Is equilibrium climate sensitivity clouding our judgement?

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Abstract

Equilibrium climate sensitivity – ECS – is easily-understood as the global mean atmospheric warming for a doubling of CO2. It is widely applied, has been studied for over 150 years and is therefore appealing as a metric for communication of climate model results. However, here we argue that ECS is not a good metric for comparing different climate models and is no longer appropriate because of expanding model design and conditions. Using 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 [1]; so much so in fact that we have altered the geological record (isotope spike) and arguably entered a new geological period proposed to be called the Anthropocene [2]. Quantifying the amount of warming expected for an additional, marginal amount of greenhouse gases in the atmosphere is generally known as the climate sensitivity. In particular, the equilibrium climate sensitivity – ECS – is defined as the global mean atmospheric warming after equilibration when carbon dioxide, CO2, levels are doubled. That said, there is no universal definition of 'equilibrium' or the time after which it is defined to have equilibrated. 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, yet this relies on the assumption that the earth system's response is indeed calculable at all and, if so, that it is single-valued for a given forcing (i.e. no hysteresis in its response function [3]). This however, obscures the fact that applying the concept of ECS is somewhat misleading in it's simplicity when applied to today's complex climate models.

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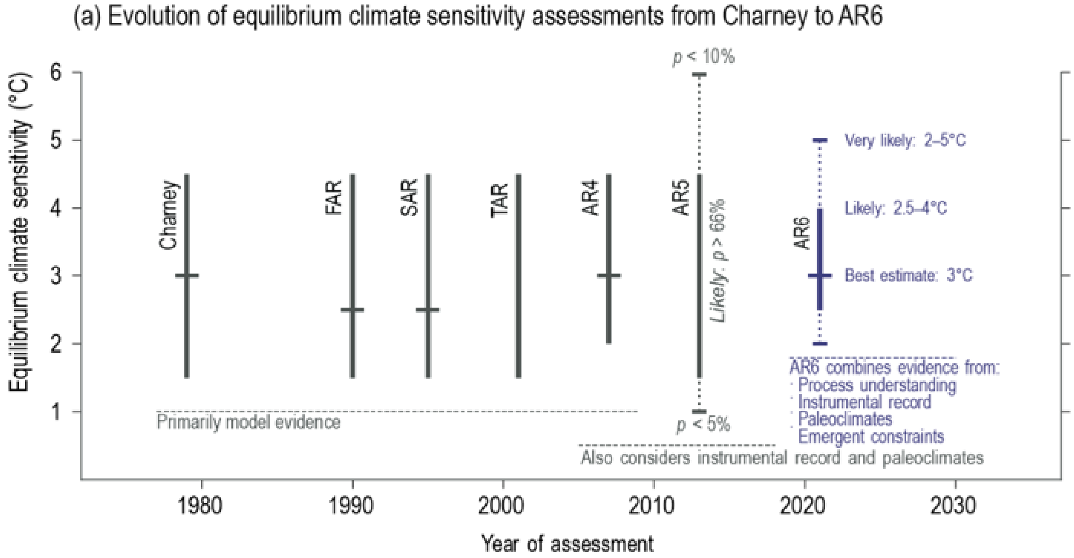

Figure 1: Figure TS.16(a) in IPCC, 2021: Technical Summary. In [1].

2 History

Estimates of ECS date back to the late 19th century when Arrhenius estimated values between approximately 4-6°[4]. Ever since, and in spite of spectacular advances in fundamental scientific understanding and computational resources, 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 25 system being studied. The first studies were the best part of a century before the first computational estimates of ECS were 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 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 an increasing number of 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 [5].

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 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 [6]. Even recent advances in ocean biogeochemistry [7] 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 [8]; for example, London, England has the same latitude as Calgary, Canada! All of this is without any discussion at all of the longer-term implications gleaned from paleoclimate studies, e.g. [9]. 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 we are deliberately not considering the related metric of transient climate response, or TCR, here for brevity and the interested reader is referred elsewhere [10, 11].

With the initial publication of climate model data from CMIP6, it quickly became apparent that some models were producing ECSs which were noticeably higher than before [12]. Higher ECS in CMIP6 suite of models has been proposed as a result of larger positive cloud feedbacks [13] and aerosol parameterisation [14] . However, there has been some hesitancy to 'believe' the results produced by the models and they they are 'too hot'. Regardless, many argue, as we do, that these high ECS simulations still have value and leads us to discuss the 'what if' situation of very high ECS.

4 Overheated arguments?

Some studies have questioned ECS values at the high end of CMIP6 predictions. While some view high ECS as more consistent with warmer past climate climates [15] others have questioned this [16]. Further to this latter example, Zhu et al. argue that the high values obtained in CMIP6 are not supported by paleoclimate evidence[17]. However, in [17] the period studied is approximately 50 million years ago, when – in common with essentially the entire climatic history of the Earth – climate shifted from one quasi-equilbrium state to another quasi-equilibrium state via changes in e.g., paleogeography [18], orbital cycles [19] and the balance between large-scale volcanism and weathering[20]. 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. [21]. The current situation with respect to anthropogenic climate change is that the climate system is no longer moving in a sequence of quasi-equilibrium states 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 CO2 concentrations exceeded 400 parts per million; the value recently exceeded in 2013 AD [22]. The mid-Pliocene warm Period, between 3 and 3.3 million years ago, had comparable atmospheric CO2 concentrations to today, yet was characterised by 20m amplitude of sea-level change [23], extreme polar amplification of warming [24] and a significantly smaller Antarctic ice-sheet compared to today (see e.g. Cross-Chapter Box 2.4, Figure 1 in [25]). At this point it is important to stress that we are 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. To ignore this possibility because of models designed on modern observable change, that could ignore feedbacks of unknown magnitude, considered to be represented in the response of past climate and geological records, 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 repre- sentations of land-atmosphere exchange, there are potentially large and unaccounted-for climate impacts from the release of methane from tropical wetlands [26] and permafrost melt [27]. 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, at least we have considered the potential outcomes and are collectively better prepared for more extreme feedbacks.

On this point, recent work by several groups of authors [28, 29, 30] argue that simple means of the many different climate models in the CMIP6 archive is not appropriate because the ones with high ECS skew the results away from the 'right answer'. These arguments are complex and some involve highly-detailed mathematical weighting of models' results. Some model development groups have even started deciding on what the ECS is, and then using the resultant model in future climate projections [31]. To be clear, we are not saying that these studies are wrong, or misguided, but we do feel that as a community we are in danger of 'throwing the baby out with the bath water' just because a model is 'too hot'. Of course, we should treat the models with high ECS with caution (as one should treat *all* scientific results), but the potential insights gained for uncertain futures are of particular importance when climate change is already being felt by those who are less able to adapt.

There's also the issue of confirmation bias, whereby people tend to give more weight to things which confirm what they already think, or know. In the scientific context, the Nobel physics Laureate Richard Feynmann argues [32] puts the search for the now-accepted value of a fundamental constant as follows (edited for brevity):

> *If you plot [experimental values] as a function of time, you find that one is a little bit bigger ... and the next one's a little bit bigger than that, and the next one's a little bit bigger than that, until finally they settle down to a number which is higher. Why didn't they discover the new number was higher right away? It's a thing that scientists are ashamed of – this history – because it's apparent that people did things like this: When they got a number that was too high ... they thought something must be wrong and they would look for and find a reason why something might be wrong*

Although clearly there are many differences between a laboratory measurement as alluded to above, and climate models' emergent ECS, the analogy of reported values using 'known' values of quantities which turned out later to be incorrect is clear. A sobering example was recently seen in the awarding of a science prize to a student who – after being advised that her results were false – ended up showing that copper has better protective properties than lead in some medical applications [33]. Because we all *know* that lead is the best shielding material against radiation, don't we?

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 has consequently become the single solution we are seeking from climate models, 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, is important not to over-rely on an idealised quantity, for which 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 which has remained approximately constant over the past few decades – e.g. Figure 1 – it seems 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* [34].

Communicating uncertainty in projections of future climate is one of the most 'wicked' problems of our time [35], but over-simplification is not the answer that future generations need.

6 Note on author interests

JW is a computational climate scientist and primarily works on climate models developed by the Unified Model Partnership [1]. 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. GG is a paleoclimate researcher whose work has focused on the Earth system response to past warmer climates.

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