# Overestimate of committed warming

**ARISING FROM** C. W. Snyder *Nature* **538,** 226–228 (2016); doi:10.1038/nature19798

Palaeoclimate variations are an essential component in constraining future projections of climate change as a function of increasing abundances of anthropogenic greenhouse gases[1]. The Earth system sensitivity (ESS) describes the multi-millennial response of Earth (in terms of the change in global-mean temperature) to a doubling of atmospheric $CO_2$ 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 that the ESS from present-day $CO_2$ concentrations is about 9 °C and to imply a long-term commitment of 3–7 °C even if greenhouse gas concentrations remain at present-day levels. 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[4–7]. Although it is clear that greenhouse gases have a large role, quantifying that role is difficult because of simultaneous changes in many factors that also influence the energy balance of Earth (such as the extent of the ice sheets, snow cover, vegetation, dust load and cloud cover)[4]. However, it is widely accepted that orbital forcing is the ultimate trigger for glacial–interglacial cycles[4–7], enhanced by fast and slow feedbacks that involve the ice albedo, clouds, the carbon cycle, vegetation, and so on[1], sometimes resulting in hysteresis behaviour[6]. Therefore, the strong correlation that is seen in the datasets analysed in ref. 2 is a conflation of the sensitivity of the climate to $CO_2$ and the response of the carbon cycle to variations in temperature and ice-sheet extent. The Charney climate sensitivity (which includes fast atmospheric feedbacks, but not long-term changes in ice-sheet extent or in vegetation) can be constrained by these data by treating the 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 between orbital forcing and ice sheets, or that include a model-based assessment of the response to other forcings[1,9–11].

To illustrate the lack of connection between the ESS and the scaled regression of temperature and greenhouse gas forcing, we use a simple, coupled, three-component model[12] for land ice, temperature and carbon that incorporates the effects of orbital forcing on ice sheets, short- and long-term feedbacks to changes in atmospheric concentrations of $CO_2$, and two-way coupling between temperature and ice. On the basis of approximate differences in sea level, temperature and $CO_2$ concentrations between the pre-industrial era and the Last Glacial Maximum[8], we fix the response of $CO_2$ to temperature (20 p.p.m. $K^{-1}$) and the radiative forcing related to ice (0.025 W $m^{-2}$ per metre of sea-level equivalent), and vary the non-Planck climate feedback and the ice-sheet response to temperature to span a wide but plausible range of Charney and Earth system sensitivities. The system is driven by an external 80-kyr periodic signal that is 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 the canonical estimate of $2 \times CO_2$ forcing, 3.7 W $m^{-2}$; equivalent to the ESS presented in ref. 2) and plot their ratio (Fig. 1b). If the latter were a good estimate of the response to $CO_2$ forcing alone, then the ratio would be close to unity everywhere. This is clearly not the case—biases are very large and pervasive. For the chosen ranges of the model parameters, the scaled regression is a considerable overestimate of the actual model ESS.

This result shows that applying an aggregate regression from glacial periods, in which orbital forcing as well as greenhouse gases cause temperature variations, to the committed warming from current radiative forcing will probably overestimate future warming. In addition, given the current estimate of the radiative imbalance[12], the future changes to vegetation and ice sheets that would be required in response to current and committed short-term warming in order to produce long-term warming of 3–7 °C necessitate at least a doubling of the original forcing of 3.7 W $m^{-2}$. But such a doubling seems implausible, owing to the limited extent to which the areal coverage of current ice sheets can

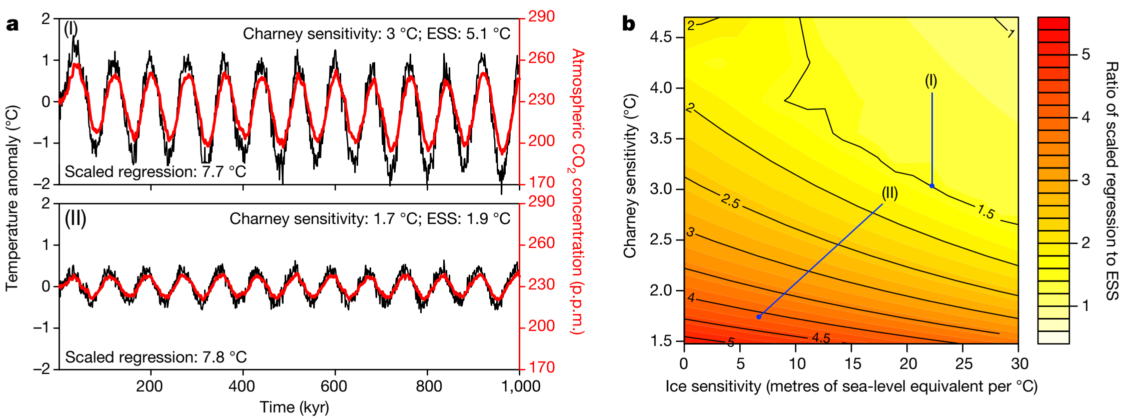


**Figure 1 | Glacial–interglacial cycles in a simple model with varying Earth system sensitivity. a,** Two examples (with parameters as indicated in **b**) of synthetic temperature (black) and $CO_2$ (red) cycles over one million years, driven by an 80-kyr cycle in ice-sheet forcing. The cycles shown are obtained from a simple, three-component model for temperature, $CO_2$ and glacial ice (see Supplementary Information). A temperature anomaly of 0 °C corresponds to a nominal average temperature over the glacial–interglacial cycles (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 $m^{-2}$; equivalent to the ESS presented in ref. 2) to the model ESS over a plausible range of parameter space.

change and the expected range of effects on vegetation. Furthermore, the response to global forcing probably depends on the state of the climate[1,13]. Any palaeo-derived ESS, if it is to be applied to the present-day radiative imbalance, must be defined in such a way that it estimates the effect of external radiative forcing only, and should be drawn from evidence from non-glacial base climate states.

In summary, we demonstrate that the ESS of about 9 °C defined in ref. 2 cannot be used to project future warming and that there is no reason to alter the most recent assessment of the present-day committed warming[14].

**Data Availability** The R code to generate the data in Fig. 1 is available as Supplementary Information.

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**Received 17 November 2016; accepted 3 April 2017.**

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**Supplementary Information** accompanies this Comment.

**Author Contributions** G.A.S. and J.S. jointly conceived this Comment, G.A.S. and K.M. developed the simple model, and all authors contributed equally to the writing.

**Competing Financial Interests** Declared none.

**doi:**10.1038/nature22803

# Snyder replies

**REPLYING TO** G. A. Schmidt *et al. Nature* **547,** http://dx.doi.org/10.1038/nature22803 (2017)

The Earth system sensitivity (ESS) summarizes the feedback behaviour of Earth's climate system and includes ice sheets, vegetation and dust as internal feedbacks. This definition of the ESS is in contrast to that of the equilibrium climate sensitivity (ECS), for which those feedbacks are considered external forcings[1,2]. As previously quantified from palaeoclimate records, the ESS[3–7] and palaeoclimate sensitivity parameter $S_{[GHG]}$ (ref. 2) do not test causation, but summarize the past aggregate, correlational relationships among those feedbacks. In the accompanying Comment[8], Schmidt *et al.* contend that I miscalculated the ESS by defining it to include all changes to ice sheets as internal feedbacks[9]. However, previous research had applied the same definition of the ESS[3–7] or $S_{[GHG]}$ (ref. 2), yielding estimates of the ESS of 8.6 ± 2.8 °C ($1\sigma$)[2], 7.4 °C (6.2–9.1 °C, 95% confidence interval)[3] and 6 °C (refs 4, 5) from the late Pleistocene and exceeding 6 °C from Cenozoic periods with large ice sheets[6]. These values are comparable to my estimate of 9 °C (7–13 °C, 95% credible interval)[9]. Moreover, my estimates of the ESS[9] are consistent with recent IPCC estimates of the ECS[1].

The primary debate regards the utility of the concept of ESS for providing insights relevant to future warming. I estimated the ESS from the late Pleistocene and applied this estimate to current greenhouse gas concentrations to quantify the implied future warming over millennial timescales[9]. The purpose of this was to provide a general perspective on potential warming under the assumption that the correlational relationship between greenhouse gas concentrations and global temperature from mid-glacial and interglacial conditions over the past 800 kyr will be similar in the future. This approach has two main sources of uncertainty.

First, it assumes that, at equilibrium, the relationships between the internal climate feedbacks will be the same for different causal triggers—that is, regardless of the initial source of change to the global energy balance (such as changes in orbital forcing, ice-sheet extent, temperature or greenhouse gas concentrations), the resultant internal feedbacks iterate until they converge at equilibrium to the same aggregate relationship. In complexity theory, such a phenomenon is referred to as emergence. If instead the ESS depends on the source of the initial trigger, then the ESS calculated from the past 800 kyr would not be applicable to future warming triggered by anthropogenic emissions.

Second, although I found that the ESS was constant across mid-glacial and interglacial conditions over the past 800 kyr, and was higher under those conditions than under deep glacial conditions[9], states warmer than the present day may have different ESS.

How much Earth will warm over millennial timescales in response to anthropogenic emissions remains uncertain. For example, in ref. 2 (see figure 4) it is assumed that no longer-timescale feedbacks occur during future warming. Yet we already observe that some longer-timescale feedbacks that are not included in the ECS, such as changes in ice-sheet extent, sea level and vegetation, are occurring today[1].

The modelling presented in Schmidt *et al.*[8] does not add further insight to this discussion. They assert that a certain amount of change in ice-sheet extent is caused by orbital forcing that is entirely independent of interactive changes with temperature or greenhouse gas concentrations, and therefore that a certain amount of changes to ice sheets should not be included as internal feedbacks in calculating the ESS. This conflicts with previous work on the ESS[3–7]. Although the causes of the glacial–interglacial quasi-cycles of the late Pleistocene continue to be debated[10–18], most theories include iterative feedbacks between temperature, ice sheets, greenhouse gases and other key climate features regardless of the initial trigger[10–18].

The simple model of Schmidt *et al.*[8] does not test their assertions about the ESS. Rather, the construction of their model (via the term $F_I$ for orbitally driven changes in ice-sheet extent) and the equation that they use to quantify the ESS (in which $F_I = 0$) predetermine their new estimate of the ESS. These factors also predetermine that the ratio that Schmidt *et al.* present between the two different calculations of the ESS is variable, not equal to one. Moreover, Schmidt *et al.*[8] do not provide justification from published research or palaeoclimate data for their exclusion from the calculation of the ESS of specific changes to ice sheets.

The views expressed here are those of the author and do not necessarily reflect the views or policies of the US Environmental Protection Agency.

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**doi:**10.1038/nature22804

doi:10.1038/nature22803

# Overestimate of Committed Warming: Supplementary Information

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*Feb 1, 2017*, doi: 10.1038/nature22803

## A simple coupled ice sheet-temperature-carbon model

We describe a three-component model for glacial cycles that includes two-way coupling between ice sheets and temperature, and between temperature and carbon dioxide levels. This is perhaps the simplest model that allows us to distinguish correlations between temperature and $CO_2$ in the presence of high latitude oscillatory forcing of the ice sheets resulting from shifts in the Earth's orbit from the Earth System Sensitivity (ESS), the long-term response (including ice sheets) of the system to $CO_2$ forcing.

We define three prognostic variables as means and anomalies: $T_0$ and $T(t)$ for temperature (K); $C_0$ and $C(t)$ for $CO_2$ (ppm); $L_0$ and $L(t)$ for sea level (meters of sea level equivalent, mSL). (Anomalous ice amount is the negative of $L$). For mid-glacial conditions, we take $T_0$, $C_0$ and $L_0$ as 285 K, 230 ppm and -60 mSL, respectively. The governing equations of this simple model are as follows:

$$\tau_L \frac{dL}{dt} = F_I + (aT - L) \quad (1)$$
$$\tau_C \frac{dC}{dt} = bT - C \quad (2)$$
$$H \frac{dT}{dt} = \mu L + F_{CO_2}(C) + \lambda T - P(T, T_0) + \epsilon \quad (3)$$

where in Eq. (1) $F_I$ is the high latitude forcing of the ice sheets, $a$ is the sensitivity of ice sheets to temperature (mSL $K^{-1}$) and $\tau_L$ is a time constant for the response of ice sheets. In Eq. (2), $b$ is the sensitivity of the carbon cycle to temperature (ppm $K^{-1}$) and $\tau_C$ is the carbon cycle response time. In Eq. (3), H is the heat capacity of the system (but this falls out if one assumes that $T$ is in balance with $C$ and $L$ over these timescales); $\mu$ is the radiative forcing associated with the ice sheet (W $m^{-2}$) $mSL^{-1}$, $\lambda$ is the non-Planck feedback W $m^{-2}$ $K^{-1}$, $P(T, T_0)$ is the Planck function, and $\epsilon$ is a source of random noise, N(0,0.2) W $m^{-2}$. Eq. (3) includes the standard radiative forcing for carbon dioxide $F_{CO_2}(C) = 5.3 \log((C + C_0)/C_0)$ and the full fast-feedback term (split into the Planck feedback and the non-Planck terms). The Planck function in its full form is $P(T, T_0) = \sigma((T + T_0)^4 - T_0^4)$ (where $\sigma$ is the Stefan-Boltzmann constant). The parameters of this model are summarized in Table 1.

If we consider longer-than-millennial variations, we can assume that temperature is in equilibrium with the ice and $CO_2$, thus Eq. (3) is a polynomial in $T$ (that can have zero to 2 solutions depending on the parameters and the form of the Planck function). The equations are stepped forward with time steps of 1000 years. To prevent unphysical values, we force $CO_2$ to remain positive (minimum value is 1 ppm, corresponding to a radiative forcing of -29 W $m^{-2}$ with respect to pre-industrial levels).

The Charney sensitivity (K for $2\times CO_2$) in this system can be calculated by setting $C = C_0$ and fixing $L = 0$. The Earth System Sensitivity additionally allows for a change in the ice in response to increased $CO_2$ and is calculated similarly assuming $L$ is in equilibrium with $T$ with $F == 0$, i.e. $L = aT$. The regression between $T$ and the radiative forcing associated with $C$ over the glacial cycles is also easily calculated, and when scaled by multiplying by 3.7 W $m^{-2}$ has the same units as the ESS. Note that in situations where the model becomes unstable, the regression is only calculated over a partial time-series.

Some parameters can be estimated roughly based on inferences from the real world[1] (outlined in Table S1). For the simulations below we specifically choose $\mu$=0.025 W $m^{-2}$ $mSL^{-1}$, $b$=20 ppm $K^{-1}$, $\tau_L$ is 10000 yrs and $\tau_C$ is 3000 years. The high latitude forcing in the specific case looked at here is $F = 30 \sin(\pi t/\tau_F)$, where $\tau_F$ is 40,000 yrs, giving a 60 mSL peak-to-trough driving function and ≈12 glacial cycles over a million simulated years. We performed 20×20 experiments varying $\lambda$ (so that we vary the Charney sensitivity roughly within the accepted range), and varying $a$ between 0 and 30 mSL $K^{-1}$.

With the full Planck response, the Charney sensitivity and ESS don't have a simple analytical expression, but with the range of $\lambda$ of [2.8,4.6] W $m^{-2}$ $K^{-1}$ and $a$ of [0,30]mSL $K^{-1}$, give rise to a range of $S_{2\times CO2}$ of [1.5,5.6]K and ESS of [1.5,>30]K.

In the main text we show two example time series of $T, C$ and $L$ for ($\lambda$,$a$) = (3.2,6.2) and (4.1,22.1), which are equivalent to a Charney Sensitivity/ESS pair of (1.7,1.9)K and (3.0,5.1)K respectively (Main Text Fig. 1a). The scaled regression between $T$ and the radiative forcing due to $C$ in each case is near 7.8K (Fig. S1).

Over the whole range of the experiments the ratio of regression (after scaling for $2\times CO_2$) and the actual model ESS is shown in Main text Fig. 1b. If the regression was a good estimate for ESS,

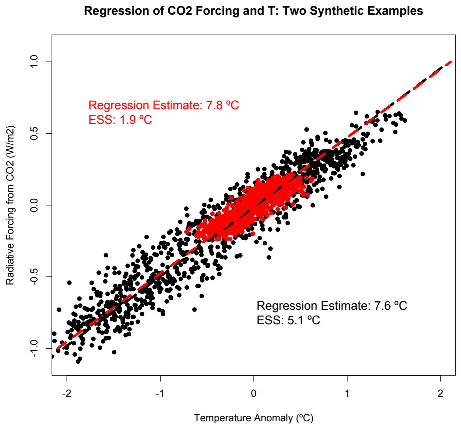


Figure S1: a) Scatterplot of temperature and $CO_2$ forcing for the two selected cases in Main text Fig. 1a.

the field would be near unity, instead, it varies widely and we conclude that ESS is almost always over-estimated by this procedure in the presence of independent forcing of the high latitude ice sheets.

| Name | Description | Units | Value |
|---|---|---|---|
| $a$ | Ice sheet sensitivity to temp. | mSL $K^{-1}$ | 0-30 |
| $b$ | Carbon cycle sensitivity to temp. | ppm $K^{-1}$ | 20 |
| $F_I$ | High latitude forcing of ice sheets | $Wm^{-2}$ | $30\sin(\pi t/\tau_F)$ |
| $H$ | Heat capacity of the system | J $m^{-2}$ $K^{-1}$ | N/A |
| $\mu$ | Ice sheet radiative forcing | $Wm^{-2}$ $mSL^{-1}$ | 1/40 |
| $\tau_C$ | Carbon cycle response time | kyr | 3 |
| $\tau_F$ | Glacial cycle half-period | kyr | 40 |
| $\tau_L$ | Ice sheet response time | kyr | 10 |

Table S1: Description of model parameters and values.

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