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COMMENTARY

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Key Points:

- The model hierarchy can be seen as a cartesian product of individual hierarchical axes
- The hierarchy facilitates the generation and testing of hypotheses
- The diversity of models still poses issues, which will likely require further model "elegance"

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A perspective on climate model hierarchies

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Abstract To understand Earth's climate, climate modelers employ a hierarchy of climate models spanning a wide spectrum of complexity and comprehensiveness. This essay, inspired by the World Climate Research Programme's recent "Model Hierarchies Workshop," attempts to survey and synthesize some of the current thinking on climate model hierarchies, especially as presented at the workshop. We give a few formal descriptions of the hierarchy and survey the various ways it is used to generate, test, and confirm hypotheses. We also discuss some of the pitfalls of contemporary climate modeling, and how the "elegance" advocated for by Held (2005) has (and has not) been used to address them. We conclude with a survey of current activity in hierarchical modeling, and offer suggestions for its continued fruitful development.

1. Introduction

> *. . ..In that Empire, the Art of Cartography attained such Perfection that the map of a single Province occupied the entirety of a City, and the map of the Empire, the entirety of a Province. In time, those Unconscionable maps no longer satisfied, and the Cartographers Guilds struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it. The following Generations, who were not so fond of the Study of Cartography as their Forebears had been, saw that that vast Map was Useless, and not without some Pitilessness was it, that they delivered it up to the Inclemencies of Sun and Winters. In the Deserts of the West, still today, there are Tattered Ruins of that Map, inhabited by Animals and Beggars; in all the Land there is no other Relic of the Disciplines of Geography.*
>
> –Borges, "On Exactitude in Science"
>
> *Come, let us go down and there confuse their language, that they may not understand one another's speech.*
>
> –Genesis 11:6, King James Version

In attempting to digitally represent the Earth system, climate models have grown to be some of the most elaborate computer programs in existence. They are comprised of millions of lines of code and run on the world's largest supercomputers. As such they are worlds unto themselves, and studying the Earth through these models can sometimes blur into studying just the models themselves. Given the unavoidable gulf between models and reality, this presents a danger. This danger is compounded by the fact that there are dozens of such models worldwide [*Flato et al.*, 2013, Table 9.1], and they are sufficiently different that an understanding of one does not translate to an understanding of another.

By studying a proliferation of vast maps, rather than the territory itself, do we modelers make our studies irrelevant, both to reality and each other? Have we at once become Borges's cartographers as well as denizens of Babel? On the other hand, could the modeler's omnipotent control over these artificial Earths actually enable an understanding of the real Earth which might otherwise be impossible? Such questions were at the fore at the World Climate Research Programme's Model Hierarchies Workshop, held 2–3 November 2016 in Princeton, New Jersey (see also https://www.wcrp-climate.org/gc-model-hierarchies-home). That workshop, inspired by the influential essay of *Held* [2005] (hereafter H05), explored answers to these questions in relation to climate model *hierarchies*, or arrays of climate models that span a spectrum of complexity and comprehensiveness. The present essay, inspired by and drawing heavily from the ideas exchanged at the workshop, attempts to synthesize those ideas, assess the progress we have (and have not) made since H05, and serve as a point of introduction for those wishing to understand climate model hierarchies and their role in climate science. As in the workshop, we emphasize atmospheric processes, and examples are drawn primarily from recent literature, and in particular workshop presentations, where possible.

2. Modeling the Hierarchy

All models are wrong, but some are useful.

–George Box

We can define the climate model hierarchy as the set of all configurations of models of Earth's climate, together with some hierarchical structure in which model configurations are ordered from least to most realistic. In attempting to formalize this, however, one quickly realizes that a strict ordering of all configurations is not possible; how, for instance, can one compare a moist, non-rotating cloud-resolving simulation in a planar geometry to a dry, rotating, coarse-resolution global simulation? One is not clearly more realistic than the other, at least in any general sense. The term "hierarchy" is thus a misnomer, and it becomes clear that if a strict, hierarchical ordering is sought, it must exist along multiple axes simultaneously. This leads to a formalization of the climate model hierarchy as a Cartesian product space of individually hierarchical axes, each representing a single model component:

$$\overset{\textbf{Fluid}}{\begin{pmatrix}\text{compressible}\\ \text{hydrostatic}\\ \text{QG}\\ \text{static}\end{pmatrix}} \times \overset{\textbf{Rotation}}{\begin{pmatrix}\text{Coriolis}\\ \beta-\text{plane}\\ f-\text{plane}\\ \text{none}\end{pmatrix}} \times \overset{\textbf{Ocean}}{\begin{pmatrix}\text{dynamical}\\ \text{column}\\ \text{slab}\\ \text{non-uniform } T_s\\ \text{uniform } T_s\end{pmatrix}} \times \overset{\textbf{Surface}}{\begin{pmatrix}\text{land+ice}\\ \text{real land}\\ \text{ideal land}\\ \text{aqua}\end{pmatrix}} \times \overset{\textbf{Convection}}{\begin{pmatrix}\text{explicit moist}\\ \text{super}-\text{param.}\\ \text{parameterized}\\ \text{large}-\text{scale}\\ \text{dry}\end{pmatrix}} \times \overset{\textbf{Radiation}}{\begin{pmatrix}\text{spectral}\\ \text{gray}\\ \text{Newtonian}\\ \text{fixed}\end{pmatrix}}. \tag{1}$$

This list of axes is, of course, not exhaustive, and neither is the list of points within a given axis. One could easily add axes corresponding to insolation, microphysics schemes, atmospheric chemistry, and so on, and the ocean and surface columns could each be expanded into their own multidimensional hierarchies. One could also add other modeling frameworks, such as weak-temperature and weak-pressure gradient approximations [*Daleu et al*., 2015], or the quasi-equilibrium tropical circulation model [*Neelin and Zeng*, 1999]. Such elaborations are omitted, though, to provide a manageable (if biased) picture of the hierarchy, which hopefully still captures the most common hierarchical variations.

Two aspects of equation (1) deserve comment. First, note that since the convection configuration for a given model is largely determined by its horizontal resolution (e.g., low-resolution parametrized or high-resolution explicit), the convection axis is implicitly a resolution axis. Second, there is an implicit "symmetry" axis among the rotation, ocean, and surface axes: nonrotating aquaplanets with uniform surface temperature T_s exhibit full spherical symmetry, aquaplanets in general typically exhibit zonal (azimuthal) symmetry, and configurations with realistic land exhibit no spatial symmetry.

As a further idealization, the six axes in (1) may be naturally grouped pairwise as

$$\underbrace{\text{Fluid}\times\text{Rotation}}_{\text{Dynamics}}\times\underbrace{\text{Ocean}\times\text{Surface}}_{\text{Boundary Forcing}}\times\underbrace{\text{Convection}\times\text{Radiation}}_{\text{Bulk Forcing}}, \tag{2}$$

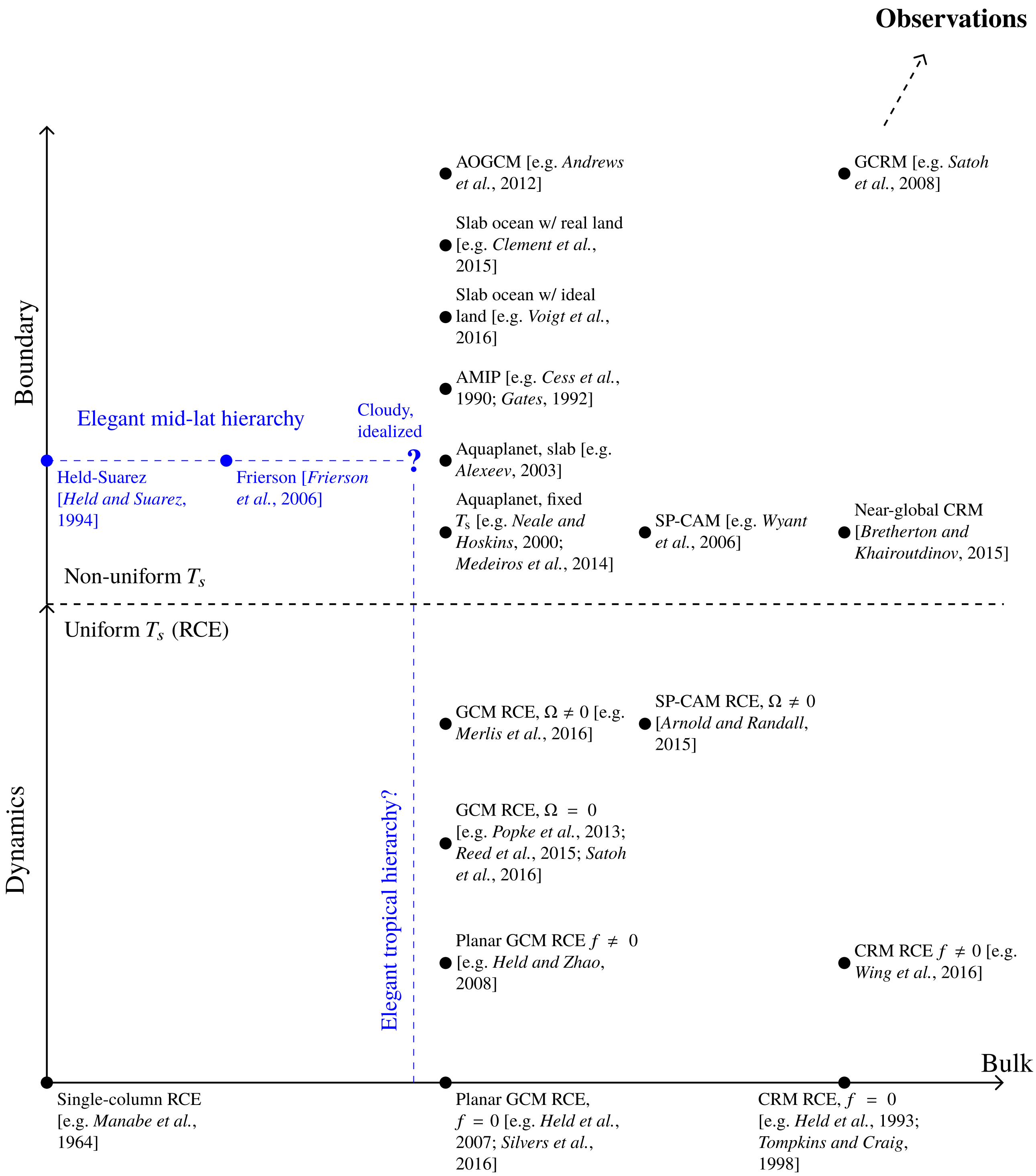

Figure 1. A planar climate hierarchy, with "bulk" forcings (mainly convection) on the horizontal axis, and the vertical axis split into two pieces: a lower "dynamics" axis (mainly rotation), with uniform surface temperatures T_s (i.e., RCE), and a higher "boundary" axis with non-uniform T_s. The Earth's angular velocity is Ω, and *f* is the Coriolis parameter. References for different configurations are only representative, and were subjectively chosen as suitable introductions to those configurations and their applications. The horizontal blue line shows the currently existing, elegant "midlatitude" hierarchy spanned by the Held-Suarez and Frierson models; this hierarchy should also include the QG model of Charney and Philips (not shown). The vertical blue line highlights the possibility of an elegant "tropical" hierarchy, which would include elegant versions of some of the GCM RCE configurations. (One could also draw this line further to the right to denote elegant cloud-resolving RCE as well.) The midlatitude and tropical hierarchies terminate in a nonexistent elegant model with interactive clouds, the need for which was highlighted in H05 and the absence of which is still conspicuous today.

where we refer to convection and radiation as "bulk" forcings since they produce diabatic forcings in the bulk of the atmosphere, rather than just at the surface or boundary. Collapsing axes this way aids conceptualization and visualization, but in principle also makes strict ordering along a given axis more difficult. In practice, however, for the dynamical system and bulk forcing groups, the significant factors seem to be the rotation and convection axes, respectively, so we will order models accordingly. For the boundary forcing group neither axis seems to stand out as more significant, though, so we just tolerate some ambiguity in the ordering there.

Another point regarding equation (2) is that as a community, we mostly seem to climb the boundary forcing hierarchy only after climbing the rotation hierarchy. In other words, models with a planar geometry and without the full Coriolis effect tend to have fixed, uniform surface temperatures $T_{s,}$ with no land or ice. Important exceptions certainly exist, such as doubly periodic cloud-resolving simulations with nonuniform $T_s(x)$ [e.g., *Kuang*, 2012], idealized land [e.g., *Becker and Stevens*, 2014; *Cronin et al*., 2015], and slab oceans [e.g., *Hohenegger and Stevens*, 2016]. Nonetheless, we take the liberty of simplifying the 3-D hierarchy of equation (2) by combining the boundary and dynamics axes, with dynamics (especially rotation) forming the lower tier. This leads to a planar climate hierarchy, shown in Figure 1. Though not comprehensive, Figure 1 provides a manageable visualization of the hierarchy which displays many of the model configurations in use today, and especially those developed recently. For other, complementary visualizations of the model hierarchy see *Bony et al*., 2013, Figure 4 and *McGuffie and Henderson-Sellers*, 2014, Figure 2.2.

Figure 1 also highlights in blue those configurations which are or could be part of "elegant hierarchies" (H05). The two such hierarchies we highlight embody very different points of view. The horizontal hierarchy takes the dry dynamics of the midlatitudes as fundamental, and elaborates by adding moist processes. We will refer to this as the "midlatitude" hierarchy. The vertical hierarchy, on the other hand, takes the moist dynamics of the convecting tropics as fundamental, and elaborates by adding rotation and then T_s gradients. We will refer to this as the "tropical" hierarchy. We will return to model elegance and these particular hierarchies in sections 5 and 6.

3. Using the Hierarchy

3.1. Simplification

> *If you have a problem that you do not know how to solve, then there exists a simpler problem that you do not know how to solve, and your first job is to find it.*
>
> –George Polya

One major benefit of model hierarchies is in providing simplified versions of systems of interest, which are easier to study and generate hypotheses about. A classic example is the quasi-geostrophic (QG) system of *Charney* [1948] and *Philips* [1956]. This system has provided a fundamental understanding of some key aspects of the midlatitude atmospheric circulation, such as eddy-mean flow interactions [*Holton and Mass*, 1976; *Robinson*, 2000] and the generation, propagation, and scales of baroclinic eddies [*Eady*, 1949; *Held and Larichev*, 1996; *Held*, 2000]. In recognition of this fundamental role, and in analogy to the hierarchy of "model organisms" studied by biologists [*Fields and Johnston*, 2005], H05 dubbed the QG model the *E. Coli* of climate models. As for the tropics, basic questions such as what sets its temperature profile, convectively available potential energy, and relative humidity, have recently been answered by turning to simulations of radiative-convective equilibrium (RCE) in doubly-periodic, cloud-resolving models (CRMs) [*Singh and O'Gorman*, 2013; *Seeley and Romps*, 2015; *Romps*, 2014]. This model configuration might thus be considered the *E. coli* of the tropics. Another class of important simpler models, which do not fit neatly into our idealized formalism but must be mentioned, are the Budyko-Sellers energy balance models [*Budyko*, 1969; *Sellers*, 1969]. These provided early insight into the sensitivity of Earth's climate to insolation and albedo, as reviewed by *North et al*. [1981].

Conversely, hierarchies can also tell us that things that are difficult to understand in the comprehensive system may remain so even in simplified systems. Climate sensitivity furnishes an excellent example of this, in that its famous uncertainties persist across a surprisingly large hierarchy of simulations. For example, recent work has shown that uncertainties in climate sensitivity are undiminished by disabling convective parameterizations [*Webb et al*., 2015] or running in aquaplanet mode [*Medeiros et al*., 2014]. Even more surprisingly, it is possible to generate a factor of two uncertainty in climate sensitivity in highly idealized, doubly periodic, RCE runs with parameterized convection, simply by varying the domain size [*Silvers et al*., 2016]. While the connections between climate sensitivity in these different configurations need elucidation, these results nonetheless suggest that there may be simpler versions of the climate sensitivity problem which we do not know how to solve, and which perhaps deserve further study.

3.2. Hypothesis Testing

In addition to providing simplified systems which are easier to study, model hierarchies also provide a framework for hypothesis testing. One class of such tests are "mechanism-denial" experiments, in which a mechanism that is hypothesized to be *necessary* for a particular phenomenon is disabled by descending down the hierarchy.

One example is given by the surface albedo feedback mechanism for polar amplification. The necessity of this mechanism can be straightforwardly tested by descending down the "surface" hierarchy of equation (1) from an ocean with land and ice to an aquaplanet. The latter turns out to still exhibit arctic amplification [*Alexeev*, 2003], suggesting that this mechanism is not necessary. Another example is given by the hypothesis that variability in the Atlantic Meridional Overturning Circulation (AMOC) drives the Atlantic Multi-decadal Oscillation (AMO) in North Atlantic SSTs. *Clement et al*. [2015] tested this claim by descending down the "ocean" hierarchy of equation (1) from a dynamical ocean to a slab ocean. The latter turns out to have an AMO similar to that of coupled models and observations, raising the possibility that the AMOC does not drive the AMO. (Note that controversy over this persists, however [see, e.g., *Zhang et al*., 2016; *O'Reilly et al*., 2016].)

Complementary to mechanism-denial experiments are what might be called "mechanism-affirmation" experiments, in which one confirms the *sufficiency* of a mechanism (for a given phenomenon) across model configurations of variable complexity. As an example, *Thompson and Barnes* [2014] showed that the spatiotemporal properties of the newly discovered Southern Hemisphere extratropical oscillation are remarkably similar, and in agreement with observations, across a hierarchy of GCMs, including a dry dynamical core, an idealized moist GCM, and a comprehensive GCM. Such robustness across configurations supports their hypothesis that the source of this oscillation is the two-way interaction between the baroclinicity and eddy heat flux in the lower troposphere. Another example is given by *Merlis* [2015], in which the weakening of tropical circulations by cloud masking of CO_2 forcing is demonstrated in a comprehensive GCM, an aquaplanet with prescribed clouds, and in a highly idealized one-layer model of (one branch of) the Hadley circulation.

When taken to its logical extreme, such mechanism affirmation results in highly idealized models or theories which apply to only a small number of climate variables (and hence a highly restricted range of phenomena), but which nonetheless emulate the behavior of those same variables in much more comprehensive models. Examples include the one-layer Hadley cell employed in *Merlis* [2015], the linear model of time-dependent climate sensitivity of *Rose and Rayborn* [2016], and the well-known "wet-get-wetter" paradigm [*Mitchell et al*., 1987; *Chou et al*., 2004; *Held and Soden*, 2006], among many others. The existence of such specialized, simple models, along with an affirmation of their mechanisms across the hierarchy, is probably what we *mean* by "understanding" for a complex system such as the climate.

3.3. Robustness to Model Physics

> *Hence, our truth is at the intersection of independent lies*.
>
> –Richard Levins

In addition to mechanism denial and affirmation, we can also use the hierarchy to check the robustness of modeling results to different formulations of uncertain physics. Though this is often done by comparing models within a single point of the hierarchy (e.g., a CMIP5 multi-model comparison of AOGCMs), it can also be done by moving across the hierarchy. An example of this is the significant warming of Snowball Earth climates by cloud radiative effect. This was demonstrated first with modern GCMs [*Abbot et al*., 2012], and then in a CRM [*Abbot*, 2014]. Such a move across the hierarchy, which trades in realistic geometry and boundary forcing for more realistic bulk forcing (equation (2) and Figure 1), shows a robustness of this effect to resolution and whether or not convection is parameterized.

Of course, even if a hypothesis appears to be robustly true within a single tier or even across the hierarchy, there is always the chance that *all* the models are missing something crucial, since they can never truly reproduce the Earth (see the gap between the model hierarchy and observations in the upper right of Figure 1). For instance, many GCMs lack interactive ozone chemistry, which likely impacts changes in the height of the tropopause [*Harrop and Hartmann*, 2012] as well as circulation changes [*Chiodo and Polvani*, 2016] with warming. Another caveat is that robustness of phenomena across models is no guarantee of correctness, as models may exhibit systematic biases. Examples of these in the Tropics include the well-known double-ITCZ and southeastern Pacific SST biases [e.g., *Zhang et al*., 2015], and in the midlatitudes include storm track location and orientation [*Zappa et al*., 2013; *Pithan et al*., 2016].

For such phenomena, truth may not reside at the intersection of independent lies. Indeed, confidence in model projections requires not just robustness across models, but also an argument that the models in question are "fit for purpose," and an understanding of the relevant physical mechanisms (often achieved via hierarchical thinking). The absence of any one of these elements can indeed render our vast maps useless; this underscores the need for understanding in simulation [*Held*, 2014; *Bony et al*., 2013], as well as the need for constant vigilance with regard to model assumptions and their appropriateness for a given application.

4. The Modeler's Conundrum

The previous section outlined some scientific uses (and attendant risks) of the climate model hierarchy. But, the model hierarchy can also be put to use in the service of model development. For instance, single-column models (SCMs) can isolate the behavior of GCM parameterizations without interference from large-scale feedbacks. In another direction, higher-resolution models such as large-eddy simulations (LES) and CRMs can be used to more explicitly simulate those processes which are only parameterized in GCMs. Such "process modeling" yields insights which may improve parameterizations, and can also be used to benchmark them. A good example of all these approaches is given by the CGILS campaign to study low-cloud feedbacks [*Zhang et al*., 2012]. This campaign performed inter-comparisons of both SCMs and LES [*Zhang et al*., 2013], and also found mechanistic insight through a detailed LES study [*Bretherton et al*., 2013].

Such efforts, however, do not always lead to the hoped-for improvements in parameterizations and hence GCM performance. The central difficulties are similar to those faced by Borges's cartographers and the denizens of Babel. In constructing models (and parameterizations especially), we only crudely represent reality. Yet, at the same time, we are constantly changing these representations and making them more ornate, so old ones become obsolete and their replacements ever more unwieldy and harder to understand. Furthermore, we are focused not on one map of the Empire but many, whose subtle differences make it hard to translate knowledge of one into knowledge of another.

This modeler's conundrum is exemplified in Figure 2, which shows Hovmoller plots of precipitation from GFDL's Atmospheric Model version 2 (AM2), run in a 2-D mock Walker configuration with nonuniform $T_s(x)$. By making slight changes to the column physics, a striking diversity of precipitation patterns is produced. Such behavior is fascinating but complicated, and could take years to untangle. Would such an investment be worth it? How relevant would the resulting knowledge be? There are several risks. For one, if the behavior in Figure 2 results from model pathologies, rather than mechanisms that operate in nature, then understanding Figure 2 tells us little about the real world. For another, even if studying Figure 2 only tells us something useful about models, if the relevant model pathologies are specific to AM2 and not other models, then our results may be of little interest to the broader modeling community. Finally, even if we only learn something useful about our model, there is the further possibility that model physics will change in the next round of model development, rendering our results obsolete and hence of limited interest even within our own modeling center. Such a change of model physics indeed happened with AM2, as its relaxed Arakawa-Shubert deep convection scheme [*Anderson et al*., 2004; *Moorthi and Suarez*, 1992] was changed to the Donner convection scheme for AM3 [*Donner et al*., 2011].

These risks discourage the study of phenomena like Figure 2. At the same time, however, there are also risks to not investing in such study. Models tend to only grow more comprehensive over time, and while this

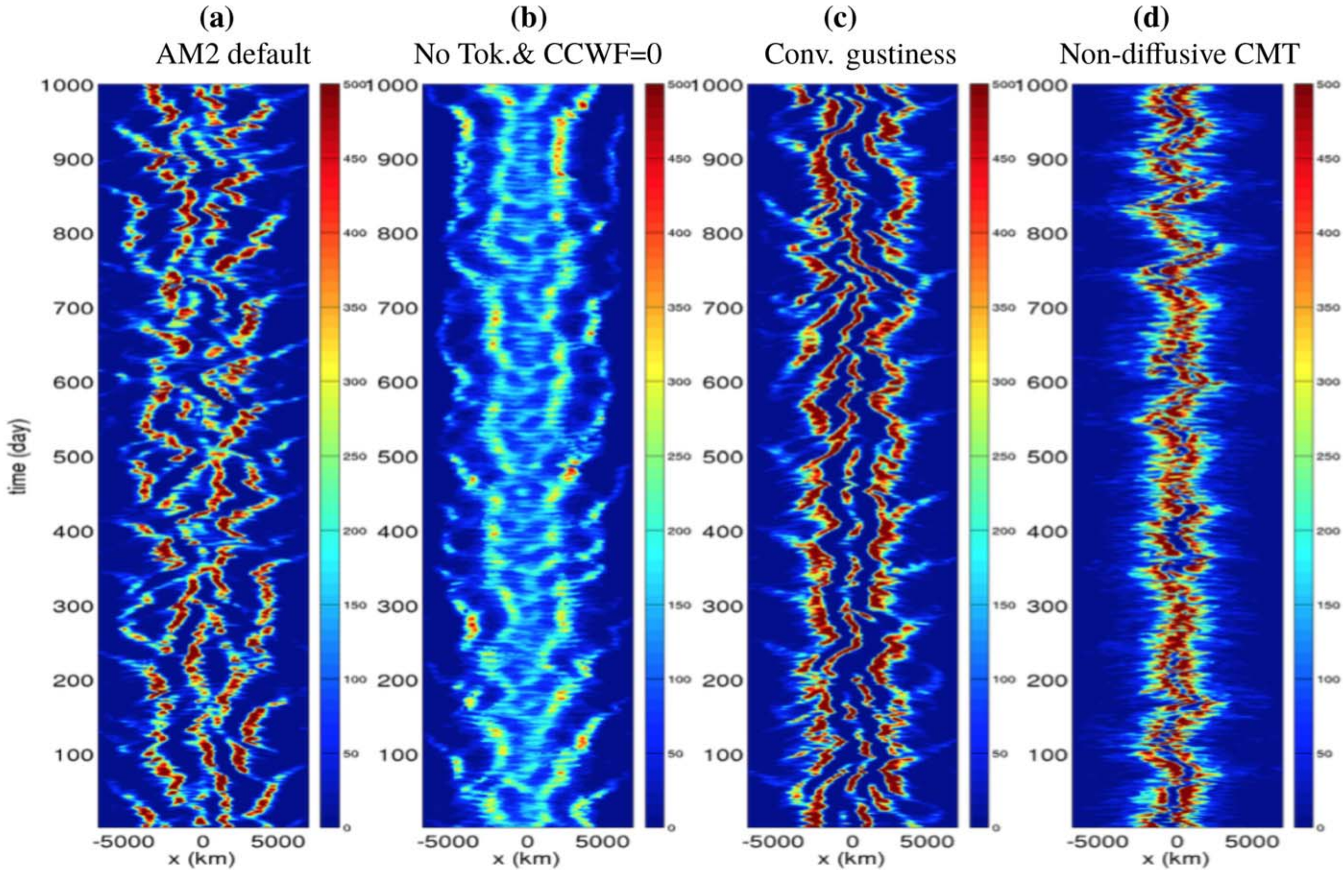

Figure 2. *The modeler's conundrum*. Hovmoller diagrams of precipitation (in energy units, W/m^2) from GFDL's AM2.1 [*Anderson et al*., 2004]. Simulations performed in a 2-D mock Walker cell configuration with non-uniform $T_s(x)$. A striking diversity of precipitation patterns is produced by varying only the column physics, as follows: (a) AM2 default, including a minimum entrainment rate for convective plumes (Tokioka parameter [*Tokioka et al*., 1988]), a critical cloud work function (similar to dilute CAPE) for plume activation, and vertical transport of horizontal momentum performed diffusively, with a contribution to the diffusivity from convective mass flux. (b) AM2 default, except no minimum entrainment rate and no critical cloud work function (CCWF). (c) AM2 default, but with enhanced surface fluxes when convection is active (i.e., a convective gustiness parameterization). (d) AM2 default, but with nondiffusive convective momentum transport performed within the relaxed Arakawa-Shubert convection scheme. Figure courtesy of Ming Zhao.

makes them more realistic, it can also pile additional layers of ill-understood complexity upon that already evident in Figure 2, compounding our difficulties [e.g., *Bony et al*., 2013].

5. Elegance, Then and Now

Make everything as simple as possible, but not simpler.

–Albert Einstein (paraphrase)

A remedy for some of these issues was articulated by H05, who stressed the need for a hierarchy of "elegant" models, each of which contains *no inessential complexity* relative to the problem at hand. Schematically, this can be accomplished by starting at the bottom of each axis in equation (1) and, for the processes of interest, selecting the first level at which those processes can be reasonably expected to emerge. H05 argued that elegance is necessary for progress in climate science, as inessential complexity obstructs understanding, hinders comparison with other studies of the same phenomena (the Babel effect), and discourages adoption by other researchers who disagree with the inessential elaboration.

Of course, by defining elegance in terms of "reasonable" expectations and "essential" complexity, we are introducing significant subjectivity. Who is to say whether a given configuration is elegant? This must be determined over time, as a given configuration is (or is not) widely adopted to study certain phenomenon.

Thus, elegant models by definition must appeal broadly and be worthy of study in their own right, despite their idealizations. As such they provide lasting value by furnishing common objects of study for researchers, whose collective efforts are often stymied by the modeler's conundrum described above.

By the above definition, then, a model's elegance is emergent. Beyond the QG configuration of *Philips* [1956], another configuration that seems to have emerged as elegant is the Held-Suarez configuration [*Held and Suarez*, 1994], which solves the full (rather than QG) primitive equations over a rotating sphere with no topography, ocean, or ice, and with idealized surface drag and radiative cooling. This configuration, which might be considered the *fruit fly* of climate models (https://www.gfdl.noaa.gov/blog_held/28-the-fruit-fly-of-climate-models), has been used (with some modifications) to study eddy-mean flow interactions [*Gerber and Vallis*, 2007], extratropical temperature profiles [*Schneider*, 2004], and stratospheric forcing of the tropospheric jet [*Polvani and Kushner*, 2002], among other topics.

The Held-Suarez configuration was extended to a moist aquaplanet by *Frierson et al*. [2006]. This configuration adds moisture and hence latent heat release, replaces the Newtonian radiation scheme with a two-stream gray approximation, Rayleigh surface drag with a diffusive boundary layer model, and adds a slab ocean. The Frierson GCM (also with some modifications) has been widely used to study a diverse array of topics, including midlatitude eddies and their associated energy transports [*Frierson et al*., 2006, 2007], the global hydrological cycle and precipitation extremes [*O'Gorman and Schneider*, 2008, 2009], monsoon transitions [*Bordoni and Schneider*, 2008], the ITCZ position [*Kang et al*., 2009], and the CO_2 direct effect on tropical circulations discussed above [*Merlis*, 2015], among others.

The Frierson GCM was introduced by H05 as an example of a potentially elegant model, and its widespread adoption by the community over the last decade seems to have realized this potential. Indeed, the Frierson and Held-Suarez configurations form two rungs of the elegant midlatitude hierarchy highlighted in Figure 1. But, H05 also pointed out the need for an elegant model configuration with more comprehensive bulk forcings, including interactive cloud radiative effects, to enable a focused study of cloud feedbacks. To date, however, no such model seems to exist (Figure 1, center). This forms one of our most conspicuous "gaps between simulation and understanding" (H05).

Why does this gap exist? One answer is that bridging the gap would require elegant parameterizations for convection, cloud microphysics, and cloud macrophysics (cloud fraction), each of which seems to lack canonical first-order approximations analogous to the diffusive boundary layer and gray radiation schemes employed in *Frierson et al*. [2006]. A focused effort on such approximations, perhaps building on earlier efforts such as *Molteni* [2003] (see also https://www.ictp.it/research/esp/models/speedy.aspx) will be needed to construct an elegant cloudy model, and thus more fully realize the vision of H05.

6. Outlook

The previous sections have discussed the utility (and pitfalls) of model hierarchies, as well as our progress to date in cultivating elegance. Where are we headed now in these regards?

Our utilization of the hierarchy appears to be growing. New rungs in the hierarchy continue to appear, such as global RCE with and without rotation (see Figure 1 and references therein), global CRM aquaplanets [*Bretherton and Khairoutdinov*, 2015; *Satoh et al*., 2016], dry RCE with and without rotation (Cronin 2017, model hierarchies workshop presentation), and slab ocean simulations with highly idealized land surfaces [*Voigt et al*., 2016]. A hierarchical approach is yielding insight into familiar phenomena such as tropical cyclones [e.g., *Reed et al*., 2015; *Wing et al*., 2016; *Merlis et al*., 2016], and is also being used to work through new ideas, such as the controversial relation between arctic amplification and high-impact, midlatitude "blocking" events [*Mori et al*., 2014; *Hassanzadeh and Kuang*, 2015; *Kennedy et al*., 2016].

Furthermore, there are a growing number of ways to span multiple configurations in the hierarchy within a single modeling framework. For instance, the widely used Community Earth System Model (CESM) now includes both dry dynamical core as well as aquaplanet configurations [*Medeiros et al*., 2016; *Neale and Hoskins*, 2000] (see also http://www.cesm.ucar.edu/models/simpler-models). Taking a more bottom-up approach, the Climate Modeling Toolkit [*Moeiro and Caballero*, 2016] is a nascent framework for combining various model components, such as those enumerated in equation (1), in a high-level, "plug-and-play" fashion, potentially allowing one to criss-cross the hierarchy of Figure 1 with relative ease (see also the Planetary Simulator PLASIM [*Fraedrich et al*., 2005] for an earlier, similar effort)

Such active use and development of model hierarchies evinces the vitality of our field, and allows us to more effectively and efficiently test hypotheses. But, is it necessarily in line with H05's recommendation to "reduce the number of idealized models we analyze"? Are we allowing models to proliferate while neglecting elegance? The answer is arguably "yes." We still lack an elegant moist GCM with interactive clouds, as well as a corresponding elegant tropical hierarchy (Figure 1). The tropical hierarchy has of course been populated, but mostly by models employing comprehensive cloud and convection schemes which are difficult to understand and whose intricate phenomenologies are difficult to relate to each other.

How might we ameliorate this? One step we could take now is to adopt a warm-rain, Kessler-type microphysics scheme [*Kessler*, 1969] as a potentially elegant parameterization for simulations where ice is inessential. Such a scheme may have only two condensed species, cloud condensate and rain, and only one parameter, namely the timescale over which cloud condensate converts to rain. Such a scheme is easily implemented, and its transparency facilitates an understanding of cloud fraction which is virtually impossible with comprehensive schemes [*Seeley et al*., 2017]. Wide adoption of such simple microphysics could also greatly ease comparison of idealized modeling studies in which cloud fraction and cloud radiative effects (CRE) are important, including studies of the MJO [*Arnold et al*., 2013], convective aggregation [*Wing et al*., 2017], and the double-ITCZ [*Harrop and Hartmann*, 2016].

Another step we could take now is to adopt mock Walker cell configurations, similar to that of Figure 2, as a standard case for model development and intercomparison. This case lays bare the uncertainties in the spatiotemporal structure of convection due to parameterization, but is much simpler than even a zonally symmetric aquaplanet, and would be less feedback-dominated than global RCE, due to the organization of the mock walker cell by the externally specified $T_s(x)$. Most importantly, and as emphasized by *Schneider et al*. [2017], computer power now makes it possible to also perform high-resolution cloud-resolving versions of these same simulations. If the nonconvective parameterizations are potentially elegant (e.g., Kessler microphysics and fixed radiative cooling), and are also consistent between the CRM and GCM, then the CRM should provide a straightforward benchmark for the GCM and its convective parameterization. Intercomparison between CRMs with the same set of elegant parameterizations should give a sense of how robust this benchmark is to CRM numerics.

Such an intercomparison could be a useful second-tier experiment in the upcoming "RCEMIP" borne out of the hierarchies workshop [*Satoh et al*., 2016]. Such idealized model intercomparison projects (MIPs) provide key opportunities to create new, elegant structures, much as the dynamical core intercomparison proposal of *Held and Suarez* [1994] gave birth to the Held-Suarez configuration. One could also imagine elegant configurations being generated through idealized MIPs focused more specifically on particular phenomena, such as polar amplification or double ITCZ biases.

Perhaps progress lies in such a redirection of our energies, away from inessential complexity and towards elegance. Our scientific understanding is necessarily hierarchical, but unless our hierarchies are elegant we will have difficulty understanding what our models are doing, or relating their results to each other. Elegant structures should also help with comprehensive model development, by helping us isolate complexity where we want it and eliminate it where we do not. Comprehensive model development must continue, of course, so that we may bridge the gap between our models and the real Earth, but a parallel effort in cultivating elegance also seems to be required, to keep Babel and Borges in the distance and so ensure that our model hierarchies provide the understanding that progress requires.

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