Comment on "Climate forcing by the volcanic eruption of Mount Pinatubo" by David H. Douglass and Robert S. Knox

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[1] *Douglass and Knox* [2005, hereinafter referred to as DK], present an analysis of the observed tropospheric cooling following the 1991 Mt. Pinatubo eruption, and claim that these data imply a very low value for the climate sensitivity (equivalent to 0.6°C equilibrium warming for a CO_2 doubling). We show here that their analysis is flawed and their results are incorrect.

[2] We begin with a very simple analysis of the response to volcanic forcing. If 'S' is the climate sensitivity (°C/Wm^{-2}) and the maximum forcing is ΔQ, then the maximum equilibrium cooling is $\Delta T_{eq} = S\Delta Q$. Because of oceanic thermal inertia, the actual maximum temperature reduction, ΔT, will be substantially less than ΔT_{eq}. The ratio of actual cooling to equilibrium cooling, $\alpha = \Delta T/\Delta T_{eq}$, may be referred to as the fractional realized cooling. For short term volcanic forcing, conventional values for α are around 0.3.

[3] What do DK's results imply for α? DK have S = 0.15°C/Wm^{-2}, $\Delta Q \approx -3$ Wm^{-2}, and $\Delta T \approx -0.5$°C (see DK, Figure 3). Here, ΔQ is obtained by multiplying the peak visible optical depth change of 0.16 (see DK, Figure 2) by a scaling factor of 18.5, their central estimate, and ΔT is their smoothed value for the maximum cooling. These values imply that $\alpha = \Delta T/(S\Delta Q) \approx 1.1$. (A larger cooling estimate, such as the unsmoothed value of −0.7°C, would give an even larger value for α.) DK's results therefore imply that the actual cooling from the Pinatubo eruption was more than the equilibrium cooling! This is an improbable result, and it is difficult to think of a physical mechanism through which it might occur.

[4] We can test the validity of the DK approach directly using a model case where we know the climate sensitivity, and see whether their approach can recover the known value. The case we consider is a coupled atmosphere-ocean general circulation model simulation of the effects of volcanic eruptions on climate [*Ammann et al.*, 2003]. The model used is the NCAR/DOE Parallel Climate Model (PCM). This is the same model that was used by DK to obtain the post-Pinatubo optical depth time series (DK, Figure 2). In contrast to the real-world case, the Pinatubo response signal in PCM is very well-characterized, because multiple model realizations allow the noise of internally-generated variability to be reduced significantly [see *Wigley et al.*, 2005]. We also know from earlier work [*Raper et al.*, 2001] that the climate sensitivity for this model is 0.46°C/Wm^{-2}, smaller than in most other models but still substantially greater than the DK result of 0.15°C/Wm^{-2}.

[5] It is a simple matter to fit DK's analytical solution for the Pinatubo response (DK, equation (6)) to the PCM results for Pinatubo. Their analytical solution contains two free parameters, the climate sensitivity and a response time (τ). By minimizing the root-mean-square difference between the PCM 'observed' and DK 'model' values we obtain S = 0.166°C/Wm^{-2} and τ = 8.3 months for PCM. This best-fit result is shown in Figure 1. (Note that PCM's peak cooling is slightly less than the best estimates of the observed peak cooling.) It is clear that, while the DK method can provide a reasonable fit to the data, it is unable to recover the known value of S for PCM, underestimating the true sensitivity by a factor of almost three. Given this gross failure, DK's method is unlikely to be able to estimate a reliable sensitivity value from real-world observational data.

[6] The reason for this failure lies in the over-simplified one-box climate model that is used by DK. To see this, we write this simple type of climate model equation in its conventional form [see, e.g., *Raper et al.*, 2001]:

$$C\, d\Delta T/dt + \Delta T/S = \Delta Q - \Delta F$$

where C is the heat capacity and ΔF is the change in the flux of heat at the base of the mixed layer. DK ignore the heat flux term, effectively absorbing ΔF into the heat capacity term. This is not a legitimate simplification, since ΔF is not, in general, proportional to $d\Delta T/dt$.

[7] At the time when the cooling after Pinatubo reaches its maximum (when $d\Delta T/dt = 0$) the first term in the above equation is zero; so we have

$$S = \Delta T/(\Delta Q - \Delta F).$$

If ΔF is ignored, S = $\Delta T/\Delta Q$. Using the smoothed value for the observed maximum cooling (0.5°C) and the estimated forcing at the time of maximum cooling from DK's Figure 2 ($0.14 \times 18.5 = 2.6 Wm^2$) gives S = $-0.5/-2.6$ = 0.19°C/Wm^{-2}, quite similar to the DK result.

[8] Now let us use the more correct expression that accounts for changes in the heat flux at the base of the mixed layer. Unfortunately, the observed value of ΔF at the time of maximum cooling is not known. It cannot be

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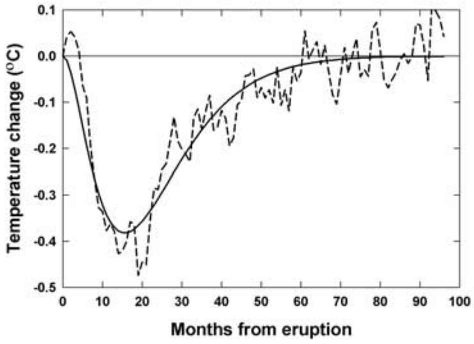

Figure 1. Simulation of the surface temperature response to the Mt. Pinatubo eruption from PCM (average of 16 realizations, dashed line) compared with an empirical fit using the DK method. Although the fit is good, the implied sensitivity and response time values are unrealistic.

determined from available ocean temperature observations, such as those of *Levitus et al.* [2005], because of insufficient temporal resolution in these data and spatial sampling inadequacies [*AchutaRao et al.*, 2005]. A reasonable estimate for ΔF is around -2Wm^{-2}, consistent with values obtained from AOGCM simulations that successfully simulate observed changes on longer (decadal) time scales [*Barnett et al.*, 2005]. Note that $d\Delta T/dt$ is zero at this time, so assuming that the heat flux term can be absorbed into the heat capacity term is clearly wrong. For $\Delta F = -2\text{Wm}^{-2}$, the implied value for S is approximately $0.5/(2.6 - 2) = 0.83°\text{C/Wm}^{-2}$, in accord with conventional estimates based on volcanic eruptions such as *Soden et al.* [2002] and *Robock* [2003], and with the results of *Wigley et al.* [2005].

[9] The above sensitivity estimate is subject to considerable uncertainty through uncertainties in all three terms, ΔT, ΔQ and ΔF. Nevertheless, the neglect of ΔF makes a radical difference and must lead, as it does in DK's analysis and in our parallel analysis of the PCM results using their flawed method, to a considerable underestimate of the climate sensitivity.

[10] DK suggest that other analyses produce incorrect results because these analyses have assumed "that the intrinsic response time is much greater than the volcano event time" (the latter being 7.6 months in DK's analysis). This is incorrect. The climate system's characteristic time scale is not an assumed quantity in any realistic model, from the simplest (with a one-dimensional diffusive or upwelling-diffusive ocean) to the most complex (AOGCMs). This time scale is a quantity that is generated by the internal physics of the models. In fact, there is no single characteristic time scale for the climate system [see, e.g., *Wigley and Schlesinger*, 1985; *Harvey*, 2000]: using a single time scale is part of the reason why the simple one-box model of the climate system used by DK is inadequate.

[11] In conclusion, neither the physics nor the results in the DK paper are correct. In a test case where we know the answer, their method underestimates the climate sensitivity by a factor of three. Their unconventional result that the climate sensitivity is very low is simply an artifact of their use of an over-simplified model to fit the observed cooling from Pinatubo. Other flaws in their analysis have been noted by *Robock* [2005].

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