D8.2: Emergent constraints on climate sensitivities

Mark Williamson[1]

Chad Thackeray[2], Peter Cox[1], Alex Hall[2], Chris Huntingford[3] and Femke Nijsse[4]

[1]CEMPS & GSI, University of Exeter

[2]Atmos & Ocean Sci, UCLA

[3]CEH Wallingford

[4]CLES & GSI, University of Exeter

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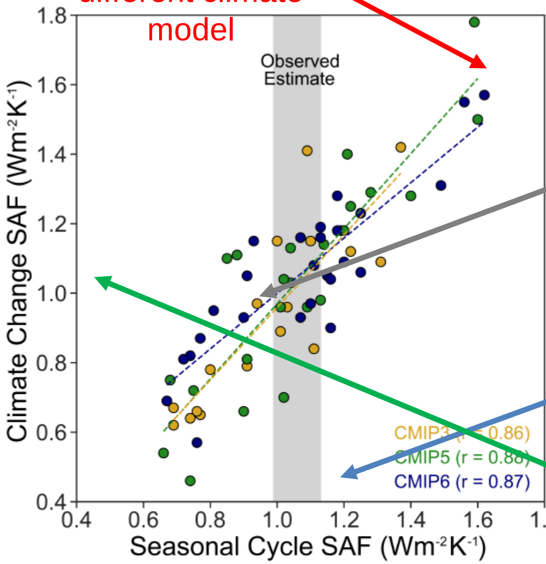
What are emergent constraints?

A method to constrain a real world unknown using model ensembles and observations

Each dot is a different climate model



Emergent relationship: Low dimensional relationships in model ensembles between something that one can measure in the real world (trend or variation, x axis) and something you want to know for the real world (Earth system sensitivity, y axis)

Observable measured in real world

Emergent constraint: Emergent relationship combined with value of observable in real world implies a constraint on real world value of Earth system sensitivity

Snow albedo feedback (SAF) - Hall, A. & Qu, X. Using the current seasonal cycle to constrain snow albedo feedback in future climate change. *Geophysical Research Letters* **33** (2006).

Emergent constraints found

Since the snow albedo feedback emergent constraint many more have been found.

Emergent constraints on:

- Climate sensitivity
- Carbon cycle
- Cloud feedbacks
- Cryosphere
- Hydrological cycle

Comprehensive table in **Rev. Mod. Phys. (in press)/arXiv:2012.09468.**

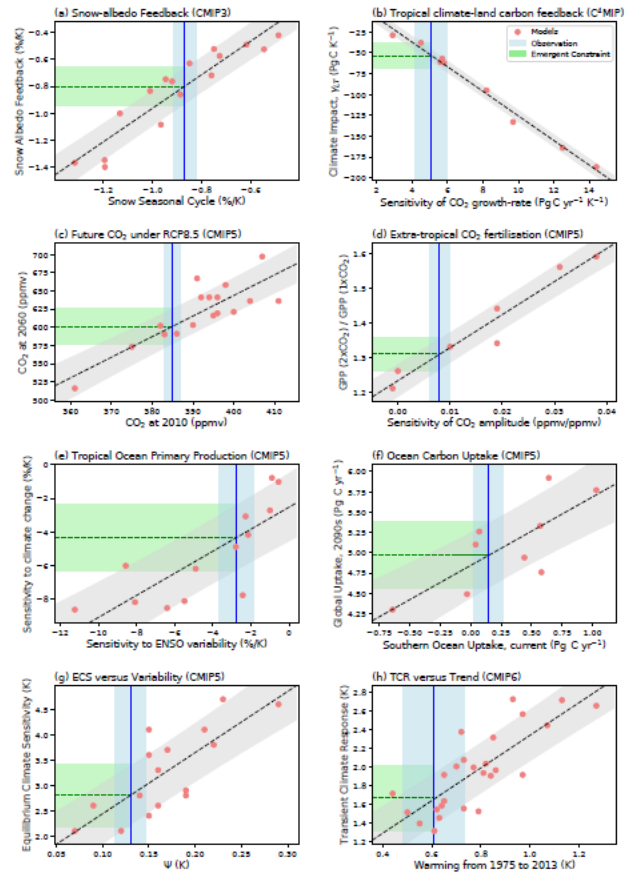


FIG. 3 Emergent constraints on Earth System sensitivities based on some key examples published in the literature: (a) snow-albedo feedback, from snow seasonal cycle (Hall and Qu, 2006); (b) sensitivity of tropical land carbon to global warming, from interannual variability in CO_2 (Cox *et al.*, 2013); (c) atmospheric CO_2 concentration at 2060, from atmospheric CO_2 concentration at 2010 (Hoffman *et al.*, 2014); (d) CO_2 fertilization of plant photosynthesis, from changes in the seasonal cycle of CO_2 (Wenzel *et al.*, 2016); (e) sensitivity of tropical ocean primary production to warming, from interannual variability (Kwiatkowski *et al.*, 2017); (f) global ocean carbon sink in the 2090s, from the current day carbon sink in the Southern Ocean (Kessler and Tjiputra, 2016); (g) Equilibrium climate sensitivity, from interannual variability of temperature (Cox *et al.*, 2018a); (h) Transient climate response, from increase in global mean temperature (Nijsse *et al.*, 2020). In each case the emergent constraint was reconstructed from data available in the literature or provided directly by the authors. The model ensemble used in each original study is shown in the brackets after the panel title.

How might (low) dimensional emergent relationships appear in ensembles of complex models?...

…given climate models (and the real world) have very high dimensional parameter spaces and their responses are generally functions of all these parameters?

Null hypothesis: They occur by chance and are not indicative of a deeper, predictive mechanistic relationship – This is a real danger in small ensembles of models with large numbers of outputs (Caldwell et al, 2014)

- Dangers of data mining and *p*-hacking
- Statistical errors/assumptions

Non-null hypothesis (!): They are indicative of an approximate, deeper mechanistic relationship

- Certain responses may be dominated by a few degrees of freedom – effective dimension reduction.
- Can happen when a particular response becomes sensitive (close to an instability for example) or when the range of values of one process in the model ensemble is large relative to the other processes controlling that response.
- Other parameters are relatively weakly coupled to that response.

How might ECs go wrong and how to guard against it?

- **Chance relationships**: Guard against using predictive theoretical basis for emergent relationships that can be independently falsified
- **Overconfidence in constraints**: Guard against by taking into account all sources of uncertainty
- **Missing processes/feedbacks in latest models**
- **Compensating errors in models**
- **Errors in observations/observations not directly comparable to model outputs**

Emergent constraints can be a powerful tool to reduce uncertainty and promote understanding of the important processes in a variety of climate projections provided one is aware of the possible pitfalls

Awareness and understanding of these pitfalls should lead to EC research becoming more rigorous and more useful

Emergent constraints on climate sensitivities

Mark S. Williamson,[1,2] Chad W. Thackeray,[3] Peter M. Cox,[1] Alex Hall,[3] Chris Huntingford,[4] and Femke J. M. M. Nijsse[1]
[1] *College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK*
[2] *Global Systems Institute, University of Exeter, UK*
[3] *Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA, USA*
[4] *Centre for Ecology and Hydrology, Wallingford, UK*

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Despite major advances in climate science over the last 30 years, persistent uncertainties in projections of future climate change remain. Climate projections are produced with increasingly complex models which attempt to represent key processes in the Earth system, including atmospheric and oceanic circulations, convection, clouds, snow, sea-ice, vegetation and interactions with the carbon cycle. Uncertainties in the representation of these processes feed through into a range of projections from the many state-of-the-art climate models now being developed and used worldwide. For example, despite major improvements in climate models, the range of equilibrium global warming due to doubling carbon dioxide still spans a range of more than three. Here we review a promising way to make use of the ensemble of climate models to reduce the uncertainties in the sensitivities of the real climate system. The emergent constraint approach uses the model ensemble to identify a relationship between an uncertain aspect of the future climate and an observable variation or trend in the contemporary climate. This review summarises previous published work on emergent constraints, and discusses the huge promise and potential dangers of the approach. Most importantly, it argues that emergent constraints should be based on well-founded physical principles such as the fluctuation-dissipation theorem. It is hoped that this review will stimulate physicists to contribute to the rapidly-developing field of emergent constraints on climate projections, bringing to it much needed rigour and physical insights.

CONTENTS

I. INTRODUCTION

Numerical methods have become a standard technique to simulate complex systems. The equations governing components of such systems may be well-known. But their solutions cannot be solved analytically, creating a need for numerical approaches. Because of the discretization of time and space inherent in numerical techniques, modelling complex systems must involve ways to include effects of unresolved processes. Often there is no 'first principles' approach to do this. Typically, the effects of unresolved processes are included by resorting to quasi-empirical relationships between them and explicitly-resolved variables, otherwise known as 'parameterization'. There are usually multiple defensible ways to parameterize unresolved processes. Thus, independently developed models of the same complex system might incorporate different parameterization choices. The more models that are independently developed, the greater the diversity of approaches for modelling the same natural system.

A classic example of this model diversity is the use of numerical models of the atmosphere to predict hurricane development. Initial conditions are imposed on a model at some time, and it is integrated forward in time to produce simulations of critical hurricane features such as intensity and track. This approach might be replicated for multiple models incorporating different parameterization choices, producing an 'ensemble' of hurricane forecasts. The spread in the forecasts is a measure of the uncertainty in the future hurricane behaviour, given the range of plausible approaches to atmospheric
time, with enough hurricanes and associ
the various models can be evaluated for
skill. Certain parameterization choices
producing systematically better predict
els can then be rebuilt or re-calibrated
choices. Over time the ensemble will be
ful, with less spread. In fact, this is ap
process that has resulted in dramatic in
only in hurricane prediction, but in we
generally over the past seven decades.

Earth's climate is another example of a
whose governing equations can only be
numerical methods. (In fact, the dyna
for the atmospheric component of a cl
typically almost identical to those in the
els referred to above.) As expected, th
of plausible approaches to parameteriza
ponents of Earth system models (ESM
elling groups throughout the world have
ESMs with different approaches to paran
cause of these differences, these models
future climate states, even when the sam
diative forcing is imposed (associated, fo
an increase in greenhouse gases).

A classic climate change experiment i
concentrations in the atmospheric compo
and measure the surface warming that
simulation has equilibrated (Manabe
1975), an important number in climate s
as equilibrium climate sensitivity (ECS)
equilibrium with a full complexity ESM
computationally expensive simulations
years so ECS is usually estimated fro
tion CO_2 doubling experiments. When t
are done with contemporary ESMs, the
across the ensemble of ESMs is large,
6 degrees Celsius (Forster *et al.*, 2019
equilibrium values are higher (median
genstein *et al.* (2020)). The internationa
community has organised itself to gene
greenhouse gas (GHG) emissions that r
alistic future radiative forcing than the C
periment. These correspond to scenario
lack thereof) on future GHG emissions (
Riahi *et al.*, 2017). The scenarios are

[1] State-of-the-art climate models are also co
eral circulation models (GCMs). This was
the past when they consisted of just an atm
times an ocean. As time has progressed and
been included the term ESM has become m
ously ESM may have referred to models of
featuring a carbon cycle). In this review we u
mean a full complexity dynamical state-of-th
although this could be used interchangeably

Summary

- Emergent constraints can be a powerful tool to reduce uncertainty and promote understanding of the important processes in a variety of climate projections provided one is aware of the possible pitfalls
- Awareness and understanding of these pitfalls should lead to EC research becoming more rigorous and more useful
- One way to make ECs more rigorous is to base them on testable, simplified models
- This should also allow a better understanding of the important processes in complex climate models and ultimately the real world
- These models imply a fundamental link between climate sensitivity, climate variability and climate trends

Williamson, M.S., Thackeray, C. W., Cox, P. M., Hall, A. Huntingford, C., & Nijsse, F. M. M. Emergent constraints on climate sensitivities, Rev. Mod. Phys. (in press) and arXiv:2012.09468.