Emergent Constraints

FACTSHEET
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Climate-Carbon Interactions in the Current Century

In this factsheet, we explore emergent constraints, how they can be used to reduce model uncertainties in climate projections, and their value for climate mitigation and adaptation.

EARTH SYSTEM MODELS AND CLIMATE PROJECTIONS

Emissions of greenhouse gases (GHGs) have continued to grow over recent decades, causing global warming and climate change. The effects of the changing climate and increase in temperature have been observed around the world, and include among others heatwaves, coral bleaching, droughts, and wildfires. To prepare for the future and adapt to climate change, projections of the future climate are essential.

The state-of-the-art tool for climate projections are Earth System Models (ESMs). ESMs simulate the vastly complex Earth system, including physical, chemical, and biological processes taking place in the atmosphere, ocean, and land.

ESMs can be used in many different ways, for example to simulate the Earth under pre-industrial conditions (i.e., without human influence on the climate) or to reproduce the historical evolution of the climate over the last 250 years. Moreover, ESMs are able to simulate the evolution of the future climate under predefined scenarios of GHG emissions.

Climate projections allow comparison of future climate conditions under different socio-economic futures, for example a world in which strong emission reductions will be implemented in contrast to a world in which humanity continues emitting vast amounts of GHGs into the atmosphere. Thus, projections by ESMs can help us to understand the impact of our actions on the Earth's future climate, to determine the emission reductions necessary to keep within certain climate goals (such as the 1.5°C target of the Paris Agreement), and to implement appropriate adaptation measures.

However, ESMs developed by modelling centres around the world can differ in the represented processes, the parameterisation of sub-grid scale processes, and their resolution. These intrinsic differences in ESMs cause climate projections for a given future scenario to differ across the different ESMs. For example, while one model may project a global mean temperature increase of 2°C by the year 2100 for a given emission scenario, another model could project a warming of 3°C for the same future emission scenario.

Climate scientists refer to this as **model uncertainty** (Hawkins and Sutton, 2009). One popular method to reduce this model uncertainty in multi-model projections is the **emergent constraint** approach.

REDUCING UNCERTAINTIES IN CLIMATE PROJECTIONS WITH EMERGENT CONSTRAINTS

The differences in the climate projections across models lead to more or less plausible representations of Earth system processes. In the past, the quality of ESMs was often evaluated and rated by comparing model results over the historical period with observations.

However, such a comparison only assesses how well the models represent the past and present-day climate, and does not necessarily allow to evaluate the models' performance when simulating a future climate that strongly differs from the past and present climate.

Emergent constraints can offer a solution to this problem, since they do not evaluate or rank individual ESMs, but rather assume that all models can simulate a given relationship between an observable variable of the current or past climate and a non-observable target quantity of the future climate. In combination with observations of the past and present-day climate, this relationship among the different ESMs can then be used to constrain the future target quantity (see Box).

Box: Emergent constraints approach

Figure 1 is an idealised sketch of how the emergent constraint approach is applied. Each blue dot in the figure corresponds to the output of a single ESM. These dots lie almost on a line (red), which is called the emergent relationship between x and y. If all models lie on the same line, it can be assumed that each model would simulate the same value for y if the input in x was the same. Therefore, this emergent relationship can be exploited with observations of variable x (blue shaded area) to derive a constrained value for the desired target quantity y (grey shaded area).

The uncertainty given by the emergent constraint (grey shaded area) is a combination of the uncertainty of the emergent relationship (red shaded area) and the uncertainty of the observations (blue shaded area). A more robust emergent relationship among the different ESMs and more accurate observations lead to a less uncertain projection of the target variable. The results of such a constraint can only be robust if the identified emergent relationship between x and y is based on an explainable and robust physical mechanism.

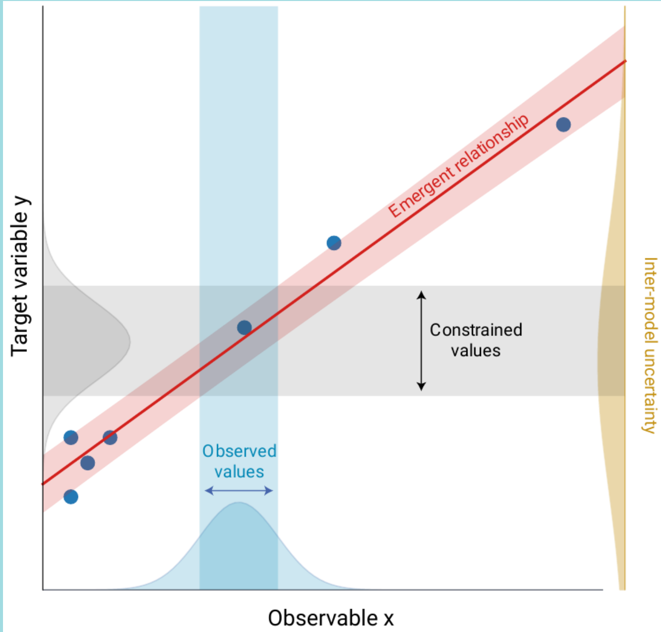

Figure 1. Illustration of the emergent constraint approach that can be used to constrain future climate projections (i.e., the target variable y) using a physically-interpretable and robust relationship among different ESMs (red line and shading) and an observation x of the past or current climate (blue shaded area). Adapted from Eyring et al. (2019).

EXAMPLE OF AN EMERGENT CONSTRAINT: THE SOUTHERN OCEAN ANTHROPOGENIC CARBON SINK

An emergent constraint was identified in the 4C project to reduce the uncertainty related to the uptake of carbon in the Southern Ocean (Terhaar et al., 2021). The ocean is a major carbon sink, but its strength and future evolution remain highly uncertain. Most of the uncertainty of the ocean carbon uptake stems from the Southern Ocean, the largest ocean carbon sink, because of its complex circulation that is difficult to simulate, and the few observations that exist in this remote and hostile region.

This major uncertainty of the future Southern Ocean carbon sink was cut in half with an emergent constraint, according to the study by Terhaar et al. (2021). The authors detected an emergent relationship between the future Southern Ocean anthropogenic carbon uptake and the sea surface salinity in the part of the Southern Ocean where waters are subducted below the surface ocean.

A higher salinity increases the density of the ocean surface waters, causing more water to sink into the ocean interior, making room for deeper waters to come back to the ocean surface, which can in turn take up more carbon from the atmosphere.

By exploiting this emergent constraint, with observations of the ocean surface salinity, the uncertainty around the uptake of anthropogenic carbon in the Southern Ocean could be reduced by 46 to 54% (Figure 2).

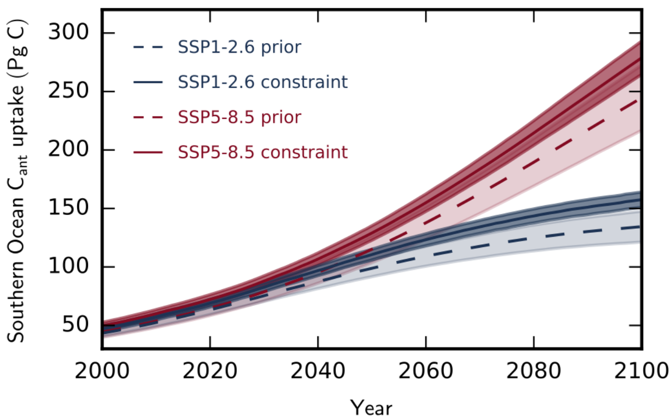

Figure 2. Projections of Southern Ocean anthropogenic carbon (C_{ant}) uptake over the 21st century for two emission scenarios (blue = low-emissions high-mitigation; red = high-emissions no-mitigation) before and after applying emergent constraints. Source: Terhaar et al., 2021.

CAVEATS AND LIMITATIONS

Emergent constraints are a powerful tool to reduce the uncertainty in multi-model climate projections. However, these constrained projections cannot go beyond the limitations of these ESMs.

If, for example, an unknown process that is not simulated in any of the ESMs will impact the target variable in the future, neither the multi-model mean nor the constrained result will account for such a process.

Examples for the Southern Ocean anthropogenic carbon sink would be the melting of Antarctic sea ice, or changes in carbon and nutrient riverine delivery, which are not yet represented in most ESMs. Thus, although the constrained results reduce the uncertainty, they cannot remove uncertainties from unknown or unrepresented processes.

IMPLICATIONS FOR POLICYMAKING

Earth system models are invaluable tools to quantify future climate change. However, the simulated projections are always associated with uncertainties. Emergent constraints are a powerful method to reduce these uncertainties with observational data, which ultimately helps to define targeted mitigation and adaptation measures that are necessary to minimise climate change and its impacts.

References

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