Horizon 2020 Societal challenge 5:
Climate action, environment,
resource efficiency and raw materials

The role of Climate Model Emulators in the IPCC 6th Assessment Report

An Online Workshop for the Scientific Community

30 September 2021

Workshop Report

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Lawrence Jackson and Piers Forster

School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

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Executive summary

On 30 September 2021, the EU CONSTRAIN project hosted an online workshop "The Role of Climate Model Emulators in the IPCC 6th Assessment Report". The workshop appraised recent developments in the use of climate model emulators in the 6th Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) which was published on 9 August 2021.

The workshop highlighted the many ways in which climate model emulators contributed to AR6. Some of the notable benefits are:

- Synthesis of multiple lines of evidence and production of 100s of projections central to the assessments of WG1 and WG3.
- Supporting the IPCC's ambition to produce open science using transparent, accessible models and data.
- Facilitating communication, collaborative working, and consistency between the working groups and between the chapter teams in WG1.

The discussion at the workshop made it clear that emulators offer considerable opportunities to enhance both future climate research and the communication of climate science, in terms of:

- Advancing emulations from global means to regional climate changes, and from changes in climate means to changes in climate extremes.
- Facilitating capacity building, and promoting communication and dialogue about climate science with a wider community of scientists and interested parties such as policymakers and decision makers.

This workshop was dedicated to the early career scientists who made a substantial contribution to the work on emulators in the IPCC AR6.

Introduction

Climate model emulators are simple models that can reproduce the behaviour of more complex climate models but require less time and computational resources to run.

The purpose of the workshop was to share recent developments in the use of climate model emulators in the 6th Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC). The IPCC Working Group 1 (WG1), which focuses on physical climate science, used climate model emulators to make projections of future temperatures and sea level. The emulators developed by WG1 will be used by the IPCC Working Group 3 (WG3) in their assessment of climate change mitigation.

Motivated by the desire of the IPCC and the European Commission, CONSTRAIN's funding body, to provide "open science", the workshop was advertised to the wider scientific community and was attended by more than 90 people from a wide range of institutions.

The workshop was organised by members of the IPCC and the EU CONSTRAIN project. CONSTRAIN is an €8 million, 4-year (2019-2023) programme of research and stakeholder engagement, funded by Horizon 2020. CONSTRAIN is led by the University of Leeds and the CONSTRAIN consortium involves 14 partners with around 40 researchers from 9 countries across Europe and Israel. CONSTRAIN scientists played a major role in the development and application of emulators in the IPCC AR6.

Workshop introduction

Valérie Masson-Delmotte (Co-Chair of WG1) opened the workshop with a short introduction describing the key roles played by climate model emulators in the WG1 climate assessment.

Emulators were used to:

- Bring together multiple lines of evidence. For example, building on the assessed climate sensitivity and constrained projections from complex climate models to provide future temperature responses consistent with process understanding.
- Augment results available from more complex climate models. For instance, there are relatively few climate model simulations available for future temperature projections beyond 2100.
- Enhance the consistency of AR6 across the different chapters and across the working groups. The emulators developed by WG1 have been shared with researchers working on WG3 and will be used to generate hundreds more scenarios to inform the assessment of climate change mitigation.

The introduction also highlighted how climate model emulators offer opportunities for future research. The focus of WG1 was on future projections of temperature and sea level. In future, emulators could be developed to produce projections for other aspects of a changing climate (e.g. precipitation changes and changes in climate extremes) providing inputs for impact studies and scenario planning.

Session I: Presentations

Session I comprised presentations from IPCC researchers who described how climate model emulators were used by WG1 and the benefits they provided to the WG1 assessment. The presentations were followed by a question and answer session.

Presentation 1: The overall purpose of emulators and the Reduced Complexity Model Inter-comparison Project (RCMIP)

Malte Meinshausen (University of Melbourne, WG1 Co-Lead Author for Chapter 1)

A brief overview of the history of emulators in the IPCC assessments was presented. Climate model emulators have been used, to varying degrees, in all of the IPCC assessment reports. In the first assessment report (1990), for example, an upwelling diffusion energy balance model was used to translate greenhouse gas forcing into a temperature response based on a prescribed climate sensitivity. The emulator was used to provide headline results in both the main report and the summary for policymakers.

The use of emulators in AR6 represents a methodological advance over previous assessments. Headline results in AR6 used a 50:50 mix of projections from constrained CMIP6 models and emulators that were constrained to low, medium and high equilibrium climate sensitivity (ECS) / transient climate response (TCR). The evolution of climate model emulators has also culminated in the Reduced Complexity Model Intercomparison Project (RCMIP), a research community initiative. Findings from RCMIP contributed to the emulator comparison in Chapter 7 of AR6 WG1.

Presentation 2: Combining an emulator and CMIP6 models to assess future warming

Sebastian Milinski (Max Planck Institut für Meteorologie & National Center for Atmospheric Research (NCAR), WG1 Contributing Author and Chapter Scientist for Chapter 4)

Sebastian Milinski described how a physically-based climate model emulator, combined with CMIP6 projections, were used to produce the assessed global mean surface air temperature (GSAT) projections in Chapter 4 of AR6 WG1.

The GSAT projections from comprehensive global climate models were emulated using a two-layer energy balance model. The emulator was calibrated to different combinations of ECS and TCR by tuning the climate feedback parameter and ocean heat uptake efficiency. Tuning was based on the assessment of AR6 WG1 Chapter 7. The methodology used is summarised in Figure 1.

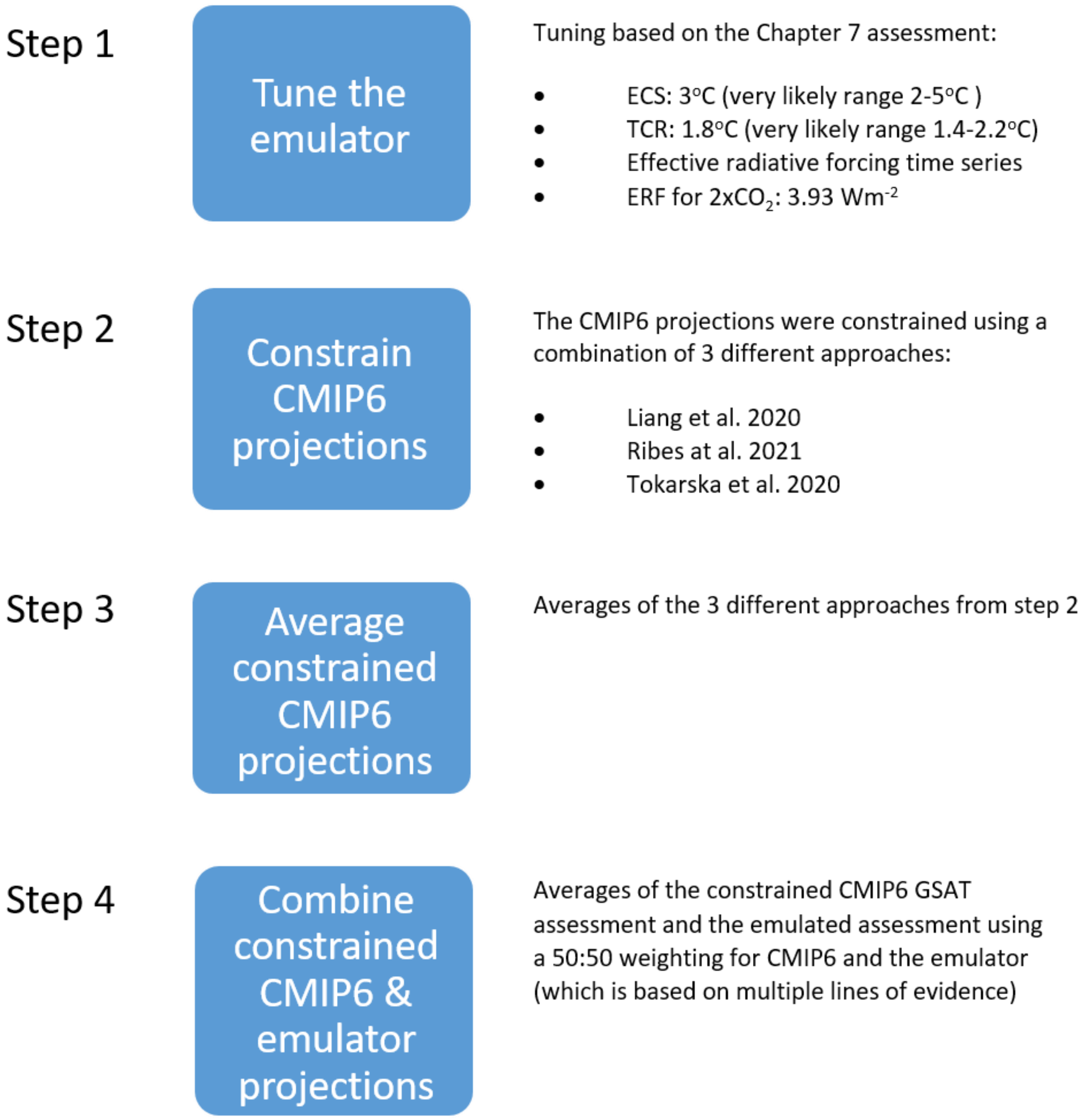

Figure 1. The method used to combine projections from climate model emulators and projections from CMIP6 models in AR6 WG1 Chapter 4.

The approach summarised in Figure 1 yielded time series projections of assessed GSAT to 2100. The projections include a central estimate and a 5-95% range for five future climate scenarios. These results were used to determine future rates of warming, crossing times for 1.5°C and 2°C warming, and to inform the assessment of several other chapters in the WG1 report (Figure 2). Use of climate model emulators, therefore, facilitated the consistency of GSAT projections between Chapters 4 and 7 of AR6 WG1.

The assessment of regional climate change was partly based on unconstrained CMIP6 projections anchored to the times when the assessed GSAT exceeded specific warming levels, as it has been found that there is not a strong pathway dependence for temperature and precipitation patterns at a stated level of GSAT change.

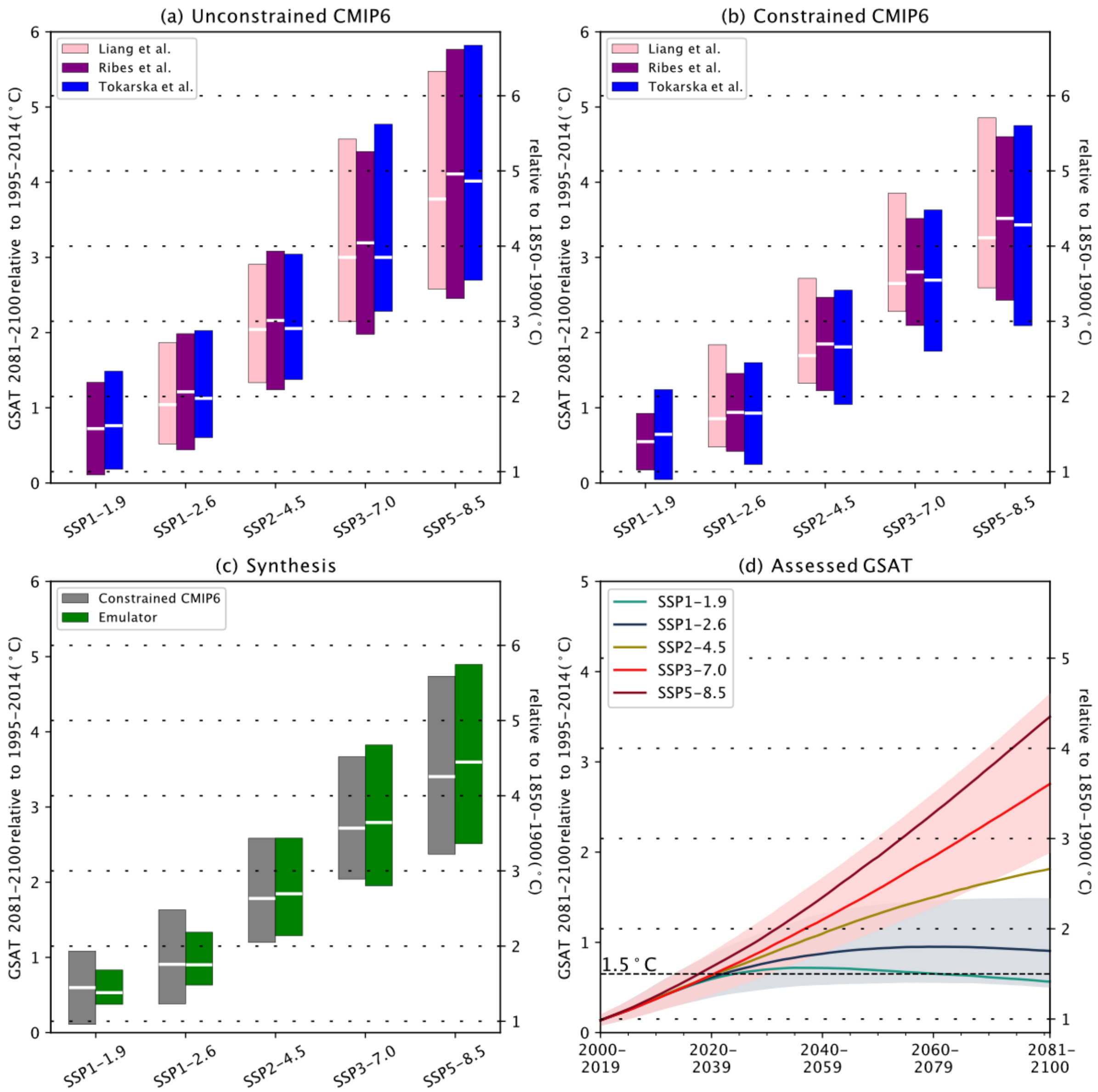

Figure 2. CMIP6 projections (panels a, b and c), and emulator projections (panel c) used to produce projections of assessed GSAT to 2100 (panel d). (Source: AR6 WG1 Chapter 4 Figure 4.11).

Presentation 3: Effective radiative forcing and contributions to historical and future warming

Chris Smith (University of Leeds, International Institute for Applied Systems Analysis (IIASA), WG1 Chapter 7 Contributing Author and Chapter Scientist)

Chris Smith described how physically-based climate model emulators were used to extend the results from complex climate models to produce projections of effective radiative forcing (ERF) and to attribute warming to forcing.

Observations provide limited information on how short-lived forcers, such as ozone and aerosols, vary before the satellite era, and complex climate models are generally the best tools available. Emulators tuned to the climate responses for short-lived forcers in complex climate models enable projections to be produced for scenarios where few climate model simulations are available. Further, combining forcing emulators and climate response emulators helps determine the contribution of different forcers and emission species to historical warming including a combined assessment of uncertainty in forcing and climate response.

In the IPCC AR6 WGI Report Summary for Policymakers (SPM), present-day warming was attributed to source emissions with the aid of emulators. One example of the insight gained is that the temperature attribution to methane emissions is approximately twice that based on the change in methane concentrations alone. This arises from the indirect effects of methane emissions on ozone and stratospheric water vapour forcings. The attribution of warming to underlying forcers was also extended to future projections. This helped identify the predominant contribution to future warming (CO_2 forcing) and highlights the priorities for achieving the climate change targets in the Paris Agreement.

Presentation 4: Emulation and integration in ocean, cryosphere, and sea level projections

Robert Kopp (Rutgers University, WG1 Chapter 9 Co-Lead Author)

Emulators were used in the following areas within Chapter 9 of the WG1 report:

- Projections of thermal expansion that fed into the integrated sea level projections. These projections were built from surface temperature and deep ocean heat content projections from the physically-based two-layer emulator used by AR6 WG1 Chapters 4 and 7, and scaling with outputs from the CMIP6 models.
- The contributions of glaciers and ice sheets to sea level rise. There is a limited set of model simulations available in the GlacierMIP and ISMIP6 exercises and the forcings used were predominantly based on CMIP5. Gaussian process emulators, which are non-parametric statistical models and not simple physics or parametric statistical models, were used to extend the range of projections and enforce consistency with the Shared Socio-economic Pathway (SSP) temperature based projections.

The Framework for Assessing Changes to Sea Level (FACTS) was developed to produce the integrated assessment of sea level change. FACTS is a modular framework that enables assessment of different assumptions and their propagation to global, regional and extreme sea level changes. For example, alternative modules based on structured expert judgement were used to assess deep structural uncertainty and investigate processes in which there is currently low confidence.

Using FACTS, assessments of global mean sea level (GMSL) were produced for the 5 SSPs extended to 2150. As well as medium confidence projections, low confidence projections were used to assess structural uncertainties. Further, FACTS supports the extrapolation of global projections to regional sea level change. In partnership with the NASA sea level change team, a sea level projection tool has been developed which will provide local sea level projections that correspond to the projections in AR6 WG1 Chapter 9.

Presentation 5: Cross-Chapter box 7.1 and the WG1-WG3 handover

Zebedee Nicholls (University of Melbourne & IIASA, WG1 Chapters 1, 4, 5, 6, and 7 Contributing Author)

Cross-Chapter box 7.1 describes how emulators were used in the WG1 report and documents the performance of the emissions driven emulators which were provided to WG3.

The assessment of WG3 requires ~2000 probabilistic projections of GSAT that all need to be defined in terms of emissions scenarios. Emissions driven, probabilistic emulators are the only viable option. Table 2 of Cross-Chapter box 7.1 compares the performance of the emulators to the best estimates and ranges of key climate metrics as assessed by WG1.

The large majority of simulations from complex climate models were driven by specified concentrations. The performance evaluation, therefore, involved the comparison of concentration driven emulators with the complex models and the comparison of concentration driven and emissions driven emulators. Emissions driven emulations have a lower median change in GSAT than concentration driven emulations. Emissions driven emulations also have a wider range of GSAT changes because of carbon-cycle uncertainty that was not captured in the concentration driven emulations. The evaluation of emissions driven emulations remains a key area for further research, substantially more evaluation work was done on the concentration driven emulations.

The conclusions provided to WG3 are that the FaIR and MAGICC emulators are consistent and acceptably close to the assessments of WG1. Two other emulators, CICERO-SCM and OSCAR, are also available to provide additional information for evaluating the sensitivity of scenario classification to model choice, but they do have identified limitations.

Session II: Panel discussion

The panel discussion was chaired by Jan Fuglestvedt (Vice Chair of WG1) and the panel comprised: Malte Meinshausen (Co-Lead Author WG1 Chapter 1), Joeri Rogelj (Co-Lead Author WG1 Chapter 5), Keywan Riahi (Co-Lead Author WG3 Chapter 3), Sonia Seneviratne (Co-Lead Author WG1 Chapter 11), and Valérie Masson-Delmotte (Co-Chair WG1).

The panel discussion focused on two themes: the benefits from using emulators in WG1 and the handover to WG3; and, future opportunities offered by the use of emulators. The key points are summarised below in Figure 3.

Benefits

- Consistency between WG1 chapters
- Consistency between the climate assessment of WG1 and the scenarios of WG3
- Useful tool for synthesizing multiple lines of evidence
- Broader appreciation of uncertainties in the climate assessment of WG1
- Transparent approach with accessible models and data
- Explicit calibration of the emulators (intentional use of the term emulator)

Opportunities

- Develop statistical regional emulators to enhance the coherency between the assessed global response and regional implications
- Develop statistical emulators for climate extremes
- Enhance the handover to WG3 by coupling to IAMs and considering case studies
- Capacity building, outreach, training
- A tool for communication and engagement with a wider community – anyone can assess their own scenarios consistent with the IPCC assessment
- A tool for deeper understanding of the questions e.g. by inverting the analysis working backwards from specific questions

Figure 3. Key points raised during the panel discussion and subsequent questions and answers discussion.

Some issues associated with the use of emulators were raised during the panel discussion and online chat:

- Some slight inconsistencies remain between WG1 chapters (e.g., in the approach to the relationship between ECS and TCR).
- There is a potential risk of overconfidence. Examples include unwarranted precision in emulated climate outcomes, and in overshoot scenarios which differ greatly from the available observational constraints.
- The domain of validity for the emulators and the propagation of uncertainty needs to be better understood.
- There is a need to assess the tails of distributions, e.g. ECS, and consider low likelihood, high impact outcomes.

The availability of probabilistic, emissions driven emulations is central to the task of categorising 100s of different mitigation scenarios into categories based on prescribed ranges of future temperature change. This approach to categorisation helps identify differences between scenarios with different temperature change outcomes, for example, between scenarios that limit temperature change to 2°C and those that limit it 1.5°C.

Work is already underway on the development of regional climate emulators. The MESMER model (Beusch et al. 2020) produces regional temperature projections from global temperature trajectories. A version of MESMER has been coupled with MAGICC (Beusch et al. 2021, in review) and a monthly version of MESMER is also in review (Nath et al. 2021).

Another example of the open science approach of the IPCC is the interactive atlas https://interactive-atlas.ipcc.ch/.

Acknowledgements

This workshop is dedicated to the early career scientists who, in large part, delivered the work on climate model emulators for the IPCC AR6. We would like to express our gratitude to the workshop participants and our appreciation to Jessica Clarke and Debbie Rosen for their assistance in organising the workshop. The workshop was organised and funded by project CONSTRAIN, a programme of research and stakeholder engagement which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 820829.

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Appendix: Workshop agenda

12:00-12:05 Welcome and Introduction

New developments since AR5 and workshop objectives

Speaker: Valérie Masson-Delmotte (LSCE (CEA-CNRS-UVSQ/IPSL), Université Paris Saclay)

12:05-12:30 Part 1 - Presentations

The contribution of climate model emulators to the IPCC AR6

Chairperson: Kasia Tokarska (ETH Zurich)

Speakers: Malte Meinshausen (University of Melbourne)

Sebastian Milinski (Max Planck Institut für Meteorologie)

Chris Smith (University of Leeds & International Institute for Applied Systems Anal (IIASA))

Robert Kopp (Rutgers University)

Zeb Nicholls (University of Melbourne)

12:30-12:45 Part 2 – Q and A

Moderated Q and A session

Chairperson: Kasia Tokarska (ETH Zurich)

12:45-13:25 Part 3 – Panel Discussion

Reflections from the panel members on the presentations and subsequent Q and A session

Chairperson: Jan Fuglestvedt (CICERO)

Panel: Malte Meinshausen (University of Melbourne)

Joeri Rogelj (Imperial College London)

Keywan Riahi (International Institute for Applied Systems Analysis (IIASA))

Sonia Seneviratne (ETH Zurich)

Valérie Masson-Delmotte (LSCE (CEA-CNRS-UVSQ/IPSL), Université Paris Saclay)

13:25-13:30 Conclusion

Speaker: Piers Forster (University of Leeds)