Southern Hemisphere atmospheric circulation effects of the 1991 Mount Pinatubo eruption

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Received 25 July 2007; revised 2 October 2007; accepted 7 November 2007; published 13 December 2007.

[1] Global average cooling and Northern Hemisphere winter warming are well-known climatic responses to the June 15, 1991 eruption of the Mount Pinatubo volcano in the Philippines. Here we investigate the Southern Hemisphere response. Using National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis, European Centre for Medium-Range Weather Forecasting Reanalysis, and simulations with the National Aeronautics and Space Administration Goddard Institute for Space Studies ModelE climate model, we find that, in contrast to the Northern Hemisphere, there were no strong significant anomalies in atmospheric circulation in the Southern Hemisphere. We examined 50 mb and 500 mb circulation patterns, as well as the Southern Hemisphere Annular Mode index, and found no consistent significant anomalies associated with the volcanic eruption, or the previous large volcanic eruptions of the past 50 years, the 1963 Agung and 1982 El Chichón eruptions. The few anomalies that occurred after Pinatubo are consistent with patterns found during an El Niño event, which took place that same year.
Citation: Robock, A., T. Adams, M. Moore, L. Oman, and G. Stenchikov (2007), Southern Hemisphere atmospheric circulation effects of the 1991 Mount Pinatubo eruption, *Geophys. Res. Lett.*, *34*, L23710, doi:10.1029/2007GL031403.

1. Introduction

[2] The Mount Pinatubo volcanic eruption of June 15, 1991, injected 20 Mt of SO_2 into the stratosphere [*Bluth et al.*, 1992], which converted to sulfate aerosols. The effects on the global climate and Northern Hemisphere circulation of this aerosol cloud, which persisted for several years, are well known. Our goal for this study is to determine if there was any effect on Southern Hemisphere (SH) circulation.

[3] As discussed in detail by *Robock* [2000] and *Stenchikov et al.* [2002a], large tropical eruptions are followed by a positive phase of the Arctic Oscillation (AO) for one to two years, which is associated with a negative anomaly in sea level pressure (SLP) over the pole and a positive SLP anomaly in the mid-latitudes. The associated tropospheric circulation pattern in the winter produces a general warming over both North America and Eurasia coupled with a cooling over Greenland and the eastern Mediterranean [*Groisman*, 1992; *Robock and Mao*, 1992, 1995; *Graf et al.*, 1993; *Perlwitz and Graf*, 1995; *Parker et al.*, 1996; *Stenchikov et al.*, 2002a].

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0094-8276/07/2007GL031403

[4] While a combination of tropical lower stratospheric heating, high latitude ozone depletion from the volcanic aerosols, reduction of tropospheric temperature gradient, and phase of the quasi-biennial oscillation all combined to produce a stronger polar vortex in the Northern Hemisphere winters of 1991–1992 and 1992–1993 [*Stenchikov et al.*, 2002a, 2004], we wonder whether the same processes would operate in the SH. Certainly there are no large continents at the mid-high latitudes that could warm in winter, but was the stratospheric circulation similarly changed? As the Pinatubo aerosols were fairly evenly distributed in both hemispheres, we might expect tropical lower stratospheric heating to be similar. But the SH has one large difference with the Northern Hemisphere. Because of the lack of large continents at the mid-high latitudes, the jet stream is stronger and steadier, with a stronger polar vortex. This same effect is responsible for the ozone hole appearing only in the SH. Will it also, by virtue of the vortex being stronger, resist perturbations forced by volcanic aerosols, as suggested by *Stenchikov et al.* [2002b]?

[5] When considering changes in SH circulation we use the Antarctic Oscillation Index, now called the SH annular mode (SAM) index, defined as the difference in normalized zonal-mean SLP between latitudes 40°S and 65°S [*Gong and Wang*, 1999]. SAM has also been represented by *Thompson and Wallace* [2000] as the amplitude of the leading empirical orthogonal function of monthly mean SH 850 mb height poleward of 20°S. *Marshall* [2003] used the *Gong and Wang* [1999] definition to calculate SAM for the period of 1958 to 2000 from station observations, as opposed to the National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis (NNR) [*Kalnay et al.*, 1996; *Kistler et al.*, 2001] used by *Gong and Wang* [1999], and showed that errors in NNR in earlier years had produced spurious trends in SAM.

[6] *Gong and Wang* [1999], *Marshall* [2003], *Thompson and Solomon* [2002], and *Arblaster and Meehl* [2006] all found a long-term upward trend in SAM, and observed that the SAM has been in a high index state for the past few decades. This implies that there has been a general cooling over Antarctica with a warming over the mid-latitudes, which causes a positive phase, or increase in the polar vortex [*Arblaster and Meehl*, 2006]. *Thompson and Solomon* [2002] suggested that this is most significantly related to the change of ozone concentrations in the stratosphere. *Arblaster and Meehl* [2006] used climate model simulations to show that ozone depletion was the leading cause, but that greenhouse gas increases also contributed to the observed trend. They showed that volcanic eruptions were not important to the long-term trend, but did not examine their short term impact. Here we use a combination of climate modeling and observations to do that. *Cai and Cowan*

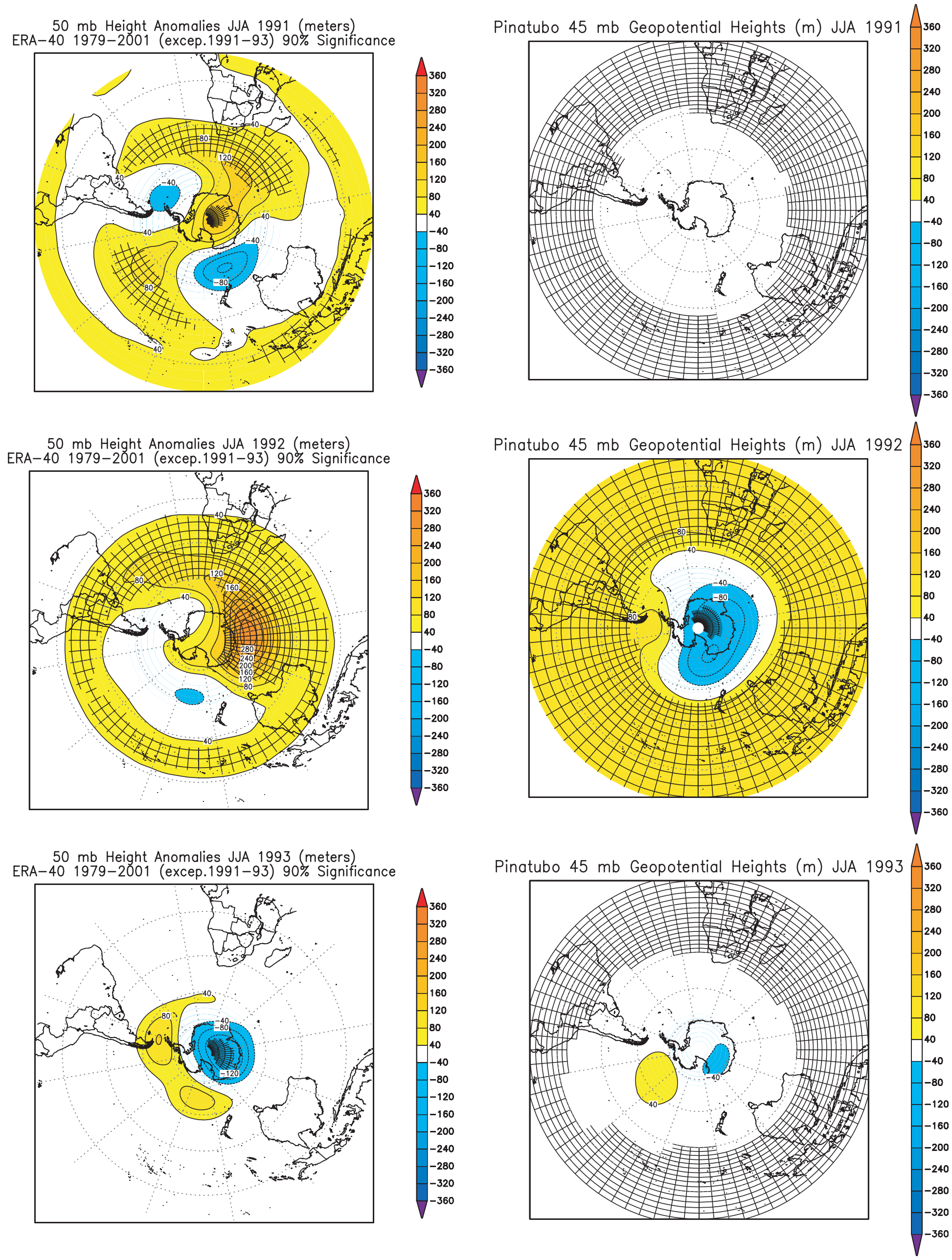

Figure 1. Geopotential height anomaly (m) for both (left) ERA-40 reanalysis and (right) ModelE for the three SH winters following the Pinatubo eruption measured at the 50 or 45 mb level. Hatchmarks indicate 90% statistical significance. Significance in the model runs was evaluated using a local student t-test in which the difference of means is scaled by an estimate of its own standard deviation. Significance in excess of 90% was determined using a two-tailed distribution.

[2007] also showed that ozone depletion has been the leading cause of the SAM trend since 1970, by examining recent climate model simulations.

[7] There was a moderate El Niño event at the same time as the Pinatubo eruption, which may have contributed to some of the patterns and anomalies detected in our results. Observed El Niño effects in the SH include more zonally symmetric circulation anomalies, which correlate with increased height at low and high latitudes and decreased height in middle latitudes [*Karoly*, 1989]. *Turner* [2004] confirmed this, noting that the most pronounced signals of El Niño are found over the southeast Pacific with positive height anomalies over the Amundsen-Bellingshausen Sea. These changes in geopotential height are caused by the tropical sea surface temperature anomalies associated with El Niño, which cause circulation anomalies over large areas of the SH [*Solman and Menéndez*, 2002]. Therefore, these effects must be taken into account when analyzing the model output and data.

2. Observations and Climate Model Experiments

[8] To study the SH circulation response to the Pinatubo eruption, we examined geopotential height anomalies at 50

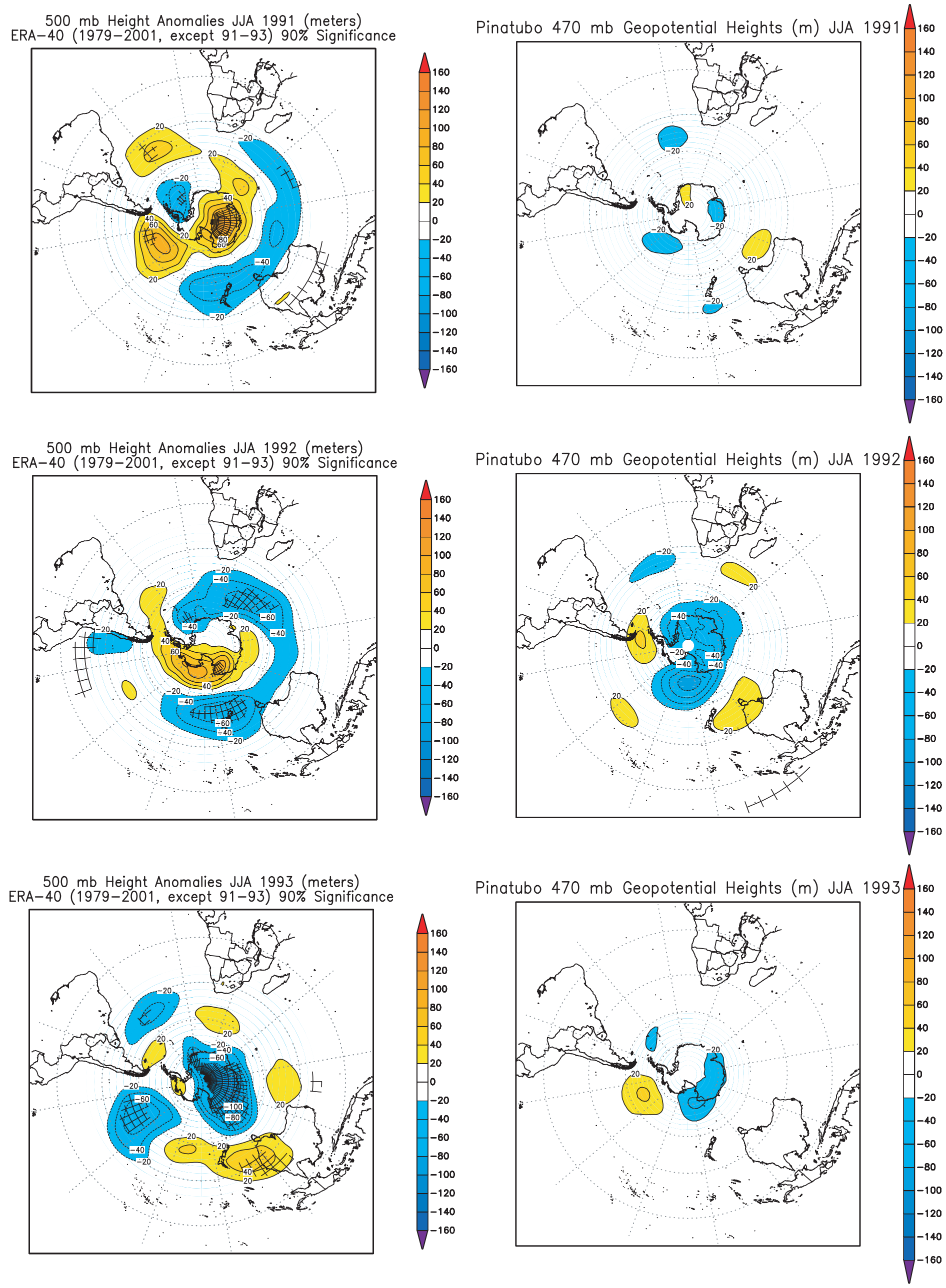

Figure 2. Geopotential height anomaly (m) for both (left) ERA-40 reanalysis and (right) ModelE for the three SH winters following the Pinatubo eruption measured at the 500 or 470 mb level. Hatchmarks indicate 90% statistical significance. See Figure 1 caption for details.

and 500 mb, in the lower stratosphere and mid troposphere, using the NNR, the European Centre for Medium-Range Weather Forecasting Reanalysis (ERA-40; *Simmons and Gibson* [2000]), and climate model simulations of the response to the Pinatubo eruption we conducted using National Aeronautics and Space Administration Goddard Institute for Space Studies ModelE, first described by *Oman et al.* [2005]. *Marshall* [2003] suggested that ERA-40 would be superior to NNR in the early years of both time series, before satellite data were incorporated, but we note that both should be similar for the Pinatubo period. Nevertheless we conducted our analyses with both, and found that indeed they are very similar.

[9] To calculate circulation anomalies for the Pinatubo period, and to address issues such as climatic trends and the influence of other volcanic eruptions, we calculated reanalysis anomalies with respect to the means for the periods 1961–1990, 1979–2001 (with the exception of the years examined, 1991–93) to only consider the satellite era and be consistent with *Arblaster and Meehl* [2006], and for 1985–1990 to avoid trends and eliminate the possible influence of the 1982 El Chichón eruption. The individual

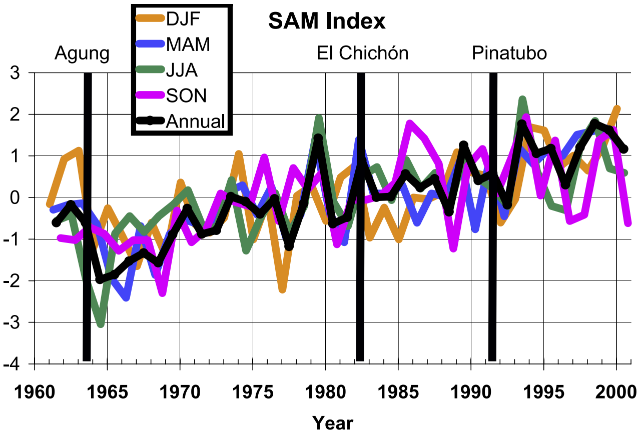

Figure 3. SAM index time series using NNR data for each season and for annual average. A steady increase over time, indicative of a stronger polar vortex, is evident. The three largest volcanic eruptions of the period are also shown, and there is no evidence of any effect of these eruptions on the index.

seasonal anomaly patterns are so strong, however, that the method of calculating the mean makes little difference, so we show anomalies calculated with the second method. Furthermore, the NNR and ERA-40 patterns for the seasons following the Pinatubo eruption are very similar, so we just show the ERA-40 patterns.

[10] The ModelE climate model simulations were run with a 4° × 5° latitude-longitude horizontal resolution and 18 vertical layers. *Schmidt et al.* [2006] describe the climate model in detail. We used five ensemble members run for the period December 1990 through February 1994 with specified evolution of the volcanic aerosol distribution in the stratosphere based on observations [*Sato et al.*, 1993]. Sea surface temperatures were fixed at the seasonally-varying climatological mean from 1990-1999, for which the model uses a quadratic approximation to interpolate the fixed daily value at each grid point [*Schmidt et al.*, 2006]. Therefore the model does not include the El Niño which occurred at the same time as the Pinatubo eruption. Greenhouse gases, tropospheric aerosols, and solar radiation were set to 1991 values. The model does not calculate exactly on standard pressure levels, so we used 45 mb and 470 mb levels, the ones closest to the observations. We also ran five control runs for the same period with no volcanic aerosols and present the anomalies from the mean of the forced runs minus the control runs. *Raphael and Holland* [2006] and *Miller et al.* [2006] found that ModelE did a good job of simulating SAM, so a lack of SAM response to volcanic eruptions in this model would not likely be due to an inadequacy in the model.

[11] To quantify the changes in SH circulation, we calculated a SAM index from both NNR and ModelE outputs using output sampled from the locations of the same 12 stations used by *Marshall* [2003], six from latitude 40°S and six from 65°S. This avoids spurious NNR trends by only sampling in data-rich regions, and uses exactly the same technique for reanalysis and climate model output, so that the same quantities are compared. We used seasonal mean SLPs, and calculated the normalized differences between the zonal means, using a similar definition as *Gong and Wang* [1999] and *Marshall* [2003]. However, as *Cai and Cowan* [2007] did, we first took the difference in the mean SLP, and then normalized the time series, to measure the actual pressure gradient trend rather than give extra weight to the data from 40°S, which had much less interannual standard deviation. The index thus defined is more closely related to the strength of the polar vortex.

3. Results

[12] The Pinatubo eruption occurred on June 15, 1991, and it took more than a month for the sulfate aerosols to form and become distributed in a tropical band [*Stenchikov et al.*, 1998], so it might not be expected that they would have a strong influence on SH polar circulation that same winter (JJA, June, July, and August, 1991). Figure 1 (50 mb) and Figure 2 (500 mb) indeed show very small circulation anomalies in the ModelE simulations. The observations, however, show a very characteristic El Niño pattern, with positive anomalies in the Bellingshausen Sea area just west of the tip of South America, as shown in Figure 6 of *Turner* [2004]. Thus the circulation anomalies in the winter of 1991 seem to be dominated by the El Niño, and show no signs of a volcanic influence.

[13] In the second winter following Pinatubo, JJA 1992, the model simulates a slightly stronger polar vortex (Figure 1), but no significant anomalous tropospheric circulation (Figure 2). Observations, on the other hand, show a weakened vortex (Figure 1), and tropospheric anomalies different from the model, but not very significant. We interpret the circulation this winter as dominated by random atmospheric circulation variations, with no clear El Niño or volcanic pattern. While there may have been a small tendency to a stronger vortex forced by Pinatubo, it was overwhelmed by other factors. The third winter tells the same story (Figures 1 and 2) – no volcanic signal and random atmospheric variations.

[14] We examined all the other seasons following the Pinatubo eruption, comparing observations and model simulations and found no significant volcanic effect. (We also examined the circulation at 150 mb for observations (130 mb at the closest model level), lower in the stratosphere where the effects might be different because of aerosol effects on ozone [*Hofmann and Oltmans*, 1993], but found results very similar to those at 50 mb.) While the model produced a stronger polar vortex in the first summer following the eruption (DJF 1991–1992), this did not agree with observations or with results for any other seasons before or after. For the reasons discussed in the introduction, we would not expect a strong volcanic signal.

[15] We also examined the SAM index for the past 45 years (Figure 3) and compared the observations and model simulations following Pinatubo in detail (Figure 4). Figure 3 shows the well-known upward trend in SAM for the period. If the eruptions increased the polar vortex, SAM would go up, particularly in the winter. There is no evidence for a volcanic signal following the three large eruptions of the period, Agung (March 17, 1963), El Chichón (April 4, 1982) or Pinatubo. While it appears that SAM decreased immediately after Agung, the index stays low for more than

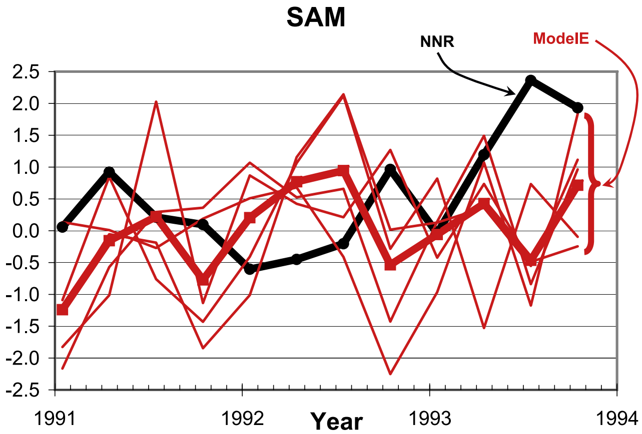

Figure 4. The seasonal-average SAM index produced from NNR data (black with dots) and from ModelE output (red) for the years following the 1991 eruption. For ModelE each of the five ensemble members are indicated with thin red lines and the mean is shown with a thick red line and boxes.

five years after that, so it could not be a volcanic signal, which would last for one or two years at the most. *Marshall* [2003] suggested that the downward spike following Agung was forced by surface temperature gradients, with more cooling in the tropics than at high latitudes by Agung, but we see no evidence of this mechanism in our simulations. SAM does nothing unusual after Pinatubo. While SAM does go up in 1993, it is two years after the Pinatubo eruption, so again could not be a volcanic effect.

[16] The detailed evolution of SAM after Pinatubo (Figure 4) shows no agreement between observations and the model simulation. The plot has the appearance of noise about a value of 0. The observations have a mean >0 because of the upward trend (Figure 3), as opposed to the mean of 0 for the model, but adjusting this would not produce a different interpretation.

[17] We used an ensemble of multiple realizations to evaluate the climate model results. While the real world only conducts one experiment, the agreement of the observed response with the model mean gives us more confidence that the absence of a significant observed SH circulation response was not a strong random anomaly. The individual model ensemble members are also shown in Figure 4, and the actual time series does not obviously have a different character.

4. Conclusions

[18] Neither atmospheric observations nor climate model simulations show effects of the three largest volcanic eruptions of the past 50 years on the strength of the Southern Hemisphere polar vortex. It appears that the same forcing mechanisms that do produce such an effect in the Northern Hemisphere cannot work in the SH because of the combination of the lack of large continents at the latitude of the jet stream and the stronger vortex there, which of course are related.

[19] **Acknowledgments.** This work is supported by NASA grant NNG05GB06G and NSF grants ATM-0313592 and ATM-0351280. Tyler Adams and Mary Moore were supported by an NSF Research Opportunity for Undergraduates grant ATM-0632218. We thank Susan Solomon for asking about this, which prompted the research effort. Model development and computer time at GISS is supported by NASA climate modeling grants.

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