Knowledge Gains: Summary and Implication Report

Climate model emulators

October 2022

Authors and affiliations

Vincent Humphrey¹, Yann Quilcaille¹, Lawrence S. Jackson², Christopher D. Wells²

¹ETH Zürich, Zürich, Switzerland
²School of Earth and Environment, University of Leeds, Leeds, UK

Key messages

- This KGSIR summarizes state-of-the-art assessments of climate emulators and of their ability to provide reliable global-scale climate projections.
- The skill of an emulator is greatly dependent on the climate models, scenarios, and climate metrics with which it was calibrated. It is thus crucial for users of emulators to be aware of the emulator’s “domain of validity”.
- Emulators that are calibrated in a similar way are more consistent with each other. Constrained emulators described in the Chapter 7 of IPCC AR6 WG1 are generally consistent and provide acceptable global temperature projections for climate mitigation scenarios.
- Constrained emulators generally project lower warming than CMIP6 models for a given scenario. This is not a shortcoming of emulators. Rather it occurs because the fraction of climate models producing a very strong warming is overrepresented in CMIP6.
Context
What are climate model emulators?

Physically-based climate emulators are simplified climate models used to calculate how the Earth’s climate responds to external perturbations caused by human activities (like fossil fuel emissions) and natural factors (like volcanic eruptions or solar cycles). These emulators are considered low-complexity models because they represent the most critical components of the Earth’s climate (like the energy, carbon, or ocean heat budgets), and do so in an aggregated fashion at the global scale. This is unlike more complex climate models, such as Earth system models (ESMs), which solve physical equations with the purpose of actually representing the atmospheric and oceanic circulation in three spatial dimensions. In other words, climate emulators directly calculate the Earth’s global mean climate, whereas more complex models have to first resolve the Earth’s weather (the long-term average of which gives the Earth’s climate). One main advantage of emulators compared to complex models is that they can calculate a reasonably accurate global climate projection on a personal computer in a few seconds. To achieve the same task, state-of-the-art climate models need to be run on dedicated supercomputers for several weeks if not months.

Climate models often form the basis on which emulators are developed. Emulators mimic the global-scale behavior that emerges from the more complex climate models using global-scale parameters like the equilibrium climate sensitivity (ECS). These parameters (and their uncertainties) are estimated using just a small subset of numerical experiments performed with the complex models. By slightly varying the emulator parameters, some uncertainty around a given temperature projection can also be estimated.

Figure 1. Climate emulators are simplified models calibrated to capture the overall response of the Earth’s climate to changes in natural and anthropogenic radiative forcing agents, as simulated by more complex models.
Emulators can evaluate a multitude of climate scenarios

Because they are computationally very cheap to run, emulators are ideal tools to explore a wide range of climate scenarios. This is particularly helpful for assessing which combinations of mitigation strategies and emissions reduction objectives are compatible with the climate targets set by international agreements. In its latest report on the Mitigation of Climate Change, the Intergovernmental Panel on Climate Change (IPCC) evaluated several hundreds of such proposed mitigation scenarios using climate emulators (Riahi et al., 2022). Below, we illustrate a climate projection, calculated with a climate emulator (FaIR v1.6.3), for a hypothetical scenario where CO₂ emissions from fossil fuels drop to zero in the year 2023. This figure illustrates that as soon as CO₂ emissions from fossil fuels are stopped, past CO₂ emissions cause no further surface warming in the long term (Dvorak et al. 2022).

Figure 2. (a) all types of greenhouse gas emissions, with a hypothetical net-zero CO₂ emissions from fossil fuels occurring in 2023 and onwards (all other emissions are based on SSP1-2.6). (b) projected global mean temperature response to this hypothetical scenario (black line) and individual contributions of the different forcing agents to warming. Credit: Cyril Brunner, ETH Zürich.

Summary of Knowledge Gains
How well do emulators reproduce climate model projections?

Emulators are typically calibrated against a small number of climate model simulations, for instance those made in the context of the sixth Coupled Model Intercomparison Project (CMIP6). These simulations include historical conditions (where climate models reproduce the observed past warming), standardized diagnostic experiments (e.g. with quadrupling atmospheric CO₂ concentrations), or future climate projections based on shared socio-economic pathways (SSPs) with pre-defined emission scenarios (Eyring et al., 2016). In principle, a well-calibrated emulator should be able to accurately reproduce the results of climate models for all these types of simulations. To verify whether this is the case, the CONSTRAIN project carried several evaluations of the skill of climate emulators.

In a recent study, Jackson et al. (2022) evaluated the performance of a two-layer energy balance model in emulating CMIP6 projections of historical and future temperature. They show that while an
emulator can generally reproduce the behavior of those scenarios that were initially included in the calibration of the emulator, this is not necessarily the case for out-of-sample scenarios which were never seen by the emulator. These findings show that a rigorous evaluation of an emulator’s actual performance should rely on an independent testing set of climate models and simulations.

In another study, Quilcaille et al. (in revision) evaluated the ability of the climate emulator OSCAR (v3.1) to reproduce CMIP6 climate model simulations. To characterize the uncertainty of the emulator projections, they first generate an ensemble of parameter values. They show that constraining these parameter combinations using historical observations is crucial in order to discard combinations that lead to unphysical, unrealistic, or unlikely projections. The constrained parameter sets are then used to reproduce individual CMIP6 simulations for various variables such as global mean surface temperature, ocean heat content, or carbon stocks. Their results show that, with the exception of high warming scenarios, the constrained emulator overall reproduces the behavior and responses of complex climate models well in terms of warming, radiative forcing, and atmospheric CO₂ concentrations. The projected evolution of the carbon stocks is more uncertain. In particular, compensating effects can lead to some errors in the partitioning of carbon stocks, without strong consequences for the projected warming. One example is when a too weak land carbon sink is compensated with a too strong ocean sink (and vice versa). Such compensating errors were also reported by Jackson et al. (2022), who found that opposing errors in the emulation of greenhouse gas versus aerosol forcings could give a misleading impression of an emulator’s overall performance.

**Figure 3. Example of compensating errors in carbon fluxes in the OSCAR v3.1 emulator.** (a) Simulated ocean carbon uptake compared with observational estimates from the global carbon budget (GCB 2020). (b) Simulated land carbon uptake. (c) Simulated atmospheric CO₂ concentrations compared with observational estimates from IPCC AR5.

How well do emulators agree with each other?

The Reduced Complexity Model Intercomparison Project (RCMIP) compared nine different emulators which were all calibrated using procedures specific to each of the modeling groups (Nicholls et al., 2020; Nicholls et al., 2021). The results showed that emulators may disagree, not only in terms of projected overall warming but also in terms of their attribution of warming to forcing agents (for aerosols in particular). To reduce this spread, Nicholls et al. 2021 suggested integrating observational constraints directly within the emulator calibration (instead of correcting the climate projections a posteriori).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 820829.
In Chapter 7 of the Sixth Assessment Report of the IPCC, four emulators (CICERO-SCM, FaIR, MAGICC and OSCAR) were calibrated to match a larger array of constraints (including future warming projections under different SSPs), as estimated from multiple lines of evidence in the IPCC report. The evaluation and intercomparison of these similarly calibrated emulators showed that they are generally able to reproduce the targeted constraints with only minor differences (Forster et al. 2022). Emulator projections also generally agree with each other, which represents an important improvement from the inconsistencies that were identified in Nicholls et al. (2021) or in the previous IPCC special report on the impacts of 1.5 and 2 degrees of warming (SR1.5). These emulators (used in their associated configurations) currently represent the best available tools to evaluate alternative emission scenarios beyond existing SSP trajectories at a low computational cost.

Figure 4. Emulation of SSP1-2.6 by three different emulators and CMIP6 climate models. This figure shows that when emulators are calibrated in a similar fashion, they tend to agree well with each other. Source: Smith et al. 2021, Figure 7.SM.2.

Are emulators and CMIP6 ensembles consistent?

In CMIP6, some climate models have a rate of warming that is currently considered too strong and unlikely when compared against historical observations (Tokarska et al. 2020). As emulators often incorporate observational constraints themselves, this can lead to an apparent discrepancy (e.g. Figure 4) if they are directly compared to all available CMIP6 models (including those that warm too fast), and not to a similarly constrained ensemble of CMIP6 models (Nicholls et al. 2021). To address this problem, observational constraints as well as metrics of model independence can be used to generate appropriate model weights that reduce the importance of these ‘too warm’ CMIP6 models when calculating multi-model averages (Brunner et al. 2022). Current work within CONSTRAINT (ETH Zürich) aims to develop a universal and flexible approach for generating CMIP6 model weights that are as consistent as possible with the climate sensitivity metrics typically targeted by climate emulators. This shall facilitate comparisons between emulator results and the CMIP6 ensemble for a wider range of variables, experiments, and subsets of the available models.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 820829.
Next steps: towards emulating regional temperatures

Future developments within the CONSTRAIN project aim to improve our ability to make regional temperature projections on the basis of emulators. As temperature changes at the local scale are often approximately linearly related to global mean temperature changes, it is in principle possible to predict a regional warming pattern from an emulator-based projection of global warming. This technique, commonly referred to as pattern scaling, improves the applicability of emulators in the context of climate impacts modeling. Current work within CONSTRAIN (University of Leeds) focuses on evaluating the reliability of pattern scaling for various types of scenarios and how to address the main identified shortcomings (Wells et al., in review). Future work within the CONSTRAIN project will include an intercomparison on spatial emulation techniques, to assess their relative effectiveness and make recommendations for their use.

Implications

Constrained emulators are more reliable

Evaluation of climate emulators has shown that using an adequate (constrained) set of model parameters is crucial to providing robust climate projections. In situations where multiple parameter values are randomly combined to estimate a projection uncertainty, some combinations of parameters will likely yield results that are either unphysical or not consistent with historical observations (Quilcaille et al., in revision). Thus, using thoroughly tested and constrained parameter sets provided by model developers is strongly recommended. Emulators that were calibrated or constrained in the same way (Forster et al. 2022) are in much better agreement with each other than emulators calibrated in a non-unified fashion (Nicholls et al. 2021).

Emulators are more reliable within the range of existing SSPs

Recent work by CONSTRAIN authors has shown that the reliability of an emulator greatly depends on what models and scenarios are used for the calibration of the emulator parameters (Jackson et al. 2022). Thus, it is crucial for users of emulators to be aware of the emulator’s “domain of validity”. Generally, emulators have been shown to produce larger errors in the case of high-emission scenarios, for scenarios with a large temperature overshoot, as well as when projections are extended very far into the future (i.e. after year 2100). Scenarios that are merely variations of existing SSPs are likely to be more accurately simulated compared to those with substantial differences.

An emulator is a good alternative to climate models at short-range

Considering near-term projections of anthropogenic warming (for instance, over the next 20 years), emulators can provide quite reliable estimates (see our previous report on near-term warming in Bonnet et al., 2022). Emulators may even be better equipped for near-term projections than CMIP6 models which, unlike emulators, also include a significant amount of natural variability that is not relevant in terms of the Paris Agreement targets (Lanson et al., 2022). For cases where near-term natural variability should be considered, recent work conducted by CONSTRAIN authors also showed that adding natural variability to emulator outputs was a good alternative to climate models (McKenna et al., 2021).
Unconstrained CMIP6 models overestimate warming compared to emulators

Emulator projections may not be directly comparable to the full ensemble of CMIP6 models because some models within CMIP6 have been identified as warming faster than what is suggested by historical observations. Users of climate emulators constrained on observations should expect emulator projections to yield lower warming levels than CMIP6 models for a given SSP scenario (Forster et al. 2022). Observationally constrained CMIP6 multi-model averages are more comparable to emulator results.

References


This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 820829.


About the Authors
Vincent Humphrey is a postdoctoral researcher at ETH Zürich within CONSTRAIN Work Package 4. His work focuses on constraining large ensembles of climate model simulations in a way that also accounts for average model performance and statistical independence between models sharing the same code or origin.

Yann Quilcaille is a postdoctoral researcher at ETH Zürich, now under the ERC Proof-Of-Concept MESMER-X (Grant Agreement 964013). His work focuses on the development of the spatially resolved emulator of climate extremes MESMER-X.

Lawrence Jackson is a postdoctoral researcher at the University of Leeds within CONSTRAIN Work Package 4. His work focuses on the development of a climate model emulator to incorporate the pattern effect and its impact on future global temperature projections.

Chris Wells is a postdoctoral researcher at the University of Leeds within CONSTRAIN Work Package 4. He researches the accuracy of spatial emulation techniques.

About this Knowledge Gains: Summary and Implication Report
CONSTRAIN’s Knowledge Gains: Summary and Implication Reports outline CONSTRAIN’s contributions to the peer reviewed literature (knowledge gains), and summarise the implications for both the scientific community and broader society. This report and other CONSTRAIN publications are available at http://constrain-eu.org.

Acknowledgements
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 820829.

How to cite

About CONSTRAIN
The 2015 Paris Agreement sets out a global action plan to avoid dangerous climate change by limiting global warming to well below 2°C, whilst pursuing efforts to limit warming to 1.5°C. However, predicting how the climate will change over the next 20-50 years, as well as defining the emissions pathways that will set and keep the world on track, requires a better understanding of how several human and natural factors will affect the climate in coming decades. These include how atmospheric aerosols affect the Earth’s radiation budget, and the roles of clouds and oceans in driving climate change.

The EU-funded CONSTRAIN project, a consortium of 14 European partners, is developing a better understanding of these variables, feeding them into climate models to reduce uncertainties, and creating improved climate projections for the next 20-50 years on regional as well as global scales. In doing so, CONSTRAIN will take full advantage of existing knowledge from the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) as well as other Horizon 2020 and European Research Council projects.

web: http://constrain-eu.org

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 820829.
twitter: @constrain-eu

For more information or to contact the authors please email constrain@leeds.ac.uk

This work is licensed under a Creative Commons Attribution 4.0 International License

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 820829.