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 a confusing and erroneous description of climate feedbacks and the climate response to the 1991 Mt. Pinatubo eruption. Their conclusions of a negative climate feedback and small climate sensitivity to volcanic forcing are not supported by their arguments or the observational evidence. As pointed out by *Wigley et al.* [2005a], this is the consequence of assuming a one-box representation for the climate system, and ignoring energy exchange with the deep ocean.

[2] In the description of their analysis, DK make a fundamental mistake in describing the problem. They claim to use "standard linear response theory," but they confuse the response with the forcing. They say, "The *LW* [longwave] effect is by definition the forcing function ΔF for the climate, represented by the measured surface temperature anomaly ΔT." *LW* radiation changes, however, are produced by both the presence of a forcing agent, in this case stratospheric aerosols, and the response of the climate system. It is the instantaneous net radiation change with no response that is the forcing. The temperature anomaly is the response to forcing, and not the forcing itself, and the *LW* changes reflect both the true forcing and the effects of the temperature response.

[3] In spite of their statement to the contrary, DK apparently do use the correct forcing, as characterized by their equation (5) and illustrated in their Figure 2. Confusion arises because the forcing they use is a scaled version of the estimated aerosol optical depth changes, which represents the true forcing, yet they continually refer to the scaled optical depth as the *LW* changes. That the two items are different is clear from DK's Figure 1.

[4] The forcing of climate change can be defined as the change in the net radiation at the top of the atmosphere, the tropopause, or the surface, without any response of the climate system, or allowing for the stratosphere to equilibrate. *Stenchikov and Robock* [1995], *Houghton et al.* [1996], and *Hansen et al.* [2005] discuss the standard definitions of radiative forcing and considerations for forcing from aerosols, which are not uniformly mixed in the atmosphere. For our purposes, it is sufficient to consider the forcing at the top of the atmosphere, allowing for no equilibration [*Stenchikov and Robock*, 1995; *Stenchikov et al.*, 1998]. This forcing can be defined as:

$$\Delta Q(t) = \Delta SW(t) + \Delta LW(t) \tag{1}$$

where $\Delta Q(t)$ is the radiative forcing, $\Delta SW(t)$ is the change in net downward shortwave radiation and $\Delta LW(t)$ is the change in net downward longwave radiation. *Minnis et al.* [1993] provide observations of changes in *SW* and *LW* separately after the 1991 Mt. Pinatubo eruption, but, of course, these observations combine the effects of forcing and response. Nevertheless, the *SW* changes are the largest, by an order of magnitude, and dominate the forcing. One cannot do a correct analysis if *SW* changes are ignored.

[5] Consider a global-average, time-dependent, anomaly energy-balance climate model:

$$C\frac{d\Delta T(t)}{dt} + \frac{\Delta T(t)}{\lambda} = \Delta Q(t) \tag{2}$$

where C is the heat capacity, $\Delta T(t)$ is the change in global temperature, λ is the climate sensitivity ($\lambda = \frac{dT}{dQ}$), and $\Delta Q(t)$ is the externally applied radiative perturbation. (Much of the climate literature uses λ^{-1} or S as the climate sensitivity, but here the same nomenclature as DK is used to avoid confusion.) For a step-function forcing, at steady state the first term in (2) goes to zero and the final temperature change is:

$$\Delta T = \lambda \Delta Q \tag{3}$$

If ΔQ is due to a doubling of CO_2, then ΔT is called ΔT_{2x}. It is now conventional to characterize λ in units of ΔT_{2x}. The e-folding time scale of climate response is τ ($\tau = C\lambda$). The amplitude of the climate response and the time it takes to respond to an episodic forcing are both dependent on ΔT_{2x}.

[6] The value of λ proposed by DK, 0.15 K/(W m^{-2}), corresponds to an unrealistic value of ΔT_{2x} of 0.6 K. There is no evidence in the record of past climate change or in climate model simulations that the climate sensitivity could be so low.

[7] *Soden et al.* [2002] conducted general circulation model (GCM) simulations with the Geophysical Fluid Dynamics Laboratory Manabe climate model, forced by the observed distribution of Pinatubo aerosols. When run with prescribed clouds, their climate model, which has a $\Delta T_{2x} \approx 3.0$ K, accurately reproduced not only the observed surface air temperature, but also the observed upper tropospheric humidity changes (consistent with a positive water vapor feedback), and the observed top of atmosphere

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changes in both *SW* and *LW*. To investigate feedbacks further, Soden et al. used two different versions of the model with explicitly modified sensitivity: the standard configuration, and a configuration with no water vapor feedback. Both GCMs had the same mixed-layer ocean heat capacity and were driven with the same forcing. The integrated cooling in the "no water vapor feedback" configuration was only 60% of that from the model with water vapor feedback. This is consistent with what one would expect for a gain factor of 0.4 from water vapor feedback (which is the expected value under the assumption of constant relative humidity), i.e.,

$$\lambda(\text{with water vapor}) = \lambda(\text{no water vapor})\ (1 - 0.4). \quad (4)$$

Because they were able to observe each component of the feedback process, including the reduction of upper tropospheric water vapor with the Pinatubo-induced global cooling (a positive water vapor feedback), the Soden et al. study correctly showed how the Pinatubo eruption can be used to diagnose the sensitivity of the climate system and demonstrated that the sensitivity was in the conventional range.

[8] *Wigley et al.* [2005b], using a very different approach, obtained the same result as *Soden et al.* [2002]. They clearly showed that for episodic forcing, the transient temperature response of the climate system depends on C and ΔT_{2x}, as characterized by both the maximum temperature change ($\Delta T_{\max}$) and the time scale of the response. (The response time in the Wigley et al. study is that for relaxation back to an equilibrium state, a time scale specific to volcanic forcing. It is called τ_V here, with the V used to indicate that it is specific to the volcanic forcing case. This time scale is not the same as the time scale that DK attempt to calculate, although they appear to think that it is.) Wigley et al. assigned to their MAGICC energy balance, upwelling diffusion climate model the same sensitivity as the National Center for Atmospheric Research PCM coupled ocean-atmosphere GCM. They found that, with this sensitivity, the MAGICC volcano results accurately matched the GCM, giving both the correct time scale and amplitude of climate response to volcanic eruptions, confirming that MAGICC can be used to measure the sensitivity of the climate system.

[9] *Wigley et al.* [2005b] then compared the results of MAGICC simulations with different sensitivities to the observed climate response after different eruptions. They found that $\Delta T_{\max} \propto (\Delta T_{2x})^{0.20}$ and τ_V [months] = 30 $(\Delta T_{2x})^{0.23}$. This is in contrast to the results of *Lindzen and Giannitsis* [1998], whose climate model results are inconsistent with GCM results. *Lindzen and Giannitsis* had found that $\Delta T_{\max} \propto (\Delta T_{2x})^{0.37}$ and $\tau_V = 57\ (\Delta T_{2x})^{0.41}$ and they erroneously implied from this that ΔT_{2x} was quite low. By analyzing the observed temperature changes in response to the 1963 Agung eruption and the 1991 Pinatubo eruption, and fitting the response to their MAGICC model, Wigley et al. found that ΔT_{2x} = 2.8 K for the 1963 Agung eruption and ΔT_{2x} = 3.0 K for Pinatubo, and that τ_V = 38 months for both cases.

[10] As shown by the above two climate model analyses, in which the time delay and inertia of the ocean are explicitly accounted for in the model physics, we expect the climate system to have a ΔT_{2x} of about 3.0 K and for the peak cooling response after Pinatubo to be about 30% of the equilibrium response. The sensitivity calculated by DK, λ = 0.15 K/(W m^{-2}), corresponding to ΔT_{2x} of 0.6 K, means that if we use the observed maximum forcing of about -3.0 W m^{-2} [-0.165 (DK, Figure 2) times A (-18.5 W m^{-2}/K, the mean of the DK values, -16 to -21 W m^{-2}/K)], the actual $\Delta T_{\max}$ of -0.45 K (DK, Figure 3) is exactly equal to the equilibrium climate response we can expect (λ x forcing) if the forcing were maintained. This is clearly wrong. Their failure to properly account for the entire climate system has led them to derive a climate sensitivity and response time that are much too small.

[11] To summarize, if the analysis is done correctly, the 1991 Mt. Pinatubo eruption serves as a valid test of the response of the climate system to external forcing [*Robock*, 2003]. As also discussed by *Kerr* [2004], this test provides additional evidence that the sensitivity of the climate system to doubling CO_2 (ΔT_{2x}) is about 3 K and that the water vapor greenhouse feedback is positive and can be observed.

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