APPENDIX D

Climate Models

(Supplemental to Chapter 3)

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D.1 GEOPHYSICAL FLUID DYNAMICS LABORATORY

Climate simulations at GFDL used the coupled climate model recently developed at NOAA's Geophysical Fluid Dynamics Laboratory, which has been previously described in detail (Delworth *et al.*, 2006). A brief summary is provided here. The model simulates atmospheric and oceanic climate and variability from the diurnal time-scale through multi-century climate change without employing flux adjustment. The control simulation has a stable, realistic climate when integrated over multiple centuries and a realistic ENSO (Wittenberg *et al.*, 2006). Its equilibrium climate response to a doubling of CO_2 is 3.4°C (Stouffer *et al.*, 2006). There are no indirect particle effects included in any of the simulations. The resolution of the land and atmospheric components is 2.5° longitude x 2° latitude and the atmospheric model has 24 vertical levels. The ocean resolution is 1° latitude x 1° longitude, with meridional resolution equatorward of 30° becoming progressively finer, such that the meridional resolution is 1/3° at the Equator. There are 50 vertical levels in the ocean, with 22 evenly-spaced levels within the top 220 m. The ocean component has poles over North America and Eurasia to avoid polar filtering.

Using a five-member ensemble simulation of the historical climate (1861 to 2003), including the evolution of natural and anthropogenic forcing agents, the GFDL climate model is able to capture the global historical trend in observed surface temperature for the twentieth century as well as many continental-scale features (Knutson *et al.*, 2006). However, the model shows some tendency for too much twentieth century warming in lower latitudes and too little warming in higher latitudes. Differences in Arctic Oscillation behavior between models and observations contribute substantially to an underprediction of the observed warming over northern Asia. El Niño interactions complicate comparisons of observed and simulated temperature records for the El Chichón and Mt. Pinatubo eruptions during the early 1980s and early 1990s (Knutson *et al.*, 2006). In Figure 7d of Knutson *et al.* (2006), where the model ensemble and observations are compared grid box by grid box, ~60 percent of those grid boxes with sufficient observational data have twentieth century surface temperature trends that agree quantitatively with the model ensemble. In general, many observed continental-scale features, including a twentieth century cooling over the North Atlantic, are captured by the model ensemble, as Figures 7a and 7c in Knutson *et al.* (2006) show. However, the model ensemble does not capture the observed cooling over the southeastern United States, and it produces a twentieth century cooling over the North Pacific that is not observed.

D.2 GODDARD INSTITUTE FOR SPACE STUDIES

The GISS climate simulations were performed using GISS ModelE (Schmidt *et al.*, 2006). We use a 20-layer version of the atmospheric model (up to 0.1 hPa) coupled with a dynamic ocean without flux adjustment, both run at four by five degree horizontal resolution, as in the GISS-ER IPCC AR4 simulations (Hansen *et al.*, 2007). This model has been extensively evaluated against observations (Schmidt *et al.*, 2006), and has a climate sensitivity in accord with values inferred from paleoclimate data and similar to that of mainstream GCMs: an equilibrium climate sensitivity of 2.6°C for doubled CO_2.

The modeled radiatively active gases and particles influence the climate in the GCM. Ozone and particles can affect both the short and long wavelength radiation flux. Water uptake on particle surfaces influences the particle effective radius, refractive index and extinction efficiency as a function of wavelength and the local relative humidity (Koch *et al.*, 2007), which in turn affects the GCM's radiation field.

The GISS model also includes a simple parameterization for the particle indirect effect (Menon *et al.*, 2002) (Box 3.1). For the present simulations, we use only cloud cover changes (the second indirect effect), with empirical coefficients selected to give roughly -1 W per m^2 forcing from the preindustrial era to the present, a value chosen to match diurnal temperature and satellite polarization measurements, as described in Hansen *et al.* (2005). We note, however, that this forcing is roughly twice the value of many other model studies (Penner *et al.*, 2006). The particle indirect effect in the model takes place only from the surface through ~570 hPa, as we only let particles affect liquid-phase stratus clouds.

D.3 NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

The transient climate simulations use the NCAR Community Climate System Model CCSM3 (Collins *et al.*, 2006). This model had been run previously with evolution of short-lived gases and particles in the future for the IPCC AR4. The model was run at T85 (~1.4° x 1.4° resolution). For this study, a new simulation was performed for 2000 to 2050 in which ozone and particles were kept at their 2000 levels. The equilibrium climate sensitivity of this model to doubled CO_2 is 2.7°C.