Equilibrium Climate Sensitivity and Transient Climate Response – the determinants of how much the Earth's surface will warm as atmospheric CO_2 increases

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1. In this note I review recent scientific evidence regarding equilibrium climate sensitivity (ECS) and the transient climate response (TCR), the two key climate system parameters that have the greatest influence on future warming arising from increases in atmospheric greenhouse gases.[1] In its latest assessment, AR5, the IPCC concluded it was *likely*[2] that ECS lay between 1.5 and 4.5 °C, and TCR between 1 and 2.5 °C, both very wide ranges, with no best estimates given. An idea of the importance of improving estimation of these parameters can be gained from a recent paper published by the Royal Society,[3] which estimated the value gained by halving the uncertainty range for TCR to be $10 trillion.

2. ECS is defined as the increase in global mean surface temperature (GMST) arising from a doubling of atmospheric equivalent CO_2, once the ocean has fully equilibrated. Changes in slow components of the climate system (e.g., ice sheets, vegetation) are included in Earth system sensitivity (ESS) but not in ECS.

3. TCR is the increase in GMST, from a previous equilibrium state, when atmospheric CO_2 rises by 1% p.a. until it has doubled (taking 70 years). It is lower than ECS since at the time of CO_2 doubling the ocean has not fully warmed up, which takes many centuries. TCR is generally thought to largely determine the rise in GMST during this century in response to increasing CO_2, but in current climate models the projected GMST rise is actually more closely related to ECS than to TCR. ECS is in any event more relevant than TCR for longer term warming and for sea level rise.

4. ECS is closely linked to underlying physical concepts of effective radiative forcing (ERF)[4] and climate feedbacks. ERF measures the effect on the Earth's radiation balance of changes in atmospheric CO_2 and other forcing agents. GMST is thought to respond fairly linearly to total ERF, however composed, implying additivity of forcings and reasonable stability of ECS (at least up to GMST 6°C or so above its preindustrial level). The ERF from CO_2 varies approximately logarithmically with its atmospheric concentration; the ERF from a doubling of CO_2 is designated F_{2xCO2} and is estimated at ~3.7 Wm^{-2} (for a doubling from the preindustrial level).

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[1] Meaning well-mixed greenhouse gases, being CO_2, CH_4, N_2O and many halogenated species but not short lived O_3

[2] In IPCC parlance, *likely* means at least 66% probability, implicitly centred on the median (50% point)

[3] Hope, C, 2015. The $10 trillion value of better information about the transient climate response. Roy Soc Phil Trans A, 327, DOI: 10.1098/rsta.2014.0429

[4] Effective radiative forcing is the change in net TOA [top of atmosphere] downward radiative flux after allowing for atmospheric temperatures, water vapour and clouds to adjust, but with surface temperature or a portion of surface conditions unchanged. [IPCC AR5 WG1 Box 8.1]

5. In global terms, over a period during which ERF changes, the Earth's energy budget implies[5] that:

$$\mathrm{ECS} = \Delta T \times \mathrm{F}_{2\mathrm{xCO2}} / (\Delta F - \Delta Q) \qquad (1)$$

and (if the change in ERF was fairly linear and principally occurred over approximately a final 70-year period)

$$\mathrm{TCR} = \Delta T \times \mathrm{F}_{2\mathrm{xCO2}} / \Delta F \qquad (2)$$

where ΔT refers to the change in GMST resulting from a change ΔF in ERF, and ΔQ refers to a change in the planetary heating rate Q, mainly (>90%) reflected in ocean heat uptake.

6. ECS is also related to the climate feedback parameter λ,[6] the negative sum of all feedbacks, including: the primary (negative) Planck radiative feedback λ_p from a warmer Earth emitting more radiation; water vapour and lapse rate feedbacks, closely linked and combined as λ_{wv+lr} ; combined short- and long-wave cloud feedbacks λ_{cl} ; and albedo feedback λ_{alb} – which arises mainly from decreasing seasonal snow cover as GMST rises. Thus:

$$\mathrm{ECS} = \mathrm{F}_{2\mathrm{xCO2}} / \lambda = -\mathrm{F}_{2\mathrm{xCO2}} / (\lambda_p + \lambda_{wv+lr} + \lambda_{cl} + \lambda_{alb}) \qquad (3)$$

7. All estimates of ECS based on instrumental observations reflect feedbacks operating during a period of disequilibrium, and thus strictly estimate so-called effective climate sensitivity. Little distinction is drawn between effective climate sensitivity and ECS in AR5.

8. AR5 concluded[7] that estimates of ECS based on:

    - past climate states very different from today
    - timescales different than those relevant for climate stabilization (e.g. climate response to volcanic eruptions)
    - forcings other than greenhouses gases (e.g. volcanic eruptions or solar forcing)

    may differ from the climate sensitivity based on the climate feedbacks of the Earth system today. That implies that no reliance should be based on such estimates. I concur.

9. Accordingly, instrumental-observation ECS estimates reflecting equation (1) are usually based on the relationship between temperature, forcing and planetary energy gain over a multidecadal period during which greenhouse gas forcing dominated. Usually, data for the entire period during which reasonable instrumental estimates of GMST exist, from the third quarter of the 19th century until now (the instrumental period), or for all except an early part of it, are used. Analysing changes over the full instrumental period also has the benefit of minimising the influence of natural multidecadal internal climate system variability and of uncertainty in the (unmeasured) initial rate of ocean heat uptake, which would have been fairly small 100+ years ago. TCR can

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[5] IPCC AR5 WG1 10.8.1

[6] Sometimes instead designated α

[7] IPCC AR5 WG1 12.5.3

also be estimated from changes over the entire instrumental period, as the rise in ERF approximates a linear ramp largely occurring over the last ~70 years.

10. Uncertainty in the ΔT term of equations (1) and (2) is relatively small, but uncertainty in $\Delta F / F_{2xCO2}$ is substantial, despite it being small in respect of the dominant (positive) CO_2 component of ΔF, largely because of high uncertainty about the smaller (negative) anthropogenic aerosol component of ΔF. Uncertainty in $\Delta Q / F_{2xCO2}$, whilst considerable, is much less important than that in $\Delta F / F_{2xCO2}$, and is irrelevant for estimating TCR. The large relative uncertainty in the denominator of (2) and, even more so, in the (smaller) denominator of (1), results in the TCR and, particularly, ECS estimates having skewed probability densities with long upper tails. Most observational ECS studies used subjective Bayesian methods with unsuitable prior distributions that fattened these upper tails, sometimes hugely, resulting in upwardly biased estimation.

11. Estimates of total aerosol forcing were strongly negative at the time of IPCC AR4 (2007), which gave a best estimate[8] of -1.3 Wm^{-2} since preindustrial, largely derived from bottom-up parameterized calculations in 3D coupled atmosphere-ocean global climate models (AOGCMs). On that basis, ECS estimates using Eq.(1) were in line with mean AOGCM ECS values at ~3°C. Since AR4, better satellite observation-based estimates of aerosol forcing have become available, pointing to weaker values, as do inverse estimates that infer aerosol forcing strength from latitudinally-resolved temperature differentials (aerosol emissions and forcing being spatially inhomogeneous). In AR5, the aerosol forcing best estimate was cut to -0.9 Wm^{-2} since preindustrial, or -0.7 Wm^{-2} over the instrumental period,[9] much weaker than in typical current generation (CMIP5) AOGCMs. A powerfully argued recent paper[10] by a highly regarded climate scientist estimates the aerosol forcing change over the instrumental period as being even weaker, at -0.5 Wm^{-2}. New evidence suggesting higher levels of natural aerosols than previously thought supports this revision.[11] Weaker negative aerosol forcing implies lower instrumental-observation ECS and TCR estimates, *ceteris paribus*, since it implies a higher ΔF value in (1) and (2).

ECS best estimates from multidecadal instrumental-observation studies published in the last few years that reflect either the AR5 aerosol forcing estimate or an inverse estimate they formed using latitudinally-resolved data, and do not involve subjective prior distributions that strongly bias estimation, are set out below. CMIP5 models ECS values are given for comparison. The width of each 'violin' shows the estimate's probability density at each ECS level. The two green violins are from a study[12] that employed multimodel estimates of warming attributable purely to greenhouse gases, isolated from inhomogeneous aerosol forcing and other forcings, taken from the two main detection and attribution studies used for the IPCC AR5 anthropogenic influence statements. Otto

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[8] Best estimates are medians, the only invariant central estimate for skewed distributions, unless otherwise stated

[9] The AR5 best estimate aerosol forcing strengthens by -0.2 Wm^{-2} between 1750, the notional start of the industrial period, and 1860, around the start of the instrumental period.

[10] Stevens, B., 2015. Rethinking the lower bound on aerosol radiative forcing. J. Climate 28, 4794-4819

[11] Because the major, cloud albedo effect, component of aerosol forcing is believed to be logarithmically related to total (natural plus anthropogenic) aerosol loading.

[12] Lewis, N, 2016. Implications of recent multimodel attribution studies for climate sensitivity. Clim Dyn, 46, 1387–1396. DOI 10.1007/s00382-015-2653-7

et al (2013)[13] was a particularly influential study as its authors included fourteen key AR5 lead authors working in areas relevant to climate sensitivity. Lewis and Curry (2014)[14] updated Otto et al by using actual AR5 forcing estimates, which were by then available, as well as AR5 planetary heat uptake estimates, and allowed more comprehensively for uncertainty. It thus represents, as its title implies, the implications of AR5 forcing and heat uptake estimates for ECS and TCR. The remaining studies[15] were all published between 2012 and 2014. The alternative results from Aldrin et al. (2012) using a prior distribution with the form ECS^{-2} (a uniform prior in 1/ECS), which appears to be more appropriate, are shown as well as the main results using a uniform in ECS prior. In those cases where sensitivity of ECS estimates to inclusion of the post early 2000s hiatus period was tested, it was found to be minor.

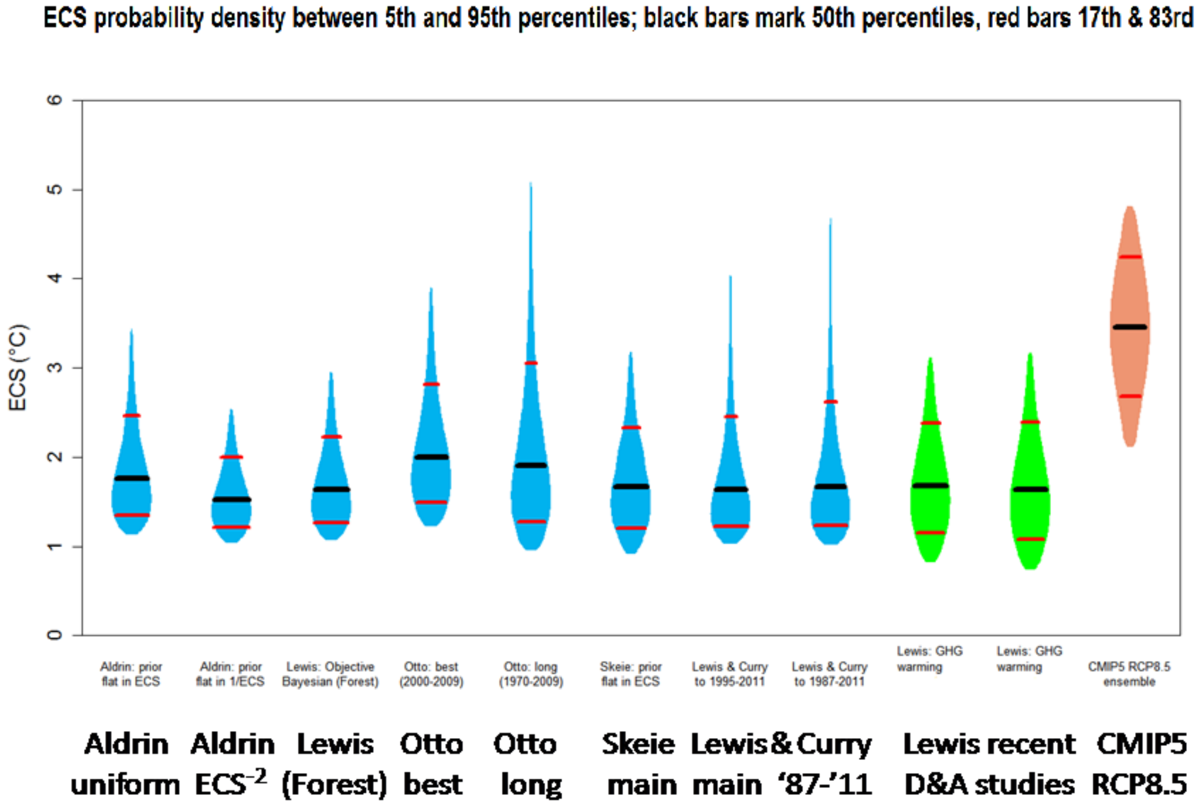

Figure 1

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[13] Otto, A., et al., 2013. Energy budget constraints on climate response. Nature Geoscience, 6: 415–416.

[14] Lewis N., Curry J.A., 2014: The implications for climate sensitivity of AR5 forcing and heat uptake estimates. Clim. Dyn. DOI 10.1007/s00382-014-2342-y

[15] Aldrin, M., M. Holden, P. Guttorp, R. B. Skeie, G. Myhre, and T. K. Berntsen, 2012. Bayesian estimation of climate sensitivity based on a simple climate model fitted to observations of hemispheric temperatures and global ocean heat content. Environmetrics, 23, 253-271.
Lewis, N., 2013: An objective Bayesian, improved approach for applying optimal fingerprint techniques to estimate climate sensitivity. Journal of Climate, 26, 7414-7429.
Skeie, R.B., T. Berntsen, M. Aldrin, M. Holden and G. Myhre, 2014. A lower and more constrained estimate of climate sensitivity using updated observations and detailed radiative forcing time series. Earth Syst.Dynam., 5, 139–175.

12. Figure 2 below shows an equivalent comparison, but for TCR not ECS. Although the difference between observational and CMIP5 estimates appears smaller than for ECS, 21st century warming projected by CMIP5 models is significantly higher than that derived from the projected forcing increase and their TCR values even after allowing for "warming in the pipeline" corresponding to the current positive *Q*.

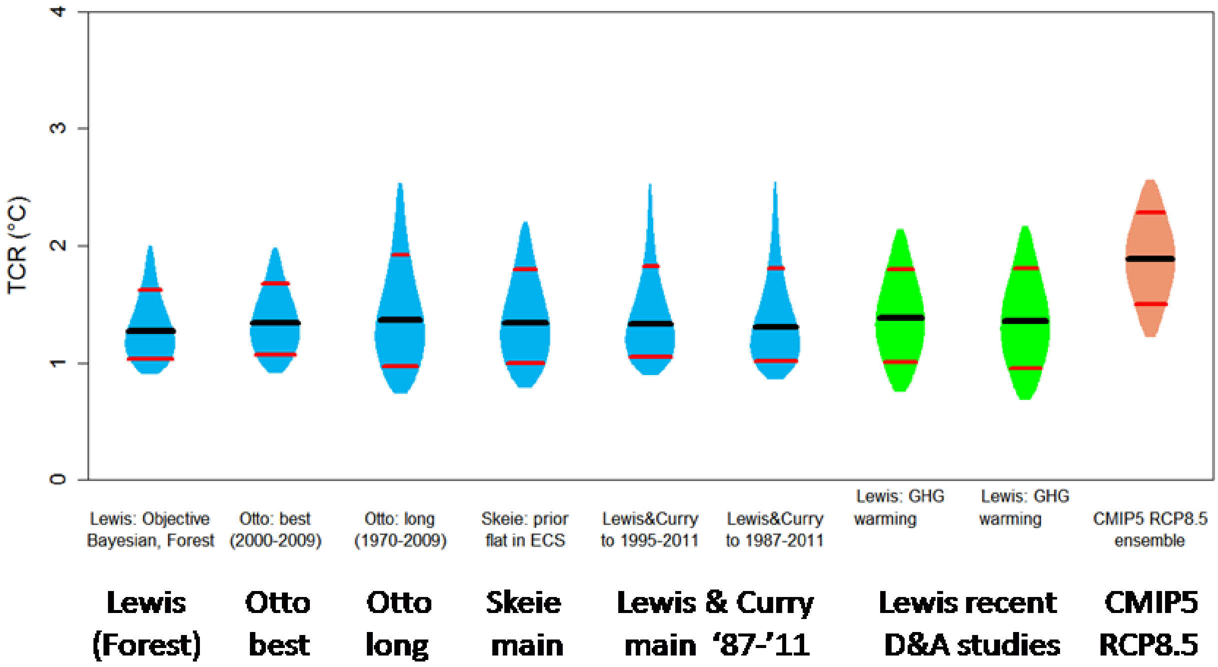

Figure 2

13. Energy budget studies using global-only variables (such as Otto et al 2013 and Lewis & Curry 2014) make the assumption that the realised transient GMST response to inhomogeneous non-GHG forcings, principally from aerosols (but to an extent also ozone, and to a minor extent land use change) bears approximately the same relation to their ERF as it does for well-mixed greenhouse gases. This has recently been challenged, with the implication (if correct) that energy-budget estimates of TCR (and hence of ECS) may be biased low.[16] However, the work is based on CMIP5 model simulations designed for other purposes and has methodological weaknesses. Other work, based on more accurate single-forcing AOGCM simulations, has found no evidence of this effect for aerosols – if anything, the contrary.[17] Moreover, it is very difficult to reconcile the claimed much greater transient sensitivity to (northern hemisphere focussed) aerosol forcing with estimates of the historical evolution of zonal temperatures and of the relative transient sensitivity of northern extratropical temperature since the Little Ice Age. The consistency of ECS and TCR estimates from global-only energy budget studies with those from other methods, that either use

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[16] Shindell, DT, 2014. Inhomogeneous forcing and transient climate sensitivity. Nature Clim Chg: DOI: 10.1038/NCLIMATE2136

[17] Ocko IB, V Ramaswamy and Y Ming, 2014. Contrasting Climate Responses to the Scattering and Absorbing Features of Anthropogenic Aerosol Forcings J. Climate, 27, 5329–5345.
Forster PM, 2016. Inference of climate sensitivity from analysis of Earth's energy budget Annu. Rev. Earth Planet. Sci., 44. doi: 10.1146/annurev-earth-060614-105156

latitudinally resolved data or are based on greenhouse gas only warming isolated using 3D CMIP5 models, provides further reason for considering that no significant estimation bias in fact arises.

14. All sound studies based on warming over the instrumental period (including several not shown)[18] reach much the same ECS and/or TCR best estimates, which is what one would expect since they all rely on much the same data (save for estimating aerosol forcing in different ways). Although other studies exist that produce higher ECS and/or TCR estimates, I have identified serious problems in each of them which led to upward estimation bias.[19] To narrow uncertainty in ECS one must bring in independent data, palaeoclimate proxy data being the obvious choice. The transition from the last glacial maximum to the Holocene (LGM studies) has been much studied; all but one of the palaeo ECS estimates shown in AR5 are based on it, and AR5 concluded that estimates of ECS from more distant palaeoclimate periods are difficult to directly compare with ECS in today's climate state.

15. Simple calculations in which the global temperature anomaly at the LGM is divided by the total estimated forcing relative to the preindustrial state have long been used to generate estimates of the equilibrium climate sensitivity.[20] Although ECS estimates from earlier LGM studies that did so were typically around 3°C, current best estimates of GMST[21] and of relevant forcings[22] at the LGM imply an ECS estimate of ~1.75 °C. A more sophisticated approach using AOGCM simulations to relate temperature change post the LGM to ECS in the current climate state gave an ECS best estimate of 2.0 °C.[23]

16. As AR5 states,[24] true uncertainties for palaeoclimate ECS estimates are likely greater than those for multidecadal instrumental-observation estimates. As a result, combining representative palaeoclimate and instrumental-period warming based estimates does not, when correctly effected, greatly change the 5–95% range from the instrumental-observation evidence, although it does curtail the far upper tail of the uncertainty distribution, and it only slightly increases the best

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[18] E.g., Masters, T., 2013. Observational estimate of climate sensitivity from changes in the rate of ocean heat uptake and comparison to CMIP5 models. Clim. Dyn., DOI 10.1007/s00382–013–1770–4; Ring, M.J., D. Lindner, E.F. Cross, and M.E. Schlesinger, 2012. Causes of the global warming observed since the 19th century. Atmos. Clim. Sci., 2: 401–415; Schwartz, S.E., 2012. Determination of Earth's transient and equilibrium climate sensitivities from observations over the twentieth century: Strong dependence on assumed forcing. Surv.Geophys., 33: 745–777.

[19] See https://niclewis.wordpress.com/ipcc-ar5-climate-sensitivity-and-other-issues/ and https://niclewis.wordpress.com/pitfalls-in-climate-sensitivity-estimation/ Similar serious problems arise with the one or two more recently published instrumental-observation warming studies that reach ECS estimates above 2°C.

[20] Annan, J and Hargreaves, J., 2015. A perspective on model-data surface temperature comparison at the Last Glacial Maximum. Quaternary Science Reviews 107 1-10

[21] 4 °C below preindustrial: Annan, J.D., Hargreaves, J.C., 2013. A new global reconstruction of temperature changes at the Last Glacial maximum. Clim. Past 9 (1), 367-376.

[22] 8–11 Wm^{-2} below preindustrial: Annan, J.D., Hargreaves, J.C., 2006. Using multiple observationally-based constraints to estimate climate sensitivity. Geophys. Res. Lett. 33, L06704.

[23] Hargreaves, J.C., Annan, J.D., Yoshimori, M., Abe-Ouchi, A., 2012. Can the Last Glacial Maximum constrain climate sensitivity? Geophys. Res. Lett. 39 (24). The reference is to the estimate corrected for omitted dust forcing.

[24] Section 10.8.2.4 of AR5, penultimate sentence.

estimate from that given by the instrumental-observation evidence even if the palaeoclimate best estimate is substantially higher.[25]

17. As well as 'top down' ECS estimates reflecting equation (1), one can use a "feedback analysis" approach, estimating individual climate feedbacks in models and/or from observations, and hence ECS from equation (3). However, it has recently been found that $F_{2xCO2,}$ the ERF from increased CO_2, varies greatly between CMIP5 AOGCMs, which implies inaccurate radiation codes and increases uncertainty regarding estimates of feedbacks in AOGCMs. For a quadrupling of atmospheric CO_2, for which the expected ERF is ~7.4 Wm^{-2}, CMIP5 models have ERF varying between 5.5 and 9 Wm^{-2}.[26] Feedback analysis is in practice closely related (via effective climate sensitivity) to ECS as exhibited by AOGCMs, so I will not separately critique the raw ECS and TCR ranges exhibited by CMIP5 models, which as already shown are centred substantially above best estimates from sound instrumental-observation studies. The mean ECS and TCR values of climate models used for IPCC projections of future warming are respectively ~3.4°C and ~1.9°C. Their estimated ECS and TCR values lie in the ranges 2.1–4.7°C and 1.1–2.6°C respectively.

18. Turning to feedbacks, the Planck radiative feedback λ_p is fairly consistently estimated by AOGCMs at ~−3.2 $Wm^{-2}\,°C^{-1}$, so in the absence of other feedbacks ECS should be ~3.7 / 3.2 = 1.15 °C. The minor albedo feedback is estimated reasonably consistently by AOGCM simulations at ~+0.3 $Wm^{-2}\,°C^{-1}$, equating to another ~0.1°C on ECS. AOGCM estimates of both these feedbacks are generally considered to be reasonably realistic.

19. There is more doubt about whether the combined water vapour + lapse rate feedback in AOGCMs is realistic, despite model estimates being fairly consistent at around +1.0 $Wm^{-2}\,°C^{-1}$. This feedback is concentrated in the tropics, where AOGCMs simulate strong warming in the upper troposphere with specific humidity (the amount of water vapour), which has a particularly powerful effect there, increasing and absorbing more radiation. Saturation water vapour pressure increases rapidly with temperature, so this would happen if relative humidity were constant. Observational evidence does not appear to support the existence of such a strong tropical "hot spot". This suggests that water vapour feedback (and the weaker, opposing, lapse rate feedback) may be overestimated in AOGCMs. The below chart[27] compares tropical warming trends in CMIP5 models and various observationally-based datasets over recent decades. The 100000 Pa (1000 mb) pressure level is near surface level, 30000 Pa (300 mb) is in the mid-upper troposphere.

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[25] This is based on fitting an appropriate probability distribution to the median for all palaeoclimate estimates featured in AR5 (being 2.75°C) and a 10–90% range of 1–6 °C (consistent with the palaeoclimate ECS estimate range given in AR5), and using the primary Lewis & Curry (2014) instrumental-period estimate (which reflects the AR5 forcing and heat uptake estimates).

[26] Chung, E-S and Soden, B., 2015 An assessment of methods for computing radiative forcing in climate models. Environ. Res. Lett. 10 074004

[27] Source: Professor John Christy, University of Alabama at Huntsville

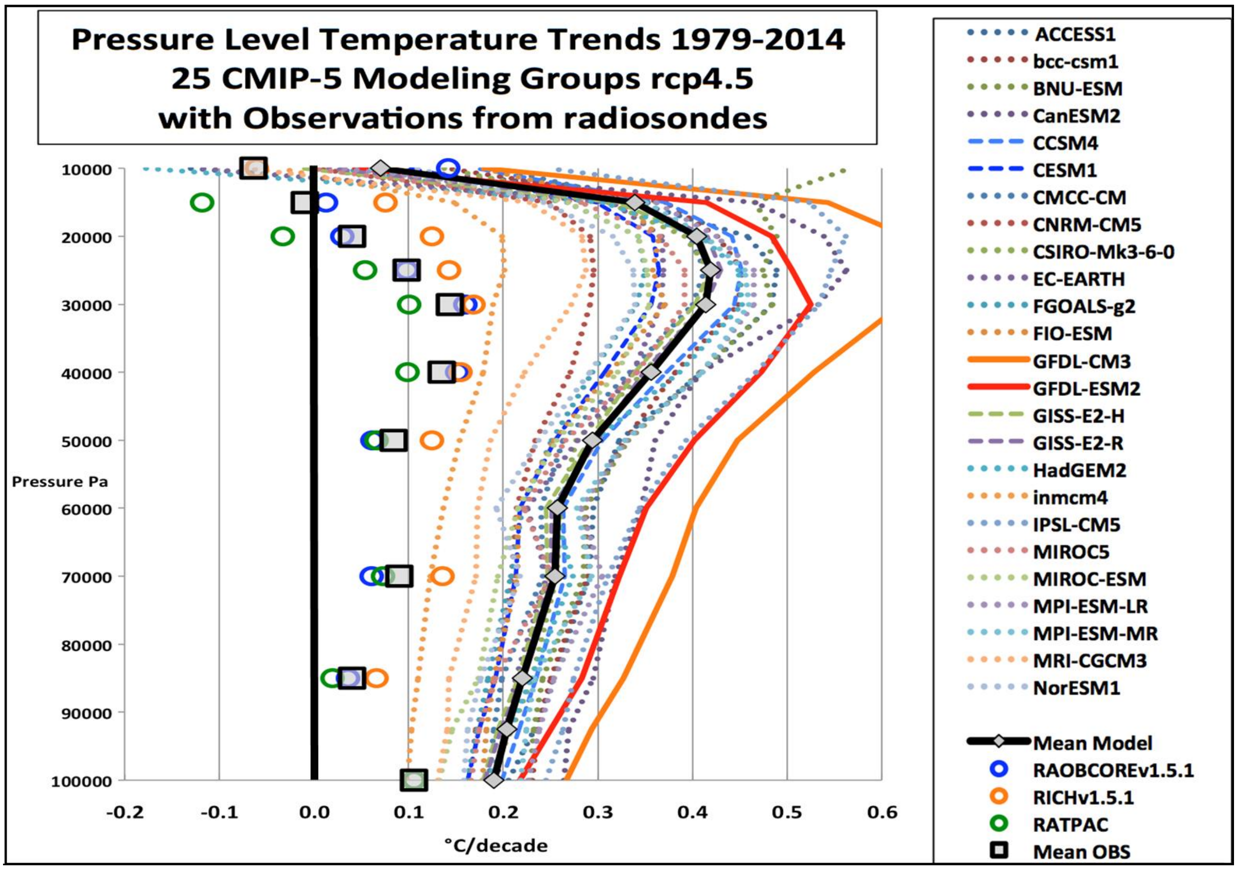

Figure 3

20. Related to this, although some evidence suggests specific humidity has gone up (with relative humidity changing little)[28], as in most AOGCMs, other evidence suggests it has been steady or fallen,[29] [30]. NOAA data[31] shows a marked decline in tropical upper tropospheric water vapour over recent decades, although this represents a model-based reanalysis and may not be accurate.

21. Even if the CMIP5 average water vapour + lapse rate feedback of ~1.0 Wm^{-2} °C^{-1} were correct, combining it with the Planck and albedo feedbacks would only generate an ECS of ~2°C, much lower than the diagnosed ECS values of the CMIP5 models used to generate projections of warming over this century, which average 3.4°C.[32] The difference relates primarily to positive cloud feedbacks in AOGCMs. Clouds are unresolved sub-grid scale phenomena in AOGCMs and are represented by parameterized approximations. Clouds at different levels have very different

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[28] Chung E-S. et al, 2014. Upper-tropospheric moistening in response to anthropogenic warming. PNAS doi/10.1073/pnas.1409659111

[29] Vonder Haar, T.H.,J.L. Bytheway, and J. M. Forsythe, 2012.Weather and climate analyses using improved global water vapor observations, Geophys. Res. Lett.,39: L15802, doi:10.1029/2012GL052094.

[30] http://www.drroyspencer.com/2015/08/new-evidence-regarding-tropical-water-vapor-feedback-lindzens-iris-effect-and-the-missing-hotspot/ Also see graphs in www.friendsofscience.org/assets/documents/NVAP_March2013.pdf

[31] NOAA ERSL water vapour data. Specific humidity, 300 mb, 30N-30S, 0-360E, monthly values, area weighted grid. 300 mb, the highest level available, is in the upper troposphere.

[32] For models used for the RCP8.5 scenario

effects. Low clouds generally cool the Earth by reflecting incoming short-wave solar radiation, whilst having little effect on outgoing long-wave radiation (although they are opaque to long-wave radiation, most of it that leaves Earth is emitted higher in the atmosphere). High level, thinner, clouds generally warm the Earth by transmitting most short-wave radiation, but blocking outgoing long-wave radiation. Current models do not even succeed in representing basic features such as total cloud extent at all accurately, as this graph[33] comparing percentage total cloud fraction in CMIP5 AOGCMs with that per satellite observations shows:

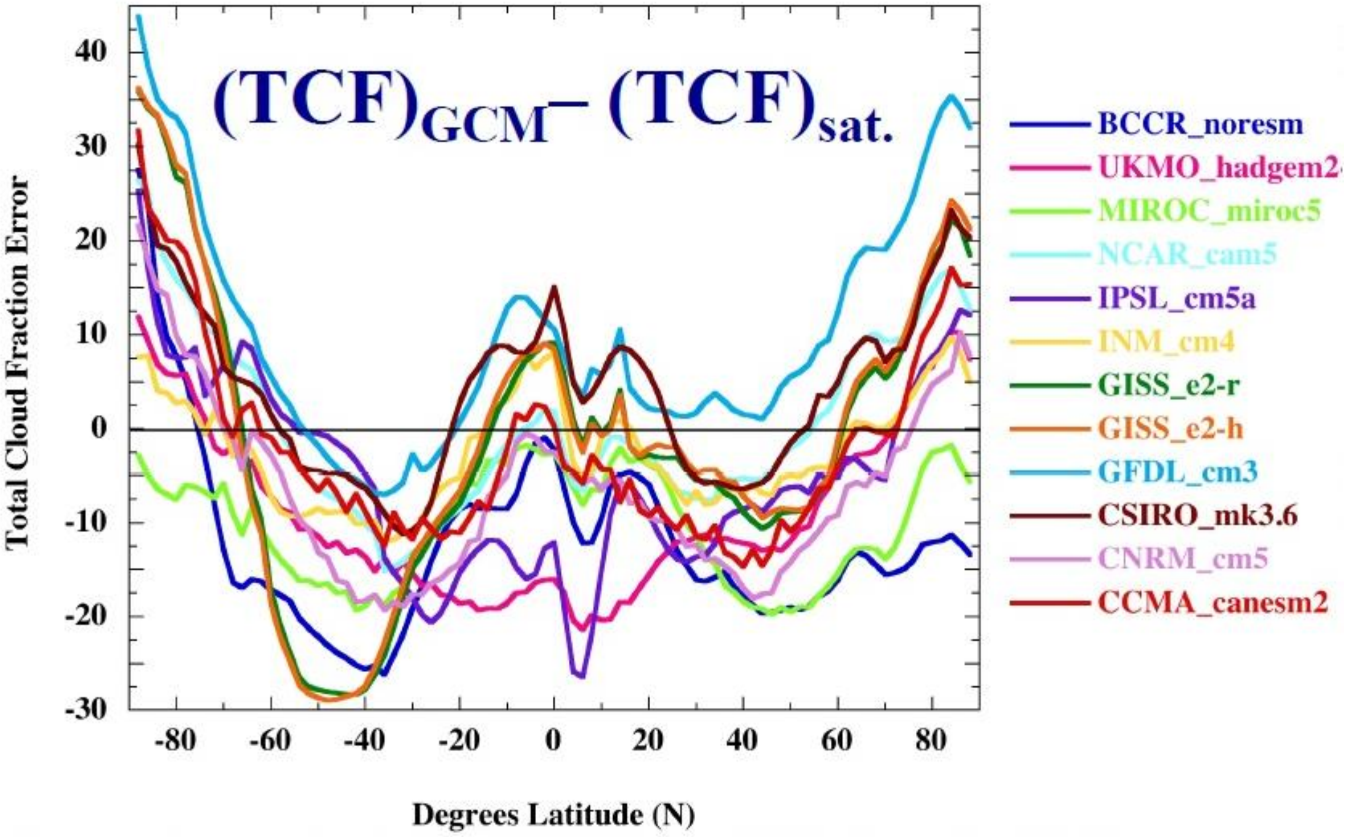

Figure 4

22. Most CMIP5 models exhibit significantly positive cloud feedback. The mean model value of 0.3 Wm^{-2} °C^{-1} in Table 9.5 of AR5 (for models producing the required data) understates the true impact of clouds, maybe significantly. Based on Table 9.5 values, it would increase the mean model ECS from 1.95 °C (3.7/− (−3.2+1.0+0.3), allowing for Planck, water vapour + lapse rate and albedo feedbacks, to 2.3 °C (3.7/− (−3.2+1.0+0.3+0.3). But the mean diagnosed ECS for these models is far higher, at 3.3 °C, which suggests that the effect of clouds on model ECS values is significantly underestimated by the study concerned.

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[33] Pat Frank: Propagation of Error and The Reliability of Global Air Temperature Projections. 2013 AGU conference

23. Cloud behaviour is highly complex and still poorly understood. Various likely cloud feedbacks have been identified, of both positive and negative sign,[34] but it does not yet appear possible to determine from observations whether overall cloud feedback is positive or negative. AR5 concluded that there was no evidence of a robust link between any of the observables in relevant studies and global cloud feedback.[35] It is difficult to see grounds for placing any reliance on current generation AOGCM projections of how clouds will respond to greenhouse gas warming, and it is doubtful that the situation will be much improved in the next generation of models.

24. Simulation of convection is another, closely related, major problem area for AOGCMs. Like clouds, convection is a sub-grid scale process that has to be modelled by parameterized approximations. How convection is parameterized in a model has a major impact on its behaviour, including on the cloud and water vapour fields it simulates and how they change with increasing greenhouse gases, and thereby on the model's ECS. For instance, when the French IPSL modelling group recently improved the clouds and convective parameterization of its main model, the ECS reduced (per AR5 Table 9.5) from 4.1°C to 2.6°C It is also notable that a new German model that, uniquely, simulates convective aggregation – which observational evidence suggests occurs – generates a substantially weaker tropical hot spot than other AOGCMs, as well as having a significantly reduced ECS (~2.2°C vs 2.8°C).[36] The simulated convective aggregation changes long-wave cloud feedback from significantly positive to significantly negative (although a good part of this change is cancelled out by a strengthening of positive short-wave cloud feedback).

25. Even more seriously, a 2016 study[37] found that they could vary ECS over a wide range by changing a single parameter that controlled how "cumulus cloud condensate is converted into precipitation in a model’s convection parameterization, processes that are only crudely accounted for in GCMs", without retuning other parameters. They concluded that:

    > "Given the current level of uncertainty in representing convective precipitation microphysics, this study suggests that one can engineer climate sensitivity in a GCM by the approach used for parameterizing convective precipitation. … So far, we have not found a clear [observational] constraint that we feel would make one model choice more plausible than another. Therefore, holistic measures of the overall quality of the mean climate simulations do not appear to provide adequate guidance for choosing between these models."

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[34] E.g., negative feedbacks: Stephens, G, 2010. Is There a Missing Low Cloud Feedback in Climate Models. WCRP GEWEX News, 20, 5-7; Myers, T A and Norris, J R, 2013. Observational Evidence That Enhanced Subsidence Reduces Subtropical Marine Boundary Layer Cloudiness J Climate, 26, 7507-7524; and per next but one footnote.

[35] Section 7.2.5.7 of AR5

[36] Mauritzen, T. and Stevens, B., 2015. Missing iris effect as a possible cause of muted hydrological change and high climate sensitivity in models. Nature Geoscience DOI: 10.1038/NGEO2414 Compare bottom right and top left panels of Figure S7, and examine Figure S8, in the Supplementary Information

[37] Ming Zhao et al., 2016: Uncertainty in Model Climate Sensitivity Traced to Representations of Cumulus Precipitation Microphysics. J Climate, 29, 543–560.

This study, together with the other findings cited in the two preceding paragraphs, strongly suggests that neither the range of ECS values exhibited by AOGCMs nor their mean can be viewed as scientifically satisfactory evidence as to the value of ECS in the real climate system.

26. There have been various attempts to observationally-constrain AOGCM ECS and/or TCR values using perturbed physics ensembles (PPEs), in which a model's key adjustable parameters were systematically varied and the resulting model-variant simulations compared with observations. The results, however, appear primarily to reflect the characteristics of the particular model involved, not the observational data. In the case of the Met Office PPE study underlying UKCP09, the official UK 21st century climate projections, not only did the PPE appear unable to explore much of the ECS-aerosol forcing space that is consistent with observations,[38] but a very unsatisfactory subjective Bayesian statistical method was employed.[39]

27. Another approach to observationally-constraining AOGCM ECS values, based on so-called emergent constraints, has now become popular. The idea is to find some variable that, across a multimodel ensemble such as CMIP5, is correlated with model ECS and can be compared with observed variables. However, not only are there many thousands of such variables to choose from, leading to data-mining dangers, but the fact that a relationship exists in one model ensemble does not mean that it is robust, even if it seems physically plausible. For instance, there was a good correlation between ECS and cooling at the LGM in CMIP3 (AR4) models, as one would expect for physically-realistic models, but there is no such correlation in CMIP5 models. Moreover, even if a robust relationship between ECS and some variable exists in AOGCMs, and seems physically justified, that does not by any means prove that the same relationship exists in the real world. And relationships between variables may be very different over seasonal, interannual or decadal timescales than they are over the multidecadal upwards periods relevant to climate change. So I think that the emergent constraints approach should be regarded with great caution.

28. An important issue has come to light recently, relating to the dependence in AOGCMs of cloud feedbacks, and hence climate sensitivity, on patterns of surface temperature change – primarily in sea surface temperature (SST).[40] In most CMIP5 AOGCMs, two or three decades after a CO_2-based forcing increase is imposed, their effective climate sensitivity increases, largely because short-wave cloud feedback becomes (more) positive. This leads, on average, to their diagnosed ECS being ~10% higher than their effective climate sensitivity when estimated from global changes corresponding to those that took place during the instrumental period. In typical CMIP5 models, intensified warming develops in the eastern tropical Pacific a few decades after an imposed increase in atmospheric CO_2. This appears to be the main reason for the increase in short-wave cloud feedback, and hence the principal underlying cause for effective climate sensitivity increasing over time in most AOGCMs. Moreover, even in the first two decades after imposing a step increase in atmospheric CO_2, CMIP5 models show strong warming in the deep

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[38] See Box 1 of niclewis.files.wordpress.com/2013/09/metoffice_response2g.pdf

[39] Frigg, R. et al, 2015. An assessment of the foundational assumptions in high-resolution climate projections: the case of UKCP09. Synthese DOI 10.1007/s11229-015-0739-8

[40] Andrews, T, Gregory, J M and Webb, M J, 2015. The dependence of radiative forcing and feedback on evolving patterns of surface temperature change in climate models. J. Climate 28, 1630–1648

tropical eastern and central Pacific. This is associated with a robust weakening of the Pacific Walker atmospheric circulation (easterly near the surface, westerly high in the troposphere) in these models, which *inter alia* reduces the upwelling of cool water in the eastern tropical Pacific. There is a theory as to why the Pacific Walker Circulation may be expected to weaken under greenhouse gas warming,[41] but reasons to expect the opposite have also been put forward.[42] In reality, CMIP5 models have been proved wrong to date: the Pacific Walker Circulation has fluctuated, but does not show a long term weakening trend and, far from warming strongly, the eastern and central Pacific have warmed little (apart from during El Nino events).

29. It turns out that the climate sensitivity of CMIP5 models is highly sensitive to the pattern of SST warming. In the case of the UK Met Office HadGEM2 model, used in much of this work, its effective climate sensitivity when SST increases with a pattern matching reality is only 2.3°C over 1900-2012, only half the ECS that it exhibits when it is allowed to generate its own pattern of SST increases in response to CO_2 warming, and its effective sensitivity is even lower over the satellite era.[43] The Met Office authors interpret this result as implying that observational estimates of ECS based on warming over the instrumental period may be biased low. However, a more appropriate scientific conclusion, in the absence of any evidence that multidecadal internal climate system variability has caused a substantial but temporary strengthening of the Pacific Walker Circulation, seems instead to be that AOGCMs may exhibit excessive climate sensitivity due to incorrect simulation of atmospheric circulation in the tropical Pacific. That could arise from either atmospheric or oceanic modelling deficiencies.

30. It is well known that, in the mean, the evolution of GMST in CMIP5 models from the start of their historical simulations (1850 or 1860) matches observations well until the early 2000s. On the other hand, over the satellite era, from 1979, the observed GMST increase to 2014 is only 0.16°C dec^{-1} whilst the CMIP5 mean increase is 0.25°C dec^{-1}.[44] The forcings included in the CMIP5 historical simulations vary considerably from model to model, particularly but not only in respect of aerosol forcing, and have unknown aggregate strengths. However, all models should use the same greenhouse gas concentrations. It so happens that if the new (Stevens 2015) reduced aerosol forcing estimates are melded with the AR5 estimates for all other forcings, there is almost no difference between the historical evolutions of total forcing and of greenhouse gas forcing save for years significantly affected by volcanism.[45] Since volcanic eruptions are short lived and have

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[41] Vechhi, G A and Soden, B J, 2007. Global Warming and the Weakening of the Tropical Circulation. J. Climate 20, 4316–4340

[42] E.g., Hoyos, C D and Webster, P J, 2012. Evolution and modulation of tropical heating from the last glacial maximum through the twenty-first century. Climate Dynamics, 38, 1501-1519

[43] Andrews, T, Webb, M J, and Gregory, J M, 2015. Feedbacks: their inconstancy & dependence on SST patterns. Talk given at the Ringberg 2015 WRCP Grand Challenge workshop

[44] The decadal linear trend increases for respectively HadCRUT4v4 and all CMIP5 models with RCP8.5 scenario projections. Although it has been claimed that HadCRUT4 somewhat underestimates the GMST increase over the last few decades, evidence from the well-regarded ERA-interim reanalysis indicates otherwise.

[45] With black carbon on snow forcing, the only forcing for which AR5 gives an efficacy factor, multiplied by the mean efficacy factor given, land use change forcing scaled down by 75% (since AR5 concluded at 8.3.5.6 that it was about as likely as not to have led to a net cooling of the Earth's surface), and Stevens 2015 aerosol forcing substituted for the original AR5 aerosol forcing, there is zero trend difference over 1860-2012 between AR5

very little effect on surface temperature beyond the following 5-10 years, comparing the evolution of GMST in CMIP5 models during their historical greenhouse gas only simulations with the observational record would be a fair test over the long term. The below chart shows this comparison, taking the mean for the twenty CMIP5 models for which data are available.[46]

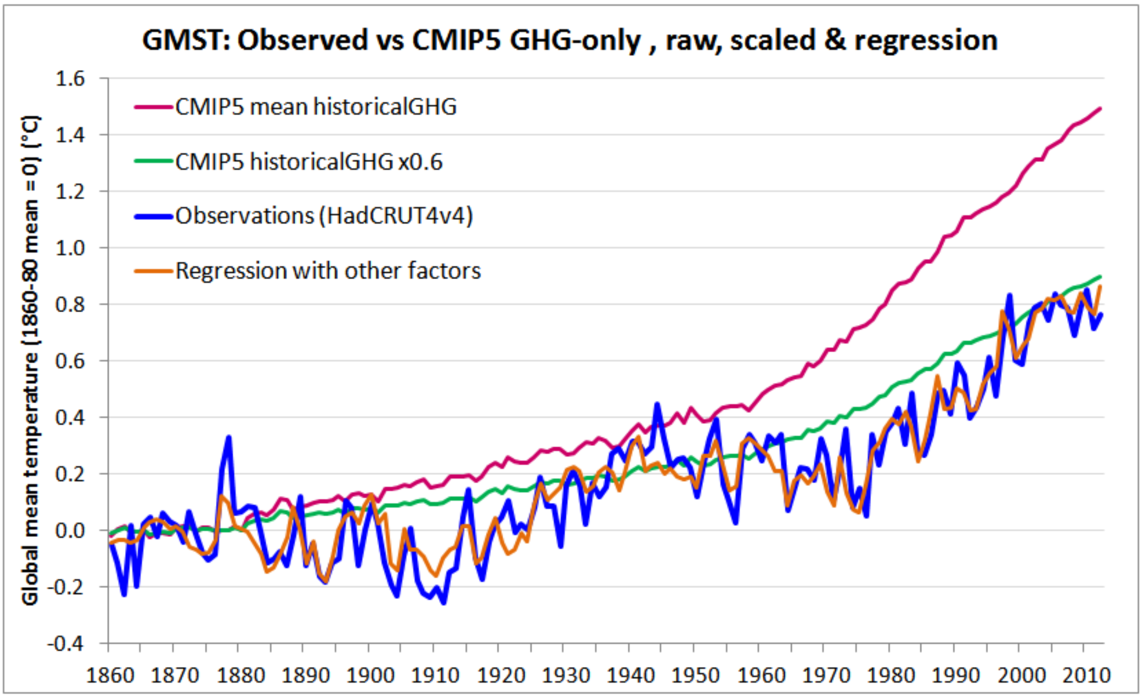

Figure 5

31. It is evident that the unscaled greenhouse gas only CMIP5 model simulations warm far more than per the historical observational record. Scaling the mean model simulation down to 0.6x of the raw level produces a more reasonable match. This is consistent with the 0.64x (0.16/0.25) scaling required to match the CMIP5 mean historical all-forcing warming to the observational record over 1979-2014, a period when aerosol forcing changed little.[47] The well-matching orange line is from regressing observed GMST on CMIP5 mean historicalGHG warming (which is thereby scaled down to 0.525x) as well as on two trendless indices of internal variability – for the Atlantic Multidecadal Oscillation (AMO) and the El Nino-Southern Oscillation (ENSO) – and on volcanic forcing.[48]

32. Scaling down the mean TCR of the relevant CMIP5 models to 60% or 64% of their actual values, to bring them into line with observed warming, implies an observationally-consistent TCR

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greenhouse gas forcing and the thus adjusted AR5 total (excluding volcanic) forcing, and their absolute difference is small in all sub-periods.

[46] Four of the twenty CMIP5 models with historicalGHG simulations are understood to have included tropospheric ozone as a greenhouse gas. An appropriate adjustment has been made to allow for this. Some models' simulations ended before 2012; an adjustment was made to prevent a discontinuity arising in the plotted mean model warming.

[47] The subset of twenty CMIP5 models with historicalGHG simulations appears to have a mean TCR several percent higher than for all CMIP5 models, which would account for most of the difference between the two scaling factors.

[48] Regression is on a 5 year centred mean of the AMO index (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/), the annual mean MEI.ext index (http://www.esrl.noaa.gov/psd/enso/mei.ext/) and the mean of the current and previous years' volcanic forcing per AR5. Regression is over 1860-2012; all coefficients are highly significant.

estimate of slightly under 1.2°C. This is closely consistent with the TCR estimate in an update of Lewis and Curry (2014) in which the AR5 aerosol forcing estimate was replaced by that per Stevens (2015).[49] Scaling by the regression coefficient of 0.525 implies a TCR of only 1.0°C.

33. From a practical aspect, it is the influence of ECS and TCR on future climate change that is most important. Changes in many climatic variables scale approximately with changes in GMST, so it is usual to concentrate on the magnitude of GMST increase. The following table shows the CMIP5 multimodel mean projected GMST rises on the four IPCC scenarios up to the late twenty-first century, the same period as given in AR5, both from the 1850–1900 period that the IPCC used to represent preindustrial conditions and from a representative recent year.[50] It also shows projections based on instrumental-observation best estimates of 1.75°C for ECS and 1.35°C for TCR, slightly above the means of the estimates shown in the respective violin plots.[51]

Scenario	**Warming to 2081–2100 based on CMIP5 models (in °C) from:**		**Warming to 2081–2100 based on 1.35°C TCR (in °C) from:**		**CMIP5 / TCR warming from**
Baseline	***1850–1900***	***2012***	***1850–1900***	***2012***	***2012***
RCP2.6	1.6	0.8	1.0	0.2	3.4x
RCP4.5	2.4	1.6	1.6	0.8	2.0x
RCP6.0	2.8	2.0	2.0	1.2	1.7x
RCP8.5	4.3	3.5	2.9	2.1	1.7x

Table 1

34. For the RCP6.0 and RCP8.5 scenarios – which involve continued growth in greenhouse gas forcing this century – the ratio of mean projected future warming by CMIP5 models to that projected using instrumental-observation studies, of 1.7x, is higher than one would expect from the ratio of the TCRs involved. The mean TCR of the CMIP5 models, at ~1.9°C, is only 1.4x the observationally-estimated TCR value used of 1.35°C. The difference appears to relate primarily to the much higher ECS of the CMIP5 models, which leads to their projected future warming arising from past forcing being much greater than for the instrumental-observation estimate based projections. Part of the difference may relate to CO_2 forcing increasing slightly faster than logarithmically with concentration in AOGCMs (and in reality), which only the CMIP5 model projections allow for. But any resulting low bias in the instrumental-observation estimate based

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[49] See https://niclewis.files.wordpress.com/2015/10/ar5_ebstudy_stevens15faer1e.pdf

[50] To minimise rounding discrepancies, 0.8°C has been deducted from the CMIP5 global mean surface temperature projected warming from 1850–1900 (taken as representing preindustrial conditions) to obtain warming from 2012, and 0.8°C added to the warming based on TCR from 2012 to obtain warming from 1850–1900. But the unrounded 0.76°C temperature rise from 1850–1900 to 2012 (per HadCRUT4v2) has been used to compute the ratios of CMIP5 model to TCR-based warming.

[51] The global warming estimates are based on multiplying the TCR estimate of 1.35°C by the change in total forcing on each scenario between 2012 and 2081–2100 per the RCP forcings dataset, and adding 0.15°C for unrealised warming attributable to existing forcing, that as at 2012 was heating the ocean, becoming realised by 2081–2100. These TCR-based projections are consistent with more sophisticated calculations using a 2-box model. Using the mean temperature for the decade ending in 2012 instead of that for 2012 would make no difference.

projections is more than compensated by carbon-climate feedbacks being much lower when temperatures rise less than per the average CMIP5 model.[52]

35. Another issue concerning model projections is the widely held assumption that a multimodel ensemble provides an uncertainty distribution. This is statistically unsound, not only because there is little reason to believe the mean or median model projection lies at the centre of the distribution of possible actual outcomes, but because the collection of models involved is far from independent. Almost all CMIP5 models can trace the ancestry of their atmospheric components back to a few original models, and there seems to be even less diversity in their ocean components. Some of the apparent 40-odd CMIP5 models are mere variants of a main model; others are quite close copies of models from other groups. Some CMIP5 models are generally agreed to be very poor quality, but have been included for 'political' reasons. Indeed, a senior Met Office scientist expressed the view that only three modelling centres produce good models.

36. Finally, I will briefly mention the hiatus – the period since the early to mid-2000s during which GMST rose little, whilst almost all CMIP5 models simulated continued fast warming. Discounting years affected by strong El Nino events – 1997/98 (and 2014/15) – the hiatus is really only about a decade long. The change in decadal mean GMST from the 1990s to the 2000s is very similar to that from the 1980s to the 1990s (and from the 1970s to the 1980s). The hiatus is in my view, and I think the view of most other climate scientists, explainable largely as a manifestation of natural internal climate system variability. AR5 tentatively reached that conclusion, mentioning also the possibility of contributions from forcing errors in CMIP5 models and of some of them overestimating the response to increasing anthropogenic forcing.[53] However, a recent thorough comparison of forcing changes during the hiatus with RCP forcings showed an almost exact match.[54] AR5 goes on to state that it is more likely than not that internal climate variability in the near-term will enhance and not counteract the surface warming expected to arise from the increasing anthropogenic forcing. I disagree (ignoring ENSO and similar short term variability).

37. The AMO, which a majority of climate scientists appear to accept is a natural quasi-periodic oscillation with a typical period of 60-70 years, is known to affect GMST and was in an upswing phase from the mid 1970s to the mid 2000s. This can be expected to have boosted the observed trend in GMST over that period; the underlying forced GMST trend will have been even further below mean CMIP5 projections than the actual trend, a point that most climate scientists appear not to have recognised. Although many CMIP5 models do generate AMO-like internal variability, the phasing thereof is not synchronised with that of the actual AMO and it therefore, on average, does not contribute to model-simulated GMST trends. The internal variability that accounts for the hiatus may be some combination of a downturn in the AMO and negative shorter term Pacific (and maybe other) variability. Whilst the latter may well reverse before long, it is unclear that will be sufficient to outweigh the shift in the AMO from an upwards phase to a downwards phase.

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[52] That is because the RCP forcings dataset was computed from emission scenarios, using a carbon-cycle model, on the basis that warming would be in line with that projected by the average CMIP5 model.

[53] Box 9.2 of AR5

[54] Outten, S et al, 2015. Investigating the recent apparent hiatus in surface temperature increases: 1. Construction of two 30-member Earth System Model ensembles. J Geophys Res: Atmos, 120, DOI 10.1002/2015JD023859