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Editorial

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Editorial on Hansen et al. '*Global warming in the pipeline*' (this issue)

In their Perspective article '*Global warming in the pipeline*', Jim Hansen and colleagues [1] review a wide range of climatological information to quantify the eventual, so-called equilibrium, warming that might be expected over many centuries unless greenhouse gas emissions are rapidly phased out. We call this equilibrium because it is the temperature change after climate has adjusted to the initial perturbation (today, human emissions) and all the internal feedback responses and other slow processes (e.g. ocean warming) related to that initial perturbation, which operate over timescales of many centuries to millennia. Note that Hansen *et al.* emphasize that extremely rapid reduction to true net zero emissions could still avoid most of this equilibrium warming. But human-caused aerosols cause cooling, so that reduction of aerosol emissions—for example by cleaning particulate emissions from fuel combustion, or by combusting less—would therefore drive a warming effect. The authors take this into account along with the delayed response of slow processes in the climate system and find that the 1.5°C warming limit of the Paris Agreement is likely to be crossed within the 2020s, and the 2°C warming limit before 2050. This is even earlier than had been argued previously in an independent manner (∼2035 and ∼ 2055, respectively) [2]. Hansen *et al.* then argue about the consequences and ways to avoid this predicament. This Editorial discusses the reasons behind the finding of Hansen *et al.* that the Paris Agreement limits for global warming may be breached so soon.

The Hansen *et al.* study draws heavily on information from studies of past climates in pre-historic time (so-called paleoclimate studies), mostly from the ice-age cycles of the past 1 million years but even reaching as far back as 66 million years ago. This paleoclimate information is useful because it covers timescales that include full responses of the various slow processes (e.g. ice sheets), and because climate models for computational reasons still cannot run high-resolution models with fully interactive representations of the slow processes over thousands of years. In addition, different climate models give very different cloud changes in response to climate change, and cloud cover is another important (albeit fast) parameter in determining temperature response to a change in the radiative forcing of climate [3]. An example of slow processes in the climate system concerns the response of the world's great continental ice-sheets to climate change, which takes many centuries to millennia. And once the ice sheets are shrinking or expanding, they in turn influence climate via their impact on Earth's reflectivity to incoming sunlight—that is, they exert a so-called positive feedback. There are several such slow feedbacks, and they operate at different intensities, and over different timescales. Core to Hansen *et al.* is improving understanding of the total impacts of slow feedbacks in climate change, using past data. This is important because these feedbacks greatly increase Earth's temperature response to change in the radiative change of climate over centuries to millennia; this response is known as equilibrium climate sensitivity (ECS).

However, ECS is not a direct observable in models or the real world. Instead, model derived ECS typically uses a linear extrapolation to zero radiative perturbation over short timeseries (150 years), thereby neglecting the multiple response times in the complex climate system [4]. Moreover, slow processes are not dynamically included in such model simulations. Both these shortcomings mean that is implicitly assumed that feedback processes (slow and fast) do not change substantially through time, which may not be correct. Hansen *et al.* use the temperature response function in their estimates, which can be determined via corresponding Greens functions. The response time, which they define as the time needed to reach a certain fraction of equilibrium warming, increases with ECS itself. This implies that the model-based ECS estimation methods using short timeseries will by comparison underestimate high ECS values. Recently, more sophisticated (but still linear) regression methods that consider longer response times have been applied to model results, yielding better agreement with the models' true multimillennial temperature response [5]. Moreover, using such methods, long-term changes in the fast feedback processes are reflected as a climate background state-dependence of the response [6, 7].

Hansen *et al.* evaluate the amount of radiative forcing increase due to human activity since 1750 across all greenhouse gases and find that it is already equivalent to the radiative forcing of a $2 \times CO_2$ scenario (a CO_2 doubling scenario, considering only CO_2). The global mean radiative forcing for a doubling of CO_2 is about 4 W/m^2. They then seek to apply ECS estimates from paleoclimate studies to evaluate the eventual equilibrium warming that might be expected (including slower response components). From a variety of paleo-information, the authors then infer an ECS of $4.8\ ^{+1.2}/_{-1.2}$°C. A decade ago another paleo-climate estimate [8] suggested $3.2\ ^{+1.6}/_{-0.8}$°C (here adjusted for 4°C per CO_2 doubling), and a review from 2020 estimated $3.2\ ^{+0.9}/_{-0.6}$°C in their baseline assessment based on paleo, modern, and theoretical information [9]. Part of these differences may be due to different choices made on how to use particular data, or re-interpretation of such data, and the uncertainty bands overlap between all three estimates, but the high value inferred by Hansen *et al.* is intriguing: it suggests that past climate changes may indicate larger implications of modern climate change than we had estimated before. This elevates 'high impact, low probability' impacts toward the 'high impact, high probability' level, and this is enough reason to publish the new estimates. It should make everyone sit up and take notice. The previous paleo-estimates for ECS [8, 9] were toward the high end of models of only a decade ago, and only started to get approached by later models [3]. The Hansen

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et al. re-evaluation of paleo-information suggests that the discrepancy may have been even larger, and that continued work on the climate models is warranted to ensure that emissions reduction and mitigation targets are not systematically set too low.

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