Climate forcing by the volcanic eruption of Mount Pinatubo

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[1] We determine the volcano climate sensitivity λ and response time τ for the Mount Pinatubo eruption, using observational measurements of the temperature anomalies of the lower troposphere, measurements of the long wave outgoing radiation, and the aerosol optical density. Using standard linear response theory we find $\lambda = 0.15 \pm 0.06$ K/(W/m^2), which implies a negative feedback of -1.4 (+0.7, -1.6). The intrinsic response time is $\tau = 6.8 \pm 1.5$ months. Both results are contrary to a paradigm that involves long response times and positive feedback. **Citation:** Douglass, D. H., and R. S. Knox (2005), Climate forcing by the volcanic eruption of Mount Pinatubo, *Geophys. Res. Lett.*, *32*, L05710, doi:10.1029/2004GL022119.

1. Introduction

[2] A primary objective of climatology is to determine how the various forcings affect the climate of Earth. The essential elements of the climate scenario are:

[3] 1) A forcing ΔF [solar, CO_2, CH_4, ENSO, volcanoes, etc.] disturbs the climate system;

[4] 2) The temperature T of the earth changes by ΔT with a response time τ;

[5] 3) The magnitude of the response is determined by a sensitivity λ;

[6] 4) The forcing ΔF may involve feedback, resulting in a gain g which is a factor in λ.

[7] The Pinatubo volcano climate event (June 15, 1991) dominated all other forcings during its occurrence. As *Hansen et al.* [1992] said: this dramatic climate event had the potential to "...[exceed] the accumulated forcing due to all anthropogenic greenhouse gases added to the atmosphere since the industrial revolution began"... and should "provide an acid test for global climate models." Earth's temperature decreased by 0.5 C and the long wave flux decreased by 2.5 W/m^2. We present a new analysis based upon observational data alone that yields the values of the climate parameter $\lambda = 0.15 \pm 0.06$ K/(W/m^2), which implies negative feedback of -1.2 (+0.7, -1.9), and an intrinsic response time $\tau = 6.8 \pm 1.5$ months. These values are quite different from those that have been assumed or found by previous investigators, many of whom we believe assumed, either explicitly or implicitly, that climate relaxation times are long compared to the relevant volcano time scales. Our results confirm suggestions of *Lindzen and Giannitsis* [1998, 2002] that a low sensitivity and small lifetime are more appropriate.

[8] The forcing $\Delta F(t)$ is defined in terms of an equivalent change in net irradiance (in W/m^2) referred to the top of the atmosphere [*Shine et al.*, 1995]. This forcing causes a change in the mean temperature. It is assumed that this formalism applies to $\Delta F(t)$ and $\Delta T(t)$ as global averages. Climate models seek to predict a sensitivity parameter λ that connects these quantities,

$$\Delta T(t) = \lambda \Delta F(t), \tag{1}$$

for very slow variations in forcing ("steady state"). When the system is not in steady state a response time τ introduces a delay between $\Delta F(t)$ and $\Delta T(t)$. Energy balance models incorporating such a response time have been used for many years [e.g., *North et al.*, 1981], with the dynamics expressed in the form

$$\tau \frac{d\Delta T}{dt} + \Delta T = \lambda \Delta F. \tag{2}$$

Douglass et al. [2004a, 2004b] have shown the connection of equation (2) to a two-level atmosphere model in the case of solar forcing and in the presence of explicit (but unspecified) feedback. In the following analysis, we make no assumption about τ. Its value is determined by the data.

2. Data

[9] We consider three data sets that clearly show this influence.

2.1. Aerosol Optical Density (AOD)

[10] This index is the generally accepted proxy for volcano climate forcing. *Hansen et al.* [2002] have shown that

$$\Delta F = A \cdot \text{AOD}, \tag{3}$$

where $A = -21$ W/m^2. The most recent determination of AOD is by *Ammann et al.* [2003].

2.2. Temperature Anomalies

[11] We use the global monthly satellite MSU lower troposphere temperature (TLT) anomaly data [*Christy et al.*, 2000] that begins in 1979 (updates are available at http://vortex.nsstc.uah.edu/data/msu/t2lt/). *Douglass and Clader* [2002] and *Douglass et al.* [2004c] used TLT to determine the solar sensitivity in a multiple regression analysis using solar irradiance, El Niño, and AOD as predictor variables, finding

$$\Delta(\text{TLT}) = k \cdot \Delta(\text{AOD}), \tag{4}$$

with $k = -2.9 \pm 0.2$ K and a delay of 3 months. In addition a modified TLT data set was produced with El Niño and solar effects removed, designated as TLTm. Our analysis is based

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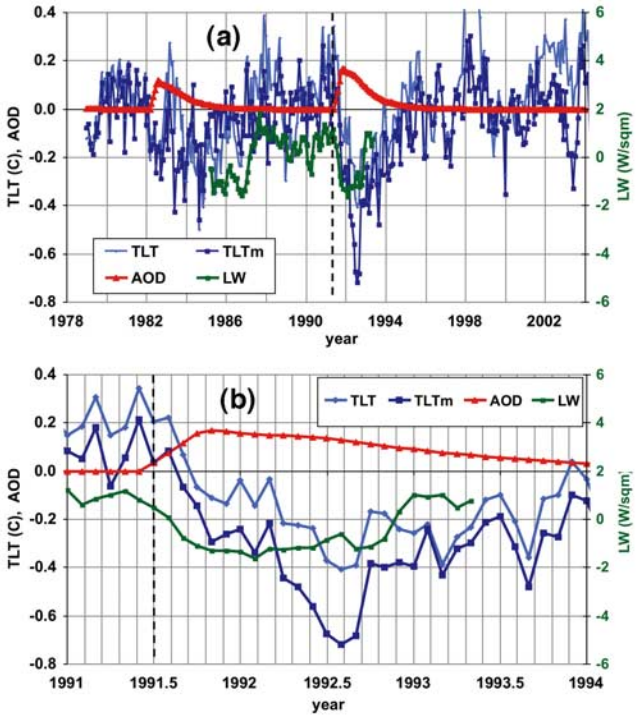

Figure 1. Data sets for temperature (TLT), modified temperature (TLTm), aerosol optical density (AOD), and outgoing long wave radiation (LW). The modified data set has the El Niño and solar signals removed (see text). (a) Complete sets and (b) expanded view showing the subsets used in the Pinatubo analysis.

on TLTm with comparisons to analysis based on TLT. Both produce essentially the same results.

2.3. Long Wave Radiation (LW)

[12] The outgoing long wave radiation data are from *Minnis* [1994] (tabular data from P. Minnis, personal communication, 2002). The LW fluxes were determined in the Earth Radiation Budget Experiment and are referenced to 1985–89 monthly means. The measurements are confined to latitudes between 40°N and 40°S, comprising 77% of Earth's surface. We assume that the radiation outside of this band will not seriously change the average flux values reported.

[13] Figure 1a shows TLT, TLTm, LW and AOD for the period 1979 to 2003. The LW data cover only 1985 through May 1993, the duration of those measurements. Figure 1b is an expanded plot for the period of the Pinatubo volcanic event.

3. Analysis

[14] Pinatubo produced aerosols that reflected solar radiation, causing a general change in the energy balance. These events are quantified in the aerosol optical density (AOD) and longwave emission (LW) data sets, respectively. The LW effect is by definition the forcing function ΔF for the climate, represented by the measured surface temperature anomaly ΔT (TLT). Since ΔT clearly lags ΔF, it is reasonable to apply the linear response theory represented by equation (2). We use the AOD time dependence to obtain a solution of this equation, assuming with Hansen that ΔF is proportional to AOD, $\Delta F = -Aq(t)$, where $q(t)$ is a function that very closely fits the AOD data,

$$q(t) = 0.439(t/t_V)\exp(-t/t_V). \qquad (5)$$

The time t is in years measured from 1991.42 and t_V is the time that AOD reaches its maximum, in our case 0.63 yr = 7.6 mo. Below we use the LW data set to establish the factor A. The function $q(t)$ is compared with AOD [*Ammann et al.*, 2003] in Figure 2.

[15] The exact analytic solution of equation (2) with the above forcing is

$$\Delta T(t) = -0.439\lambda A \cdot \frac{t_V\tau}{(\tau - t_V)^2} \cdot \left\{ \exp(-t/\tau) - \left[\left(\frac{1}{t_V} - \frac{1}{\tau} \right) t + 1 \right] \exp(-t/t_V) \right\}, \qquad (6)$$

where λA and τ are to determined by fitting to the ΔT data set TLTm. By least-squares analysis we obtain a best fit with $\tau = 0.47$ yr and $\lambda A = 3.72$. The fit is shown in Figure 3. A few points near $t = 0$ and many at $t > 6t_V$ lie far outside the predicted value. When we omit these points we find no change in the values of λA and τ. Making the same fit to TLT, we find $\tau = 0.50$ yr and $\lambda A = 1.97$. The close agreement of the relaxation times provides a measure of the accuracy of our dynamical fit.

[16] We have also found the solution of equation (2) numerically from the AOD data set itself. In the critical region of 0–3 years, the two methods agree with each other closely, having an rms difference of 1.2% of the peak value.

[17] We now determine λ and A separately. The three data sets are analyzed by the delayed correlation method described by *Douglass et al.* [2004a, 2004b]. We demonstrate the method using the TLT and LW data sets:

[18] (1) LW changes from a background level to a large value and returns. (2) TLT does the same but is delayed by a

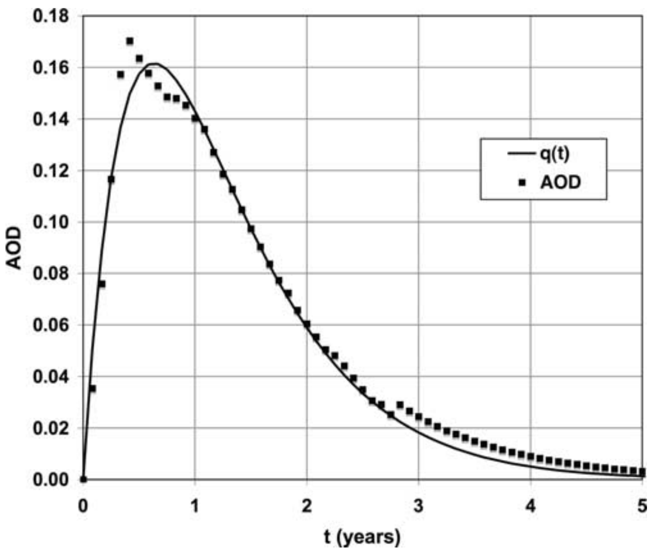

Figure 2. Volcano AOD function (detail from Figure 1) and the analytic fit $q(t)$ (text, equation (5)).

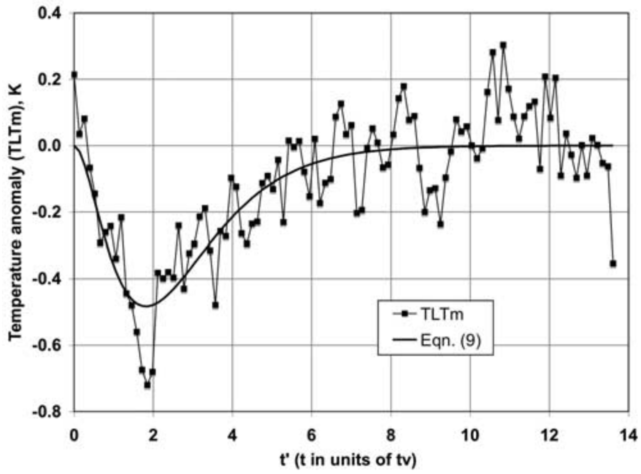

Figure 3. Fit of the analytic solution $\Delta T(t)$, equation (6), to the temperature data set TLTm.

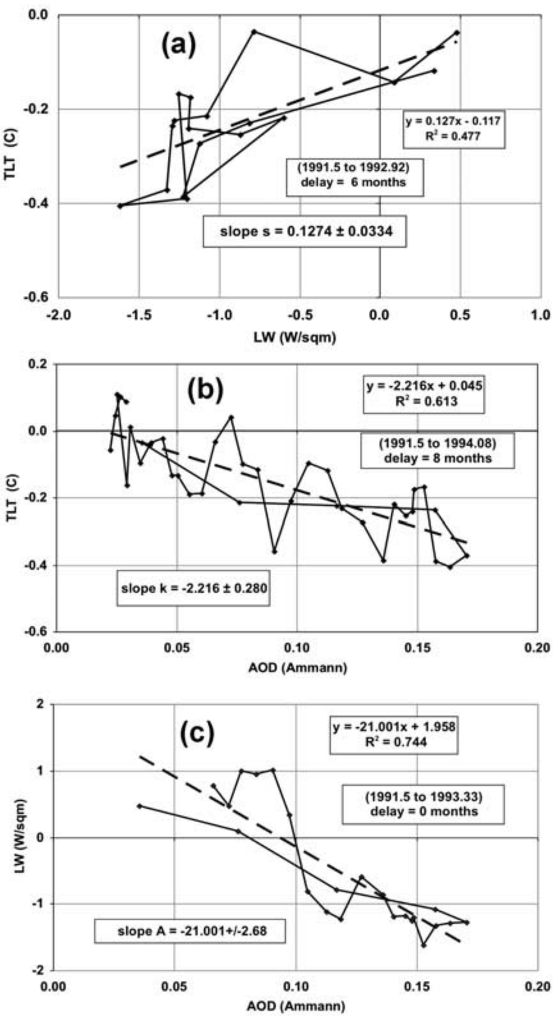

Figure 4. Lissajous patterns used to evaluate delays and amplitudes. (a) TLT and LW, (b) TLT and AOD, and (c) LW and AOD.

time t_d. (3) A plot of TLT against LW is a "Lissajous loop" whose area is roughly proportional to the time delay. This area would be exactly proportional in the case of sinusoidal functions. For the volcano forcing and response, the peaks are of different half-widths and there is only a "quarter cycle" of a sinusoid. As a result only the values near the peaks contribute to a loop.

[19] (4) By varying the time lag of one of the variables, LW, one can find the time lag that minimizes the area of the loop. This value of lag determines t_d and, importantly for us, the proportionality constant s between TLT and LW. Figure 4a shows TLT *vs.* LW, Figure 4b shows TLT *vs.* AOD, and Figure 4c shows LW *vs.* AOD. The resulting relationships are written

$$\Delta(\mathrm{TLT}) = s \cdot \Delta(\mathrm{LW}), \tag{7}$$

$$\Delta(\mathrm{TLT}) = k \cdot \Delta(\mathrm{AOD}), \tag{8}$$

$$\Delta(\mathrm{LW}) = A \cdot \Delta(\mathrm{AOD}). \tag{9}$$

The values of s, k, and A and the associated delays are listed in Table 1. No delay between LW and AOD is observed, as expected. The delays between TLT/TLTm and LW or AOD are expected to be the same. There are four different estimates, whose average and standard deviation are t_d = 6.8 ± 1.5 months.

[20] Equations (7), (8), and (9) imply that $A = s/k$, which we call an indirect value of A, written A_{ind}. From the slopes of Table 1, we find that A_{ind} has the value −16.2 and −17.5, in appropriate units, when evaluated from TLTm and TLT, respectively. When these results are combined with the two different values of λA determined above, there are four comparable values of the climate sensitivity to consider, as shown in Table 2. The consolidated result is

$$\lambda = (\lambda A)_{\mathrm{data\ fit}}/A_{\mathrm{regression}} = 0.15 \pm 0.06\ ^{\circ}\mathrm{C}/\left(\mathrm{W/m^2}\right). \tag{10}$$

The standard deviation is a measure of the systematic error.

4. Results and Discussion

4.1. Gain and Feedback

[21] The conventional value of sensitivity for global average quantities with radiative forcing and no feedback is the Stefan-Boltzmann value λ_{SB} = 0.30 K/(W/m^2) [*Kiehl*,

Table 1. Values of s, k, A: The Coefficients of the Lissajous Linear Regressions Described in the Text[a]

Coefficient	Value	Delay (mo.)	τ (mo.)
s from TLT *vs* LW	0.127 ± 0.033 K/(W/m^2)	6	5.5
s from TLTm *vs* LW	0.182 ± 0.0486 K/(W/m^2)	6	5.5
k from TLT *vs* AOD	−2.216 ± 0.298 K	8	8.4
k from TLTm *vs* AOD	−2.948 ± 0.42 K	7	7.6
A from LW *vs* AOD	−21.0 ± 2.7 W/m^2	0	0

[a]"Delay" is the time from forcing peak to response peak. The last column is the relaxation time as estimated by the loop-minimization method; the average and standard deviation (first four values) are τ = 6.8 ± 1.5 months.

Table 2. Values of the Climate Sensitivity Determined From a Range of Statistical Methods, as Discussed in the Text[a]

ΔT Data	$(\lambda A)_{FIT}/A_{regression}$ With Direct Value of A	$(\lambda A)_{FIT}/A_{regression}$ With Indirect Value of A
TLTm	$\lambda = (-3.72)/(-21.0)$ = **0.18**	$\lambda = (-3.72)/(-16.2)$ = **0.23**
TLT	$\lambda = (-1.97)/(-21.0)$ = **0.094**	$\lambda = (-1.97)/(-17.5)$ = **0.11**

[a]The mean and standard deviation of the four numbers: $\lambda = 0.15 \pm 0.06$ K/((W/m^2). These units apply to all four cases in the table.

1992, p. 324]. One of us has shown [*Knox*, 2004] that the surface-to-atmosphere non-radiative flux makes a correction to the Stefan-Boltzmann sensitivity, $\lambda_0 = \lambda_{SB}/(1-\gamma)$, where γ is proportional to the non-radiative flux and has a typical value 0.16. The correction is not a feedback effect, so λ_0 is still properly described as the no-feedback sensitivity, and its value is 20% higher than λ_{SB}, or 0.36 K/(W/m^2).

[22] The gain and feedback of the climate system can now be estimated, using $\lambda = g\lambda_0$ and $g = 1/(1-f)$. We have

$$g = \lambda/\lambda_0 = (0.15 \pm 0.06)/0.36 = 0.42 \pm 0.17. \qquad (11)$$

Associated with this gain is a negative feedback, $f = -1.4$ (+0.7, -1.6). If the gain and feedback are evaluated without the non-radiative correction, a similar result is obtained, $g = 0.50 \pm 0.20$, with the feedback again always negative.

4.2. Aerosol Forcing

[23] We determined A to be in the range -16 to -21. The closeness to the *Hansen et al.* [2002] value of -21 supports their calculation of this coefficient.

4.3. Mechanisms

[24] This work raises the question of the origin of a response time as short as several months. This is just the characteristic time it takes for atmospheric disturbance to propagate over the earth. We conclude that the climate event that begins in the atmosphere remains in the atmosphere and that there is negligible coupling to the deep ocean. In addition, we conclude that there is no "climate left in the pipeline," as discussed below.

[25] Since our analysis yields a gain less than unity, a second issue raised is the origin of the required negative feedback. Negative feedback processes have been proposed involving cirrus clouds [*Lindzen*, 2001], and *Sassen* [1992] reports that cirrus clouds were produced during the Mt. Pinatubo event. The Lindzen et al. process involving clouds yields a negative feedback factor of $f = -1.1$, which is well within the error estimate of the feedback found by us.

[26] Why has no one come to these conclusions before? From the observations, with no analysis at all, one can estimate $\Delta T/\Delta LW \sim (-0.5)/(-2.5) = 0.2 \sim \lambda$ and one also sees that the peak of ΔT occurred about 7 months after the peak in AOD. This is surprisingly close to the values that our detailed analysis yields. We suggest that this solution was rejected because of a widely held belief in a paradigm that assumes that the intrinsic response time is much greater than the volcano event time, mathematically, that $\tau \gg t_V$. This paradigm also includes/induces a belief that positive feedback processes are present. How can the observation be explained within this paradigm? In the limit $\tau \gg t_V$ one sees that equation (6) becomes

$$\Delta T(t) \xrightarrow[\tau \gg t_V]{} -0.439\lambda A \cdot \frac{t_V}{\tau} \cdot \left\{\exp(-t/\tau) - \left(1 - \frac{t}{\tau}\right)\exp(-t/t_V)\right\}. \qquad (12)$$

The first exponential term dominates when $t > t_V$, so the tail of the response drops very slowly, with a characteristic time τ, if τ is large. This "memory effect" has often been called a volcano effect in the pipeline. This is *not* supported by the Pinatubo data. Also, the factor t_V/τ acts as a dynamical factor and reduces the peak value. The above "back of the envelope" calculation now becomes $\Delta T/\Delta LW \sim (-0.5)/(-2.5) = 0.2 \sim \lambda(t_V/\tau)$. The final factor is there because in this calculation "ΔLW" refers to the peak amplitude, which now contains an effective, smaller λA as seen in equation (12). So if one were to believe that $\tau \sim 3$ to 10 t_V, one would estimate $\lambda \sim 0.5$ to 2 and infer $g > 1$ and positive feedback. Thus one "explains" the observations within the paradigm, but on the basis of a solution of the equations that does not take account of the forcing shape. Note that the proportionality between λ and τ implied by equation (12) is guaranteed only in the limit $\tau \gg t_V$. It is not a feature of the exact solution, equation (6).

[27] In summary, we have shown that Hansen's hope that the dramatic Pinatubo climate event would provide an "acid test" of climate models has been fulfilled, although with an unexpected result. The effect of the volcano is to reveal a short atmospheric response time, of the order of several months, leaving no volcano effect in the pipeline, and a negative feedback to its forcing.

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