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• **News & Views** •

Constraining the Emergent Constraints

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An accurate estimate of equilibrium climate sensitivity (ECS) is pivotal to humankind's responses, including both the mitigation and adaptation, to future global climate change (not necessarily that of a distant future). However, the uncertainty in estimates of ECS remains large, as shown in the past assessments by the Intergovernmental Panel on Climate Change (IPCC) (see IPCC, 2013), though the level of understanding on the physics and dynamics of Earth's climate system has improved considerably during the past four decades since the appearance of the Charney report (Charney et al., 1979).

To narrow the gap in ECS estimates, a new approach, called the emergent-constraint method, has been developed during the past two decades. In this approach, a particular climate variable [referred to as the "predictor" in Brient (2020)], which is observable and hence available in the present climate conditions, for instance the changes in albedo or low-cloud fraction per degree of surface temperature variation, is first singled out as a variable that has a clear and definite relationship with the ECS [referred to as the "predictand" by Brient (2020)], i.e., the relationship is consistent across multi-model ensembles. Then, the ECS (predictand) can be constrained based on the observed probability distribution of that particular climate variable (predictor). By "emergent" it is meant that, while the ECS is basically a theoretical and unobservable value, it may emerge from the observable shorter-term variations of the past and present climate. It is unsurprising that, due to the complexity of the climate system and the inter-linkage of physical processes therein, various emergent constraints have "emerged" during the past two decades. Caldwell et al. (2018) systematically evaluated the robustness/weakness and the correlation of the existing 19 emergent constraints in the literature. While confirming shortwave cloud feedback as the main contributor to the correlations among the emergent constraints, Caldwell et al. (2018) cast more doubt than confidence on about 10 of the total 19 emergent constraints. Hall et al. (2019) further suggested a possible use of the emergent constraints in constraining climate extremes, teleconnections, and tipping points of the climate system.

In this issue of *Advances in Atmospheric Sciences*, Brient (2020) provides a thorough survey on the concept of emergent constraints while emphasizing some fundamental issues associated with the concept—namely, the importance of physical understanding, observational uncertainties, and statistical inference in the uncertainty of emergent constraints. Furthermore, the emergent constraints on the changes in the earth system, in a wider sense than the ECS, including the hydrological cycle, carbon cycle, and regional patterns of climate change are also briefly reviewed, though understandably these constraints are even less robust given the lack of available observational data and more uncertain representation in models.

Based on 11 available emergent constraints providing the best estimates of the ECS, Brient (2020) tentatively presents a combined "*a posteriori*" distribution of ECS, which is similar to the "*a priori*" distribution, but skewed toward a higher ECS [Fig. 4 in Brient (2020)]. However, the emergent-constraint-based posterior distribution does not narrow the spread in the original ECS distribution, suggesting the need for further constraining the emergent constraints.

Given the accumulation of massive data about the climate system in the age of big data, the utilization of available data in constraining the ECS cannot be more natural. However, some fundamental issues should be addressed carefully before emergent constraints can really reduce the uncertainty in estimates of climate sensitivity.

Indeed, several theoretical assumptions have been made implicitly when applying emergent constraints to constrain the

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ECS by using the probability distribution of observed predictors. The first is that the statistical predictor–predictand relationship obtained from the climate (or earth) system model ensemble is close to the (unverifiable) reality. This assumption is questionable because of the possible structural biases existing in the imperfect and under-sampled models, but acceptable owing to the fact that these models based on established laws of mathematics and physics are so far the best available tools for climate projections and predictions.

The second assumption is that the consistency established in models between the predictor in internal climate variation and the same predictor in forced climate change might be translated into the observation and real climate system. Such a model–reality translation seems physically plausible, but is far from self-evident. Proper justification for the translation is needed from theoretical, observational modeling perspectives, and hence forms an essential source of the physical robustness of the emergent constraints based on the particular predictor. Let us take the predictor $\delta\alpha_c / \delta T$, i.e., the covariance of de-seasonalized tropical marine low-cloud reflectance (α_c) with surface temperature (T), as shown on the abscissa in Fig. 2a of Brient (2020), as an example. It has been found that those models with internal $\delta\alpha_c / \delta T$ close to observations are also the high-climate-sensitivity models, and the forced $\delta\alpha_c / \delta T$ usually has the same sign as the internal $\delta\alpha_c / \delta T$, albeit with smaller magnitude (Brient and Schneider, 2016). The consistency of the predictor between internal variation and forced climate change is only established in model ensembles so far, and logically it should be further verified with more available data and targeted model simulations guided with robust physical understanding. This in turn may well deepen our understanding of the dynamics of climate change. For instance, it would be valuable to understand the underlying mechanisms responsible for the similarities and differences in the variations of α_c with surface temperature, on the interannual- and interdecadal time scales and on the time scale of anthropogenic climate change.

The ECS is basically the theoretical upper limit of the transient climate response (TCR). Less attention has been paid to constrain the TCR, possibly due to the lack of direct observations of ocean heat content in the past. However, the accumulation of worldwide oceanic observations during the past two decades, and the continuation of this in the near future, will allow the development of emergent constraints on the TCR, and hence may also infer and constrain the ECS from the TCR through the well-established theoretical frameworks developed by Held et al. (2010) and Geoffroy et al. (2013).

Brient (2020) suggests an ECS skewed toward values higher than the original CMIP5 estimate. Indeed, recent several models have reported even higher ECS at the level of 5°C (Gettelman et al., 2019; Golaz et al., 2019; Voosen, 2019). Refined emergent constraints may well help determine if these ECS estimates are plausible.

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