Overestimate of committed warming

ARISING FROM C. Snyder. Evolution of global temperature over the past two million years. *Nature* (2016); doi: 10.1038/nature19798

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Palaeoclimate variations are an essential component in constraining future projections of climate change as a function of increasing anthropogenic greenhouse gases[1]. The Earth System Sensitivity (ESS) describes the multi-millennial response of Earth (in terms of global mean temperature) to a doubling of CO_2 concentrations. A recent study[2] used a correlation of inferred temperatures and radiative forcing from greenhouse gases over the past 800,000 years[3] to estimate the ESS from present day CO_2 is about 9ºC, and to imply a long-term commitment of 3-7ºC even if greenhouse gas levels remain at present-day concentrations. However, we demonstrate that the methodology of ref. 2 does not reliably estimate the ESS in the presence of orbital forcing of ice age cycles and therefore conclude

that the inferred[2] present-day committed warming is considerably overestimated. There is a Reply to this Comment by Snyder, C. W. *Nature* 547, http://dx.doi.org/10.1038/ nature22804 (2017).

The previous analysis[2] was based on the assumption that greenhouse gases were solely responsible for long-term global-mean glacial– interglacial temperature changes. This is not correct[4-8]. While it is clear that greenhouse gases played a significant role, quantification of that role is difficult because of simultaneous changes in many factors that also influence the energy balance of the Earth (e.g. the extent of the ice sheets, snow cover, vegetation, dust load, cloud cover)[5]. By contrast, it is widely accepted that orbital forcing is the ultimate trigger for glacial-interglacial temperature change[4-8], enhanced by fast and slow feedbacks involving the ice albedo, clouds, the carbon cycle, vegetation, etc.[1], sometimes even resulting in hysteresis behaviour[6]. Hence, the strong correlation seen in the analysed datasets[2] is a conflation of the sensitivity of the climate to CO_2 and the response of the carbon cycle to temperature and ice sheet variations. The Charney climate sensitivity (including fast atmospheric feedbacks, but not including long term ice sheet and vegetation changes) can be constrained by these data by treating those long-term factors as forcings[8]. However, estimating the long-term sensitivity to greenhouse gas forcing alone requires constraints from periods that are not affected by the interaction of orbital forcing and ice sheets, or that include a model-based assessment of the response to other forcings[1,9,10,11].

To better illustrate the lack of connection between ESS and the scaled regression of temperature and greenhouse gas forcing, we use a simple three-component coupled model[12] for land ice, temperature and carbon that allows for orbitally-forced impacts on the ice sheets, as well as both short and long-term feedbacks to changes in carbon dioxide, and a two-way coupling between temperature and ice. Based approximately on differences between pre-industrial and the last glacial maximum[4], we fix the response of CO_2 to temperature (20 ppm K^{-1}) and the radiative forcing related to ice (0.025 W m^{-2} mSL^{-1}), and vary the non-Planck climate feedback and the ice sheet response to temperature in order to span a wide but plausible range of Charney and Earth System sensitivities. The system is driven by an external 80 kyr periodic signal applied directly to the ice sheet component (Fig. 1a). We calculate the model ESS and the scaled regression over the glacial cycles (the linear slope in K $W^{-1}m^2$ multiplied by 3.7 W m^{-2}) and plot the ratio (Fig. 1b). If the latter were a good estimate of the response to CO_2 forcing alone, the ratio would be close to unity everywhere, but this is clearly not the case: biases are very large and pervasive. For the ranges of model parameters chosen the scaled regression is a significant overestimate of the actual model ESS value.

This shows that application of an aggregate regression from glacial periods, in which orbital forcing as well as greenhouse gases caused temperature variations, to the committed warming from current radiative forcing will therefore likely overestimate future warming. In addition, given the current estimate of the radiative imbalance[12], the future changes in vegetation and ice sheets that would be required as a response to current and committed short term warming to reach a 3-7ºC warming would imply at least a doubling of the original forcing. Given the limited extent to which the current ice sheets can change areal coverage and the expected range of vegetation impacts, this seems implausible. Furthermore, the response to global forcing likely depends on the climate state[1,13]. Any paleo-derived ESS must, if it is to be applied to the present day radiative imbalance, be defined in a way that estimates the impact of external radiative forcing only, and should be drawn from evidence from non-glacial base climate states.

In summary, we demonstrate that an ESS of ~9ºC as defined[2] cannot be used to project future warming, and no evidence was presented to alter the most recent assessment of the present-day committed warming[14].

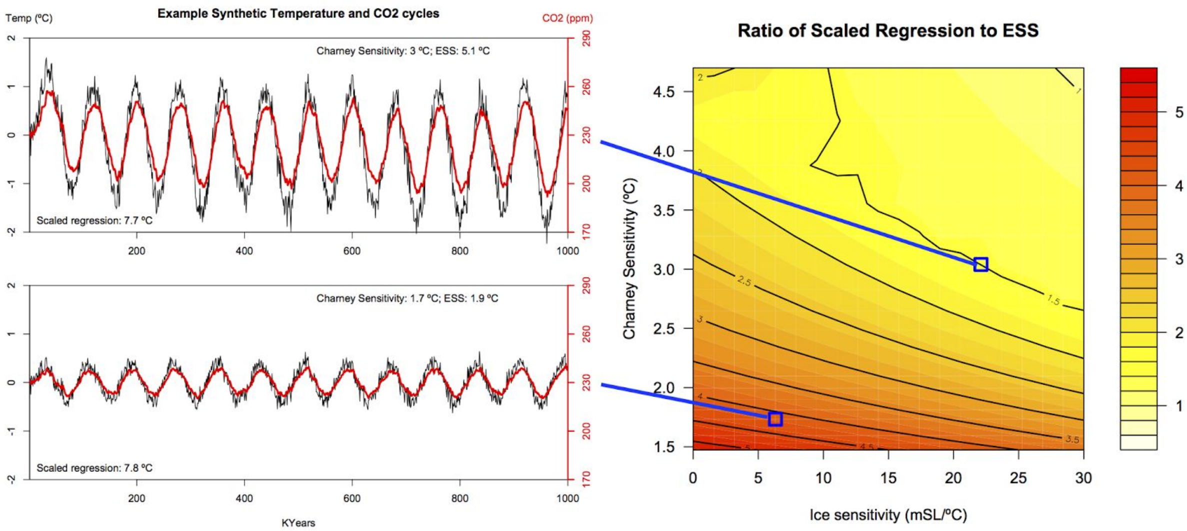

Figure 1. a) Two examples of synthetic temperature and carbon dioxide cycles over 1 million years driven by an 80 kyr cycle in ice sheet forcing using a simple 3-component model for temperature, CO_2 and glacial ice (see Supplementary Information). b) The ratio of the scaled regression (the linear regression coefficient in $K\ W^{-1}m^2$ multiplied by 3.7 $W\ m^{-2}$) to the model ESS over a range of plausible parameter space.

Supplementary Information

Model code and fuller documentation are available in the SI:

1. Simple-coupled-ice.pdf (PDF file)
2. iceage_cycles.R (R code, plain text)
3. Python notebook (ipynb file)

References

1. PALAEOSENS Project Members. Making sense of palaeoclimate sensitivity. *Nature* 491, 683–691 (2012).
2. Snyder, C. Evolution of global temperature over the past two million years. *Nature* 538, 226-228 (2016)
3. Bereiter, B. et al. Revision of the EPICA Dome C CO_2 record from 800 to 600 kyr before present. *Geophys. Res. Lett.* 42, 542–549 (2015).
4. Köhler, P. et al. What caused Earth's temperature variations during the last 800,000 years? Data-based evidence on radiative forcing and constraints on climate sensitivity. *Quat. Sci. Revs.* 29, 129–145 (2010).
5. Hays, J. D., J. Imbrie, and N. J. Shackleton, Variations in the Earth's Orbit: Pacemaker of the Ice Ages, *Science* 194, 1121-1132 (1976).

6. Raymo, M. E., L. E. Lisiecki, K. H. Nisancioglu, Plio-Pleistocene Ice Volume, Antarctic Climate, and the Global $\delta^{18}O$ Record, *Science* 313, 492-495 (2006).
7. Abe-Ouchi, A., et al. Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume, *Nature* 500, 190-194 (2013).
8. Paillard, D., Quaternary glaciations: From observations to theories, *Quat. Sci. Rev.* 107, 11-24 (2015).
9. Hansen, J. et al. Target atmospheric CO_2: Where should humanity aim? *Open Atmos. Sci. J.* 2, 217–231 (2008).
10. Lunt, D. J. et al. Earth system sensitivity inferred from Pliocene modelling and data. *Nature Geosci.* 3, 60–64 (2010).
11. Pagani, M et al. High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations. *Nature Geosci.* 3, 27-30 (2009).
12. Johnson, G. C., et al. Ocean heat content [in "State of the Climate in 2015"]. *Bull. Amer. Meteor. Soc.* 97 (8), S66–S70.
13. von der Heydt, A. S., et al. Lessons on climate sensitivity from past climate changes. *Curr Clim Change Rep* (2016)
14. IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (2013)

Author Contributions:

G.A.S and J.S jointly conceived of this comment, G.A.S and K.D.M developed the simple model, and all authors contributed equally to the writing.