Reply to comment by A. Robock on "Climate forcing by the volcanic eruption of Mount Pinatubo"

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Received 17 June 2005; revised 9 August 2005; accepted 14 August 2005; published 25 October 2005.

Citation: Douglass, D. H., and R. S. Knox (2005), Reply to comment by A. Robock on ''Climate forcing by the volcanic eruption of Mount Pinatubo,'' *Geophys. Res. Lett.*, *32*, L20712, doi:10.1029/2005GL023829.

1. Introduction

[1] In our Pinatubo paper [*Douglass and Knox*, 2005a, hereinafter referred to as DK] we concluded that there was negative climate feedback and a short climate response time. *Robock* [2005, hereinafter referred to as R] claims that the outgoing long-wave radiation (LW) was incorrectly described as the forcing and that interchange of energy with the thermocline was unjustifiably neglected in determining our results. Although we made certain incorrect statements about the LW radiation, these were not part of our determination of the parameters. As to energy flow to the thermocline, as we argue elsewhere [*Douglass and Knox*, 2005b, hereinafter referred to as DK2], this flow is estimated be small and to affect our lifetime and sensitivities by less than 15%, not by a factor of three, as claimed.

2. Forcing

[2] Despite some of our own words to the contrary, we did not use the LW as the forcing. We used the proxy $\Delta F = A$*AOD (DK, equation (3)) in solving the dynamical equation (DK, equation (2)). Here AOD (obtained from data tables referenced by *Ammann et al.* [2003]) stands for aerosol optical density and A is the scaling coefficient in the notation of *Hansen et al.* [2002], who provide a computed value $A = -21$ W/m^2. This value generates the first column of Table 2 (DK).

[3] During our analysis we found that the LW has no delay with respect to AOD and its measured amplitude is in fact equal to -21 W/m^2 to within 14% (see DK, Table 1, bottom row). This coincidence led us to mis-identify the LW with the forcing, even though we had not used it to obtain the Pinatubo response function. Unfortunately, the impression lasted long enough for us to write the third sentence of paragraph [14] of DK, rightly criticized by R. We regret the error and apologize for the confusion. Nonetheless, the correlation between LW and AOD does exist with a coefficient $A' = -21 \pm 2.7$ W/m^2 and a delay of 0 ± 2 months. Further correlation analyses that we called "indirect determinations of A" are actually indirect determinations of A', and to within their error bars they verify its value.

3. Response Times and Heat Flux to the Thermocline

[4] Following is a very brief version of a discussion (DK2) made in response to a similar comment [*Wigley et al.*, 2005, hereinafter referred to as WAST]. In the DK analysis there are two distinct time constants. The forcing is characterized accurately by a function proportional to $t\exp(-t/t_V)$, where t_V (the first time constant), is a property of the eruption. Its value is 7.6 months. Because the kinetics of the thermocline layer are not explicitly included, there is a single kinetic response time τ (the second time constant), which relates to the surface system, particularly the ocean mixed layer, whose temperature is represented by TLT or TLTm. In our paper we found the solution of an equation of the following form that was a good fit to the data:

$$\tau' \frac{d\Delta T}{dt} + \Delta T = \lambda' \Delta F. \qquad (1)$$

As written in this equation, τ' and λ' are the climate response time and sensitivity, respectively, in the absence of coupling to the thermocline. In the presence of coupling, they can be related to the underlying τ and λ by $\tau = \tau'/\alpha$ and $\lambda = \lambda'/\alpha$, where $\alpha = 1 - s\lambda'$ and s is a coupling constant. Whereas WAST and R consider α to be of the order of 0.3, DK2 show that it may well be close to unity. The critical matter (as all authors will certainly agree) is the nature and size of the coupling and the approximation by which it is found. We repeat here the critical part of the argument of DK2.

[5] The heat flow from mixing layer to thermocline, ΔQ, is assumed proportional to ΔT with the coefficient s. A value of $\alpha = 0.3$ requires that the parameter s have the value $(1 - \alpha)/\lambda' = 4.7$. From *Wigley and Schlesinger* [1985] and *Lindzen* [1994] one has

$$s = c_V \kappa \left(-\frac{\partial \theta(x)}{\partial x} \right)_{x=0}, \qquad (2)$$

where θ is the thermocline temperature in units of its value at the interface of the mixed layer and thermocline, x is distance (downward) and κ is the eddy diffusion coefficient. The derivative in (2) is the slope of θ at the interface and has values in the range of 1.0 to 5.0×10^{-3} m^{-1} [*Billups et al.*, 1999; *Farmer*, 2000]. We estimate s by using this slope along with $\kappa = 1.2 \times 10^{-5}$ m^2/s (the eddy diffusion coefficient in the thermocline [*Ledwell et al.*, 1998]) and

0094-8276/05/2005GL023829$05.00

$c_V = 4.1 \times 10^6$ J/m^3 with the result $s = 0.024$ to 0.12. Combining this with the peak excursion in ΔT, -0.48 K, we have $\Delta Q = -0.05$ to -0.25 W/m^2, small compared with the peak forcing $\Delta F \sim -21*(0.162) = -3.4$ W/m^2. Our value of α is consequently nearly indistinguishable from unity. There is clear disagreement with "$\alpha = 0.3$".

[6] The value of κ used above may be contentious in this discussion. Most earlier modeling work, including that of *Wigley and Schlesinger* [1985], assumed a value of $\sim 1.0 \times 10^{-4}$ m^2/s, which value is characterized by IPCC [*Dickinson et al.*, 1996, p. 214] as follows: "[T]hese diffusion values are ... often selected to ensure numerical stability of the simulation. A tracer experiment ... has recently indicated that the correct vertical diffusion coefficient for the ocean interior is closer to $\kappa = 1.0 \times 10^{-5}$ m^2/s, an order of magnitude smaller than often used."

4. "Disagreement With Models"

[7] R suggests that the Pinatubo results of *Soden et al.* [2002] are inconsistent with our results. These authors did a model calculation in which they turned the water vapor feedback of the CO_2 interaction on and off, showing the presence of a positive feedback. The feedback in any system is some combination of many processes and is evaluated relative to some reference no-feedback sensitivity. The DK Pinatubo negative feedback determination, being based on observation, includes contributions from all operative processes. These two results are not a priori inconsistent, because (a) additional negative feedback could be required in the model, (b) the positive feedback in the model could be incorrect, (c) the model may use a reference sensitivity different from $\lambda_0 = 0.30$ K/(W/m^2), or (d) a combination of these. DK2 discuss "disagreement with models" more fully.

5. Summary

[8] Our paper (DK) does contain a mis-statement about the role of LW radiation that has a minor effect on our quantitative results, namely in that the "corroboration" of our sensitivity value by the LW-AOD correlations is removed. Our revised conclusion is that if the *Hansen et al.* [2002] AOD forcing proxy is correct, the feedback relative to purely radiative forcing of 0.30 K/(W/m^2) is observed to be -1.2 (+0.5, -1.0). This of course assumes the validity of our claim that the thermocline heat loss is sufficiently small ($\alpha \sim 1$).

[9] R does point out our implicit assumption that heat flow to the thermocline was small, for which we are appreciative. However, our estimate of the effect of ocean coupling on sensitivities indicates that our neglect of mixed layer-to-thermocline energy flow is less than 15%.

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