# Introduction: Mount Pinatubo as a Test of Climate Feedback Mechanisms

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The June 15, 1991 Mount Pinatubo eruption was a large but relatively shortlived shock to the Earth's atmosphere. It thus provided an excellent opportunity to study the workings of the climate system, to test climate models, and to examine the impacts of climate change on life. The largest eruption of the 20th Century inspired a large amount of research on the connection between volcanic eruptions and the Earth's atmosphere in the 12 years since that eruption, as exemplified by the chapters in this book. Here several additional examples of our new understanding of these connections are presented. While the global cooling after Pinatubo was not surprising, the observed winter warming over Northern Hemisphere continents in the two winters following the eruption is now understood as a dynamic response to volcanically produced temperature gradients in the lower stratosphere from aerosol heating and ozone depletion, and to reduced tropospheric storminess. Interactions of the Quasi-Biennial Oscillation of tropical stratospheric winds with the climate system are also now better understood by examining their role in the Pinatubo response. We have more confidence in the sensitivity of climate models used for attribution and projection of anthropogenic effects on climate because the strength of the water vapor feedback has been validated with Pinatubo simulations. The response of the biosphere to the Pinatubo eruption also illustrates its sensitivity to climate change and clarifies portions of the carbon cycle. Death of coral in the Red Sea in the winter of 1991-1992 and an unusually large number of polar bear cubs born in the summer of 1992 were two responses to the characteristic winter and summer temperature responses of the climate system. This strengthens our concern about negative impacts of global warming on polar bears and other wildlife. Enhanced vegetation growth from more diffuse and less direct solar radiation took more carbon dioxide out of the atmosphere than normal, temporarily reducing the observed long-term increase in carbon dioxide. Continued research on the Pinatubo eruption and its aftermath will undoubtedly enhance our understanding of the climate system.

# 1. INTRODUCTION

Volcanism and the Earth's Atmosphere Geophysical Monograph 139 Copyright 2003 by the American Geophysical Union 10.1029/139GM01 Volcanic eruptions have been an important cause of weather and climate change on timescales ranging from hours [*Robock and Mass*, 1982] to centuries [*Humphreys*, 1913]. Their atmospheric aerosol and gas inputs, in addition to being potentially very dangerous to people nearby and to

aircraft during explosive eruptions, produce local air pollution and haze that not only can have a strong atmospheric impact while being erupted, but also when concentrated in peat that is much later dried and burned [*Langmann and Graf*, 2003]. Major eruptions, such as the Santorini blast in the 17th Century BCE, have had major impacts on civilization and changed history.

For 51 years before the 1963 Gunung Agung eruption in Bali, Indonesia, there had not been a major volcanic eruption on Earth. Starting then, Agung and the 1980 Mt. St. Helens, 1982 El Chichón and 1991 Mount Pinatubo eruptions have stimulated research on the impacts of volcanic eruptions on the atmosphere. The 12 years since the June 15, 1991 Mount Pinatubo eruption in the Philippines have been particularly productive, and the chapters in this book, based on presentations at the Chapman Conference on Volcanism and the Earth's Atmosphere in Thera, Greece, June 17–21, 2002, give many examples of this excellent work. Here I present examples of additional recent research to paint a broader picture of the new understanding we have gained.

A comprehensive survey of the effects of volcanic eruptions on climate was presented by *Robock* [2000], updated by *Robock* [2002a, 2003]. While we have gained much new understanding, the work presented in this book and at the Chapman Conference raises more sophisticated questions that will inspire continued work on the subject [*Robock*, 2002b].

## 2. VOLCANIC ERUPTIONS AND CLIMATE

Most causes of climate change are gradual shifts in atmospheric composition or land surface characteristics. Volcanic eruptions, however, can produce a very large, but short-lived, perturbation to the Earth's radiative balance. While we cannot use these perturbations to test long-term processes, such as changes in the thermohaline circulation, we can take advantage of them to examine some short timescale feedback processes and impacts.

Plates 1 and 2 show the lower tropospheric temperature anomalies for the Northern Hemisphere winters of 1991/92 and 1992/93. Before the Pinatubo eruption, cooling was the only well-understood response of climate to volcanic eruptions. The large continental warming seen in this plate was not predicted, but we now understand it as a dynamical response to the radiative perturbation from the volcanic aerosols and ozone depletion from the eruption. *Stenchikov et al.* [2002] recently presented atmospheric general circulation model simulations which illustrate that this winter warming phenomenon, a positive mode of the Arctic Oscillation [Thompson and Wallace, 1998], can be produced by the enhanced temperature gradient in the lower stratosphere from aerosol heating in the tropics, or from aerosol-induced ozone depletion in the higher latitudes, or by reduced winter synoptic wave activity (storminess) in the troposphere caused by reduced latitudinal temperature gradients (Figure 1). The Arctic Oscillation is the dominant mode of interannual variability of Northern Hemisphere atmospheric circulation, and a positive mode corresponds to a stronger than normal polar vortex, with strong westerly winds in the midlatitudes in the lower stratosphere and upper troposphere. The references in that paper and in Robock [2000] provide a detailed description of other observational and modeling studies that support this conclusion. We might expect similar Arctic Oscillation responses to long-term ozone depletion and increases in greenhouse gases, a mechanism now better understood by examining the response of the climate system to the Pinatubo eruption. Stenchikov et al. [2003] have shown that the Quasi-Biennial Oscillation of tropical lower stratospheric winds [Angell and Korshover, 1964] significantly modifies the response of stratospheric winds to the volcanic aerosols, making the polar vortex stronger in the second winter following the eruption, amplifying the response to a diminished aerosol loading and producing winter warming for the second winter, too. Thus, our understanding of stratospheric dynamics has also been enhanced by studying the reaction to an explosive volcanic eruption.

Plate 3 shows the lower troposphere temperature anomalies for the Northern Hemisphere summer of 1992, one year after the Pinatubo eruption. Virtually the entire planet was cooler than normal, as expected. But the amount of



**Figure 1.** Ways volcanic eruptions cause a positive mode of the Arctic Oscillation. (Figure 13 from *Stenchikov et al.* [2002].)











cooling depended on the sensitivity of the climate system to radiative perturbations, and the strength of the most important positive feedback in the climate system, the water vapor-greenhouse feedback [Schneider and Dickinson, 1974]. As the planet cools, the amount of water vapor in the atmosphere goes down, reducing the greenhouse effect, and amplifying the cooling. (Of course, this positive feedback also works for warming.) The timing and amplitude of future global warming depend on this sensitivity of the climate system. Soden et al. [2002] used the global cooling and drving of the atmosphere that was observed after the eruption of Mount Pinatubo to test model predictions of the climate feedback from water vapor. By comparing model simulations with and without water vapor feedback, they demonstrated the importance of atmospheric drying in amplifying the temperature change and showed that, without the strong positive feedback from water vapor, their atmospheric general circulation model was unable to reproduce the observed cooling (Figure 2). These results provide quantitative evidence of the reliability of water vapor feedback in current climate models, which is crucial to their use for global warming projections.

### 3. IMPACTS OF CLIMATE CHANGE

The impacts of global warming depend on the response of various natural and human systems to climate changes. Pinatubo was a short, but large, perturbation to the climate system, but we can still take advantage of this natural climate experiment to learn about the impacts of anthropogenic forcings.

The winter pattern for 1991/92 (Plate 1) actually is a wave response to an enhanced polar vortex, and has both

warm and cold anomalies. While the lower stratospheric circulation is guite symmetric, in the troposphere the enhanced circulation is affected by mountain ranges, which produces southeasterly (warm) and northeasterly (cold) winds. One of these cold regions was in the eastern Mediterranean. It was so cold that winter that Jerusalem experienced rare snowfall and coral at the bottom of the Red Sea died, because the water at the surface cooled and convectively mixed the entire depth of the water [Genin et al., 1995]. The resulting enhanced supply of nutrients produced huge algal and phytoplankton blooms, which smothered the coral. This coral death had only happened before in winters following large volcanic eruptions [Genin et al., 1995]. As some global warming scenarios predict more frequent positive modes of the Arctic Oscillation, this volcanic response informs us about possible biological responses to future climate.

The largest cooling in the summer of 1992 was in the center of North America (Plate 3). As a result, the ice on Hudson Bay melted almost a month later than normal that year. Polar bears, who feed and have babies on the ice, were much heavier and had more healthy cubs that summer. Biologists call those now 11-year olds "Pinatubo Bears" [Stirling, 1997]. The cool conditions in the summer after the Pinatubo eruption was very beneficial for the Hudson Bay polar bears, and there were many more bears born that year than the year before or after. The long-term concern for these bears, and many other plants and animals in the Arctic, however, is the opposite impact from global warming. This temporary positive impact from Pinatubo strengthens the argument of the negative impacts of the predicted warming. Pinatubo produced global cooling, but impacts work in both directions, so the benefits of Pinatubo from global cooling teach us about the negative impacts of anthropogenic global warming.



**Figure 2.** Observations (MSU – Microwave Sounding Unit [*Spencer et al.*, 1990] and MSU (ENSO removed) – with the effects of sea surface temperatures removed) and climate model simulations (GCM – general circulation model). The simulation was only successful with the positive water vapor feedback. (Figure 4 from *Soden et al.* [2002].)

#### 4. CARBON CYCLE

The carbon dioxide concentration has been measured at the Mauna Loa observatory since 1958 [*Keeling and Whorf*, 2002], and is representative of global trends since  $CO_2$  has such a long atmospheric lifetime (~100 years). Figure 3 shows that the Mauna Loa  $CO_2$  concentration has a large upward trend superimposed on the terrestrial biologically induced seasonal cycle. This trend is not uniform however (Figure 4), and changes in emissions and El Niño and La Niña episodes explain part, but not all, of these interannual variations.

The tropical ocean warming associated with El Niño results in enhanced emissions from the ocean. The terrestrial component of the carbon cycle, however, is less well understood, and the Pinatubo eruption has provided another opportunity to learn about a part of the climate system that increases our understanding of the global warming problem. Enhanced forward scattering of incoming solar radiation caused by the Pinatubo aerosols increased the diffuse radiation reaching the surface and decreased the direct flux [Robock, 2000]. This allowed plants to photosynthesize more of the time, increasing the CO<sub>2</sub> sink [Gu et al., 2002, 2003; Farguhar and Roderick, 2003]. Jones and Cox [2001] model experiments showed that the cool temperatures over land following volcanic eruptions produced reduced soil and plant respiration globally and enhanced gross primary productivity in the tropics, both of which would also reduce atmospheric  $CO_2$  concentrations. These effects can be seen in the reduced rate of increase of  $CO_2$  following each large volcanic eruption (Figure 4). This reponse somewhat mimics the effect of tropospheric clouds, and illustrates a biospheric climate feedback.



Figure 3. Record of  $CO_2$  concentration at the Mauna Loa Observatory. Data are from *Keeling and Whorf* [2002].



**Figure 4.** Annual rate of increase of  $CO_2$  in the atmosphere. Data are from *Keeling and Whorf* [2002]. Thin line is monthly values and thick line is 9-month running mean. Minima following the largest volcanic eruptions of the period are indicated. Other interannual variations are partially due to El Niños, La Niñas, and emission variations.

### 5. SUMMARY

This brief introduction presents just a few examples of how studies of the responses to a large, recent volcanic eruption have deepened our understanding of the climate system. As a result, our confidence in our projections of the carbon cycle, the climatic response to anthropogenic greenhouse gases and land surface changes, and the biological response to the predicted warming has increased. Future studies, addressing outstanding issues in the impacts of volcanic eruptions on the atmosphere [Preface; *Robock*, 2002b], will surely add to this understanding.

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