Patrick Frank 12 April 2015

On the reliability of global air temperature projections in light of propagated error: A critical review

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Response to Reviewer #3

Summary

- The review is constructive and helpful.
- The ±4 Wm^{-2} is noted to have survived 560 model years of model error-damping, Author Response (AR) items 2 & 3, and is only a lower-limit of error, AR item 6;
- The Stefan-Boltzmann perturbation relaxation is considered in light of CO_2 as non-condensable, AR item 4;
- The meaning of uncertainty bars is clarified in light of the reviewer concern about scatter in projected temperatures, AR items 5 & 7;
- A new paragraph has been added to Section 2.4.3, to clarify that the uncertainty bars are an ignorance width, rather than an indication of scatter in projected temperatures, AR item 7;
- It is hoped that these responses alleviate the reviewer's concerns.

Reviewer comments are presented in full, indented, numbered, and in italics. Each separate reviewer idea is sectioned out. Author responses follow.

1. This is very interesting paper. If his claim is proven to be true, the issue of climate scenarios' uncertainty raised in this paper will resound in so many science communities which rely on the reliability of long-term climate prediction outputs. The claim that errors due to cloud bias are propagating should be important in quantifying the accuracy (not precision) of climate prediction. In my opinion, despite the claim that very large uncertainty is inherent in model predictions for 2100 is very striking, it sounds fairly reasonable like what is always required in physical science. Thus I think that this paper needs to be published in the end.

1. The reviewer is thanked for this constructive overview and positive recommendation. It is fully agreed that an assessment of predictive capacity is completely standard in science.

2. There are some important questions to make sure that the claim of this paper is correct. The forcing error due to cloud bias may be damped by Stefan-Boltzmann feedback that may be intrinsic in current climate models. **[Author Response (AR)**

item 2]

2. The reviewer may well be correct about error-damping. However, the ±4 Wm^{-2} long-wave cloud forcing (LWCF) error is the average of 28 CMIP5 models across 20 years of hindcast. These 560 model-years included whatever Stefan-Boltzmann error damping as may be present in the models. The ±4 Wm^{-2} is the average magnitude of error that survived this damping. (Lauer and Hamilton, 2013) provided the 20-year range of model LWCF rms error as 4-11 Wm^{-2}.

Please note however, that the manuscript is about the growth of uncertainty rather than the evolution of model error. These are not identical.

Error is the difference between a predicted magnitude and an observed magnitude. However, in a futures projection, the trajectory and magnitude of error are necessarily unknown because future observables are unknowable.

Propagation of known error yields the predictive uncertainty. This uncertainty defines the *a priori* reliability of the prediction. Off-setting errors do not correct the underlying physics. Predictive uncertainty, *inter alia*, represents model bias itself. It is calculated before any observation can be made and before any physical error of the projection can be known.

3. The perturbed surface temperatures at time i due to cloud bias will be partly restored at time i+1 by the release of energy proportional to the surface temperature change since the climate system should follow Stefan-Boltzmann law. **[AR item 3]**

3. Again, please note that the ±4 Wm^{-2} total cloud fraction (TCF) error is an average across 28 CMIP5 models and 20 years of hindcast, making 560 model years of output. (Lauer and Hamilton, 2013)

Across 560 model-years, the $i \rightarrow i+1$ walk of error should have averaged out to a reasonable estimate of mean annual error. This mean error can then be propagated through a projection to yield an estimate of predictive reliability.

The contrast between unknowable error but knowable confidence intervals is discussed in manuscript Section 2.4.3. Confidence intervals are obtained from known error propagated through a prediction. Known error is obtained by comparing hindcast observables with measured observables.

Please note also, that only a complete theory of climate can determine that the troposphere strictly follows the Stefan-Boltzmann law.

4. That is, the warmer surface temperature by 1°C would naturally cause more *emission of thermal flux from the surface by approximately 3.7 W m-2 to space, reducing the system's internal energy and naturally restoring the surface temperature back to the initial state when unperturbed. There is an issue of restoration time depending on climate sensitivity and heat capacity, but in any event, restoration of perturbed temperatures by climate forcings is indeed the basic characteristic of nature.* **[AR item 4]**

4. The reviewer is correct when the GHG is condensable, as is water vapor. Radiation to space cools water vapor causing droplet condensation. Condensation removes the water vapor and allows the atmosphere to return to its initial state of humidity.

However, when the gas is non-condensable CO_2, so goes the theory, the perturbed state involves an increased GHG concentration which is semi-permanent, and the atmosphere cannot return to its initial state.

That is, consider when excess CO_2 is emitted into the atmosphere: short-wave insolation is constant, the flux of surface-emitted long-wave energy also remains constant, and the CO_2 remains at its increased atmospheric concentration. Then increased $[CO_2]_{atm}$ means the absorption by CO_2 of surface-emitted 15μ radiation remains enhanced, and the thermal density of the troposphere is increased. This increased thermal density, plus a constant lapse rate, forces an increase in the height of the TOA 255 K radiation boundary. When the 255 K boundary is higher and the lapse rate is constant, the 1°C of surface warming thereby remains present. So says the consensus theory.

5. I presume that the cloud forcing bias per se may be amplified, but the temperature responses to that cloud forcing may not be amplified due to this climate system characteristic, making modeled projections not to be scattered as much as this paper has estimated. Please discuss this possibility somewhere. **[AR item 5]**

5. The paper does not estimate a scatter of model projections. The paper estimates the reliability of the model projections, which reliability is presented as an uncertainty envelope.

The uncertainty bars are not simulated air temperatures. The central point is that LWCF error means the simulated thermal state of the troposphere is not more accurately resolved than ±4 Wm^{-2}, at each step in the projection. Each step "*i*" in the projection then begins with an incorrect climate energy state, because of the ±4 Wm^{-2} LWCF error in the "*i-1*" state.

This incorrect state is then projected further but again with an average ±4 Wm^{-2} LWCF error in the next step of the projection. That is, the step "*i*" climate state is already incorrect, and step "*1+i*" compounds the inaccuracy with a fresh LWCF error. The incorrect state is projected incorrectly.

This steady impact of a persistent theory-bias error means that our knowledge of the simulated climate decreases with each step of the climate simulation. This is the meaning of the increased uncertainty bars across simulation time.

This topic is covered in Auxiliary Material Section 10.1. Please also see manuscript section 2.4.1, par. 1, section 2.4.2, par. 1-4, and all of section 2.4.3.

6. In addition, cloud fraction bias is not all, leading to error of ±4 W/m2 of cloud forcing. Models have many different substances such as sea ice/snow, vegetation, cloud properties, and precipitation, etc. all of which also act to add error, or compensate error. **[AR item 6]**

6. The reviewer is quite correct. The average ±4 Wm^{-2} LWCF error is merely a lower limit of GCM resolution. A more complete inventory of GCM errors would propagate into a greatly increased width of the uncertainty envelope.

7. Then even so, why are model-projected temperatures not too variant in the year of 2100 in Figure 4. I hope that the author can properly reflect my concerns in the manuscript, so readers can be confident with the claim of this study. **[AR item 7]**

7. The uncertainty bars reflect the reliability of the temperatures. The models themselves always project discrete temperatures.

Uncertainty bars do not reflect the magnitudes of the model temperatures. As noted in Auxiliary Material Section 10, uncertainty bars are an ignorance width. They tell us how much knowledge is represented by the temperature magnitudes projected by the model.

This point is discussed in Section 2.4.1, paragraph 1. However, a new first paragraph has now also been added to Section 2.4.3 detailing uncertainty as an ignorance width.

The author thanks this reviewer and hopes these responses resolve the reviewer's concerns.

References:

Lauer, A. and Hamilton, K., 2013. Simulating Clouds with Global Climate Models: A Comparison of CMIP5 Results with CMIP3 and Satellite Data. J. Climate, 26(11): 3823-3845.