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Effects of changes in well-mixed gases and ozone on stratospheric seasonal temperatures

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[1] Monthly and seasonal stratospheric zonal-mean temperature trends arising from recent changes in stratospheric ozone and well-mixed greenhouse gases (WMGGs) are simulated using a general circulation model and compared with observed (1979–2000) trends. The combined effect of these gases yields statistically significant cooling trends over the entire globally averaged stratosphere in all months. In the Arctic (60°N–90°N), statistically significant trends occur only in summer and extend through the entire stratosphere. In the Antarctic (90°S–65°S), the simulations reproduce the observed seasonal pattern of the lower stratosphere temperature trend. Seasonal trends at 50 hPa are consistent with observed trends at all latitudes, considering model dynamical variability and observational uncertainty. The lack of robustness in simulated and observed Arctic winter trends indicates the futility of attributing these trends to trace gas concentration changes. Such attribution arguments may be made with greater confidence regarding middle and high latitude Northern Hemisphere summer temperature trends. *INDEX TERMS:* 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 1610 Global Change: Atmosphere (0315, 0325). **Citation:** Schwarzkopf, M. D., and V. Ramaswamy, Effects of changes in well-mixed gases and ozone on stratospheric seasonal temperatures, *Geophys. Res. Lett.*, *29*(24), 2184, doi:10.1029/2002GL015759, 2002.

1. Introduction

[2] Satellite and sonde observations have documented the presence of recent temperature trends in the stratosphere on both the annual-mean and the seasonal time scales [*Ramaswamy et al.*, 2001, hereinafter R01]. A new study [*Ramaswamy and Schwarzkopf*, 2002, hereinafter RS] has demonstrated that the observed changes in the annual-mean stratospheric temperature structure are reasonably well simulated by a general circulation model (GCM) by including the effects of observed changes in ozone and the well-mixed greenhouse gases (WMGGs) between 1979 and 1997. Here, we examine the monthly and seasonal temperature trends produced by the GCM simulations discussed in RS and compare these to recently available observed seasonal and monthly trends for the 1979–2000 period (R. Lin, personal communication). In evaluating these results, we pay particular attention to those time periods, latitude regions and altitude layers in which model trends are statistically significant, and those for which the observed trends show significance.

2. Model and Observations

[3] The model employed is the "SKYHI" 40-level GCM with specified sea-surface temperatures, described in further detail in RS. The computations in this study are those designated in RS as "Set B". Three equilibrium calculations are discussed: one (control) uses 1979 ozone concentrations and 1980 WMGG volume mixing ratios; the second (B1) uses 1997 ozone concentrations and 1980 WMGG volume mixing ratios; the third (B2) uses 1997 ozone concentrations and WMGG volume mixing ratios. The WMGG species included here, their concentrations and vertical distribution, the background ozone climatology (*Fortuin and Kelder* [1998]), the ozone depletion data (*Randel and Wu* [1999]), and the derivation of 1979 and 1997 ozone concentrations are described in RS. Each experiment is run for 21 model years; temperature trends (degrees per decade) are obtained from averages of the last 20 years of the control and perturbation simulations.

[4] The observations employed in this study are zonal-mean monthly and seasonal temperatures from the Microwave Sounding Unit (MSU) and Stratospheric Sounding Unit (SSU) instruments and from Berlin Northern Hemisphere (NH) radiosonde data. The MSU and Berlin observations extend from 1979 through 2000; SSU observations are available from 1979 to May 1998.

3. Simulation Results

[5] Monthly temperature trends for the global-mean, Arctic (60°N–90°N) and the Antarctic (90°S–65°S) from the B1 and B2 simulations are shown in Figure 1, together with altitudes and months where the student t-test indicates that temperature changes are statistically significant (with 95% confidence). The main feature of the global-mean results (panels (a)–(b)) is that a statistically significant stratospheric cooling trend is obtained for each month when the effects of changes in both ozone and WMGGs are included. This extends the finding in RS that the effects of changes in ozone and WMGGs produce a statistically significant cooling trend in the global, annual-mean stratosphere. In the lower stratosphere (50–100 hPa), the B1 and B2 simulations both give cooling trends of ~0.3K/decade, indicating that the effects of ozone changes dominate the global-mean signature in every season. The relative contribution of WMGGs to the total cooling trend increases with altitude in each month, as in the annual-mean result (RS). Upper stratospheric trends are 0.5–0.75 K/decade larger in all months when the effects of WMGGs are included, a result similar to recent findings by Langematz (U. Langematz, personal communication).

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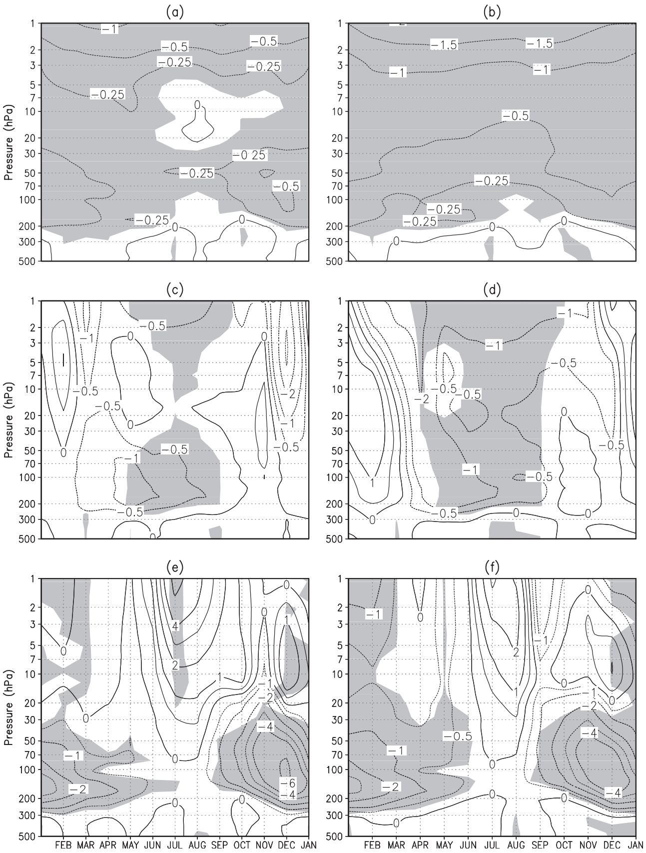

Figure 1. Simulated monthly-mean stratospheric temperature trends (K/decade) due to the observed stratospheric ozone depletion and WMGG changes between 1979 and 1997. Global-mean (a), Arctic (c), Antarctic (e) trends for experiment B1 (ozone-only). Global mean (b), Arctic (d), Antarctic (f) trends for experiment B2 (ozone+WMGGs). Areas with statistically significant trends (at 95%) are shaded.

[6] In the Arctic (panels (c)–(d)), the B1 and B2 simulations both predict statistically significant cooling trends in the lower stratosphere in May–September, with the B2 trends being somewhat larger. In the middle and upper stratosphere, the B2 result gives a statistically significant cooling trend (exceeding 1 K/decade in the upper stratosphere) at almost all altitudes, while the B1 simulation obtains cooling trends generally smaller than 0.5 K/decade. Neither simulation gives statistically significant temperature trends in other seasons. This lack of robustness results from the large interannual temperature variability in the model simulations, especially in winter and early spring (December–March). The results indicate that in high northern latitudes, summer is the only season in which the model response to the ozone + WMGG perturbation yields a response from which one can determine a temperature trend with high confidence. This inference is consistent with the ozone-only perturbation results of *Rosier and Shine* [2000] for the lower stratosphere and with conclusions drawn from sonde-based observations [*Labitzke and van Loon*, 1995].

[7] In the Antarctic (panels (e)–(f)) the B1 and B2 simulations both give similar, statistically significant cooling trends (reaching ~5–6 K/decade) in October–December in the ~50–150 hPa layer; significant cooling in the lowermost stratosphere (100–200 hPa) extends into May. The result indicates that lower stratospheric ozone losses are the dominant contributor to temperature trends in this region throughout the year, a conclusion that extends the ozone-only findings in *Langematz* [2000] and *Rosier and Shine* [2000], and in RS for the annual-mean. Both simulations also show a warming tendency at ~5–15 hPa in December–January, with the trend from B1 exceeding ~1 K/decade. This warming is expected as a consequence of compressional heating associated with change in the residual circulation RS. In January–February, the B2 result gives a statistically significant cooling trend in nearly all stratospheric altitudes, while the B1 result does not, a situation similar to the Arctic result for the corresponding season (July–August). Trends in Antarctic winter (June–August) are generally not significant, even when large (as in the upper stratosphere). As in the global-mean result, upper stratospheric cooling trends are smaller (or warming trends greater) in the B1 simulation in every month.

4. Comparisons with Observed Trends

[8] Figure 2 displays zonal-mean, monthly-mean temperature trends for the 50–100 hPa layer from the B2 (panel (a)) and B1 (panel (b)) simulations, with the shading denoting domains where these trends are statistically significant at the 95% confidence level. Also shown are zonal-mean, monthly-mean MSU (Channel 4) trends (panel (c)) and SSU (15x) trends (panel (d)), with the regions and months of significance shaded. The observed monthly trends have been evaluated using the least-squares method. The trends are considered significant when the temperature change for a given month over the entire observational period evaluated using the calculated trend exceeds twice the standard deviation of the de-trended observed time series for that month.

[9] In the Antarctic, the simulations yield a cooling trend of at least 2 K/decade in October–December, with the largest magnitude between mid-November and mid-December; this result is similar to findings from other studies [*Rosier and Shine*, 2000; U. Langematz, personal communication]. Trend estimates for these months derived from the MSU measurements agree well in timing with those from the model simulations, but are slightly smaller in magnitude. The corresponding cooling trends from the SSU instrument are similar to those from the model simulations, but peak slightly earlier. Since the SSU instrument weighting function peaks at ~50 hPa, while that of the MSU peaks at ~90 hPa, this temporal pattern is roughly consistent with results in Figure 1 (e–f) which shows the peak Antarctic spring cooling occurring earlier at lower pressures. The model cooling trends remain significant during December–May, in general correspondence with the observations (especially MSU). The lack of significance in the MSU trends in October–November is at least partially due to the choice of the end year 2000; for instance, the 1979- May 1998 MSU trends (R01) in the Antarctic are statistically significant in November (as are the SSU trends for that time period).

[10] In high latitudes of the NH, the model simulations and the MSU and SSU observations yield a statistically significant cooling trend in summer (June–August) ranging from 0.5 to 1 K/decade in the simulations, and exceeding 0.5

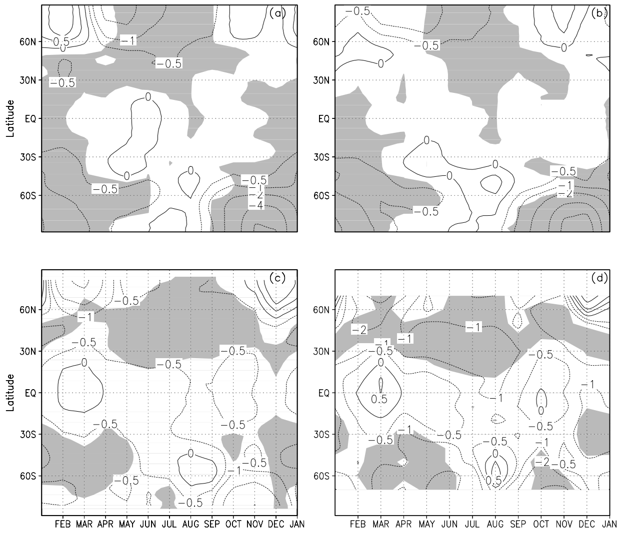

Figure 2. Latitude-month temperature trends (K/decade) in the 50–100 hPa altitude region. (a) experiment B2; (b) experiment B1; (c) MSU (Channel 4) observations (1979–2000); (d) SSU 15x observations (1979–May 1998). Regions with statistically significant trends (at 95% for the simulations and at 2-sigma for the observations) are shaded.

K/decade in the observations. The similarity between the B1 and B2 temperature trends in this season indicates that ozone change is the principal contributor to temperature change, as in the Antarctic. In the winter (December–March), the B1 result gives some cooling throughout the period, while the B2 simulation shows pronounced warming in December–February, with cooling only after mid-March. However, neither model trend shows any statistical significance in this season. The MSU and SSU observations show warming in December and early January, but cooling after late January. Again, however, the magnitude and significance of these trends depend greatly on the choice of the end year; thus, the MSU March polar cooling trend for 1979–1998 (R01) is far larger and more statistically significant than the corresponding trend for 1979–2000 (panel (c)).

[11] In low and middle latitudes, the model simulations and the MSU and SSU observations show a cooling trend in almost all months. In the tropics, both the B1 and B2 simulations predict statistically significant cooling only in December–February, while the MSU and SSU trends have no significance in any month. The situation differs somewhat in mid-latitudes of the NH; here the B2 simulation gives cooling trends 40–80% larger than those from B1 in all months except autumn (September–November); further, the trends from B2 attain statistical significance (at a 95% confidence level) in all such months. This strongly suggests that WMGGs have enhanced the cooling trends in this region. MSU and SSU trends in this region attain significance in most months, similar to the B2 result; the observed mean trend estimates (especially SSU) are generally larger than those from the B2 simulation.

[12] Figure 3 displays zonal-mean seasonal trends from model simulations and from satellite and sonde observations (1979–2000) at 50 hPa in the boreal winter (DJF, panel (a)) and summer (JJA, panel (b)). The estimated errors in the observed trends and the statistical significance of the model trends are also shown. In DJF, both the B1 and B2 simulations predict statistically significant cooling trends in the Southern Hemisphere (SH) and low latitudes of the NH. The model simulations in the Antarctic give a somewhat larger cooling trend than the observations, but the differences are smaller than the uncertainties in model and observed trend estimates in that region. Neither model result gives a statistically significant trend poleward of ~40°N. The B2 simulation gives a larger cooling trend than the B1 result in northern mid-latitudes (and shows significance for an additional fifteen degrees in latitude), suggesting a role for WMGGs in the cooling trends in this region (see also Figure 2). The observed trends predict statistically significant cooling in the ~30°N–50°N region, consistent with the annual-mean result (RS). In the Arctic, trends lack significance in both the models and the observations; even the sign of the trend (if any) remains unclear.

[13] In JJA, model cooling trends are significant (generally ~0.5 K/decade) for the entire NH, and extend to ~40°S, while the observed trends are significant in all of this latitude range except for equatorial latitudes. As in the winter case, in northern mid-latitudes, the B2 simulation (which includes WMGGs) agrees better with trend estimates from observations than the B1 results. The agreement between the B2 trend and the observed trend estimates in middle and high latitudes of the NH indicates the strong possibility of attribution of the temperature trends in these regions to the changes in ozone and WMGGs. The relative lack of variability (and hence statistical significance) in model calculations near the equator is likely due to the inability of the GCM to simulate the quasi-biennial oscillation. In the Antarctic, model simulations show little trend, while the MSU cooling trend is significant; again, the choice of end points of the time series is important, as the MSU cooling trends for 1979–1998 in June–August (R01) are smaller and show no significance.

5. Discussions

[14] The results of this study indicate that the observed monthly and seasonal stratospheric temperature trends in the 1980–2000 period are reasonably well accounted for by a GCM simulation including the effects of changes in stratospheric ozone and well-mixed greenhouse gases during that period. This model simulation produces a statistically significant global-average cooling trend in all months, as well as significant trends in the Arctic summer stratosphere and the Antarctic spring and summer lower stratosphere (Figure 1). In the lower stratosphere, the latitude-month patterns of temperature trends are generally consistent with the MSU and SSU observed patterns, in regions where temperature trends are significant (Figure 2); at 50 hPa, the simulated temperature trends are consistent with observed trends in all latitudes in both winter and summer, when uncertainties in the simulated and observed trends are taken into account (Figure 3).

[15] The importance of inclusion of the effects of WMGGs, demonstrated for the annual-mean in RS, is also evident in the seasonal-mean results; in every month, upper stratospheric cooling trends in the B2 (ozone + WMGG) simulation exceed those of the ozone-only (B1) simulation by 0.5 to 0.75 K/decade. In the lower stratosphere, the effects of WMGGs are most important in the mid-latitudes

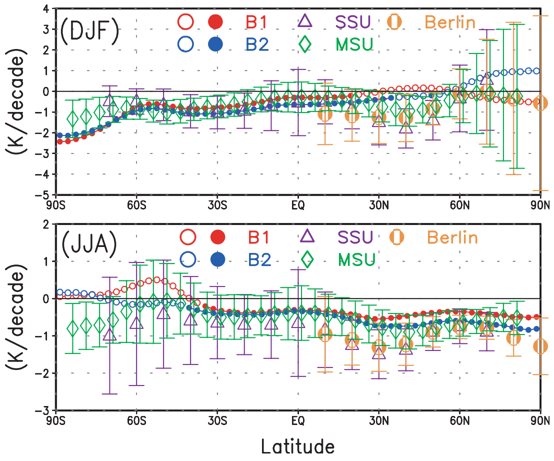

Figure 3. Zonal-mean temperature trends (K/decade) for December-February (top panel) and June-August (bottom panel) from satellite (MSU Channel 4, SSU 15x) and radiosonde (Berlin 50 hPa) datasets, and 50–100 hPa model trends (circles). Vertical bars denote 2-sigma observational uncertainties. Filled circles denote statistically significant (at 95%) model trends.

of the NH, where cooling trends in December–August are enhanced by up to 80%. Inclusion of these effects in this region gives simulated temperature trends that correspond to the observed trends (taking into account model and observational uncertainty), especially in summer. By contrast, the effects of ozone are the dominant contributor to Arctic and Antarctic temperature trends for all months in which the trends are robust.

[16] Results from this study indicate that in the mid-to-high latitudes of the NH, summer is a better season than winter for carrying out attribution studies that compare observed temperature trends with trends from simulations incorporating trace gas changes. Here, we conclude that stratospheric ozone losses and WMGG changes have likely played a large role in causing the recent mid-to-high latitude NH summer temperature trends. On the other hand, it is not possible and could be meaningless to make such inferences for temperature trends in high latitudes of the NH during winter and early spring. This stems from the large interannual variability in temperatures in this region and season, together with the overly short duration (20 years) of the data considered here in obtaining trend estimates. The observed temperature trends (as well as their significance) depend substantially on the starting and ending times chosen for trend calculations. As an example, the MSU cooling trend in March near the North Pole is ~7.6 K/decade when evaluated from 1979 to 1997, but only ~4.7 K/decade (not statistically significant) when evaluated from 1979 to 2000. Further, model dynamical variability is far larger in the NH winter than in the summer (as in observations), and at present it is not possible to separate the effects of this variability from the model temperature time series.

[17] One limitation in this study is that the model trends are obtained as the difference between two equilibrium simulations. In future work, it would be highly useful to run transient model simulations that account for the year-by-year changes in ozone and WMGGs, and to compare those results with the equilibrium simulation results. A more realistic representation of the vertical profile of the non-CO_2 WMGGs may also be desirable; however, a supplementary calculation indicates that WMGG-induced effects are dominated by the change in CO_2, except in the immediate vicinity of the tropopause. In addition, inclusion of the effects of changes in water vapor may decrease the remaining differences between model-simulated and observed trends in mid-latitudes of the NH [*Forster and Shine*, 2002; RS]; however, this may not hold for all latitudes. This suggests that factors other than water vapor may also need to be considered to improve the agreement between the model and observed temperature trends.

[18] **Acknowledgments.** We are grateful to the SPARC-STTA group for the data on stratospheric temperature trends. W. Randel provided the ozone trends data used here. R. Lin provided updated stratospheric temperature trends through 2000. J Austin provided monthly SSU temperature trends.

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