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COMMENTARY
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The Fall and Rise of the Global Climate Model

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Key Points:

- Global models are deficient in how they represent the aerosol influence on clouds and regional circulation patterns
- Nevertheless, global models are essential for reliable regional climate projections
- Recent advances make it more likely that future global models will be greatly improved

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Abstract Global models are an essential tool for climate projections, but conventional coarse-resolution atmospheric general circulation models suffer from errors both in their parameterized cloud physics and in their representation of climatically important circulation features. A notable recent study by Terai et al. (2020, https://doi.org/10.1029/2020ms002274) documents a global model capable of reproducing the regime-based effect of aerosols on cloud liquid water path expected from observational evidence. This may represent a significant advance in cloud process fidelity in global models. Such models can be expected to give a better estimate of the effective radiative forcing of the climate. If this advance in cloud process representation can be matched by advances in the representation of circulation features such as monsoons, then such models may also be able to navigate the complex tangle between spatially heterogeneous aerosol–cloud interactions and regional circulation patterns. This tight link between aerosol and circulation results in anthropogenic perturbations of climate variables of societal importance, such as regional rainfall distributions. Upcoming global models with km-scale resolution may improve the regional circulation and be able to take advantage of the Terai et al. (2020, https://doi.org/10.1029/2020ms002274) improvement in cloud physics. If so, an era of significantly improved regional climate projection capabilities may soon dawn. If not, then the improvement in cloud physics might spur intensified efforts on problems in model dynamics. Either way, based on the rapid changes in aerosol emissions in the near future, learning to make reliable projections based on biased models is a skill that will not go out of style.

Plain Language Summary Human activity releases particles into the atmosphere. Some of these particles are small enough to remain suspended in air, forming an "aerosol." Aerosols interact with clouds to make them brighter or dimmer. Clouds are very good sunlight reflectors, so changing their properties even slightly results in large changes to how much sunlight is absorbed by the Earth. Over time, this changes the rate at which the climate warms. It also affects the regional circulation, that is, recurring weather patterns at the regional scale. This is especially important to society when it affects regions that experience intense rainfall, such as the summer monsoon. If circulation patterns change, locations that used to experience intense rain may receive far less rain than they are used to, and vice versa. To predict how human activity will change regional rainfall in the future requires using models. Unfortunately, the models that are currently available struggle with both the interactions between aerosols and clouds and with some regional circulation features, so their regional predictions are not as reliable as society needs them to be. A recent study describes a model that appears to be much better at aerosol–cloud interactions than previous global models, potentially solving half the problem. Many groups are currently at work on a new generation of models that may be better at regional circulation, which would solve the other half, although it may be good to temper any optimism until this has actually been demonstrated. If these two advances can be combined within the same model, then that model will be able to provide a much more reliable estimate of future regional climate. But model development is hard and slow work, while aerosol emissions are changing rapidly, so it is also important to find ways to extract useful information from imperfect models.

The atmosphere is a tangle of tangles: a web of competing and compensating cloud processes, interwoven with the atmospheric circulation, which itself is threaded across vastly different spatiotemporal scales. Anthropogenic aerosol perturbations subtly shift this web of interactions. This introduces imbalances in the planet's energy budget on the order of a percent of the unperturbed radiative energy fluxes and moves circulation features, such as the ITCZ and monsoons, with small changes at continental scales having large impacts at local scales. For models to be able to project these changes, they need to represent the tangle of diabatic processes, the tangle of atmospheric circulation, and the tangle of those two tangles, each at the appropriate level of complexity. This level of complexity is the minimal degree of model elaboration required to reproduce the emergent properties of the system. It varies with resolution, and finding it has been elusive. One approach is the "superparameterization" multiscale modeling framework (Randall et al., 2003), which conjoins a general circulation model (GCM) to represent large scales with a higher-resolution model running in each GCM column to begin probing cloud process scales. Initially, this approach was devised for deep convection, with the convection handled by a km-scale cloud-resolving model (CRM) (Grabowski & Smolarkiewicz, 1999; Khairoutdinov & Randall, 2001). Parishani et al. (2017) extended the method to shallow clouds by increasing the resolution of the CRM, enabling this "ultraparameterized" model to estimate low-cloud feedbacks (Parishani et al., 2018). Terai et al. (2020) describe the latest development, which endows the Parishani et al. (2017) ultraparameterized model with a representation of aerosol–cloud interactions. A novel result in this work is the model's qualitative agreement with one of the key aspects of observed regime dependence in aerosol–cloud interactions, namely that increasing aerosol concentration increases the liquid water path of precipitating warm clouds but decreases the liquid water path of nonprecipitating warm clouds. This behavior has not been reported in a global model before, potentially because of a structural bias in the model physics, which explicitly represents a mechanism for aerosols thickening raining clouds but not for thinning nonraining clouds. If the behavior of the ultraparameterized model is indeed due to the closing of this gap in the model physics, then Terai et al. (2020) have taken an important step toward identifying the appropriate level of complexity for modeling the climate impacts of aerosols, including their role in regional climate projections.

How do Terai et al. (2020) improve the representation of aerosol–cloud interactions in global models? The perturbation to the Earth's energy budget, on time scales faster than the warming of the ocean surface, is often referred to as the effective radiative forcing (ERF) by aerosol–cloud interactions (Boucher et al., 2014; Myhre et al., 2014). This is the sum of the near-instantaneous effect of more numerous, smaller droplets when aerosol concentrations are increased (Twomey, 1977), termed the radiative forcing (RF); and the slower (hours to days) responses of the clouds, termed adjustments, that follow the change in droplet number. Under the right set of conditions, the smaller cloud droplets in higher-aerosol conditions are slower to form precipitation (Squires, 1958), which increases average cloud amount (Albrecht, 1989) and thickness (Pincus & Baker, 1994). But they also evaporate more easily, which can beget a turbulent feedback that leads to even more evaporation, reducing average cloudiness (Ackerman et al., 2004; Bretherton et al., 2007). Paradoxically, what happens at the raindrop scale (micrometers to millimeters) is easier to include in the mechanics of a coarse-resolution model than what happens at the turbulent scale (meters to hundreds of meters). This results in an asymmetry in the treatment of these opposite-sign effects (Michibata et al., 2016; Mülmenstädt & Feingold, 2018; Salzmann et al., 2010; C. Zhou & Penner, 2017), with a big part of the physics simply missing or potentially overwhelmed by artificial mixing across a poorly resolved cloud-top inversion at the model scale. In the observed atmosphere, the liquid water path responds weakly to aerosols (Malavelle et al., 2017; Toll et al., 2019) or perhaps slightly decreases (Gryspeerdt et al., 2019), consistent with an enhanced evaporation effect sufficiently large to cancel or perhaps exceed the precipitation suppression effect that is explicitly represented in most models. Thus, while RF is far from well constrained (Quaas et al., 2020), the adjustments are where traditional cloud parameterizations used in GCM-scale models appear to go most wrong. In Terai et al. (2020), the CRM running within each GCM column has a resolution approaching large eddy simulations (LESs) suitable for boundary-layer clouds. LES at this resolution is known to be able to represent entrainment, albeit with quantitative uncertainty, through a combination of the resolved dynamics and subgrid turbulence parameterization. Our interpretation is that the model used by Terai et al. (2020) has been the first to hit the sweet spot between global coverage, resolution, and model physics required to understand the balance between precipitation suppression and evaporation enhancement.

There are two major problems with approaches that do not include global modeling. The first is that models that come closer to resolving the relevant cloud processes are too expensive to run across the full spectrum of conditions that real clouds encounter, a problem naturally solved by ergodicity in a climatology-length global model run. Second, the atmospheric circulation—at scales larger than are accessible to LES runs—and the spatial pattern of aerosol forcing mutually influence each other. Anthropogenic aerosol changes have been the dominant driver of trends in the ITCZ and global monsoons since the mid-twentieth century

(Lau & Kim, 2010; Polson et al., 2014; Ridley et al., 2015; Song et al., 2014), which in turn influences cloud distribution and aerosol distribution and deposition. The change in regional rainfall that accompanies the changes in these circulation features is one of the aspects of climate change that society most urgently requires us to project accurately. Therefore, both for global and especially for regional climate projections, global models are the only tool that allows us to explore the tight links between large-scale circulation and strongly localized aerosol sources.

As a proof of concept, the more realistic cloud physics behavior in the Terai et al. (2020) model is highly encouraging, but some drastic trade-offs were needed to get an ERF estimate. The host GCM is too coarse to resolve regional circulations crucial to aerosol–circulation interactions, likely a step backwards in representing regional circulations accurately given moderate improvements in the Asian summer monsoon (Goswami & Goswami, 2017; Johnson et al., 2016; Ramu et al., 2016) and substantial improvements in the ITCZ (Song & Zhang, 2020) with increasing GCM resolution. The embedded model is too coarse to resolve the turbulent feedback leading to enhanced evaporation, so its quantitative representation of boundary layer entrainment is likely uncertain. The model runs are also too short to sample internal variability in the atmospheric circulation, so distinguishing between forced response and internal variability is not possible. Thus, this is not yet the modeling system the community needs in order to make reliable climate projections. The global km-resolution models currently being developed by a number of groups may offer a pragmatic solution. They have the potential of outright solving enough of the cloud physics and the circulation problem, and, if so, they inherently solve the problem of the interaction between clouds and circulation. Barring that, if they lead to significant progress on only one of these problems, that may sharpen the community's focus on solving the other.

On the cloud physics side, the enhanced evaporation mechanism, which occurs at process scales on the order of meters (Mellado, 2017), is still far beyond the resolved scale of km-scale models. But it is also far beyond the resolved scale of the 250 m CRM in Terai et al. (2020). While the parameterized turbulence and cloud physics will have to do a lot of heavy lifting at the km scale, their task is less gargantuan than at the traditional GCM scale. Approaches exist for representing the cloud-scale turbulence in km-scale models, by eddy-diffusivity–mass-flux (EDMF) schemes (e.g., Siebesma et al., 2007; Tan et al., 2018) or higher-order turbulence closures (e.g., Bogenschutz & Krueger, 2013; Cheng & Xu, 2011; M. Wang et al., 2015), and the enhanced evaporation mechanism can be included in the parameterized physics (Guo et al., 2011). Fundamentally, the struggle is how to represent the limited mixing between the boundary layer and the free troposphere, which in the real stratocumulus-topped boundary layer are separated by a sharp inversion. In models with limited resolution, numerical diffusion leads to artificial mixing, perhaps great enough to drown out any parameterized microphysics–turbulence interaction that would represent the enhanced evaporation effect. For a given combination of model resolution and physics, the strength of the artificial mixing could give an indication of how parameterizable the aerosol-enhanced evaporation effect is in that model (Karset et al., 2020; Sato et al., 2018). Indications are that Terai et al. (2020) have found a combination of resolution and physics that mitigates the numerical diffusion problem; quantifying the numerical diffusion in other combinations of resolution and turbulence scheme (be it ultraparameterization, higher-order closures, EDMF, or any other) could identify other viable combinations. The advance that such models represent is trading a structural problem—a missing, or perhaps drowned out, physical mechanism—for a parametric one. While parametric uncertainty is a tough problem (Lee et al., 2016; Regayre et al., 2018; Tsushima et al., 2020), we have a hunch (Mülmenstädt et al., 2020, 2021) that the right types of observables—in this case, perhaps the regime-dependent liquid water path susceptibilities of Gryspeerdt et al. (2019)—make it more tractable than it currently appears.

On the circulation side, km-scale models' explicit, rather than parameterized, deep convection may improve their regional-scale circulation features (Oouchi et al., 2009), for example by better capturing the interaction between convection and circulation that is an essential feature of the monsoon initiation (Marsham et al., 2013; Willetts et al., 2017). However, regional biases can have remote origins (C. Wang et al., 2014), so long-standing biases in the global circulation, such as the position and structure of the eddy-driven jet. also need to be tackled. These may also benefit from the improved representation of orography that goes alongside increased horizontal resolution (Berckmans et al., 2013). As more groups begin performing longer model runs at higher resolution, we look forward to learning which circulation problems they can mitigate, and which circulation problems will be thrown into starker relief by potential improvements in the cloud physics.

Models have an essential role to play in filling gaps in our understanding of the climate effects of aerosol-cloud interactions. Theories of precipitation suppression as a microphysical effect and enhanced evaporation as an interaction between microphysics and turbulence have existed for quite some time, as have observations of cloud and aerosol state. However, they are not sufficient to paint a global picture. At least in part, this is because theories of phenomena at one spatiotemporal scale in a complex system have limited predictive power on other scales. Models can synthesize our process knowledge across scales—from the cloud scale to the global circulation. Global models can sample the full range of meteorological variability and covariability in a way that more localized cloud process scale modeling cannot. Models based on physical process understanding, unlike empirical relationships in the present day, can provide accurate projections into a future where these empirical relationships may no longer hold. Importantly, they can also establish causation, which observations alone cannot. Global satellite datasets show what can be interpreted as the respective fingerprints of precipitation suppression and enhanced evaporation by aerosols in precipitating and nonprecipitating clouds (Gryspeerdt et al., 2019). The total observed effect of aerosols on liquid water path appears to be small (Malavelle et al., 2017; Toll et al., 2019). The observational evidence is consistent with opposing mechanisms that come close to canceling, but it cannot prove that this is the case. Confounding by meteorological covariability or by other processes cannot be disentangled from the processes hypothesized to cause the observed effect, limiting what observations alone can tell us. Model experiments where processes can be disabled or decoupled from each other, and where aerosol properties can be varied independently of meteorology, can give us a clear answer, provided that the model represents the processes under investigation. If causation can be demonstrated, global models can go further and translate the observed relationships between liquid water path and aerosols into parameters that are left unspecified by theory, namely the strength of precipitation suppression and evaporation enhancement. One of the rays of hope emanating from Terai et al. (2020) is that global models may soon attain the required level of physical completeness where they can play translator between observations and theory. The situation is similar in the theory and observation of regional circulations. There is a plethora of theoretically established mechanisms contributing to monsoons, the seasonal cycle of insolation, differential heating of land and ocean, and orography among them. But theory and the observational record alone do not translate into sufficient quantitative understanding of these mechanisms, their interactions with each other, and their interactions with external influences to yield the reliable regional climate projections that we need. In sufficiently complete models, process denial experiments could again translate between theory and observations.

Improving physics parameterizations is likely to expose remaining errors in models, such as those in large-scale atmospheric circulation patterns. While global models are essential for establishing causation, biases in their representation of the global circulation can limit their simulation of the response to forcing, in addition to causing uncertainty in aerosol ERF. This is particularly pressing for near-term (20–40 years) projections, where the combination of scenario, radiative, and dynamical uncertainty makes anthropogenic aerosol a key factor in the spread in near-term projections of regional climate (Wilcox et al., 2020). Fortunately, the combination of theory, observations, and modeling may help to overcome deficiencies in any one. For example, recent decades have seen a weaker East Asian summer monsoon circulation, leading to flooding in southeast China and drought in the north. Global climate models capture this weakened circulation (Song et al., 2014; Wilcox et al., 2015), and indicate that it is driven by increases in anthropogenic aerosols (Li et al., 2015; Song et al., 2014). However, systematic errors in their representation of the monsoon circulation mean that the associated precipitation change is not correctly captured. In examples like this, where we can learn the mechanism underlying a change from models, there is the potential to combine models with observations to apply physically informed bias corrections to improve our confidence in projections, despite the known biases in the models (Zhou et al., 2020). Such approaches may be a solution when model developments cannot keep pace with society's need for projections.

For over a decade, the climatic effect of anthropogenic aerosol has appeared an intractable problem. Largely separate bodies of literature have attempted to tackle the uncertainties in global-mean ERF and regional climate responses. But these are strongly interwoven problems, and a satisfactory solution—one that permits reliable projections of regional climate change—requires a more unified treatment. This reunification of mechanisms would be aided by more reliable global models, which are, at least in principle, capable of synthesizing the cross-scale interactions from cloud processes to the planetary circulation that have so far stymied every tool at our disposal: theoretical understanding, empirical observations, process-scale modeling, and global modeling. The results in Terai et al. (2020) make us hopeful that cloud physics is not an insurmountable problem in km-scale global models. There is also reason to be optimistic that these km-scale models, by better capturing the interplay between circulation and convection, may resolve some (but by no means all) longstanding circulation biases. We take this as evidence that the arc of our ability to model the climate response to aerosol is bending in the right direction, toward reliable projections of regional climate change, toward helping us test hypotheses built to explain observations, and toward giving global context to the process-scale understanding derived from LES of a limited set of conditions. It is a slowly bending arc, however, fundamentally limited by the fact that a perfect model is neither possible (Oreskes et al., 1994) nor perhaps desirable (Emanuel, 2020). There is no similar limitation on the speed with which society can continue to change its impact on the climate, so continuing to learn how to interpret the messages of biased models, alongside improving the models, remains an essential skill.

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