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COMMENTARY

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Key Points:
- Understanding climate dynamics with feedbacks on multiple timescales remains a challenge
- The approach of Saint-Martin et al provides a novel opportunity for reaching faster climate equilibrium
- This approach could be extended to allow alternative configurations of Earth System Models without lengthy ocean spin-ups

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The End of the Wait for Climate Sensitivity?

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Abstract The Earth system responds on a range of timescales to a change in radiative forcing, and full equilibration takes centuries to millennia in many models. In their recent paper, Saint-Martin et. al (2019, https://doi.org/10.1029/2019GL083031) propose a technique for reaching a faster equilibrium temperature response to alternative CO_2 concentration levels by briefly overshooting the desired concentration level to warm the deep ocean faster than a conventional step change experiment. Understanding how these timescales interact is essential for better representing the relationship between transient climate change and the warming which should be expected as greenhouse gas concentrations stabilize. But the technique also raises new possibilities about how Earth System Models could be developed and whether we could gain the capacity to spin-up alternative model configurations such as perturbed parameter simulations or alternative control states to explore historical forcing uncertainty.

1. Introduction

The climate sensitivity of the Earth System (ECS, the equilibrium warming in response to a sustained change in greenhouse gas forcing produced by a doubling of atmospheric carbon dioxide concentrations) is a metric which has long been used to encapsulate our uncertainty in radiative climate feedbacks (Charney et al., 1979; but generally not including slower elements of Earth System response such as ice sheet melt or changes in vegetation cover). Although knowledge of other metrics such as Transient Climate Response may be more useful for near-term climate evolution Knutti et al. (2017) and the Transient Response to Cumulative Emissions may be more useful for carbon budgeting for climate targets if concentrations peak and decline Allen et al. (2009), the equilibrium response remains relevant to understand how the climate system would respond if concentrations can be stabilized, but not rapidly reduced, in the course of mitigation.

For many years, as part of the Coupled Model Intercomparison Project (Eyring et al., 2016, and its predecessors), ECS has routinely been estimated using the method of Gregory et al. (2004). In the idealized CO_2 quadrupling experiment, the initial step in CO_2 concentrations causes an imbalance of radiation at the top of the atmosphere such that there is a net flux of energy into the system. By a assuming a constant feedback parameter for the model, one can measure the increase in outgoing radiation per unit surface temperature increase during the first 150 years of the experiment and the equilibrium temperature response is estimated by linearly extrapolating the warming to the point at which the system is in energetic balance. This "Effective" climate sensitivity is the value reported as a property of a climate model in the fourth and fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2013; Solomon et al., 2007).

However, recent years have seen increased understanding about how the Earth System reaches equilibrium. Longer CO_2 quadrupling experiments have shown that the assumption of a constant feedback is unlikely to hold on long Rugenstein et al. (2016) or short (Andrews et al., 2015; Winton et al., 2010) timescales. This finding implies that feedbacks in the Earth System might be dependent on surface warming pattern, global temperatures, the amount of radiative forcing, or all—which has implied that it might be more difficult than previously thought to constrain the real-world climate sensitivity from past transient warming (Andrews et al., 2018; Proistosescu & Huybers, 2017). It also creates a practical problem, because running an idealized climate simulation to near-equilibrium conditions requires many centuries of simulations, which is a nontrivial computational undertaking.

2. A Shortcut to Equilibrium

The methodology of Saint-Martin et al. (2019) provides a possible shortcut, to reach a near-equilibrium state of warming in response to a set forcing without running a model for millennia (Li et al., 2013; Paynter et al.,

10.1029/2019GL084685

2018). The method relies on the authors' previous work Geoffroy et al. (2013) which fits general circulation model output to a simple Energy Balance Model (EBM), which is capable of resolving multiple timescales of response to greenhouse gas emissions by representing heat uptake by a shallow and deep ocean layers. This EBM, fitted to existing simulations, is used to calculate the likely properties of an overshoot "pulse" which can rapidly warm the deep ocean, before returning the forcing to the target concentration when the deep ocean reaches its predicted equilibrium warming level. Such an approach creates near-stable equilibrium conditions in a fraction of the computational time of a fixed concentration experiment.

This approach provides new opportunities to study physical and ecological phenomena in alternate equilibrium states. For paleoclimate applications and ice sheet simulations, this approach could potentially allow alternative means of initialization of the Earth System in past states. The ability to rapidly simulate a stable warm climate could potentially allow a cleaner test of how vegetation and ocean biota respond to warming and greenhouse gas forcing. For the ocean, the approach could provide and an as-yet impossible opportunity to assess the physical and biological response to stabilized deep ocean warming.

3. A Note of Caution

As with any new technique, though, the community should be aware of both the potential power and the limitations of an approach—what it should and should not be used to do. The characteristics of the pulse-profile used to achieve the rapid equilibrium state in Saint-Martin et al. (2019) are the product of a simple EBM—which is an approximation of the true system response. As such, the equilibrium state which the Earth System Model is "fast forwarded" to is only a prior estimate and not the "true" equilibrium state of the system. If there is a small anomaly between the equilibrium climate sensitivity of the EBM and that of the true Earth System Model, the technique of Saint-Martin et al. (2019) will get the model closer to equilibrium, but the model would still be expected to slowly asymptote toward the true value over the centuries after the pulse application (and clearly, for paleo applications, the technique provides no information on the equilibrium state of slow feedbacks such as ice sheets and vegetation which might alter long-term equilibration temperatures; Caballero & Huber, 2013).

Second, if the method is to be deployed operationally, there is more work to do in assessing the long-term stability of the fast-forward simulations. The inferred stability of the quasi-equilibrium is based on the evolution of global temperatures and top of atmosphere energetic balance, but these global mean values hide the multiple degrees of freedom in the thermal structure of the ocean which could potentially influence its long-term evolution. It remains to be understood the degree to which ocean overturning responds to forcing pulses and whether rapid adjustment can lead to nonphysical ocean states (Jansen et al., 2018; Rind et al., 2018).

4. A Pathway to Faster Model Development

However, the technique can potentially accelerate the initialization of a model to a near-equilibrium state in response to perturbed boundary conditions. The potential applications of this go beyond climate sensitivity experiments—with the possibility of drastically reducing the computational burden of climate model development, where the spin-up of ocean component of an Earth System Model remains a huge computational burden Séférian et al. (2016). The necessity of a century to millennium spin-up period of the coupled climate system to reach a control-state equilibrium effectively is a significant obstacle for objective parameter calibration of coupled climate models, leading to inconsistent model tuning strategies in the CMIP (Coupled Model Intercomparison Project) model archive Schmidt et al. (2017).

Spinning up an ocean to an altered atmosphere, land, or sea ice model, like the abrupt-4xCO2 experiment, represents a step change in ocean boundary conditions requiring thousands of years to reach a new equilibrium. This technique opens up the door to new thinking on how equilibrium might be achieved—not simply by waiting for a new model to stabilize but by modulating input forcing combined with some prior inference on how the system might respond. For estimating the response to CO_2 concentration change, this inference comes from a modulation of CO_2 forcing combined with an EBM fit of predicted model response. For a more generic nonequilibrium initial state, this inference could come from modulating initial top of atmosphere radiative flux imbalances in a similar fashion.

Using this approach could reduce the computational burden of producing multiple structural variants and perturbed physics ensembles to explore a range of potential climate responses using fully coupled configurations, where previously groups were limited by time and computational resources to a single model configuration. Previous efforts to explore coupled GCM parameter uncertainty have been forced to make inferences from atmosphere-only simulations Ogura et al. (2017), use older or cheaper model configurations Williamson et al. (2015), or use flux-corrected models Frame et al. (2008).

This capacity could break the deadlock of climate information, where each successive generation of CMIP provides an ensemble of opportunity containing only one (or a small number) of models from each major center Knutti (2010), many of which share components Sanderson et al. (2015). Such an ensemble is an inadequate statistical sample to properly test proposed emergent constraints on future response Caldwell et al. (2014), and the computational necessity of each modeling center to only produce its most likely model configuration raises the possibility that CMIP is underestimating the full range of possible future response to ongoing greenhouse gas forcing increase. Allowing the capacity for multiple model variants spanning parameter uncertainty and a range of plausible response to climate forcing agents would revolutionize the way we think about ensembles and how they relate to our confidence in model projections. One of our greatest barriers in doing this is the computational cost of spinning up a new model, so investigating novel means of accelerating an equilibrium state such as Saint-Martin et al. (2019) is worthwhile direction for future research.

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