Guest blog James Annan

Introduction

The sensitivity of the climate to atmospheric CO_2 concentrations is obviously an important consideration in any discussion of energy policy and emissions targets. The transient climate response (TCR) is arguably more directly informative regarding the future warming which we will experience due to an (anticipated) increase in CO_2 forcing over the 21st century, but the equilibrium sensitivity is more relevant to stabilisation scenarios and long-term change over perhaps 100-200 years (and beyond). For this reason, it has been a major topic of research in climate science for many decades.

One rather fundamental point need to be clearly understood at the outset of the discussion: there is no "correct" pdf for the equilibrium sensitivity. Such a pdf is not a property of the climate system at all. Rather, the climate sensitivity is a value (ignoring quibbles over the details and precision of the definition) and a pdf is merely a device for summarising our uncertainty over this value. An important consequence of this is that there is no contradiction or tension if different lines of evidence result in different pdfs, as long as their high probability ranges overlap substantially. All that this would mean is that the true value probably lies in the intersection of the various high-probability ranges. Thus the question of weighting different methods higher or lower should not really apply, so long as the methods are valid and correctly applied. If one result generates a range of 1-3.5°C and another study gives 2-6°C then there is no conflict between them.

Adjusting for a bit of over-optimism in each study (i.e. underestimation of their relevant uncertainties) we might conclude in this case that an overall estimate of 1.5-4°C is probably sound - the result in this hypothetical case having been formed by taking the intersection of the two ranges, and extending it by half a degree at each end. Additionally, if one result argues for 2-4°C and another 1-10°C, then the latter does not in any way undermine the former, and in particular it does not represent any evidence that the former approach is overconfident or has underestimated its uncertainties. It may just be that the former method used observations that were informative regarding the sensitivity, and that the latter did not.

A formally superior approach to calculating the overlap of ranges would be to combine all the evidence using Bayes' Theorem (e.g. Annan and Hargreaves 2006). In this paradigm, "down weighting" one line of evidence would really amount to flattening the likelihood, that is, acknowledging that that the evidence does not distinguish so strongly between different sensitivities. In principle it is not correct to systematically down weight particular methods or approaches, so long as their uncertainties have been realistically represented. It is more a case of examining each result on its merits. Just as some papers have underestimated their uncertainties, other papers have surely overestimated theirs.

Recent (~20th century) temperature change

Around ten years ago, Bayesian methods using the observed transient warming over the 20th century (also variously using ocean heat uptake and/or spatial patterns of climate change) became popular, although most researchers concluded that, at that time, these data didn't provide a very tight constraint. Actually, even as far back as 2002, there was enough data to provide useful estimates such as the 1.3-4.2°C of Forest et al (2002), but these results were unfortunately ignored in favour of methods which have since been shown to generate an inappropriate focus on higher values (Annan and Hargreaves 2011).

More recently, as data improves in both quantity and quality, and helped by better understanding of aerosol effects, it is widely agreed that the gradual warming of the climate system points to a sensitivity somewhere at the low end of the traditional IPCC range (e.g. Aldrin et al 2012, Ring et al 2012, Otto et al 2013). One important limitation of these methods is that they typically assume a rather idealised low-dimensional and linear system in which the surface temperature can be adequately represented by global or perhaps hemispheric averages. In reality the transient pattern of warming is likely to be a little different from the equilibrium result, which complicates the relationship between observed and future (equilibrium) warming (e.g. Armour et al 2014).

GCM ensemble-based constraints

Some (including me) have tried to generate constraints based on creating an ensemble of GCM simulations in which parameters of the GCM are varied, and then the models are generally evaluated against observations in some way to see which seem more likely. Unfortunately, the results of these experiments seem to be highly dependent on the underlying GCM, as was first shown by Yokohata et al 2010 and has also been confirmed by others (Klocke et al 2011). Therefore, I no longer consider such methods to be of much use. The underlying problem here appears to be that changing parameters within a given GCM structure does not adequately represent our uncertainty regarding the climate system. An alternative which might have the potential to overcome this problem is to use the full CMIP3/CMIP5 ensemble of climate models from around the world. These models generate a much richer range of behaviour, though debate still rages as to whether this range is really adequate or not (and for what purposes).

Some recent papers which explore the CMIP ensembles have presented arguments that the climate models with the higher sensitivities tend to be more realistic when we examine them in various ways (e.g. Fasullo and Trenberth 2012, Shindell 2014). If these results are correct, then the current moderate warming rate is a bit of an aberration, and so a substantial acceleration in the warming rate can be expected to occur in the near future, sufficient not only to match the modelled warming rate, but even to catch up the recent lost ground. It must be noted that these analyses are primarily qualitative in nature, in that they do not provide quantitative probabilistic estimates of the sensitivity (instead merely arguing that higher values are preferred). Thus it is difficult to judge whether they really do contradict analyses based on the recent warming.

Paleoclimate evidence

When averaged over a sufficiently long period of time, the earth must be in radiative balance or else it would warm or cool massively. This enables us to use paleoclimatic evidence to estimate the sensitivity of the climate. The changes to the climate system over the multi-million year time scales that may be considered here are generally far more complicated than just a change in GHG concentrations, including changes to ice sheets, continental drift and associated mountain range uplift, opening and closing of ocean passages, and vegetation changes.

It may be naively assumed or expected that we can just add up the forcings and use the temperature response to determine the equilibrium sensitivity, but model simulations suggest that there is significant nonlinearity in how the climate system responds to the multiple changes that have occurred. For example, Yoshimori et al (2011) found that the combined response to ice sheet changes and the reduction in GHG concentration at the Last Glacial Maximum is not the same as the sum of the responses to each of these forcings in isolation. Therefore, it would be difficult to derive a precise estimate of the sensitivity to CO_2 forcing from an analysis of paleoclimatic evidence.

Nevertheless, paleo studies have a number of important consequences for understanding climate change. Firstly, the evidence does help to rule out both very high and very low sensitivities. The global mean temperature has clearly varied by several degrees over long time scales (in tandem with substantial changes to radiative forcings), which can only really be reconciled with an overall sensitivity around the 2-4.5°C level or thereabouts (Rohling et al 2012). Secondly, models do a reasonable job at reproducing this, though they are far from perfect (data limitations make it hard to say quite how bad they are). Thirdly, at more regional scales, models disagree quite substantially both with each other and often with the data, which suggests that future projections might be also some way off. And finally, paleoclimate data also carries a message for how substantial an issue climate change really is. Our recent estimate was that the LGM was 4°C colder than the pre-industrial state (others might argue for a value closer to 6°C) and for this global average change, much of the North American continent and northern Scandinavia were covered in ice sheets several thousand metres thick. Obviously the changes in a warmer future will be rather different, but we can't expect them to be small. Overall, the paleoclimate evidence does not tightly constrain the equilibrium sensitivity but it does provide reasonable grounds for expecting a figure around to the IPCC canonical range (which could be used as a prior, for Bayesian analyses).

Summary

The recent transient warming (combined with ocean heat uptake and our knowledge of climate forcings) points towards a "moderate" value for the equilibrium sensitivity, and this is consistent with what we know from other analyses. Overall, I would find it hard to put a best estimate outside the range of 2-3°C.

Biographical sketch

Originally a mathematician, Dr James Annan has worked in research areas including agriculture, and ocean forecasting. For the past 13 years, he worked in the Japanese climate change research institute FRSGC/FRCGC/RIGC (perhaps better known as the home of the Earth Simulator). His (frequent co-author) wife and he were the two most highly cited scientists based in Japan in the recent IPCC AR5. They left Japan last year, returned to the UK, and will continue to present their research at http://www.blueskiesresearch.org.uk

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