

# Constraining Possibilities Versus Signal Detection

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## ABSTRACT

Rather than concentrate on the problem of greenhouse signal *detection*, one can exploit the intimate relation of climate sensitivity to length of ocean delay in order to *constrain* possibilities. It is noted that the observed record of surface temperature is “broadly” consistent with equilibrium sensitivity to CO<sub>2</sub> doubling of between 0°C and 4.8°C—provided that the ocean delay for the higher sensitivity is of the order of 160 years. If ocean delay can be independently established as being shorter, then one must reduce the maximum consistent sensitivity. It is suggested that volcanic responses can be used to estimate ocean delay. Preliminary results suggest very short delays.

## REMARKS

As noted in the papers in this section by North and Kim (1995) and by Wigley and Raper (1995), simple box-diffusion-upwelling models yield useful insights into the issues of the seasonal and long-term delay in climate response to changes in geophysical forcing quantities that results from the ocean’s heat capacity. The point, quite simply, is that the more rapidly heat is mixed downward into the ocean, the greater the ocean’s effective heat capacity and the longer the delay. Also evident is the fact that the delay itself is time dependent and is different for each transient problem and for the annual cycle.

The geometry of simple energy-balance box-diffusion-upwelling models is shown in Figure 1. No attempt will be made here to repeat the mathematical development of

such a model. However, certain points are worth noting. The equilibrium response to forcing,  $\Delta S$ , is  $\Delta T_{\text{eqbm}} = \Delta S/a$ . Also, the intensity of the coupling of the atmospheric climate system to the ocean is given by  $a$ . As noted by Hansen et al. (1985), the larger  $\Delta T_{\text{eqbm}}$  is for a given  $\Delta S$ , the smaller  $a$  must be, and with the weaker coupling, the ocean delay will be longer.

Reasonable parameter choices are  $h = 75$  m,  $k = 1.5$  cm<sup>2</sup> sec<sup>-1</sup>, and upwelling, which limits downward diffusion to about  $H = 400$  m. A common choice for  $a$  is 1.55 W m<sup>-2</sup> deg<sup>-1</sup> (viz., Sellers, 1969; North and Kim use a somewhat different value, but for our purposes the small differences are not of consequence). Other values involve negative or positive feedbacks in the atmospheric climate system. If we refer to the original choice of  $a$  as  $a_0$ , then

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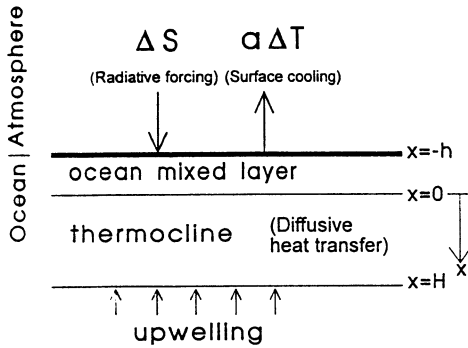


FIGURE 1 Schematic of the geometry of the box-diffusion-upwelling model used in these remarks.

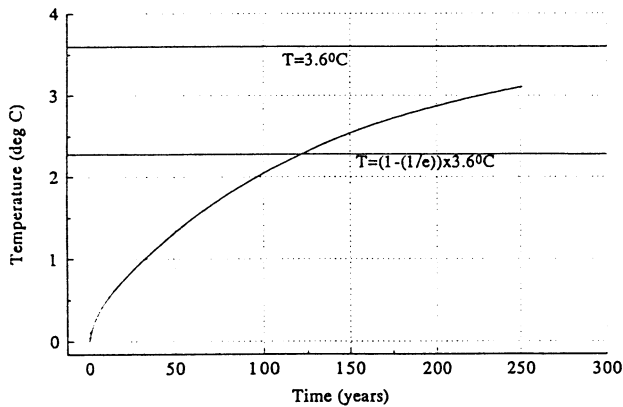


FIGURE 2 Temperature versus time for the impulsive doubling of CO<sub>2</sub> at  $t = 0$  in a model with  $\Delta T_{2 \times \text{CO}_2} = 3.6^\circ\text{C}$ .

$a = a/g$ , where  $g =$  system gain, and the relation between  $g$  and total feedback,  $f$ , is  $g = 1/(1 - f)$ . Negative  $f$ 's lead to  $g < 1$ , while  $f > 1$  implies an unstable system. If we associate a doubling of CO<sub>2</sub> with a  $\Delta S$  (at the surface as opposed to the "top of the atmosphere") of  $1.8 \text{ W m}^{-2}$ , then, in the absence of feedbacks,  $\Delta T = 1.2^\circ\text{C}$ . Models that yield  $\Delta T_{2 \times \text{CO}_2} = 4^\circ\text{C}$  involve a gain of 3.3 (or  $f = 0.7$ ). An idea of the nature of ocean delay can be seen in Figure 2, where we consider the transient response to an impulsive doubling of CO<sub>2</sub> in a system where  $\Delta T = 3.6^\circ\text{C}$ . Clearly, the approach to equilibrium is not simply exponential. However, for simplicity of discussion, we will identify a response with a time scale  $\tau$ , corresponding to the time it takes  $\Delta T$  to reach to within  $(1 - 1/e)$  of its equilibrium value when the system is impulsively forced. Figure 3 shows how  $\tau$  varies with  $g$ . Over the range of interest, the dependence is almost linear. (As Hansen et al. (1985) note, the relation becomes quadratic as  $H \rightarrow \infty$ .)

A main point of these remarks is that in dealing with these simple models, it is occasionally useful to consider  $\tau$  rather than  $g$ , and  $\Delta T_{2 \times \text{CO}_2}$  rather than  $\Delta S_{2 \times \text{CO}_2}$  as variables to focus on. Doing so will suggest constraints on both  $\tau$

and  $\Delta T_{2 \times \text{CO}_2}$ , which can be determined from considering responses to both volcanos and increasing greenhouse gases. It must be emphasized that it is just as useful to use data to constrain the likely response to doubled CO<sub>2</sub> as it is to detect the actual response (which might prove small).

Figure 4 shows  $T$  vs.  $t$  for the IPCC "business as usual" (BAU) emissions scenario (which leads to a quadrupling of "effective" CO<sub>2</sub> by 2100; viz., Houghton et al., 1990). The different curves correspond to various choices of equilibrium  $\Delta T_{2 \times \text{CO}_2}$ . We see (consistent with IPCC results) that expectations for current warming range from  $0.15^\circ\text{C}$  for  $\Delta T_{2 \times \text{CO}_2} = 0.24^\circ\text{C}$  to  $0.8^\circ\text{C}$  for  $\Delta T_{2 \times \text{CO}_2} = 4.8^\circ\text{C}$ . The observed warming over the past century of  $0.45^\circ\text{C} \pm 0.15^\circ\text{C}$  (viz., Figure 5) corresponds to about  $\Delta T_{2 \times \text{CO}_2} = 1.2^\circ\text{C}$ ,<sup>2</sup> but given the natural variability in  $T$ , it is difficult to rule out any of the choices on the basis of the observed global

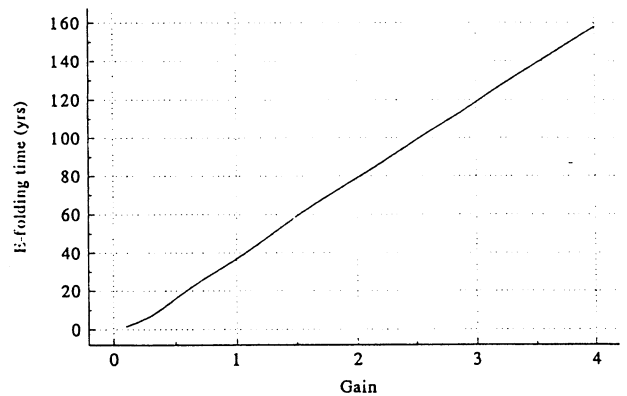


FIGURE 3 Characteristic ocean delay ( $\tau$ ) versus gain ( $g$ ). See text for discussion.

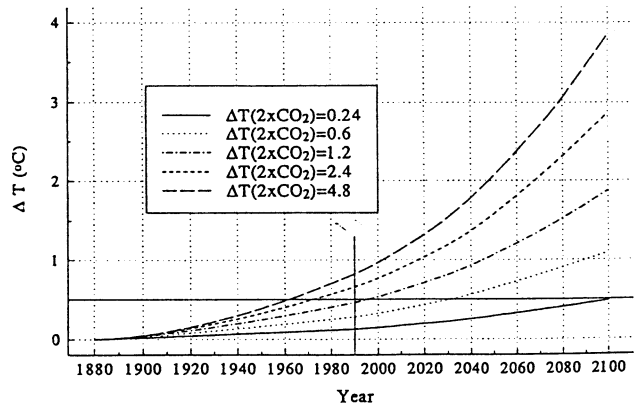


FIGURE 4 Temperature change since 1880 for IPCC "business as usual" emissions scenario and various model sensitivities.

<sup>2</sup>Wigley and Raper consider the impact of sulfate cooling; however, according to recent calculations of Kiehl and Briegleb (1993), this has been reduced to  $0.3 \text{ W m}^{-2}$  and is no longer of such great consequence.

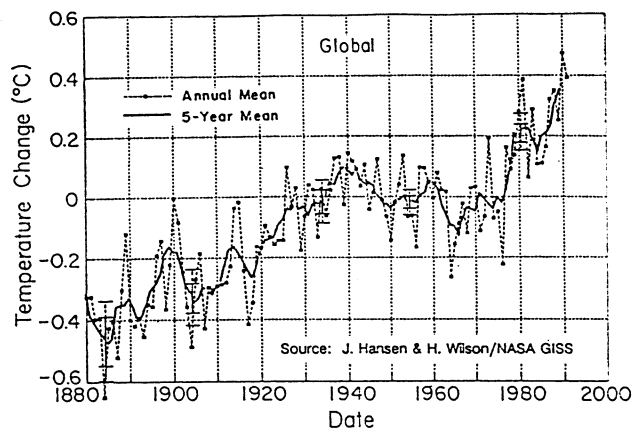


FIGURE 5 Global mean temperature since 1880 (Hansen and Wilson, personal communication).

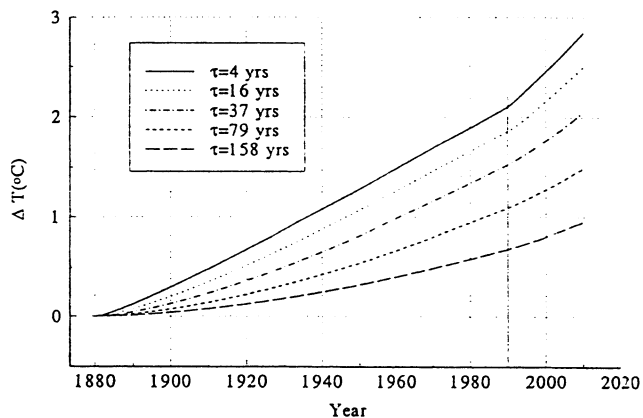


FIGURE 6 Temperature changes since 1880 for IPCC "business as usual" emissions scenario and  $\Delta T_{2 \times \text{CO}_2} = 4^\circ\text{C}$  for various choices of characteristic ocean delay.

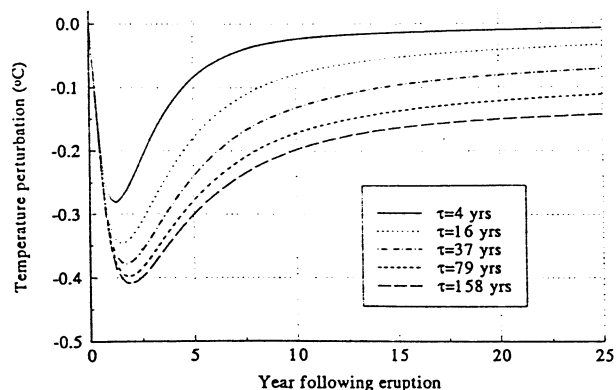


FIGURE 7 Response of global temperature to Krakatoa-type eruption for various choices of characteristic ocean delay.

warming. It is also worth pointing out that none of the choices of  $\Delta T_{2 \times \text{CO}_2}$  leads to more than  $3.5^\circ\text{C}$  of warming by the year 2100—despite the fact that effective  $\text{CO}_2$  is assumed to have quadrupled, and hence for  $\Delta T_{2 \times \text{CO}_2} = 4.8^\circ\text{C}$  the equilibrium warming in 2100 would be  $9.6^\circ\text{C}$ . This dramatically illustrates the importance of ocean delay.

The question we deal with is whether we can do better than the above in constraining expectations. We wish to suggest that the answer may well be yes. Figure 6 shows  $T$  vs.  $t$  for  $\Delta T_{2 \times \text{CO}_2} = 4^\circ\text{C}$  and various choices of  $\tau$  (again using the IPCC BAU scenario). Here we see that for  $\Delta T_{2 \times \text{CO}_2} = 4^\circ\text{C}$  to be compatible with the observed warming,  $\tau$  must be greater than 100 years. The point is that natural variability is unlikely to cancel out more than about  $0.5^\circ\text{C}$  of warming over relatively short periods. There are, indeed, model results that suggest both  $\Delta T_{2 \times \text{CO}_2} = 4^\circ\text{C}$  and short  $\tau$ 's (Manabe et al., 1991), but as we see here, such suggestions are highly problematic.

We finally turn to volcanos. Wigley and Raper (1995) note that atmospheric response to volcanic dust is largely independent of  $\tau$  because of the short time scales involved. These claims are true only for the first year or two after eruption. For longer times, there are significant dependencies. We represent the forcing from a volcano as  $\Delta S = kt$  for  $t \leq 3$  months, and  $\Delta S = S_0 e^{-t/d}$  for  $t > 3$  months, where  $S_0 = k \times 3 \text{ months} = 9.3 \text{ W m}^{-2}$ , and  $d = 13$  months. These values are crudely chosen to correspond to Krakatoa (Oliver, 1976). Figure 7 shows the response to a single eruption for various choices of  $\tau$  (or, equivalently, of gain, using Figure 2). We see that we can expect a cooling of  $0.25\text{--}0.35^\circ\text{C}$  within a year or two of eruption, regardless of climate gain.<sup>3</sup> However, for large  $\tau$  (or system gain) long-term behavior is very different. For short  $\tau$ 's ( $\tau < 16$  years or  $g < 0.5$ ) the cooling maximizes by  $t = 1$  year and decays to relatively undetectable levels within less than 10 years. However, for longer  $\tau$ 's almost half the maximum cooling persists for many years. Also, the maximum cooling seems to occur at  $t = 2$  years rather than 1 year. Neither of these features has been much remarked on. What is going on is that the short-term volcanic cooling is disequilibrating the surface temperature vis-à-vis both the atmosphere and the ocean. For long  $\tau$ 's, the atmospheric coupling is weak and the ocean delay plays a larger role. Detecting such differences for a single volcano is likely to be non-trivial. Figure 8, from Hansen et al. (1992), shows predicted responses to Pinatubo in a general-circulation model with different assumed greenhouse-warming scenarios. The upper panel clearly shows that Pinatubo leaves

<sup>3</sup>Hansen et al. (1992) claimed that the prediction of cooling following the eruption of Pinatubo constituted an "acid test" of their model. They failed to indicate what aspect of their model was being tested. The prediction certainly did not constitute a test of the predictions of climate response to increasing greenhouse gases.

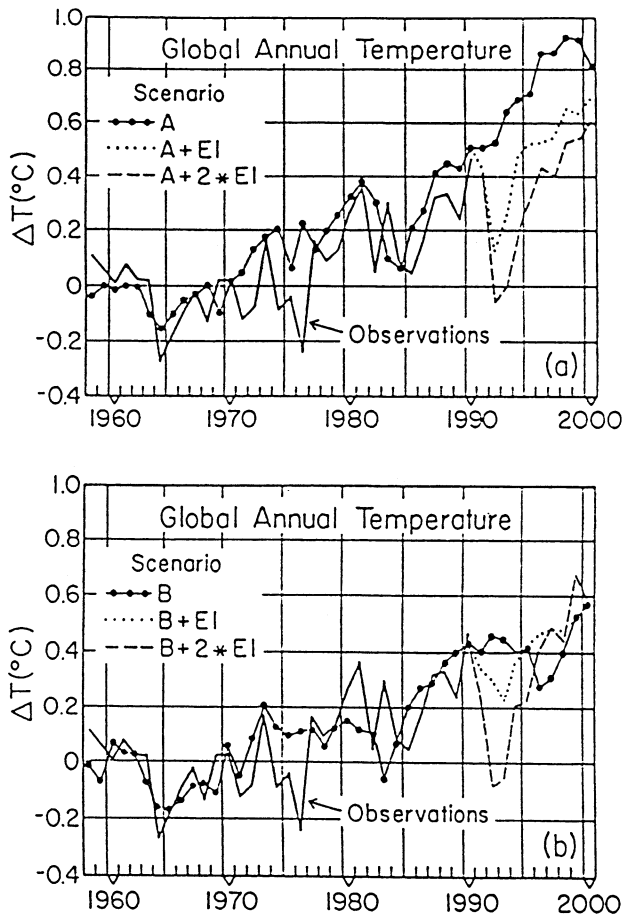


FIGURE 8 Response to Pinatubo for various scenarios calculated by Hansen et al. (1992). See text for details. (From Hansen et al., 1992; reprinted with permission of the American Geophysical Union.)

global temperature cold compared to the expected warming for a long time; however, the lower panel fails to show this persistence in a model where expected greenhouse warming is reduced. A reading of the text of Hansen et al. (1992)

TABLE 1 Ersatz Distribution of Volcanic Eruptions

Year of Eruption	Actual Volcano(s)	Relative Magnitude
1883	Krakatoa	1.000
1885	Falcon Island	0.100
1886	Tarawera, Niafu	0.500
1888	Bandai San, Ritter Island	0.375
1892	Bogoslav (1890), Awu	0.150
1902	Una Una (1898), Mt. Pelée, Soufrière	0.400
1903	Santa Maria, Minami Iwoshima (1904)	0.630
1907	Shtyubelya Sopka	0.150
1912	Taal (1911), Katmai, Sakurashima (1914)	0.185

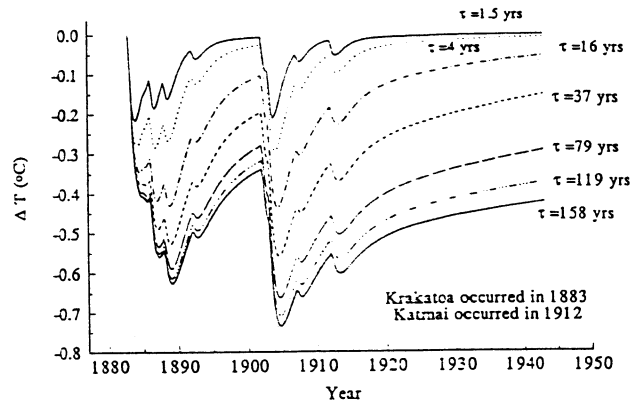


FIGURE 9 Calculated response to all volcanos between Krakatoa and Katmai for various choices of model gain (expressed in terms of characteristic ocean delay).

shows that this scenario also included an additional volcanic eruption in 1995!

There would appear to be some possibility of distinguishing different  $\tau$ 's by considering sequences of volcanos, since larger  $\tau$ 's imply cumulative effects for a sequence of volcanos while smaller  $\tau$ 's imply largely independent responses to each individual volcano within a sequence.

These considerations should be relevant to the period 1883-1912 (Krakatoa to Katmai), when there were a number of major eruptions whose total dust production was about three times that of Krakatoa alone (Oliver, 1976). This period was followed by a relative absence of eruptions until about 1950. We have modeled the volcanism of the period 1883-1912 by an ersatz distribution in which various closely spaced eruptions are combined. This is described in Table 1. Figure 9 shows the response to this distribution of volcanism for various choices of  $\tau$ . Clearly, for larger  $\tau$ 's (greater than 16 years) each eruption adds cooling to the response of successive volcanos, leading to cumulative, long-lasting cooling following the period 1883-1912, while for smaller  $\tau$ 's (less than 16 years) the response has little cumulative character, although the large number of eruptions leaves the temperature depressed for the period 1883-1912.

On the whole, the temperature record shows no evidence of a cumulative effect of volcanism (viz., Figure 5),<sup>4</sup> suggesting that appropriate  $\tau$ 's are less than 16 years, while Figure

<sup>4</sup>Granted, the warming trend seen after 1920 might be an extension of a similar trend that would have occurred during 1883-1912, had it not been for the cooling due to the volcanos. However, there is no evidence of such a trend before 1883. In addition, the warming ceased after 1940. Finally, had the volcanos been masking a strong trend before 1912, the net warming that would have occurred would have been unprecedented and in excess of anything we could account for by greenhouse considerations—especially given the long ocean delay that would pertain to large greenhouse sensitivity.

6 suggests that  $\tau < 100$  years is incompatible with  $\Delta T_{2\times\text{CO}_2} = 4^\circ\text{C}$ .<sup>5</sup> Indeed, reference to Figure 3 suggests that  $\tau < 16$  years corresponds roughly to  $g = 0.5$  and  $\Delta T_{2\times\text{CO}_2} < 0.6^\circ\text{C}$ .

Certainly, these matters require more careful analysis. However, the present remarks suggest that consideration of a variety of known climate-forcing perturbations as probes of the climate system may allow the use of a simple methodology for constraining our expectations for greenhouse warming. For example, if responses to volcanoes imply short

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<sup>5</sup>Conceivably, support for this conclusion might also emerge if the climate response to volcanoes tends to peak at one year rather than two years after eruption (viz., Figure 7).

characteristic ocean delays, then we would also expect small climate responses to increasing  $\text{CO}_2$ . One will of course want to understand in detail the physics determining climate sensitivity. However, this hardly justifies ignoring the possibility that it may be possible to bypass these details in approaching the issue of sensitivity directly.

#### ACKNOWLEDGMENTS

I should like to acknowledge the support of the National Science Foundation under Grant 8520354-ATM and of the National Aeronautics and Space Administration under Grant NAGW-525.