Uncertainties in the evolution of stratospheric ozone and implications for recent temperature changes in the tropical lower stratosphere

Susan Solomon,[1] Paul J. Young,[2,3] and Birgit Hassler[2,3]

Received 12 June 2012; revised 31 July 2012; accepted 3 August 2012; published 14 September 2012.

[1] Observations from satellites and balloons suggest that ozone abundances have decreased in the tropical lower stratosphere since the late 1970s, but this long-term change is occurring in a region of large interannual variability. Three different ozone databases provide regression fits to the ozone observations, and are available for use in model studies of the influence of ozone changes on stratospheric and tropospheric temperatures. Differences between these ozone databases suggest that the estimated decreases of tropical lower stratospheric ozone in recent decades are uncertain by about a factor of two to three. The uncertainties in ozone decreases lead to similar uncertainties in cooling of the tropical lower stratosphere, a key area of focus in climate change studies. **Citation:** Solomon, S., P. J. Young, and B. Hassler (2012), Uncertainties in the evolution of stratospheric ozone and implications for recent temperature changes in the tropical lower stratosphere, *Geophys. Res. Lett.*, *39*, L17706, doi:10.1029/2012GL052723.

1. Introduction

[2] Understanding the factors that can influence temperatures near the tropical lower stratosphere is important for interpreting past climate change and projecting future changes. One driver of temperatures in this region is the abundance and variability of ozone, but water vapor, volcanic aerosols, and dynamical changes such as the Quasi-Biennial Oscillation (QBO) are also significant [e.g., *Fueglistaler et al.*, 2009, and references therein]; anthropogenic increases in other greenhouse gases such as carbon dioxide play a lesser but significant role in the lower stratosphere [*Shine et al.*, 2003]. Due to the important role of ozone in driving temperature changes in the stratosphere as well as radiative forcing of surface climate, several different groups have provided databases characterizing the time-varying concentrations of this key gas that can be used to force global climate change simulations (particularly for those models that do not calculate ozone from photochemical principles). The three ozone databases used in this work are (i) *Cionni et al.* [2011, hereinafter SPARC], (ii) *Randel and Wu* [2007, hereinafter RW], and *Hassler et al.* [2009, hereinafter BDBP].

[3] Here we examine tropical ozone changes in each of the databases for 1979–1981 versus 1995–1997; this choice of time periods deliberately includes a time before ozone depletion became readily apparent, as well as a later period when observations suggest that ozone was especially low (see Figure 1 below). We impose the stratospheric ozone changes from each of the three databases in a global atmospheric general circulation model (the NCAR Community Atmosphere Model, or CAM) with fixed greenhouse gas concentrations and sea surface temperatures to examine the accompanying effects on stratospheric temperature during these two time slices. We use 100-year integrations (analyzing the last 80 years) for each simulation, so that a coherent forced signal can emerge against the backdrop of internal variability (as *Polvani et al.* [2011]). Tropospheric ozone changes are not considered, as these are not specified by all of the datasets. The climatology of tropospheric ozone suggested by *McPeters et al.* [2007] was used in all model runs.

[4] The goal of this study is not to determine which, if any, of the stratospheric ozone datasets may be considered to be the most accurate. Nor do we seek to simulate measured total temperature trends, which would require consideration not just of ozone but also of other forcing agents as well as uncertainties in the temperature data [e.g., *Sherwood et al.*, 2008; *Free*, 2011]. Rather, our purpose is to examine the range of the estimated ozone changes obtained from available databases for the tropical lower stratosphere and to explore implications for changes in temperature.

2. Ozone Databases

[5] We briefly summarize the key features of the three ozone databases that affect estimates of tropical lower stratospheric values. The RW database is the output of a fitting process that makes use of SAGE-1 and 2 satellite observations to characterize ozone concentrations in the tropics above 20 km, but uses only SAGE 2 data (from 1985 on) below that level, due to concerns about the uncertainty in altitude registration of the SAGE-1 data as discussed by *Wang et al.* [1996]. RW apply a multiple linear regression model to account for the seasonal cycle, two terms to represent the QBO, and a long-term function that assumes that ozone decreases in proportion to increases in ozone-depleting halocarbon content (equivalent effective stratospheric chlorine, or EESC). RW also include a solar cycle term above 20 km but not below. Unlike polar ozone, tropical lower stratospheric ozone is not expected to be

[1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.
[2]Chemical Sciences Division, Earth System Research Laboratory, NOAA, Boulder, Colorado, USA.
[3]Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, Colorado, USA.

Corresponding author: S. Solomon, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, USA. (solos@mit.edu)

0094-8276/12/2012GL052723

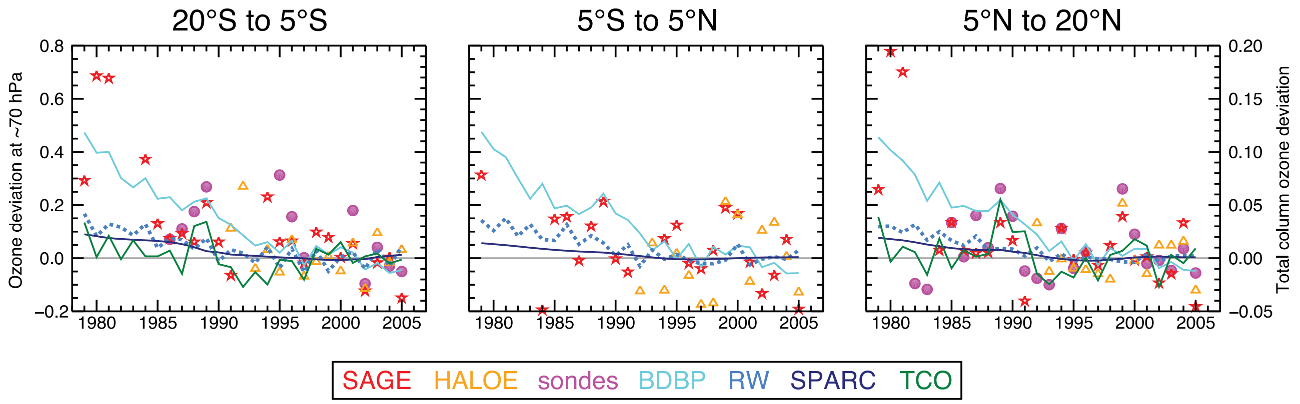

Figure 1. Annually averaged fractional changes in ozone from 20°S–5°S, 5°S–5°N, and 5°N–25°N at 70 mbar (left scale) for the season June–July–August. Where data are given in height coordinates, they are converted to pressure. Data for SAGE-1, SAGE-2, and HALOE satellites are indicated. The regression fits to the trends from three ozone databases are shown (SPARC, RW, and BDBP –black, blue dotted, and cyan lines) along with raw data from SAGE-1 and 2, HALOE, and Samoa (at 14.3°S, 170.6°W) and Hilo (19.7°N, 155°W) ozonesondes (symbols). Data coverage is sparse in some locations and years, but all available years are plotted for completeness. Total ozone column changes from the Samoa and Mauna Loa stations are also shown in the respective latitude bins (right scale, green line).

chemically depleted by halocarbons, owing to the fact that chlorine and bromine have not yet been released as the source gases pass through this region. Therefore, ozone changes in tropical lower stratosphere may not follow the functional form of EESC [see, e.g., *Douglass et al.*, 2010].

[6] The SPARC database was developed to support the fifth Coupled Model Intercomparison Project (CMIP-5) [*Taylor et al.*, 2012] and includes estimates of both tropospheric and stratospheric ozone changes. It spans the period 1850 to 2100. The stratospheric portion of the observations-based dataset (1979 to 2010) is largely based upon the RW regression approach including a mean annual cycle, EESC and solar cycles, but does not include the QBO.

[7] The BDBP database includes available balloon-borne ozonesondes as well as SAGE 1, SAGE 2, HALOE, and POAM observations. Among other stations, two of the longest ozonesonde datasets in the tropics come from Hilo, Hawaii (19.7°N, 155°W) and Samoa (14.3°S, 170.6°W). The data are fit using a multiple regression model with an annual cycle, EESC, a linear term to allow for possible greenhouse gas impacts, two QBO terms, solar cycle, El Nino Southern Oscillation (ENSO) and volcanic perturbations. Even during times when the volcanic loadings are relatively low, including a volcanic basis function can affect other terms (such as the linear slope) in the regression model fit.

[8] More detail regarding the fits used, and a comparison of the three datasets is provided in B. Hassler et al. (Comparison of three vertically resolved ozone data bases: Climatology, trend and radiative forcings, submitted to *Atmospheric Chemistry and Physics*, 2012).

[9] Figure 1 shows annually averaged ozone changes at 70 mbar for three tropical latitude bands. The raw data are shown, along with the output of the regression fits of the three ozone databases. The ten years from 1996–2005 are averaged for both the raw data and the databases to provide a reference for each, and all values are plotted as the fractional anomaly compared to that reference. The absolute amounts of the anomalies differ between the databases due to different climatologies (see Hassler et al., submitted manuscript, 2012).

[10] The ozonesonde data for Samoa and Hilo are plotted in Figure 1 for those bins in which these stations fall. Total column measurements from Samoa and Hawaii using the Dobson direct sun method (for maximum accuracy) are also shown for comparison using a separate scale (right). The changes at 70 mbar are not expected to quantitatively match the total column, which can only provide a qualitative comparison.

[11] While the raw data in Figure 1 suggest a long-term decrease in ozone in much of the region from 20°N–20°S, the figure also gives a sense of the difficulties faced in regression fitting of the highly variable raw ozone data to quantify the underlying longer-term changes. *Randel and Wu* [2007] noted that the fitting terms they used explained up to 70% of the ozone variance in much of the tropical mid- and upper-stratosphere in their study, but below about 20 km the fits accounted for less than 50% of the variance, corresponding to large uncertainties. None of the three published ozone databases provide estimates of the fitting errors on the long-term changes shown in Figure 1. It is possible that the differences between the databases as shown in Figure 1 are within respective uncertainties in fitting the raw data. SPARC and RW use the same observations but obtain different results, hence the regression model can be important. Differences in both the regression model and in input observations probably contribute to the different results obtained in BDBP.

[12] Figure 1 indicates that the long-term changes in tropical lower stratospheric ozone are subject to large uncertainties, due in part to the relatively large interannual variability. It has been noted that the tropical total ozone column changes implied by the changes observed from SAGE 1 to 2 are difficult to reconcile with available total column data suggesting little or no ozone loss in this region, unless there has been a 15% increase in tropical tropospheric abundances [*Randel and Wu*, 2007]. Some studies using piece-wise linear trends rather than EESC fitting suggest larger tropical total column changes in some periods that may be more consistent

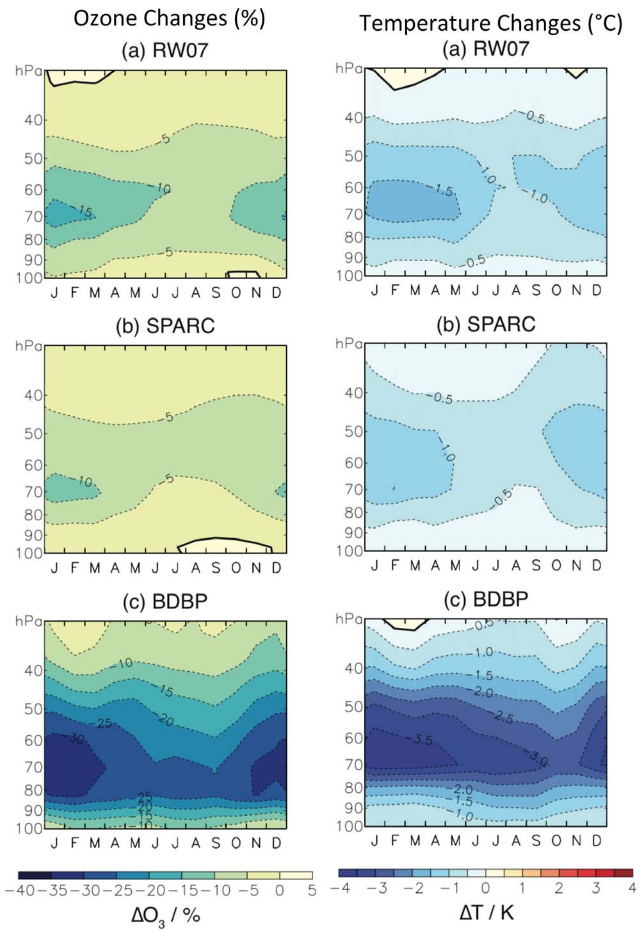

Figure 2. Seasonal cycles of the changes for 1995–1997 versus 1979–1981 in tropical average (20°S–20°N) (left) ozone and (right) corresponding model-calculated temperatures, for each of the three ozone datasets.

with the differences between SAGE 1 and 2 [*Douglass et al.*, 2010, and references therein]. While the Samoa total column measurements suggest a decrease in ozone from the late 1970s to mid 1990s, there is little evidence of a decline from 1979–2005, nor has the total column decreased at Mauna Loa. The goal of this paper is not to resolve these long-standing issues, but rather to examine some of their implications for uncertainties in estimated changes in temperature.

3. Effect of Uncertainties in Ozone on Tropical Lower Stratospheric Temperatures

[13] Time-slice integrations were run using the NCAR CAM version 3.6 for 100 years, of which the last 80 years were analyzed. The model configuration used in this study includes a horizontal resolution of 2° latitude by 2.5° longitude and 26 levels from the surface to 3.5 hPa (about 40 km). Further information on the model formulation, including the radiative transfer module, is documented by *Collins et al.* [2006]. P. J. Young et al. (Modelling the climate impact of late 20th century stratospheric ozone changes: Sensitivity to different forcing data sets, submitted to *Atmospheric Chemistry and Physics*, 2012) provide further examination of the simulations conducted here.

[14] The atmospheric model simulations used ozone data from each of the three databases in the two different time periods considered (1979–1981 and 1995–1997). Figure 2 shows the seasonal cycles of the imposed changes in ozone averaged from 20°S to 20°N, along with computed temperature changes from 100 to 30 mbar based on the three databases. All three databases show a similar seasonal structure, with maximum tropical ozone losses in Dec–Jan–Feb and minima in Jul–Aug–Sep, but the amplitude of the ozone loss and related cooling is smallest in SPARC, larger in RW, and considerably larger in BDBP. *Polvani and Solomon* [2012] presented a qualitatively similar seasonality of temperature changes in runs using the same model driven by the SPARC ozone database. They showed that the seasonality of calculated temperature changes compared favorably to observations. Comparisons of tropical temperature data display a seasonality in their cooling trends that is robust across different temperature databases, but with substantial uncertainties in amplitude [*Free*, 2011]. We emphasize that the changes shown here refer specifically to the mid/late 1990s (1995–1997) versus the late 1970s/early 1980s (1979–1981) and do not represent trends. They do, however, indicate how sensitive temperatures in this region are to temporal changes in ozone.

[15] Figure 3 presents vertical profiles of the annual average temperature changes between the period from 1979–1981 and 1995–1997 as shown in Figure 2 for each of the three databases. Cooling trends are often provided in degrees per decade. Since ozone and temperature changes in this region have occurred in two steps in the early 1980s and 1990s [see *Ramaswamy et al.*, 2006; *Thompson and Solomon*, 2009], the ozone-induced trends per decade from 1979–2011 would therefore be about a third of the

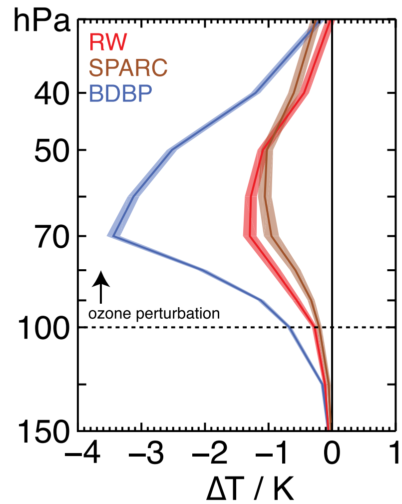

Figure 3. Vertical profile of the change in model-calculated tropical average (20°S–20°N) annual mean temperatures for the lower stratosphere. The Figure shows the temperature change between three pairs of simulations, using 1979–81 and 1995–7 average ozone concentrations from each of the three ozone datasets. The shading about each line indicates the 95% confidence interval for the temperature change. The dotted line indicates the lower altitude limit for where the ozone was different in each simulation. Below this line, all simulations used a tropospheric ozone climatology.

values shown in Figures 2 and 3, i.e., about 0.5°C per decade for RW and SPARC at 70 mbar, but about 1.2°C per decade for BDBP. The shading about the lines in Figure 3 shows the 95% confidence ranges for the temperature changes, as calculated from the 80-year time slices. This does not represent the total error but only the statistics of the runs with this particular model. While other models would likely yield different absolute cooling, the relative values of the cooling implied by the three different ozone databases can be expected to be robust to the model chosen.

[16] While the ozone changes are imposed only in the stratosphere in these runs, there is a slight cooling at lower altitudes in the model simulations. *Forster et al.* [2007] noted a similar effect in simulations that considered ozone losses only above 70 mbar, due to the effects of reduced longwave emission upon upper tropospheric temperatures.

4. Conclusions

[17] Several different ozone databases are available for use by global climate modelers, and here we have probed how computed temperature changes in the tropical lower stratosphere could differ depending upon which ozone database is chosen to describe this important forcing. The underlying raw ozone data used to construct these databases are subject to significant uncertainties, including (but not limited to) the differences between SAGE 1 and 2. While the three ozone databases all show a reduction in ozone in the lower tropical stratosphere, the magnitude of this change differs substantially between them and occurs against a backdrop of much larger interannual variability. The SPARC database that was used for many global model runs for the Climate Modelling Intercomparison Project 5 (CMIP5) displays the least interannual variability and the most conservative trends in ozone of the available databases. Uncertainties in the regression models and fits used to distinguish between periodic variations and trends in the different databases appear to be a significant source of uncertainty in the estimates of long-term trends. The three different ozone databases yield changes in tropical lower stratospheric temperatures that differ by more than a factor of two at 70 mbar, although all have qualitatively similar seasonal cycles. Therefore, the uncertainties in ozone changes in the tropical lower stratosphere and their characterization in different databases using regression fits constitute a major barrier to understanding temperature trends and radiative forcing. According to the present model, the changes in lower stratospheric ozone may also influence temperatures in the tropopause region and thereby perhaps water vapor, although we emphasize that further testing with additional models is required.

[18] **Acknowledgments.** We are grateful to Bryan Johnson for providing quality-checked preliminary ozonesonde data from the Samoa station.

[19] The Editor thanks two anonymous reviewers for assisting in the evaluation of this paper.

References

Cionni, L., et al. (2011), Ozone database in support of CMIP5 simulations: Results and corresponding radiative forcing, *Atmos. Chem. Phys.*, *11*, 11,267–11,292, doi:10.5194/acp-11-11267-2011.

Collins, W. D., et al. (2006), The Community Climate System Model Version 3 (CCSM3), *J. Clim.*, *19*, 2122–2143, doi:10.1175/JCLI3761.1.

Douglass, A., et al. (2010), Stratospheric ozone and surface ultraviolet radiation, in *Scientific Assessment of Ozone Depletion: 2010*, *Global Ozone Res. Monit. Proj. Rep. 52*, pp. 2.1–2.76, World Meteorol. Organ., Geneva, Switzerland.

Forster, P. M., G. Bodeker, R. Schofield, S. Solomon, and D. W. J. Thompson (2007), Effects of ozone cooling in the tropical lower stratosphere and upper troposphere, *Geophys. Res. Lett.*, *34*, L23813, doi:10.1029/2007GL031994.

Free, M. (2011), The seasonal structure of temperature trends in the tropical lower stratosphere, *J. Clim.*, *24*, 859–866, doi:10.1175/2010JCLI3841.1.

Fueglistaler, S., A. E. Dessler, T. J. Dunkerton, I. Folkins, Q. Fu, and P. W. Mote (2009), Tropical tropopause layer, *Rev. Geophys.*, *47*, RG1004, doi:10.1029/2008RG000267.

Hassler, B., G. Bodeker, I. Cionni, and M. Dameris (2009), A vertically resolved, monthly mean, ozone database from 1979 to 2100 for constraining global climate model simulations, *Int. J. Remote Sens.*, *30*, 4009–4018, doi:10.1080/01431160902821874.

McPeters, R. D., G. J. Labow, and J. A. Logan (2007), Ozone climatological profiles for satellite retrieval algorithms, *J. Geophys. Res.*, *112*, D05308, doi:10.1029/2005JD006823.

Polvani, L. M., and S. Solomon (2012), The signature of ozone depletion on tropical temperature trends, as revealed by their seasonal cycle in model integrations with single forcings, *J. Geophys. Res.*, doi:10.1029/2012JD017719, in press.

Polvani, L. M., D. W. Waugh, G. J. P. Correa, and S.-W. Son (2011), Stratospheric ozone depletion: The main driver of 20th century atmospheric circulation changes in the Southern Hemisphere, *J. Clim.*, *24*, 795–812, doi:10.1175/2010JCLI3772.1.

Ramaswamy, V., M. D. Schwarzkopf, W. J. Randel, B. D. Santer, B. J. Soden, and G. Stenchikov (2006), Anthropogenic and natural influences in the evolution of lower stratospheric cooling, *Science*, *311*, 1138–1141, doi:10.1126/science.1122587.

Randel, W. J., and F. Wu (2007), A stratospheric ozone profile data set for 1979–2005: Variability, trends, and comparisons with column ozone data, *J. Geophys. Res.*, *112*, D06313, doi:10.1029/2006JD007339.

Sherwood, S. C., C. L. Meyer, R. J. Allen, and H. A. Titchner (2008), Robust tropospheric warming revealed by iteratively homogenized radiosonde data, *J. Clim.*, *21*, 5336–5352, doi:10.1175/2008JCLI2320.1.

Shine, K. P., et al. (2003), A comparison of model-simulated trends in stratospheric temperatures, *Q. J. R. Meteorol. Soc.*, *129*, 1565–1588, doi:10.1256/qj.02.186.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, *93*, 485–498, doi:10.1175/BAMS-D-11-00094.1.

Thompson, D. W. J., and S. Solomon (2009), Understanding recent stratospheric climate change, *J. Clim.*, *22*, 1934–1943, doi:10.1175/2008JCLI2482.1.

Wang, H. J., D. M. Cunnold, and X. Bao (1996), A critical analysis of Stratospheric Aerosol and Gas Experiment ozone trends, *J. Geophys. Res.*, *101*, 12,495–12,514, doi:10.1029/96JD00581.