Patrick Frank 24 March 2014
Propagation of Error and the Reliability of Global Air Temperature Projections
JGR-Atm submission 2013JD021338

Response to Reviewer #2:

Summary

- The reviewer suggestion of an insubstantial prior response is factually incorrect.
- The reviewer has inverted the physical logic of the error analysis.
- The reviewer declaration that ms eqn. 6 includes author assumptions is not correct.
- The reviewer has misunderstood the meaning of confidence intervals and of propagated error.

Reviewer comments are presented in full, justified, numbered, and in italics.

1. *This paper sets out to show that model projections are too error-prone to make meaningful statements on detection and attribution.*

The manuscript it not written clearly enough to follow a logical argument through the paper.

Response 1. It is difficult to understand the reviewer's difficulty. The Introduction draws the distinction between precision and accuracy, noting that common evaluations of climate models fall under the definition of precision. It then describes the standard method of estimating model accuracy by propagation of physical error.

The Introduction then goes on to state that, "*Herein a method of error propagation is developed that estimates the reliability of the projected GASAT futures made using general circulation models (GCMs) of climate.*" Immediately following, the step-by-step methodological approach is described.

This seems like fair warning. The manuscript then explicitly follows the described method.

How much more clear must logic be so that the reviewer can follow it?

Nevertheless, to accommodate the reviewer's inferential difficulty, new first sentences of the abstract are explicitly informative of the approach. The final paragraphs of the Introduction have been revised to connect the step-wise logic to the relevant manuscript sections.

2. *The author did not address critical points made by previous reviews, but rather tried to pick holes in the review comments so as not to consider their legitimate points.*

R2.1 From the prior round of reviews, the author accommodated reviewer concerns about comparing modeled and observed cloud fraction by removing the linearly approximated global cloud forcing error and substituting the tropospheric total cloud fraction (TCF) long wave thermal error derived in [*Lauer and Hamilton*, 2013].

Further:

- The author did a case-by-case examination of reviewer-offered precedents and showed that neither first round reviewer understood propagation of error.
- The author showed reviewer #1 was mistaken in supposing that the manuscript eq. 6 simulation model was not validated.
- The author showed the reviewer #1 is mistaken to suppose that differencing simulations removes physical error.
- The author addressed reviewer #1 concerns about literature precedent, e.g., [*Bony et al.*, 2011].
- The author extensively examined the reviewer #1 declaration that the mean free path argument to onset of CO_2 forcing appears in textbooks.
- The author addressed the mistaken reviewer #2 view that the author "*assumes all clouds produce the same cloud forcing*", which the author manifestly did not.
- The author addressed the reviewer #2 mistake in equating global energy balance to model energy resolution.
- The author addressed the reviewer #2 argument that tuning models to TOA energy flux removes projection uncertainty.
- The author accepted the pertinent other concerns expressed by reviewer #2, and revised the manuscript accordingly.

In short, evidence shows the author addressed the prior reviewer concerns point-by-point and in detail. In contrast, reviewer #2 here presented no factual support for dismissing the author's prior response as "*picking holes*."

R2.2 The reviewer statement of author intent, "*... so as not to consider their legitimate points,*" is unsubstantiated and has no place in a scientific review. The reviewer can have no knowledge of the author's internal states.

> 3. *At least two major points make the paper unsuitable to JGR, and I think it should be rejected.*
>
> 3.1. *The physical model. The author purports to be using a mathematical (non physical) model, and therefore states that they do have to worry about model physics. Yet their model clearly makes assumptions about radiation and cloud physics ...*

R3.1 The reviewer did not specify these assumptions, despite that they were apparently clear.

R 3.1.1 In response, however, the author looked through the PWM, manuscript eq. 6, for assumptions.

The 33 K of baseline greenhouse warming is a common-place of climatology, and is not an assumption made by the author.

The *wve* CO_2 forcing fraction is derived from the results published by [*Manabe and Wetherald*, 1967]. See manuscript Figure 1b and the associated text. Therefore, any assumptions about "*radiation and cloud physics and their interaction*" are of Manabe and Wetherald, and are not made by the author.

The GHG forcings included in the PWM eq. 6 model are calculated using the equations in [*Myhre et al.*, 1998]. Therefore, any pertinent assumptions therein are of Myhre, et al., and are not made by the author.

The GCM tropospheric TCF thermal flux error used in the propagation equation is a product of [*Lauer and Hamilton*, 2013], and thus includes no author assumptions.

The mean free path calculations of manuscript Figure 1a, and the IR spectrum of CO_2 and its fit, Figure 1a inset, are standard spectroscopy that include no assumptions at all about the interactions of clouds and radiation.

That exhausts the elements of the PWM of manuscript eq. 6 and the subsequent error analysis. None of them include author assumptions. The assumptions it does include are either encoded within climate models or standards of their fields.

3.1.2 ... and their interaction that are never tested and its limitations never discussed.

R 3.1.2 The tested interactions of radiation and clouds are those represented by the CMIP5 climate models. See manuscript Figure 3, Figure 4 and Table 1.

As itemized in R 3.1.1, the PWM itself includes no assumptions concerning radiation, clouds, and their interactions, that are not already present in GCMs. The PWM was derived specifically in order to test those GCM-embedded assumptions.

Thus, the reviewer concern has the situation exactly backwards. The assumptions are in the GCMs and the entire manuscript presents their test.

It is an author <u>hypothesis</u> that manuscript eq. 6 can be used to simulate the air temperature projections of climate models. This brings the author response to:

R 3.1.3 The reviewer suggested that the limitations of the PWM are never discussed.

However, manuscript Figure 2 and Figure 6, and prior Auxiliary Information Figures S1-S6 are that discussion. That discussion strongly tested the limitations of the PWM by comparison of its output with the air temperature projections of a large number of advanced climate models.

The PWM fully passed those tests.

Whatever limitations the PWM has, they do not include the ability to simulate the GHG-driven temperature projections of advanced climate models.

The PWM fully demonstrates that advanced climate models project GHG-driven air temperatures by linear extrapolation of forcing. Use of the PWM for the propagation of GCM error follows directly.

> 3.2.1.1 *As stated by an earlier review they assume that errors in cloud forcing translate into errors in climate response.*

R3.2.1.1 The reviewer has the logic backwards. The error in modeled climate response translates into an error in modeled cloud forcing.

> *3.2.1.2 They never justify this approach adequately or explain their reasoning on page 20.*

R 3.2.1.2 All of this is discussed well before page 20. Section 2.3, page 16ff describes the multi-year hindcast average of global annual total cloud fraction errors exhibited by multiple CMIP5 climate models, as judged by comparison of simulations with observations.

Hindcasts are the model response to modeled climate forcings and feedbacks. Hindcast errors relative to observations are the errors in model response.

Page 16: "*CMIP5 TCF hindcasts were compared to the A-train observations, comprising 25-year (1980-2004) annual means. [Jiang et al., 2012]*"

Section 2.3.1 then describes the structure of cloud forcing error. This error is shown to result from model theory-bias, i.e., to be a consequence of the physical errors within the model itself.

Section 2.4 goes on to describe the magnitude of cloud forcing error produced by the error in model physics.

Sections 2.3 and 2.4 provide a complete justification and explanation for the translation of model error into error in modeled climate response.

R3.2.1.3 It should not be a mystery that modeled global annual cloud fraction is the modeled climate response to the modeled forcing and feedback energy flux. The error in simulated cloud forcing follows directly from the error in the simulated total cloud fraction.

The model error in tropospheric total cloud long wave forcing translates into a model uncertainty in the tropospheric thermal energy flux. The model uncertainty in tropospheric thermal energy flux is a measure of model resolution. The ±4 Wm^{-2} global average annual TCF forcing uncertainty is finally a lower limit of model resolution.

The average annual model TCF thermal energy flux uncertainty of ±4 Wm^{-2} means that models cannot resolve the impact of any climate forcing or feedback of a magnitude that falls within this interval.

This is standard physical reasoning that should be second nature to the reviewer.

The ±4Wm^{-2} limit of model resolution completely subsumes the 0.035 Wm^{-2} average annual forcing increase of greenhouse gas emissions.

> 3.2.2 *Saying that 4Wm^{-2} of error is felt by the climate system is one thing,...*

R3.2.2 The manuscript does not say that 4 Wm^{-2} error is felt by the climate system. It says that the ±4 Wm^{-2} of forcing uncertainty is a measure of model resolution. Page 19, line 432: "*The LCF error of ±4 Wm^{-2} is thus an average resolution limit of CMIP5 GCMs.*"

The text continues on to explain the meaning of this statement: "*This uncertainty in cloud forcing defines a lower limit of ignorance concerning the annual average energy flux through a simulated atmosphere. GHG forcing enters into and is not separate from the total flux of thermal energy within the atmosphere. [Berger and Tricot, 1992] Therefore, simulations of the response to changes in GHG atmospheric forcing must recognize ±4 Wm^{-2} of uncertainty in the amount of energy entering, and partitioned among, the various climate modes.*"

That explanation does not seem at all obscure.

> 3.2.3 ... *but then translating this into an annual error in climate response, as they seem to, is totally unjustified.*

R3.2.3 As noted in 3.2.1.1, the ±4 Wm^{-2} is not, "*[translated] into an annual error in climate response.*"

Rather, ±4 Wm^{-2} <u>is</u> the annual (average) error in (simulated) climate response. This error was determined by [*Lauer and Hamilton*, 2013].

Lauer and Hamilton describe the ±4 Wm^{-2} error statistic as the "rmse," i.e., the root-mean-square-error (p. 3833), and go on to state, "*The overall comparisons of the <u>annual mean cloud properties</u> with observations are summarized for individual models and for the ensemble means by the Taylor diagrams for CA, LWP, SCF, and LCF shown in Fig. 3.*"

The Legend to Lauer and Hamilton Figure 3: "*Taylor diagrams showing the <u>20-yr annual average performance</u> of the (top) CMIP3 and the (bottom) CMIP5 models for (left to right) CA, LWP, and ToA SCF and LCF as compared to satellite observations*." Author-added underlining throughout.

Note the references to annual error.

The ±4 Wm^{-2} is an annual average error in the long wave cloud forcing response within the climate simulations made by CMIP5 GCMs. This is a published fact of analysis, and is not an author translation.

R 3.2.4 To say that this error indicates that temperatures could hugely cool in response to CO_2 shows that their model is unphysical

R3.2.4 Confidence intervals do not have the reviewer's meaning. Nor is propagated error equivalent to model response. Confidence intervals do not imply the behavior of the physical state, or that air temperature may cool (or warm).

Manuscript line 505ff explains that confidence intervals express a lack of knowledge concerning the physical state.

The meanings of confidence intervals and of propagated error are further discussed in Summary Conclusions Section 3, line 648ff. The reviewer is recommended to these sections.

Propagated error indicates the step-wise growth of ignorance. The ever larger confidence intervals follow from the fact that the theory-biased TCF long wave forcing error must cause the simulated future climate to systematically diverge from a physically correct representation of future climate, but always by an unknown amount.

The reviewer is recommended to manuscript section 2.4.3, which shows that theory bias necessarily causes the transmission of systematic error of unknown magnitude.

As the true physical error in the representations of future climate states cannot be known, the only alternative is to use a statistical measure that expresses the increasing lack of knowledge concerning the climate states projected into the future.

The large uncertainty in air temperature at the end of a centennial projection means that the projected state transmits no knowledge, no information, about the physically true future climate state.

References:

Bony, S., M. J. Webb, C. S. Bretherton, S. A. Klein, A. P. Siebesma, G. Tselioudis, and M. Zhang (2011), CFMIP: Towards a better evaluation and understanding of clouds and cloud feedbacks in CMIP5 models, *Clivar Exchanges*, *16*(56), 20-24.

Lauer, A., and K. Hamilton (2013), Simulating Clouds with Global Climate Models: A Comparison of CMIP5 Results with CMIP3 and Satellite Data, *Journal of Climate*, *26*(11), 3823-3845, doi:10.1175/jcli-d-12-00451.1.

Manabe, S., and R. T. Wetherald (1967), Thermal Equilibrium of the Atmosphere with a given Distribution of Relative Humidity, *J. Atmos. Sci.*, *24*(3), 241-259.

Myhre, G., E. J. Highwood, K. P. Shine, and F. Stordal (1998), New estimates of radiative forcing due to well mixed greenhouse gases, *Geophys. Res. Lett.*, *25*(14), 2715-2718.