Clim. Past Discuss., 5, C866–C875, 2009
www.clim-past-discuss.net/5/C866/2009/

Climate of the Past Discussions

Interactive comment on "Comment on "Using multiple observationally-based constraints to estimate climate sensitivity" by J. D. Annan and J. C. Hargreaves, Geophys. Res. Lett., 33, L06704, doi:10.1029/2005GL025259, 2006" *by* S. V. Henriksson et al.

J. Annan

jdannan@jamstec.go.jp

Received and published: 26 October 2009

(Reply submitted jointly from J. D. Annan and J. C. Hargreaves)

We are grateful to the editors of Climate of the Past for hosting this discussion.

To summarise our review, our main criticism of the Comment is that, in response to some perceived problems with AH06 (which we discuss in more detail below), the

main recommendation of the Comment is to revert to results from earlier literature, even though AH06 identified an important problem in that work. The Comment does not address the limitations of this previous work in any detail, and as a result provides no evidence that approximations in AH06 are worse than those that were made before. Moreover, the main result of AH06 has now been substantially superseded by Annan and Hargreaves (2009) (AH09). We suggest that a more useful approach would be to improve on the methods of AH06 and AH09, rather than abandon the idea completely, especially as the Comment explicitly agrees that the main point raised by AH06 is valid.

The authors have two main criticisms of AH06, which we address in turn below. In order to provide some additional context, it might be helpful first to outline the motivation for the original paper. It was written in a short interval following the publication of the first public draft version of the IPCC AR4, which had presented the notion of *averaging* together different pdfs for the climate sensitivity in order to generate an overall result. We were not aware of any theoretical or practical basis for that operation, but through informal discussion we were persuaded that the only way to argue successfully against it would be to publish a paper presenting an alternative viewpoint. The strict deadlines of the IPCC process made this a challenging task, and as a result the analysis of AH06 is necessarily a little superficial. While these factors obviously could not justify the publication of an article that was actually misleading or inadequate, they may help to provide some understanding of the approach we took.

1 Bayesian Inference

The authors first criticise AH06 for not "applying the strict rules of Bayesian statistical inference" in deriving the individual constraints. To this charge, we plead guilty. The underlying data and models that would be required for detailed calculations were not immediately available to us, and therefore we made what we considered (and still

consider) to be reasonable assumptions, and presented these assumptions clearly in AH06. It is notable that the Comment does not actually offer any specific criticism of these assumptions in quantitative terms. For example, if the authors consider AH06's expression for the likelihood $f(O_2|x)$ to be inappropriate, we invite them to suggest an alternative likelihood and demonstrate how this would this have affected the results.

We fully agree with the Comment that a detailed Bayesian analysis of the various data we discuss would be interesting. Indeed we are disappointed that no-one has undertaken this task in the three years subsequent to the publication of our paper. For while we consider that the approximations we made are reasonable, and also think that we have investigated the robustness of our results fairly thoroughly, we would be happy to admit that other researchers may have different interpretations of the available evidence, which continues to accumulate.

AH06 is further criticised in this section of the Comment for the manner in which it switches between likelihoods and probabilities. Formally, we agree that of course these are conceptually different entities (for example the integral of the former has no probabilistic interpretation), but the use of uniform priors, which was virtually ubiquitous in this area of research at that time, enabled us to readily switch between the two using Bayes' theorem. We apologise if the presentation of likelihoods and probabilities in AH06 was confusing, but do not accept that this actually affects the results numerically.

We note that although AH06 did not directly consider the choice of uniform prior, we have returned to this subject more recently in AH09 and as a result now consider the results of AH06 to be rather pessimistic as regards the uncertainty over the climate sensitivity.

2 Combining data from different sources

The more substantive criticism contained in the Comment concerns the treatment by AH06 of the different constraints as being "independent". In this context and using the Comment's notation, this means the conditional independence expressed as

$$f(O_1, O_2, H|x) \simeq f(O_1|x)F(O_2|x)f(H|x)$$

We agree with the Comment that a more complete treatment of the various "nuisance parameters" such as ocean heat uptake and aerosol forcing would be preferable to the approach taken by AH06, but unfortunately such an analysis has not so far been forthcoming.

It is important to recognise that any attempt to estimate the climate's sensitivity should really be calculating the posterior pdf determined by

$$f(x|O_1, O_2, H, \Omega) = f(O_1, O_2, H, \Omega|x)f(x)/f(O_1, O_2, H, \Omega)$$

where Ω represents all the evidence that is not explicitly accounted for in the three selected observational constraints O_1, O_2 and H used by AH06. In AH06, we briefly mentioned a few other relevant components of Ω, and argued that they provided a margin of error against any possibility that our analysis was over-optimistic. Subsequent to the publication of that paper, another useful contribution has been provided by Forster and Gregory (2006). This research is particularly valuable in our context as their results do not depend at all on estimates of aerosol forcing or uncertainty in ocean heat uptake, and therefore the concerns about nuisance parameters and independence simply cannot apply to this work. This should therefore provide a useful update to existing studies, which suggests that the main result of AH06 could now more reasonably be considered too narrow rather than too broad (eg see the discussion in AH09).

The authors of the Comment agree that in principle it should be possible to combine data from different sources and arrive at an improved estimate for the climate sensitivity parameter. However, this can be stated much more strongly than it is in their manuscript. We *always* expect more information to reduce uncertainty (eg Wynn 2008), so excluding different sources of information virtually guarantees an over-wide result, compared to that which would be obtained by a complete analysis. Of course, such exclusion was routine in the prior research cited (and preferred) by the Comment, which essentially focussed on what could be learnt from the temperature changes in the 20th century. That is, this earlier research implicitly adopted the approximation

$$f(O_1, O_2, H, \Omega|x) \simeq f(H|x)$$

The implication of this approach is that all knowledge of the climate system is thrown away at the outset, other than that arising from the specific limited set of observations which formed the focus of the study. In the previous literature, this approach was invariably taken without any discussion or justification. The Comment does not discuss how reasonable this approach is, nor why it should be considered more credible than the approach of AH06

In contrast to the procedure of simply throwing away large quantities of data, the approximation of independence (conditional on x), made in AH06, may result in a bias in the result towards either too narrow or too broad an outcome. This issue seems to have been widely enough misunderstood that we think it is worth illustrating with the following simple example. Although the values we use are intended to be reasonable, the calculation presented here is intended to be conceptually, rather than quantitatively, useful.

We consider combining two constraints, which arise from the planetary warming during the 20th century, and the cooling at the Last Glacial Maximum, respectively. For the 20th century, we use the simple energy balance model presented in the Comment,

approximating the total forcing over the 20th century as $2.6-k\ Wm^{-2}$ where the aerosol forcing k is an unknown, assigned a uniform prior over the range $0-2\ Wm^{-2}$. The climate sensitivity is also unknown, and for simplicity we assign a prior which is uniform over the range $0-8$C.

For the LGM equilibrium state, we assume a forcing of $7+k\ Wm^{-2}$ relative to the present day, where k is the unknown cooling due to aerosol dust (which coincidentally also takes a uniform prior range of $0-2Wm^{-2}$). The resulting temperature changes for the 20th century and LGM, as a function of both unknowns, are plotted in Figure 1. We make the implicit assumption that the aerosol effects are the same for dust and anthropogenic sulphates, but if in contrast they are considered to be independent, the issue of dependence through nuisance parameters does not arise in the first place. Other uncertainties such as those arising from the transient ocean heat uptake over the 20th century and the albedo due to larger ice sheets at the LGM can be reasonably claimed to be independent and if formally considered (which we do not do here) could therefore be integrated out before the constraints are combined.

The solid blue lines bound the area in the joint parameter space supported by a 20th century warming of 0.6 ± 0.2K, and the solid red lines indicate the range of cooling at the LGM of 6 ± 3K used by AH06. Posterior pdfs for sensitivity are shown in Figure 2. We can see that for each constraint considered independently, the range of sensitivity supported is substantially greater than when the likelihoods are correctly combined in the two-dimensional parameter space, and moreover the correct answer is narrower than the result obtained using the approximation of AH06, in which the uncertainty in k is first integrated out of each constraint individually before they are combined using the assumption of independence. The analysis of Urban and Keller (2009) further demonstrates the same fundamental point in a different application. The conclusion to be drawn here is that the approximation of AH06 made may either underestimate or overestimate the uncertainty compared to the full calculation.

3 Conclusions

The Comment proposes that, based on the limitations of AH06, the earlier work cited should be preferred. However, at no point in the Comment are the limitations of this prior work discussed. We certainly agree that AH06 is not the last word in the matter, and indeed we consider it effectively superseded by AH09. However, it is our contention that the conclusion of the Comment actually requires a rather different analysis to the one presented, in that they need to address the problems of this previous work and argue that the (unstated and unjustified) approximations made in those papers are a better choice than the ones made in AH06. If the authors are really prepared to argue that $f(O_1, O_2, H, \Omega|x)$ is better approximated by $f(H|x)$ than by $f(O_1|x)F(O_2|x)f(H|x)$, then they should state this clearly in the manuscript, along with their reasoning.

The Comment does suggest several opportunities for improvement on the results of AH06, such as applying the strict rules of Bayesian statistical inference to the analysis of the different observational data, and also performing a careful multivariate analysis of their joint likelihood. We agree that such analyses would represent methodological improvements to AH06. It is therefore a little disappointing that the authors have not made any attempt to undertake these improvements or investigate how they might quantitatively affect our conclusions. We believe there are very clear reasons to consider the earlier corpus of work to be biased towards an unrealistically high level of uncertainty, and AH06 provides a calculation which supports this view. Moreover, AH09 already strengthens the results of AH06.

4 Figure captions

Figure captions are poorly formatted, so are repeated here:

Figure 1: Temperature changes in 20th century (blue) and LGM (red) from simple

energy balance considerations, as a function of sensitivity and aerosol forcing. Observational bounds ($\pm 2\sigma$) are indicated in bold.

Figure 2: Posterior pdfs arising from different calculations. LGM (red) and 20C (blue) indicate results using single constraints, AH06 method (mauve) combines these constraints using a univariate independent approximation, and the correct multivariate result is shown in cyan.

5 References

J. D. Annan and J. C. Hargreaves, Using multiple observationally-based constraints to estimate climate sensitivity, *Geophysical Research Letters*, 33(L06704), 2006

J. D. Annan and J. C. Hargreaves, On the generation and interpretation of probabilistic estimates of climate sensitivity, *Climatic Change*, 2009
DOI:10.1007/s10584-009-9715-y

P. M. Forster and J. M. Gregory, The Climate Sensitivity and Its Components Diagnosed from Earth Radiation Budget Data, *Journal of Climate* 19(1), 39–52, 2006

N. M. Urban and K. Keller, Complementary observational constraints on climate sensitivity, *Geophysical Research Letters*, 36(L04708), 2009

H. P. Wynn, Bayesian information-based learning and majorization, *Biometrika* (Submitted), 2008

Interactive comment on Clim. Past Discuss., 5, 2343, 2009.

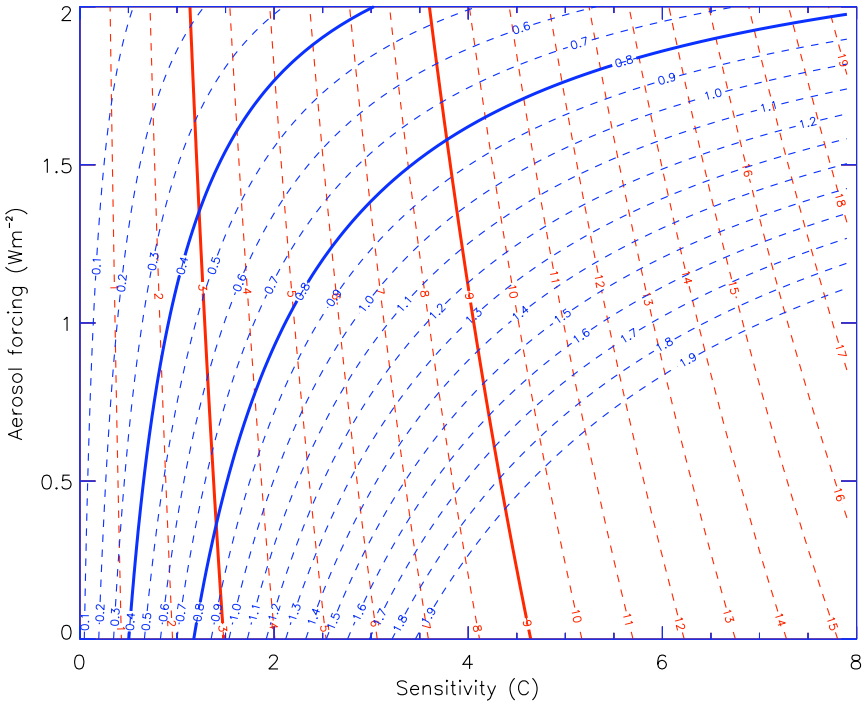

Fig. 1. Temperature changes in 20th century (blue) and LGM (red) from simple energy balance considerations, as a function of sensitivity and aerosol forcing. Observational bounds ($\pm 2\sigma$) are indicated

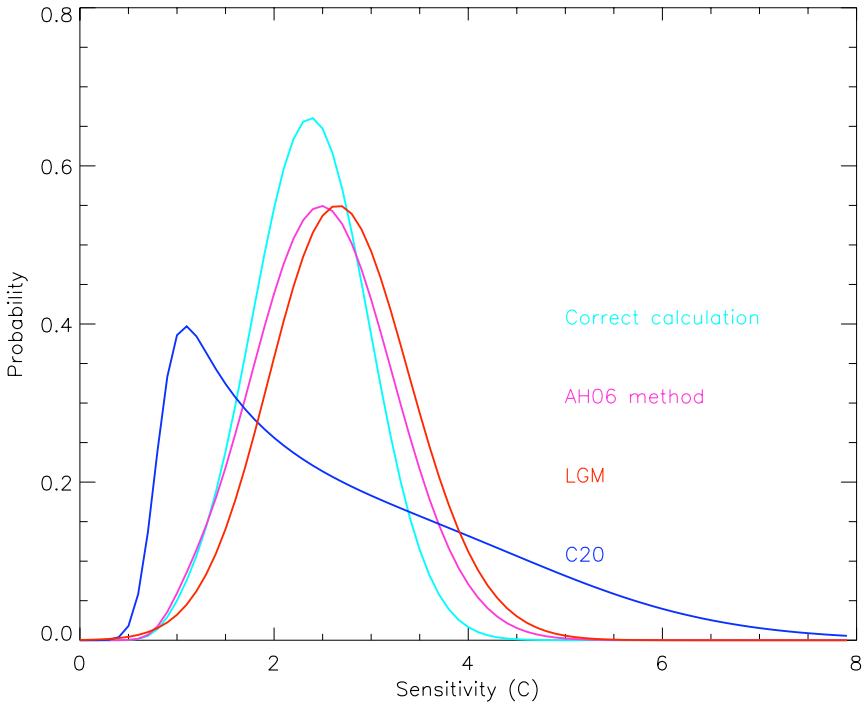

Fig. 2. Posterior pdfs arising from different calculations. LGM (red) and 20C (blue) indicate results using single constraints, AH06 method (mauve) combines these constraints using a univariate independent ap