

Sensitivity of 21st century stratospheric ozone to greenhouse gas scenarios

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[1] To understand how greenhouse gas (GHG) emissions may affect future stratospheric ozone, 21st century projections from four chemistry-climate models are examined for their dependence on six different GHG scenarios. Compared to higher GHG emissions, lower emissions result in smaller increases in tropical upwelling with resultant smaller reductions in ozone in the tropical lower stratosphere and less severe stratospheric cooling with resultant smaller increases in upper stratospheric ozone globally. Increases in reactive nitrogen and hydrogen that lead to additional chemical ozone destruction mainly play a role in scenarios with higher GHG emissions. Differences among the six GHG scenarios are found to be largest over northern mid-latitudes (~20 DU by 2100) and in the Arctic (~40 DU by 2100) with divergence mainly in the second half of the 21st century. The uncertainty in the return of stratospheric column ozone to 1980 values arising from different GHG scenarios is comparable to or less than the uncertainty that arises from model differences in the larger set of 17 CCMVal-2 SRES A1B simulations. The results suggest that effects of GHG emissions on future stratospheric ozone should be considered in climate change mitigation policy and ozone projections should be assessed under more than a single GHG scenario. **Citation:** Eyring, V., et al. (2010), Sensitivity of 21st century stratospheric ozone to greenhouse gas scenarios, *Geophys. Res. Lett.*, 37, L16807, doi:10.1029/2010GL044443.

1. Introduction

[2] To project the future evolution of stratospheric ozone and attribute its behavior to different forcings, Chemistry-Climate Models (CCMs) are widely used [*World Meteorological Organization (WMO)*, 2007]. Simulations from 17 CCMs were recently examined to project the evolution of stratospheric ozone through the 21st century [*Austin et al.*, 2010; *SPARC CCMVal*, 2010, chap. 9] as part of the second round of coordinated model inter-comparison organized by the

Chemistry-Climate Model Validation Activity (CCMVal-2). These simulations were further analyzed by *Eyring et al.* [2010] who assessed the two distinct milestones of ozone returning to historical values (ozone return dates) and ozone no longer being influenced by anthropogenic halogenated ozone depleting substances (ODSs; full ozone recovery). However, these model simulations were performed under a single GHG scenario, the SRES A1B scenario [*Intergovernmental Panel on Climate Change*, 2000], in which 21st century CO₂ nearly doubles by 2100. While increasing GHGs warm the troposphere, they cool the stratosphere. This cooling slows gas-phase ozone loss cycles [*Haigh and Pyle*, 1982], thereby increasing ozone concentrations. Other studies have highlighted increased tropical vertical velocities (upwelling) under elevated GHG concentrations leading to reduced transport time scales and a decrease in mean age of air [*Butchart and Scaife*, 2001; *Butchart et al.*, 2010]. Increases in nitrous oxide (N₂O) and methane (CH₄) could also impact ozone by accelerating catalytic ozone destruction cycles [e.g., *Ravishankara et al.*, 2009], but changes in abundances of reactive nitrogen (NO_y) and hydrogen (HO_x) play only a minor role in long-term ozone changes under the A1B GHG scenario [*Oman et al.*, 2010]. However, the relative importance of the factors affecting ozone may differ under a different GHG scenario.

[3] The SRES A1B scenario represents only one plausible future and it is therefore important to study the future chemistry-climate system under different GHG evolutions. In the past this has been done with 2D models [e.g., *Chipperfield and Feng*, 2003]. Recently GEOSCCM has been used to investigate differences in future stratospheric ozone evolution between the SRES A1B and A2 GHG scenarios [*Oman et al.*, 2010]. Here, in addition to the SRES A1B simulations, projections from five GHG sensitivity simulations are analyzed for their differences in 21st century stratospheric ozone and how the milestone of ozone returning to 1980 values changes among the GHG scenarios.

2. Models and Simulations

[4] Four CCMs performed a total of five GHG sensitivity simulations (GHG-x) in addition to the CCMVal-2 reference simulations (REF-B2) that were evaluated as part of *SPARC CCMVal* [2010], see Table 1. The GHG-x simulations are seamless extensions of REF-B2 from 2000 to 2100 but with a future GHG scenario different to SRES A1B. Two CCMs (CCSRNIES, GEOSCCM) simulated 21st century ozone under SRES A2 and three CCMs (CAM3.5, CCSRNIES and WACCM) under SRES B1. To reduce sampling issues that arise from the analysis of a

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Table 1. Summary of CCMVal-2 Simulations Used in This Study^a

	CAM3.5	CCSRNIES	GEOSCCM	WACCM	CO ₂ in 2100 (ppmv)	CH ₄ in 2100 (ppmv)	N ₂ O in 2100 (ppbv)
REF-B2	1	1	1	1	703	1.97	372
SRES B1	1	1	-	1	540	1.57	375
SRES A2	-	1	1	-	836	3.73	447
RCP 2.6	1	-	-	-	421	1.25	344
RCP 4.5	1	-	-	-	538	1.57	372
RCP 8.5	1	-	-	-	935	3.74	435

^aThe last three columns show the GHG concentrations in 2100 in the various scenarios.

single model simulation, the SRES scenarios are analyzed from the 2- or 3-model mean and compared to the corresponding model mean of REF-B2. In addition, CAM3.5 provided simulations constrained by Representative Concentration Pathways (RCPs) generated by Integrated Assessment Models and harmonized with historical emissions from Lamarque *et al.* [2010]. The CAM3.5 RCP simulations are 8.5 [Riahi *et al.*, 2007], 4.5 [Clarke *et al.*, 2007], and 2.6 [van Vuuren *et al.*, 2007], where the number after ‘RCP’ indicates the radiative forcing in W/m² reached by 2100 in each scenario. Since RCP simulations from a climate model were not yet available, sea surface temperatures from SRES simulations closest to the RCP GHG scenarios were used (CCSM3 commitment, SRES B1, and SRES A2 for RCP 2.6, 4.5, and 8.5, respectively). The RCP scenarios include ODS projections that are somewhat different to the adjusted A1 projections used in the SRES simulations, but the differences are small and lead to only minor differences in equivalent stratospheric chlorine (ESC). By 2100, CO₂ concentrations in the RCP 8.5 and SRES A2 scenarios is ~200 ppm and ~100 ppm higher than in SRES A1B, while in the SRES B1/RCP 4.5 and RCP 2.6 scenario it is ~150 ppm and ~250 ppm lower, respectively (see Table 1). Unlike in previous studies that assessed SRES A1B simulations, trends in tropospheric column ozone from ozone precursor emissions contribute substantially to trends in total column ozone in the CAM3.5 RCPs simulations. Therefore, to isolate the effects of future GHG emissions on stratospheric ozone, the long-term stratospheric evolution as well as the milestone of ozone returning to 1980 values is assessed using ozone columns above 200 hPa only.

3. Long-Term Ozone Evolution for Different GHG Scenarios

[5] Figure 1 shows differences in ozone between the 2090s and 2000s, and between the GHG-x simulations and the REF-B2 simulations. A robust feature in the tropics in all CCMs is that the sensitivity to GHG scenarios is opposite in sign in the lower and upper stratosphere (Figure 1b). In the tropical lower stratosphere, scenarios with GHG concentrations lower than SRES A1B result in higher ozone (due to reduced tropical upwelling), whereas in the tropical upper stratosphere lower GHG concentrations result in lower ozone due to less GHG-induced stratospheric cooling. However, in the upper stratosphere factors other than GHG-induced cooling play a role. Oman *et al.* [2010] found that the SRES A2 GEOSCCM simulation shows, in contrast to the SRES A1B scenario, significant increases in NO_y and HO_x that lead to a long-term decrease in ozone in the upper stratosphere. These decreases were largely offset by a slightly larger positive contribution from GHG-induced

cooling, resulting in an ozone evolution in the SRES A2 simulation similar to that of the SRES A1B simulation. These results are confirmed by the 2-model mean of GEOSCCM and CCSRNIES. In contrast, the 3-model mean of the SRES B1 simulations shows suppressed upper stratospheric ozone throughout the 21st century compared to SRES A2 or REF-B2. The models show smaller cooling in the SRES B1 simulation than in the other two SRES scenarios (not shown) and, since the NO_y and HO_x increases are even smaller than in the SRES A1B scenario, they have a negligible impact on upper stratospheric ozone changes, which in the SRES B1 scenario are therefore mainly determined by GHG-induced cooling. Similar sensitivity to ozone changes is simulated in the three RCP simulations that were performed by CAM3.5. The evolution of tropical stratospheric column ozone in the different GHG simulations is a combination of the upper and lower stratospheric behavior, and differences among the GHG scenarios are generally small, except that the 2-model mean of the SRES A2 simulations shows larger decreases in the 2nd half of the 21 century (~3 DU differences by 2100, see Figure 2b). This is further illustrated in Figure 3 which shows the sensitivity of stratospheric column, partial upper and partial lower stratospheric column to changes in CO₂ in the last decade of the 21st century. The tropics is the only region where a negative sensitivity of stratospheric column ozone to CO₂ is simulated (black regression line). This sensitivity arises from the lower stratosphere column contribution which is negative (green regression line) whereas in the upper stratosphere the sensitivity is positive (blue regression line).

[6] In the midlatitude upper stratosphere, differences between the 2090s and 2000s in the GHG-x simulations compared to REF-B2 are very similar to those in the tropics (Figures 1c and 1d), while in the lower stratosphere the inter-scenario spread in the 2090s-2000s ozone differences are less pronounced than in the tropics. The combination of upper and lower stratospheric behavior leads to smaller increases in stratospheric column ozone over the 21st century in the scenarios with lower GHG concentrations (Figures 2c and 2d). Larger differences are found in the northern midlatitudes between the highest and lowest RCP scenarios (RCP 8.5 and 2.6) in the CAM3.5 simulation (~20 DU by 2100), and also between the model mean REF-B2 and SRES B1 GHG simulations (~10 DU by 2100). In southern midlatitudes differences among the simulations are smaller than in northern midlatitudes (Figure 2d), which is also confirmed by the smaller sensitivity of stratospheric ozone to CO₂ changes in 2100 (Figures 3c and 3d). This inter-hemispheric difference in the midlatitudes has been noted previously [Shepherd, 2008].

[7] The springtime Arctic and Antarctic upper stratosphere has a similar behavior to the tropical upper strato-

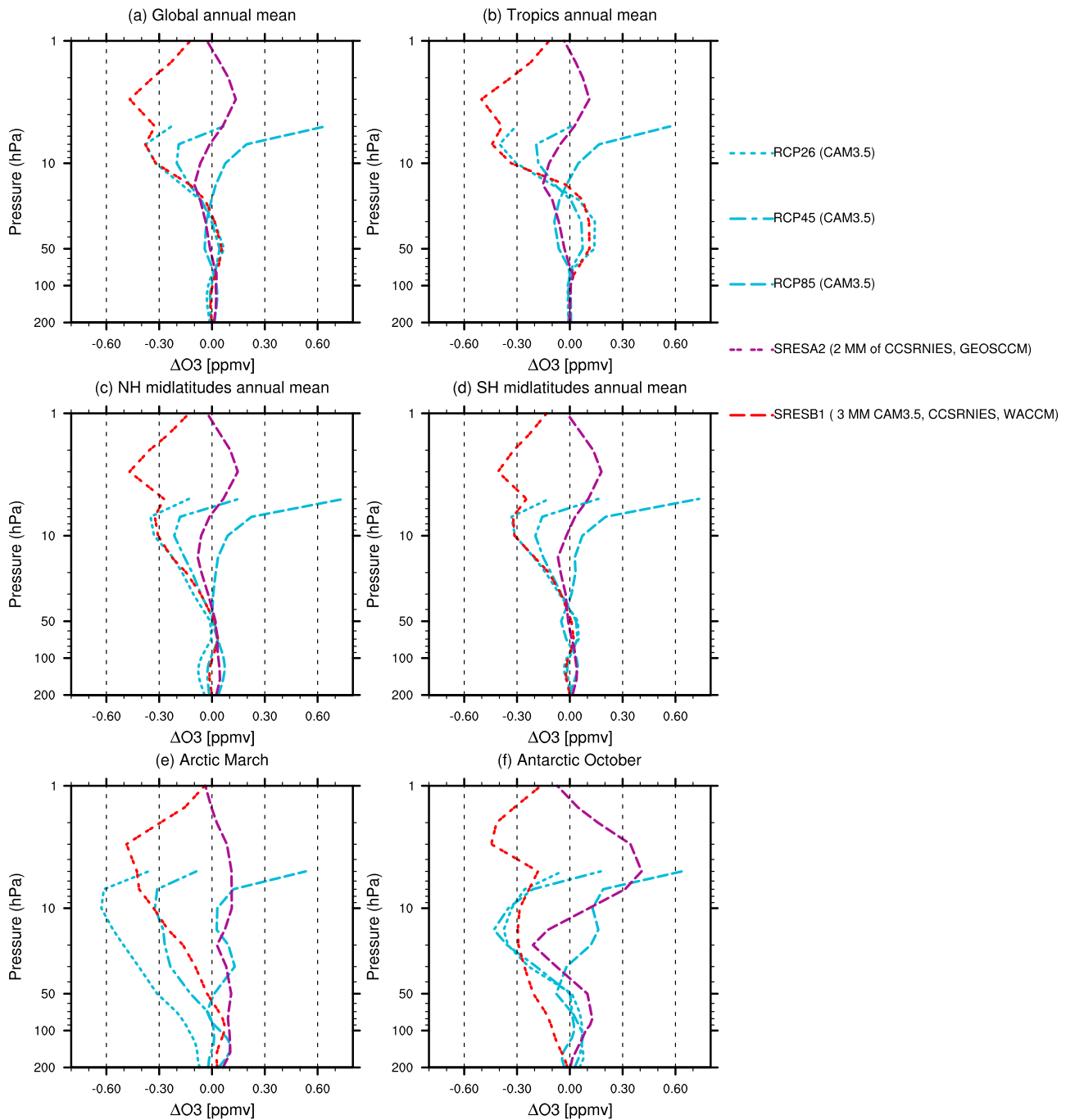


Figure 1. Differences in vertically resolved ozone between the 2090s and 2000s, and between the GHG-x simulations and REF-B2 simulations for (a) global (90°S – 90°N) annual mean, (b) tropical (25°S – 25°N) annual mean, (c) NH midlatitudes (35°N – 60°N) annual mean, (d) SH midlatitudes (35°S – 60°S) annual mean, (e) Arctic (60°N – 90°N) March mean, and (f) Antarctic (60°S – 90°S) October mean. For the SRES A2 and B1 scenarios which were used in simulations by more than one CCM, the 2- and 3-model mean (MM) is shown, respectively.

sphere (Figures 1e, 1f, 3e, and 3f). However, the 2-model mean of the SRES A1B and A2 simulations is more different in the polar regions than in the extratropics. In the Antarctic spring, differences in lower stratospheric ozone (Figure 1f) and stratospheric column ozone (Figure 2f) are generally smaller than in the Arctic, confirming that the evolution of Antarctic ozone in the 21st century is dominated by halogens rather than GHGs. However, as can also be seen in the simulations with GHGs fixed at 1960 con-

centrations of Eyring *et al.* [2010], climate change in the Antarctic does play a role and the column ozone trends in the SRES B1 simulation in the 3-model mean is smaller than in REF-B2, resulting in differences of ~ 10 DU by 2100. The springtime Arctic shows the largest regional sensitivity of stratospheric column ozone to the GHG scenario dominated by lower stratospheric changes (Figure 3e) and all CCMs consistently simulate lower ozone at all altitudes in the scenarios with GHG emissions lower than those

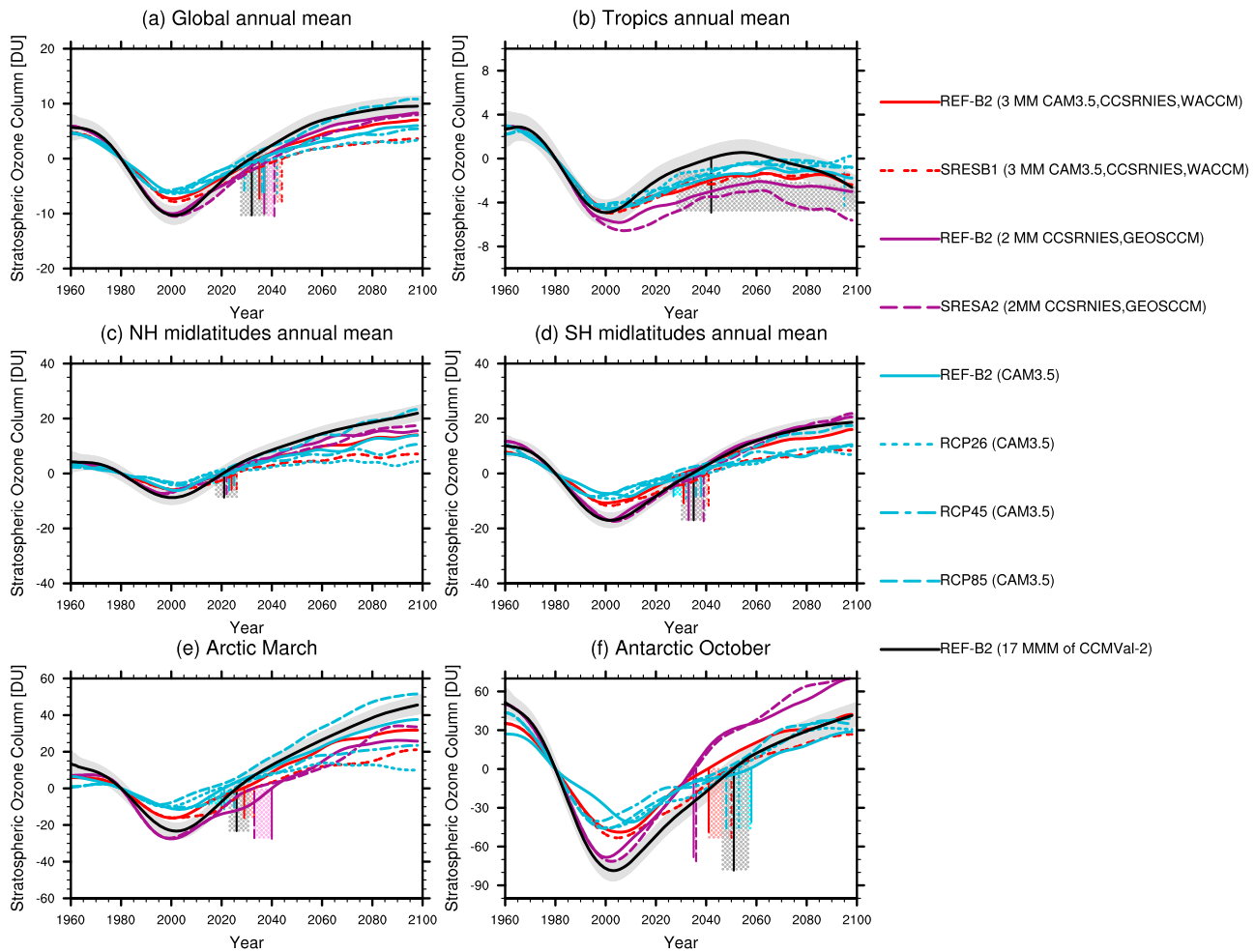


Figure 2. 1980 baseline adjusted stratospheric column ozone time series from 1960 to 2100 for REF-B2 and GHG-x simulated by the four CCMs (colored lines) and the multi-model mean of the 17 CCMs of *Eyring et al.* [2010] (black line). All time series by construction go through 0 in 1980. The grey shaded area shows the 95% confidence interval of the 17 CCMs' REF-B2 simulations. For the SRES A2 and B1 GHG scenarios which were performed by more than one CCM, the 2- and 3-model mean is shown, respectively. The vertical lines and colored shaded areas indicate 1980 ozone return dates from REF-B2 and GHG-x simulations, while the vertical grey shaded area gives the uncertainty in the 1980 return dates from the 17 CCMs REF-B2 simulations. The time series are smoothed with a 1:2:1 filter applied 30 times for the extra-polar regions and applied 90 times for the polar regions.

in REF-B2, and slightly higher ozone in the scenarios with GHG emissions higher than those in REF-B2 (Figure 1e). This results in large differences in springtime Arctic stratospheric column ozone between the CAM3.5 RCP 8.5 and 2.6 simulations (~ 40 DU by 2100) and between the model mean of REF-B2 and SRES A2 or SRES B1 (~ 10 DU by 2100), see Figure 2e.

4. Sensitivity of Ozone Return Dates to GHG Scenario

[8] A key milestone in the evolution of ozone through the 21st century is the return of ozone to mean 1980 values [WMO, 2007]. This date is different to the date of full recovery of ozone from ODSs (i.e. when ozone is no longer affected by ODSs) in part because of GHG induced changes in ozone and because of ozone loss that has already occurred before 1980 [Vaughn et al., 2009; Eyring et al., 2010]. The

effect of different GHG scenarios on 1980 return dates are assessed here based on simulations by the four CCMs.

[9] Under all six GHG scenarios, tropical ozone columns remain smaller than in 1980 until the end of the simulations in 2100 (Figure 2b). In the REF-B2 simulations, northern midlatitudes experience the earliest date of ozone returning to 1980 values, in around 2020. This explains that, despite the large differences among the GHG simulations in the long-term evolution of ozone (see Section 3 and Figure 2c), the variations in 1980 return dates are small (~ 10 years), because these differences occur mainly after stratospheric column ozone has returned to 1980 values. In southern midlatitudes, the differences between the GHG-x simulations become larger before or around the time when ozone returns to 1980 values (compare Figures 2c and 2d), thereby causing similar differences in ozone return dates. In the Antarctic in spring, differences in the long-term evolution of stratospheric column ozone among the GHG-x simulations are generally small except that slightly lower columns are

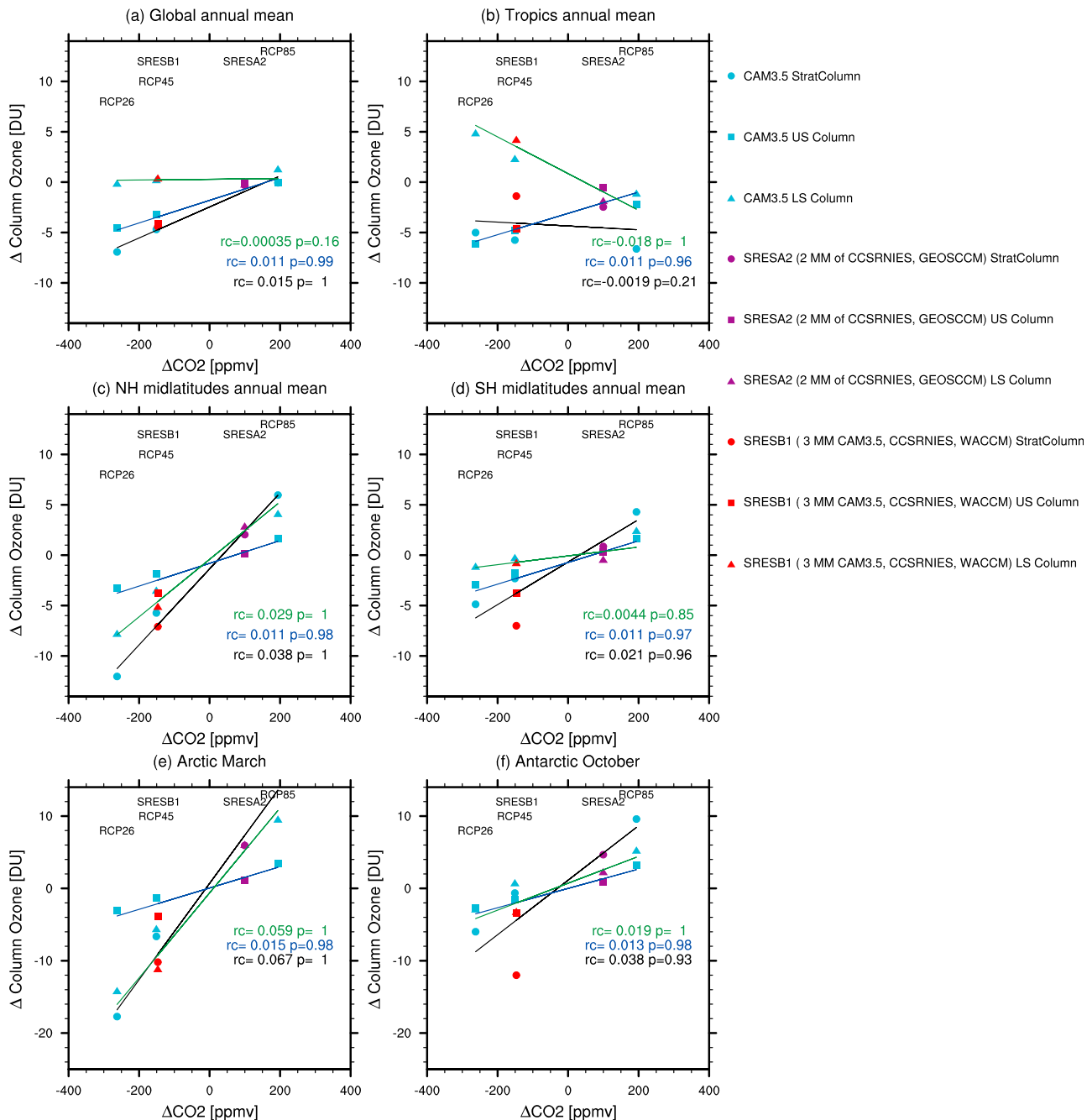


Figure 3. Partial column ozone vs. CO_2 differences between the GHG-x and REF-B2 simulations in the last decade of the 21st century. The black, blue and green lines show the linear-regressions for stratospheric column ozone (Stratcolumn: 200–0 hPa), upper stratospheric column (US: 20–0 hPa), and lower stratospheric column (LS: 200–20 hPa) in each plot, respectively. rc values indicate the slope of the linear regression, and p gives the probability that a 0 trend can be rejected.

simulated in the SRES B1 model mean. However, since in the REF-B2 simulations' spring-time total column ozone over Antarctica returns to 1980 values later than in any other region, this leads to differences in ozone return dates that are comparable to those in midlatitudes. In the Arctic in spring the largest differences in the long-term evolution of stratospheric column ozone are simulated among the GHG scenarios (Figure 2e), which however mostly occur after the time when stratospheric ozone returns to 1980 values. This is earlier than in Antarctica, and thus the impact on ozone

return dates for Arctic spring is similar to that in the Antarctic and midlatitudes (~ 10 years).

5. Discussion and Conclusions

[10] Projections of stratospheric ozone throughout the 21st century have been examined from four CCMs. In the future reference simulations (REF-B2), long-lived GHGs follow the SRES A1B scenario. In addition, five different GHG scenarios were analyzed and a first estimate was provided

on how the timing of the return of ozone to historical values might change under different GHG emissions scenarios.

[11] In the extra-polar upper stratosphere, increases in upper stratospheric ozone are smaller in the scenarios with reduced GHG concentrations due to less GHG-induced cooling. Increases in N₂O and CH₄ play a minor role in upper stratospheric ozone depletion under the SRES A1B and lower GHG scenarios. However, under the SRES A2 scenario, enhanced ozone destruction from NO_y and HO_x radicals partly compensate the positive influence on ozone due to GHG-induced cooling which leads to a very similar ozone evolution in the upper stratosphere between REF-B2 and SRES A2, confirming earlier results by *Oman et al.* [2010]. In the tropical lower stratosphere, a robust result simulated by all CCMs is a steady decline of ozone from 1960 to 2100 due to increased tropical upwelling in all GHG scenarios, confirming previous results [*Eyring et al.*, 2007; *Butchart et al.*, 2010]. The CCMs consistently show that higher (lower) GHG concentrations result in lower (higher) ozone due to increased (decreased) tropical upwelling.

[12] Because of compensating effects in the upper and lower stratosphere, differences in projected tropical stratospheric column ozone among the GHG simulations are small compared to extra-tropical regions (~3 DU by 2100). In the northern midlatitude stratosphere, differences in stratospheric column ozone among the GHG simulations are larger (~20 DU by 2100), but occur mainly after stratospheric column ozone is projected to have returned to 1980 values, thus causing only small changes in the ozone return dates (~10 years). In southern midlatitudes, the differences between the various GHG simulations are smaller, but occur partly before or around the time when ozone returns to 1980 values, thus causing a similar range in ozone return dates than in northern midlatitudes.

[13] The evolution of spring-time Antarctic stratospheric column ozone generally shows a smaller sensitivity to changes in GHGs than in the Arctic, and correspondingly only small changes are simulated among the GHG scenarios except for the SRES B1 simulation which is slightly lower than REF-B2 (differences of ~15 DU by 2100). This is consistent with results of the fixed GHG simulation analyzed by *Eyring et al.* [2010]. Since ozone returns to 1980 values late over Antarctica when ozone in the GHG scenarios has diverged, ozone return dates vary by ~10 years. In the Arctic in spring large differences among the GHG scenarios are simulated (~40 DU by 2100). However, these differences mostly occur after the time when stratospheric ozone returns to 1980 values, which is earlier than in Antarctica, so that the impact on ozone return dates is similar to that in the Antarctic and midlatitude.

[14] These results suggest that the uncertainty in the return of stratospheric column ozone to 1980 values is comparable to or less than the uncertainty that arises from model differences in the larger set of 17 CCMVal-2 SRES A1B simulations analyzed by *Eyring et al.* [2010]. This result is consistent with *Charlton-Perez et al.* [2010], who quantified the uncertainty in projections of stratospheric ozone. However, more CCMs will need to perform the GHG sensitivity simulations to arrive at more robust conclusions. It is hoped that this study will provide guidance on the potential advances in ozone projection which might be gained from such scenario simulations.

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