Model hierarchies for understanding atmospheric circulation

Penelope Maher [1], Edwin P. Gerber [2], Brian Medeiros [3], Timothy M. Merlis [4], Steven Sherwood [5], Aditi Sheshadri [6,7], Adam H. Sobel [6,8], Geoffrey K. Vallis [1], Aiko Voigt [8,9], Pablo Zurita-Gotor [10]

[1]Department of Mathematics, University of Exeter, UK.
[2]Courant Institute of Mathematical Sciences, New York University, USA.
[3]National Center for Atmospheric Research, USA.
[4]McGill University, Canada
[5]Climate Change Research Centre, University of New South Wales, Australia.
[6]Department of Applied Physics and Applied Mathematics, Columbia University, USA.
[7]Department of Earth System Science, Stanford University, USA.
[8]Lamont-Doherty Earth Observatory, Columbia University, USA
[9]Inst. of Meteorol. and Climate Res., Dept. Troposphere Res., Karlsruhe Inst. of Technology, Germany
[10]Universidad Complutense de Madrid, and Instituto de Geociencias, Spain

Key Points:

- Model hierarchies help address open research questions. We focus on how they have improved our understanding of atmospheric circulation.
- Key benchmark models are identified that have helped to advance our understanding of the atmospheric circulation.
- The model hierarchies are commonly referred to but remain poorly defined. We identify three principles to organize models into hierarchies.

Corresponding author: Penelope Maher, p.maher@exeter.ac.uk

Abstract

In this review, we highlight the complementary relationship between simple and complex models in addressing key scientific questions to describe Earth's atmospheric circulation. The systematic representation of models in steps, or hierarchies, connects our understanding from idealized systems to comprehensive models, and ultimately the observed atmosphere. We define three interconnected principles that can be used to characterize the model hierarchies of the atmosphere. We explore the rich diversity within the governing equations in *dynamical hierarchies*, the ability to isolate and understand atmospheric processes in *process hierarchies*, and the importance of choices in the physical domain and resolution in *hierarchies of scale*.

We center our discussion on the large scale circulation of the atmosphere and its interaction with clouds and convection, focusing on areas where simple models have had a significant impact. Our confidence in climate model projections of the future is embedded in our efforts to ground the climate predictions in fundamental physical understanding. This understanding is, in part, possible due to the hierarchies of idealized models that afford the simplicity required for understanding complex systems.

1 Introduction

In this review, we showcase idealized models which have enabled a deeper understanding of the large-scale circulation of the atmosphere and provide a set of principles for organizing them into hierarchies. We regard a *hierarchy* to be a sequence that connects our most simple models to our most complex, with the ultimate goal of explaining and predicting the behavior of Earth's atmosphere. The *simplicity*, or idealization, of a model is thus defined relative to other members of the hierarchy, where a simpler model seeks to reduce the problem to its most fundamental components at the cost of quantitative accuracy and realism.

We use simple models to ask fundamental science questions, which are ideally validated against observations of the real atmosphere. In practice, simple models are often validated against more complex models in the hierarchy. This is necessary when observations are sparse, such as in the upper stratosphere or Southern Hemisphere storm tracks, or not available, such as projecting future climates with different emission rates.

We are conscious of the subtle differences between a 'theory' and a 'model'. Here we consider a *model* to be a set of equations which seek to capture the behavior of the system in question, without necessarily regarding the model as representing the truth or having any general applicability. (A model is sometimes also taken to imply the *implementation* of an idea.) *Theory* may be regarded as the assumptions and, if needed, equations needed to economically describe or predict the behaviour of some phenomena or system. Still, the distinction is blurry, for a simple, testable model will have many of the attributes of a theory. Further, the behavior of a complex system may not be directly explainable by a simple theory in the conventional sense, and a model hierarchy itself then becomes a theory, or at least a hypothesis, for the system; some of these issues are discussed further in *Vallis* [2016]. In this review, we focus on models that may be deliberately simplified, and which implement a set of (usually time-dependent) equations in a more or less complex fashion, sometimes independently of any specific theory. Having differing degrees of complexity, connected to each other in some way, is the key step in sorting models into a hierarchy.

While the spectrum of available models has increased in the last decade or two, the idea of a 'hierarchy of climate models' in itself is not new. *Schneider and Dickinson* [1974] may have been the first to explicitly discuss the hierarchy in the sense we understand today, commenting that 'solid progress in understanding . . . climate change will require steady development of an almost continuous spectrum or hierarchy of models of increasing physical or mathematical complexity'. A decade later *Hoskins* [1983] noted the 'unhealthy' trend toward building models which are disconnected from one another and the real world, advocating, like Schneider and Dickinson, for a spectrum of connected models to provide a complete and balanced approach. *Nof* [2008] criticized the trend in climate modeling for higher resolution over increased understanding, and pointed out the danger of regarding comprehensive models as 'truth'. *Polvani et al.* [2017] noted that 'Earth system models may be good for simulating the climate system but may not be as valuable for understanding it'.

This gap between our understanding of the atmospheric circulation and the increasing complexity of global circulation models was the focus of *Held* [2005] and *Held* [2014]. In these essays, Held echoed earlier concerns about relying too much on comprehensive models that we do not fully understand. He argued, however, that we should be equally concerned that our simpler models are capable of addressing our key scientific questions. He called for more study of 'elegant' models that are sufficiently complex to capture key elements of the real atmosphere, but still simple enough to provide understanding.

There is certainly no single unique hierarchy. Instead, a suitable model hierarchy may be constructed based on the key scientific questions of interest, as not all models are suitable for all purposes. Even for a given scientific problem different scientists will make different, perhaps equally defensible, choices. Nevertheless, we can attempt to produce a classification system to describe models as being simple or complex within the spectrum of available models. *Bony et al.* [2013] intuitively describe the complexity of climate models, see Figure 1a, as a balance between simplicity of the model and complexity of the system that is being modelled. More recently, *Jeevanjee et al.* [2017] describe the climate model hierarchy, see Figure 1b, in terms of dynamics, boundary layer forcing, and bulk forcing. In section 2 we propose an alternative, but complementary, description based on organizing the model hierarchies in terms of three principles.

In this discussion of the large-scale circulation of the atmosphere, we focus our review on the science questions that have been addressed using key idealized models. We structure our review to start with the most simple models and build up toward the more complicated models used to investigate the large-scale circulation within the mid-latitudes, middle atmosphere and tropics, Sections 3, 4 and 5, respectively. We then discuss the important role moisture plays in setting the atmospheric circulation in Section 6 and how the hierarchies have helped improve the representation of, and theory for, the Madden-Julian Oscillation in Section 7. We then summarize in Section 8.

We do not attempt to review all models. Instead, we describe a subset of simple models, discuss their broad use and then make connections from the simple models through to the coupled atmosphere-ocean General Circulation Models (GCMs). (The role of GCMs are discussed more in *Ghil and Robertson* [2000].) We will not discuss Earth System Models, the very complex models that include more processes than typical GCMs (e.g., biogeochemistry), but we do acknowledge that Earth System Models form an end point (if only by definition) in modelling processes that affect Earth's climate and biogeochemistry.

2 Three principles guiding model hierarchies

There is no single or ubiquitous model hierarchy for the atmosphere. Many model hierarchies are possible, depending in part on the science questions to be addressed. Nevertheless, a broad classification of the hierarchies is useful and here we define three principles that can be used to guide the categorization of the model hierarchies.

The first principle is the *dynamical* hierarchies of the atmospheric fluid flow. The dynamical hierarchies allow us to isolate and explore the importance of different temporal and spatial scales on the governing equations.

The second principle is the *process* hierarchies of the atmosphere. The process hierarchies allow for the stepwise integration of important atmospheric processes into the governing equations of the fluid flow. We systematically advance terms with the thermodynamic equation to form a sequence of models that make a smaller 'diabatic hierarchy'. An additional aspect of the process hierarchies are the boundary conditions, such as surface properties such as aquaplanets, topography or orography.

The third principle is the *hierarchies of scale*, implicit to both the dynamical and process hierarchies, where the choice of physical domain and numerical resolution allows for the systematic exploration of different dynamical and physical processes across all time and spacial scales. There are practical trade offs between scale and complexity due to the computation expense. Perhaps unlike the first two, this is not so much a hierarchy of complexity, but it does describe the practical decisions about space and time scales which are required when building a model.

Almost all theory and modeling efforts can be classified into a hierarchy of some form, so attempting to catalogue *all* the hierarchies is not helpful. In the remainder of this paper, we selectively highlight examples of model hierarchies, specifically those that include simple models and that have advanced our understanding of the large scale circulation of the atmosphere. We focus on these models not because they necessarily optimally cover the complexity of available models, but rather because they have been extensively studied, thus establishing their impact. In the remainder of this review we incrementally build upon the different aspects of the process hierarchy, starting with the circulation within the mid-latitudes.

3 The Mid-Latitude Circulation

The large-scale extratropical circulation provides one of the best success stories for hierarchical climate modeling: some key aspects of the underlying dynamics are now reasonably well understood and part of modern textbooks [e.g. *Vallis*, 2017]. Other aspects are still areas of active research, such as the non-linear dynamics related to eddy-mean flow interaction. Idealized simulations have played an instrumental role in this progress, providing key insights on the non-linear behavior of extratropical disturbances. Since the early days of climate modeling, theorists recognized the great power of numerical computing as a means to overcome the stringent limitations of analytical work. Idealized simulations aimed at understanding the atmosphere were performed in parallel with comprehensive simulations. Some of the insight gained with these early simulations constitute the basis of prevalent paradigms on the extratropical circulation.

We begin by highlighting two models that have allowed us to isolate the key elements of the mid-latitude circulation. The first is a class of *barotropic vorticity equation models*, where collapsing the vertical dimension allow us to focus on feedbacks between the zonal mean flow, Rossby waves, and the spherical geometry of the planet. The second is the *two-layer quasi-geostrophic (QG) channel model*, which provides perhaps the most simple context for understanding baroclinic instability. We then discuss an idealized approach to combining elements of the baroclinic and barotropic dynamics together in eddy life cycle experiments.

3.1 Rossby-wave dynamics: The barotropic vorticity equations on the sphere

Rossby-wave propagation plays a fundamental role in both upper-troposphere synoptic variability and the remote atmospheric response to forcing. The barotropic model provides a simple framework for studying these processes. In addition to providing the first numerical weather simulations [*Charney et al.*, 1950], the barotropic model served as a test bed to understand the influence of topography and localized heating on the general circulation [*Grose and Hoskins*, 1979; *Hoskins and Karoly*, 1981]. These experiments revealed the important role played by the mean flow structure for Rossby wave refraction in the upper troposphere. The widely used concepts of waveguides and propagation windows are based on these ideas, which are key to our understanding of the extratropical response to El Niño.

So-called 'stirred' barotropic models [e.g., *Vallis et al.*, 2004] have seen a resurgence in recent years for understanding upper-troposphere synoptic variability and the dynamics of eddy momentum fluxes and eddy-driven jets without the complexity of baroclinic dynamics. In this model, the impact of baroclinic instability is approximated by a prescribed forcing (the stirring) in the vorticity equation at the synoptic scales. As a result, there are explicitly no feedbacks of the barotropic circulation on eddy generation. The model has been used as a conceptual model of annular mode variability to explain the dependence of zonal index persistence on latitude [*Barnes et al.*, 2010] and to study the interaction between the tropical and subtropical jets [*O'Rourke and Vallis*, 2013], among other problems.

As a further simplification, when the model is linearized it is possible to obtain a set of closed solutions (for simple forms of stirring) using stochastic theory [*DelSole*, 2001]. *Lorenz* [2014] has devised a very sophisticated method to calculate the eddy momentum flux given the full space-time characteristics of the stirring, which can play an important role due to the impact of wave phase speeds on refraction indices and wave propagation [*Barnes and Hartmann*, 2011]. The barotropic model can be a useful tool for exploring 'eddy-momentum-flux closures', i.e., the sensitivity of the direction of wave propagation to the mean state and/or model configuration. This remains a challenging open question in general circulation theory.

3.2 Baroclinic instability: The two-layer quasi-geostrophic model

To capture the essence of the eddy generation process, the *two-layer quasi-geostrophic model on the -plane* stands out as a benchmark, indeed classical, model of the extratropical baroclinic circulation [*Phillips*, 1956]. It vies with the Eady model [*Eady*, 1949] as the simplest model that can produce baroclinic instability in a fashion relevant to the real world. There is only one baroclinic mode and the stratification and radius of deformation are prescribed.

The model also provides a simplified framework for studying the nonlinear extratropical circulation in a forced-dissipative configuration, in which the flow is typically forced by thermal relaxation to a baroclinic jet and the lower layer wind is damped using Rayleigh friction [e.g. *Zurita-Gotor*, 2007]. The -plane approximation and constant deformation radius make upper-troposphere dynamics simpler than in the spherical case (the symmetry of the model makes northward and southward propagation equally likely). In this sense, the model is complementary to the barotropic model in that it is devoid of the barotropic feedbacks associated with sphericity that play an important role in the dynamics of that model. The two-layer model not only reproduces qualitatively the main features of the observed extratropical circulation but it also captures more subtle aspects of extratropical dynamics like the clustering of eddies in wavepackets [*Lee and Held*, 1993], the driving of low-frequency baroclinicity variability [*Zurita-Gotor et al.*, 2014] or the character of lower-troposphere eddy momentum fluxes [*Lutsko et al.*, 2017].

In its forced configuration, the two-layer model provides the lower end of a dynamical hierarchy of forced-dissipative dry models, in which the mean climate is determined by the competition between the eddy fluxes and very idealized forms of forcing. These models can be formulated at different levels of complexity along the dynamical hierarchy depending on the scientific problem of interest [e.g. *Zurita-Gotor and Vallis*, 2009; *Lachmy and Harnik*, 2014; *Jansen and Ferrari*, 2013].

At the high end of this dynamical hierarchy, the model of *Held and Suarez* [1994] has been widely used to study various aspects of the extratropical circulation and its sensitivity to climate change [e.g *Lorenz and DeWeaver*, 2007; *Butler et al.*, 2010; *Yuval and Kaspi*, 2016] due to its realistic circulation. This model uses a primitive-equation formulation and a spherical domain and is forced by relaxation towards a state approximating radiative convective equilibrium (described in Section 6.1), with near moist-neutral stratification in the vertical but strong meridional temperature gradients. Above the tropopause, the atmosphere is simply relaxed towards an isothermal state. A variant of this model better suited for the tropical circulation combines relaxation to pure radiative-equilibrium with an idealized convection scheme designed to mimic the stabilizing effect of latent heating by moist convection [*Schneider and Walker*, 2006].

3.3 Connecting eddy growth, propagation, and decay: The eddy life-cycle paradigm

Even in the very idealized physical setting described above, the time-dependent evolution of forced-dissipative models is inherently nonlinear and turbulent. As a key simplification to the full non-linear problem, the series of experiments systematized by Hoskins and collaborators in the 1970's, building on pioneering numerical work by *Edelmann* [1963] and others, provided insight on the nonlinear evolution of baroclinic modes. The analysis of an eddy lifecycle by *Simmons and Hoskins* [1978] introduced the notions of baroclinic growth and barotropic decay as an idealized conceptual model for the nonlinear evolution of extratropical disturbances. Similar ideas, but in the more general context of a statistical steady state and using quasi-geostrophic theory to interpret the simulations, were introduced independently by *Salmon* [1980]. This simple paradigm has survived to today and plays a fundamental role for our understanding of wave–mean-flow interaction and the maintenance of the mean circulation. Additional analysis [*Simmons and Hoskins*, 1980] uncovered the sensitivity of the decay stage in the lifecycle to the mean state, identifying two distinct patterns of evolution.

As theoretical advancements clarified the relation between eddy propagation and wave-mean flow interaction [*Andrews and McIntyre*, 1978; *Edmon et al.*, 1980] and the focus on Potential Vorticity (PV) dynamics highlighted the important role of wave breaking [*McIntyre and Palmer*, 1983], *Thorncroft et al.* [1993] proposed a conceptual model for understanding the two idealized lifecycles based on the direction of propagation and the typology of wave breaking. Idealized simulations were also useful for demonstrating the relevance of critical layer theory for eddy dissipation and wave-mean flow interaction in eddy lifecycles [*Feldstein and Held*, 1989]. The critical layer is a powerful concept for constraining upper-troposphere propagation [*Randel and Held*, 1991] and plays an important role for extratropical variability and climate sensitivity [*Lee et al.*, 2007; *Chen and Held*, 2007; *Ceppi et al.*, 2013].

The association between the direction of propagation, the topology of wave breaking and the sign of the eddy momentum flux uncovered by the idealized studies is central to our understanding of jet shifts and phenomena like the North Atlantic Oscillation [*Rivière and Orlanski*, 2007]. On the sphere, equatorward propagation and poleward momentum fluxes dominate [*Thorncroft et al.*, 1993; *Balasubramanian and Garner*, 1997] so that we might expect extratropical jets to shift poleward as they strengthen if the stirring does not move. However, idealized studies show that the direction of propagation is affected by many other factors, such as the latitude and scale of the eddies, the barotropic shear and the low-level baroclinicity [*Simmons and Hoskins*, 1980; *Hartmann and Zuercher*, 1998; *Rivière*, 2009], among others. Due to this complexity, we are still far from a complete theory for the eddy momentum flux closure.

3.4 Case Study: Eddy feedbacks and the variability of the jet stream

To illustrate the use of hierarchical modeling in the extratropics, we discuss its application to the analysis of eddy feedbacks in unforced jet variability. We have chosen this example because it lends itself well to the hierarchical approach and because it is a topic of current research.

The leading (and more persistent) mode of extratropical zonal wind variability consists of a meridional shift of the eddy-driven jet concomitant with annular mode variability [*Thompson and Wallace*, 2000]. *Lorenz and Hartmann* [2001] found a positive correlation between the jet anomalies and their eddy momentum driving in the Southern Hemisphere when the jet leads by a few days, see Figure 2a, which implies that the anomalous eddy momentum fluxes tend to extend the duration of the jet anomalies. They interpreted this positive correlation as depicting the sensitivity of the anomalous eddy momentum flux on the state of the jet, or a positive eddy feedback (but see *Byrne et al.* [2016] for an alternative interpretation).

Climate models are known to be too persistent [*Gerber et al.*, 2008], see Figure 2b, particularly idealized models [*Gerber and Vallis*, 2007]. This is mostly associated with too slow decay of the autocorrelation function at lags beyond 5 days, see Figure 2c, suggesting an excessive eddy feedback. Two different types of mechanisms have been proposed in the literature for this feedback: barotropic and baroclinic. Barotropic mechanisms rely on changes in upper-troposphere propagation due to changes in refraction in the presence of the anomalous jet, which may involve a number of different mechanisms [*Lorenz*, 2014; *Burrows et al.*, 2017]. In contrast, baroclinic mechanisms attribute the eddy momentum flux changes to changes in the stirring driven by the changes in the barotropic flow [*Robinson*, 2000].

Idealized models provide a useful framework for studying these two aspects of the problem in isolation. Using the stirred barotropic model, *Barnes et al.* [2010] investigated the sensitivity of the eddy momentum fluxes to the anomalous jet with fixed stirring. They showed that on the sphere, the eddy momentum flux becomes more asymmetric (equatorward propagation is enhanced) when the jet moves poleward, leading to a positive feedback. This may be understood in terms of changes in the turning latitude/reflecting level [*Lorenz*, 2014].

In the opposite direction, *Zurita-Gotor et al.* [2014] analyzed the dynamics of jet variability in idealized two-layer QG simulations and showed that the enhanced persistence in that model was consistent with the baroclinic feedback mechanism of *Robinson* [2000]. They found evidence of baroclinicity driving the barotropic flow and very large coherence between the eddy heat and momentum fluxes at low frequency, with the momentum fluxes leading the variability, see Fig 2e. The co-variability between the barotropic and baroclinic components of the wind is also a robust result in observations [*Blanco-Fuentes and Zurita-Gotor*, 2011] and comprehensive climate models. In Figure 2d the large correlation between the long-lag decay rates of (barotropic) jet anomalies and baroclinicity is shown for a selection of CMIP5 models, so that models with more persistent jet variability also tend to have more persistent baroclinicity.

Stirred barotropic models can capture some aspects of the observed jet variability, like the sensitivity of persistence to latitude [*Barnes et al.*, 2010]. On the other hand, the baroclinic mechanism may help explain the excessive persistence bias in comprehensive climate models (which cannot be corrected by eliminating the jet latitude bias; *Simpson et al.* [2013]) or in idealized baroclinic models. Finally, diabatic effects may also play a role for annular mode persistence [*Xia and Chang*, 2014]. The jet persistence problem underscores the importance of making connections across the full model hierarchy, as the mechanisms at work may not be the same in all steps of the hierarchy, in comprehensive climate models and in the real atmosphere.

4 The Middle Atmosphere Circulation

Work over the last two decades has established the highly coupled nature of the circulation in the troposphere and stratosphere. Many comprehensive atmospheric models now treat the stratosphere-troposphere as one system [e.g. *Gerber et al.*, 2012], recognizing the consequences of underresolving the middle atmosphere for weather and climate prediction [e.g., *Sigmond et al.*, 2013; *Manzini et al.*, 2014]. Historically, however, the middle atmospheric research proceeded on a different track after *Charney and Drazin* [1961] showed that a detailed representation of the stratosphere was not necessary to capture the basic structure of synoptic variability in the troposphere.

Wave-mean flow theory was developed, in part, to explain and understand the stratospheric circulation. The gross structure of the stratosphere can not be explained without understanding the essential role of waves in the transport of momentum, mass, and tracers. We highlight three models that capture these interactions, and the more sophisticated steps in the hierarchy they have inspired.

4.1 Sudden Stratospheric Warming Events: The *Holton and Mass* [1976] Model

Cooling during the polar night generates a strong westerly jet in the winter stratosphere, often referred to as the stratospheric polar vortex, where wind speeds can sometimes reach 100 ms^{-1}. In the early 1950s, however, it was observed that the polar vortex in the boreal hemisphere aperiodically undergoes a rapid breakdown. The reversal of the westerly winds is associated with a dramatic warming (40 K or more in the course of a few days) and hence known as a Sudden Stratospheric Warming (SSW) [*Scherhag*, 1952]. SSWs occur on average once every other year in the Northern Hemisphere, but only one such event (in 2002) has been observed in the austral hemisphere. *Baldwin and Dunkerton* [2001] showed that SSWs affect the troposphere, shifting the jet stream equatorward with substantial impacts on weather in Europe and Eastern North America. The tropospheric impact persists on the 1-2 month time scale that it takes the stratospheric vortex to recover back to its climatological state.

Matsuno [1971] proposed a dynamical mechanism for SSWs based on planetary scale wave propagation from the troposphere. Long before this process could be captured in atmospheric GCMs, *Holton and Mass* [1976] developed a simple, stratosphere-only, model that captures the essence of these abrupt events. They constructed a highly truncated baroclinic quasi-geostrophic model, retaining only wavenumber 1 and the mean flow. The mean state is forced by Newtonian relaxation toward a specified state of radiative equilibrium, the wave generated by specifying a forcing amplitude on the bottom boundary. The model exhibits an abrupt transition between subcritical and supercritical behavior depending on the amplitude of the wave forcing: in the subcritical state, westerly winds coexist with a stationary Rossby wave. If the wave amplitude at the lower boundary exceeds a critical threshold, however, the model transitions abruptly to a new equilibrium: the waves grows, weakening the westerlies until they reverse, i.e., a prototypical SSW.

Multiple flow equilibria have also been demonstrated in more complex 3-dimensional stratosphere-only models – again forced by specifying the amplitude of planetary waves at the lower boundary – but permitting arbitrary height and latitude structure above [e.g., *Scott and Haynes*, 2000; *Scott and Polvani*, 2006]. The highly idealized *Holton and Mass* [1976] model, however, has continued to inspire research on the role of gravity waves in SSWs [e.g., *Albers and Birner*, 2014], and the role of the stratosphere on regulating wave activity [e.g., *Sjoberg and Birner*, 2014].

These models suggest that the near absence of SSWs in the austral hemisphere is due to the fact that stationary wave amplitude is weaker, a process explored in full 3-D atmospheric models using a *Held and Suarez* [1994] forcing, albeit with a modified equilibrium temperature profile in the stratosphere to establish a polar vortex. *Taguchi et al.* [2001], *Taguchi and Yoden* [2002], and *Sheshadri et al.* [2015] show how one can transition from a Southern Hemispheric state to a Northern Hemispheric state by increasing the amplitude of surface topography. *Held and Suarez* [1994] type models have also allowed for exploration of the impact of the vortex strength on the troposphere, both in response to forced changes [*Polvani and Kushner*, 2002] or SSWs [*Gerber and Polvani*, 2009].

4.2 The Quasi-Biennial Oscillation: A physical model

While high latitude variability in the stratosphere is dominated by interactions between planetary scale waves and the mean flow, tropical variability is effected by wave-mean flow interactions involving much smaller-scale gravity waves. The Quasi-Biennial Oscillation (QBO) is an oscillation of the zonal mean wind in the tropical stratosphere with a period of approximately 28 months, associated with the slow downward migration of alternative westerly and easterly jets [see *Baldwin et al.*, 2001, for a comprehensive review]. The long time scales of the QBO make it a potential source of predictability in the troposphere. For example, it was recently observed that the QBO is associated with changes in the strength and predictability of the Madden-Julian Oscillation [e.g., *Yoo and Son*, 2016]. The QBO also provides another example of the advances that a simplified system can bring about, well ahead of our ability to simulate the phenomenon in comprehensive models.

Pioneering work by *Lindzen and Holton* [1968] and *Holton and Lindzen* [1972] proposed that the QBO could be explained as an interaction between gravity waves and the mean flow. Selective absorption (breaking) of waves carrying easterly (westerly) momentum on the lower flank of easterly (westerly) jets leads to a momentum tendency that pulls the jet downward, enough to oppose the tendency of the mean tropical upwelling to advect the jet upward. The balance between the two effects leads to the slow, 28 month period of the jets. These models came long before we had the ability to observe (or simulate) the small scale gravity waves implicated in the mechanism. Even today, gravity waves provide a challenge to observe and model [*Alexander et al.*, 2010].

Given the challenges associated with observing or directly simulating the processes involved in the mechanism, *Plumb and McEwan* [1978] developed a novel physical model of the phenomenon. Models of the atmosphere generally refer to numerical models, but *Plumb and McEwan* [1978] is a rare example of an experiment using a physical model. The *Plumb and McEwan* [1978] model consists of an annulus of stratified salt water and internal waves forced by mechanically oscillating the lower boundary. The waves generate spontaneous formation of jets (an azimuthal circulation in the annulus), with slow oscillations and reversal of the flow, similarly to the QBO of the atmosphere.

4.3 Stratospheric transport: The leaky pipe

Transport and chemistry play key roles in the distribution of trace gases throughout the stratosphere, including water vapor, ozone, and the substances that deplete ozone. The meridional overturning circulation of the stratosphere, known as the Brewer-Dobson Circulation, was first inferred from trace gas measurements, decades before we could observe the circulation directly [*Brewer*, 1949; *Dobson*, 1956]. Trace gases are advected by the mean Lagrangian circulation of mass and mixed along isentropic surfaces in the process of wave breaking. The latter mixing process produces no net transport of mass, but will transport a trace gas if there is a horizontal gradient in its concentration.

Efforts to understand stratospheric transport began with limiting cases in the balance between transport of tracers across isentropic surfaces by the mean overturning mass circulation vs. the mixing of tracers along isentropic surfaces. *Plumb and Ko* [1992] consider a circulation where mixing along isentropic surfaces is extremely efficient. In contrast, *Plumb* [1996] developed the idea of a 'tropical pipe', where upwelling air in the tropics is entirely isolated from the downwelling air in the higher latitudes and transport is set by the mean mass circulation alone. These two limiting cases were combined in a benchmark model in our understanding of transport processes, the 'leaky pipe' model of *Neu and Plumb* [1999].

The leaky pipe divides the stratosphere into two regions, an upwelling 'pipe' in the tropics, and a downwelling pipe in the extratropics of both hemispheres. Mass is advected up the tropical pipe by the Lagrangian mean circulation, detraining continually out to the extratropics. The boundary between the two regions, the edge of the stratospheric surf zone, is a barrier to transport, but the 'leaky' pipe allows for some mixing of mass between the two. The most important parameters are the net detrainment (or equivalently, the net Lagrangian transport) and total mixing as a function of height, and can be solved for analytically with appropriate simplifying assumptions. A key result of the model is that an increase in the net Lagrangian mass transport will tend to freshen the stratosphere, cycling tracers more quickly through it, while an increase in mixing tends to slow the cycling, as mixing leads to recirculation of air through the stratosphere.

While designed primarily as a conceptual model, the leaky pipe has been applied in a more realistic context to understand the make up of the stratosphere, and its response to anthropogenic forcing. *Garny et al.* [2014] use it to interpret changes in the stratospheric circulation in comprehensive models, separating the roles of mixing from the mean Brewer-Dobson Circulation. *Ray et al.* [2010] build on the leaky pipe to explain the distribution of trace gases, and *Linz et al.* [2016, 2017] use it to quantify the strength of the Brewer-Dobson Circulation from satellite measurements.

5 The Large Scale Circulation of the Tropics

Significant progress in understanding the large-scale circulation of the mid-latitudes and middle atmosphere was possible in the context of "dry dynamics". Removing the non-linearities associated with moist processes simplifies the problem, both conceptually and in terms of the numerical equations, processes, and scales that must be represented or parametrized. Indeed, all the simple models highlighted in Sections 3 and 4 do not include moist effects. In the tropics, the circulation and moist processes are more intimately coupled. A key scientific challenge for understanding tropical circulation has been: How do we deconvolve the tight coupling between circulation, moisture, clouds, and convection?

Nonetheless, there are still "dry" frameworks for understanding the gross features of the tropical circulation. In Section 5.1 we explore the Matsuno-Gill model, a model that captures the equatorial zonal overturning circulation, or Walker circulation, using the dry shallow water equations. In Section 5.2 we then focus on the zonal mean tropical overturning circulation, the Hadley circulation, again starting the discussion with a dry atmospheric model, but quickly introducing an idealized GCM that begins to capture moist processes.

5.1 The Walker Circulation: The Matsuno-Gill model

The Walker circulation describes equatorial atmospheric cells with ascent over the Maritime Continent (equatorial Western Pacific) and descent in the Eastern Pacific or Indian Oceans. The number of equatorial circulation cells and the location of ascending/descending branches are coupled with SSTs and the phase of ENSO [*Julian and Chervin*, 1978]. Research questions for the Walker cell include: How does convection and circulation interact within the Walker circulation? How does the Walker circulation and El-Niño Southern Oscillation influence the onset of the monsoon? How will the Walker circulation change with global warming?

Similarly to the mid-latitudes, many simple models for the tropical circulation hinge on reducing the dimensions of the atmospheric flow and a key simplification is to vertically truncate the fluid governing equations. One such model that has been fundamental for understanding the structure of the Walker circulation is the Matsuno–Gill model [*Matsuno*, 1966; *Gill*, 1980], that uses the dry shallow water equations on an equatorial-beta plane with a stationary heating source [e.g. *Vallis*, 2017, section 8.5]. This single-layer model provides an analytic solution for the horizontal structure associated with the first baroclinic mode. This vertical mode captures the circulation driven by heating associated with tropical deep convection, and is characterized by opposite signed flow in the upper vs. lower troposphere. As the troposphere does not have a rigid upper boundary, it is not a true "mode" as in the ocean, but it often behaves like one.

The model's solution is generally described as the Matsuno–Gill pattern, in which two steady-state circulation cells develop in response to the applied heating, with low-level convergence into and upper-level divergence out of the heating region. This generates eastward propagating Kelvin waves and westward propagating Rossby waves. Two off-equatorial low pressure systems form as Rossby waves can not propagate along the equator [see Figure 8.11 of *Vallis*, 2017]. This equatorially-symmetric component of the Matsuno-Gill model generally describes the observed structure of the Walker circulation, with analogous tropical convection in the West Pacific and descent over the cold SST in the East Pacific (due to deep water upwelling).

The Matsuno–Gill model has also been used as the atmospheric component of the first successful numerical ENSO prediction model, the Cane-Zebiak model [*Cane et al.*, 1986]. a very influential reduced complexity coupled atmosphere-ocean model. In addition, the Matsuno-Gill model captures monsoonal circulations, using off-equatorial heating to mimic the seasonal cycle. *Gill* [1980] showed that the anti-symmetric Matsuno-Gill pattern (see Figure 3 of *Gill* [1980]), describes the general structure of the monsoon flow [*Rodwell and Hoskins*, 1996]. Furthermore, the Matsuno–Gill model is important for understanding the propagation of the Madden-Julian Oscillation, as detailed in Section 7.

While some aspects of the Walker circulation are captured by the Matsuno–Gill model, there are still many limitations. The primary limitation of the Matsuno-Gill model is that it does not interactively include moisture and, as a result, many important moist feedback mechanisms are absent. One approach to studying the moist Walker circulation is to impose a large-scale gradient of SST in a two-dimensional atmospheric model domain, creating a steady-state Walker circulation, commonly called the "mock" Walker circulation.

Bretherton et al. [2006] studied the moist Walker circulation using an idealized non-rotating 2D model, that is vertically truncated (one vertical moisture mode) following the approach of the quasi-equilibrium tropical circulation model [*Neelin and Zeng*, 2000], which assumes the weak temperature gradient (discussed more in Section 6.1), and has simple precipitation and cloud schemes; see their Figure 4 for the resulting circulation. This is a useful prototype model configuration because it allows explicit cloud resolving model (CRM) and GCM-physics comparisons of a climate relevant problem [*Jeevanjee et al.*, 2017]. The beauty of this idealized model is that it includes feedbacks between convection and the large-scale circulation. In comparing to 3D CRMs, *Bretherton et al.* [2006] showed many interesting features within the two models: similar precipitation but different humidity distributions, narrowing of the circulation with warming SSTs and the importance of moist static energy in understanding feedbacks between convection and the large-scale circulation within the Walker circulation.

5.2 The Hadley Circulation: Gray Radiation Aquaplanets

The Hadley circulation describes the zonally averaged atmospheric circulation cell with net ascent near the equator, poleward outflow in the upper troposphere, descent in the subtropics, and an equatorward near-surface return flow. The Hadley circulation separates the moist tropical regions from the dry subtropical climate zones and as such is important for setting the surface climate. Key research questions for the Hadley cell include: What controls its strength? What controls the position of the descending branch (i.e., the tropical edge) and the near-equatorial ascending region? How will these components change with global warming?

Dry models of the atmosphere have been illuminating in studying some of these research questions. The dry models used to investigate the dynamics of the Hadley cell range from axisymmetric models amenable to theoretical progress [*Held and Hou*, 1980; *Lindzen and Hou*, 1988] through to idealized dry GCMs with extratropical eddies that interact with the tropical circulation [*Kim and Lee*, 2001; *Walker and Schneider*, 2006]. The behavior across this dry model hierarchy has revealed two important insights. First, that the Hadley circulation has a finite extent—unlike the Brewer-Dobson circulation in the stratosphere the Hadley cell sinks before reaching the pole—even in the absence of extratropical eddies [*Held and Hou*, 1980]. Second, eddies are important for setting the circulation strength and extent [*Held*, 2000]. Dry models have set the foundations for our understanding of the Hadley cell, but moist processes are critical for determining the width of the ascending branch of the Hadley cell the circulation's net energy transport.

A next logical step in the hierarchy of models to study the Hadley circulation is to include moist effects. One such model is the idealized moist primitive equation of *Frierson* [2007]. This model has a "gray radiation" scheme that neglects cloud and water vapor feedbacks, so that dynamic moisture feedbacks are decoupled from radiative feedbacks. The model uses an idealized large-scale precipitation scheme (condensation upon saturation) and a simple convection scheme that relaxes the atmosphere towards a stable vertical profile. The Hadley cell is very sensitive to the representation of convection. For example, the convection scheme impacts the energetic stratification. The moist static energy difference between the upper- and lower-level Hadley circulation in turn plays a key role in the strength of the mass overturning [*Frierson*, 2007].

The idealized model of *Frierson* [2007] can be linked to higher levels of the hierarchy by including more processes. The monsoons and ITCZ, among others problems, can be studied with greater realism by including the seasonal cycle. A second addition is to include the spatial variability in the radiative forcing, and feedbacks, for a more realistic atmospheric energy transport with climate change [*Feldl et al.*, 2017; *Merlis*, 2015]. A third addition is an idealized ocean heat transport coupled to the surface wind stress of the Hadley cell [*Held*, 2001; *Levine and Schneider*, 2011; *Codron*, 2012] that begins to bridge the gap between full-ocean GCMs and slab-ocean boundary conditions. A further extension is to couple the atmosphere and ocean for more realistic ocean heat uptake and transport that results in more realistic atmospheric energy transport by the Hadley circulation [*Zelinka and Hartmann*, 2010; *Feldl and Bordoni*, 2016]. Finally, radiative feedbacks can be introduced to the model by replacing the gray radiation scheme with a more realistic representation or radiative transfer [e.g. *Merlis et al.*, 2013; *Jucker and Gerber*, 2017; *Vallis et al.*, 2018].

In addition to understanding the fundamental properties of the Hadley circulation, models such as *Frierson* [2007] are a valuable step in the model hierarchy to investigate how changes in atmospheric water vapor with global warming impact the Hadley circulation. A key science question is: how will the tropical edge change in response to warming? The idealized moist physics GCM has been used to test and extend theories that were originally developed for dry flows [*Held*, 2000] to those that include moisture [*O'Gorman*, 2011; *Levine and Schneider*, 2015]. Furthermore, models such as *Frierson* [2007] have been important for understanding the forced response of the ITCZ, which is formed as a result of converging air toward the equator within the Hadley cell [*Kang et al.*, 2009; *Byrne et al.*, 2018].

In addition, simplified moist GCMs have been useful to unravel the controls on monsoonal circulations with the aim to identify the minimal ingredients needed to develop the cross equatorial tropical overturning circulations that resemble monsoon flow over South Asia. Interestingly, idealized GCMs can capture aspects of the monsoon without zonally asymmetric land distributions or elevated orography [*Bordoni and Schneider*, 2008]. When idealized orography is included, an important "ventilation" mechanism is revealed: the poleward progression of the monsoon is prevented by mid-latitude dry air that is blocked by the elevated topography. This mechanism has been found in reduced vertical structure models, idealized GCMs, and comprehensive GCMs [*Chou et al.*, 2001; *Privé and Plumb*, 2007; *Boos and Kuang*, 2010]. Furthermore, the role of stationary eddies on the monsoons has been addressed in simulations with idealized lower boundary conditions [*Shaw*, 2014; *Geen et al.*, 2018] to assess seasonal circulation transitions in zonally asymmetric GCM configurations.

6 Coupling Clouds and Convection to the Large-scale Circulation

A key simplification of the idealized moist models discussed in Section 5.2 is to leave out the impact of clouds microphysics on the circulation. Clouds, visible manifestations of atmospheric convection, play a vital role in the radiative budget, both locally within a single convective system, and globally: clouds are a key uncertainty in predicting the global temperature response to greenhouse gas forcing (see Section 6.3). Individual convective clouds can be isolated and appear as random noise in an otherwise homogeneous environment, such as patchy, fair weather cumulus, but can also interact with nearby convection and the environment to form mesoscale convective systems such as squall lines. Organized convection impacts the radiation budget by changing the distribution of cloudy and clear sky. This is important as the radiative properties of clouds shape the large-scale circulation of the atmosphere [*Hunt et al.*, 1980; *Slingo and Slingo*, 1988; *Randall et al.*, 1989].

Clouds and convection are also embedded within the large-scale circulation of the atmosphere. The ascending branches of the circulation cells create the lifting force required for deep convection to develop within the ITCZ and the descending branches create suppressed regions in which clear sky or low-level clouds dominate. This two way interaction is referred to as cloud-circulation coupling. Understanding cloud-circulation coupling, and representing it in models, is one of the World Climate Research Program's "Grand Challenges" on clouds, circulation and climate sensitivity [*Bony et al.*, 2015].

In Section 6.1 we focus our discussion on Radiative Convective Equilibrium (RCE), a conceptual model of the tropical atmosphere that has helped us better understand the organization of convection. In Section 6.2 we discuss a "cloud locking" approach that decouples cloud radiative effects from the circulation, forming a bridge from the idealized moist GCMs to full atmospheric models. In Section 6.3 we describe how the more complex models within the hierarchy are used to study Earth's climate sensitivity.

6.1 Convective Organization: Radiative-Convective Equilibrium

In Section 5.2 we painted a picture of broad ascent within the equatorial branch of the Hadley circulation, associated with latent heating. This view of tropical precipitation is a reasonable approximation on longer time scales (weeks or more). On shorter time scale (hours-days), however, the tropical atmosphere is highly variable, with both ascent and descent in most regions. Convection on these shorter time scales is organized on small spatial scales, as within a single convective system, and on large scales, as with the Inter-tropical Convergence Zone (ITCZ) and MJO.

Convective organization is not well represented in most atmospheric models [*Del Genio*, 2012]. This deficiency has been partly attributed to convective parametrizations that have a number of shortcomings. For example, convection is parametrized in the vertical column without any horizontal interactions, models have limited memory of convection from one time step to the next, and parametrizations generally do not represent interactions with the (unresolved) mesoscale circulation [*Mapes and Neale*, 2011]. A number of persistent model biases have been linked to errors in representing convection [*Randall et al.*, 2016]. For example, models (i) exhibit too much light rain, which results in insufficient extreme rainfall, (ii) trigger convection too early, resulting in the wrong diurnal cycle, and (iii) often generate a double ITCZ in the central and eastern Pacific [*Stephens et al.*, 2010; *Dai*, 2006; *Sun et al.*, 2006; *Oueslati and Bellon*, 2015].

The need to improve comprehensive atmospheric models motivates the use of a hierarchy of models to understand, and (ultimately) address long-standing model biases. Models can also be used to improve our theoretical understanding of convection and identify how convection interacts with both the local environment and larger scales [e.g., *Muller and Bony*, 2015].

Radiative-convective equilibrium (RCE) describes a state in which atmospheric radiative cooling is balanced by convective heating in a domain with no externally imposed horizontal structure, e.g., uniform SST and insolation. RCE was first considered in the 1960s by *Manabe and Strickler* [1964], who originally proposed it to explain the vertical structure of the atmosphere. Since then, it has evolved into a test-bed for understanding convection in the absence of large-scale circulation. RCE is an important component of a hierarchical approach connecting physical laws to the complex behaviour of the Earth system [*Popke et al.*, 2013]. High-resolution models in RCE are a useful starting point for theories of convective organization [*Muller and Bony*, 2015].

Using a non-rotating cloud resolving model (CRM) in RCE, *Bretherton et al.* [2005] showed that convection can spontaneously self-organize (see Figure 3), a process sometimes known as "self-aggregation". The integration is initialized from a uniform state, and in the first weeks of integration, seemingly random convection is observed homogeneously across the domain. After approximately 50 days, however, the system transitions to a single convecting cluster. Self-aggregation is not solely a spatial reorganization of convection; it dramatically changes the mean climate in CRMs resulting in a dryer troposphere, more outgoing long wave radiation (OLR), warmer free troposphere and surface. Please see *Wing et al.* [2017a] for more details and a full list of references, *Mapes* [2016] for a broader perspective and *Holloway* [2017] for a comparison to observations.

Convection also organizes in RCE simulations using GCMs with parametrized convection, in which large convective clusters form spontaneously [*Popke et al.*, 2013; *Reed and Chavas*, 2015; *Coppin and Bony*, 2015; *Becker et al.*, 2017]. Once convection begins to organize, a large-scale circulation develops and helps maintain the convection. In GCMs with prescribed SST, in RCE and non-RCE simulations, convection is more clustered in simulations without parametrized convection, compared to those with active convection parametrizations, and have larger rain rates [*Becker et al.*, 2017; *Maher et al.*, 2018].

When planetary rotation is included in RCE simulations, self-aggregation transforms into tropical cyclones. Aquaplanet simulations in RCE have been particularly useful for understanding tropical cyclone characteristics [*Shi and Bretherton*, 2014; *Satoh et al.*, 2016; *Reed and Chavas*, 2015] and their response to increasing SSTs [*Held and Zhao*, 2008; *Khairoutdinov and Emanuel*, 2013; *Merlis et al.*, 2016]. *Satoh et al.* [2016] used a hierarchy of configurations with a global model to show the multiscale nature of tropical convective systems and how the effects of rotation change the vertical structure of the systems, see Figure 3.

The multiscale structure is also apparent in CRM simulations of RCE. The emergent structures remain similar across domain sizes, but the response to perturbations (like imposed surface warming) can vary depending on the domain size [*Silvers et al.*, 2016]. Similar experiments with global models are computationally expensive, but one alternative is to test the convergence characteristics of a model's physics by reducing the planetary radius to mimic increased horizontal resolution; *Reed and Medeiros* [2016] use this strategy to show how the large-scale convective aggregation seen in GCMs transitions to CRM-like self-aggregation without the increased computational cost.

Convective organization more generally is not well understood [*Muller and Bony*, 2015]. For example it is not clear how important self-aggregation is compared to organization by the mean wind or by waves or other mesoscale disturbances. There are a number of factors that contribute to organization such as cloud-radiative feedbacks, SST and convective-moisture feedbacks, see *Sessions et al.* [2016] for a full list. The model hierarchies has provided insight into why convection organizes and how it is maintained. In this section we have focused on RCE and while it is an idealized model, it is still very complicated.

A further useful idealization, complementary to RCE, is the Weak Temperature Gradient (WTG) approximation. Under WTG the large-scale circulation, specifically the vertical velocity, is parametrized [*Sobel and Bretherton*, 2000; *Sobel et al.*, 2001; *Raymond and Zeng*, 2005]. This is done by assuming that horizontal temperature gradients and the local time tendency of temperature are both negligible at synoptic scales in the tropics – an observational fact explained dynamically by *Charney* [1963] – thus reducing the otherwise prognostic temperature equation to a diagnostic equation that can be solved for the large-scale vertical velocity given the diabatic heating. WTG is a horizontal truncation, as opposed to the vertical truncation in the Matsuno-Gill model described in Section 5.1.

WTG has been used to study a range of phenomena, including the Walker and Hadley circulations [*Bretherton and Sobel*, 2002; *Polvani and Sobel*, 2002; *Burns et al.*, 2006; *Bellon and Sobel*, 2010; *Kuang*, 2012]; ENSO teleconnections [*Chiang and Sobel*, 2002]; tropical cyclogenesis [*Raymond*, 2007] and the MJO [*Wang et al.*, 2013, 2016]. Other related parametrizations of large-scale dynamics, solving the same problem in different ways, have also been developed [*Kuang*, 2008; *Romps*, 2012; *Herman and Raymond*, 2014], and WTG and one other, the 'damped wave' method [*Blossey et al.*, 2009] applied to a wide range of models in a recent intercomparison [*Daleu et al.*, 2015, 2016]. These parametrizations of large-scale dynamics represent the circulation on scales smaller than the global scale at which RCE is relevant – the domain-average vertical motion being parametrized must vanish in RCE by definition – and the domain of a WTG single-column or cloud-resolving simulation can be thought of as representing a small fraction of an RCE simulation's domain.

In such WTG simulations, more than one statistical equilibrium state can occur, depending on the initial humidity, with either dry or persistent deep convection states developing from identical forcing conditions [*Sobel et al.*, 2007; *Sessions et al.*, 2010] depending on initial conditions. These so-called 'multiple equilibria' are analogous to self-aggregation in RCE simulations in which a convecting cluster is surrounded by dry subsiding air [*Sessions et al.*, 2016], with the different WTG equilibria representing the convecting and dry regions separately. RCE and WTG together thus form a hierarchy of their own, providing distinct but qualitatively consistent views of the self-aggregation phenomenon.

Representing convective organization in Earth system models remains problematic. Progress is being made through a variety of modelling approaches to develop theories of convective organization and to better represent organization in GCM. These approaches cover broad resolutions with high resolutions LES and CRM, and GCMs with different treatments of convection. The convection approaches include: resolved convection in global CRMs [*Tomita et al.*, 2005; *Miyamoto et al.*, 2013; *Bretherton and Khairoutdinov*, 2015; *Judt*, 2018], with and with parametrized convection [*Popke et al.*, 2013; *Maher et al.*, 2018], and super-parametrization [*Arnold and Randall*, 2015].

6.2 Decoupling clouds and circulation: Cloud locking

A primary challenge in representing clouds and convection in climate models is to adequately describe the interactions between clouds, convection, and precipitation, which must be parameterized in global models, with radiation and the resolved circulation. One opportunity to explore the role of clouds in the climate system is to adapt the diabatic hierarchy to decouple cloud-radiative effects from the circulation in which they are embedded. A few different approaches have been developed to achieve this: (i) a dry GCM forced with atmospheric cloud-radiative effects simulated from GCMs [*Voigt and Shaw*, 2016], (ii) reduced-complexity physics (e.g., Frierson-like without clouds [*Kang et al.*, 2009]), (iii) clouds that are transparent to radiation [*Stevens et al.*, 2012], and (iv) prescribing the cloud fields (cloud locking) [*Zhang et al.*, 2010].

The cloud-locking model approach has proven particularly helpful to understand how changes in the radiative properties of clouds impact the circulation response to global warming or hemispheric energy perturbations. Cloud-locking removes the coupling between clouds and circulation by prescribing the cloud properties seen by the model's radiation scheme, generally from an earlier model simulation, and this isolates the circulation response to a perturbation as the clouds are invariant [*Zhang et al.*, 2010]. All four modelling approaches listed in the previous paragraph have been used to understand how changes in clouds with increased greenhouse gases will impact the position of the eddy-driven jet [*Voigt and Shaw*, 2015, 2016; *Ceppi and Hartmann*, 2016; *Ceppi and Shepherd*, 2017].

The eddy-driven jet (discussed in Section 3.4) is an interesting example, as its equatorward bias in coupled GCMs [*Kidston and Gerber*, 2010] is associated with Southern Ocean clouds that reflect too little shortwave radiation [*Ceppi et al.*, 2012]. Coupled GCMs show diverse responses in the eddy driven jet to global warming, especially in the Southern Hemisphere see Figure 4 a. These broad differences persist in aquaplanet simulations (Figure 4 b), making aquaplanets a desirable configuration to understand the eddy-driven jet response.

Cloud-radiative changes lead to a poleward shift in the eddy driven jet in cloud-locking simulations for the MPI-ESM aquaplanet model (Figure 4 c). The cloud-radiative changes with global warming can be attributed to high-level tropical (orange line) and mid-latitude clouds (blue line). Interestingly, the cloud impact is as large as the differences in jet shifts found in coupled GCMs, which suggests that clouds contribute to uncertainty in future jet shifts. The cloud impact is also reproduced in the dry Held-Suarez simulations perturbed with radiative changes from the cloud-locking simulations (Figure 4 d).

A complementary modelling technique to cloud-locking is the transparent-cloud approach, that prevents the radiation scheme from 'seeing' the clouds and hence sets the radiative heating to cloud free conditions [*Randall et al.*, 1989; *Merlis*, 2015]. This is easier to implement than cloud-locking and is simply achieved by setting the cloud fraction to zero in the radiation scheme. The transparent-cloud approach has helped to demonstrate the importance of cloud radiative effects for the present-day circulation. Such simulations have highlighted that cloud radiative effects strengthen the Hadley cell and eddy driven jet stream, reduce tropical-mean precipitation, and narrow the ITCZ [*Li et al.*, 2015; *Harrop and Hartmann*, 2016; *Popp and Silvers*, 2017; *Albern et al.*, 2018].

The primary task for understanding the role clouds play in the climate system is to understand their coupling with the circulation, and the implications of that coupling for the circulation response to climate change. In this regard, the transparent-cloud approach has proven helpful for understanding the role of clouds in the present-day climate, and the cloud-locking approach for understanding changes in clouds and circulation with global warming. While recent work has clearly shown that a quantitative understanding of the circulation must consider the coupling to clouds, this remains a rather young area of research with many open research questions, including for example cloud impacts on internal variability of the extratropical circulation [*Li et al.*, 2014].

6.3 The role of circulation in Earth's equilibrium climate sensitivity

How sensitive is the climate system to greenhouse gas emissions? Clouds are at the heart of this question because they remain the largest source of uncertainty in projections of future climate change. Despite the broad improvements in climate models, early estimates of the equilibrium climate sensitivity – a measure of globally averaged surface temperature change to doubling CO_2 – have not changed since the Charney report in 1979 with a range of 1.5–4.5 K [*Stevens et al.*, 2016].

The representation of clouds in different climate models is diverse. This results in widely varying cloud responses to the same perturbation [*Boucher et al.*, 2013; *Chung and Soden*, 2018]. Climate models show a relatively robust positive longwave (infrared/greenhouse) cloud feedback [*Zelinka and Hartmann*, 2010], attributed to the fixed anvil temperature hypothesis [*Hartmann et al.*, 2001; *Hartmann and Larson*, 2002]. The shortwave (visible/albedo) cloud feedbacks, however, remains highly uncertain despite the fact that most coupled GCMs suggest a weak positive feedback [*Ceppi et al.*, 2017]. Answering the open research questions about climate sensitivity comes down to understanding shortwave feedbacks for low-level clouds which account for much of the model uncertainty in cloud feedbacks. These low-level clouds form below regions of radiative cooling in the descending branches of the Hadley and Walker circulations [*Bony and Emanuel*, 2005]. As such, circulation is key in setting their distribution, but cloud effects also feed back on the circulation, adding complexity to the problem.

Single column models (SCMs) have been used to investigate how parametrized physics can respond to climate sensitivity [*Dal Gesso et al.*, 2015]. Using SCMs with several configurations, *Zhang et al.* [2013] showed in idealized climate change experiments that the shallow convection and boundary layer turbulence are key differences among models. Care must be taken to meaningfully comparing an SCM to a GCM, however, because of the disconnection of cloud-circulation coupling in SCMs. In addition, physics packages can exhibit different cloud responses in a GCM and SCMs, creating obstacles for understanding cloud feedback. Progress has been made to understand cloud feedbacks in the gap between SCMs and GCMs, such as using WTG to parametrize a circulation in SCMs [*Raymond*, 2007; *Zhu and Sobel*, 2012] and GCMs in RCE to simplify the circulation [*Bony et al.*, 2016; *Popke et al.*, 2013; *Wing et al.*, 2017b] – in a conceptually similar way to *Manabe and Strickler* [1964] who used SCMs.

To capture the impact of circulation on climate sensitivity, efforts have focused at the top of the model hierarchy: coupled atmosphere-ocean GCMs (AOGCM) [*Otto et al.*, 2013; *Stevens et al.*, 2016; *Caldwell et al.*, 2016]. This is because simpler models make severe assumptions about the system, removing non-linear behavior that may project on to climate sensitivity [*Knutti and Rugenstein*, 2015]. From the perspective of the model hierarchy, AOGCMs are a moving target that evolves in response to both improvements in our understanding of the climate system, and to increasing computational resources.

The complexity of modern climate models, however, make it challenging to interpret their results, including the relative role of cloud feedbacks in climate change. The challenges in understanding climate sensitivity in AOGCM makes a hierarchical approach appealing. The goal then becomes understanding the response of state-of-the-art AOGCMs in a simpler setting to reveal the underlying mechanisms and improve our physical understanding of the system. For example, using a range of boundary conditions and model configurations (ESM, GCM, aquaplanet, SCM) with the same model parametrizations, *Brient and Bony* [2013] identified a positive feedback that depends on how moist static energy is transported between the free troposphere and the boundary layer. Progress has been made using aquaplanet simulations to identify shallow cumulus clouds as driving the spread in climate sensitivity [*Medeiros et al.*, 2008; *Ringer et al.*, 2014; *Medeiros et al.*, 2015].

7 Case study: The Madden–Julian Oscillation

In Sections 5-6 we described the models that have been fundamental for advancing our understanding of tropical circulation and the important role that moisture plays in setting the circulation, specifically how convective organization and clouds impact the radiative structure of the atmosphere. In this section we will focus our attention the Madden-Julian Oscillation (MJO). The MJO is an organized convective system and the primary source of tropical intraseasonal variability. The MJO continues to challenge our understanding of how circulation couples to clouds, convection and radiation. Progress in being made in our theoretical understanding of the mechanisms that initiation, propagate and maintain the MJO, however, there is currently no complete theory for the MJO [*Ahn et al.*, 2017]. As a result, the MJO is generally poorly represented in comprehensive climate models. In this review, we use the MJO as a case study to highlight how the model hierarchies—in particular idealized models—have been used to progress our understanding, develop new theories and improve the representation of the MJO in comprehensive models.

The MJO is an envelope of organized tropical convection that drifts eastward from the Indian Ocean into the Pacific. It is distinct from most convectively coupled equatorial waves in having a relatively slow speed of propagation ($\approx$ 4–8 m/s), longer timescales (about 1–2 months), and a relatively large scale (planetary wavenumbers 1–3) in comparison to other synoptic disturbances in the tropics. While it has also been historically difficult to simulate in global models, some recent models do much better. For the first time, some dynamical forecasts are now superior to statistical ones. This new simulation capability allows theoretical ideas to be tested.

Realistic simulations of the MJO require convection to be sensitive to free-tropospheric moisture, i.e., a positive moisture-convection feedback, where deep convection is favored in regions where free-tropospheric humidity is higher. CMIP5-class models with the largest moisture sensitivity tend to have the most realistic MJO [*Kim et al.*, 2014a]. Poor simulations of the MJO — generally those with weak to non-existent MJOs [*Ahn et al.*, 2017] — can be improved by increasing the sensitivity of convection to moisture, such as increasing the entrainment and rain re-evaporation. Such tuning to optimize the MJO generally causes biases in mean climate [e.g., *Kim et al.*, 2011], but there is some evidence to suggest a realistic MJO and mean state can occur simultaneously even with traditional convection schemes [*Crueger et al.*, 2013]. There is considerable additional evidence, apart from the MJO, that deep convection in general is quite sensitive to moisture [e.g., *Derbyshire et al.*, 2004], and that typical convective schemes have excessive undilute ascent, as opposed to entraining air about them [e.g., *Tokioka et al.*, 1988; *Kuang and Bretherton*, 2006].

More recent studies have viewed the MJO through the moist static energy budget where surface fluxes and radiation are the dominant source terms (since moist static energy is conserved under condensation, which is the dominant source term in the dry static energy budget in deep convective conditions). Feedbacks between surface turbulent fluxes and convection were emphasized in early theories [*Neelin et al.*, 1987; *Emanuel*, 1987] and appear to be important in some GCMs [e.g. *Maloney and Sobel*, 2004]. Other work, however, points to a key role for cloud-radiative feedbacks; for example, there is less longwave cooling by high-clouds in a moist atmosphere [*Andersen and Kuang*, 2012; *Chikira*, 2013]. Process-based diagnostics [*Kim et al.*, 2015] and so-called "mechanism denial" experiments [*Kim et al.*, 2012; *Crueger and Stevens*, 2015; *Ma and Kuang*, 2016] in which a process is removed in order to test its importance, have lead to progress. This is consistent with earlier work with more idealized models. *Raymond* [2001] argued that radiative feedbacks were important to the MJO based on results from a 3D model of intermediate complexity, while *Bony and Emanuel* [2005] did so based on 2D CRM simulations without rotation. In an even simpler context, *Hu and Randall* [1994] found radiative feedbacks are critical in a one-dimensional model without large-scale circulation.

The importance of moisture-convection and cloud-radiative feedbacks suggests a view of the MJO as essentially a form of self-aggregation on the equatorial -plane, in a domain much larger than CRMs simulations [e.g. *Arnold and Randall*, 2015]. In aquaplanet simulations with super-parametrized convection in RCE, *Arnold and Randall* [2015] found similar energy budgets and radiative feedbacks in non-rotating simulations, where self-aggregation dominates, and simulations with rotation, where MJO-like variability occurs.

The importance of moisture-convection and cloud-radiative feedbacks are the core assumptions in a recent set of highly idealized models of the MJO. These models represent the MJO as a moisture mode – a mode that would be absent in a dry atmosphere. In these idealized models, essential information is contained in the moisture field. Truncation to a single vertical mode, as in the Matsuno–Gill model, allows the dry dynamics to become shallow water-like. The convection schemes depend strongly, and in some cases exclusively on the moisture field, building in a strong moisture-convection feedback.

Moisture modes emerged in the idealized models of Fuchs and Raymond [*Fuchs and Raymond*, 2002, 2007; *Raymond and Fuchs*, 2007, 2009]. The moisture mode was isolated in the simple 1-D linear model of *Sobel and Maloney* [2012, 2013] that has a single moisture prognostic variable, assumes WTG in the temperature equation, and generates winds by assuming a Matsuno–Gill response to quasi-steady heating (approximately valid as long as the disturbance does not propagate too quickly). In this model it can be shown explicitly that radiative feedbacks are critical for eastward propagation in a linearly unstable mode [*Sobel and Maloney*, 2013]. While the eastward propagation was initially slower than observations, modifications by *Adames and Kim* [2016] increased the propagation speed by accounting for meridional moisture advection. Because the WTG assumption eliminates the Kelvin waves, the waves that most early theories relied on to explain the eastward propagation, the propagation of a moisture mode results largely from horizontal moisture advection, which seems to be supported by a number of observational and modeling studies [e.g., *Maloney*, 2009; *Pritchard and Bretherton*, 2014; *Kim et al.*, 2014b; *Inoue and Back*, 2015a].

Moisture mode theory — including the link to self-aggregation in idealized simulations — provides a useful framework for diagnosing models and observations, although whether moisture mode models correctly capture the MJO remains a topic of debate. The moisture mode ideas are quite different from those in earlier MJO theories, most of which excluded both radiative feedbacks and prognostic moisture (e.g., see review by *Wang* [2005]), and also differ from other, more recent models [e.g., *Majda and Stechmann*, 2009; *Yang and Ingersoll*, 2013]. Now that some comprehensive models at the top of the model hierarchy can simulate the MJO with reasonable fidelity, it is a question of linking them to our theories of MJO behavior. A connection to the moisture mode hypothesis, for example, can be traced through a hierarchical chain from self-aggregation in idealized simulations to more realistic simulations where moisture-convection and radiative feedbacks are allowed.

8 Synthesis and Outlook

All models are wrong but some are useful. The statistician George Box succinctly made two points at a workshop on statistical robustness four decades ago [*Box*, 1978]. First is the reminder that all of our models, even the most sophisticated, are inherently simplified – and so in Box's sense "wrong" – and thus unable to capture all the potentially relevant processes and scales of the climate system. But second, we can learn, understand, and make predictions with *some* models.

In this review, we have identified a number of deliberately simplified models that have proven useful for understanding and predicting the large scale circulation of the atmosphere. We have not identified all possible benchmark models, but have sought to provide a balanced view of the dynamics of the tropical, extra-tropical, and middle atmosphere, highlighting processes on scales large, e.g., planetary waves in the Holton–Mass model, to small, e.g., convection and clouds within radiative-convective equilibrium integrations.

In Section 2, we proposed three principles to help organize models into hierarchies: dynamics, process, and scale. These are motivated, in part, by decisions we make in order to create a numerical model of the atmosphere that captures the large-scale circulation. These decisions include the appropriate governing equations, the relevant processes that drive the circulation, and the domain and resolution (which determine the allowable scales). These principles are not independent of one another. Dynamical hierarchies are designed to isolate particular scales and processes, e.g., the quasi-geostrophic equations focus on Rossby wave processes by filtering out the faster and smaller scale gravity waves. Likewise, the process hierarchy influence the choice of dynamics; if we wish to look at non-hydrostatic effects, we must resolve scales with an order-one aspect ratio, and thus the kilometer scale. The models featured in Sections 3-7 provide several examples of each of these hierarchies that have organically emerged in the literature, as highlighted in Figure 5.

Dynamical hierarchies have played a key role in understanding the mid-latitude circulation, where fast rotation and stratification organize the flow. We define the **equation hierarchy**, see Figure 5, that forms a natural progression of the equation set. The equation hierarchy includes the (i) barotropic vorticity dynamics that capture the evolution of Rossby waves (Section 3.1), (ii) quasi-geostrophic flow on 2 or more layers that generally captures baroclinic instability (Section 3.2), (iii) the dry primitive equation dynamics, e.g., as represented in the the Held-Suarez model, (iv) the moist primitive equation dynamics (as in the Frierson model in Section 5.2 or a standard AGCM), and ending with (v) the non-hydrostatic equations that includes the vertical momentum equation and are accurate at higher horizontal resolutions, e.g. used in CRMs or weather forecast models. In the tropics, rotation is weak and moist processes are of first order importance. As such, the dynamical hierarchies generally only include the more complex end of the equation hierarchy. None-the-less, the primitive equations or non-hydrostatic dynamics can be used with either vertical truncation (Matsuno-Gill model in Section 5.1) or horizontal truncation (weak-temperature gradient approximation in Section 6.1) to simplify the equation set.

The focus on processes is most essential for organizing model hierarchies. The purpose of the dynamics and scale hierarchies are then used to isolate and resolve the processes of interest. An example of a process hierarchy is the **diabatic hierarchy**, a term we use to describe a series of GCMs that integrate the primitive equation dynamics on the sphere, with advancing representations of the processes driving the temperature equation and generally with a resolution on the order of 100 km. At the base of the diabatic hierarchy is (i) the *Held and Suarez* [1994] model (often referred to as a dry dynamical core) where all diabatic processes are replaced by Newtonian temperature relaxation. The Held-Suarez model has been used to understand jet stream variability (Section 3.4), tropical overturning circulation (Section 5.2), stratosphere-troposphere coupling (Section 4.1), and tracer transport (Section 4.3).

The next step in the diabatic hierarchy is to add moisture using a (ii) "gray" radiation schemes. This scheme decouples the convective latent heating from the radiation scheme so that water vapour is transparent to the radiation scheme [e.g, *Frierson et al.*, 2006; *O'Gorman and Schneider*, 2008]. The next step in the diabatic hierarchy is (iii) to include a full radiation in the absence of clouds (or with a prescribed cloud climatology) that allows water vapor to interact with radiation in a simplified context [e.g., *Merlis et al.*, 2013; *Jucker and Gerber*, 2017]. These models have elucidated the circulation of the tropics and coupling between high and low latitudes (Section 5.2). At the next step in the diabatic hierarchy are (iv) atmospheric General Circulation Models that account for the importance of cloud and aerosol processes in the diabatic forcing of the circulation (Section 6). The most complex end of the diabatic hierarchy is to include the (v) carbon cycle and interactive chemistry which enables a more realistic representation of the processes governing radiative gases, clouds, and aerosols. The complex end of the diabatic hierarchy continues to evolve with time, as more processes are included in Earth System models and computational resources continue to grow.

Another process hierarchy that helps to organized the model hierarchies focusses the lower boundary conditions. Atmospheric models can be created with oceans that have (i) constant or fixed SST, (ii) aquaplanets with a so-called “slab" ocean which only captures the local thermodynamics of the atmosphere-ocean coupling, and (iii) a slab ocean with q-fluxes which include idealized horizontal transport. These models can also be configured to have idealized land and topography by changing the heat capacity and boundary layer roughness. The representation of the land surface conditions can be idealized or more realistic e.g., bucket hydrology vs. water runnoff or a full representation of vegetation, aerosols, and carbon chemistry. The atmospheric models can also be forced with (iv) observed SSTs or (v) with an interactive ocean (vertical and horizontal) to form a coupled atmosphere-ocean model.

Figure 6 illustrates a hierarchy available within the CESM framework, incorporating elements of both the diabatic hierarchy and varying configurations of the land surface. The SimpleER project [*Polvani et al.*, 2017] makes many of these models an integral part of the CESM structure. The Isca framework [*Vallis et al.*, 2018], based on the GFDL modeling system, includes many of the lower steps of the hierarchy, but also includes hooks to add complexity and to build models of other planetary atmospheres as needed. One aspect of the process hierarchy that moves beyond these GCMs is to include more comprehensive treatments of microphysical processes that determine the distribution of clouds. An example is the Weather Research and Forecasting (WRF) model, which offers different options for representation of atmospheric processes, such as microphysics, and the treatment of boundary conditions.

Our final principal for organizing the models is scale. One example in which a hierarchy has naturally developed is for studying convective organization (Section 6.1). The model domain can vary from very high resolution in a small domain (to understand in-cloud properties) to low resolution on a global scale to understand planetary scale organization such as the MJO. Scale hierarchies are also implicit in dynamical hierarchies. Simplified models have proven useful in problems that intrinsically involve a great spread in scales, such as the QBO, where the evolution of planetary scale jets is driven by small scale gravity waves, and could only recently be captured in AGCMs.

Looking forward, we believe that model hierarchies will continue to help us improve climate and weather models. In particular, the gap in our understanding of the coupling processes between clouds, convection, and circulation is mirrored in part with a gap in simple models that isolate the key processes regulating these interactions. There is a large jump between idealized moist models that effectively neglect cloud-aerosol processes [e.g., *Frierson et al.*, 2006; *Merlis et al.*, 2013; *Jucker and Gerber*, 2017] and comprehensive GCMs that seek to parametrize all the unresolved scales which are critical to clouds and aerosols. This gulf partially reflects the difference between what can be done by an individual research group and a full modeling center. Further development of simpler GCMs that capture the essential elements of cloud and aerosol interactions are needed. It requires identifying sufficiently elegant model configurations, in the language of *Held* [2014], that would merit investment by a modeling center, or consortium of research groups, to bring in sufficient expertise.

Radiative-convective equilibrium integrations are in part aimed at this gulf between large scale dynamics and clouds processes. There is still a fundamental separation between them and the real atmosphere, however, where wind shear plays a vital role in organizing convection. This gap is visually emphasized in Figure 6 by the profound changes in circulation in CESM between simulations in RCE and an aquaplanet model (where the large-scale flow is determined by rotation and the temperature). Adding the building blocks of rotation and shear into RCE integrations may help establish these links.

In this review we have highlighted various 'benchmark' models for understanding and modelling the large-scale circulation of the atmosphere. We emphasize that their *connectedness* is essential; indeed it is what defines a hierarchy. A simple model must be connected in some way to a comprehensive model and/or to reality for it to have value, else it becomes irrelevant. Connectedness does not always need to occur in a sequence of small steps; in some cases a simple model may connect almost directly to observations or experiment (the Lindzen–Holton–Plumb model of the QBO may be an example). However, such a leap is the exception, and in most cases a simple model connects to reality via a sequence of other models.

Model hierarchies will continue to play a role in our understanding of climate projections; in fact, we argue they should play an increasingly important role. We do not believe in global warming because a GCM tells us it is so; rather, we believe in it because of very basic physical laws. However, in their simplest manifestation those laws have little quantitative predictive capability for Earth's climate. At the other extreme, when comprehensive models are forced into the warmer regimes that may lie in our planet's future, we do not have the ability to compare parametrizations with observations. A purposes of the model hierarchies is then to provide a pathway connecting robust physical laws to our complex reality, via models of varying levels of complication. Ideally, this enables us to both understand the processes involved and to make useful and trustworthy predictions.

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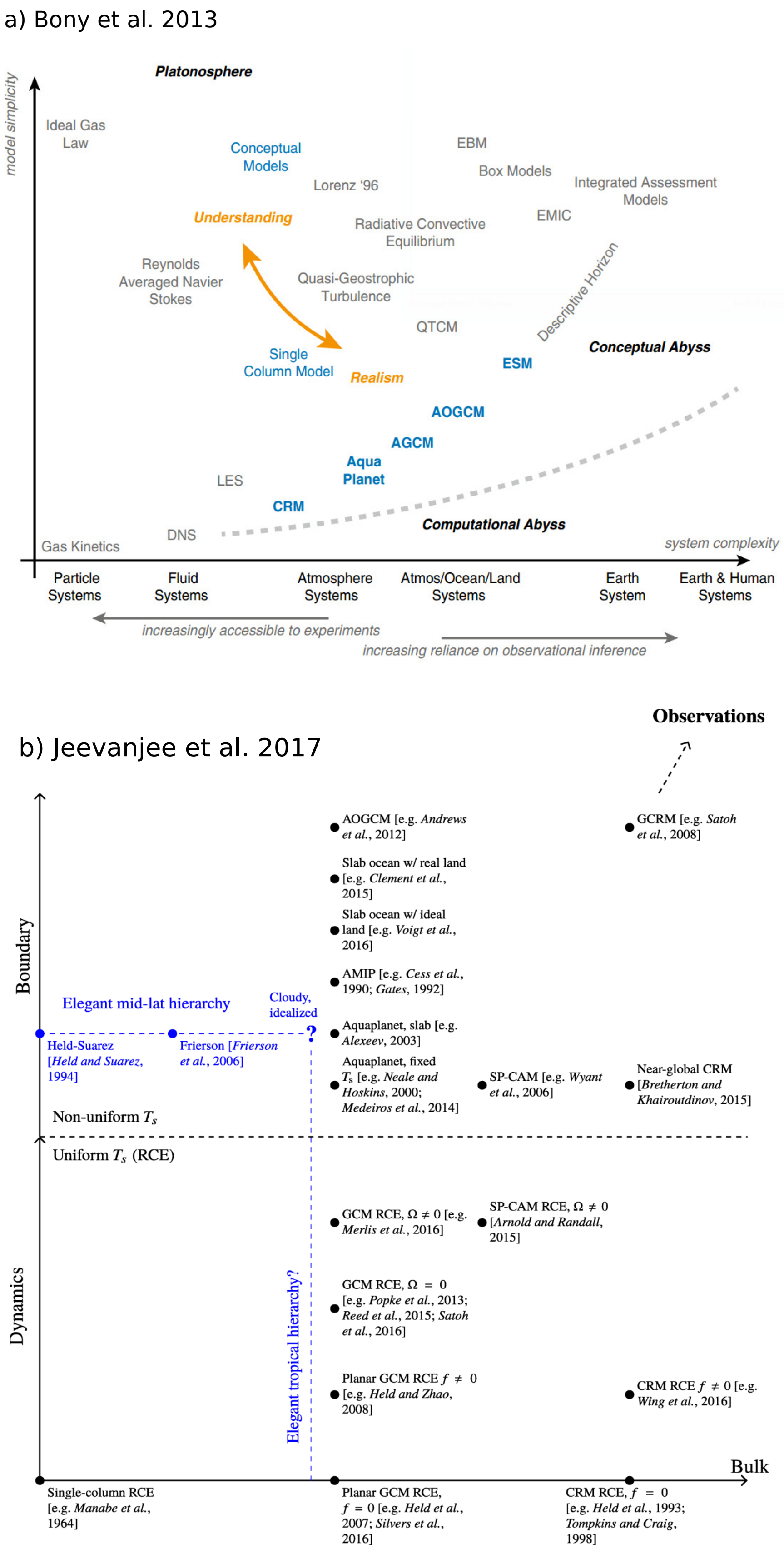


Figure 1. Categorizing atmospheric climate models in terms of complexity a) from *Bony et al.* [2013] and b) grouped in terms of model configurations for Earth's climate as in *Jeevanjee et al.* [2017].

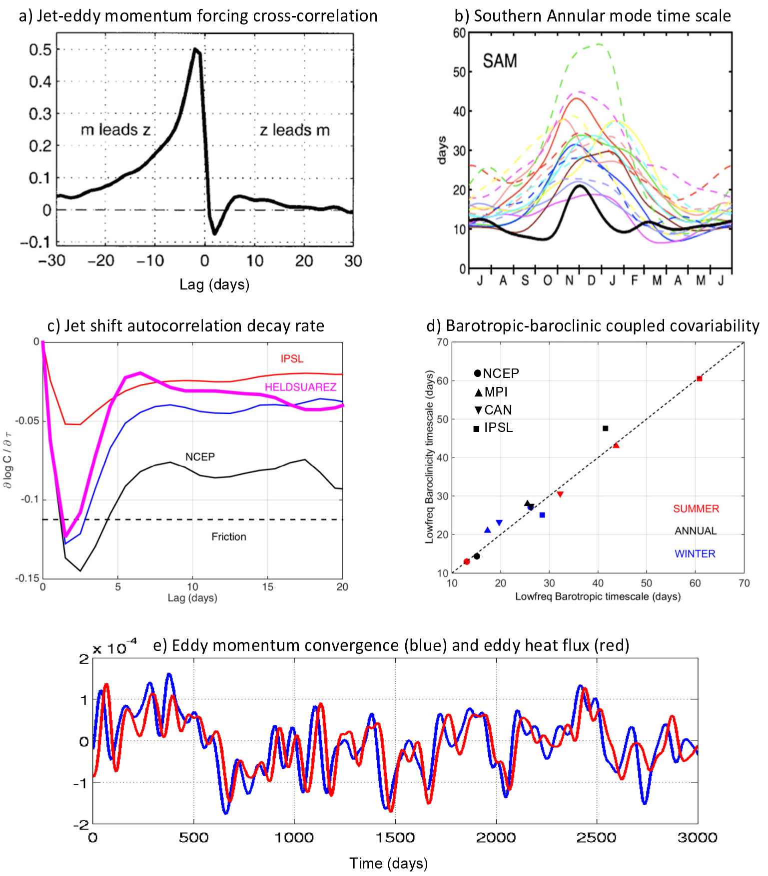


Figure 2. (a) Lagged correlation between zonal mean wind (z) and eddy momentum forcing (m) from *Lorenz and Hartmann* [2001]. (b) Autocorrelation timescale of the Southern Annular Mode for observations (black thick solid) and CMIP3 models (colors), adapted from *Gerber et al.* [2008]. (c) Logarithmic decay rate of autocorrelation for zonal wind anomalies in observations (black), two CMIP5 climate models (IPSL: red, CAN:blue) and the Held and Suarez model (magenta). (d) Scatterplot between low-frequency logarithmic decay rates of baroclinicity and barotropic wind anomalies (average from 5-20 day lags) for the models and seasons indicated. (e) Sample timeseries of the low-frequency eddy momentum (blue) and heat (red) flux contributions to the upper-layer Eliassen-Palm divergence in the QG simulations of *Zurita-Gotor et al.* [2014]

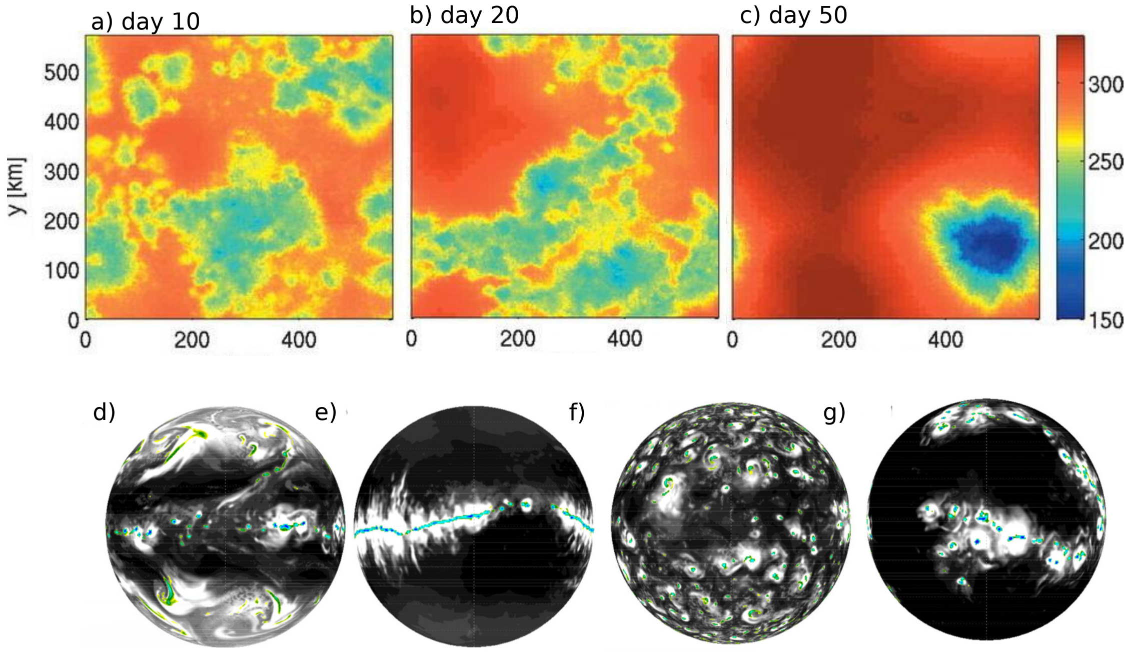


Figure 3. Radiative-Convective Equilibrium simulations in a CRM: top panel is daily OLR for a fixed SST (301K) run after a) 10, b) 20 and c) 50 days of the simulation, adapted from *Bretherton et al.* [2005]. The bottom panel is OLR for high resolution GCM aquaplanet stimulations using zonally symmetric SSTs similar to observation d) with rotation (Earth like), e) without rotation, and uniform SSTs f) with and g) without rotation (RCE case), adapted from *Satoh et al.* [2016].

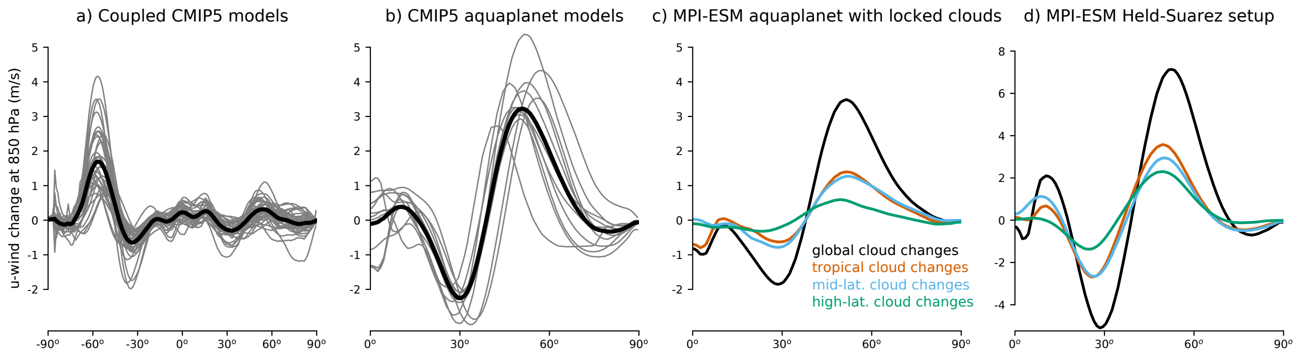


Figure 4. Extratropical cloud-circulation coupling. The impact of clouds on the eddy driven jet stream response to global warming in a hierarchy of GCMs. The zonal-mean time-mean change in 850 hPa zonal wind (ms^{-1}) for each latitude (°) for the ensemble mean (bold line) and individual models (gray) for a) CMIP5 coupled Earth system models with $4\times CO_2$ and b) aquaplanet CMIP5 models with prescribed-SST and 4 K SST warming. For the MPI-ESM model in aquaplanet prescribed-SST setup, simulations with the cloud-locking method and imposed global (black) and regional (colors) cloud changes show the cloud-radiative contribution to the eddy driven jet response to warming (panel c). The global and regional cloud impacts are reproduced in panel d) using a dry Held-Suarez setup of the MPI-ESM model perturbed with the radiative forcing from cloud changes of panel c. Because panels b-d are for aquaplanet simulations, only the Northern hemisphere is shown. Note the different y-scale in panel d, which reflects the increased jet sensitivity of the Held-Suarez setup. Figure adapted from *Voigt and Shaw* [2016].

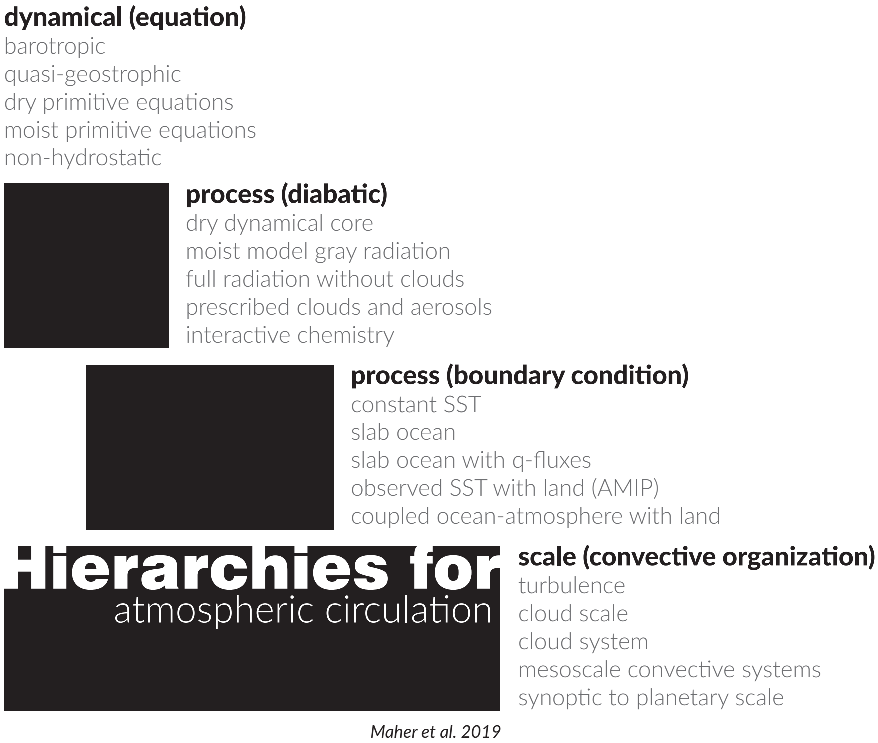
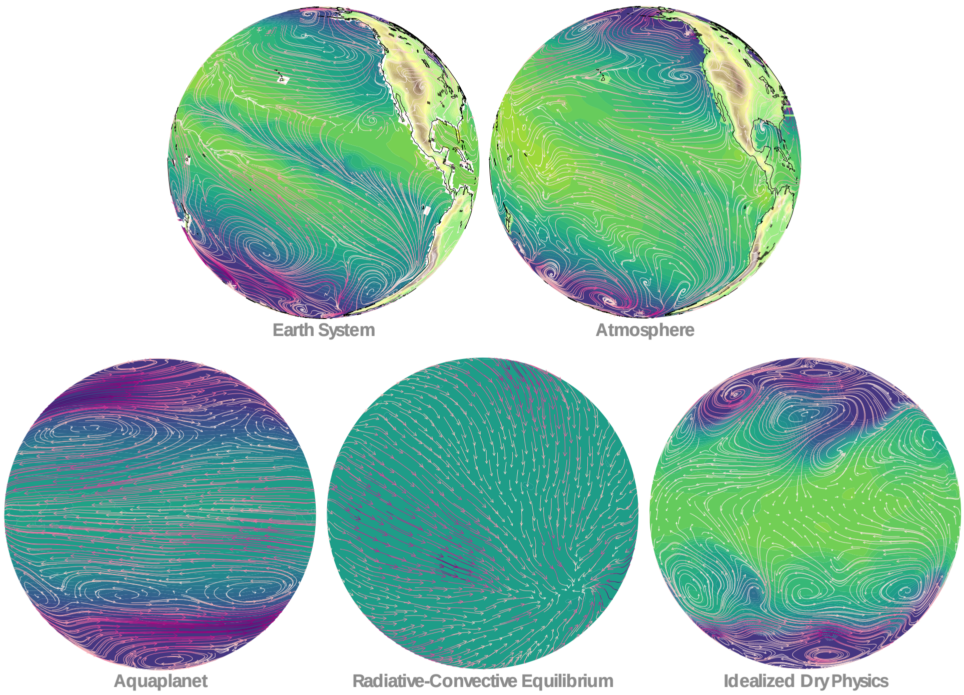


Figure 5. The three principles view of the model hierarchies used for understanding the large-scale circulation. The dynamical hierarchy is shown in terms of the equation hierarchy. The process hierarchy is described in terms of a diabatic hierarchy and the boundary conditions. Convective organization is used as an example to illustrate the scale hierarchy. For each list, the first element is the simplest or smallest-scale and builds down to the most complex or largest-scale. This is an example to illustrate the concept of the three principles and does not capture all the available models.



1605 **Figure 6.** Models available within the hierarchy in the CESM system. (Top) The Earth system model and
1606 atmosphere only models (with prescribed SST). (bottom) Aquaplanet, RCE and idealized dry physics. The
1607 colour contours over the ocean are SST and over land topography. Streamlines are the near-surface wind
1608 (thicker lines are stronger winds). Each globe is a monthly mean except for the idealized dry model which is a
1609 snapshot.