The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity

There has been considerable scientific investigation of the magnitude of the warming of Earth's climate by changes in atmospheric carbon dioxide (CO2) concentration. Two standard metrics summarize the sensitivity of global surface temperature to an externally imposed radiative forcing. Equilibrium climate sensitivity (ECS) represents the equilibrium change in surface temperature to a doubling of atmospheric CO2 concentration. Transient climate response (TCR), a shorter-term measure over 70 years, represents warming at the time CO2 concentration has doubled when it is increased by 1% a year.

For over thirty years, climate scientists have presented a likely range for ECS that has hardly changed. The ECS range 1.5−4.5 K in 1979 (Charney 1979) is unchanged in the 2013 Fifth Assessment Scientific Report (AR5) from the Intergovernmental Panel on Climate Change (IPCC). AR5 did not provide a best estimate value for ECS, stating (Summary for Policymakers D.2): "No best estimate for equilibrium climate sensitivity can now be given because of a lack of agreement on values across assessed lines of evidence".

At the heart of the difficulty surrounding the values of ECS and TCR is the substantial difference between values derived from climate models versus values derived from changes over the historical instrumental data record using energy budget models. The median ECS given in AR5 for current generation (CMIP5) atmosphere-ocean global climate models (AOGCMs) was 3.2 K, versus 2.0 K for the median values from historical-period energy budget based studies cited by AR5.

Subsequently Lewis and Curry (2015; hereafter LC15) [1] derived, using observationally-based energy budget methodology, a median ECS estimate of 1.6 K from AR5's global forcing and heat content estimate time series, which made the discrepancy with ECS values derived from AOGCMs even larger. LC15 also derived a median TCR value of 1.3 K, well below the 1.8 K median TCR for CMIP5 models in AR5.

The LC15 analysis used a global energy budget model that relates ECS and TCR to changes (Δ) in global mean surface temperature [T], effective radiative forcing (ERF) [F] and the planetary radiative imbalance [N] (estimated from its counterpart, the rate of climate system heat uptake) [2] between a base and a final period. The resulting estimates were considerably less dependent on comprehensive global climate models (GCMs) and allowed more thoroughly for forcing uncertainties than many others.[3] Further information on the energy budget model is given in the Appendix to this article.

Considerable effort has been expended recently in attempts to reconcile observationally-based ECS values with values determined using climate models. Most of these efforts have focused on arguments that the methodologies used in the energy budget model determinations result in downwards-biased ECS and/or TCR estimates (e.g., Marvel et al. 2016; Richardson et al. 2016; Armour 2017).

We have now updated the LC15 paper with a new paper that has been published in the Journal of Climate "*The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity*".[4] The paper (hereafter, LC18) addresses a range of concerns that have been raised about climate sensitivity estimates derived using energy balance models. We provide estimates of ECS and TCR based on a globally-complete infilled version of the HadCRUT4 surface temperature dataset as well as estimates based on HadCRUT4 itself.[5] Table 1 gives the ECS and TCR estimates for the four base period – final period combinations used.

Base period	Final period	ECS best estimate [°C]	ECS 17-83% range [°C]	ECS 5-95% range [°C]	TCR best estimate [°C]	TCR 17-83% range [°C]	TCR 5-95% range [°C]
1869–1882	**2007–2016**	**1.50** ***1.66***	**1.2–1.95** ***1.35–2.15***	**1.05–2.45** ***1.15–2.7***	**1.20** ***1.33***	**1.0–1.45** ***1.1–1.60***	**0.9–1.7** ***1.0–1.9***
1869–1882	1995–2016	1.56 *1.69*	1.2–2.1 *1.35–2.25*	1.05–2.75 1.15–3.0	1.22 *1.32*	1.0–1.5 *1.1–1.65*	0.85–1.85 *0.95–2.0*
1850–1900	1980–2016	1.54 *1.67*	1.2–2.15 *1.3–2.3*	1.0–2.95 *1.1–3.2*	1.23 *1.33*	1.0–1.6 *1.05–1.7*	0.85–1.95 *0.9–2.15*
1930–1950	2007–2016	1.56 *1.65*	1.2–2.15 *1.25–2.3*	1.0–3.0 *1.05–3.15*	1.20 *1.27*	0.95–1.5 *1.05–1.6*	0.85–1.85 *0.9–1.95*
Lewis and Curry (2015) results for comparison							
1859–1882	1995–2011	1.64	1.25–2.45	1.05–4.05	1.33	1.05–1.8	0.90–2.5
1850–1900	1987–2011	1.67	1.25–2.6	1.0–4.75	1.31	1.0–1.8	0.85–2.55
IPCC (2014) estimates for comparison							
AR5 (Chapter 12)		NA	1.5–4.5	1–NA	NA	1–2.5	NA–3

Table 1 (based on Table 3 in LC18) Best estimates (medians) and uncertainty ranges for ECS and TCR using the base and final periods indicated. Values in roman type compute the temperature change involved (ΔT) using the HadCRUT4v5 dataset; values in *italics* compute ΔT using the infilled, globally-complete Had4_krig_v2 (Cowtan & Way) dataset. The preferred estimates are shown in bold. Ranges are stated to the nearest 0.05 K. Also shown are the comparable results (using the HadCRUT4v2 dataset) from LC15 for the first two period combinations given in that paper. The values from the IPCC AR5 are provided for reference.

The new LC18 ECS and TCR estimates are very similar for all the period combinations used. That implies that the 'hiatus' – the period of slow warming from the early 2000s until a few years ago – had little effect on estimation. The preferred pairing is of the 1869–1882 and 2007–2016 periods, which provides the largest change in forcing and hence the narrowest uncertainty ranges, notwithstanding that both these periods are the shortest ones used. Using 1869–1882 as the base period avoids both any significant volcanism and the period of particularly sparse temperature data spanning most of the 1860s. Estimates are almost identical when using the longer 1850–1882 base period and excluding years affected by volcanism or with very sparse temperature data.

The new LC18 ECS and TCR HadCRUT4-based best estimates, respectively 1.50°C and 1.20°C, are approximately 10% lower than those in LC15. These reductions stem primarily from a significant upwards revision in estimated methane forcing following more accurate determination of the forcing-concentration relationships for the principal well-mixed greenhouse gases (WMGG)[6] and revisions to post-1990 AR5 aerosol and ozone forcing estimates that reflect updated emission data,[7] partially offset by a 2.5% upwards revision in the forcing from a doubling of preindustrial carbon dioxide (CO_2) concentration, $F_{2\times CO2}$.[8]

The 5% uncertainty bound of the AR5 2011 aerosol forcing estimate was changed from -1.9 Wm^{-2} to -1.7 Wm^{-2} to reflect substantial recent evidence against aerosol forcing being extremely strong.[9]

Doing so had virtually no effect on the median ECS and TCR estimates, and accounted for only a small fraction of the major reductions in their 83% and 95% upper uncertainty bounds from those in LC15. Most of that reduction is due to the revised forcing estimates and to average greenhouse gas concentrations over 2007–2016 being higher than over 1995–2011.

Figure 1 shows a comparison of the revised, extended forcings estimates with their original AR5 values. The significant increase in 'Other WMGG' forcing reflects the revision of the methane forcing component.[10]

There is some recent evidence that AR5 volcanic forcing estimates, which in LC18 are extended to 2016 using the AR5 calculation basis, may be biased low due to omission of volcanic aerosol in the lower stratosphere.[11] However, once an adjustment is made for the background level of volcanic aerosol there appears to be virtually no effect on the changes in volcanic forcing between the base and final periods used in LC18.[12]

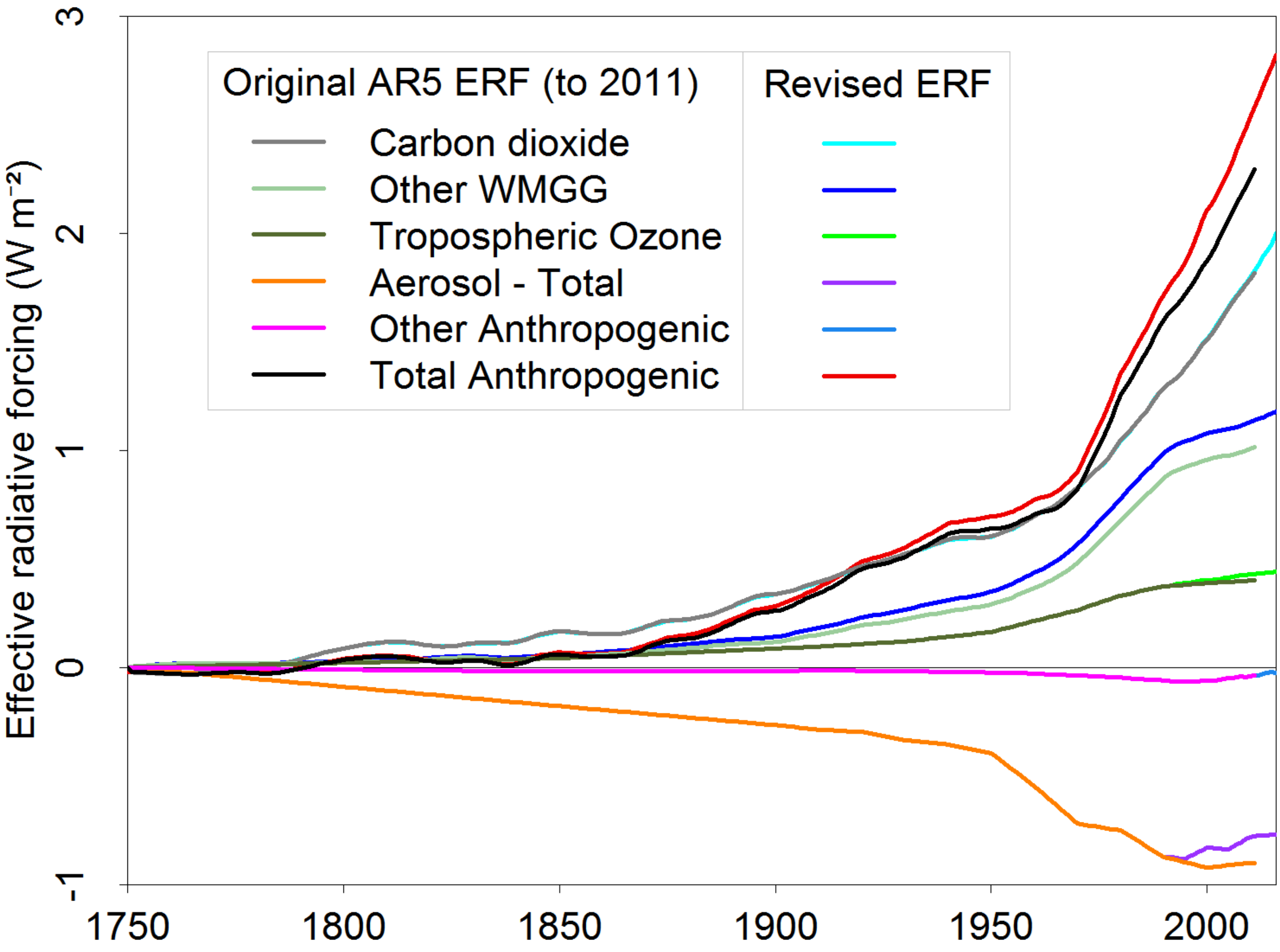

Fig. 1 (based on Figure 2 of LC18) Anthropogenic forcings from 1750 to 2016. In some cases the Original AR5 1750–2011 time-series overlay the Revised 1750–2016 time-series prior to 2012. Unrevised anthropogenic forcing components have been combined into a single 'Other Anthropogenic' time-series. Solar and Volcanic forcings are not shown; they have not been revised and their post 2011 changes are very small.

The new best estimates using globally-complete surface temperature data, of 1.66°C for ECS and 1.33°C for TCR, are almost the same as the LC15 ECS and TCR estimates based on non-infilled temperature data. Both the LC15 and LC18 'likely' (66%+ probability) ranges are both very much towards the bottom ends of the corresponding IPCC AR5 ranges.

Figure 2 shows probability density functions for each of the ECS and TCR estimates, with the AR5 'likely' ranges (shaded lime green) for comparison. The PDFs are skewed due principally to the dominant uncertainty in forcing, affecting the denominator of the fractions used to estimate ECS and TCR.

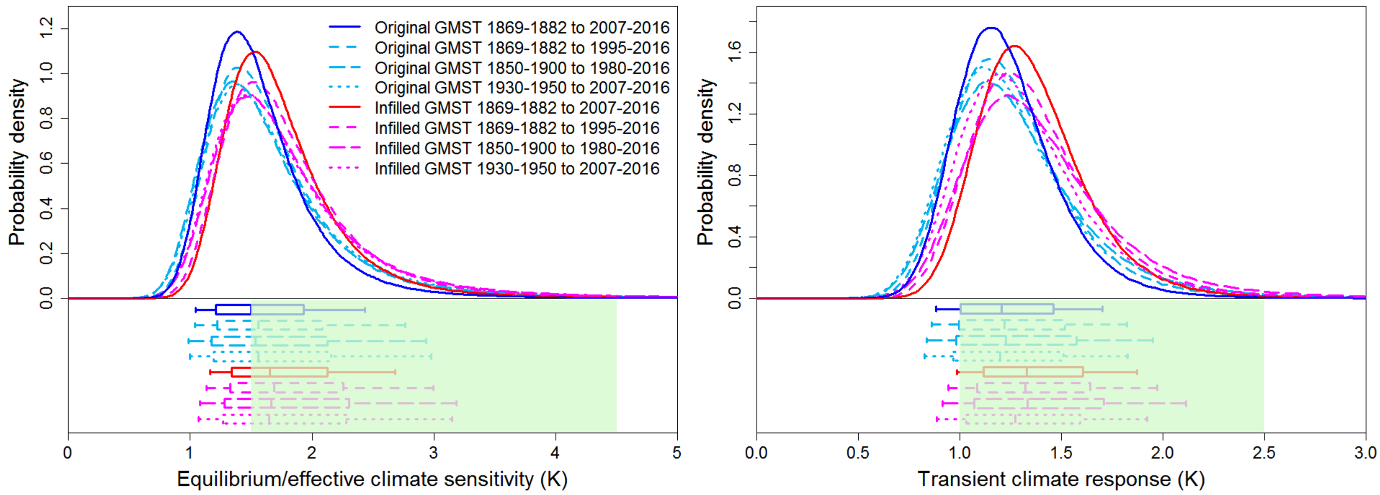

Fig. 2 (based on Figure 4 of LC18) Estimated probability density functions for ECS and TCR using each main results period combination. Original GMST refers to use of the HadCRUT4v5 record; Infilled GMST refers to use of the Had4_krig_v2 record. Box plots show probability percentiles, accounting for probability beyond the range plotted: 5–95 (bars at line ends), 17–83 (box-ends) and 50 (bar in box: median). Lime green shading shows the AR5 'likely' (17–83% or better) ranges.

LC18 also derived, on comparable bases, ECS and TCR values for all current generation (CMIP5) GCMs for which the requisite data were available.[13] A majority of this ensemble of 31 CMIP5 models had ECS and TCR values that exceeded the 2.7°C and 1.9°C 95% uncertainty bounds that we derived for those parameters using globally-complete surface temperature data.

The foregoing ECS estimates reflect climate feedbacks over the historical period, assumed time-invariant. Two recent studies asserted that ECS estimates for CMIP5 models derived from forcing data comparable to that available for use in historical period (post-1850) observationally-based energy budget studies, using a constant feedbacks assumption, were biased low. They concluded that CMIP5 model ECS estimates were on average some 30% higher when derived from their response to an increase in CO_2 concentration in a way that allows, insofar as practicable, for time-varying feedbacks.[14] We show that their calculations are biased and that, when calculated appropriately, the difference is under 10%.[15] Allowing for such possible time-varying climate feedbacks increases the median ECS estimate to 1.76°C (5−95%: 1.2−3.1°C), using globally-complete temperature data. A majority of our ensemble of CMIP5 models have ECS values, estimated in the way designed to allow for time-varying feedbacks, that exceed 3.1°C.

It has been suggested in various studies that effects of non-unit forcing efficacy, temperature estimation issues and variability in sea-surface temperature change patterns likely lead to historical period energy budget estimates being biased low.[16] We examined all these issues in LC18 and found that only very minor bias was to be expected when using globally-complete temperature data.[17]

Over half of the 31 CMIP5 models have ECS values estimated using a comparable change in forcing to that over the historical period[18] of 2.9 K or higher, exceeding by over 7% our 2.7 K observationally-based 95% uncertainty bound using infilled temperature data. Moreover, a majority of these models have a TCR above our corresponding 1.9 K 95% bound.

The implications of our results are that high estimates of ECS and TCR derived from a majority of CMIP5 climate models are inconsistent (at a 95% confidence level) with observed warming during the historical period. Moreover, our median ECS and TCR estimates using infilled temperature data imply multicentennial or multidecadal future warming under increasing forcing of only 55−70% of the mean warming simulated by CMIP5 models.

I hope to discuss in more depth in a subsequent article some of the material in LC18 and its Supporting Information that has been dealt with only very briefly here.

Appendix – Further details of the energy budget method

In the energy budget method, external global mean estimates – observationally based so far as practical – of all forcing and climate system heat uptake components, as well as of surface temperature, are used to compute the mean changes ΔF in total forcing, ΔN in total heat uptake (≡ radiative imbalance), and ΔT in surface temperature, between a base period and a final period. An estimate of the strength of climate feedbacks (the climate feedback parameter, λ) acting between the two periods is obtained as:

$$\lambda = (\Delta F - \Delta N) / \Delta T$$

By extrapolating this equation to equilibrium ($\Delta N = 0$) and scaling ΔF to represent the radiative forcing attributable to a doubling of atmospheric CO_2 concentration, $F_{2\times CO2}$, one obtains equilibrium climate sensitivity (ECS) as:

$$\text{ECS} = F_{2\times CO2} / \lambda$$

It is assumed here that all types of forcing have the same effect on global surface temperature, i.e. that they have the same 'efficacy'.

Equilibrium climate sensitivity (ECS) may thus be estimated as:

$$\text{ECS} = F_{2\times CO2}\ \Delta T / (\Delta F - \Delta N)$$

As AR5 (Section 10.8.1) says, the simple model represented by this equation follows from conservation of energy. However, as the equation is based on transient, non-equilibrium, changes what it directly estimates is an 'effective climate sensitivity', termed ECS_{hist} in LC18 when estimated using the change in forcing over the historical period or a comparable change. In order to estimate equilibrium climate sensitivity, the method makes the assumption that the feedback parameter λ is independent of ΔF and ΔT and constant over time, implying that ECS ≡ ECS_{hist}. The behaviour of CMIP5 models supports the assumed non-dependence of λ on ΔF or ΔT, at least up to a quadrupling of preindustrial CO_2 concentration and warming of up to 5°C, but in most cases CMIP5 models exhibit a decline in λ as the time since imposition of a forcing increases, implying that ECS > ECS_{hist}. The estimated ratio of ECS to ECS_{hist} in each CMIP5 model is used in LC18 to derive an adjusted ECS estimate that reflects possible time-varying climate feedbacks.[19]

AR5 (Section 10.8.1) also points out that TCR may be estimated as:

$$\text{TCR} = F_{2\times CO2}\ \Delta T / \Delta F$$

provided that the change in forcing takes place gradually over an approximately 70-year timescale, which it does for all the base and final period combinations used.

Nicholas Lewis April 2018

---

[1] Lewis, N., and J. A. Curry, 2015: The implications for climate sensitivity of AR5 forcing and heat uptake estimates. Climate Dynamics, 45(3-4), 1009-1023. Note: the paper was initially published online in 2014. An article about the paper and its results was posted here.

[2] Total heat uptake by the Earth's climate system, 90%+ in the ocean, necessarily equals the Earth's top-of-atmosphere radiative imbalance, neglecting the tiny and near-constant geothermal heat flux (which has a negligible effect on ΔN).

[3] Although none of the forcing estimates used are fully independent of GCMs, they do not appear to be materially affected by the ECS and TCR values of the GCMs involved. The early industrial heat uptake estimates used are GCM-derived and dependent on the GCM's sensitivity, but they are small and a correction factor is applied to allow for the sensitivity of the GCM being higher than the energy budget derived sensitivity estimate.

[4] Lewis, N. ,and J. Curry, 2018:The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *J. Clim.* JCLI-D-17-0667 A copy of the final submitted manuscript, reformatted for easier reading, is available at my personal webpages, here. The Supporting Information is available here.

[5] Cowtan, K., and R. G. Way, 2014: Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quart. J. Roy. Meteor. Soc*., ***140***(683), 1935-1944 (update at http://www.webcitation.org/6t09bN8vM).

[6] Etminan, M., G. Myhre, E. J. Highwood, and K. P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophys. Res. Lett.* **43**(24) doi:10.1002/2016GL071930.

[7] Myhre, G., and Coauthors, 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990–2015. *Atmos. Chemistry and Phys.*, **17**(4), 2709-2720.

[8] The almost identical proportional reduction in HadCRUT4-based ECS and TCR estimates between LC15 and the new study reflects the fact that heat uptake and forcing changes increased in similar proportions relative to the temperature change.

[9] See extensive discussion in section 3a of LC18. Note that the (revised) 2011 AR5 aerosol forcing uncertainty range is – as for all the AR5 forcing uncertainty ranges – merely used, after dividing by its median, to estimate fractional uncertainty in the ERF best estimate time series, as revised.

[10] The reason why recent CO_2 forcing is almost unchanged despite $F_{2\times CO2}$ being 2.5% higher is that the revised greenhouse gas forcing formulae embody a slightly faster than logarithmic increase in CO_2 forcing with concentration.

[11] Andersson, S. M., et al., 2015: Significant radiative impact of volcanic aerosol in the lowermost stratosphere. *Nature communications*, **6**, 8692.

[12] LC18 Supporting Information, S1

[13] We excluded FGOALS-g2 as its 1pctCO2 simulation results are abnormal and the p2 variants of GISS-E2-H and GISS-E2-R as their model physics is intermediate between the main (p1) and p3 physics versions. That left 31 CMIP5 models. See Table 2 in the Supporting Information for their calculated ECS and TCR values. Note that the reference to ECS calculated on a comparable basis (to our observational energy budget ECS estimates) is to the ECS_{hist} values in Table 2.

[14] Armour, K. C., 2017: Energy budget constraints on climate sensitivity in light of inconstant climate feedbacks. *Nature Climate Change*, **7**, 331-335.
Proistosescu, C., and P. J. Huybers, 2017: Slow climate mode reconciles historical and model-based estimates of climate sensitivity. *Science Advances*, ***3***(7), e1602821.

[15] Section 7f and Supporting Information S5.

[16] Marvel, K., G. A. Schmidt, R. L. Miller and L. S. Nazarenko, 2016: Implications for climate sensitivity from the response to individual forcings. *Nature Climate Change*, **6**(4), 386-389.
Richardson, M., K. Cowtan, E. Hawkins, and M. B. Stolpe, 2016: Reconciled climate response estimates

from climate models and the energy budget of Earth. *Nature Climate Change*, **6**(10), 931-935.
Gregory, J. M., and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical period. Geophys. Res. Lett., **43**: 3911–3920.

[17] See sections 7a, 7c and 7e of LC18.

[18] Where types of ECS estimate are distinguished in LC18, this type is termed ECS_{hist}. Since forcing in CMIP5 models' historical simulations is model-dependent and unknown, their ECS_{hist} is estimated (in LC18 and other studies) using data from their simulations driven by known changes in CO_2, in such a way as to mimic the ECS estimates that would be derivable from their responses to representative historical forcing.

[19] See the fourth from last paragraph of section 7f in LC18 for details, and section S4 of the LC18 Supporting Information for the calculation of ECS_{hist} and ECS values for CMIP5 models.