pospheric historical O_3 change in our climate simulation is from a chemistry climate model (Shindell et al. 2003) driven by prescribed changes of O_3 precursor emissions and climate conditions. Stratospheric O_3 change in recent decades is included based on observational analyses of Randel and Wu (1999). Some influence of stratospheric O_3 depletion on tropospheric O_3 change is included by extrapolating O_3 trends in the Antarctic all the way to the surface and reducing O_3 growth rates in the Arctic troposphere.

Figure 2 shows the global mean total O_3 versus time, the O_3 change as a function of altitude and latitude for the periods 1880–1979 and 1979–1997, and the stratosphere and troposphere O_3 changes for these same periods as a function season and latitude. The resulting O_3 adjusted forcing, with global average 0.28 W/m^2 over 1880–2003, is illustrated in Fig. 10b of Efficacy (2005).

Future stratospheric O_3 may increase as halogens decline in abundance as a result of emission constraints, but the O_3 amount will also be affected by climate change. Tropospheric O_3 would increase strongly for most IPCC (2001) scenarios of CH_4 and other O_3 precursors (Gauss et al. 2003). However, it is possible that efforts to control air pollution and climate change may result in tropospheric O_3 levels leveling off or even declining. Given that future O_3 changes are highly uncertain and probably not a dominant forcing, we keep O_3 in our simulations of the twenty-first century fixed at the 1997 values (Hansen et al. 2002).

The other inhomogeneously mixed anthropogenic GHG included in our climate simulations is CH_4-derived stratospheric H_2O. Production of stratospheric H_2O, based on the two-dimensional model of Fleming et al. (1999), is proportional to tropospheric CH_4 amount with a 2-year lag. As shown in Fig. 9 of Efficacy (2005) CH_4-derived H_2O increases stratospheric H_2O amount from about 3 ppmv to as much as 6–7 ppmv in the upper stratosphere. Simulated H_2O is in good agreement with observations in the lower stratosphere, which is the region that is important for causing climate forcing. Climate forcing due to CH_4-derived H_2O for 1880–2000 is about 0.06 W/m^2.

Change in the total greenhouse gas effective climate forcing between 1880 and 2003 is Fe ~3.0 W/m^2 (Table 1). Our partly subjective estimate of uncertainty, including imprecision in gas amounts and radiative transfer is ~ ±15%, i.e., ±0.45 W/m^2. Comparisons with line-by-line radiation calculations (A. Lacis and V. Oinas, personal communication) suggest that CO_2, CH_4 and N_2O forcings in the climate model are each accurate within several percent, but the CFC forcing may be 30–40% too large. If that correction is needed, it will reduce our estimated GHG forcing to Fe ~2.9 W/m^2. The documented version of modelE, employed for simulations reported here, in modelE (2006), Efficacy (2005), and Dangerous (2006) has GHG forcings as defined in Table 1 here and Fig. 2 of Dangerous (2006).

3.2 Aerosols

3.2.1 Tropospheric aerosols

Aerosol distributions in our climate model in 2000 are shown in Fig. 3a. All aerosols except sea salt and soil dust are time-variable in the current model, i.e., sulfate, black carbon (BC), organic carbon (OC), and nitrate. The changing geographical distributions of sulfate, BC and OC are from an aerosol-climate model (Koch 2001) that uses estimated anthropogenic aerosol emissions based on fuel

Table 1 Climate forcings (1880–2003) used to drive our climate simulations and surface air temperature changes (based on 5-year running mean) obtained for several periods

Forcing agent	Run name	Forcing (1880–2003)				ΔT_S change (Year to 2003)			
		Fi	Fa	Fs	Fe	1880	1900	1950	1979
Well-mixed GHGs	E3WMGo	2.62	2.50	2.65	2.72	0.96	0.93	0.74	0.43
Stratospheric H_2O	E3OXo	–	–	0.06	0.05	0.03	0.01	0.05	0.00
Ozone	E3O3o	0.44	0.28	0.26	0.23	0.08	0.05	0.00	–0.01
Land use	E3LUo	–	–	–0.09	–0.09	–0.05	–0.07	–0.04	–0.02
Snow albedo	E3SNA2o	0.05	0.05	0.14	0.14	0.03	0.00	0.02	–0.01
Solar irradiance	E3SOo	0.23	0.24	0.23	0.22	0.07	0.07	0.01	0.02
Stratospheric aerosols	E3SAo	0.00	0.00	0.00	0.00	–0.08	–0.03	–0.06	0.04
Trop. aerosols, direct	E3TADo	–0.41	–0.38	–0.52	–0.60	–0.28	–0.23	–0.18	–0.10
AIE:CldCov	E3TAIo-E3TADo	–	–	–0.87	–0.77	–0.27	–0.29	–0.14	–0.05
Sum of above	No Run	–	–	1.86	1.90	0.49	0.44	0.40	0.30
All forcings at once	E3f8yo	–	–	1.77	1.75	0.53	0.61	0.44	0.29

Instantaneous (Fi), adjusted (Fa), fixed SST (Fs), and effective (Fe) forcings are defined in Efficacy (2005)