Imagining Simpler Worlds to Understand the Complexity of Our Own

Edwin P. Gerber, Kevin DallaSanta, and Aman Gupta

[1]Courant Institute of Mathematical Sciences, New York University, New York NY

Key Points:

- The atmospheric circulation response to global warming is both a challenge to predict and to understand
- Models of idealized atmospheres allow a process-oriented investigation of the circulation response
- A growing number of models of simpler atmospheres are being developed and shared

---

Corresponding author: Edwin P. Gerber, `gerber@cims.nyu.edu`

Abstract

The atmospheric circulation response to global warming is critical for accurate prediction of climate change on regional scales. For the midlatitudes, shifts in the extratropical jet streams have important consequences for precipitation, blocking, and extreme events. It has proven a challenge, however, to predict. For example, the North Atlantic jet stream plays a vital role in the climate of eastern North America and Europe; in the last intercomparison of state-of-the-art climate models, there was not even agreement on the sign of its wintertime response to global warming. We also lack a comprehensive theory for the impact of warming on the midlatitude circulation.

In a recent study, Tan et al. (2019) constructed models of simpler atmospheres to explore the response of the midlatitude jet to global warming. Their idealized atmospheres highlight the difficulty of developing a comprehensive theory for the midlatitude circulation, but also provide pathways to improve models of Earth's atmosphere. Models of simpler atmospheres allow one to isolate the impact of specific atmospheric processes, and connect theoretical understanding with comprehensive climate prediction systems. Such models can also be used to explore very different atmospheric regimes, from Earth's past to distant planets.

1 A long time ago, in a galaxy far, far away...

Four planets orbited stars just like our own Sun. They were the same size as Earth, with a similar orbit and rotation rate, but lacking a tilt to their planetary axes of rotation, had no seasonal cycle. They were "swamp worlds", with moist surfaces of uniform heat capacity that could not transport heat like our ocean, and they exhibited no topographic features or differences in albedo to perturb the zonal structure of the climate, i.e., "slab ocean aquaplanets", as referred to in the climate modeling literature. Most curiously, the atmospheric composition on each planet varied substantially, leading to different interactions with outgoing terrestrial (infrared) radiation.

On the first planet, the atmosphere interacted uniformly with all infrared frequencies. This is referred to "gray radiation" in the atmospheric science literature (e.g., Frierson et al., 2006), in that this atmosphere does not differentiate between frequencies, or "colors", of infrared light. The overall optical depth was comparable to Earth's atmosphere, but exhibited no temporal variation. The planet had the equivalent of a hydrological cycle, but its condensible "water vapor" was transparent to radiation. Hence the hydrological cycle transported latent energy upward and polarward, influencing both the atmospheric stability and equator-to-pole temperature gradients as on Earth, but had no direct interaction with radiative transfer.

The second planet was nearly the same, but its atmospheric composition was slightly more complex, allowing for interaction with different infrared frequencies, but only across a few, broad bands. Hence radiative heating was more similar to that on Earth, but the optical depths were still constant in time because there was no direct interaction with its "water vapor". The third planet was exactly the same as the second, except that its condensible substance could interact with infrared radiation. This allowed the hydrological cycle to directly interact with radiative transfer, and importantly, provide the equivalent of a water vapor feedback. The fourth world was the most like our Earth, with fully interactive radiative transfer and water vapor. No clouds formed on this planet, however, or on any of the others.

How would global warming impact the midlatitude atmospheric circulation on these planets? The question sounds much easier than predicting climate change on Earth: their climates are zonally symmetric, there is no annual cycle or coupled atmosphere-ocean variability, and there are no cloud feedbacks. The answer, however, is still far from trivial.

As explored by Tan et al. (2019), the midlatitude circulation would respond rather differently on each planet. On the first, with the gray atmosphere, the extratropical jet streams and storm tracks would initially contract equatorward in response to enhanced greenhouse gas concentrations. They would expand poleward in the other planets, albeit at very different rates: the circulation response becomes more sensitive to surface temperature as the transfer of long wave radiation through the atmosphere becomes more Earth-like, both in terms of the vertical structure of the radiative heating/cooling and its ability to interact with water vapor.

2 The challenge of midlatitude circulation trends

Tan et al. (2019) were not motivated by recent discoveries of exoplanets: understanding the response of the storm tracks on these hypothetical worlds has direct relevance for Earth's atmosphere. As highlighted by Shepherd (2014) and Vallis et al. (2015), we have little confidence in projections of the large scale atmospheric circulation, the extratropical jet streams and associated storm tracks in particular. Accurate prediction of the jet response is critical for understanding changes in precipitation and extreme events. Regional climate models can capture the smaller scale processes and detailed interactions with local orography associated with extremes, but they depend on global climate models for an accurate prediction of the incoming wind and moisture conditions. Put more colloquially, if you want to predict to local weather, "the answer, my friend, is blowin' in the wind."

It is generally expected that the extratropical jet streams and storm tracks will shift poleward in response to warming (e.g., Yin, 2005). Based on observations of interannual variability in the extratropical jets, a poleward shift would lead to substantial changes in storm activity, precipitation, and temperature over much of North America and Eurasia (e.g., Thompson & Wallace, 2001), and Australia and South America (e.g., Thompson et al., 2011).

When one considers the details, however, the situation quickly becomes murky. In the Coupled Model Intercomparison Project 5 (CMIP5) models, the signal is complicated in the boreal hemisphere, with substantial spread in the response of the Pacific and Atlantic storm tracks (e.g., Barnes & Polvani, 2013). As shown in Figure 1a, the response of the jets in CMIP5 models to quadrupled CO_2 varies substantially over the annual cycle, and between the North Atlantic and the North Pacific (Grise & Polvani, 2016). Furthermore, in most seasons, the model spread is at best weakly correlated with differences in the models' climate sensitivity, as seen in Fig. 1b. This is to say, models that warm more in response to greenhouse gas forcing don't necessarily exhibit stronger circulation trends.

In the austral hemisphere, there is general agreement on the sign of the response (i.e., the poleward shift), and that the trends increase the more the world warms (Grise & Polvani, 2016). Much of the signal that we have been able to observe, however, was forced by stratospheric ozone loss (e.g., Polvani et al., 2011), and uncertainty in the expected recovery of stratospheric ozone leads to substantial spread in future climate projections (e.g., Gerber & Son, 2014).

3 A focus on atmospheric processes

The difficulty in simulating midlatitude circulation trends mirrors—or perhaps stems from—a lack of understanding. There is not a generally accepted theory that predicts whether the extratropical jets should move poleward or equatorward in response to global warming, let alone the amplitude of the response. At a workshop on storm tracks held near Stockholm last summer[1], roughly a dozen theories were discussed, most equally plausible (or at least equally un-falsifiable) given the range of change we have observed.

Tan et al. (2019) help explain why a theory may be so elusive: the response of the circulation to warming differs qualitatively depending on the representation of radiative transfer in the atmosphere! At face value, this sounds hopeless for a theoretician: adding gray radiative transfer (Planet 1 in Section 1) to a dynamical theory is tough enough; none of the dozen or so theories in the literature directly incorporate radiative transfer. And even if a clever dynamicist managed to do so, a qualitatively different answer would arise if one of the more sophisticated radiation schemes were used instead. Just accounting for a few bands of radiation (Planet 2), even without water vapor feedback, is sufficient to change the sign of the response!

But all is not lost; Tan et al. (2019) argue that the key impact of radiation may lie in how it determines the mean state of the atmosphere. While they took great care to ensure that global mean temperature and climatology were consistent across the four planets they consider —which was no small task— there were still fundamental differences in the atmospheric structure. The gray radiation scheme is associated with a so-called split jet, where the subtropical jet (the baroclinic jet associated with the Hadley cell) is well-separated from the eddy-driven, or midlatitude jet (which is associated with surface westerlies generated by eddy momentum fluxes). In the other configurations with a more realistic representation of radiative transfer, the subtropical and midlatitude jets were more merged together, as they are (generally) observed on Earth.

This insight provides us two paths forward. First, an accurate representation of the basic state is essential for climate prediction. The equatorward bias in the midlatitude jets in our climate models requires further attention (e.g., Wenzel et al., 2016). There was substantial improvement on climatologies of the jets between CMIP3 (Kidston & Gerber, 2010) and CMIP5 models (Barnes & Polvani, 2013), and the DynVarMIP will focus on this in the CMIP6 (Gerber & Manzini, 2016).

Second, for further theoretical development, mechanisms must explicitly account for the mean state. If a proposed mechanism cannot differentiate the response of gray atmosphere from the more realistic configuration, it is not sufficiently discerning to help us explain the climate response to warming.

In addition, the hierarchy of atmospheres explored by Tan et al. (2019) allowed them to highlight specific processes that are critical in the circulation response. Their results support a growing awareness that stratospheric temperature trends play a key role in tropospheric circulation trends (e.g., Manzini et al., 2014; Grise & Polvani, 2017). They also find that latitudinal extent of the warming response in the tropics plays a key role in the circulation response (cf. Tandon et al., 2013). This mirrors the insight we gain from El Niño–Southern Oscillation, where a warming of the tropics causes the extratropical jets to contract towards the pole (Seager et al., 2003), while global warming tends to push the jets apart (Lu et al., 2008).

4 Connecting theory to comprehensive atmospheric models

In the language of Maher et al. (2019), Tan et al. (2019) developed a "diabatic" hierarchy, a sequence of models that are identical except for the their representation of the internal diabatic processes in the atmosphere. Beginning with the gray atmosphere developed by Frierson et al. (2006), they worked their way up to a representation of full radiation (albeit without clouds), similar to configurations established by Merlis et al.

---

[1] `http://climdyn.misu.su.se/stormtracks2018/`

(2013) and Jucker & Gerber (2017). While the quantitative response of the jet depends critically on the radiative transfer scheme, Tan et al. (2019) suggest that a fairly simple configurations, Planets 2 and 3, with only a few bands in the long wave and a simplistic water vapor feedback, may be sufficient to capture the qualitative response. It could be a good target for further theoretical development.

Model hierarchies help to build bridges between theoretical understanding of the atmospheric circulation and its representation in increasingly complex climate and weather prediction systems (Maher et al., 2019, and references therein). We are confident in attributing global warming to anthropogenic activity not just because it appears in our most comprehensive models, but because we can see it in model hierarchies, the observational record, and basic principles, perhaps most simply from the algebraic "layer models" of the atmosphere, as first developed by Arrhenius (1896). In comparison, the circulation response to anthropogenic forcing is both more difficult to observe, given the low signal-to-noise ratio, and harder to pin down at a basic process level.

Reducing the conceptual complexity, is a key element of a hierarchical approach, as illustrated in Fig. 2. There were several significant simplifications in the atmospheres of Tan et al. (2019). One was to remove zonal asymmetries: before we tackle differences in the North Atlantic and North Pacific jets (Fig. 1), can we nail down a theory for one homogeneous jet? A second key simplification was to remove the influence of clouds: before we introduce uncertainties due to parameterization of clouds, can we understand circulation feedbacks with clear sky radiation? Answering these questions for intentionally simplified planets increases confidence in, and our interpretation of, state-of-the-art models.

The work by Tan et al. (2019) joins a growing number of efforts to build up a modeling infrastructure for the atmospheric circulation. Notably, the Isca framework of Vallis et al. (2018) allows one to construct and use similar diabatic hierarchies. Isca was developed within the Geophysical Fluid Dynamics Laboratory modeling framework. The SimplER project within the Community Earth System Model framework is making available more idealized configurations of the National Center for Atmospheric Research's models (Polvani et al., 2017). In particular, these model hierarchies come with user support to both compile and configure models. When multiple groups focus on similar atmospheric models, there is a chance to both reproduce key results, identify inconsistencies (and coding bugs), and push forward new questions.

5 Exploring climate regimes beyond our own

To bring the discussion full circle, while idealized models are sufficiently motivated by the need to study Earth's climate, they do provide a pathway to explore the circulation of exoplanets as well. For example, Kaspi & Showman (2015) explore a range of exoplanetary atmospheres with essentially the same gray atmosphere model used by Tan et al. (2019), Planet 1 in the sequence of Section 1 and Fig. 2, but over a much broader range of climatologies.

Advances in observational capacity are making this work less hypothetical. One example is the recent observations of Martian atmosphere used by Kahre et al. (2015) to assess radiative-dynamic feedback due to observed dust and water cycles on Mars. Farther afield, Wolf (2017) uses an earlier version of Community Climate Model (CCM4) with a slightly modified radiation scheme to explore the range of habitability for exoplanets in the TRAPPIST-1 system. With a sufficiently high concentration of CO_2 (or other greenhouse gas), planet "e" (the fourth of 7 planets orbiting the TRAPPIST-1 dwarf star) could potentially sit within the range of habitability, warm enough to sustain liquid water, but cool enough to avoid a runaway greenhouse effect!

6 Concluding remarks

The models explored by Tan et al. (2019) are generally referred to as idealized atmospheric models, or idealized General Circulation Models. We suggest a subtle, but important rearrangement of the nomenclature. Rather than viewing them as *simple models of our atmosphere*, consider them as *models of simpler atmospheres.*

It is true that some idealized models are explicitly constructed to capture a simplified representation of the real atmosphere. In so-called Earth systems Models of Intermediate Complexity (EMIC; Claussen et al., 2002), the representation of the atmosphere, and all other components of the Earth system, are deliberately simplified to make them computationally efficient. Even our state-of-the-art climate prediction models are highly idealized compared to the real atmosphere, although here the simplification is not deliberate, but set by the limits of our understanding and computational power.

Tan et al. (2019) had a different aim. Their alternative atmospheres are well-defined and deliberately simplified, to allow them to focus in on the role of a few key processes: radiative transfer and dynamics. Their models can be viewed as "recipes" for simpler atmospheres which could be explored independent of a given model framework. For example, their results could be tested across different resolutions, to ensure an accurate representation of the dynamics, or even across different numerical representations of the underlying dynamics and radiative transfer, e.g., the model of Merlis et al. (2013) as compared to Jucker & Gerber (2017).

Held (2005) makes an analogy with biology, which has made great strides in understanding the human body by focusing large efforts on "simpler" creatures. While evolution has provided a hierarchy to biology, climate scientists must decide themselves if simpler "climate models of lasting value" can help us understand our Earth. Viewed through a dynamical lens, Tan et al. (2019) have posed a few simpler planets that could be studied with the aim of working our way up towards a full Earth atmosphere.

To make full use of these model systems, we should increase their accessibility. Efforts to *meaningfully* share code, expertise, and development through freely-available code repositories, such as in the Isca framework (Vallis et al., 2018), could make this possible. Not only does this make our science more accessible to the growing international research community, but it allows work on simplified atmospheres to progress towards an elegant and dynamically consistent hierarchy for understanding Earth's atmosphere.

Acknowledgments

No original data was produced or used in this commentary, and all conclusions are based on the works cited. Fig. 1 was reproduced from Grise & Polvani (2016).

The authors thank the National Science Foundation for support through grant AGS-1852727 to New York University. EPG also thanks the European Research Council for support through project 677756, FORECASToneMONTH.

References

Arrhenius, S. (1896). On the influence of carbonic acid in the air upon the temperature of the ground. *Phil. Mag. J. Sci.*, *41*, 237–276.

Barnes, E. A., & Polvani, L. M. (2013). Response of the midlatitude jets, and of their variability, to increased greenhouse gases in the CMIP5 models. *J. Climate*, *26*, 7117-7135. doi: 10.1175/JCLI-D-12-00536.1

Claussen, M., Mysak, L. A., Weaver, A. J., Crucifix, M., Fichefet, T., Loutre, M.-F., . . . Wang, Z. (2002). Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models. *Climate Dyn.*, *18*, 567-586. doi:

10.1007/s00382-001-0200-1

Frierson, D. M. W., Held, I. M., & Zurita-Gotor, P. (2006). A gray radiation aquaplanet moist GCM, Part 1, static stability and eddy scales. *J. Atmos. Sci.*.

Gerber, E. P., & Manzini, E. (2016). The dynamics and variability model intercomparison project (DynVarMIP) for CMIP6: Assessing the stratosphere–troposphere system. *Geosci. Model Dev.*, *9*(9), 3413–3425. doi: 10.5194/gmd-9-3413-2016

Gerber, E. P., & Son, S.-W. (2014). Quantifying the summertime response of the austral jet stream and hadley cell to stratospheric ozone and greenhouse gases. *J. Climate*, *27*, 5538–5559. doi: 10.1175/JCLI-D-13-00539.1

Grise, K. M., & Polvani, L. M. (2016). Is climate sensitivity related to dynamical sensitivity? *J. Geophys. Res. Atm.*, *121*(10), 5159-5176. doi: 10.1002/2015JD024687

Grise, K. M., & Polvani, L. M. (2017). Understanding the time scales of the tropospheric circulation response to abrupt CO2 forcing in the Southern Hemisphere: Seasonality and the role of the stratosphere. *J. Climate*, *30*(21), 8497-8515. doi: 10.1175/JCLI-D-16-0849.1

Held, I. M. (2005). The gap between simulation and understanding in climate modeling. *Bull. Am. Meteor. Soc.*, *86*, 1609-1614. doi: 10.1175/BAMS-86-11-1609

Jucker, M., & Gerber, E. P. (2017). Untangling the annual cycle of the tropical tropopause layer with an idealized moist model. *J. Climate*, *30*(18), 7339-7358. doi: 10.1175/JCLI-D-17-0127.1

Kahre, M. A., Hollingsworth, J. L., Haberle, R. M., & Wilson, R. J. (2015). Coupling the mars dust and water cycles: The importance of radiative-dynamic feedbacks during northern hemisphere summer. *Icarus*, *260*, 477-480.

Kaspi, Y., & Showman, A. P. (2015). Atmospheric dynamics of terrestrial exoplanets over a wide range of orbital and atmospheric parameters. *Astrophysical J.*, *804*, 18pp. doi: 10.1088/0004-637X/804/1/60

Kidston, J., & Gerber, E. P. (2010). Intermodel variability of the poleward shift of the austral jet stream in the CMIP3 integrations linked to biases in 20^{th} century climatology. *Geophys. Res. Lett.*, *37*, L09708. doi: 10.1029/2010GL042873

Lu, J., Chen, G., & Frierson, D. M. W. (2008). Response of the zonal mean atmospheric circulation to El Niño versus global warming. *J. Climate*, *21*, 5835–5850.

Maher, P., Gerber, E. P., Medeiros, B., Merlis, T. M., Sherwood, S., Sheshadri, A., . . . Zurita-Gotor, P. (2019). Model hierarchies for understanding atmospheric circulation. *Rev. Geophys.*. doi: 10.1029/2018RG000607

Manzini, E., Karpechko, A. Y., Anstey, J., Baldwin, M. P., Birner, T., Black, R. X., . . . Zappa, G. (2014). Northern winter climate change: Assessment of uncertainty in CMIP5 projections related to stratosphere-troposphere coupling. *J. Geophys. Res. Atm.*, *119*. doi: 10.1002/2013JD021403

Merlis, T. M., Schneider, T., Bordoni, S., & Eisenman, I. (2013). Hadley circulation response to orbital precession. Part I: Aquaplanets. *J. Climate*, *26*, 740–753. doi: 10.1175/JCLI-D-11-00716.1

Polvani, L. M., Clement, A. C., Medeiros, B., Benedict, J. J., & Simpson, I. R. (2017). When less is more: Opening the door to simpler climate models. *Eos*, *98*. doi: 10.1029/2017EO079417

Polvani, L. M., Waugh, D. W., Correa, G. J. P., & Son, S.-W. (2011). Stratospheric ozone depletion: the main driver of 20th Century atmospheric circulation changes in the Southern Hemisphere. *J. Climate*, *24*, 795–812.

Seager, R., Kushnir, Y., Robinson, W., & Miller, J. (2003). Mechanisms of hemispherically symmetric climate variability. *J. Climate*, *16*, 2960–2978.

Shepherd, T. G. (2014). Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geosci.*, *7*, 703-708. doi: 10.1038/ngeo2253

Tan, Z., Lachmy, O., & Shaw, T. A. (2019). The sensitivity to radiative assumptions of the jet stream response to climate change. *J. Adv. Model. Earth Syst.*.

Tandon, N. F., Gerber, E. P., Sobel, A. H., & Polvani, L. M. (2013). Contrasting the circulation response to El Niño and global warming. *J. Climate*, *26*, 4304–4321. doi: 10.1175/JCLI-D-12-00598.1

Thompson, D. W. J., Solomon, S., Kushner, P. J., England, M. H., Grise, K. M., & Karoly, D. J. (2011). Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geosci.*, *4*, 741–749. doi: 10.1038/NGEO1296

Thompson, D. W. J., & Wallace, J. M. (2001). Regional climate impacts of the northern hemisphere annular mode. *Science*, *293*, DOI: 10.1126/science.1058958.

Vallis, G. K., Colyer, G., Geen, R., Gerber, E. P., Jucker, M., Maher, P., … Thomson, S. I. (2018). Isca, v1.0: A framework for the global modelling of the atmospheres of earth and other planets at varying levels of complexity. *Geosci. Model Dev.*, *11*, 843-859. doi: 10.5194/gmd-11-843-2018

Vallis, G. K., Zurita-Gotor, P., Cairns, C., & Kidston, J. (2015). Response of the largescale structure of the atmosphere to global warming. *Quart. J. Roy. Meteor. Soc.*, *141*(690), 1479-1501. doi: 10.1002/qj.2456

Wenzel, S., Eyring, V., Gerber, E. P., & Karpechko, A. Y. (2016). Constraining future summer austral jet stream positions in the cmip5 ensemble by process-oriented multiple diagnostic regression. *J. Climate*, *29*(2), 673-687. doi: 10.1175/JCLI-D-15-0412.1

Wolf, E. T. (2017). Assessing the habitability of the TRAPPIST-1 system using a 3D climate model. *Astrophys. J. Lett.*, *839*, 6pp. doi: 10.3847/2041-8213/aa693a

Yin, J. H. (2005). A consistant poleward shift of the storm tracks in simulations of 21st century climate. *Geophys. Res. Lett.*, *32*, L18701,doi:10.1029/2005GL023684.

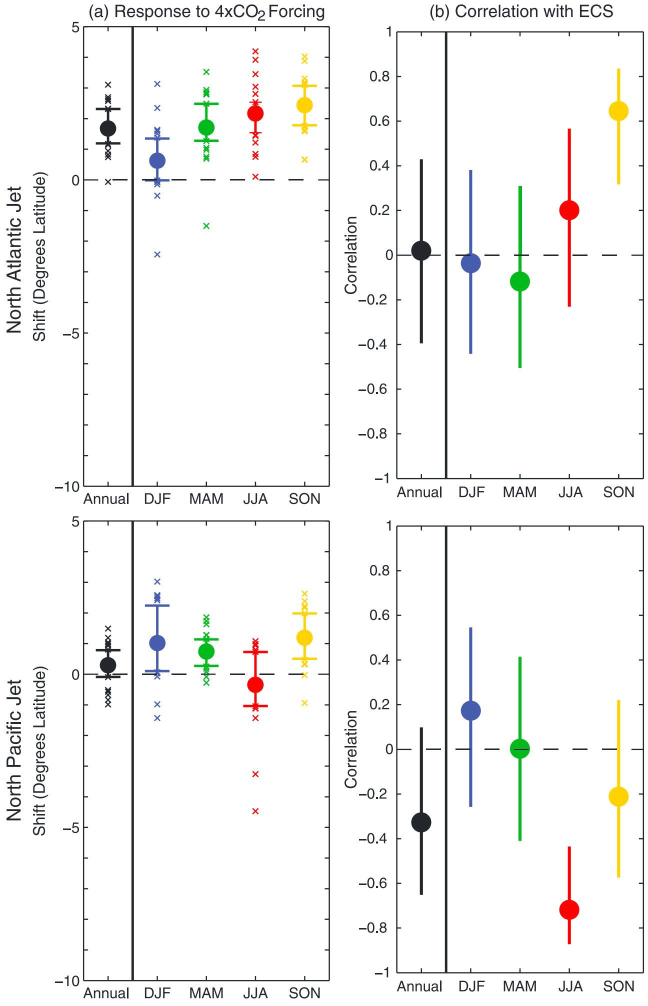

Figure 1. The response of the jets in the (top) North Atlantic sector (300-360°E) and (bottom) North Pacific sector (135-235°E) to 4xCO_2 forcing in Coupled Model Intercomparison Project, Phase 5 (CMIP5) climate models. The left panels show the multimodel mean (solid dot), 25-75 percentile range (horizontal bars), and individual model (small x marks) responses, both for the annual mean and the four seasons. The right panels show the correlation between the inter-model spread in the jet response and the models' climate sensitivity (the equilibrium response to double CO2 forcing), with a 95% error bound marked by vertical lines. It is only for autumn in the North Atlantic, and summer in the North Pacific, when there exists a statistically significant increase in the magnitude of the jet shift in models that warm more in response to CO_2 increase. Reproduced from Grise & Polvani (2016), their Figure 9.

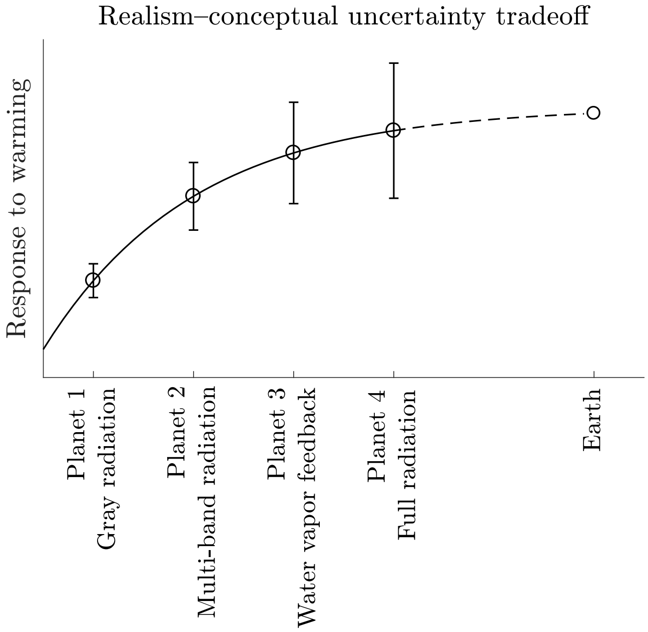

Figure 2. The tradeoff between conceptual uncertainty (i.e, the precision at which we understand the model) and realism (i.e., the accuracy of the forecast) in the model hierarchy of Tan et al. (2019). As the treatment of radiative transfer increases in realism, progressing from a gray atmosphere to full radiation (as found in a comprehensive atmospheric model), we expect the response to approach that of the true Earth. As the models increase in complexity, however, the conceptual uncertainty, represented by the error bars, also increases. While a most realistic representation of the Earth sytem is crucial for quantitative climate prediction, much can be learned by fully understanding simpler systems.