Climate Sensitivity: A new assessment

Filed under: **Climate modelling Climate Science Instrumental Record Paleoclimate** — gavin @ 22 July 2020

Not small enough to ignore, nor big enough to despair.

There is a new review paper on climate sensitivity published today (**Sherwood et al., 2020** (**preprint**) that is the most thorough and coherent picture of what we can infer about the sensitivity of climate to increasing CO_2. The paper is exhaustive (and exhausting – coming in at 166 preprint pages!) and concludes that equilibrium climate sensitivity is *likely* between 2.3 and 4.5 K, and *very likely* to be between 2.0 and 5.7 K.

For those looking for some context on climate sensitivity – what it is, how can we constrain it from observations, and what observations are available, browse our previous discussions on the topic: **On Sensitivity**, **Sensitive but Unclassified Part 1 + Part 2**, **A bit more sensitive**, and **Reflections on Ringberg** among others. In this post, I'll focus on what is new about this review.

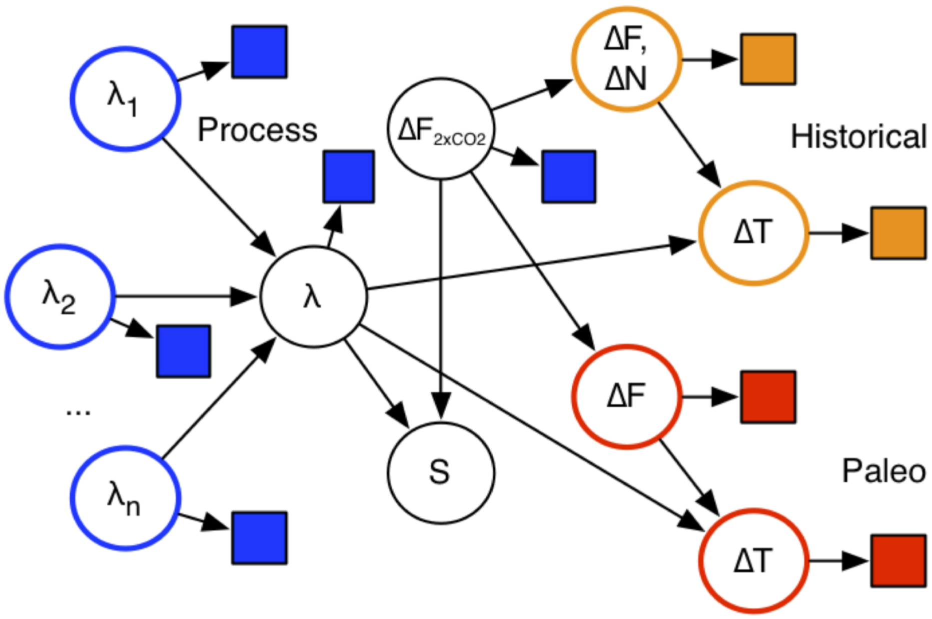


Figure 1. The dependence between different constraints on the inferred sensitivity (*S*). Circles denote uncertain variables, while square denote (independent) evidence. The Bayesian process samples the uncertainties and the best sets of parameters that match all the evidence are then examined to see what

they imply for *S*.

Climate Sensitivity is constrained by multiple sets of observations

The first thing to note about this study is that it attempts to include relevant information from three classes of constraints: processes observed in the real climate, the historical changes in climate since the 19th Century, and paleo-climate changes from the last ice age (20,000 years ago) and the Pliocene (3 million years ago) (see figure 1). Each constraint has (mostly independent) uncertainties, whether in the spatial pattern of sea surface temperatures, or quality of proxy temperature records, or aerosol impacts on clouds, but the impacts of these are assessed as part of the process.

Importantly, all the constraints are applied to a coherent, yet simple, energy balance model for the climate. This is based on the standard 'temperature change = energy in – energy out + feedbacks' formula that people have used before, but it explicitly tries to take into account issues like the spatial variations of temperature, non-temperature-related adjustments to the forcings, and the time/space variation in feedbacks. This leads to more parameters that need to be constrained, but the paper tries to do this with independent information. The alternative is to assume these factors don't matter (i.e. set the parameters to a fixed number with no uncertainty), and then end up with mismatches across the different classes of constraints that are due to the structural inadequacy of the underlying model.

This is fundamentally a Bayesian approach, and there is inevitably some subjectivity when it comes to assessing the initial uncertainty in the parameters that are being sampled. However, because the subjective priors are explicit, they can be adjusted based on anyone else's judgement and the consequences worked out. Attempts to avoid subjectivity (so-called 'objective' Bayesian approaches) end up with unjustifiable priors (things that no-one would have suggested before the calculation) whose mathematical properties are more important than their realism.

What sensitivity is being constrained?

There are a number of definitions of climate sensitivity in the literature, varying depending on what is included, and how easy they are to calculate and to apply. There isn't one definition that is perfect for each application, and so there is always a need to translate between them. For the sake of practicality and to not preclude increases in scope in climate models, this paper focuses on the Effective Climate Sensitivity **(Gregory et al, 2004)** (based on the 150 yr response to an abrupt change to 4 times CO_2), which is a little smaller than the Equilibrium Climate Sensitivity in most climate models **(Dunne et al, 2020)**. It can allow for a wider range of feedbacks than the standard Charney sensitivity, but limits the very long term feedbacks because of its focus on the first 150 years of the response.

Issues

Each class of constraint has it's own issues. For the **paleo-climate constraints**, the uncertainties relate to the fidelity of the temperature reconstructions and knowledge of the forcings (greenhouse gas levels, ice sheet extent and height, etc). Subtler issues are whether ice sheet forcing has the same impact as greenhouse gas forcing per W/m^2 (e.g. **Stap et al., 2019**), and whether there is an asymmetry between colder and warmer climates than today. For the **transient constraints**, there are questions about the difference between the pattern of sea surface temperature change over the last century compared to what we'll see in long term, and the implications of aerosol forcing over the twentieth century which is still quite uncertain.

The **process-based constraints**, sometimes called emergent constraints, face challenges in enumerating all the relevant processes and finding enough variability in the observational records to assess their sensitivity. This is particularly hard for cloud related feedbacks – the most uncertain part of the sensitivity.

The paper goes through each of these issues in somewhat painful detail, highlighting as it does so areas that could do with further research.

Putting it together

There have been a few earlier papers that tried to blend these three classes of constraints, notably **Annan and Hargreaves (2006)**, but doing so credibly while accounting for possible shared assumptions has been difficult. This paper explicitly looks at the sensitivity to the (subjective) priors, the quality of the evidence, and reasonable estimates of missing information. Notably, the paper also addresses how wrong the assumptions would need to be to have a notable impact on the final results.

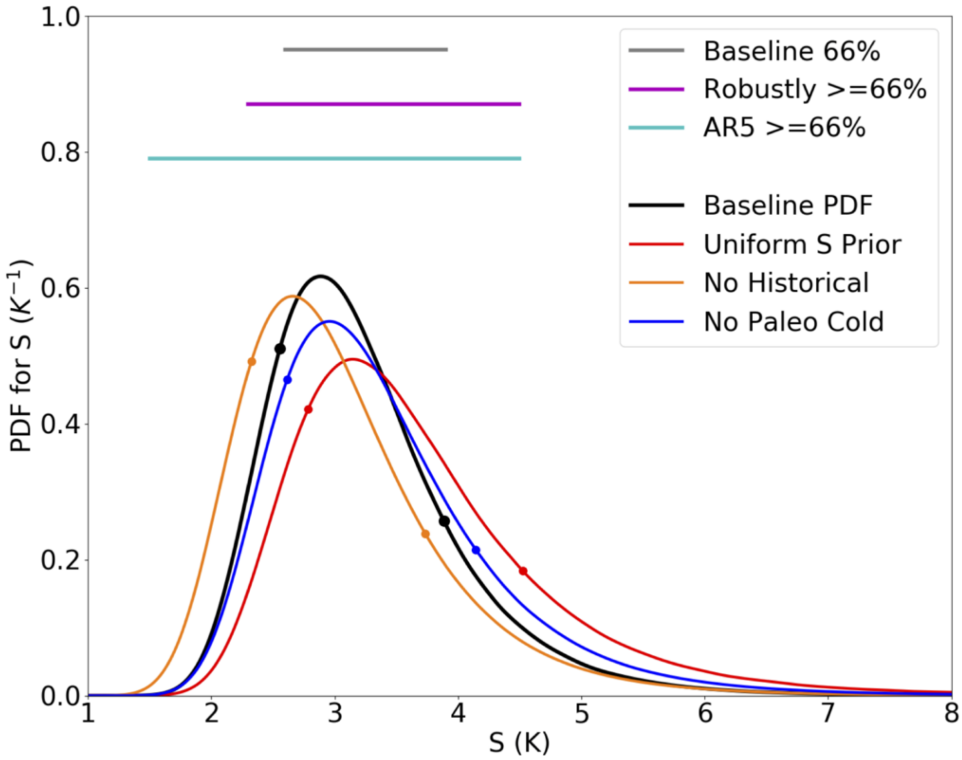


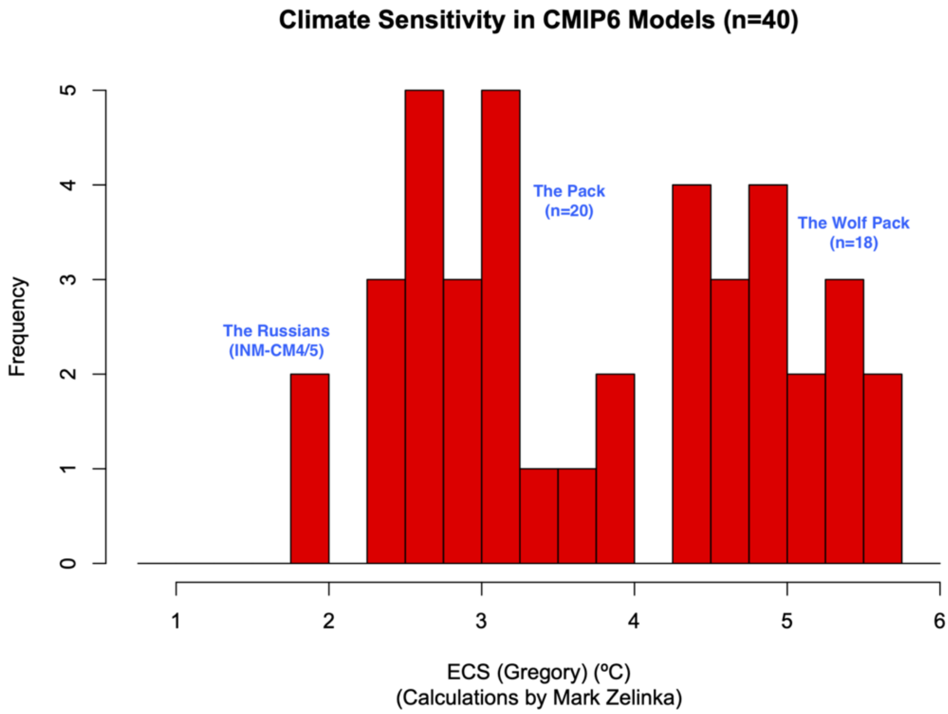
Figure 2. PDFs of *S* in comparison with AR5. The Baseline PDF is shown in black, and its 66% range (2.6-3.9 K) in grey. Colored curves show PDFs from sensitivity tests which cover a range for *S* which could plausibly arise given reasonable alternative assumptions or interpretations of the evidence, summarized by the magenta line (2.3-4.5 K). The "likely" range from AR5 (1.5-4.5 K) is shown in cyan. Circles indicate 17th and 83rd percentile values.

Bottom line

The likely range of sensitivities is 2.3 to 4.5 K, which covers the basic uncertainty ("the Baseline" calculation) plus a number of tests of the robustness (illustrated in Figure 2). This is slightly narrower than the likely range given in IPCC AR4 (2.0-4.5 K), and quite a lot narrower than the range in AR5 (1.5-4.5 K). The wider range in AR5 was related to the lack (at that time) of quantitative explanations for why the constraints built on the historical observations were seemingly lower than those based on the other constraints. In the subsequent years, that mismatch has been resolved through taking account of the different spatial patterns of SST change and the (small) difference related to how aerosols impact the climate differently from greenhouse gases.

This range the paper comes up with is not a million miles from what most climate scientists have been **saying for years**. That a group of experts, trying their hardest to quantify expert judgement, comes up with something close to the expert consensus perhaps isn't surprising. But, in making that quantification clear and replicable, people with other views (supported by evidence or not) now have the challenge of proving what difference their ideas would make when everything else is taken into account.

One further point. When this assessment started, it was before anyone had seen any of the CMIP6 model results:



As many have remarked, some (but not all) reputable models have come out with surprisingly **high climate sensitivities**, and in comparison with the likely range proposed here, about a dozen go beyond 4.5 K. Should they therefore be ruled out completely? No, or at least not yet. There may be special combinations of features that allow these models to match the diverse observations while having such a high sensitivity. While it may not be likely that they will do so, they should however be tested to see whether or not they do. That means that it is very important that these models are used for paleo-climate runs, or at least idealised versions of them, as well as the standard historical simulations.

In the meantime, it's certainly worth stressing that the spread of sensitivities across the models is not itself a probability function. That the CMIP5 (and CMIP3) models all fell within the assessed range of climate sensitivity is probably best seen as a fortunate coincidence. That the CMIP6 range goes beyond the assessed range merely underscores that. Given too that CMIP6 is ongoing, metrics like the mean and spread of the climate sensitivities across the ensemble are not stable, and should not be used to bracket projections.

The last word?

I should be clear that although (I think) this is the best and most thorough assessment of climate sensitivity to date, I don't think it is the last word on the subject. During the research on this paper, and the attempts to nail down each element of the uncertainty, there were many points where it was clear that more effort (with models or with data analysis) could be applied (see the paper for details). In particular, we could still do a better job of tying paleo-climate constraints to the other two classes. Additionally, new data will continue to impact the estimates – whether it's improvements in proxy temperature databases, cloud property measurements, or each new year of historical change. New, more skillful, models will also help, perhaps reducing the structural uncertainty in some of the parameters (though there is no guarantee they will do so).

But this paper should serve as a benchmark for future improvements. As new data comes in, or better understandings of individual processes, the framework set up here can be updated and the consequences seen directly. Instead of claims at the end of papers such as "our results may have implications for constraints on climate sensitivity", authors will be able to work them out directly; instead of cherry-picking one set of data to produce a conveniently low number, authors will be able to test their assumptions within the framework of all the other constraints – the code for doing so is **here**. Have at it!

References

1. S. Sherwood, M.J. Webb, J.D. Annan, K.C. Armour, P.M. Forster, J.C. Hargreaves, G. Hegerl, S.A. Klein, K.D. Marvel, E.J. Rohling, M. Watanabe, T. Andrews, P. Braconnot, C.S. Bretherton, G.L. Foster, Z. Hausfather, A.S.V.D. Heydt, R. Knutti, T. Mauritsen, J.R. Norris, C. Proistosescu, M. Rugenstein, G.A. Schmidt, K.B. Tokarska, and M.D. Zelinka, "An assessment of Earth's climate sensitivity using multiple lines of evidence", *Reviews of Geophysics*, 2020. **http://dx.doi.org/10.1029/2019RG000678**
2. J.M. Gregory, "A new method for diagnosing radiative forcing and climate sensitivity", *Geophysical Research Letters*, vol. 31, 2004. **http://dx.doi.org/10.1029/2003GL018747**
3. J.D. Annan, and J.C. Hargreaves, "Using multiple observationally-based constraints to estimate climate sensitivity", *Geophysical Research Letters*, vol. 33, 2006. **http://dx.doi.org/10.1029/2005GL025259**