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Energy budget constraints on climate response

To the Editor — The rate of global mean warming has been lower over the past decade than previously. It has been argued\(^1\) that this observation might require a downwards revision of estimates of equilibrium climate sensitivity, that is, the long-term (equilibrium) temperature response to a doubling of atmospheric CO\(_2\) concentrations. Using up-to-date data on radiative forcing, global mean surface temperature and total heat uptake in the Earth system, we find that the global energy budget\(^2\) implies a range of values for the equilibrium climate sensitivity that is in agreement with earlier estimates, within the limits of uncertainty. The energy budget of the most recent decade does, however, indicate a lower range of values for the more policy-relevant\(^3\) transient climate response (the temperature increase at the point of doubling of the atmospheric CO\(_2\) concentration following a linear ramp of increasing greenhouse gas forcing) than the range obtained by either analysing the energy budget of earlier decades or current climate model simulations\(^4\).

The response of the climate system to rising greenhouse gas levels is often summarized in terms of the equilibrium climate sensitivity (ECS) or the transient climate response (TCR). Both quantities are related to the global mean temperature change\(^\Delta T\), the radiative forcing change \(\Delta F\), and the change in the rate of the total increase in Earth system heat content \(\Delta Q\) (see Supplementary Section S1), by the global energy budget:

\[
\text{ECS} = \frac{F_0 \Delta T}{\Delta F - \Delta Q} \quad (1)
\]

\[
\text{TCR} = \frac{F_2 \Delta T}{\Delta F} \quad (2)
\]

where \(F_0\) is the forcing due to doubling atmospheric CO\(_2\) concentrations. We use a value of \(F_0\) of 3.44 W m\(^{-2}\) (with a 5–95% confidence interval of ±10%) from ref. 10. Using a higher estimate\(^5\) of 3.7 W m\(^{-2}\) would shift up our estimated ranges for ECS and TCR, but only by about 0.1 K (see Supplementary Section S2). Both equations (1) and (2) assume constant linear feedbacks and (2) further assumes that the ratio of \(\Delta Q\) to \(\Delta T\) for the observed period is the same as that at year 70 of a simulation in which atmospheric CO\(_2\) levels increase at 1% per year\(^6\)\(^7\), which is approximately the case over the past few decades if we exclude periods strongly affected by volcanic eruptions (see Supplementary Fig. S2). Equation (1) provides a lower bound to the fully equilibrated sensitivity, because delayed ocean warming at high latitudes can mask the impact of local positive feedbacks\(^8\).

For \(\Delta T\), we use the HadCRUT4 ensemble data set of surface temperatures averaged globally and by decade (Supplementary Fig. S1). For \(\Delta Q\), we derive annual estimates of the change in total heat content of the Earth system for the period 1970 to 2009, by combining data-based estimates for all the main components of the Earth system (ocean, continent, ice and atmosphere); the ocean component dominates the heat uptake (see Supplementary Section S1). For \(\Delta F\), we use the multi-model average of the CMIP5 ensemble of climate simulations\(^9\) with emissions that follow a medium-to-low representative concentration pathway (RCP4.5). We include the historic record from 1850–2005 and the RCP4.5 scenario values from 2006–2010, scaled to match an ensemble of possible forcing estimates for 2010 (see Supplementary Section S1) to adjust for fast feedbacks and capture uncertainties.

The most likely value of equilibrium climate sensitivity based on the energy budget of the most recent decade is 2.0 °C, with a 5–95% confidence interval of 1.2–3.9 °C (dark red, Fig. 1a), compared with the 1970–2009 estimate of 1.9 °C (0.9–5.0 °C; grey, Fig. 1a). Including the
period from 2000 to 2009 into the 40-year 1970–2009 period delivers a finite upper boundary, in contrast with earlier estimates calculated using the same method\(^1\). The range derived from the 2000s overlaps with estimates from earlier decades and with the range of ECS values from current climate models\(^2\) (ECS values in the CMIP5 ensemble\(^3\) are 2.2–4.7 °C), although it is moved slightly towards lower values. Observations of the energy budget alone do not rule out an ECS value below 2 °C, but they do rule out an ECS below 1.2 °C with 95% confidence. The upper boundary is lowered slightly, but is also very sensitive to assumptions made in the evaluation process (see Supplementary Section S2). Uncertainties include observational errors and internal variability estimated from control simulations with general circulation models.

The best estimate of TCR based on observations of the most recent decade is 1.3 °C (0.9–2.0 °C; dark red, Fig. 1b). This is lower than estimates derived from data of the 1990s (1.6 °C (0.9–3.1 °C); yellow, Fig. 1b) or for the 1970–2009 period as a whole (1.4 °C (0.7–2.5 °C); grey, Fig. 1b). This is arguably the most reliable. Our results by the eruption of Mount Pinatubo in 1991, has the strongest forcing and is less affected by biases and provide only relatively weak constraints (see Supplementary Section S2 for a sensitivity study).

References


Author contributions

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