Is equilibrium climate sensitivity clouding our judgement?

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Abstract. Equilibrium climate sensitivity – ECS – is easily-understood, has been studied for over 150 years and is therefore appealing as a metric for communication of climate model results. In this work it is argued that ECS is not a good metric for comparing different climate models. Via brief examples concerning the Pliocene epoch and the Paleocene–Eocene Thermal Maximum, it is further posited that models which produce temperatures towards the higher end of model intercomparisons are useful in spite of recent studies concluding that these models are 'too hot'. It is hoped that this brief manuscript generates discussion on how to prioritise the consideration of more useful, and potentially novel, ways of comparing climate models going forward.

1 Introduction

The climate is warming due to due anthropogenic forcing (IPCC, 2021); so much so in fact that we have entered a new geological period called the Anthropocene (Lewis and Maslin, 2015). Quantifying the amount of warming that is expected for an additional, marginal amount of greenhouse gases in the atmosphere is generallyknown as the climate sensitivity. In particular, the *equilibrium* climate sensitivity – ECS – is defined as the global mean atmospheric warming after equlibration when carbon dioxide, CO_2, levels are doubled.

The ECS has a long history and – due to its simple definition – is often used as a zeroth-order, comparative measure of different climate models' ability to reproduce observed warming. These difference models have, since the early 1990s, been compared in several generations of Model Intercomparison Projects or MIPs and the range of the predicted ECS has remained about the same, see Figure 1.

Ostensibly, this could be seen as a failure of the models to converge on the 'correct' value of the ECS. This however, obscures the fact that the application of the concept of ECS is somewhat misleading when applied to today's complex climate models.

2 History

Estimates of ECS date back to the late 19th century when Arrhenius estimated values between approximately 4-6° (Lapenis, 1998). Ever since, and in spite of spectacular advances in fundamental scientific understanding and computational resources, the ECS remains elusive.

The main reason for this stubborn refusal to converge lies in the continual 'moving of the goal posts' with respect to the system being studied. The first studies were the best part of a century before the first computational estimates of ECS were

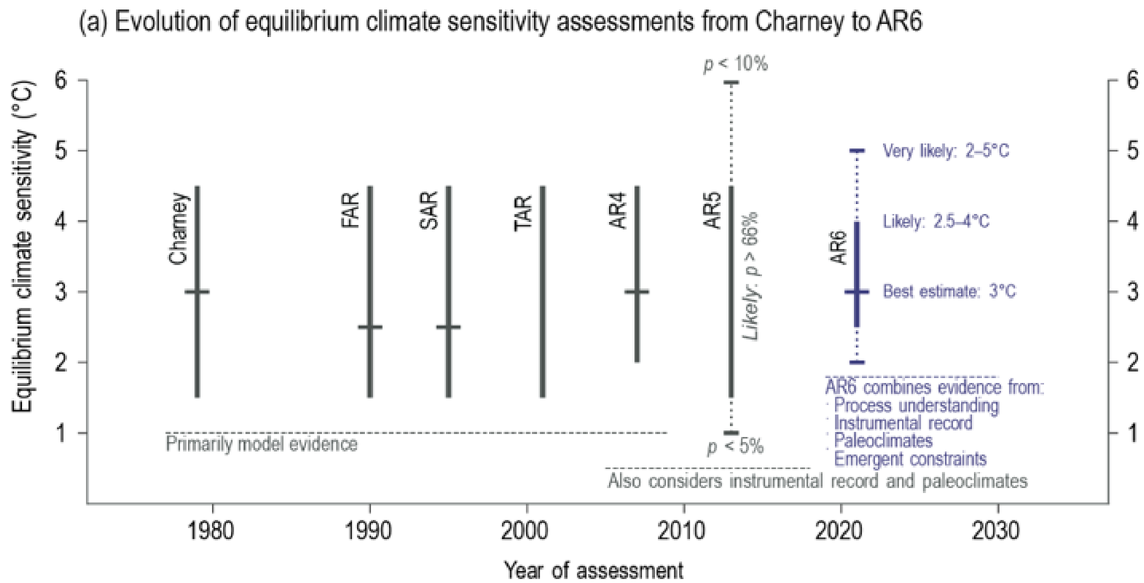

Figure 1. Figure TS.16(a) in IPCC, 2021: Technical Summary. In IPCC (2021).

published in 1967 by Manabe and Wetherald and computer simulations have steadily increased in complexity and resource requirements ever since.

Computational studies have moved from considerations of the atmosphere alone [1] to inclusion of land-surface processes, dynamic ocean models, complex atmospheric atmospheric chemistry, sea-ice, ice-sheets and ocean biogeochemistry. The addition of each of these components. while undoubtedly beneficial to the understanding in fundamental science, have each introduced additional uncertainties in the response of the combined system to increased greenhouse gas forcing. Indeed given the level of complexity and resolution that the current state-of-the-art models represent, bearing in mind that all climate models necessarily differ in terms of the processes they represent, it is surely not surprising that the estimates of ECS differ so much; $2 \lessapprox \mathrm{ECS} \lessapprox 5.5$ to the nearest 0.5° (McBride et al., 2021).

3 Feedbacks

Key to the argument that ECS is ‘under-defined’ is the concept of feedbacks, such as the relationship between ice amount and albedo, or reflectivity. As high-reflectivity ice melts and the underlying land or ocean is exposed, less sunlight is reflected directly back into space, thus causing more warming, and so on. In atmosphere-only models, this feedback is inherently absent – i.e there is no dynamic ice model – and so when ECS is predicted using an atmosphere coupled to a sea-ice model, the

[1]Even within atmosphere-only models there is a hierarchy of complexity; with and without water vapour feedbacks for example (Ingram, 2010)

estimate of ECS will change. The same is true for considerations of grounded ice sheets, the inclusion of which is one of the most recent additions to state-of-the-art climate models (Smith et al., 2021).

Even recent advances in ocean biogeochemistry (Yool et al., 2021) introduce feedbacks, for example by allowing surface gas exchange to planktonic species, which are themselves bound by predictions of ocean circulation. Following this, ocean circulation is far from constant on timescales longer than a century or so. Indeed consideration of the Gulf Stream which keeps northern Europe warmer than other similar-latitude locations make it clear that changes to ocean circulation could potentially have enormous repercussions (Robson et al., 2022); for example, London has the same latitude as Calgary! All of this is without any discussion *at all* of the longer-term implications gleaned from paleoclimate studies, e.g. (Rohling et al., 2018).

The above discussion, I hope, shows that use of the ECS as a useful metric for our ability to 'correctly' predict the amount of warming expected for a given amount of greenhouse gas forcing is far from ideal. Note that I am deliberately not considering the related metric of transient climate response, or TCR, here for brevity and the interested reader is referred elsewhere (Gregory and Forster, 2008).

With the initial publication of climate model data from CMIP6, it quickly became apparent that some models were producing climate sensitivities which were noticeably higher than before (Meehl et al., 2020). Because of this, there has been some hesitancy to 'believe' the results produced by the models. This leads us to discuss the 'what if' situation of very high ECS.

4 Overheated arguments?

Some studies have questioned ECS values towards the high end of CMIP6 predictions. For example Zhu et al. argue that the high values obtained in CMIP6 are not supported by paleoclimate evidence (Zhu et al., 2020). However, in (Zhu et al., 2020) the period studied is approximately 50 million years ago and when – in common with essentially the entire climatic history of the Earth – climate shifted from quasi-equilbrium (QE) state to QE state via changes in paleogeography (Farnsworth et al., 2019), orbital cycles (Berger, 1988) and the balance between large-scale volcanism and weathering (Shen et al., 2022) for example. Indeed, arguably the most-studied 'abrupt' climate change event known – the Paleocene-Eocene thermal maximum PETM – occurred over a period of over 100,000 years, e.g. (Röhl et al., 2007).

The current situation with respect to anthropogenic climate change is that the climate system is no longer moving in a sequence of QEs and hence we have scant idea about the impact of multi-century-timescale changes in, for example, ice-sheet dynamics. This is encapsulated by examining the last time that atmospheric CO_2 concentrations exceeded 400 parts per million; the value first exceeded in the Anthropocene in 2013 (Showstack, 2013). The Pliocene epoch, between about 2 and about 5 million years ago, had comparable CO_2 concentrations to today yet was characterised by higher sea-levels (Lisiecki and Raymo, 2005), extreme polar amplification of warming (Naish et al., 2009) and a significantly smaller Antarctic ice-sheet compared to today (see e.g. Cross-Chapter Box 2.4, Figure 1 in IPCC (2021)).

At this point it is important to stress that I am not arguing for the 'correctness' of very high values of ECS. However, if the 'true' ECS did turn out to be, say, 5° or higher the results would be societally devastating and it seems to me that to ignore this based on studies of an unknowable quantity is – at best – dangerous.

Another potentially important feedback in the climate system as the world continues to warm – although this argument holds for any currently not-quantified feedback – is that of methane release. Although many climate models do include representations of land-atmosphere exchange, there are potentially large and unaccounted-for climate impacts from the release of methane from tropical wetlands (Voosen, 2022) and permafrost melt (Schuur et al., 2015).

These possible, additional methane-induced climate impacts are just one example of a process which could increase the amount of warming for a given amount of increased greenhouse gas forcing. Therefore, the study of relatively extreme warming from high-sensitivity models is surely warranted given that if these models are 'right for the wrong reason' about a high temperature future, then at least we are collectively better prepared for it.

5 Where do we go from here?

As a community of researchers, we have learnt a vast amount about our climate system, how it has changed in the past and how we think it may change in the future. However, it is important not to over-rely on an idealised quantity, the precise value of which will arguably never be known.

The ECS is undoubtedly a convenient and simple way of distilling future temperature change projections into easily communicable information. However, the over-reliance on its utility as a useful comparative measure of climate models can give the false impression of a lack of progress in understanding fundamental climate processes.

In terms of the ECS' uncertainty bounds remaining approximately constant over the past few decades – e.g. Figure 1 – it seems to me that there is at least a passing similarity with the common misconception of a 50% probability of rainfall in a weather forecast being interpreted as *we don't know whether it will rain or not* (Handmer and Proudley, 2007).

Communicating uncertainty in projections of future climate is one of the most 'wicked' problems of our time (Rittel and Webber, 1973), but over-simplification is not the answer that future generations need.

Code and data availability. The data in Figure 1 is publicly accessible online.

Author contributions. The author prepared and wrote the manuscript.

Competing interests. The author is a computational climate scientist and primarily works on climate models developed by the Unified Model Partnership [2]. The Partnership's contributions to the latest Intergovernmental Panel on Climate Change's 6th Assessment Report (AR6) and Coupled Model Intercomparison Project (CMIP6) had some of the highest ECS of all the models submitted.

[2] https://www.metoffice.gov.uk/research/approach/collaboration/unified-model/partnership

Acknowledgements. The author was funded through the Ministry of Business Innovation and Employment of the New Zealand Government, Deep South National Science Challenge, projects number C01X1412. The author thanks Dr Georgia Grant of the Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand for useful discussions.

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