GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 20, PAGES 3089-3092, OCTOBER 15, 1999

A stratospheric ozone trends data set for global modeling studies

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Abstract. A global stratospheric ozone trends data set is described, providing monthly profile trend estimates derived for the period 1979-1997. SAGE I/II profile trends are used above 20 km outside of polar regions, and results between the tropopause and 20 km are derived by differencing SAGE and TOMS column ozone trends. In polar regions trends are derived from ozone sonde data up to 27 km, using the near-complete profile records at Syowa (69°S) and Resolute (75°N). While these polar ozonesonde trends agree well with TOMS outside of polar night, the Arctic data furthermore indicate significant ozone losses beginning in midwinter (January) that are not observable in TOMS data.

Introduction

The effects of stratospheric ozone loss during the last two decades are important for modeling and attribution of global change. The studies of *Santer et al.* [1996], *Tett et al.* [1996] and *Bengtsson et al.* [1999] show that stratospheric ozone change is a crucial ingredient for modeling the detailed vertical structure of temperature changes in the troposphere and lower stratosphere. Modeling studies also confirm that ozone loss is a dominant mechanism leading to cooling of the lower stratosphere over 1979-1996 [*Ramaswamy et al.*, 1996; *Graf et al.*, 1998; *WMO*, 1999]. In order to accurately model and assess the impacts of stratospheric ozone depletion, it is important to have detailed knowledge of the observed trends. To this end, we present here an updated climatology of ozone trends for use in global modeling studies.

The profile trend results discussed here are derived over the majority of the globe from Stratospheric Aerosol and Gas Experiment (SAGE) I and II data [*McCormick et al.*, 1989]. These data have recently undergone extensive evaluation, and they have been used to estimate near-global trends (through 1996) by *SPARC* [1998]. We furthermore use column ozone trends derived from the Total Ozone Mapping Spectrometer [TOMS, *McPeters et al.*, 1996] in conjunction with SAGE I/II to derive trends below 20 km (the SAGE I/II data are not of sufficient quality below this altitude). Because polar regions are not observed throughout most of the year by SAGE, we use profile ozone trends derived from ozonesonde measurements at Syowa (69°S) and Resolute (75°N), which have reasonably complete records over 1979-1997 up to ~ 27 km. Upper stratospheric polar regions are extrapolated from high latitude SAGE I/II trends. A novel aspect of using the ozonesonde data in polar regions is that trend estimates are available throughout the year, even during polar night (when TOMS data are unavailable). The results show substantial ozone losses in the Arctic beginning in midwinter (January). These large winter trends may have substantial effects on the modeled thermal response of the Arctic lower stratosphere, where the largest temperature changes are observed (see *Randel and Wu*, [1999] and *WMO*, [1999]).

Paper number 1999GL900615.
0094-8276/99/1999GL900615$05.00

Data and Analyses

The global trends data described here result from combining trends from satellite data (SAGE I/II and TOMS) over most of the globe (56°N-S), together with ozonesonde profile trends over both polar regions. This merging of data sets is shown schematically in Figure 1. The domain covers the globe, from the climatological tropopause (derived from NCEP reanalyses, *Kalnay et al.*, [1996]) to 50 km, with a spatial sampling of 4°latitude and 1 km. Trends for each month are derived for the period 1979-1997 (except for TOMS data which cover only 1979-1994) using a multivariate linear regression analysis, as described in *SPARC* [1998]. Standard errors are estimated using bootstrap resampling [*Efron and Tibshirani*, 1993]. Trend results are available in terms of both ozone density and percentage tendencies (the latter calculated with respect to the 1979-1997 time average).

Trends over 56°N-S, from 20-50 km, are derived from SAGE I/II profile data [see *SPARC*, 1998, for details]. SAGE I data cover the period 1979-1981. The SAGE II data use the version v5.96 retrieval algorithm, with data spanning late 1984-1997. Data are omitted for 1-2 years following the eruption of Pinatubo in June 1991, following the recommendations in Table 2.2 of *SPARC* [1998].

Trends between the tropopause and 20 km over 56°N-S are estimated by taking the difference between SAGE I/II partial column trends (integrated over 20-50 km), and total column ozone trends derived from TOMS [as shown in *McPeters et al.*, 1996]. This neglects any contribution from tropospheric ozone trends, and also ignores the temporal differences between SAGE I/II (1979-97) and TOMS (1979-94) data. We convert the (TOMS-SAGE) column difference trend into an altitude-dependent trend between the tropopause and 20 km by assuming (for simplicity) a constant

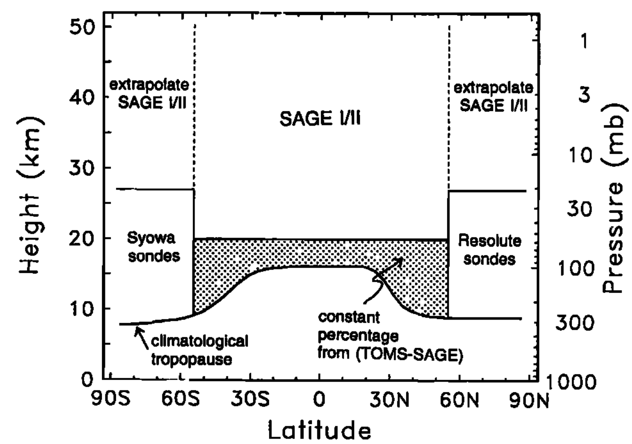

Figure 1. Schematic diagram showing the sources of data for the global ozone trends estimates.

percentage trend in this region, converting to ozone density by using a climatological background from *Fortuin and Kelder* [1998]. Application of this difference technique gives results in NH midlatitudes that are in reasonable agreement with ozonesonde trends (as shown below). However, in the tropics (~20°N-S) the (TOMS-SAGE) differences produce positive trends below 20km: the integrated SAGE I/II trends are small but negative (~ -2.9 ± 3.1 DU/decade), while TOMS has near zero trends in the tropics (~ -1.4 ± 2.0 DU/decade). Although these trends are small and not statistically significant, the small positive differences result in large percentage trends below 20 km (of order + 10% per decade), because the background ozone density profile is very small in this region. Such large positive trends in the tropics over 16-20 km are very different from the negative trends in this region derived from SAGE II-only data (see *SPARC* [1998], and updated results in *Randel et al.* [1999]). The positive tropical trends over 16-20 km are likely an unrealistic result of the (TOMS-SAGE) difference technique, possibly due to the shorter time sample of TOMS, the neglect of tropospheric ozone trends, or statistical uncertainties. We remove these results by simply setting the trends to zero below 20 km in these positive regions. Standard errors for the trend estimates below 20 km use the SAGE I/II estimates at 20 km, extended downward with constant percentage values.

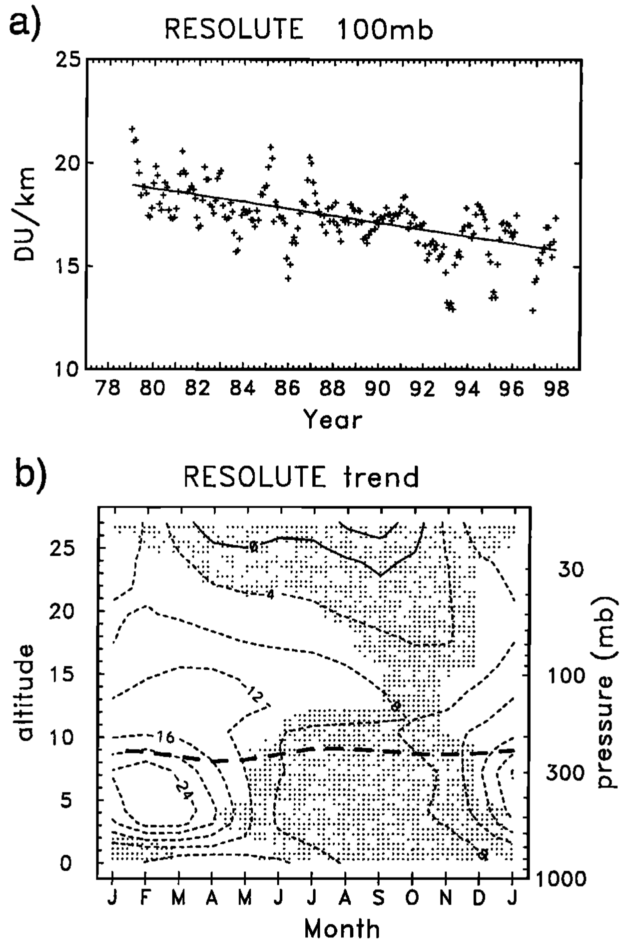

Figure 2. (a) Time series of 100 mb ozone density at Resolute. The average seasonal cycle has been removed in order to highlight the long-term trend. (b) Monthly trends derived from the Resolute ozonesonde data, in units of percent per decade (with respect to the 1979-1997 means). Shading denotes statistically insignificant trends. Heavy dashed line denotes the climatological tropopause.

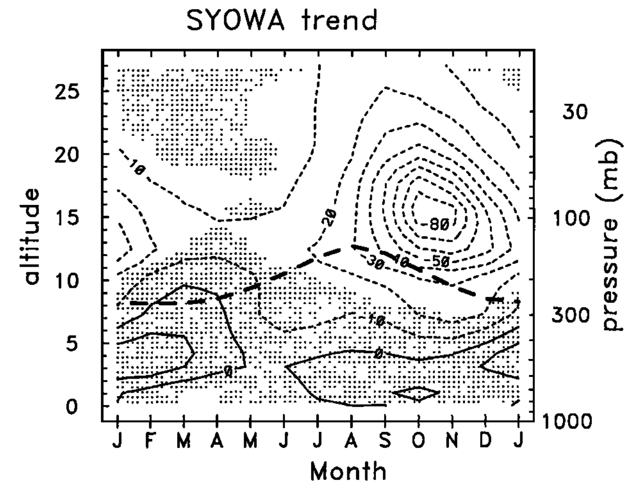

Figure 3. Ozone trends derived from Syowa ozonesonde data over 1979-1997. Details are the same as in Figure 2, but the contour interval is 10% per decade.

Ozone profile trends in polar regions are derived from ozonesonde data. For the Antarctic we use data from Syowa (69°S), while Arctic results are derived from time series at Resolute (75°N). Both of these stations have relatively complete profile records extending over 1979-1997. Figure 2 shows time series of (deseasonalized) 100 mb ozone anomalies at Resolute, together with the seasonally varying trends, and Figure 3 shows the trends at Syowa. These trends are shown for altitudes ~ 0-27 km (up to the 20 mb pressure level), but only values above the climatological tropopause are included in the global trend compilation.

The profile trends at Resolute (Figure 2) show a strong seasonal variation, with maximum negative trends during winter-spring (January-April). Trends in the lower stratosphere are of order –10 to –15% per decade, and larger percentage trends are observed below the climatological tropopause (up to –25% per decade over ~ 4-7 km). The negative trends during winter-spring are accentuated by the low ozone amounts observed in the 1990's (see the time series in Figure 2); these low values are observed at several Arctic stations [*Fioletov et al.*, 1997], and also in springtime TOMS observations [*Newman et al.*, 1997]. The Resolute trends are much smaller (and not statistically significant) during NH summer. Trends at Syowa (Figure 3) show very large negative trends during September-December over altitudes of ~ 12-20 km, associated with the ozone hole. Although ozone loss in the Antarctic has not been linear during 1979-97 (there were relatively rapid decreases during the middle 1980's and almost complete depletion at some levels during the 1990's), a linear trend fit allows quantification of change in a globally consistent manner. Maximum derived trends are near ~ 80% per decade near 100 mb in October-November, corresponding to an almost complete loss of ozone over 1979-1997. In the lower stratosphere, significant negative trends extend into the summer (~ March).

The global trend data use the Syowa ozonesonde trends as a constant percentage over 60°-90°S, and likewise for the Resolute data over 60°-90°N. The trends are smoothed across the latitude boundaries to provide a continuous final product. For altitudes above 27 km in polar regions, we use extrapolated SAGE I/II percentage trends (i.e., the trends at 56°N or S held constant to the pole).

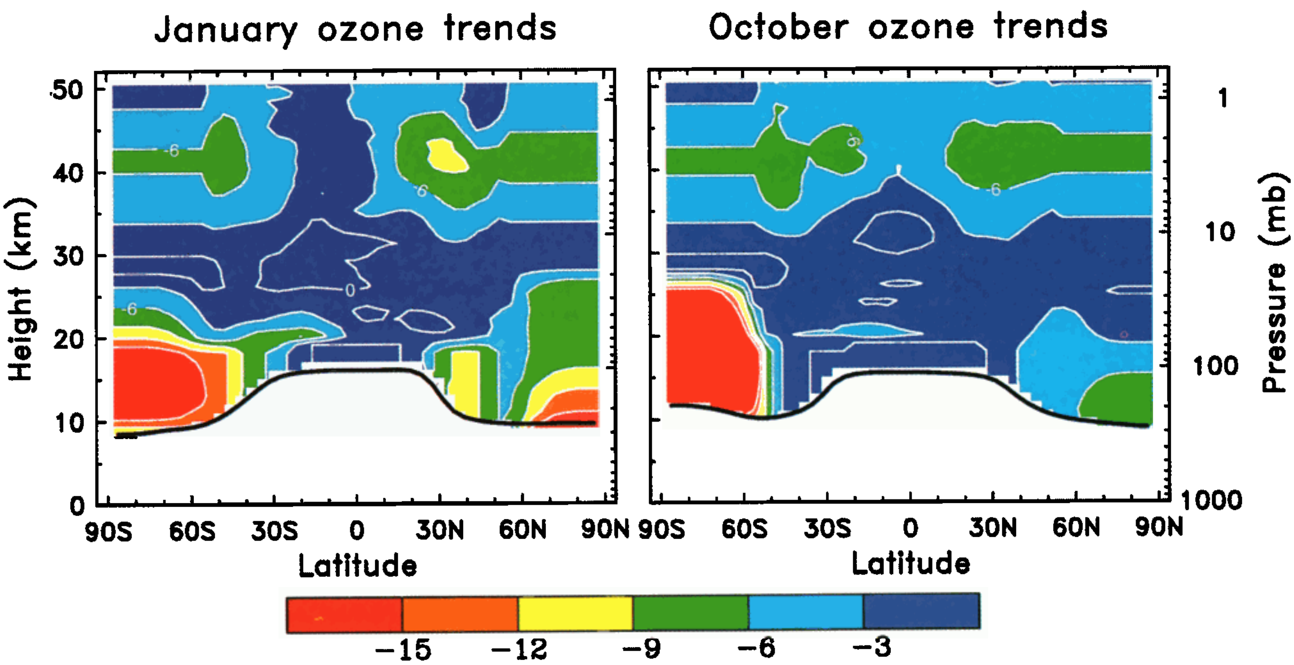

Figure 4. Global ozone trends for January (left) and October (right), shown in units of percent per decade. The local 95% statistical significance levels are on the order of 3-5 percent per decade.

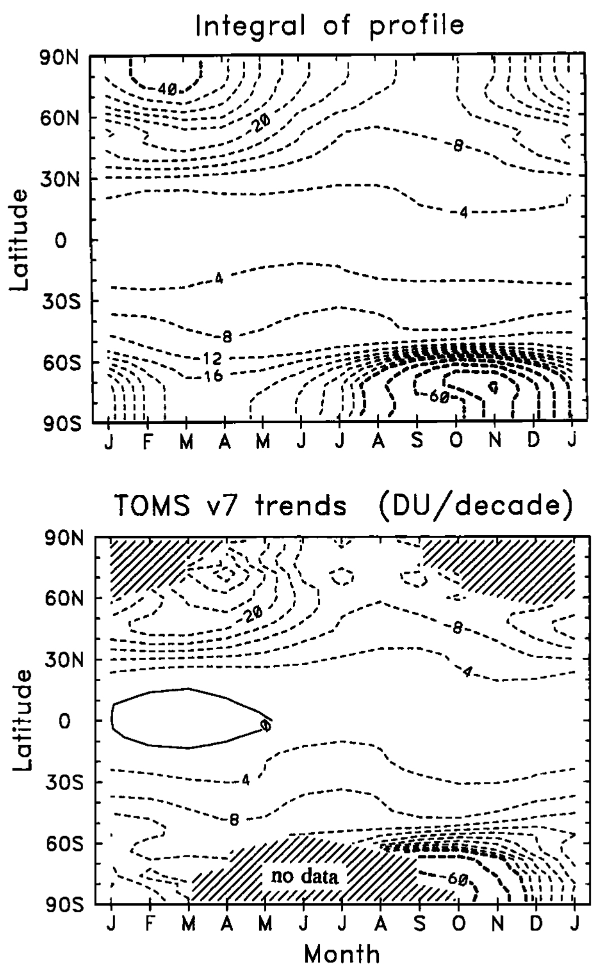

Figure 5. Trends in column ozone (DU/decade) derived from the vertically integrated profile data (top) and TOMS data (bottom).

Global Trend Results

Global trend estimates are produced for each month. Figure 4 shows cross sections of the trends for January and October. Upper stratospheric trends peak near 40 km in midlatitudes, with values of order –6% per decade. An approximate factor of two seasonal variation is evident in the upper stratosphere [see *SPARC*, 1998], with maximum negative trends during winter (see the January NH maximum in Figure 4). A relative minimum in the trends is observed in the middle stratosphere (~ 30 km). Trends in the lower stratosphere show values of order ~ -3 to–10% per decade in middle latitudes, and larger negative trends in polar regions. There is a strong seasonal variation in these trends in both middle and polar latitudes (see Figures 2-3).

The latitude-month variation of the vertically integrated ozone trends (between the tropopause and 50 km) is shown in Figure 5, expressed in units of Dobson Units (DU)/decade. Also shown in Figure 5 are column trends derived from TOMS [*McPeters et al.*, 1996]. The vertically integrated profile trends and TOMS results are nearly identical over 56°N-S, except for very small differences in the tropics introduced by the zeroing of profile trends below 20 km (discussed above). The two estimates of trends in polar regions in Figure 5 are completely independent, and we note there is quite good agreement in magnitude and seasonality for sunlit periods where TOMS data are available. The vertically integrated profile trends furthermore provide column trend estimates for polar night conditions. Results in the NH (from Resolute data, i.e., Figure 2) show substantial ozone losses during midwinter (January-February) that are not available from TOMS. We note that independent ozone and temperature data sets in the Arctic support the reality of these trends, as discussed in detail below.

The majority of the column ozone trends in middle and high latitudes seen in Figure 5 occur at altitudes below 20 km. In middle latitudes (equatorward of 56°N/S) the trends below 20 km are derived here as a difference between TOMS and SAGE data. It

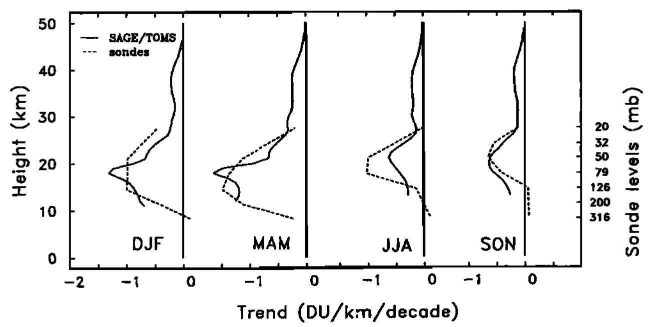

Figure 6. Seasonal variation of trends in ozone density over 40-53°N derived from ozonesondes (dashed) and SAGE/TOMS data (solid lines). Two sigma uncertainties over 15-20 km are of order ± 0.5 DU/km/decade.

is useful to compare these indirectly estimated trends with ozonesonde results over NH midlatitudes [the only region where long time series of ozonesonde data are available – see *SPARC* 1998]. Vertical profiles of trends derived from seven ozonesonde stations over 40-53°N are shown in Figure 6, compared with the SAGE and (TOMS-SAGE) results over the same region. Trends in Figure 6 are shown for each season, in units of ozone density tendency (DU/km/decade). Overall there is reasonable agreement between these data in terms of both magnitude and vertical structure, demonstrating that the (TOMS-SAGE) difference technique is appropriate in NH midlatitudes. Furthermore, the trends derived from ozonesonde data in NH midlatitudes show a strong seasonal variation in the lower stratosphere, with maxima during winter-spring, in agreement with the seasonality derived from the satellite data here.

4. Summary

We have described a global data set representing the seasonally-varying trends in stratospheric ozone over the period 1979-1997. These trends are based on SAGE and TOMS satellite data over the majority of the globe (56°N-S), with polar regions derived from ozonesonde results. The column ozone trends from our global data are constructed so as to agree with TOMS trends over 56°N-S, and we furthermore find good agreement with TOMS in polar regions (for times when TOMS is available; see Figure 5). Our polar data (based on ozonesondes) have the advantage of providing trend estimates during polar night, and one key result of these data is that significant trends are observed in the Arctic beginning in midwinter (January). Although these results are based on data from only one station (Resolute, at 75°N), there are several points which support the applicability of these results to the Arctic as a whole: 1) variations at Resolute show similar behavior as other Arctic stations during recent years [*Fioletov et al.*, 1997]; 2) column ozone variations at Resolute in March are in overall agreement with Arctic results derived from (Backscatter Ultraviolet) BUV and TOMS data [*Newman et al.*, 1997] [these are compared in *Randel and Wu*, 1999]; and 3) seasonal and interannual ozone trends in Resolute ozonesonde data agree well with trends in Arctic zonal mean stratospheric temperatures [*Randel and Wu*, 1999]. The effect of large ozone trends in the Arctic during polar night has not been studied in model simulations; the model calculations of *Ramaswamy et al.* [1996], *Santer et al.* [1996], *Tett et al.* [1996] and *Graf et al.* [1998] all use ozone trends derived from TOMS, with extrapolation over polar night, and resulting small midwinter trends. It is possible that results using the trends here may provide improved simulation of Arctic temperature changes.

The ozone trend data sets described here are available via anonymous ftp by contacting the lead author at randel@ucar.edu.

Acknowledgments. We thank the large number of contributors to the SPARC ozone trends report for the work of evaluating the SAGE ozone data. Joe Zawodny kindly provided updated v5.96 SAGE II data for 1997. Ozonesonde data were obtained from the World Ozone and Ultraviolet Radiation Data Center (WOUDC). Marilena Stone expertly prepared the manuscript. This work was partially supported by NASA ACMAP grant W-18181. NCAR is sponsored by the National Science Foundation.

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(Received May 3, 1999; revised July 19, 1999
accepted August 3, 1999.)