CHAPTER VI

CONCLUSION

In this study, a zonally averaged monthly mean dataset of the optical properties of the Pinatubo volcanic aerosol was reconstructed for the UIUC 24–layer ST–GCM, and compared with SAGE–II and AVHRR observations and with the reconstruction of Stenchikov *et al.* (1998) for the ECHAM4 GCM. The present reconstruction better represents the Pinatubo volcanic aerosol than does that of Stenchikov *et al.* (1998). Radiative forcing of the Pinatubo volcanic aerosol was calculated for the two years following the eruption by using the UIUC 24–layer ST–GCM. Solar forcing is everywhere negative and the longwave forcing is everywhere positive. The calculated maximum global–mean net radiative forcing occurs in DJF 1991–1992, about –4.9 W/m^2 at the surface, –4.8 W/m^2 at the model top, and –5.7 W/m^2 at the tropopause. The forcing over cloudy sky is smaller than over clear sky. The differences are about 4 W/m^2 for the tropical maxima and 2 to 4 W/m^2 for the maxima in high latitudes. The forcing with the stratospheric temperature adjustment was estimated by using a 1–D radiative transfer model. At the tropopause, the global–mean adjusted forcing is about 10% smaller than the instantaneous global–mean forcing.

Heating–rate calculations showed that overall the Pinatubo volcanic aerosol radiatively cooled the troposphere and radiatively warmed the stratosphere. The absorption of upward terrestrial radiation by the aerosol cloud warmed the lower stratosphere but cooled the upper stratosphere above the aerosol layer. The back–scattering of the direct incoming solar radiation in the UV and visible regions cooled the atmosphere below the top of the aerosol layer, while the absorption of the enhanced up–welling UV and visible radiation by ozone in the upper stratosphere above the aerosol layer caused minor warming. The back–scattering of the solar near–IR radiation cooled the troposphere, and the absorption of the solar near–IR radiation warmed the stratosphere. This absorption contributed about 30% of the total heating in the middle stratosphere.

Observational data analyses showed that, during the two years following the Pinatubo eruption, temperature in the tropics and mid–latitudes in both hemispheres was about 0.5°C to 1.5°C higher than normal in the lower stratosphere, and generally lower than normal in the troposphere. The north–polar vortex in the lower stratosphere was stronger than normal in the northern–hemisphere winter.

Composite analyses and the Singular Value Decomposition method were used to detect and remove the signals of the 1991~1992 and 1993 El Niño events from the observed surface–air temperature anomalies over land for the three years following the Pinatubo eruption. Composite analyses showed that over land the distribution of ΔT_s for the El Niño composite is almost everywhere opposite to that for the La Niña composite, and the patterns of ΔT_s changes from season to season. This feature is more distinct over North America than over other continents. Over North America, negative ΔT_S dominates for the El Niño composite in JJA and for the La Niña composite in DJF, and positive ΔT_S dominates for the La Niña composite in JJA and for the El Niño composite in DJF. The volcano composite is different from either the El Niño composite or the La Niña composite. The SVD analysis showed that ENSO signals were weak over Eurasia but relatively strong over the other continents. The 1991~1992 El Niño event contributed more than 50% of the observed total cooling of about –1.0°C over North America in JJA 1992. The averaged maximum cooling over Eurasia, North America, South America and Africa was about –0.5°C in JJA 1992, SON 1992 and SON 1993 with the ENSO signals removed.

Four sets of ensemble simulations were performed by using the UIUC 24–layer ST–GCM to explore the thermal and dynamical responses of the atmosphere to the Pinatubo aerosol forcing for the two years following the Pinatubo eruption. The model captured the observed surface warming in DJF 1991–1992 and DJF 1992–1993 over central North America, and the observed surface cooling in JJA 1992 over both North America and Eurasia. The model did not simulate the observed warming in DJF 1991–1992 over northern Eurasia. The simulated ΔT_s are rather sensitive to initial conditions, and vary with the type of prescribed SSTs in the model. Overall, the simulation with both the Pinatubo aerosol forcing and the observed SST anomalies included best matches the observation. When forced only by the SST anomalies, the model simulated well the observed surface–air temperature anomalies over land that can be attributed to the ENSO effect indicated by the SVD analysis. In the stratosphere, the model simulated the observed warming caused by the Pinatubo aerosol. The simulated temperature anomalies are not sensitive to initial conditions everywhere except near the poles. The magnitude of the simulated warming does not depend on the type of prescribed SSTs. The signal of SST anomalies is rather weak in the stratosphere. In the troposphere, the model captured the observed cooling. The simulated temperature anomalies are rather sensitive to initial conditions and the type of prescribed SSTs. The signal of SST anomalies is stronger than the signal of the Pinatubo aerosol forcing in the troposphere.

In the lower stratosphere, the simulated temperature anomalies are about 1°C to 2°C larger than observed in the tropics and subtropics in late 1991 and 1992. Most of the discrepancy can be explained by the observed QBO–related temperature variation and the temperature changes induced by the observed ozone depletion. The NCEP/NCAR Reanalysis showed that the equatorial zonal wind changed from easterly wind to westerly wind in the fall of 1992 along with the phase change of the QBO. In the tropical lower stratosphere, the observed warming by the

Pinatubo aerosol was diminished by up to 1°C before August 1992 and enhanced by up to 1°C after August 1992 by the QBO–related temperature changes. For the three years following the Pinatubo eruption, the observed total ozone decreased by 2% to 4% in the tropics and more than 10% in the high latitudes in both hemispheres in late winter and early spring times. Two simulations were performed to estimate the temperature changes due to the ozone depletion induced by the Pinatubo aerosol. The 24–layer ST–GCM was run with prescribed zonal–mean percent changes of ozone concentration, which were simulated by two different two–dimensional radiative–chemical–transport models. Globally averaged, the simulated temperature anomalies in the lower stratosphere induced by the ozone depletion are about –0.2°C to –0.5°C in the first year, and about –0.5°C to –1.0°C in the second year, following the Pinatubo eruption. The 24–layer ST–GCM did not simulate the observed stronger–than–normal northern polar vortex in DJF 1991–1992 and DJF 1992–1993, probably because of the model's deficiency in simulating the wave activities in the northern polar stratosphere as shown in Appendix A.

Ensemble simulations were performed by using the coupled 24–layer–atmosphere and 18–layer–ocean GCM to examine the influences of the ocean on the simulated atmospheric responses to the Pinatubo aerosol forcing. The coupled model simulates better the observed surface–air temperature anomalies over Eurasia than the uncoupled 24–layer ST–GCM. The simulated stratospheric temperature anomalies are slightly smaller than those simulated by the uncoupled 24–layer ST–GCM. This coupled model did not succeed in simulating the observed abnormally high SST in the eastern tropical Pacific in 1991 and 1992, probably due to the coarse resolutions of the AGCM and the OGCM. It would be better to use a coupled GCM with a higher horizontal resolution to study the role of the ocean in the climatic impact of the Pinatubo eruption, and possibly to test the volcano–ENSO hypothesis (Handler and Andsager 1993).

In summary, this study carried out so far the most detailed calculation of the radiative forcing by the Pinatubo aerosol and examined the dependence of the forcing on the optical properties of volcanic aerosol particles and atmospheric conditions. This dependence can be generalized to understand better the radiative forcing of other historical volcanic eruptions. This study also revealed that in the investigation of the climatic impact of volcanic eruptions the influences of El Niño events must not be ignored, even though it is still not clear if and how these two events are related. Both observational data analyses and numerical simulations showed that, globally averaged, the observed surface cooling over land in JJA 1992 and JJA 1993 was statistically significant, and was caused predominantly by the Pinatubo eruption, and less importantly by the SST anomalies in the eastern tropical Pacific, and that the observed surface warming over land in DJF 1991–1991 and DJF 1992–1993 was not statistically significant. The UIUC 24–layer ST–GCM was unable to simulate this warming. The UIUC 24–layer ST–GCM simulated reasonably well the observed stratospheric temperature changes during the two years following the Pinatubo eruption with the adjustments to the influences of the QBO and volcano–related ozone depletion. The model did not simulate well the observed circulation changes. The performance of the model in simulating the northern–hemisphere polar vortex needs to be improved. To better understand the climatic impact of the Pinatubo eruption, the atmospheric GCM should be coupled interactively with a chemical–transport model to include the feedbacks between the changes of atmospheric constituents and the responses of atmospheric temperature and circulation, be improved in simulating the QBO, and be coupled to an oceanic GCM with a higher horizontal resolution in the tropics to better represent the contributions of the oceanic thermal inertia and dynamics to the responses of the atmosphere to the Pinatubo volcanic aerosol forcing, and to test the volcano–ENSO hypothesis (Handler and Andsager 1993).