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Response to Review #1

To begin, the reviewer is thanked for the thoughtful comments, which led to an interesting analysis of shortwave and ozone forcings.

Summary response:

1. The reviewer has mistaken eqn. 6 to concern climate rather than as an emulator of GCMs; items 1 and 3.1. This mistake misguides the entire review.
2. The correlation of reflected TOA longwave and shortwave radiation has negligible impact on the tropospheric thermal flux uncertainty due to LWCF error; item 4.2.
3. The reviewer has mistaken the ±4 Wm^{-2} LWCF error statistic as an energetic perturbation; item 5. This fundamental error is fatal to the argument.
4. The reviewer has mistaken precision for accuracy; item 6.
5. The reviewer has neglected that linear extrapolation of forcing justifies linear propagation of error; item 7.
6. These mistakes absent any critical merit from the review.

The reviewer is quoted in italics below, followed by the indented response.

1. *The main idea of this paper is to use the current average greenhouse effect to establish a linear relation between the increase of the surface temperature in response to the radiative forcing from greenhouse gas.*

    1. The reviewer began by supposing that the manuscript establishes a linear physical relation between radiative forcing and air temperature. However, it does no such thing. The manuscript analysis does not concern the climate at all. It concerns climate models.

    The manuscript is concerned with how climate models project air temperature. Equation 6 is about climate models; it is not about climate. This focus on climate models, not climate, is emphasized at the outset in lines 125ff, and repeated in lines 129-135.

    Line 313ff, further establishes this point, "*a simple emulation model of how modern GCMs project [air temperature]*."

    Line 341: "*[equation 6] represents the increasing GASAT projections of GCMs to follow directly and linearly from the wve forcing due to changing GHGs.*"

    That is, the main idea is to show that climate models, themselves, project air temperature as a linear function of radiative forcing. This has nothing to do with climate.

    The focus is climate models, not climate. There was no intent to establish any physical relation between radiative forcing and surface temperature.

    This discrepancy in meaning goes to the heart of the study. The study concerns climate models, not climate. The reviewer has mistaken this focus and therefore misperceived the entire analysis. As a consequence, the entire review is misguided.

2. *And then use the errors for the GCMs to simulate longwave cloud radiative forcing, which is ~±4W/m², as an input to the estimated linear relation to yield +/-15C error in predicting the future air temperature.*

2. The author agrees with this observation, with the exception that the linear relation is demonstrated to be an inherent property of climate models. It is not an estimated physical relation between forcing and air temperature.

3. *The problems in this approach are the follows.*

3.1 *First of all, we don't reliably know the relation between the radiative forcing from greenhouse gas and the surface temperature increase. Actually, this is the relation is that all current GCM future projection is trying to find. It is kind of hard to follow the logic why Equation 6 is true. Is cloud radiative feedback considered? Probably not because the cloud fraction is fixed at 66.7%.*

3.1 The truth-content of equation 6 is demonstrated in manuscript Figures 2, 3, 4, 8 and 9, as well as Supporting Information Figures S1, S3, S4, S5, S6, S7, S8, and S11. All these Figures demonstrate that manuscript eqn. 6 successfully emulates the air temperature projections of climate models, right up through the CMIP5 versions.

The point of eqn. 6 is emulation of climate models. It is not investigation of the physical behavior of the climate.

However, the reviewer's comment, about not knowing the relation between radiative forcing and air temperature, is about climate. Likewise is the reviewer's question about radiative feedback. However, eqn. 6 is about climate models. The reviewer comments focusing on the physical climate indicate a misguided view of the analysis.

To repeat: the analysis concerns the observed behavior of climate models. It does not concern the physical climate.

The cloud fraction was fixed at 66.7% because this fraction is the observed long-term global annual average [*Jiang et al.*, 2012].

Likewise, the longwave cloud forcing (LWCF) error of climate models is a long-term global annual average [*Lauer and Hamilton*, 2013] (20 years, 27 models). Model LWCF error is a lower limit of the uncertainty within the simulation of that average cloud fraction.

3.2 *Fig 1b shows a fitting with only 3 points, an extrapolation can be very sensitive. No quantification of error is quoted for this estimation.*

Manabe and Wetherald calculated the points in Figure 1b from their physical model. Thus, the points are exact values with respect to that model, and completely define the theoretical curve. Therefore the fit has very low error.

Figure 1b legend has been modified to include the fit r^2. These were, cloud-covered sky, r^2 = 0.99990; clear sky r^2 = 0.99986. These values were incorrectly reported as r^2 = 0.94 in the prior manuscript.

The discussion in Section 2.1.2, and especially lines 270ff, shows that the log-relation of CO_2 forcing initiates when the mean-free-path of 15μ radiation through the troposphere is greater than unity.

4.1 *Second, this simple model propagates mainly the error due to the longwave cloud radiative forcing. However, there are many other important factors are not considered here and will affect the error propagation significantly.*

The author agrees with this comment. The uncertainty calculated from propagating LWCF error is represented as a lower limit.

4.2 *For example, the shortwave cloud radiative forcing, which tends to compensate the longwave cloud radiative forcing, is negatively correlated with the longwave radiative forcing. If including shortwave radiative forcing, in view of Eq. 1, the cross term involving dx/du*dx/dv for shortwave and longwave cloud radiative forcing is negative and will cancel a major portion of the 15C error projection.*

The relevant context of equation 1 is the uncertainty in tropospheric thermal energy flux (TTEF). As discussed below, short wave radiation contributes only modestly to the tropospheric thermal energy flux, through ozone heating.

However, shortwave reflected back to space does not contribute any thermal energy to the troposphere, i.e., the energy is reflected away. As discussed below, surface emission due to shortwave heating does contribute. However that contribution is through the surface transmitted irradiance (STI), not SW. Thus, the relevant correlation is between LWCF and STI, not between LWCF and SCF.

For example, in SW and ozone, Chapter 1, page 123 of the 5AR:

> *"Of the incoming solar shortwave radiation (SWR), about half is absorbed by the Earth's surface. The fraction of SWR reflected back to space by gases and aerosols, clouds and by the Earth's surface (albedo) is approximately 30%, and about 20% is absorbed in the atmosphere.*

The primary tropospheric absorber of SWR is ozone [*Pinker and Laszlo*, 1992], producing 0.4±0.1 Wm^{-2} (1σ) forcing (AR5, 8.3.3.1, p. 680). As ozone heating and its correlation to LWCF are relevant to the reviewer's concern, they are discussed further below.

To begin, Figure 1 shows simulated and observed global average cloud radiative effects, taken from AR5 Figure 9.5. As the reviewer noted, they are negatively correlated. However, analogous data taken from AR4 Figures 8.5 and 8.7 are not correlated, Figure 2.

The source of the difference between the AR4 (CMIP3) and AR5 (CMIP5) data seems obscure. Perhaps it reflects a combination of improved observations, and alternative modes of model tuning. Nevertheless, the reviewer's point is potentially relevant to CMIP5 models, but not the CMIP3 versions.

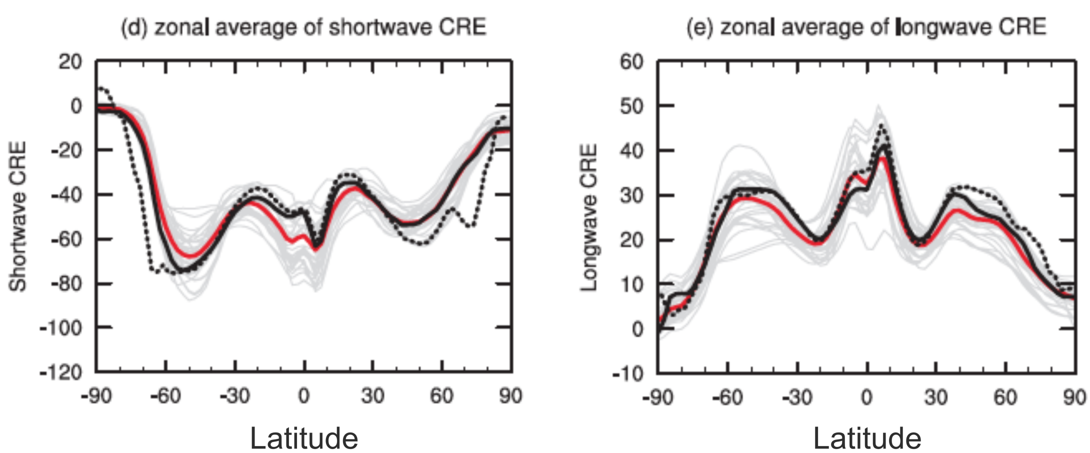

Figure 1. AR5 Figure 9.5, partial Legend: *zonal averages of the cloud radiative effects from observations (solid black: CERES EBAF 2.6; dashed black: CERES ES-4), individual models (thin grey lines), and the multi-model mean (thick red line).*

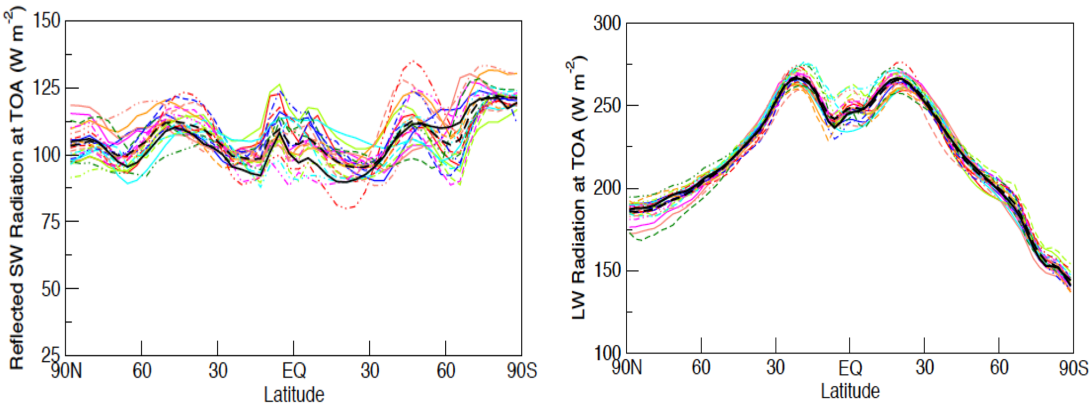

Figure 2. Partial legends for AR4 Figure S8.5 and S8.7: Left (S8.5), *Observed and simulated annual-mean, zonally-averaged shortwave radiation reflected to space.* Right (S8.7), *Observed and simulated annual-mean, zonally-averaged outgoing longwave radiation. The ERBE (Barkstrom et al., 1989) observational estimates shown here are from 1985–1989 satellite-based radiometers, and the model results are for the same period of the CMIP3 20th Century simulations.* Solid black line is observed; dashed black line is model mean, colored lines are individual simulations.

Although TOA longwave and shortwave radiation are negatively correlated, the correlation arises because they are each causally linked to cloud cover. A correlation of SW and LW through cloud cover does not indicate a causal relationship between SWR and LWCF. Although absorbed SWR is causally connected to TTEF, reflected SWR is not.

In the context of this study, manuscript eqn. 1 is relevant to the uncertainty in tropospheric thermal energy flux (TTEF). That is, following eqn. 1, *TTEF = f(u, v,...)*, where *u, v*, ... are physically causal processes that influence the magnitude of TTEF. These processes might include surface LW emission, tropospheric SW absorption, and cloud cover, among others. These causal processes do not include reflected SWR, however.

The uncertainty in TTEF is then given by eqn. 1 as a function of the magnitudes of the physically causal elements of TTEF and the uncertainties that adhere to them. One of the physically causal elements is LWCF. Because reflected SWR has no causal link to TTEF, then no $(du/dx)\times(dv/dx)$ term in the accounting of TTEF uncertainty will derive from reflected shortwave radiation.

Tropospheric thermal flux is dependent on long-wave IR upwelling from the surface; the surface transmitted irradiance (STI). STI is causally connected to SW surface heating.

Figure 3 compares the TOA out-going SW and LW radiation with upwelling longwave from surface transmitted irradiance (STI), from Figure 3 of [*Costa and Shine*, 2012].

In this case, the STI contribution to tropospheric thermal flux appears negatively correlated with TOA outgoing longwave at ±30° but positively correlated at ±30°-90°. The net $(du/dx)\times(dv/dx)$ term entering an uncertainty calculation is thus likely to be small. The STI is also positively correlated with shortwave TOA radiation at ±30° but negatively correlated at ±30°-90°.

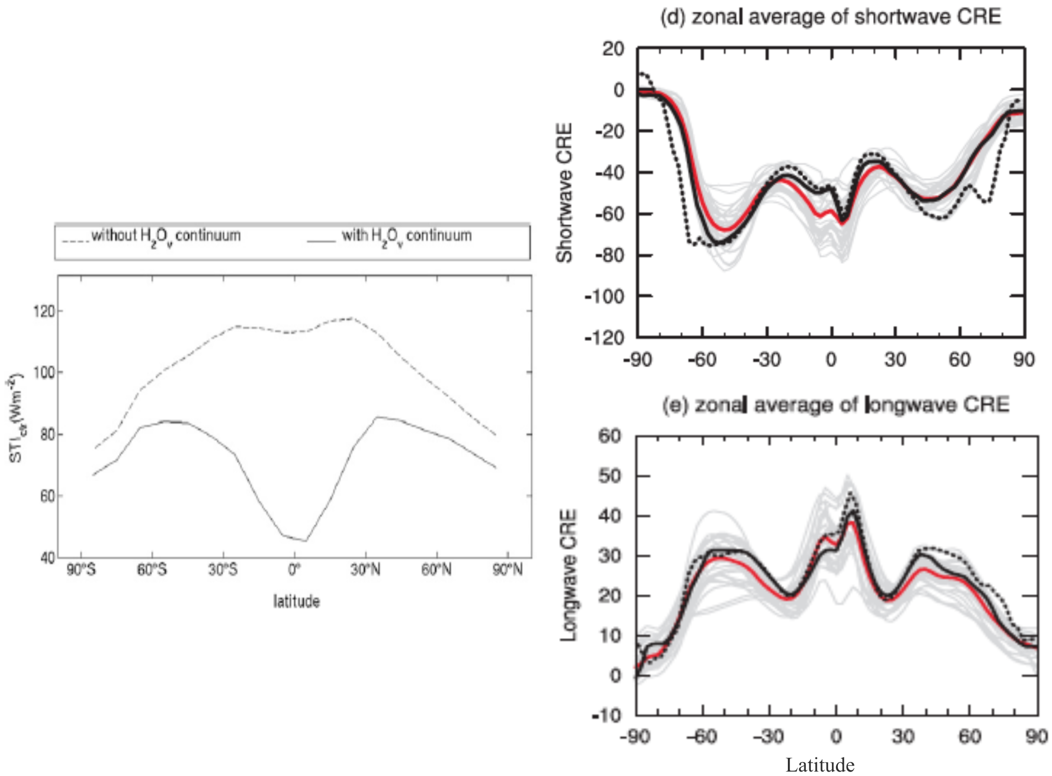

Figure 3. Left, Legend from Figure 3 of [*Costa and Shine*, 2012]: "*Zonal and annual mean of the clear-sky surface transmitted irradiance (Wm^{-2}) with (solid line) and without (dashed line) the water vapor continuum*." Right, partial Legends from the IPCC AR5: Top, Figure 8.5. "zonal averages of the cloud radiative effects from observations; " Bottom, Figure 8.7. "*Observed and simulated annual-mean, zonally-averaged outgoing longwave radiation.* For 8.5 and 8.7: "*(solid black: CERES EBAF 2.6; dashed black: CERES ES-4), individual models (thin grey lines), and the multi-model mean (thick red line)*." In [*Costa and Shine*, 2012] the STI calculation including the water vapor continuum is the physically more complete.

In order to test these ideas, the clear sky STI of [*Costa and Shine*, 2012] and the SW CRE from IPCC AR5 Figure 8.7 of Figure 3 were digitized and are compared in Figure 4.

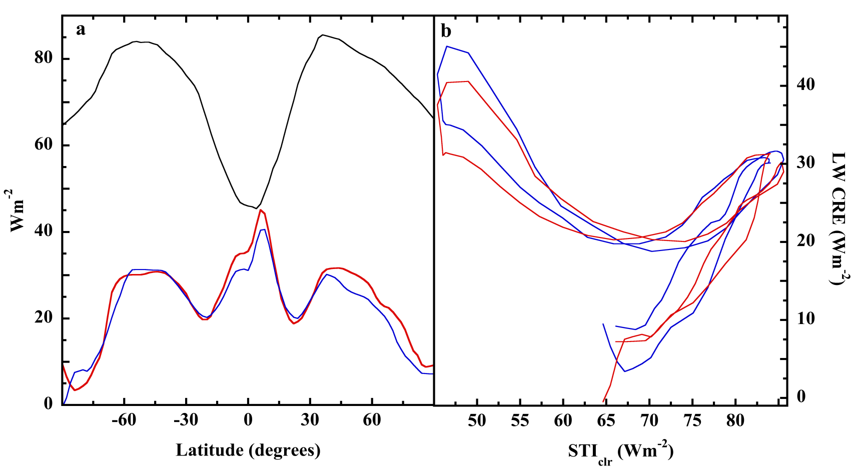

Figure 4, panel a: (black), surface STI; (red), EBAF 2.6; (blue), ES-4; *cf.* Figure 3 Legend. Panel b: CRE plotted against STI; (red), EBAF 2.6, and; (blue), ES-4.

The paired Student-t correlation R-values with STI are, EBF 2.6, R = -0.06, and ES-4, R = -0.10.

One concludes that as the intensity profiles of STI and TOA reflected SWR are negligibly correlated, the correlation of the TOA LWR and SWR profiles is not relevant to the uncertainty in TTEF.

As an aside, including the uncertainty in simulated shortwave TOA CRE would be only part of a larger appraisal of projection reliability. One would not stop at SW CRE, however, but also include the errors in other simulated observables and their cross-terms. The combined model error is likely to be very large [*Collins et al.*, 2011; *Soon et al.*, 2001].

Further, a complete inventory of the uncertainties entering a simulation would include not only simulation error but also the measurement uncertainties in the target observables being simulated.

For example, according to [*Stephens et al.*, 2012], the uncertainty in the **observed** TOA outgoing longwave radiation is ±3.3 Wm^{-2}. A complete accounting entering an evaluation of simulation uncertainty must include the known uncertainty magnitudes of the calibration targets against which the simulation is judged. Thus, while the multi-model mean error statistic with respect to observed LWCF is ±4 Wm^{-2}, the uncertainty in the observed physically real LW flux itself is ±3.3 Wm^{-2}. A more complete uncertainty in the simulated tropospheric LW flux is the rms of these two uncertainties, $\text{sqrt}[(3.3)^2+(4)^2] = \pm 5$ Wm^{-2}. The present study addresses only a lower limit of uncertainty, however, and therefore none of these additional sources of uncertainty was included.

Finally, as the reviewer's comment about SW led to the question of ozone Tropospheric heating, which is due to absorbed SWR. Figure 5 shows the maximal ozone mixing ratio at 35 km and a graphical display of the ozone heating.

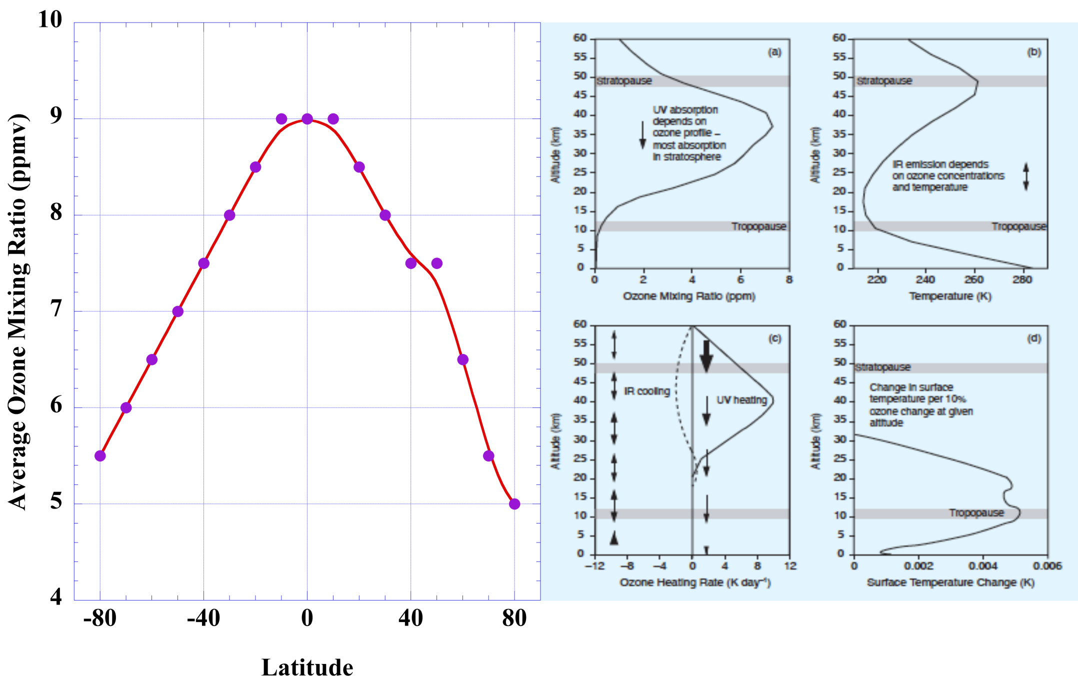

Figure 5, left, (points): the December-June average ozone mixing ratio at 35 km, taken from Figure 2 of [*Fortuin and Langematz*, 1995]; (red line), a Stineman smooth of the data. Right, Figure 1.1 taken from [*Pyle et al.*, 2016] showing the overall ozone profiles and heating effects.

The ozone heating effect, taken to follow the mixing ratio profile, is negatively correlated with LWCF at 0±30º latitude but positively correlated everywhere else. The correlation R-values are ES-4, R = 0.65 and EBAF 2.6 R = 0.71, after interpolation onto the ozone mixing latitudinal scale. The magnitude of ozone heating is tiny compared to that of LWCF. Any net ozone *(du/dx)×(dv/dx)* term must have negligible impact on TTEF uncertainty.

The conclusion following all of the above is that the correlation of TOA reflected LW and SW radiation makes no significant contribution to the uncertainty of TTEF.

5. *Because if the longwave cloud radiative forcing has an extra +4W/m^2 down to surface, there must be other cooling process to compensate to make the total TOA flux in balance (much smaller than 4W/m^2), otherwise the surface temperature will increase unrealistically.*

The reviewer here is mistaking a "±" error statistic for a positive energetic perturbation. Such a fundamental error is fatal to the reviewer's argument.

The error statistic does not at all mean the longwave cloud forcing has an extra +4 Wm^{-2} down to the surface. The ±4 Wm^{-2} error means that climate models incorrectly partition the simulated internal cloud forcing energy, with respect to the physically real climate state.

The simulated climate can be in overall energy balance, even though the internal energy is partitioned incorrectly.

Note that ±4 Wm^{-2} is simultaneously positive and negative. It can never be mistaken for a positive energetic perturbation. It is thus not at all clear from where comes the reviewer's idea of, "*an extra +4W/m^2 down to surface.*"

6. *It is unlikely such a simplified approach can be more reliable than using the GCM outputs from the ensemble runs to quantify the uncertainties of projection.*

Internal comparisons of GCM ensemble runs do not quantify physical uncertainties; nor do they indicate projection error. They indicate model precision. The manuscript Introduction fully discussed the distinction between accuracy and precision, which the reviewer has here neglected.

One notes that 'simple' also describes the fully demonstrated linear extrapolation of forcing into air temperature characteristic of advanced climate models. Ironically, the linear relation between forcing and projected air temperature is candidly admitted in box 1.3 of [*Pyle et al.*, 2016], i.e., $\Delta T_s = \lambda \Delta F$, where λ is model climate sensitivity.

This admission by the IPCC, in and of itself, fully justifies linear propagation of error through an air temperature projection.

7. *Of course, there could be a systematic bias in the projection due to a model defect that is common to all the GCMs so that the ensemble mean is incorrect. But this kind of error should be quantified by studying effect due to this common defect in the GCMs, not by the linear error propagation presented in this paper.*

The error analysis in [*Lauer and Hamilton*, 2013] is exactly the defect study that the reviewer desires. The study revealed a significant error in tropospheric energetics following from the theory-based error in cloud simulation, discussed in manuscript lines 514ff.

The comparisons in [*Lauer and Hamilton*, 2013] are a calibration experiment with cloud observables as the calibration standard. This experiment revealed systematic error inherent within CMIP3 and CMIP5 climate models, which negatively impacts their simulation accuracy.

Manuscript Table 1 shows this error is systematic and common to all tested GCMs, as discussed in Section 2.3.1 (lines 441ff). LWCF error is thus theory-based and therefore impacts every single step in a simulation.

Manuscript Section 2.2 showed that model air temperature projections are linear in forcing. Manuscript lines 564ff described the necessary logical connection to linear propagation of error. This paragraph has been expanded with reference to complex physical models.

A new paragraph has been added at previous manuscript line 531ff to make clear why combination of LCF error with the equation 6 GCM emulation model is entirely justified. This new paragraph also explains the meaning and impact of a calibration experiment.

It should be clear at this point that, while analytically complex, the present review has no critical merit.

References:

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