**Published article:**

Otto, A, Otto, FEL, Allen, MR, Boucher, O, Church, J, Hegerl, G, Forster, PM, Gillett, NP, Gregory, J, Johnson, GC, Knutti, R, Lohmann, U, Lewis, N, Marotzke, J, Stevens, B, Myhre, G and Shindell, D (2013) *Energy budget constraints on climate response.* Nature Geoscience, 6 (6). 415 - 416. ISSN 1752-0894

http://dx.doi.org/10.1038/ngeo1836

# 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[1–5] 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[6] 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[7] 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[8].

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[9] $\Delta T$, 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:

$$\mathrm{ECS} = \frac{F_{2x}\,\Delta T}{\Delta F - \Delta Q} \qquad (1)$$

$$\mathrm{TCR} = \frac{F_{2x}\,\Delta T}{\Delta F} \qquad (2)$$

where $F_{2x}$ is the forcing due to doubling atmospheric $CO_2$ concentrations. We use a value of $F_{2x}$ of 3.44 W m$^{-2}$ (with a 5–95% confidence interval of ±10%) from ref. 10. Using a higher estimate[11] of 3.7 W m$^{-2}$ would shift up our estimated ranges for ECS and TCR, but only by about 0.1 K (see Supplement 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[6,12], 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[13].

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[10] 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

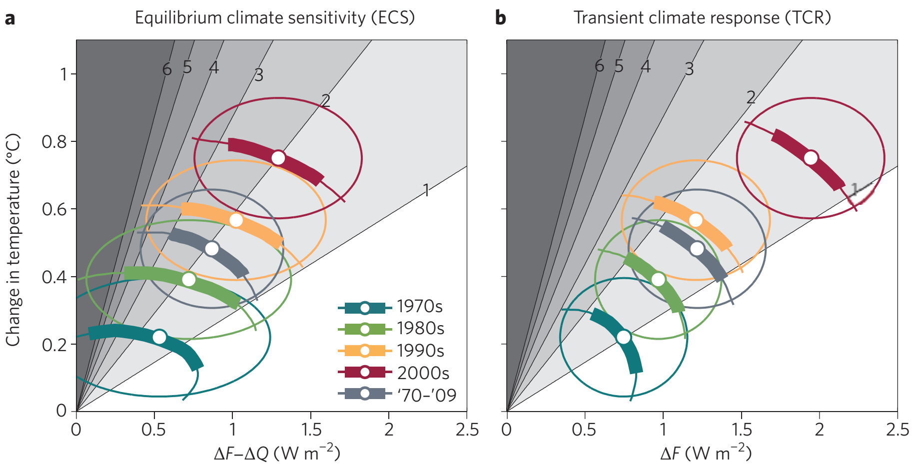


**Figure 1 |** Observations of the global energy budget and their implications. Observations of the global mean temperature change plotted against change in forcing minus heat uptake ($\Delta F$–$\Delta Q$) for the equilibrium climate sensitivity (ECS) (**a**) and against $\Delta F$ for the transient climate response (TCR) (**b**), for each of the four decades 1970s, 1980s, 1990s and 2000s and for the 40-year period 1970–2009. Ellipses represent likelihood contours enclosing 66% two-dimensional confidence regions; best-fit points of maximum likelihood are indicated by the circles; and the curved thick and thin lines represent the 17–83% and 5–95% confidence intervals of the resulting one-dimensional likelihood profile in ECS (or TCR), respectively. All time periods are referenced to 1860–1879, including a small correction in $\Delta Q$ to account for disequilibrium in this reference period[14]. Straight contours show iso-lines of ECS (**a**) and TCR (**b**), calculated using a best-fit value of $F_{2x}$ of 3.44 W m$^{-2}$ (also adjusted for fast feedbacks)[10]. Uncertainty in $F_{2x}$ is assumed to be correlated with forcing uncertainty in long-lived greenhouse gases[10]. To avoid dependence on previous assumptions[16], we report results as likelihood-based confidence intervals.

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[14]. The range derived from the 2000s overlaps with estimates from earlier decades and with the range of ECS values from current climate models[10] (ECS values in the CMIP5 ensemble[13] 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). However, because the most recent estimate has the strongest forcing and is less affected by the eruption of Mount Pinatubo in 1991, it is arguably the most reliable. Our results match those of other observation-based studies[15] and suggest that the TCRs of some of the models in the CMIP5 ensemble[10] with the strongest climate response to increases in atmospheric $CO_2$ levels may be inconsistent with recent observations — even though their ECS values are consistent and they agree well with the observed climatology. Most of the climate models of the CMIP5 ensemble are, however, consistent with the observations used here in terms of both ECS and TCR. We note, too, that caution is required in interpreting any short period, especially a recent one for which details of forcing and energy storage inventories are still relatively unsettled: both could make significant changes to the energy budget. The estimates of the effective radiative forcing by aerosols in particular vary strongly between model-based studies and satellite data. The satellite data are still subject to biases and provide only relatively weak constraints (see Supplementary Section S2 for a sensitivity study). ❐


## References

1. Aldrin, M. *et al. Environmetrics* **23,** 253–271 (2012).
2. Lewis, N. *J. Clim.* http://dx.doi.org/10.1175/JCLI-D-12-00473.1 (2013).
3. Ring, M. J., Lindner, D., Cross, E. F. & Schlesinger, M. E. *Atmos. Clim. Sci.* **2,** 401–415 (2012).
4. Stott, P. A., Good, P., Jones, G., Gillett, N. P. & Hawkins, E. *Environ. Res. Lett.* **8,** 014024 (2013).
5. Schwartz, S. E. *Surv. Geophys.* **33,** 745–777 (2012).
6. Gregory, J. M. & Forster, P. M. *J. Geophys. Res. Atmos.* **113,** D23105 (2008).
7. Allen, M. R. & Frame, D. J. *Science* **318,** 582–583 (2007).
8. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. *Bull. Am. Meteorol. Soc.* **93,** 485–498 (2011).
9. Morice, C., Kennedy, J. J., Rayner, N. A. & Jones, P. D. *J. Geophys. Res.* http://dx.doi.org/10.1029/2011JD017187 (2013).
10. Forster, P. M. *et al. J. Geophys. Res. Atmos.* **118,** 1–12 (2013).
11. Vial, J., Dufresne, J-L. & Bony, S. *Clim. Dynam.* http://dx.doi.org/10.1007/s00382-013-1725-9 (2013).
12. Held, I. M. *et al. J. Clim.* **23,** 2418–2427 (2010).
13. Armour, K. C., Bitz, C. M. & Roe, G. H. *J. Clim.* http://dx.doi.org/10.1175/JCLI-D-12–00544.1 (2012).
14. Gregory, J. M., Stouffer, R. J., Raper, S. C. B., Stott, P. A. & Rayner, N. A. *J. Clim.* **15,** 3117–3121 (2002)..
15. Gillett, N. P., Arora, V. K., Matthews, D. & Allen, M. R. *J. Clim.* http://dx.doi.org/10.1175/JCLI-D-12-00476.1 (2013).
16. Frame, D. J. *et al. Geophys. Res. Lett.* **32,** L09702 (2005).



## Author contributions

O.B., J.C., G.H., P.F., N.P.G., J.G., G.C.J., R.K., N.L., U.L., J.M., G.M., D.S., B.S., and M.R.A. conceived the analysis and designed the headline figure. P.M.F. provided the forcing data and estimates. G.C.J. provided the heat content data. A.O. conducted the analysis and produced the figures. A.O., F.E.L.O., M.R.A., P.M.F., O.B., and G.C.J contributed to writing the paper.


## Additional information

Supplementary information is available in the online version of the paper.


## Competing financial Interests

The authors declare no competing financial interests.



**Alexander Otto[1]*, Friederike E. L. Otto[1], Olivier Boucher[2], John Church[3], Gabi Hegerl[4], Piers M. Forster[5], Nathan P. Gillett[6], Jonathan Gregory[7], Gregory C. Johnson[8], Reto Knutti[9], Nicholas Lewis[10], Ulrike Lohmann[9], Jochem Marotzke[11], Gunnar Myhre[12], Drew Shindell[13], Bjorn Stevens[11] and Myles R. Allen[1,14]**

[1]Environmental Change Institute, University of Oxford, South Parks Road, Oxford, OX1 3QY, UK, [2]Laboratoire de Météorologie Dynamique, IPSL/CNRS, UPMC, Paris, France, [3]CSIRO Marine and Atmospheric Research Hobart, Castray Esplanade, Hobart Tasmani 7000, Australia, [4]Grant Institute, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, UK, [5]School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK, [6]Canadian Centre for Climate Modelling and Analysis, PO Box 3065 STNCSC, Victoria, British Columbia, Canada, [7]Department of Meteorology, University of Reading, PO Box 243, Reading RG6 6BB, UK, [8]NOAA/Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, Washington 98115, USA, [9]Institute for Atmospheric and Climate Science, ETH Zurich, 8092 Zurich, Switzerland, [10]Walden, Widcombe Hill, Bath, BA2 6ED, UK, [11]Max Planck Institute for Meteorology, Bundesstraße 53, D-20146 Hamburg, Germany, [12]CICERO, P.O. Box 1129 Blindern, N-0318 Oslo, Norway, [13]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, New York 10025, USA, [14]Department of Physics, University of Oxford, Parks Road,
Oxford OX1 3PU, UK.
*e-mail: alexander.otto@ouce.ox.ac.uk


Published online: 19 May 2013