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Misdiagnosis of Earth climate sensitivity based on energy balance model results

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Abstract Monckton of Brenchley et al. (Sci Bull 60:122–135, 2015) (hereafter called M15) use a simple energy balance model to estimate climate response. They select parameters for this model based on semantic arguments, leading to different results from those obtained in physics-based studies. M15 did not validate their model against observations, but instead created synthetic test data based on subjective assumptions. We show that M15 systematically underestimate warming: since 1990, most years were warmer than their modelled upper limit. During 2000–2010, RMS error and bias are approximately 150 % and 350 % larger than for the CMIP5 median, using either the Berkeley Earth or Cowtan and Way surface temperature data. We show that this poor performance can be explained by a logical flaw in the parameter selection and that selected parameters contradict observational estimates. M15 also conclude that climate has a near-instantaneous response to forcing, implying no net energy imbalance for the Earth. This contributes to their low estimates of future warming and is falsified by Argo float measurements that show continued ocean heating and therefore a sustained energy imbalance. M15's estimates of climate response and future global warming are not consistent with measurements and so cannot be considered credible.

Keywords Climate sensitivity · Global warming · Climate change · Climate model · Climate feedback

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1 Introduction

A recent paper, M15 [1], applies a simple energy balance model (EBM) in order to estimate climate response. Compared with other studies using a similar approach, M15 select parameters that lead to lower estimates of future global warming [2].

Many of M15's statements contradict the results of other research. We explain these contradictions in three steps: (1) M15 did not validate their model using direct observations, and we show that it performs poorly; (2) this poor performance is explained by M15 selecting parameters using a logically flawed semantic argument; and (3) M15's consideration of relevant studies is incomplete, and those studies that are considered are sometimes misinterpreted.

2 Model

The model in M15 is a form of the energy balance model (EBM) which has been used for almost 50 years [3]. Such models are not novel and have previously been used to estimate the transient climate response (TCR) and the equilibrium climate sensitivity (ECS) [4, 5]. M15 state that the anthropogenic temperature response $\Delta T_{t,a}$ at time t is given by

$$\Delta T_{t,a} = \frac{\Delta F_{t,a} \cdot r_t \cdot \lambda_\infty}{q_t}, \tag{1}$$

where $\Delta F_{t,a}$ is the change in forcing due to a change in atmospheric CO_2, q_t is the fraction of the anthropogenic forcing due to CO_2, r_t is the transience fraction (i.e. the fraction of the equilibrium temperature change attained at time t), and λ_∞ is a climate sensitivity factor in K W^{-1} m^2.

Equation (1) is a form of a lumped-parameter model in which Earth's global temperature field is represented as a single value. This extreme simplification necessarily leaves out many physical processes and does not explicitly account for how parameters may change depending on the spatial pattern of warming or background state.

The M15 approach differs from the standard in that only anthropogenic components are considered. However as M15 implicitly assume that λ_∞ is independent of non-anthropogenic forcing, it follows that it is the same for total forcing, and if we assume sufficiently long timescales such that the average unforced contribution to temperature and radiative imbalance tends to zero, we have:

$$\Delta T_t = \Delta F_t \cdot r_t \cdot \lambda_\infty, \tag{2}$$

where the temperature change ΔT_t responds to the total forcing ΔF_t. The standard approach of Eq. (2) is more useful than Eq. (1) because both ΔT_t and ΔF_t may be estimated from observations, and by combining these, the product $r_t \cdot \lambda_\infty$ may be inferred. A value of λ_∞ may therefore be estimated if the form of r_t is known. Due to Earth's thermal inertia and expected time variation in feedbacks, r_t is a time-dependent function which has been studied with a variety of models [6–14]. M15 claim to adopt values of r_t from the simple model of [6], which considered a step change in forcing. In reality, the history of radiative forcing is a more complex continuous function. This may be accounted for by a convolution of the forcing series with the temporal response function, although this requires clarity over assumptions regarding the state dependence of r_t and λ_∞, which is not discussed in M15.

3 Validation

Rather than compare model projections against observations, M15 develop synthetic data for 1990–2050, assuming that temperature changes will be between recent 17-year RSS and 63-year HadCRUT4 temperature trends. Both of these are likely to be underestimates. Statistical methods show that the 17-year RSS trend is strongly suppressed by recent El Niño variability [15] and by larger-scale, longer duration alterations in the Pacific Decadal Oscillation.

Meanwhile, the 63-year HadCRUT4 trend is in response to radiative forcing growth of approximately +0.027 W m^{-2} yr^{-1} rather than the +0.036 W m^{-2} yr^{-1} growth for 1990–2050 under transition to the RCP6.0 scenario adopted by M15 [16]. During the more analogous period 1970–2014 when forcing increased by +0.034 W m^{-2} yr^{-1}, observed temperature rise was $+0.17 \pm 0.03$ K $decade^{-1}$ [$\pm 2\sigma$, ARMA(1,1) noise assumed], significantly ($P < 0.002$) greater than the highest value assumed by M15.

Instead of using synthetic data, we use observations to assess the performance of both the M15 parameterization and the more complex models criticized in M15. We use the [4] forcing time series with the M15 parameter range for the M15 projection. The more complex models are sampled from the Coupled Model Intercomparison Project 5 (CMIP5), and we select the 5 %–95 % range of simulations available from KNMI [17], driven with RCP6.0 from 2006 and with continuous data for 1850–2100 ($N = 45$, although we note that results are similar when all KNMI runs are used). Finally, we also use Eq. (2) with the IPCC AR4 values from M15 Section 4.1, being $r_t = 0.50$ (assuming that $r_t \approx r_{100}$, as the majority of the forcing change took place over the past century) and λ_∞ falling on [0.59,1.25] K W^{-1} m^2 with a best estimate of $\lambda_\infty = 0.88$ K W^{-1} m^2.

Figure 1 shows the CMIP5 and M15 projection ranges in the upper panel, based on an 1850–1900 baseline and compared with HadCRUT4, Berkeley Earth (BEST) and Cowtan and Way (CW14) [18] global mean surface temperature (GMST) data. Observations fall within the CMIP5 range, but are mostly above the M15 projected maximum since 1990. The lower panel shows the substantial improvement in the M15 fit when AR4 values are used with the EBM instead.

If the M15 assumption of approximately constant r_t is used, then $r_t \cdot \lambda_\infty$ may be estimated by regressing ΔT_t onto ΔF_t. Using HadCRUT4, BEST and CW14 [18] temperature data with the forcing from [4], we obtain:

$$0.36 \le r_t \cdot \lambda_\infty \le 0.40. \tag{3}$$

Although in reality r_t is not constant, $r_t \le 1$ always. It follows that λ_∞ must exceed 0.35 K W^{-1} m^2, and observations exclude the range assumed by M15, where $0.21 \le \lambda_\infty \le 0.35$ K W^{-1} m^2.

Performance is assessed for the periods 1900–2010, 1970–2010 and 2000–2010 using root-mean-square error (RMSE) and bias during each period. Results are reported in Table 1. Another forcing data set [16] results in substantially worse M15 model performance; RMSE is 7 %–

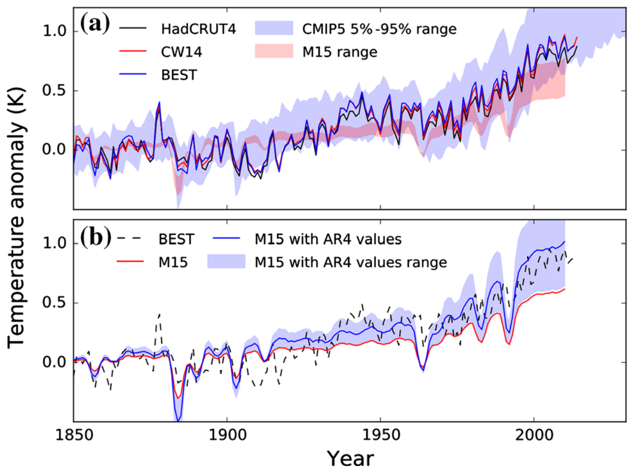

Fig. 1 **a** Comparison between modelled and observed temperature anomaly from 1850. Solid lines show observational series HadCRUT4, Berkeley Earth (BEST) and Cowtan and Way (CW14 [18]). The 5 %–95 % CMIP5 range and M15 range are shown as shaded areas as labelled in the caption (upper left). $N = 45$ CMIP5 models transitioning to RCP6.0 after 2005, M15 model forced with the Otto et al. [4] radiative forcing time series and all temperature series anomalies calculated relative to the 1850–1900 mean. **b** BEST data (dashed line) versus the mid-range Monckton of Brenchley et al. [1] estimate (solid red line), and the result of the M15 model with IPCC AR4 parameters, where the solid blue line shows the best estimate and the blue shaded area the range

23 % larger and bias magnitude 10 %–29 % larger, depending on the temperature series and time period.

The choice of baseline period affects reported performance: for any subset of the full data, it is possible to choose a baseline such that a model appears to perform better or worse. This apparent change in model performance is due to neglecting data and should not be taken as a robust reflection of the model performance. For example, if 1940–1970 is chosen, then recent observations fall within the M15 confidence limit while errors are shifted towards the earlier part of the time series. If 1900–1930 is selected, then CMIP5 underestimates recent temperatures rather than "running hot" as stated in M15. We select 1850–1900 as the period is long enough to reduce bias introduced by random internal variability, while the change in radiative forcing during this period is also small. Being at the beginning of the series, it also provides the most stringent test of models' ability to estimate recent temperatures.

M15 always perform worse than CMIP5, except for bias from 1900 to 2010 in HadCRUT4, where M15 bias is −0.06 K versus +0.07 K in CMIP5. It is well known that HadCRUT4 likely underestimates recent warming as it lacks stations in areas, such as the Arctic, that have warmed more quickly than the mean [18]. CW14 use an infilling technique that performs better in validation, while BEST includes more data. These two series largely agree and so are likely to be more representative of the true recent temperature variations.

During 1970–2010, the M15 model consistently underestimated global temperature anomaly by between −0.19 K (BEST) and −0.17 K (CW14). CMIP5 bias was +0.00 K (BEST) to +0.03 K (CW14). From 2000 to 2010, the M15 projections are biased too low by −0.27 K (BEST) to −0.26 K (CW14), while the CMIP5 median is biased too warm by 0.07 K (BEST) to 0.08 K (CW14). Over 2000–2010, M15 bias magnitude was approximately 350 % larger and RMSE approximately 150 % larger than that of the CMIP5 median. Such poor performance means that the M15 model may not be considered to have been validated.

M15 developed their parameterization based on claims of IPCC "models running hot" followed by semantic arguments to support parameter selection. Relevant research explaining the issues highlighted by M15 was not acknowledged. In the following section, we highlight some of this research and identify how it resolves some of the apparent incongruities raised by M15.

4 Reason for poor M15 model performance

The M15 model systematically underestimates recent temperature changes due to its low value of $r_t \cdot \lambda_\infty$. Instead of determining $r_t \cdot \lambda_\infty$ from quantitative analysis based on observations, M15 use rhetorical and semantic techniques. Their argument can be presented as:

(1) Earth's "surface temperature has varied by only 1 % or 3 K either side of the 810,000 year mean…[this] suggests the absence of strongly net-positive temperature feedbacks", and therefore, they are "stable".
(2) "a regime of temperature stability is represented by $g_\infty \leq 0.1$", referring to the system gain.
(3) therefore, the gain in the climate system is also $g_\infty \leq 0.1$.

This low value of gain leads to a low value of λ_∞. However, (2) is incomplete, and so (3) does not follow, as "stable" may refer to any $g_\infty < 1$. M15 suggest that $g_\infty > 0.1$ should be excluded, stating that electronic circuits are designed with $g_\infty \leq 0.1$. This assumes that climate physics is defined by the design preferences of electronic engineers and is illogical and unsupported.

Palaeoclimate evidence results in values consistent with $g_\infty > 0.1$, but M15 do not discuss this. In the next section, we will discuss a number of M15's statements that are a result of incomplete consideration, or misinterpretation, of relevant literature.

Table 1 Results of root-mean-square error (RMSE) and bias for various time periods, comparison between M15 model forced with [4] and results from CMIP5 models

Dataset	Time period	RMSE (K)		Bias (K)	
		M15 using [4] data	CMIP5	M15 using [4] data	CMIP5
HadCRUT4	1900–2010	0.16	0.13	−0.06	0.07
	1970–2010	0.18	0.14	−0.12	0.07
	2000–2010	0.21	0.17	−0.20	0.15
	1900–2010	0.18	0.11	−0.10	0.03
Cowtan and Way	1970–2010	0.22	0.11	−0.17	0.03
	2000–2010	0.27	0.11	−0.26	0.08
	1900–2010	0.20	0.12	−0.11	0.02
Berkeley Earth	1970–2010	0.23	0.11	−0.19	0.00
	2000–2010	0.28	0.11	−0.27	0.07

5 Incomplete consideration and misinterpretation of relevant literature

5.1 Palaeoclimate evidence contradicts M15's assumed climate response

Studies of Earth's climate over the past 800,000 years, including those cited by M15, contradict its assumptions. For example, [19, 20] discuss the positive feedbacks that acted during past climate change events. The M15 assertion of strong thermostasis is also contradicted by [21], whom they cite in defence of their assumption. Zachlos et al. [21] point out that the Late Palaeocene Thermal Maximum (LPTM) was associated with a rise in temperatures of as much as 8 K in high latitude areas and 5–6 K rise in global deep sea temperatures. They posit that the LPTM was forced by greenhouse gas increases.

Numerous studies (e.g. [22–28]) have examined the climate sensitivity implied by palaeoclimate temperatures and forcings. None of them have concluded that this period implies a negative climate feedback. Were climate feedbacks negative, small initial forcings from changing insolation due to Milankovitch cycles would be unable to trigger glacial–interglacial transitions. As reviewed by [29], climate sensitivity estimates (and associated feedback parameters) inferred from studying the last millennium, the last glacial maximum, and proxy data from millions of years ago are largely in line with those from CMIP models, but not with the results of M15.

5.2 Measurements of ocean heat content contradict M15's assumed heat balance

M15 state that, due to their low selected value of λ_∞, $r_t \sim 1$ and "warming is already at equilibrium", which requires zero net heat imbalance. The Argo ocean heat content measurements are relevant, but not cited. They show a net heating of $+0.50 \pm 0.43$ W m^{-2} over the period 2000–2010 [30]; therefore, $r_t < 1$. M15's statement that $r \sim 1$ is falsified [31].

5.3 Physical considerations contradict M15's assumed heat balance

The "transience fraction", r_t, was defined in M15 as the fraction of equilibrium temperature response which has occurred after t years. A related measure is the response time τ, defined in [6] using an energy balance model as

$$\tau = \frac{C\lambda_o}{1 - \sum_i f_i}, \tag{4}$$

where C is the system thermal inertia and the denominator includes the sum of the system feedbacks. M15 used [6] to estimate r_t and reported $r_t \sim 1$, equivalent to an instantaneous response $\tau = 0$. This is only true if the heat capacity of Earth is zero. Since $C > 0$ and $\lambda_0 > 0$, τ must obey $\tau > 0$ for any $\sum_i f_i$. It is important to note that the climate system has multiple thermal components each with a unique thermal inertia. For instance, as stated in [6] and elsewhere, the timescale for ocean mixed layer response is on the order of 5 years, whereas for the deeper ocean and cryosphere, τ is considerably longer.

An excellent discussion of the connection between the response time and the ocean mixed layer is provided by [32–35]. In those works, mixed layers greater than 100 m were generally found (approximately 100–200 m) and the time constant was linearly related to the mixed depth. Heat uptake or release into the lithosphere has a very low value and long-time constant and is neglected in the model [36].

Finally, the top-row entries in Table 2 of M15, which M15 stated were derived from [6], are not consistent with the referenced article and the article upon which it is based [37] according to personal communication with the author of [6].

5.4 M15 do not quantify effect of observed forcing and natural variability on CMIP5 projections

Although observed GMSTs fall within the CMIP5 confidence intervals for comparisons beginning from an 1850–1900 baseline, studies have assessed why temperature trends since approximately 1998 have been at the low end of the CMIP5 distribution. Potential factors include (1) overestimated radiative forcing, (2) internal variability, or (3) overestimates of climate response by the models, although it is likely that the differences can be explained almost entirely by (2), as will be discussed shortly.

M15 assume (3), but do not acknowledge research indicating contributions from (1) and (2). (1) is supported by evidence of a weaker-than-expected forcing due to lower-than-average solar activity [38], higher-than-average volcanic activity [39], increased anthropogenic aerosol emissions [38], and a potentially cyclical decline in stratospheric water vapour [40]. (2) is supported by an unprecedented strengthening of the Pacific trade winds linked to a decreasing trend in indices of the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) [41–44]. Including these natural effects, both climate models [43] and statistical approaches [15] support that natural variability has played a large role in the difference between multi-model median and observations since the late 1990s, with no evidence for a contribution from overestimation of modelled climate response.

5.5 M15 do not quantify effect of observed forcing on historical climate model projections

M15 state that historical projections using IPCC values of climate sensitivity have been "running hot". For example, M15 Fig. 1 compares observed GMST records with a projected trend over 1990–2014 of +0.278 K per decade and attributes this to the 1990 IPCC First Assessment Report (FAR) [45]. The caption states that surface temperature records are included, although the data shown are exclusively lower tropospheric temperature from satellites.

The 1990–2010 GMST trends range from $+0.17 \pm 0.10$ K/decade (National Oceanic and Atmospheric Administration) to $+0.21 \pm 0.10$ K/decade (CW14). During 1990–2010, the FAR [45] projected +0.17–0.36 K/decade in response to a greenhouse-gas forcing increase of $+1.4$ W m^{-2} in a business-as-usual (BAU) scenario, whereas the IPCC Fifth Assessment Report [2] estimates the realized net forcing change during that period at approximately 0.6 ± 0.3 W m^{-2}. M15 discusses the differences between IPCC-assumed radiative forcing [45] and more recent estimates, but does not identify that the differences between IPCC projections and observations may be fully explained by differences between assumed forcing changes and those observed [2].

M15 perform a similar assessment of the model projections of [46] and the IPCC Fourth Assessment Report (AR4) [47]. However, they do not note that their purported "empirical evidence of models running hot" over these time periods can largely be attributed to differences in the simulated and realized forcings. Once the other factors discussed in Sect. 5.4 are also included for the most recent period, there is no strong evidence that model–observation differences are due to overestimated climate response. M15's discussion of the literature on this point is limited and incomplete, influencing their conclusions.

5.6 M15 misinterpret IPCC feedback estimates

Figure 3 from M15 is part of an IPCC graph showing feedback strengths for the IPCC AR4 and AR5 models. The AR5 feedback sum is lower than in AR4, so M15 suggest that for climate sensitivity, "the central estimate has apparently been overstated by half". This statement results from misinterpreting the relevant literature. M15 deleted the second panel of the IPCC source figure and do not discuss the associated text and citations which show and explain this difference [48, 49].

The methods of diagnosing feedbacks and ECS differ between studies, so they must be compared with care. In AR4, atmosphere-only ("slab ocean") models were used without allowing changes in ocean circulation. In AR5, ECS was estimated by running fully coupled climate models for 150 years, then using a regression technique to obtain sensitivity [50]. This method is more computationally expensive, explaining the use of slab ocean models in AR4, but was preferred in AR5 to ensure that ECS was determined directly for the models that were used in global temperature projections. Similarly, different methods have been used to calculate feedback strengths. For example, the AR5 feedback components were estimated using a radiative kernel method which assumes a linear feedback response. This is true for small changes, but is not necessarily true for the large, long-term changes associated with the quadrupled-CO_2 simulations used to estimate ECS. The sources behind M15's Fig. 3 explain why the M15 energy balance estimates underestimate the fully diagnosed ECS, but are not discussed by M15.

6 Discussion and concluding remarks

The M15 model performs poorly against observations because its parameters were selected using a logically flawed narrative, rather than physical and mathematical analysis. Observational evidence from palaeoclimate and of ocean heat content measurements directly contradict the values adopted by M15, but are not acknowledged.

Partial use and misinterpretation of the relevant literature may explain many of the differences between statements in M15 and the results of other studies. The authors of M15 cite some studies supporting their estimate of lower climate response, but miss much of the larger body of research that contradicts the claims in M15. A number of the articles listed in [1] have been shown to contain errors. For instance, M15 cite [51], which was shown to have made four errors which invalidated the conclusions [52, 53]. Another example is [54] which was a follow-on from [55] and was collectively rebutted by five separate publications [56–60, 62].

Furthermore, many relevant results are not considered by M15. As well as failing to note results from palaeoclimate and ocean heat measurements that contradict their conclusions, they do not consider studies that perform model–observation comparisons and determine that models and observations are consistent once known forcing histories and natural variability are included. M15 present part of an IPCC figure and claim to have highlighted unresolved "discrepancies", claiming that the results imply that the IPCC AR5 overstates climate sensitivity. They do not acknowledge that the part of the figure that they removed and the associated text resolve this discrepancy.

For brevity, only one more example will be presented. M15 state that the "trend on the mean of the two satellite monthly global mean surface temperature anomaly datasets" reported by [61, 62] are lower than IPCC estimates. However, the remote sensing systems and University of Alabama Huntsville data sets cited are not of surface temperature. They are estimates of tropospheric temperature. Furthermore, the M15 authors did not discuss the accuracy issues of these data sets, particularly for the UAH set which are outlined in [63], which presents an archive of the history of satellite measurement errors and the radiosonde data which were used to verify the data [64–82].

All models are imperfect and there are known deficiencies in the CMIP5 representations of some processes: it is possible that the IPCC ranges of climate sensitivity are overstated. However, the CMIP5 estimates of climate sensitivity are consistent with recent observations, agree with estimates from palaeoclimate data and with simple energy balance models. M15's assertions to the contrary are based on an incomplete and misapplied presentation of the relevant research.

Differences between simulations and measured temperatures during short time periods are an issue that is currently under a great deal of attention. Excellent progress has been made to improve global measurements, quantify top-of-atmosphere (TOA) energy flows, increase numerical resolution, and capture more physical processes.

In summary, M15 fail to demonstrate that IPCC estimates of climate sensitivity are overstated. Their alternative parameterization of a commonly used simple climate model performs poorly, with a bias 350 % larger and RMSE 150 % larger than CMIP5 median during 2000–2010. Their low estimates of future warming are due to assumptions developed using a logically flawed justification narrative rather than physical analysis. The key conclusions are directly contradicted by observations and cannot be considered credible.

Conflict of interest The authors declare that they have no conflict of interest.

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