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An updated analysis of the attribution of stratospheric ozone and temperature changes to changes in ozone-depleting substances and well-mixed greenhouse gases

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Abstract

This paper presents an analysis of the attribution of past and future changes in stratospheric ozone and temperature to anthropogenic forcings. Recently, Shepherd and Jonsson (2008) argued that such an analysis needs to account for the ozone-temperature feedback, and that the failure to do so could potentially lead to very large errors. This point was illustrated by analyzing chemistry-climate simulations from the Canadian Middle Atmosphere Model (CMAM) and attributing both past and future changes to changes in the abundances of ozone-depleting substances (ODS) and well-mixed greenhouse gases. In the current paper, we have expanded the analysis to account for the nonlinear radiative response to changes in CO_2. It is shown that over centennial time scales the relationship between CO_2 abundance and radiative cooling in the upper stratosphere is significantly nonlinear. Failure to account for this effect in multiple linear regression analysis would lead to misleading results. In our attribution analysis the nonlinearity is taken into account by using CO_2 heating rate, rather than CO_2 abundance, as the explanatory variable. In addition, an error in the way the CO_2 forcing changes are implemented in the CMAM has been corrected, which significantly affects the results for the recent past. As the radiation scheme, based on Fomichev et al. (1998), is used in several other models we provide some description of the problem and how it was fixed.

The updated results are as follows. From 1975–1995, during the period of rapid ozone decline, ODS and CO_2 increases contributed roughly equally to upper stratospheric cooling, while the CO_2-induced cooling (which increases ozone) masked about 20% of the ODS-induced ozone depletion. From 2010–2040, during the period of most rapid ozone recovery, CO_2-induced cooling will dominate the upper stratospheric temperature trend and will contribute roughly equally with the ODS decline to ozone increases, effectively doubling the rate of ozone recovery.

1 Introduction

There has been considerable interest in global-mean stratospheric cooling as a fingerprint of ozone depletion (see e.g. Chap. 5 of WMO, 2007), since in the stratosphere, global-mean temperature is radiatively controlled. The traditional approach (e.g. Ramaswamy et al., 2001; Shine et al., 2003) has been to attribute the stratospheric cooling observed in the recent past to a combination of CO_2 increases and ozone depletion, the latter being attributed to the increase in the stratospheric abundance of ozone-depleting substances (ODS) up to about 1998. Shepherd and Jonsson (2008; hereafter SJ08) pointed out that this approach to attribution is not really correct, because ozone is not a forcing agent but rather is an internal property of the atmosphere, which (like water vapour) itself responds to anthropogenic forcings. Moreover ozone and temperature interact, especially in the upper stratosphere, so part of the past ozone changes in this region have been attributable to the increase in CO_2. In particular, CO_2-induced cooling (which increases ozone) has masked some of the ODS-induced ozone depletion.

SJ08 performed a theoretical analysis which untangled the ozone-temperature feedback and showed that the attribution of temperature changes to CO_2 and ODS changes could be quite different from that due to CO_2 and ozone changes. They illustrated their point by analyzing chemistry-climate simulations from the Canadian Middle Atmosphere Model (CMAM), which exhibited distinct linear trends in both temperature and ozone over 1975–1995 and 2010–2040, these two time periods representing the periods of approximately linear ODS buildup and ODS decline, respectively. The orthogonality of the CO_2 and ODS changes between these two time periods – with CO_2 increasing steadily, but ODS rising and then falling – allowed a simple statistical attribution of the ozone and temperature changes. SJ08 found that while about 10% of the ODS-induced upper stratospheric ozone depletion over the period of rapid ODS increases (1975–1995) was masked by CO_2-induced cooling, the traditional approach towards temperature attribution is largely valid over this period. In the future, however, full account needs to be taken of the CO_2-induced effects on ozone, as (according to SJ08) they will drive about 40% of the upper stratospheric ozone recovery over 2010–2040.

Unfortunately, the CMAM CCMVal-1 simulations used by SJ08 underestimated the impact of the CO_2 increase in the recent past, due to a problem related to the middle atmosphere radiation scheme. (This should be borne in mind when analyzing CMAM CCMVal-1 simulations.) This problem has been fixed in the recently completed CMAM CCMVal-2 simulations, and we therefore analyze those simulations here to provide an update of SJ08. A detailed description of the changes made to the radiation scheme is given in the Appendix as a documentation for other model groups using the same scheme. In addition, the analysis is expanded to account for the nonlinear relation between CO_2 abundance and heating rates, which results in a nonlinear response of temperature to CO_2 changes over centennial time scales. To our knowledge this effect has not previously been taken into account in statistical analysis of middle atmosphere trends (such as analysis using Multiple Linear Regression). The consequences of this nonlinearity for the attribution of upper stratospheric ozone and temperature changes are analysed.

2 Methods

The CMAM is a fully interactive three-dimensional chemistry-climate model (de Grandpré et al., 2000; Scinocca et al., 2008). Its performance in the SPARC CCMVal-1 model intercomparison was assessed by Eyring et al. (2006) and Waugh and Eyring (2008), where CMAM was found to be one of the better-performing models. The CCMVal-2 simulations analyzed here were forced with the SPARC CCMVal “REF2” scenario described in Eyring et al. (2005). The analysis is based on the average of an ensemble of three simulations.

There are three main differences between the CMAM versions used for the CCMVal-1 and CCMVal-2 simulations. The first and most important difference in the present context was the correction of the middle atmosphere radiation scheme. The details of this correction are described in the Appendix. In the CMAM simulations considered in SJ08 (CCMVal-1) the impact of the CO_2 change over 1975–1995 on temperature was underestimated by about a factor of 2–2.5 in the upper stratosphere, which means that the cooling over this period was unrealistically small. With the radiation scheme corrected, the CMAM temperature trends in the near past are now in line with other model results and observations (Shine et al., 2008).

The second difference was the use of an interactive ocean, rather than specifying sea-surface temperatures (SSTs) from a different coupled atmosphere-ocean model. However, using different SSTs would not be expected to lead to changes in global-mean stratospheric temperature and ozone, except perhaps in the very lowest part of the stratosphere (Fomichev et al., 2007).

The third difference was minor changes in the chemistry and transport schemes to address some deficiencies identified in the earlier version of CMAM. For the most part these would not be expected to lead to discernible effects in global-mean temperature or ozone, especially in the upper stratosphere. However, a larger set of representative ODS was used, which allowed a more realistic representation of their fractional release of chlorine, and this somewhat changed the time evolution of total inorganic chlorine.

Just as with the simulations analyzed by SJ08, global-mean ozone and temperature were found to evolve linearly in time at all stratospheric altitudes over the time periods 1975–1995 and 2010–2040. Thus, the simple statistical analysis of SJ08 is applicable. However, a deficiency in SJ08 is the assumption that temperature (and ozone) changes depend linearly on CO_2 changes. This assumption is only valid for small CO_2 changes. In fact, over centennial time scales the CO_2 heating rate sensitivity to CO_2 varies significantly, as is shown in Fig. 1. For example, over the extent of the CCMVal simulations, 1960–2100, the CO_2 mixing ratio increases from about 310 ppmv to about 700 ppmv and the CO_2 heating rate sensitivity decreases by about a factor of 1.7 around the stratopause (4–0.5 hPa). In the current attribution analysis we account for this effect by using the CO_2 heating rate as the explanatory variable (as opposed to the CO_2 abundance itself).

Note that while the CO_2 mixing ratio increases by roughly 50% over the analysis period 1975–2040 (from about 320 ppmv to about 480 ppmv), the CO_2 heating rates change by only about 10–15% (see Fig. A1 in the Appendix). So in the context of a linear attribution analysis the heating rate changes can be considered to be a small perturbation, while this is not the case for the CO_2 abundance. Moreover, the absolute CO_2 heating rate changes over 1975–2040 are generally less than 1 K/day (Fig. A1 in the Appendix), for which it is predicted that the temperature response in the middle atmosphere should be linear (Fomichev et al., 2004).

Our attribution uses the expressions (15)–(18) of SJ08. If CO_2 is used as the explanatory variable, then r (the ratio of the CO_2 increase over 2010–2040 to that over 1975–1995) is given by 3.0. If the CO_2 heating rates are used instead as explanatory variables, then r is given instead by 2.5. (Note that while the heating rates themselves vary significantly with height, r varies much less and is within 2.5±0.1 over 15–0.5 hPa.) The ratio of the ODS decrease over 2010–2040 to the increase over 1975–1995, denoted by s, is 0.44, which is about 20% smaller than the value from the CCMVal-1 simulations used in SJ08.

3 Results

Figure 2 shows the global mean ozone trend over both time periods as well as the attribution of the trend to changes in ODS and CO_2. The maximum ozone trend in the past (panel (a)) occurs at 2 hPa and is about 5%/decade, which is a little less than the 6%/decade found in SJ08. The difference results from the increased (i.e. corrected) past CO_2-induced cooling in these simulations. Both values are reasonably consistent with observations, given the uncertainties (see discussion in SJ08). In terms of attribution, it is found here that the increase in ozone from the CO_2-induced cooling masked about 20% of the ODS-induced ozone depletion in the upper stratosphere over this time period. In the future (panel (b)), the ODS decline and continued CO_2-induced cooling act in the same sense, to increase ozone, and contribute equally over nearly the entire stratosphere to ozone recovery – or stated differently, the ODS-induced ozone recovery is doubled by the effects of CO_2-induced cooling. Thus, in the future, ODS changes will no longer dominate the evolution of ozone in the upper stratosphere. In fact, the ozone recovery trend in the future is predicted to be fully two-thirds the magnitude of the ozone depletion trend in the past (3.5%/decade vs 5%/decade), even though the ODS-induced recovery trend is less than one-third the magnitude of the ODS-induced depletion trend.

Figure 3 is the same as Fig. 2 but for temperature. The maximum cooling in the past (panel a) occurs at 1 hPa and is about 1.7 K/decade, which is considerably larger than the 1.3 K/decade found in SJ08; this results from the increased (i.e. corrected) past CO_2-induced cooling in these simulations, and brings CMAM more in line with observations (Shine et al., 2008), although it should be kept in mind that the observed trends around the stratopause are associated with large uncertainties (Randel et al., 2009). In terms of attribution, it is found here that ODS-induced ozone depletion and CO_2-induced cooling have contributed approximately equally to upper stratospheric cooling, though with the ODS effect being a strong function of altitude; e.g. the ODS effect is 30% more than that of CO_2 at 1 hPa, and only 50% of it at 10 hPa. Note that if CO_2 abundance (as opposed to CO_2 heating rate) is used as the explanatory variable, this result changes drastically (Fig. 4): in that case the contribution from ODSs is much larger, such that the ODS-induced past cooling is estimated to equal that from CO_2 throughout the middle stratosphere up to 5 hPa, and to be about 80% more at 1 hPa. Therefore, multiple linear regression using CO_2 abundance as an explanatory variable over time scales encompassing both ozone depletion and ozone recovery must be used with care in the upper stratosphere. In the future (Fig. 3b), CO_2-induced cooling dominates the temperature trend, with the ODS-induced ozone recovery taking about a 20% bite out of the cooling trend in the upper stratosphere.

4 Discussion

Our analysis has focused on the changes in stratospheric global mean ozone and temperature due to CO_2 and ODS changes, as these have been shown to be the primary forcing agents for past changes and are expected to be the dominant agents in ozone recovery (Chaps. 5 and 6 of WMO, 2007). The expected effects of CH_4, N_2O and water vapour are discussed in SJ08.

Our updated results confirm the general point made by SJ08 that the ozone-temperature feedback needs to be taken into account when attributing changes in stratospheric ozone and temperature to their true forcing agents, which are ODS and well-mixed greenhouse gases. The quantitative details of SJ08 are modified, e.g. the masking of upper stratospheric ODS-induced ozone depletion in the past by CO_2 increases is now estimated to be 20% and the contribution of CO_2 increases to the future ozone recovery is now about 50%. The current analysis was performed using CO_2 heating rates rather than CO_2 abundance as explanatory variable, as it was found that the nonlinearity of the relation between the two was sufficiently large over timescales encompassing ozone depletion and recovery that using CO_2 abundance led to erroneous results. This fact should be taken into account in multiple linear regression studies, which traditionally use CO_2 abundance as the explanatory variable.

Note that there are significant compensatory effects between the two major changes applied to the analysis presented here compared to that presented in SJ08, that is, the correction of the CO_2 heating rate in the radiation scheme and the inclusion of the nonlinear response of CO_2 heating rates to CO_2 changes in the analysis. The differences between the attribution results presented here and those in SJ08 thus do not reflect the importance of the nonlinear dependence of the radiative response to CO_2 changes; the latter can be clearly seen by comparing Figs. 3a and 4 in this paper.

Appendix A

To calculate CO_2 heating rates in the middle atmosphere, the CMAM uses the matrix parameterization of Fomichev et al. (1998). This parameterization provides matrix coefficients for a set of reference CO_2 amounts (150, 360, 540 and 720 ppmv); to calculate the heating rates for an arbitrary CO_2 concentration, an interpolation of matrix coefficients between the reference points is applied. However, the matrix interpolation method suggested in Fomichev et al. (1998) provides inaccurate sensitivity of the heating rates to CO_2 changes near the reference point of 360 ppmv.

The matrix interpolation method suggested in Fomichev et al. (1998) utilizes the fact that the CO_2 dependence is present in matrix coefficients A_{ij} in both explicit and implicit forms and can be expressed as $c_{\mathrm{v}} \times F(c_{\mathrm{v}})$, where c_{v} is the CO_2 volume mixing ratio and F is some combination of second order exponential integrals. Based on this fact, linear interpolation of the values $\log(A_{\mathrm{ij}}/c_{\mathrm{v}})$ is recommended. While this method provides heating rates for arbitrary CO_2 concentrations within the parameterization accuracy of 0.3 K/day, it produces a slight discontinuity in the heating rate dependence on CO_2 near the reference points, which leads to an inaccurate sensitivity of the heating rates to CO_2 changes, in particular near the reference point of 360 ppmv, as can be seen in Fig. A1 (dashed curves).

The original interpolation procedure has been replaced with a standard 2nd order spline interpolation of A_{ij}. This correction provides a smooth dependence of the heating rate on CO_2 concentration throughout the entire range of CO_2 changes (Fig. A1, solid curves). The corrected interpolation procedure has been used for the CMAM CCMVal-2 simulations, which bring the CMAM temperature trend for the near past in line with other model results and observations (Shine et al., 2008).

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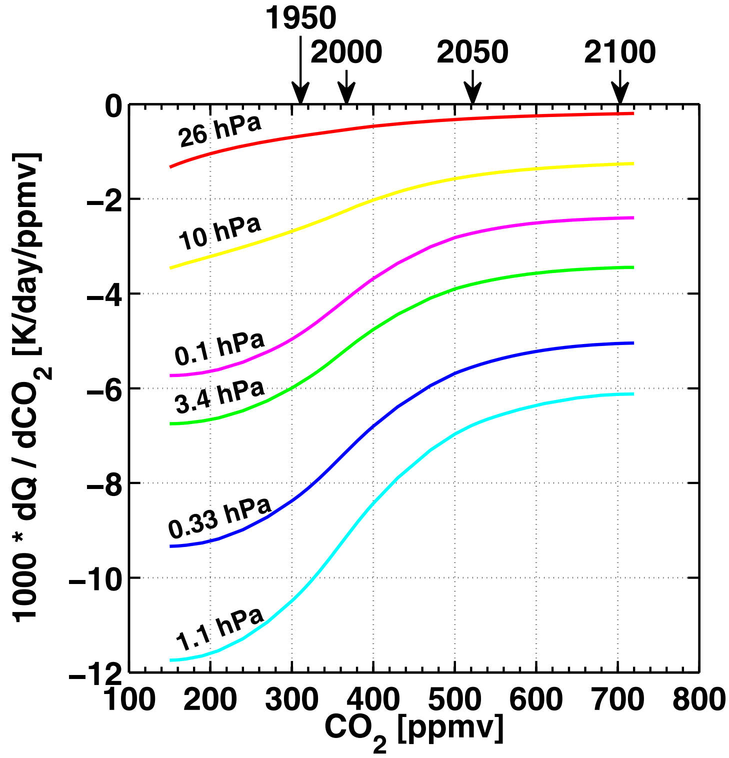

Fig. 1. Sensitivity of the CO_2 heating rate to CO_2 mixing ratio (derivative of the CO_2 heating rate with respect to CO_2 mixing ratio) as a function of CO_2 mixing ratio and pressure in the middle atmosphere. The heating rates were calculated according to the parameterization of Fomichev et al. (1998), with the suggested update outlined in the Appendix. The arrows at the top of the plot indicate the years by which a given CO_2 amount is achieved in the CCMVal "REF2" scenario.

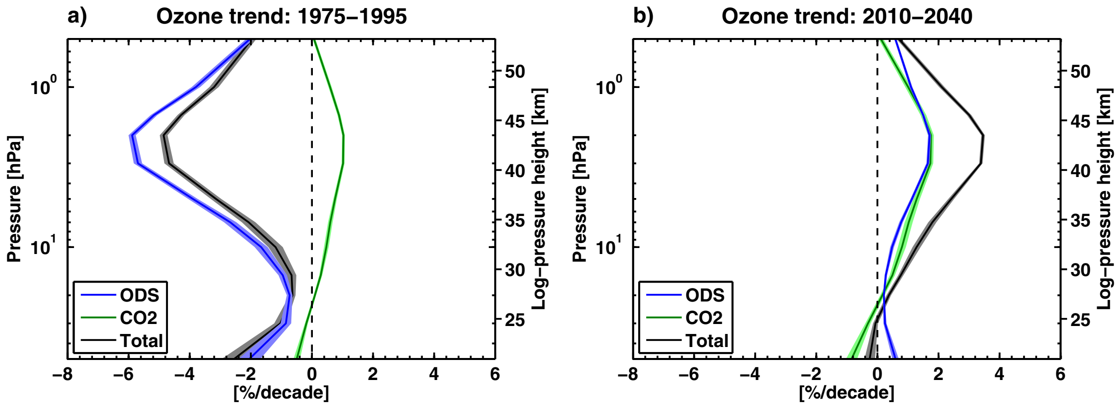

Fig. 2. Attribution of ozone changes over 50–0.5 hPa for the past (1975–1995) and future (2010–2040). The simulated ozone mixing ratio trend (%/decade) for the selected periods is shown in black while its contributions from CO_2 and ODS are shown in green and blue, respectively. The grey shaded areas indicate the 99% confidence intervals for the linear trend fits for the respective periods. The green and blue shaded regions indicate the 99% confidence intervals for the CO_2 and ODS attribution estimates (for details see SJ08). The approximate altitudes given on the right-hand side vertical axes are log-pressure heights assuming a constant vertical scale height of 7 km.

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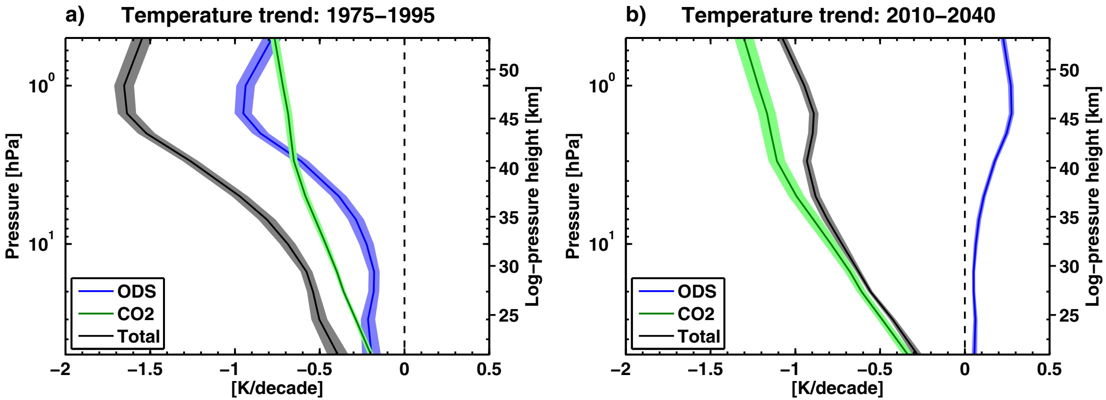

Fig. 3. Same as Fig. 2 but for temperature.

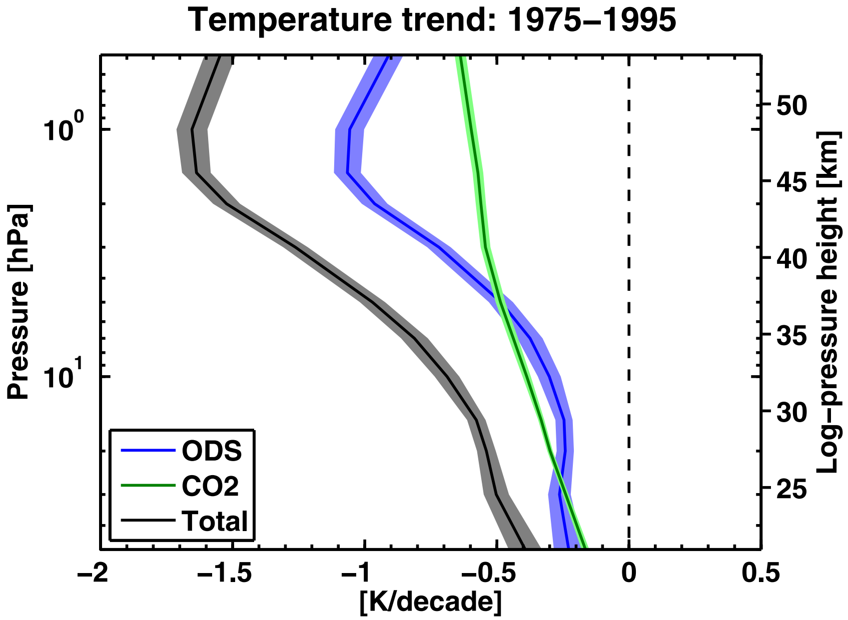

Fig. 4. Same as Fig. 3a but using CO_2 mixing ratio (as opposed to CO_2 heating rate) as the explanatory variable for the attribution analysis.

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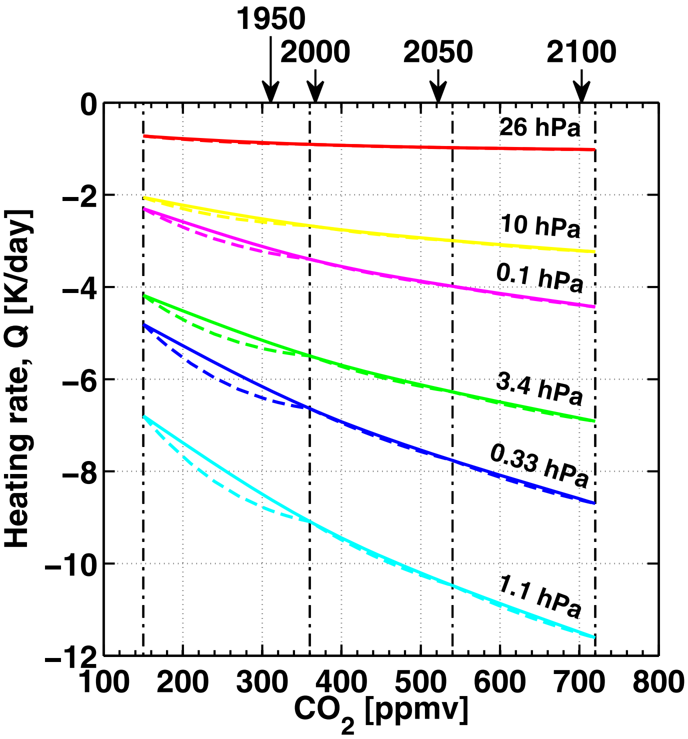

Fig. A1. Heating rate for CO$_2$ as a function of CO$_2$ mixing ratio and pressure in the middle atmosphere. The vertical dashed-dotted lines indicate the reference CO$_2$ amounts in the parameterization of Fomichev et al. (1998). The dashed curves show values achieved with the original method for interpolation of matrix coefficients (for details see text), which were used for the CMAM CCMVal-1 simulations. The solid curves show the corrected heating rates achieved with spline interpolation of matrix coefficients, which were used for the CMAM CCMVal-2 simulations. The arrows at the top of the plot indicate the years by which a given CO$_2$ amount is achieved in the CCMVal "REF2" scenario.