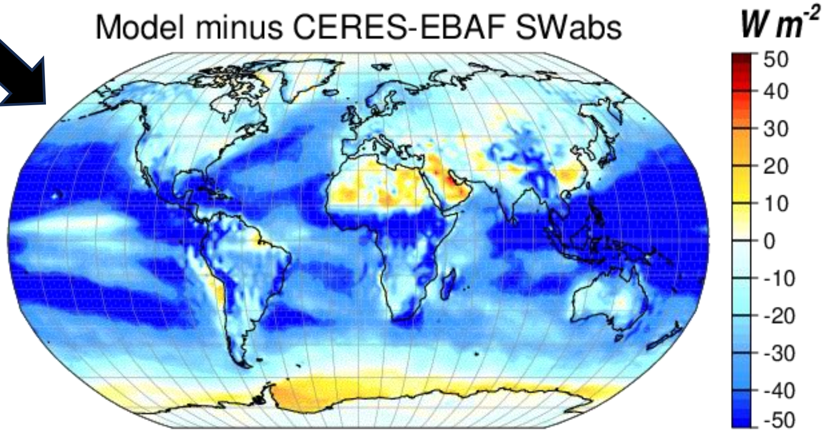


From Qingyuan Yang (LEAP, Columbia University)

…many experiments, not just the 4 as shown here!

For each experiment, compute the climate error!

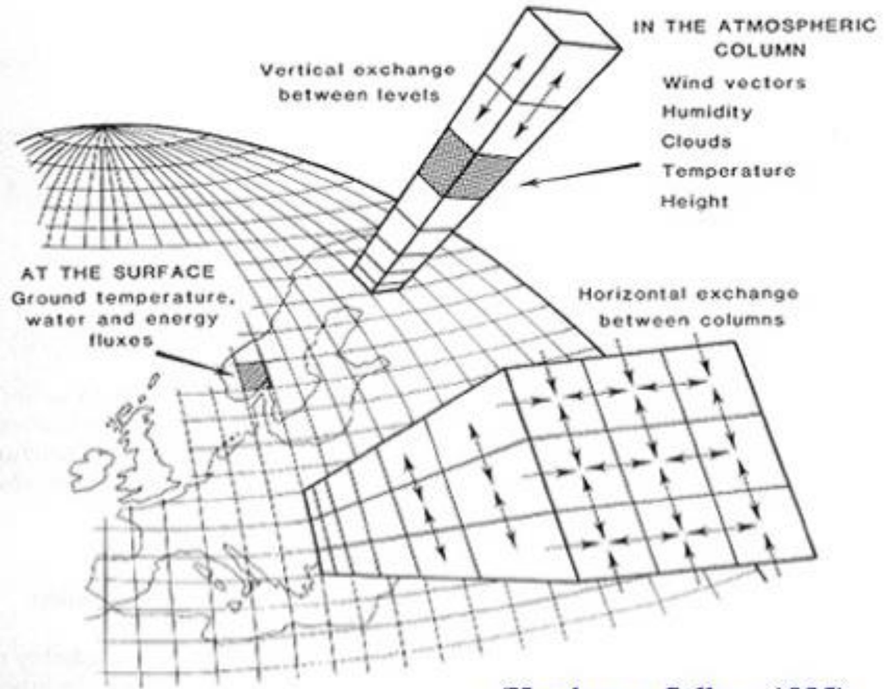


Where do we go from here? Run experiments with all 'physics parameters' randomly varied at the same time, and store the model predicted outputs.

- Temperature (T)
- Pressure (P)
- Winds (U, V)
- Humidity (Q)

…and much more, including clouds, thunderstorm properties, radiation, etc.

Use AI to fill the gaps where physics parameter combinations were not tested; now, **AI serves as a model emulator,** or an inexpensive, efficient, reliable 'surrogate model'.



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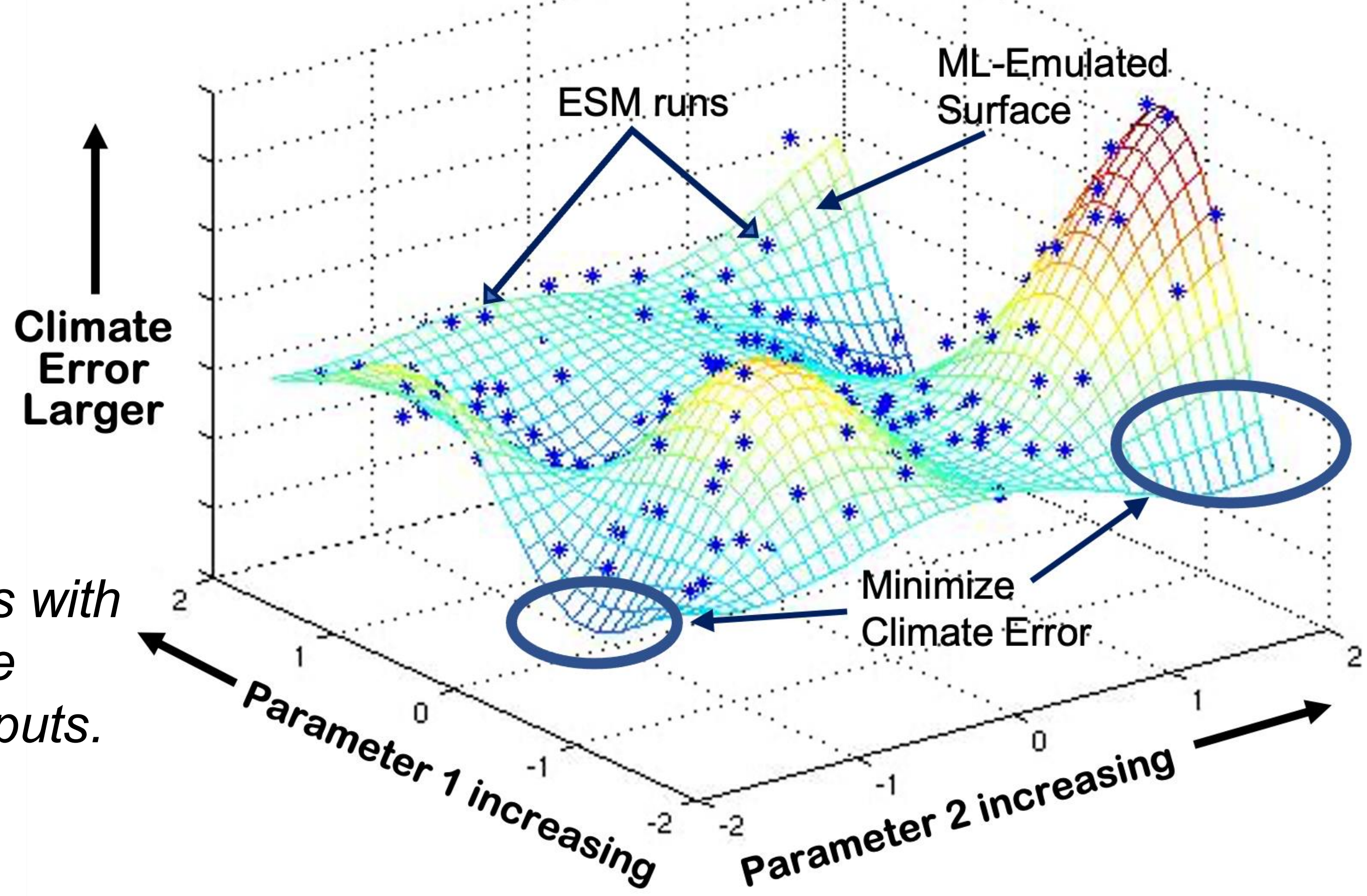

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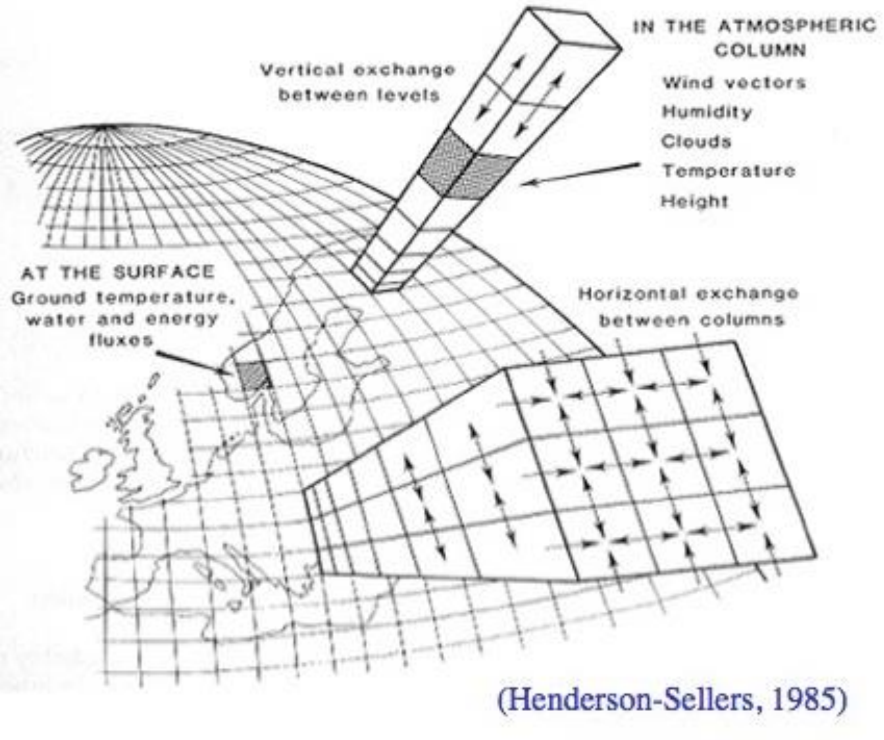

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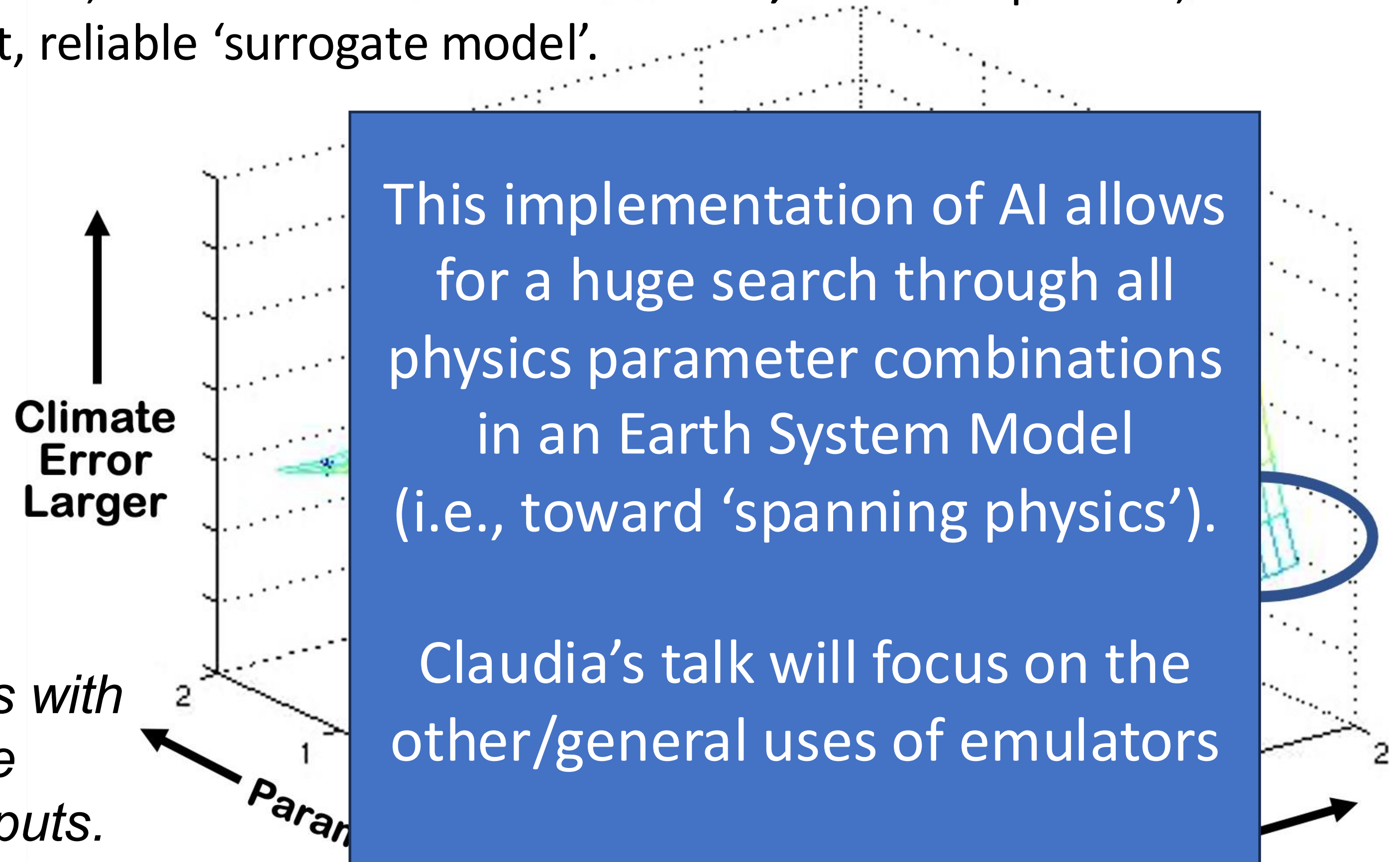

This implementation of AI allows for a huge search through all physics parameter combinations in an Earth System Model (i.e., toward 'spanning physics').

Claudia's talk will focus on the other/general uses of emulators

Now that we can span physics – where do we go next?

Where do we go from here? Run experiments with all 'physics parameters' randomly varied at the same time, and store the model predicted outputs.

- Temperature (T)
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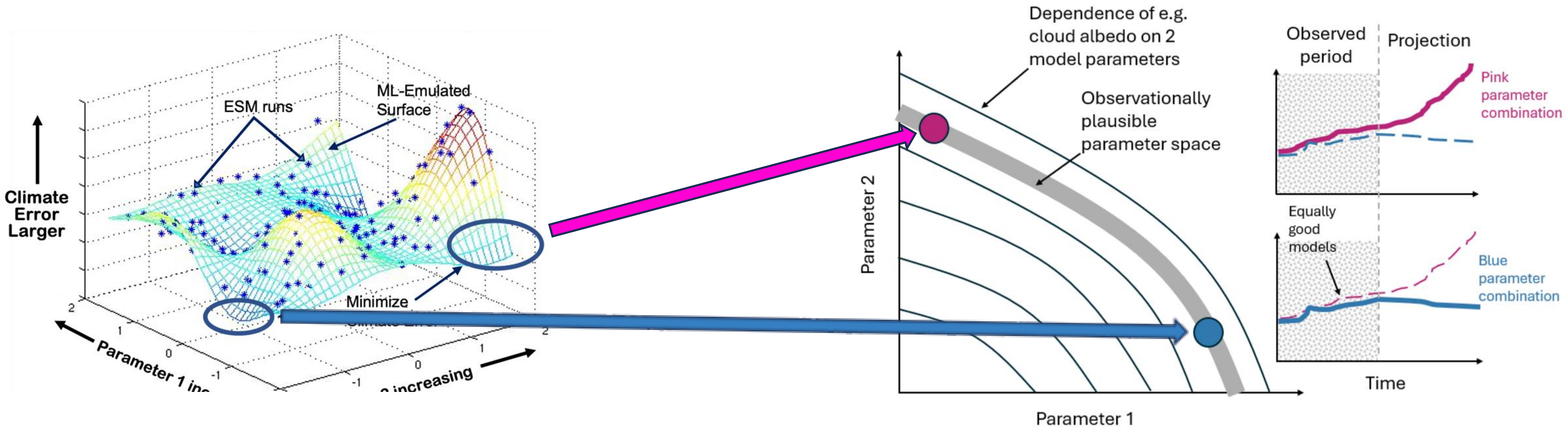
Ensemble members with small ‘climate errors’ are stored & placed in a ‘calibrated physics ensemble’ (CPE) (calibration = model output looks like satellite data).



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Using Machine Learning to Generate a GISS ModelE Calibrated Physics Ensemble (CPE)

Gregory S. Elsaesser, Marcus van Lier-Walqui, Qingyuan Yang, Maxwell Kelley, Andrew S. Ackerman, Ann M. Fridlind, Gregory V. Cesana, Gavin A. Schmidt, Jingbo Wu, Ali Behrangi ... See all authors

First published: 11 April 2025 | https://doi.org/10.1029/2024MS004713 | Citations: 3

https://doi.org/10.5194/egusphere-2025-4341

Abstract | Discussion | Metrics

17 Sep 2025

Status: this preprint is open for discussion and under review for Atmospheric Chemistry and Physics (ACP).

Opinion: The importance and future development of perturbed parameter ensembles in climate and atmospheric science

Ken S. Carslaw, Leighton A. Regayre, Ulrike Proske, Andrew Gettelman, David M. H. Sexton, Yun Qian, Lauren Marshall, Oliver Wild, Marcus van Lier-Walqui, Annika Oertel, Saloua Peatier, Ben Yang, Jill S. Johnson, Sihan Li, Daniel T. McCoy, Benjamin M. Sanderson, Christina J. Williamson, Gregory S. Elsaesser, Kuniko Yamazaki, and Ben B. B. Booth

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Short summary
A major challenge in climate science is reducing projection uncertainty despite advances in...
- Read more

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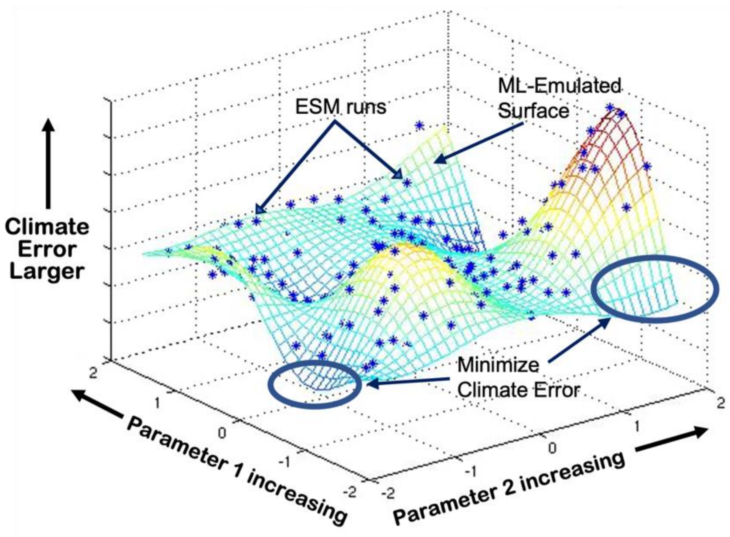
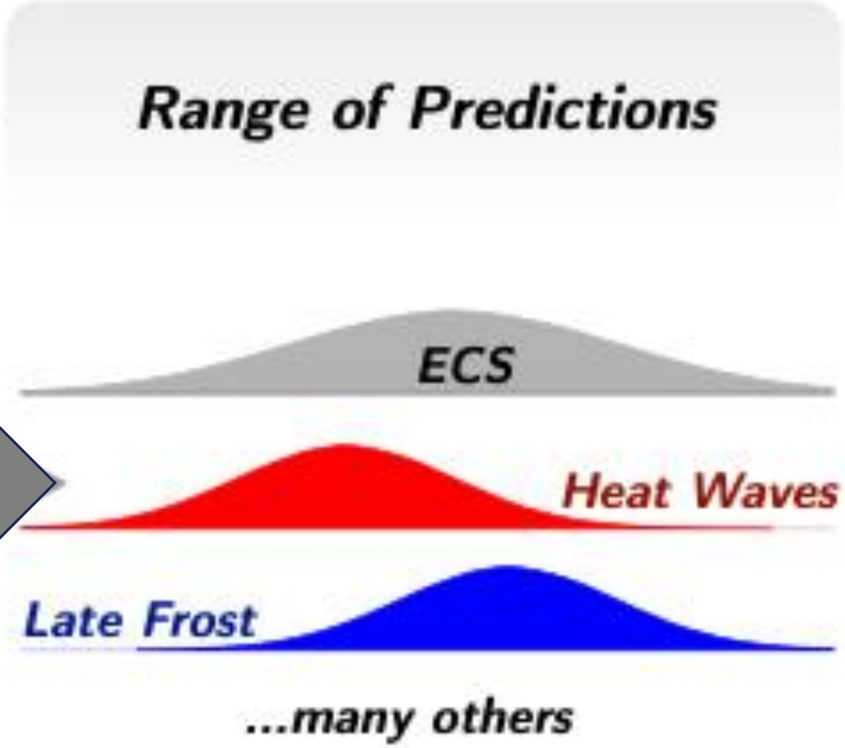


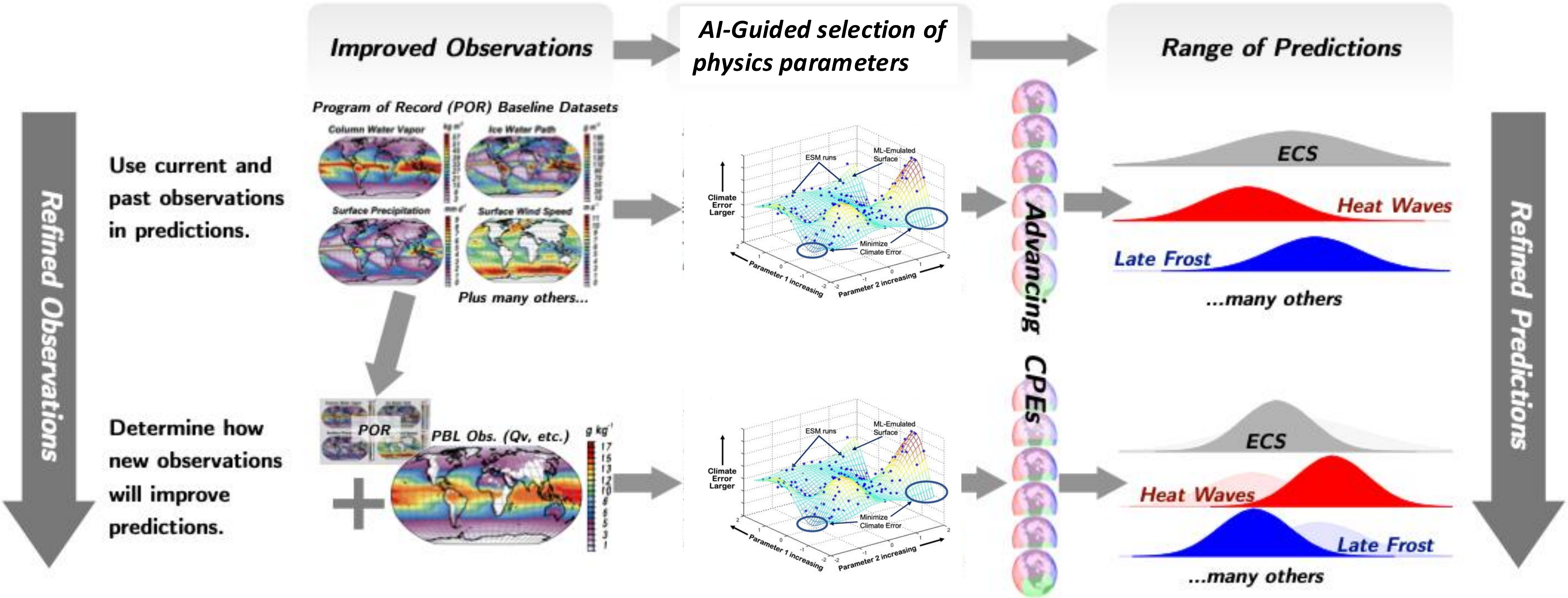
More than 2 minima;
Find **all** locations
where climate errors
are smaller



Using AI framework to create progressively improved climate model ensembles,

integrating more observations than previously possible, and testing the value of currently non-existent but future ones (e.g., planetary boundary layer [PBL] observations).

Fridlind et al. 2025, in revision for the Bulletin of the AMS; https://arxiv.org/abs/2509.00211



Summary & Looking Ahead

Models of the Earth System are complicated: But understandable given their physics foundation. Running them takes time (**$$$**), but emulators (serving as 'surrogate models') can learn their behavior, thus removing the need to run ESMs in some experiments.

Emulators for Spanning Earth System Model Physics Parameters: Finding all 'good' physics parameter combinations in a single ESM will be important for establishing a reliable range of projections (or, projection uncertainty) spanning multiple societally impactful metrics. Efforts are rapidly expanding in the U.S.

Emulators for Spanning Earth System Model Physics Structures: Parameters are part of a fixed equation or structure. Can we also span physics structures (i.e., can AI span the physical space covered by different equations representing Earth System processes?). This would be even better for refining projections.

AI being swapped for some physics equations, and AI replacing entire ESM physics suite?
Part of Claudia's talk on uses of emulators in climate modeling more broadly.