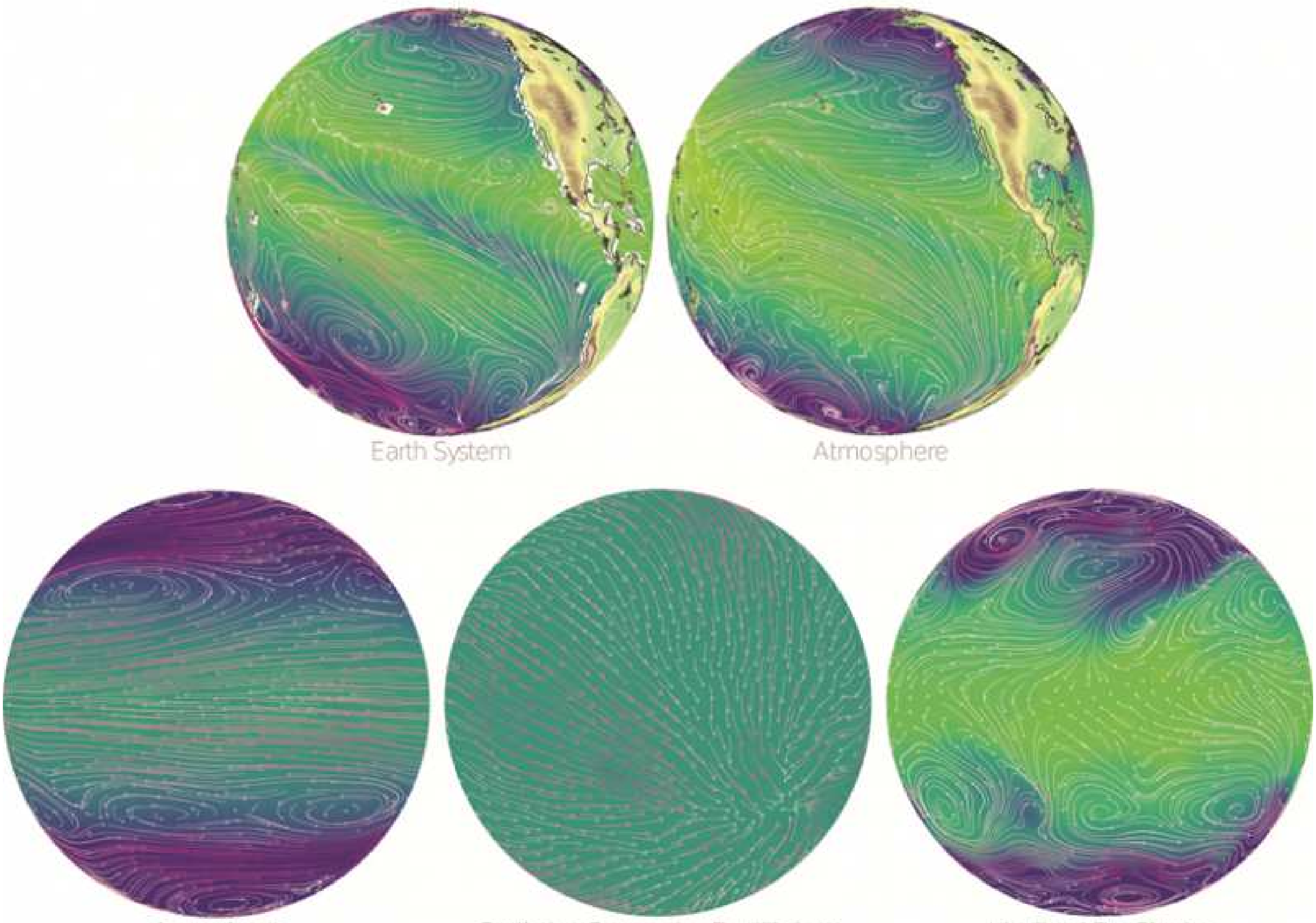
Editors' Vox

Perspectives on Earth and space science: A blog from AGU's journal editors

Atmospheric Model Hierarchies: Connecting Theory and Models

Model hierarchies are fundamental to how we model Earth's climate, allowing us to apply our theoretical understanding, connect simple ideas to the real atmosphere, and test new hypotheses.



An example of a climate model hierarchy from complex (top left) to idealized (bottom right). Credit: Maher et al. [2019], Figure 7

By Penelope Maher and Edwin P. Gerberon 4 hours ago

Model hierarchies have been fundamental for our understanding of the large-scale circulation of Earth's atmosphere. They have played a critical role in informing our ability to simulate natural variability, testing our predictive skill, and investigating how the climate will respond to external forcing, particularly increased greenhouse gas concentrations.

A recent paper (https://doi.org/10.1029/2018RG000607) in *Reviews of Geophysics* (https://agupubs.onlinelibrary.wiley.com/journal/19449208) explores the broad use of idealized atmospheric models to understand the large-scale circulation, starting with the most simple models that form the basis of our understanding of the atmosphere and how they connect to the comprehensive models used for climate prediction through model hierarchies.

Here, the two lead authors give an overview of what a climate model hierarchy is, why we use simple climate models, and how these models have helped us to understand the large-scale circulation of the atmosphere.

What is a climate model hierarchy?

Climate model hierarchies can be thought of as a ladder connecting our complex climate models to our physical understanding of nature. Credit: Dejan Krsmanovic (https://www.flickr.com/photos/dejankrsmanovic/32344618037/) (CC BY 2.0 (https://creativecommons.org/licenses/by/2.0/legalcode))

You can think of a climate model hierarchy as a ladder connecting our understanding of basic physical principles to the Earth system in all its complexity.

At the base are conceptual models, our simplest ways of describing the processes and laws governing the climate system. An example would be a zero-dimensional energy balance model of the atmosphere and its response to increase greenhouse gas concentrations, as first developed by Arrhenius in 1896 (https://www.rsc.org/images/Arrhenius1896_tcm18-173546.pdf).

At the top are our most advanced climate prediction models developed to inform the

Intergovernmental Panel on Climate Change (IPCC). These state-of-the-art models are continually evolving as they increase in realism (representing additional physical processes) and resolution (allowing a more scales).

A model hierarchy is a series of models that connect our simple conceptual models, based on our conceptual understanding, to the most advanced prediction models, and are constructed by incrementally adding key processes and scales, one by one.

Just as a tall ladder with only a few steps at the top isn't very useful if you are standing on the ground, our most advanced models need to be connected to be grounded in our conceptual understanding, validated, and improved.

Why do we use simple climate models?

Since the climate is complex, our climate models also need to be complex … but there needs to be some simplification to build understanding.

Since the climate is complex, our climate models also need to be complex, but trying to model all the details of our climate system can impede understanding (https://eos.org/opinions/when-less-is-more-opening-the-door-to-simpler-climate-models). There needs to be some simplification to build understanding.

When we strip back models to their most fundamental components, we can isolate and understand their behavior and identify "model biases" that need to be fixed. Perhaps a model is missing a key process. Perhaps a newly added process is not properly represented or coupled with the rest of the climate system. Maybe there are more fundamental problems lurking beneath in processes we thought we fully understood. We can then add in complexity incrementally to build up to a more realistic model.

In addition to fixing model biases, another aim of simple model studies is to understand a process, feedback, or mechanism. The task then becomes how to relate understanding gained from simple models back to the real climate; this is where a model hierarchy becomes essential.

How are models organized into hierarchies?

While this appears to be a simple question, there is not a simple answer. How you organize a hierarchy depends on the research questions you are exploring.

There are, however, a number of models which have been studied in broad contexts, thus establishing them as 'benchmarks' in our understanding. For example, in terms of the general circulation of the atmosphere, one benchmark is the Held and Suarez [1994] (https://doi.org/10.1175/1520-0477(1994)075%3C1825:APFTIO%3E2.0.CO;2) model, which assumes the atmosphere is dry, i.e., there is no representation of moist processes like clouds and rainfall.

Aquaplanets are a commonly used idealized model. These models have a surface that is entirely covered by ocean. Credit: Vladimir Kud (https://www.flickr.com/photos/131947100@N08/23664615949/in/photostream/) (CC BY 2.0 (https://creativecommons.org/licenses/by/2.0/legalcode))

To begin to incorporate the role of moisture in heat transport – but not on radiative transfer – the idealized aquaplanet model of Frierson [2007] (https://doi.org/10.1175/JAS3935.1) simulates a moist atmosphere with a series of simplifying assumptions that decouple moisture from radiative transfer. To allow moisture to interact with radiation (both through water vapor and clouds), we then use a conventional aquaplanet model – a full atmospheric model coupled to a simple slab ocean, or with fixed sea surface temperatures.

These models are just one illustration of a model hierarchy. They differ in their treatment of "atmospheric physics", allowing us to incrementally explore the coupling between diabatic processes (radiation and convection) and the large-scale atmospheric circulation.

In our review (https://doi.org/10.1029/2018RG000607), we describe three principles that help organize models into hierarchies. First, a dynamical hierarchy can be used to explore the fundamental equations used to predict the atmospheric flow. Second, a process hierarchy allows us to incorporate processes that drive the atmospheric circulation; the models described above fit into this category. Finally, we can organize a hierarchy based on the scales and domain size to explore the time and space dependence of the system.

How have model hierarchies improved our understanding of atmospheric circulation?

Model hierarchies allow us to make progress in addressing key research areas.

There is a rich history of dry idealized modeling studies applied to the mid-latitudes and stratosphere that dates back to the 1960s. But idealized moist models have grown in popularity over the last 15 years and are a promising approach for making progress at the frontiers of climate research, such as the coupling of clouds and circulation.

“Dry” models of the climate, i.e., atmospheric models that do not include a representation of moist processes, have enabled our understanding of eddy feedbacks, jet streams, wave mean flow interactions, stratospheric transport and the tropical Walker circulation. Meanwhile, idealized moist models have been influential in understanding the tropical circulation and feedbacks between the convection, clouds, and circulation.

Model hierarchies also allow us to make progress in addressing key research areas, such as convective organization, cloud feedbacks, Earth’s equilibrium climate sensitivity, and the Madden-Julian Oscillation.

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