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Comparison of three vertically resolved ozone data bases: climatology, trends and radiative forcings

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Abstract

Climate models that do not simulate changes in stratospheric ozone concentrations require ozone input fields to accurately calculate UV fluxes and stratospheric heating rates. In this study, three different global ozone time series that are available for this purpose are compared: the data set of Randel and Wu (2007) (RW07), Cionni et al. (2011) (SPARC), and Bodeker et al. (2012) (BDBP). The latter is a very recent data set, based on the comprehensive ozone measurement database described by Hassler et al. (2008). All three data sets represent multiple-linear regression fits to vertically resolved ozone observations, resulting in a spatially and temporally continuous stratospheric ozone field covering at least the period from 1979 to 2005. The main difference between the data sets result from using different observations and including different basis functions for the regression model fits. These three regression-based data sets are compared against observations from ozonesondes and satellites to compare how the data sets represent concentrations, trends, and interannual variability. In the Southern Hemisphere polar region, RW07 and SPARC underestimate the ozone depletion in spring as seen in ozonesonde measurements. A piecewise linear trend regression is performed to estimate the 1979–1996 ozone decrease globally, covering a period of extreme depletion in most regions. BDBP seems to overestimate Arctic and tropical ozone loss over this period somewhat relative to the available measurements, whereas these appear to be underestimated in RW07 and SPARC. In most regions, the three data sets yield ozone values that are within the range of the different observations that serve as input to the regressions. However, the differences among the three suggest that there are large uncertainties in ozone trends. These result in differences of almost a factor of four in radiative forcing, which is important for the resulting climate changes.

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1 Introduction

Using a realistic representation of the stratospheric ozone distribution and its changes over time in a climate is important not only for quantifying the flux of harmful UV radiation from the sun reaching the Earth's surface, but also to understand changes in the dynamics and energy budget of the Earth's atmosphere. It has been shown that an accurate representation of stratospheric ozone in global climate models is crucial for reproducing realistic stratospheric temperature changes (Dall'Amico et al., 2010), Southern Hemisphere tropospheric circulation changes (Son et al., 2009; Polvani et al., 2011), Southern Hemisphere climate and surface temperatures in Antarctica (Gillett and Thompson, 2003), global tropospheric temperature changes (Dall'Amico et al., 2009), and global precipitation changes (Purich and Son, 2012).

Global climate models that do not include interactive chemistry depend on a prescribed ozone field as input to incorporate these effects of ozone on the climate system. The differences in modelled climate responses arising from different input ozone fields can be significant, and can complicate the identification of climate signal uncertainty sources (e.g. Miller et al., 2006). Further, for ozone fields from global climate models that simulate ozone chemistry, a data set is necessary to validate the simulated ozone fields in the model and to help understand the modelled climate impacts. I.e., a realistic ozone data set is important both for reducing the uncertainty in the climate model output, and for validation purposes.

Although many different measurement systems provide ozone measurements with high vertical resolution (multiple satellite instruments, ozonesondes, ozone lidars, etc.), no single measurement type has the temporal and spatial coverage required to create a global, zonal mean, spatially and temporally continuous (gap-free) stratospheric ozone data set. In particular, the tropics and the high latitudes are regions where long-term coverage is especially limited. Because a data set with incomplete coverage is not suitable as a boundary condition for climate models, approaches have been designed to combine different kinds of observations and to fill any remaining gaps.

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This study focuses on three ozone data sets that are (i) highly vertically resolved, (ii) cover the entire globe throughout the period from at least 1979–2005, and (iii) have been mainly created to provide climate models with a realistic ozone input. All three data sets are created by using multiple linear regression fits to a selected set of observations, and therefore do not represent the original raw measurements. A comparison between these data sets and actual measurements is necessary to understand their quality. In Sect. 2, the three ozone data sets are characterized and briefly described. In Sect. 3, we consider how well they capture the observed interannual ozone variability as well as how their vertically integrated (ozone column) and vertically resolved climatologies compare to TOMS/SBUV (Total Ozone Mapping Spectrometer/Solar Backscatter UltraViolet instrument) and SBUV/2 data. Their respective anomalies are covered in Sect. 4. Time series from the regression-based data sets for selected months, pressure levels, and latitude zones are compared against individual, corresponding measurements from several measurement systems in Sect. 5. The ozone change from 1979 to 1996, a period of extreme depletion in many regions, was estimated by applying a regression model with a linear trend basis function to the time series of the three data sets. Although all three data sets are based on regression model output, and should therefore not be used for trend studies, as trends are effectively imposed by the fitting techniques used. To evaluate their utility for climate model studies it is necessary to assess the extent to which they capture observed ozone decreases. The trend estimates for the data sets are described and compared to ozone trends derived directly from raw measurements in Sect. 6. The differences in the three ozone data sets result in differences in global radiative forcing, which are discussed in Sect. 7. Finally, in Sect. 8, measures of the overall agreement between the three data sets and SAGE II and ozonesonde measurements are presented.

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2 Brief description of the ozone data sets

Three different ozone data sets are considered in this study. The differences between the data sets arise mainly from (i) different basis functions used for the multiple linear regression fit to the observations, (ii) the use of different observational data as the basis for the regression model, and (iii) inclusion (or not) of the troposphere. A brief description of each data set follows, and an overview is provided in Table 1.

2.1 Randel and Wu (RW07)

This ozone data set is described by Randel and Wu (2007). The observational data used to constrain their regression model fit are derived from the Stratospheric Aerosol and Gas Experiment (SAGE) I and II measurements (McCormick et al., 1989), covering ~ 55° S to 55° N and the polar regions above 30 hPa. Measurements from SAGE I are not used below 20 km. Ozonesonde data from Syowa (69° S) and Resolute (75° N) provide data for the polar regions from a climatological tropopause up to 30 hPa. These ozonesonde stations are both considered to be on the edges of their respective polar vortices, and hence may underestimate the maximum depletion (see, e.g. the comparison of Syowa and South Pole data in Solomon et al., 2005). Between 55° S and 55° N, the data are fitted with a regression model consisting of an equivalent effective stratospheric chlorine (EESC; Daniel et al., 1995) basis function; a solar activity proxy viz. the F10.7 cm radio flux (used only above 20 km); and two orthogonal basis functions representing the quasi-biennial oscillation (QBO). The ozonesonde and SAGE data are fitted only with the EESC basis function, and the obtained regression coefficients are applied at all latitudes poleward of 65°. The output from the regression model captures only ozone anomalies which are superimposed on the ozone climatology described in Fortuin and Kelder (1998; hereafter referred to "FK98") to provide a global ozone data set. FK98 use ozonesonde data from 30 stations and measurements from SBUV/SBUV2 from 1980 to 1991 to create a zonal mean, monthly mean, vertically resolved climatology. The SBUV/SBUV2 observations have a relatively low

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resolution (about 5 km). This climatology extends from the surface to 0.3 hPa on 19 pressure levels, but for the RW07 data set only the stratospheric levels were used.

RW07 spans the period from 1979 to 2005, and extends from the surface to 50 km with a vertical resolution of 1 km. Since the RW07 data set is provided on an altitude grid and in ozone units of DU km^{-1}, here it has been converted onto pressure levels and into ozone units of mixing ratio (ppmv) to facilitate comparisons with the other two data sets. A scale height of 7 km was used for the conversion (W. Randel, personal communication, 2011).

2.2 SPARC

The SPARC ozone data set was developed by the Atmospheric Chemistry & Climate (AC&C) initiative, a joint Stratospheric Processes And their Role in Climate (SPARC) and International Global Atmospheric Chemistry (IGAC) activity. The data set consists of merged chemistry-climate model and observationally based regression model output, spanning 1850 to 2100, and was developed in support of the climate model integrations conducted as part of the 5th Coupled Model Intercomparison Project (CMIP5) for the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5) (Cionni et al., 2011). Here we focus on the post 1979 observationally based part of the data set. For this period, the SPARC ozone data set is very similar to RW07, except that the QBO basis functions were omitted from the regression model. This omission is expected to lead to less variability in the data set. As in RW07, the ozone anomalies derived from the regression model are superimposed on the FK98 ozone climatology to provide complete coverage for the observationally based part of the SPARC data set. In contrast to RW07, SPARC also includes data for the troposphere, taken from chemistry-climate model simulations and merged with the stratospheric data across the climatological tropopause.

The observationally based part of the SPARC data set extends from 1979 to 2009, and has a vertical range from the surface to 1 hPa on 24 pressure levels.

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2.3 BDBP

The BDBP data set is based on a regression model fit to the ozone data from the Binary Database of Profiles (BDBP; Hassler et al., 2008). BDBP uses measurements from SAGE I and II, the Halogen Occultation Experiment (HALOE) instrument, the Polar Ozone and Aerosol Measurement (POAM) II and III instruments, the Limb Infrared Monitor of the Stratosphere (LIMS), the Improved Limb Array Spectrometer (ILAS and ILAS II), and over 130 ozonesonde stations globally, to calculate the raw monthly mean data (Tier 0; see Bodeker et al., 2012) provided as input for the regression model, representing substantially more data sources than used in the RW07 or SPARC data sets. In addition, the regression model used to fit the data contains several more basis functions than the other data sets (see Table 1). The regression model is used both for determining interannual ozone variability and for describing the underlying annual cycle. In contrast to RW07 and SPARC, the regression model was also used to calculate gap-free ozone fields in the troposphere. A more detailed description of the input data and the regression model used to create the BDBP zonal mean data set can be found in a manuscript by Bodeker et al. (2012).

The BDBP data set extends from 1979 to 2006, and from the surface to ~ 0.05 hPa (70 km) in the vertical on 70 levels spaced ~ 1 km apart. The BDBP is available in both a pressure and altitude coordinate system, and includes both ozone volume mixing ratio and ozone number density.

3 Climatologies

3.1 Integrated ozone

For all three data sets, climatologies of total column ozone were calculated for the common period 1979 to 2005. Since RW07 does not include tropospheric data, the integration for each of the data sets spans only levels from 250 hPa to 1 hPa, which is

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expected to capture much of the variation seen in total column data. These climatologies are shown in Fig. 1, where they are compared to the merged observations from the Total Ozone Mapping Spectrometer (TOMS) and the Solar Backscatter Ultraviolet instruments (SBUV/SBUV2) (Stolarski and Frith, 2006); note that the latter includes contributions from the troposphere and above 1 hPa (in contrast to the results shown from the data sets).

The overall structure is very similar for all three data sets and the TOMS/SBUV data, for example: (i) low ozone in the tropics with a weak annual cycle maximizing between August to October; (ii) larger values in the mid-latitudes, where the highest ozone values occur in the Northern Hemisphere (NH) polar region between February and April; and (iii) deep minima in Southern Hemisphere (SH) spring at high latitudes around September and October in association with the ozone hole.

Since both the RW07 and SPARC data sets use the ozone climatology described by Fortuin and Kelder (1998), their integrated climatologies should be almost identical. However, in the middle and high latitudes the RW07 climatology shows higher integrated ozone than both SPARC and BDBP, while in the tropics RW07 ozone is slightly lower than the other two. The differences in the RW07 and SPARC climatologies could be due to the different vertical resolutions of the FK98 climatology and the RW07 data set. The FK98 climatology consists of 19 levels extending from 1000 hPa to 0.3 hPa, whereas the RW07 data set has 50 levels that range from the surface to about 0.8 hPa, converted onto pressure levels with a standard atmosphere (see Table 1). In contrast, the SPARC data set has 24 levels that extend from 1000 hPa to 1 hPa, which is closer to the levels provided by the FK98 data set. The interpolation of the climatology onto the more highly resolved RW07 data set levels may introduce a slight bias that produces the higher overall integrated climatological ozone values. In addition, the column climatologies shown in Fig. 1 represent ozone from 250 hPa to 1 hPa. The RW07 data set consists of stratospheric ozone only, so that in locations where 250 hPa lies below this threshold (e.g. in the tropics), the RW07 data set cannot provide ozone values. The layer integrated RW07 climatology in the tropics is most likely biased low.

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The BDBP climatology shows the lowest integrated ozone of all three data sets, particularly in the SH polar region in spring, and also the lowest maximum ozone in the NH polar region in late winter/early spring. The lower ozone of the BDBP climatology is mainly caused by the different time periods on which the climatologies are based. Fortuin and Kelder (1998) used ozonesonde and SBUV/SBUV2 measurements from 1980 to 1991, whereas the BDBP climatology is based on the period from 1979 to 2005, which includes many more years of substantial ozone depletion.

Compared to the climatology derived from TOMS/SBUV, RW07 shows similar integrated ozone values, SPARC is lower by an average of about 25 DU, and BDBP is lower by an average of about 25 to 40 DU. As shown by Ziemke et al. (2011), the tropospheric partial ozone column varies between 25 and 40 DU, depending on location and season. Highest values for tropospheric partial columns (around 36–42 DU) occur between 30°–40° in both hemispheres, between May and September in the NH and between August and December in the SH. Values in the tropics range between 24–30 DU, and high latitude values lie around 30 DU in the NH and are lower at around 20 DU in the SH. Ozone integrated from 1 hPa to the top of the atmosphere is on average below 2 DU (McPeters et al., 2007). Adding these values to the climatologies of the three data sets would lift the BDBP climatology to values that are similar to TOMS/SBUV, while SPARC would be slightly higher than TOMS/SBUV values, and RW07 would be clearly higher.

3.2 Vertically resolved ozone

The vertically resolved climatologies show similar patterns to the total column ozone climatologies. Due to the construction of the SPARC and RW07 data sets, with the regression-based variability added to the climatology of FK98, differences between these data sets should be negligible. SPARC and the FK98 data set are essentially identical at all analysed levels. Small differences might be due to the extrapolation of the FK98 climatology onto the slightly different SPARC pressure levels and the higher latitudinal resolution of the SPARC data set. However, differences between the RW07

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and the FK98 climatology are more pronounced, with climatological ozone values from RW07 being higher in the lower stratosphere up to 50 hPa for all latitudes. For lower pressures the differences in climatologies between FK98 and RW07 vanish almost completely, so that at 10 hPa the climatologies of the three FK98 based data sets are identical.

Figure 2 shows mean climatological ozone profiles for the three data sets for the Antarctic (90° S to 70° S), the tropics (20° S to 20° N), and the Arctic (70° N to 90° N), for two different seasons (MAM and SON). The BDBP climatology is lowest globally in the lower stratosphere, with distinctly lower ozone values in Antarctica in spring. The lower ozone values in Antarctica in spring exist for all analysed pressure levels, not just in the lower stratosphere. This might be mainly based on the fact that a logarithmic transformation of the input data allows the BDBP regression model to track low ozone values well (Bodeker et al., 2012). At around 50 hPa differences between the BDBP climatology and the three other climatologies generally become smaller. At the 30 hPa level, all four climatologies are almost identical in the tropics, and BDBP is only slightly lower in the high latitudes. At 10 hPa the differences between climatologies change sign in the tropics, with BDBP having clearly higher climatological ozone values. However, in the polar regions, RW07 is clearly higher than BDBP and SPARC at that pressure level. In the tropics RW07 shows the highest climatological values again above about 7 hPa, placing the maximum climatological ozone value clearly higher than BDBP and SPARC. These differences in climatologies throughout the stratosphere could be caused by the different measurements used as input data for the regression models (e.g. the low ozone in Antarctic spring in BDBP). In addition, the different covered time periods on which the BDBP climatology and the FK98 climatology (basis for the RW07 and SPARC climatologies) are based could cause some differences in climatological values.

When calculated for the same time period as that covered by FK98, the values for the BDBP climatology levels that are based on the shorter time period are clearly higher up to about 50 hPa, then become more and more similar to the values of the BDBP climatology that is based on the longer time period for levels above 30 hPa. Overall

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the comparison between the FK98 climatology levels and the BDBP climatology levels that are based on the same time period is better than for the BDBP climatologies based on the longer time period. Nonetheless, on all pressure levels there are regions where the values of the BDBP climatology that is based on the short time period differ slightly from the FK98 climatology. This is most likely caused by the differences in the measurements used to create the BDBP data set and the FK98 climatology.

4 Anomalies

4.1 Integrated ozone

Anomalies were calculated for each of the data sets relative to their respective 1979 to 2005 climatologies (Fig. 3). Although the TOMS/SBUV data set includes ozone in the troposphere, whereas the three data sets are only integrated between 250 hPa and 1 hPa, by comparing the anomalies, we remove this systematic bias and concentrate on interannual variability. Furthermore, anomalies calculated from the layered SBUV/2 data set (Bhartia et al., 2004), where ozone was integrated from approximately 64 hPa upward, show an almost identical pattern to those of the TOMS/SBUV, albeit with slightly weaker positive anomalies at the beginning of the time series and slightly stronger negative anomalies at the end of the time series. This indicates that tropospheric ozone only has a small influence on the total column ozone anomalies, justifying the comparison of the ozone anomaly patterns from the three integrated data sets and TOMS/SBUV.

The TOMS/SBUV anomalies show the well-known pattern of the ozone hole evolution in the SH polar region, with positive anomalies before the late 1980s and increasingly more negative anomalies thereafter. Note that TOMS/SBUV can only perform measurements when the satellite can see the sun, so that anomalies cannot be calculated at high latitudes for all months (white regions in Fig. 3a). Ozone depletion is also detectable in the NH polar region, although not as strong as in the SH. In the early

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1990s, ozone anomalies were especially low when unusually deep NH polar ozone losses were recorded (see, e.g. Newman et al., 1997). In the tropics and sub-tropics, variability of the anomalies is significant; in particular, the QBO signal is strong.

All three data sets show the development of SH ozone loss in spring and the Antarctic ozone hole (Fig. 3b–d); the most negative anomalies at high southern latitudes appear in the mid-1990s with similar magnitudes in all data sets. In addition, all data sets show negative NH anomalies in the boreal spring, but the deepest NH ozone losses appear in the BDBP data. The presence of these more negative anomalies in the BDBP data is likely due, in part, to the volcano basis functions; several studies have linked enhanced ozone depletion to the eruption of Mt. Pinatubo (e.g. Rosenfield et al., 1997; Solomon et al., 1998; Telford et al., 2009). The BDBP more closely replicates the TOMS/SBUV NH polar temporal evolution, but its anomalies are more positive in the beginning of the time period (early 1980s), and stay more negative at the end of the time period. Overall, this results in a larger negative trend with BDBP than with SPARC, RW07 or TOMS/SBUV.

Outside of the polar regions, the impact of the inclusion of additional basis functions in the BDBP regression model is clearly apparent, with the anomalies having much more structure than in RW07 and, especially, in the SPARC data. The BDBP variability compares well to the TOMS/SBUV anomalies, suggesting that the BDBP data set is in this sense closer to reality than RW07 or SPARC. The lack of a QBO basis function in the SPARC data leads to the anomalies in the tropical and mid-latitudes having very little temporal structure. Tropical ozone loss is strongest in the BDBP data. The evolution of the tropical column ozone anomalies seems to be captured well in RW07, while it suggests, as for the NH polar region, that ozone loss in the BDBP data set might be too strong, whereas it might be slightly too weak in SPARC. However, the lack of inclusion of a possibly changing tropospheric column contribution could contribute to these differences.

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4.2 Vertically resolved ozone

As for the vertically resolved climatologies (Sect. 3.2), anomalies at several different pressure levels from the three data sets were analysed. Characteristics evident in the integrated ozone anomalies of the three data sets are consistent across all vertical levels. Antarctic ozone loss is present in RW07 up to about 30 hPa, with a similar magnitude up to about 50 hPa, and weakening higher up. There is an annual cycle in the Antarctic ozone anomalies that is not evident in the Arctic (except to some extent in the SPARC data set). In the tropics and subtropics the RW07 anomalies are mainly characterised by a QBO pattern.

The SPARC anomalies show the least variability of all three data sets. Polar ozone depletion and a general global tropical trend are represented, but there is much less interannual variability that in the other data sets considered. This is to be expected given the smaller number of basis functions included in the fit. However, the underlying tropical ozone decrease over time is comparable in magnitude to RW07 for all pressure levels.

BDBP shows the most interannual variability in the regression based data sets, but does agree reasonably well with the other data sets in the trend in Antarctic anomalies. This signal extends across different pressure levels up to 10 hPa, however, weakens with decreasing pressure. In the Arctic, ozone loss in the BDBP is strongest compared to the other two data sets, with the most negative anomalies at pressure levels up to 50 hPa in 1992/1993, following the Mt. Pinatubo eruption. At lower pressures this strong anomaly disappears. Negative tropical ozone anomalies are largest for the BDBP data set. At lower stratospheric pressure levels anomalies do not show the QBO pattern as clearly, as for example RW07, but extend further into the mid-latitudes. At those levels, anomalies in recent years show the most negative values of the time series. Mid-stratosphere pressure levels show the QBO pattern more clearly, but with more variability than in RW07.

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5 Time series

Although the comparison of the vertically integrated ozone climatologies, and anomalies, of the three different data sets against TOMS/SBUV provides some validation of the three data sets, high latitude data gaps in the TOMS/SBUV data preclude validation in these regions. A comparison between the three data sets and data from several independent measurement systems (besides TOMS/SBUV), particularly during time of polar darkness, provides additional validation of the data sets. The following three subsections provide a more detailed description of the comparison in the Arctic, the tropics, and the Antarctic for selected months. An expanded range of these comparisons can be found in the supplementary material.

Vertical profiles from SAGE I and II, HALOE, POAM II and III, and ozonesondes were used for this comparison, and can be obtained from the BDBP database (Hassler et al., 2008). Measurements are stored in the BDBP on a common vertical grid and are quality-checked, but are unaltered otherwise. In addition, time series of SBUV/2 monthly mean layer data (Bhartia et al., 2004) were added at the pressure levels and in the latitude regions where they are available. This latter data set acts as a fully independent data source since it is not used in any of the three data sets as input for the regression models.

5.1 Northern Hemisphere polar region

Figure 4 shows the January and April time series of 80°–85° N lower stratospheric ozone at four pressure levels from the three different data sets with individual measurements from ozonesondes. RW07 is displayed as a red line, SPARC as a blue line, and BDBP Tier 1.4 (Bodeker et al., 2012) as a black line in the figure, and the vertical grey line represents the break point selected for a piecewise linear trend analysis, described in more detail in Sect. 6. Between 80° N and 85° N, no satellite data is available for the comparison, so only ozonesonde data is shown. All displayed ozonesonde measurements (grey open circles) were taken at the two Canadian sounding stations

Eureka and Alert. There are more data at the higher pressure levels since the altitude reached by the ozonesonde varies between soundings.

For both January and April, the RW07 and SPARC time series are almost identical in shape at higher pressures, with SPARC being consistently lower. For lower pressures, RW07 shows more variability than SPARC originating from the QBO basis functions used to create this data set, and the offset between RW07 and SPARC becomes smaller. The BDBP time series shows more interannual variability at all pressure levels with distinct QBO related features and, especially in the lower stratosphere, influences of the Mt. Pinatubo eruption are apparent. In addition, the BDBP time series shows larger changes between the beginning of the time series and the mid 1990s. At lower pressures the overall slope of the BDBP time series is more similar to RW07 and SPARC, and the QBO-related variability dominates the time series structure. For all pressure levels, the BDBP time series shows lower ozone than RW07, and at lower pressures BDBP ozone is lower than SPARC. In the lower stratosphere (100 hPa and 70 hPa) offsets between BDBP and SPARC are smaller. Offsets between BDBP and the other two data sets appear to depend on season, most likely due to the data set differences in climatologies (Sect. 3).

Time series of all three data sets fall within the range of the available ozonesonde measurements at all pressure levels despite their offsets, partly because the spread in the ozonesonde measurements is large. The RW07 time series tends to be biased high relative to the ozonesondes, whereas the SPARC and BDBP time series agree better with the ozonesondes. In the absence of soundings earlier than the late 1980s, it is difficult to judge how well the ozone decrease in the NH polar region is represented in the three data sets. It is also unclear from this comparison which data set gives the most realistic ozone loss as deduced from the raw measurements.

5.2 Tropics

Tropical ozone time series between 5° S and 5° N for all three data sets are shown in Fig. 5 for April and July. In addition to ozonesonde measurements from seven stations

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(Brazaville/Congo, Malindi/Kenya, Nairobi/Kenya, San Cristobal/Ecuador, Christmas Island/Australia, Sepang/Malaysia, Kaashidoo/Maldives), measurements from SAGE I and II, HALOE, and SBUV/SBUV2 were available for the comparison. Note that no data is available in April for RW07 at the lowest level (100 hPa).

The spread between the three data sets varies for the different pressure levels shown, but, generally, values from the SPARC time series lie between RW07 and BDBP values. At 100 hPa in July, RW07 is around 60 % higher than SPARC, and 60 % to 100 % higher than BDBP. At 70 hPa, RW07 is only slightly higher than both BDBP and SPARC, and at 30 hPa the three data sets are almost identical. Overall there is less interannual variability in the SPARC time series because it does not include a QBO basis function. Both RW07 and BDBP show a strong QBO related pattern at 30 hPa; this pattern is even more pronounced in RW07 at 10 hPa. The RW07 time series is higher than the other two data sets at altitudes below 30 hPa, but is lower at 10 hPa. For April at 10 hPa, the difference between the RW07 and SPARC time series ranges from 0.5 ppmv to 1 ppmv, and between RW07 and BDBP is at least 1 ppmv for all years. While all three data sets show minimal ozone decreases with time at the 30 hPa and 10 hPa levels, at 70 hPa and 100 hPa a clear decrease in ozone is present in the BDBP time series from the beginning of the time series until the late 1990s (as described in Sect. 4).

The spread between measurements from the different data sources, and even between measurements from the same data source, can be large between 5° S and 5° N (Fig. 5). In particular, there appears to be a step-function type difference between SAGE I (1979–1981) and later measurements. At 100 hPa in July, RW07 ozone is substantially higher than all the measurements except SAGE I values, SPARC falls in the higher range of the measurements, whereas BDBP values are consistent with the data from the other sources. At the lowest pressure level (10 hPa), the BDBP time series track the ozone values from the bulk of the measurements, whereas SPARC, and especially RW07, are biased low. While at some pressure levels, ozone decreases during the first 15 to 20 yr of the period appears to be present in the measurements (e.g. July at 70 hPa), that change is linked to the ozone values provided by SAGE I at the beginning of the period. Since those values are highly variable for the different months and the analysed pressure range (see figures in the supplementary material), the validity of this ozone loss in the BDBP time series cannot be confirmed. On the other hand, the lack of ozone loss in RW07 and SPARC also cannot be confirmed.

5.3 Southern Hemisphere polar region

Figure 6 shows October ozone mixing ratios for the three data sets at 100, 70, 30 and 10 hPa for the latitude zone 85° S–90° S. This time and location was chosen for comparison to examine the maximum depletion in the Antarctic ozone hole (e.g. Solomon, 1999). For this latitude zone, ozonesonde data are available only from the station South Pole/Antarctica (grey open circles in Fig. 6). However, Fig. 6 shows additional measurements from both POAM instruments, which are available from the mid-1990s onward. Note that the graphs for 100 hPa and 70 hPa are displayed with a logarithmic y-axis to show the severe depletions that are often measured within the ozone hole.

RW07 and SPARC time series for 100 hPa and 30 hPa are similar, with a strong ozone decrease through the late 1990s. At 10 hPa SPARC is offset from RW07 and BDBP by about 1 ppmv. There is a QBO-like pattern in RW07, and there is no trend in SPARC, differing significantly from the other layers shown. The SPARC time series for 70 hPa is somewhat unusual since it follows RW07 closely until the early 1990s and then drops to much lower values in the late 1990s. This is the atmospheric region of highest ozone loss in Antarctic spring (e.g. Solomon et al., 2005) and a realistic representation of ozone depletion is important for climate change attribution studies with climate models, a task for which all three data sets are intended. BDBP shows a distinctly stronger and earlier ozone decrease than RW07 and SPARC at the levels of higher pressure, but a similar net decrease at the levels with lower pressure. BDBP is lower than the two other data sets by up to approximately 1.5 ppmv in this region, although for the time series at 100 hPa and 70 hPa all three data sets start at approximately the same values in 1979. BDBP appears to agree better with the South Pole

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data, which is not surprising since ozone abundances are lower in the heart of the south polar vortex than they are at the Syowa station at 69° S used to construct the RW and SPARC databases.

South Pole ozonesonde measurements show a clear decrease in ozone after the mid-1980s, with lowest values in the late 1990s/early 2000s, between 100 hPa and 30 hPa. Although no electrochemical sonde data are available at South Pole prior to 1986, Solomon et al. (2005) showed that earlier measurements from the Brewer system also support a strong decline in ozone in the 1980s. The BDBP time series capture the decrease at the three lower levels well, and are centred in the measurement spread. This is expected given the South Pole ozonesonde measurements were included in the creation of the monthly means used in the regression model, and omitted from the others. While the RW07 and SPARC underestimate the ozone loss described by the measurements, the sharp decrease in SPARC at 70 hPa from the early to late 1990s shifts that time series closer to the centre of the measurement spread. At 10 hPa, the spread in the measurements is large, encompassing the time series of all three data sets. SPARC lies at the higher end of the measurements, RW07 is lower than SPARC but still at the higher end of the measurements, and BDBP closer to the centre of the sonde observations.

6 Trends

As mentioned in Sect. 2, all three data sets that are part of this comparison are generated using multiple linear regression methods. The ozone decrease due primarily to anthropogenic emissions of chlorine and bromine compounds described by the EESC fits does not necessarily represent the full extent of the ozone loss, but only the ozone loss described by a linear scaling of the EESC time series. The purpose of the trends calculated in the following sections is therefore not to provide the most accurate measures of ozone decreases and increases over the 1979 to 2005 period, but to serve as basis for an evaluation of the differences between the three data sets, and to serve as reality-check when compared to trends derived from other measurement time series.

A multiple linear regression model similar to that used to construct the three data sets, but now with the EESC basis function replaced by two piecewise linear trends (Reinsel et al., 2002), was applied to all three data sets. The inflection point, i.e. the time when the second trend term of the piecewise linear trend method is allowed to deviate from the first trend term, was set at the end of 1996, as suggested by Reinsel et al. (2002). This approach was also applied to describe ozone loss up to the peak of anthropogenic chlorine and bromine concentrations in the stratosphere as, for example, in the studies from Newchurch et al. (2003), Steinbrecht et al. (2006), and Jones et al. (2009). In addition to the two trend terms, the regression model included an offset term (to describe the average annual ozone amount) and basis functions to describe ozone variability due to the QBO, solar cycle and ENSO. Autocorrelation in the residuals of the regression model was considered, as described by Bodeker et al. (1998). Only results for the first trend term, describing the ozone change from the beginning of 1979 to the end of 1996, are discussed in more detail in the following sections.

6.1 Annual mean trends

In Fig. 7 the annual mean trends calculated from all three data sets for the period 1979 through 1996, are shown as a function of latitude and pressure. Although it is possible to calculate trends for the troposphere from BDBP and SPARC, these trends are not discussed here since this comparison focuses on the stratosphere, and the tropospheric trends are not statistically significantly different from zero for the analysed time period.

Annual mean ozone trends displayed as a function of latitude and pressure or altitude show a distinct pattern: strong ozone depletion in the high latitude lower stratosphere, with stronger trends in the SH than the NH (as suggested by total column ozone trends, e.g. WMO, 1999, Fig. 4-18; Randel and Wu, 2007), a weaker ozone decrease in the tropics, and a region in the middle stratosphere where trends are not statistically signifi-

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cantly different from zero (e.g. WMO, 1999, Fig. 4-32; Randel and Wu, 2007; McLinden et al., 2009). In the upper stratosphere between 40 km and 50 km (4 hPa to 1 hPa) stronger ozone loss occurs again, especially in the high latitudes of both hemispheres (e.g. McLinden et al., 2009). These general features are all reproduced by all three data sets, although small differences exist. The polar lower stratosphere trends in RW07 and SPARC are very similar in structure and amplitude, and both show lower trends in the Arctic compared to the Antarctic. The maximum amplitude of the ozone loss in Antarctica is slightly greater in RW07 than in SPARC. The BDBP shows larger ozone losses at the highest latitudes near 100 hPa to 70 hPa in both polar regions, while RW and SPARC display constant changes poleward of the latitudes where the Syowa and Resolute ozonesonde stations that provide input to these databases are found.

Table 2 summarizes the mean decadal trends for different regions of the stratosphere for all three data sets. In the top section of Table 2, annual mean trends are listed, with differences between RW07 and SPARC in the Antarctic lower stratosphere of about 2–3 % per decade. Results for BDBP in this region are only slightly larger than RW07 (approx. 2 % more ozone loss per decade), however, strong negative trends in BDBP extend higher in the atmosphere and farther into the mid-latitudes. Trends in the Arctic lower stratosphere from BDBP are much stronger than in either RW07 or SPARC. This trend pattern is not supported by total column ozone trend analyses (e.g. WMO, 1999, Fig. 4-18; Randel and Wu, 2007), and most likely is an artefact of the creation of the BDBP data set. Individual raw measurements in the Arctic (see Fig. 4) show a wide spread amongst measurements during the same month; however, a decrease in ozone over the years appears to exist in that latitude zone at least for the lower stratospheric pressure levels. The magnitude of this decrease in the BDBP data set is mainly determined by two factors: (1) the lack of measurements available at the beginning of the time series in this latitude zone, and (2) the presence of unusually low ozone values at the end of the fitting period (mid 1990s; WMO, 2003, Figs. 3-30 and 3-31), see the time series for 70 hPa in April in Fig. 5. With no data to anchor the trend at the beginning of the time series, the method used to create the BDBP data

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set (Bodeker et al., 2012) likely overestimates the ozone decrease in the Arctic lower stratosphere.

The annual mean trends in the tropical lower stratosphere also differ considerably amongst the three data sets. Trends derived from RW07 and SPARC are similar, with RW07 trends being slightly larger than in SPARC (Fig. 7 left column and Table 2). BDBP trends are two to four times larger in that region. Forster et al. (2007) calculated tropical lower stratospheric ozone trends from SAGE II measurements between 1984 and 2005. While the trend pattern they obtained appears similar to the pattern shown for the BDBP trends (Forster et al., 2007), the magnitude of their trends is approximately −5 % to −7 % per decade, more similar to the range of the trends from RW07, but somewhat larger than SPARC. This suggests that it may be the inclusion of SAGE I data in the BDBP data set that is creating the anomalously large ozone trends in BDBP. Randel and Thompson (2011) combined SAGE II ozone measurements from 20° S to 20° N with tropical ozonesonde measurements for the period from 1984 and 2009 and estimated an ozone decrease of approximately −4 % per decade between 1984 and 2009 at ∼ 70 hPa. This value is closer to trends derived from the RW07 and SPARC data sets than to BDBP. However, trends shown in Fig. 7 and Table 2 describe the ozone changes from 1979 to 1996, covering a different time period than either Forster et al. (2007) or Randel and Thompson (2011). Trends from these studies might therefore not necessarily be directly comparable to the trends derived here.

Several studies show only annual mean trends between 60° S and 60° N, from around 70 hPa up to around 1 hPa (e.g. Wang et al., 2002; McLinden et al., 2009; WMO, 2010, Fig. 2-4). This is the region of the stratosphere that is well covered by SAGE II measurements, and therefore trend calculations are rather straightforward there. Figure 7 (right column) shows the annual mean trends calculated from the three data sets, displayed for the same geographical and atmospheric region as the SAGE data. Trends at around 70 hPa for RW07 are only slightly larger than for SPARC, and both agree well with trends derived from SAGE I/II by Wang et al. (2002). This is expected since both RW07 and SPARC are heavily based on SAGE data in this region. BDBP trends in this

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region can be more than double these values, especially in the tropics, which is likely due to additional data sources being used for the creation of the data set and the more complex regression method.

Another region of special interest for annual mean ozone trends is the upper stratosphere because trends there are significant and a response to climate change (e.g. increasing greenhouse gas concentrations) is expected, in addition to the impact of ozone depleting substances. Upper stratospheric trends for all three data sets, strengthen with increasing latitude, but are overall weaker than in the lower stratosphere (Fig. 7, left column). The magnitudes of the trends for the three data sets are similar, with BDBP showing a slightly weaker annual mean ozone decrease (ca. −4 % per decade) than RW07 (ca. −5 % decade) and SPARC (ca. −5.5 % per decade; Table 2). A small area of positive trends in the Antarctic in the BDBP data set, around 2 hPa, does not likely represent a real ozone increase from 1979 to 1997, but is more likely caused by constraining errors of the BDBP regression method, as described by Bodeker et al. (2012). Overall, SPARC trends are slightly more negative than RW07 and BDBP in the tropics and mid-latitudes in the upper stratosphere. They are strongest in the SH polar region, poleward of 60° S, and between 4 hPa and 1 hPa (see Cionni et al., 2011). This pattern does not appear in RW07 or BDBP.

SAGE data alone show trends in the upper stratospheric region up to −8 % per decade (McLinden et al., 2009) and slightly higher (Wang et al., 2002), with a very similar spatial pattern to the trend for the databases. SPARC is the database with trends closest to the SAGE trends. Trends derived by analysing only SBUV data, as shown in McLinden et al. (2009), are slightly lower (up to −6 % per decade) and are therefore closer to the trends derived from RW07 and BDBP.

6.2 Seasonal trends

Table 2 shows seasonal trends and their purely statistical uncertainties for the three different data sets. All calculated seasonal trends are statistically significant at the 2-σ level, except the MAM trend for BDBP in the SH polar lower stratosphere. Uncertainties

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are up to three times higher for the BDBP trends than for RW07 and SPARC, owing to the higher variability in this data set. The uncertainties presented in Table 2 show that the three databases seldom overlap within their respective statistical errors; instead structural rather than statistical uncertainties dominate the differences between them. Nevertheless, it is useful to examine the seasonality of the statistical uncertainties.

Differences between the data sets are most pronounced for the tropical lower stratosphere, where BDBP trends are up to three times higher than RW07 and SPARC trends in all seasons, although trends differ only slightly between the seasons for a given data set. Trends in the upper stratosphere also do not differ much for the different seasons, and the three different data sets are ranked in the same pattern for all seasons: BDBP shows the smallest trend, followed by RW07 and SPARC with the largest trends. In JJA BDBP trends are up to 40 % smaller than those of SPARC, and RW07 trends are up to 15 % smaller than SPARC.

The largest seasonal difference in trends is present for the SH polar lower stratosphere. For BDBP, the trends are not significant in MAM and are approximately −38 % per decade in SON. Seasonal variability in trends for that region is not as high for RW07 and SPARC; however, both these data sets are similar with their smallest trends in MAM and their largest trends in SON. In most seasons, trends for RW07 are larger than for SPARC (except JJA), and trends for BDBP are stronger than for RW07 (except MAM). Differences are largest in Antarctic spring (SON) when most ozone depletion happens: trends for BDBP are approximately 35 % higher than RW07 trends, and twice as large as SPARC trends.

Trends in the NH polar lower stratosphere are largest in all seasons for BDBP, and are of comparable magnitude for RW07 and SPARC. Differences between BDBP and the other two data sets can reach up to four times the trend value (e.g. in DJF), and are only of comparable magnitude for JJA. Seasonal differences are largest in BDBP, ranging from −18 % per decade in DJF to −6 % per decade in JJA. The weakest seasonal cycle in trends is found for SPARC, where trends range from −4.8 % per decade in DJF to 3 % per decade in JJA.

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7 Radiative forcing

Next the radiative forcing implied by the three databases is compared. The ozone radiative forcing is defined as the net change in radiation entering the troposphere due to a change in ozone. The adjusted radiative forcing is computed, where stratospheric temperatures are adjusted to the ozone changes using the fixed dynamical heating approximation. The adjustment due to stratospheric temperature change is a first order effect for stratospheric ozone changes, whereas for other forcing agents it is typically only a 10–20 % effect. The radiative forcing for stratospheric ozone changes is examined over the period of maximum ozone depletion, using averages of 1979–1981 for the background state and 1995–1997 for the heavily depleted period. Data from the International Satellite Cloud Climatology Project (ISCCP) are used for the temperature and cloud fields and the calculation is done using seasonal averages. This radiative forcing code is the same as Portmann et al. (2007); it has been shown to compare well with other codes in Forster et al. (2005).

Table 3 shows the computed radiative forcing values. Tropospheric ozone changes are not included because they are relatively small during this time period and because one of the data sets (RW07) does not include tropospheric ozone. The table shows the large cancellation between the instantaneous forcing and the stratospheric adjustment, which makes the accurate calculation of the total forcing sensitive to small differences. The uncertainty in the total radiative forcing is proportional to the instantaneous and adjustment values. Thus, even a modest 10 % uncertainty in these values translates to a 0.03 $W m^{-2}$ uncertainty in the total forcing. The BDBP data set induces considerably more radiative forcing than RW07 or SPARC data sets. This is largely caused by larger ozone decreases in the subtropics in both hemispheres and the mid-latitudes in the Southern Hemisphere (see Fig. 8). The differences in radiative forcing between the ozone data sets imply different surface climate responses when the ozone data sets are used in climate models; further, the larger ozone decreases at mid and high latitudes

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in the BDBP data set can be expected to cause larger responses of climatic modes of variability (e.g., the SAM and NAM) compared with RW07 and SPARC data sets.

8 Discussion and summary

This study describes three recent, long-term, global, zonal mean, ozone profile data sets, All three data sets are based on regression model output, and therefore the degree of variability described by them depends strongly on the number and the choice of basis functions used for their creation. Their climatologies, anomalies, and annual and seasonal trends have been compared with each other, as well as with several satellite-based and in situ measurements.

The overall pattern of the climatologies look very similar for all three data sets, and compare well to TOMS/SBUV data and the Fortuin and Kelder (1998) climatology. However, absolute values differ for the three data sets. RW07 tends to have the highest climatological values at lower altitudes in the stratosphere and for the total column, whereas it tends to be the lowest for higher altitudes, implying that the vertical gradient in ozone is different to BDBP and SPARC. BDBP climatological values tend to be the lowest, possibly related to the fact that its underlying climatology is derived from the full 1979–2005 period of the input data, in contrast to RW07 and SPARC, which are based on the FK98 climatology, covering 1980 to 1991 and being based on low resolution SBUV data. The anomaly patterns from the three data sets differ markedly, with SPARC showing the least variability and BDBP showing the most, due to the different number of basis functions used. In general, BDBP shows the strongest change in the anomalies over the whole period (1979–2005), especially in the polar regions and the tropics, whereas SPARC shows the weakest. This is then reflected in the calculated trends and the resulting radiative forcing.

Comparisons with individual measurements from several different measurement systems show very good agreement of the overall magnitude of the ozone values with BDBP, good agreement with SPARC, and a fair agreement with RW07. The biases

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present in the RW07 climatologies (see Sect. 3) also bias the overall magnitude of the time series. As a measure of how well the time series of the three data sets represent the ozone values measured by SAGE II, monthly mean, zonal mean values from all available, quality-screened SAGE II measurements (Hassler et al., 2008) were calculated and interpolated onto the pressure levels from SPARC (see Sect. 2.2). The BDBP and RW07 data set were also interpolated onto the same pressure levels. For each latitude zone and pressure level, the sum of the squared residuals between the available SAGE II data and the three data sets were calculated, then normalized to the number of the available SAGE II monthly means for that specific time series, and the resulting average squared difference related to the overall SAGE II mean of the whole time series for the respective latitude zone and pressure level. The results for this measure of matching the SAGE II data are shown in Fig. 9. Shown are only the pressure levels from 100 hPa to 1 hPa since RW07 does not provide tropospheric data and SAGE II data is sparser lower down in the atmosphere. Black, blue and blue-green colours indicate an average deviation of the respective data set from SAGE II up to about 10 %. Yellow to red colours indicate average deviations of at least 50 %. The match to SAGE II data is best for the BDBP data set with most of the average squared difference for the shown pressure levels being below 7.5 %, in the tropics and mid-latitudes even below 5 %. Average squared differences for SPARC are only slightly higher than for BDBP, but overall still mostly below 7.5 %. For RW07 the average squared differences are clearly higher than for the other two data sets, with the majority of the values below 40 %. As mentioned above, the bias that is present in the RW07 climatologies cause the bias for the overall time series, and increases therefore the difference of the RW07 time series from SAGE II.

A second set of monthly means was calculated from global ozonesonde data as described in Hassler et al. (2008). The calculated average squared differences between the three data sets and the ozonesonde measurements are shown in Fig. 10. Only pressure levels from 100 hPa to 10 hPa are considered for this comparison since ozone soundings often do not reach altitudes above the 10 hPa pressure level. For all

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three data sets the agreement with the ozonesondes is not as good as with SAGE II data, with more values in the range of 10 % and 30 % than before. This might be partially caused by spatially biased zonal means. Longitudinal biases are possible for the different latitude zones due to the location of the available ozone sounding stations. While these were considered for the creation of the monthly means for the BDBP regression (Bodeker et al., 2012), they were not considered for the calculation of the average squared differences shown in Fig. 10. Overall, the comparisons of the three data sets to sonde data are similar to the comparisons with SAGE II data: differences between BDBP and sondes are smallest, they are slightly larger for SPARC and sondes, and largest for RW07 and sondes. Average squared differences between SAGE II and the ozonesonde measurements are predominately below 7.5 % (see Supplement), so differences between data sets and either SAGE II or sondes of that magnitude fall within the range of measurements uncertainties.

For global climate modellers, the best choice of ozone data set for their model studies will depend on the application. Although all three data sets cover the same time period and the whole globe, clear differences exist between them that would likely influence the model results. For example, Solomon et al. (2012), showed that the modelled temperature response in the tropical lower stratosphere is significantly larger if the BDBP data set is used in a climate model, compared to simulations with SPARC or RW07. Given the difficulties in determining the uncertainties in both ozone trends and the resulting ozone forcing for each of the three data sets, the availability of all three, provides some indication of how accurately trends are known. This can allow climate modellers to estimate the impact of this uncertainty, as well as the sensitivity of climate responses to different ozone forcings.

Based on the comparisons in this study, the following features of each data set can be deduced, which bears on their utility in different applications:

- RW07 – This data set shows a more conservative estimate of tropical and polar ozone changes than the BDBP data set, but does not match absolute ozone observations well in some latitudinal and atmospheric regions. This data set would

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be most useful where only ozone anomalies are necessary for a particular study, and if a more conservative ozone change estimate is desirable.

- SPARC – This is the only data set that covers more than only the observational period (1979 to 2005) and runs from 1850 to 2100. This data set would be most helpful for studies that require historical or future ozone, are not concerned with much variability besides an annual cycle and desire a generally conservative ozone change.
- BDBP – This data set includes the most detailed interannual variability, the most realistic SH polar ozone loss and the best agreement with absolute SAGE II and ozonesonde values. It displays the largest ozone changes over much of the lower stratosphere. This data set would be most helpful for studies that focus on these characteristics.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/12/26561/2012/ acpd-12-26561-2012-supplement.pdf.

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References

Bhartia, P. K., McPeters, R. D., Stolarski, R. S., Flynn, L. E., and Wellemeyer, C. G.: A quarter century of ozone observations by SBUV and TOMS, Proceedings of the XX Quadrennial Ozone Symposium, Kos, 1–8 June, Greece, 2004.

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Bodeker, G. E., Boyd, I. S., and Matthews, W. A.: Trends and variability in vertical ozone and temperature profiles measured by ozonesondes at Lauder, New Zealand: 1986–1996, J. Geophys. Res., 103, 28661–28681, 1998.
Bodeker G. E., Hassler, B., Young, P. J., and Portmann, R. W.: A vertically resolved, global, gap-free ozone database for assessing or constraining global climate model simulations, Earth Syst. Sci. Data, submitted, 2012.
Cionni, I., Eyring, V., Lamarque, J. F., Randel, W. J., Stevenson, D. S., Wu, F., Bodeker, G. E., Shepherd, T. G., Shindell, D. T., and Waugh, D. W.: Ozone database in support of CMIP5 simulations: results and corresponding radiative forcing, Atmos. Chem. Phys., 11, 11267–11292, doi:10.5194/acp-11-11267-2011, 2011.
Dall'Amico, M., Stott, P. A., Scaife, A. A., Gray, L. J., Rosenlof, K. H., and Karpechko, A. Y.: Impact of stratospheric variability on tropospheric climate change, Clim. Dyn., 34, 399–417, doi:10.1007/s00382-009-0580-1, 2009.
Dall'Amico, M., Gray, L. J., Rosenlof, K. H., Scaife, A. A., Shine, K. P., and Stott, P. A.: Stratospheric temperature trends: impact of ozone variability and the QBO, Clim. Dyn., 34, 381–398, doi:10.1007/s00382-009-0604-x, 2010.
Daniel, J. S., Solomon, S., and Albritton, D. L.: On the evaluation of halocarbon radiative forcing and global warming potentials, J. Geophys. Res., 100, 1271–1285, 1995.
Forster, P. M. D. F., Burkholder, J. B., Clerbaux, C., Coheur, P. F., Dutta, M., Gohar, L. K., Hurley, M. D., Myhre, G., Portmann, R. W., Shine, K. P., Wallington, T. J., and Wuebbles, D.: Resolution of the uncertainties in the radiative forcing of HFC-134a, J. Quant. Spectrosc. Ra., 93, 447–460, 2005.
Forster, P. M., Bodeker, G., Schofield, R., Solomon, S., and Thompson, D.: Effects of ozone cooling in the tropical lower stratosphere and upper troposphere, Geophys. Res. Lett., 34, L23813, doi:10.1029/2007GL031994, 2007.
Fortuin, J. P. F. and Kelder, H.: An ozone climatology based on ozonesonde and satellite measurements, J. Geophys. Res., 103, 31709–31734, 1998.
Gillett, N. P. and Thompson, D. W. J.: Simulation of recent Southern Hemisphere climate change, Science, 302, 273–275, doi:10.1126/science.1087440, 2003.
Hassler, B., Bodeker, G. E., and Dameris, M.: Technical Note: A new global database of trace gases and aerosols from multiple sources of high vertical resolution measurements, Atmos. Chem. Phys., 8, 5403–5421, doi:10.5194/acp-8-5403-2008, 2008.

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12, 26561–26605, 2012

Comparison of three vertically resolved ozone data bases

B. Hassler et al.

Jones, A., Urban, J., Murtagh, D. P., Eriksson, P., Brohede, S., Haley, C., Degenstein, D., Bourassa, A., von Savigny, C., Sonkaew, T., Rozanov, A., Bovensmann, H., and Burrows, J.: Evolution of stratospheric ozone and water vapour time series studied with satellite measurements, Atmos. Chem. Phys., 9, 6055–6075, doi:10.5194/acp-9-6055-2009, 2009.

McCormick, M. P., Zawodny, J. M., Viega, R. E., Larson, J. C., and Wang, P. H.: An overview of SAGE I and II ozone measurements, Planet. Space Sci., 37, 1567–1586, 1989.

McLinden, C. A., Tegtmeier, S., and Fioletov, V.: Technical Note: A SAGE-corrected SBUV zonal-mean ozone data set, Atmos. Chem. Phys., 9, 7963–7972, doi:10.5194/acp-9-7963-2009, 2009.

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

Miller, R. L., Schmidt, G. A., and Shindell, D. T.: Forced annular variations in the 20th century Intergovernmental Panel on Climate Change Fourth Assessment Report models, J. Geophys. Res., 111, D18101, doi:10.1029/2005JD006323, 2006.

Newchurch, M. J., Yang, E. S., Cunnold, D. M., Reinsel, G. C. Zawodny, J. M., and Russell, J. M.: Evidence for slowdown in stratospheric ozone loss: First stage of ozone recovery, J. Geophys. Res., 108, 4507, doi:10.1029/2003JD003471, 2003.

Newman, P. A., Gleason, J. F., McPeters, R. D., and Stolarski, R. S.: Anomalously low ozone over the Arctic, Geophys. Res. Lett., 24, 2689–2692, 1997.

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

Portmann, R. W. and Solomon, S.: Indirect radiative forcing of the ozone layer during the 21st century, Geophys. Res. Lett., 34, L02813, doi:10.1029/2006GL028252, 2007.

Purich, A. and Son, S.-W.: Impact of Antarctic ozone depletion and recovery on Southern Hemisphere precipitation, evaporation, and extreme changes, J. Clim., 25, 3145–3154, doi:10.1175/JCLI-D-11-00383.1, 2012.

Randel, W. J. and Wu, F.: 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, 2007.

Randel, W. J. and Thompson, A. M.: Interannual variability and trends in tropical ozone derived from SAGE II satellite data and SHADOZ ozonesondes, J. Geophys. Res., 116, D07303, doi:10.1029/2010JD015195, 2011.

Reinsel, G. C., Weatherhead, E. C., Tiao, G. C., Miller, A. J., Nagatani, R. M., Wuebbles, D. J., and Flynn, L. E.: On detection of turnaround and recovery in trend for ozone, J. Geophys. Res., 107, D10, doi:10.1029/2001JD000500, 2002.
Rosenfield, J. E., Considine, D. B., Meade, P. E., Bacmeister, J. T., Jackman, C. H., and Schoeberl, M. R.: Stratospheric effects of Mount Pinatubo aerosol studied with a coupled two-dimensional model, J. Geophys. Res., 102, 3649–3670, 1997.
Solomon, S.: Stratospheric ozone depletion: a review of concepts and history, Rev. Geophys., 37, 275–316, 1999.
Solomon, S., Portmann, R. W., Garcia, R. R., Randel, W. J., Wu, F., Nagatani, R., Gleason, J., Thomason, L., Poole, L. R., and McCormick, M. P.: Ozone depletion at mid-latitudes: Coupling of volcanic aerosols and temperature variability to anthropogenic chlorine, Geophys. Res. Lett., 25, 1871–1874, 1998.
Solomon, S., Portmann, R. W., Sasaki, T., Hofmann, D. J., and Thompson, D. W. J.: Four decades of ozonesonde measurements over Antarctica, J. Geophys. Res., 110, D21311, doi:10.1029/2005JD005917, 2005.
Solomon, S., Young, P. J., and Hassler, B.: 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, 2012.
Son, S.-W., Tandon, N. F., Polvani, L. M., and Waugh, D. W.: Ozone hole and Southern Hemisphere climate change, Geophys. Res. Lett., 36, L15705, doi:10.1029/2009GL038671, 2009.
Steinbrecht, W., Claude, H., Schoenenborn, F., McDermid, I. S., Leblanc, T., Godin, S., Song, T., Swart, D. P. J., Meijer, Y. J., Bodeker, G. E., Connor, B. J., Kaempfer, N., Hocke, K., Calisesi, Y., Schneider, N., de la Noe, J., Parrish, A. D., Boyd, I. S., Bruehl, C., Steil, B., Giorgetta, M. A., Manzini, E., Thomason, L. W., Zawodny, J. M., McCormick, M. P., Russell, J. M., Bhartia, P. K., Stolarski, R. S., and Hollandsworth-Frith, S. M.: Long-term evolution of upper stratospheric ozone at selected stations of the Network for the Detection of Stratospheric Change (NDSC), J. Geophys. Res., 111, D10308, doi:10.1029/2005JD006454, 2006.
Stolarski, R. S. and Frith, S. M.: Search for evidence of trend slow-down in the long-term TOMS/SBUV total ozone data record: the importance of instrument drift uncertainty, Atmos. Chem. Phys., 6, 4057–4065, doi:10.5194/acp-6-4057-2006, 2006.

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Telford, P., Braesicke, P., Morgenstern, O., and Pyle, J.: Reassessment of causes of ozone column variability following the eruption of Mount Pinatubo using a nudged CCM, Atmos. Chem. Phys., 9, 4251–4260, doi:10.5194/acp-9-4251-2009, 2009.

Wang, H. J., Cunnold, D. M., Thomason, L. W., Zawodny, J. M., and Bodeker, G. E.: Assessment of SAGE version 6.1 ozone data quality, J. Geophys. Res., 107, 4691, doi:10.1029/2002JD002418, 2002.

WMO (World Meteorological Organization): Scientific Assessment of Ozone Depletion: 1998, Global Ozone Research and Monitoring Project – Report No. 44, Geneva, Switzerland, 1999.

WMO (World Meteorological Organization): Scientific Assessment of Ozone Depletion: 2002, Global Ozone Research and Monitoring Project – Report No. 47, Geneva, Switzerland, 2003.

Ziemke, J. R., Chandra, S., Labow, G. J., Bhartia, P. K., Froidevaux, L., and Witte, J. C.: A global climatology of tropospheric and stratospheric ozone derived from Aura OMI and MLS measurements, Atmos. Chem. Phys., 11, 9237–9251, doi:10.5194/acp-11-9237-2011, 2011.

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Table 1. Overview of the characteristics of the three different data sets and information about the basis functions (BF) included in the regression model that was used to create the data sets.

	RW07	SPARC	BDBP
Ozone units	DU/km	ppmv	ppmv molecules m^{-3}
Vertical units	km	hPa	km hPa
Temporal resolution	monthly	monthly	monthly
Zonal bands	90° S–90° N, 5° zones (37)	90° S–90° N, 5° zones (37)	87.5° S–87.5° N, 5° zones (36)
Number of vertical levels	50	24	70
Highest pressure level	50 km (0.81 hPa*)	1.0 hPa	70 km 0.046 hPa
Time period covered	Jan 1979–Dec 2005	Jan 1979–Dec 2010	Jan 1979–Dec 2006
Includes troposphere	–	√	√
Includes stratosphere	√	√	√
Linear Trend BF	–	–	√
EESC BF	√	√	√
QBO BF (2 orthog.)	√	–	√
Solar cycle BF	√	√	√
Volcano BF	–	–	√
ENSO BF	–	–	√

* if converted with a standard atmosphere (scale height of 7 km).

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Table 2. Annual and seasonal mean ozone trends and their 1-σ uncertainty for the three different data sets for four different atmospheric regions. Trends are given % per decade and are calculated for the time period 1979 to 1996.

	RW07	SPARC	BDBP
Annual means			
Antarctic lower strat. (200–50 hPa)	−15.41 ± 0.10	−12.88 ± 0.13	−17.88 ± 0.30
Arctic lower strat. (200–50 hPa)	−5.04 ± 0.07	−4.20 ± 0.08	−12.85 ± 0.31
tropics, lower strat. (100–50 hPa)	−4.70 ± 0.21	−2.58 ± 0.21	−12.74 ± 0.53
upper strat. (10–1 hPa)	−4.89 ± 0.06	−5.52 ± 0.06	−3.94 ± 0.04
Seasonal means – DJF			
Antarctic lower strat. (200–50 hPa)	−11.50 ± 0.36	−8.28 ± 0.38	−15.99 ± 0.97
Arctic lower strat. (200–50 hPa)	−3.89 ± 0.19	−4.75 ± 0.26	−17.55 ± 0.93
tropics, lower strat. (100–50 hPa)	−5.49 ± 0.77	−3.43 ± 1.03	−13.38 ± 2.11
upper strat. (10–1 hPa)	−5.06 ± 0.20	−5.44 ± 0.20	−4.31 ± 0.14
Seasonal means – MAM			
Antarctic lower strat. (200–50 hPa)	−6.23 ± 0.36	−5.55 ± 0.46	−1.47 ± 0.97
Arctic lower strat. (200–50 hPa)	−7.80 ± 0.17	−5.44 ± 0.18	−12.85 ± 0.72
tropics, lower strat. (100–50 hPa)	−3.93 ± 0.26	−2.48 ± 0.64	−12.68 ± 2.10
upper strat. (10–1 hPa)	−5.40 ± 0.27	−6.15 ± 0.19	−4.57 ± 0.14
Seasonal means – JJA			
Antarctic lower strat. (200–50 hPa)	−18.09 ± 0.33	−19.16 ± 0.46	−19.79 ± 1.21
Arctic lower strat. (200–50 hPa)	−4.99 ± 0.26	−3.00 ± 0.27	−6.20 ± 1.20
tropics, lower strat. (100–50 hPa)	−4.09 ± 0.66	−1.53 ± 0.49	−11.74 ± 1.41
upper strat. (10–1 hPa)	−4.41 ± 0.19	−5.31 ± 0.19	−3.20 ± 0.16
Seasonal means – SON			
Antarctic lower strat. (200–50 hPa)	−28.11 ± 0.38	−19.33 ± 0.40	−38.17 ± 0.89
Arctic lower strat. (200–50 hPa)	−2.46 ± 0.27	−3.05 ± 0.36	−15.24 ± 1.36
tropics, lower strat. (100–50 hPa)	−5.68 ± 0.68	−2.70 ± 0.63	−13.47 ± 1.51
upper strat. (10–1 hPa)	−4.58 ± 0.19	−4.83 ± 0.19	−3.10 ± 0.14

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Table 3. The Radiative Forcing ($W m^{-2}$) due to stratospheric ozone changes between 1979–1981 and 1995–1997. The instantaneous shortwave (SW), instantaneous longwave (LW), adjustment due to stratospheric temperature changes, and total radiative forcing are shown.

	SW	LW	Adjustment	Total
RW07	0.147	−0.062	−0.124	−0.038
SPARC	0.141	−0.061	−0.113	−0.033
BDBP	0.209	−0.087	−0.241	−0.119

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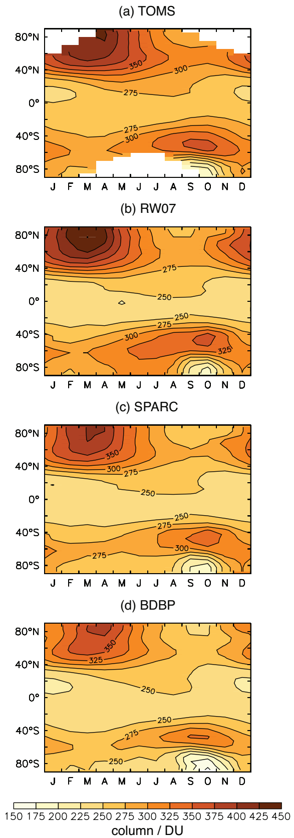

Fig. 1. (a) Total column ozone climatology (based on the period 1979 to 2005) as a function of month and latitude for TOMS/SBUV, and integrated ozone climatologies (based on the period 1979 to 2005, from 250 hPa to 1 hPa) for the **(b)** RW07, **(c)** SPARC, and **(d)** BDBP data set.

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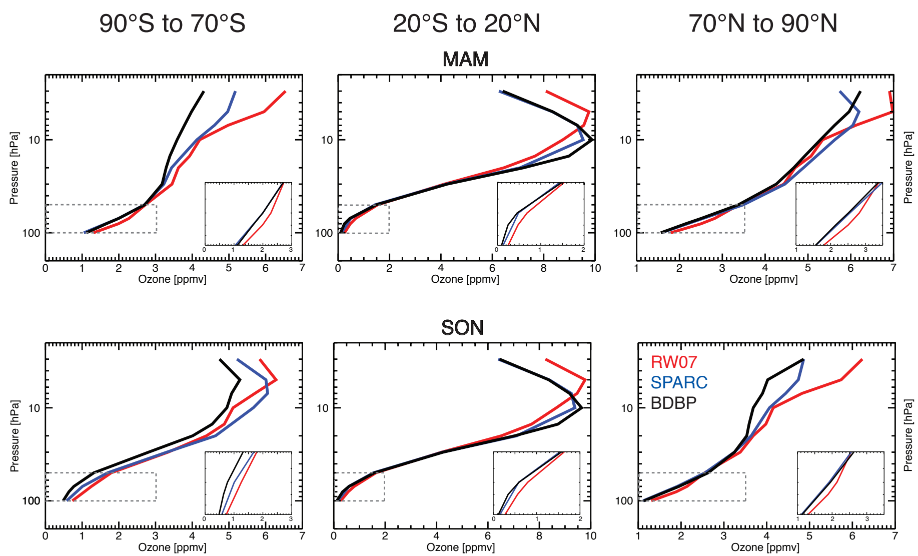

Fig. 2. Climatological ozone profiles from the three ozone data sets for three latitude regions (columns) and two seasons (rows). The lower stratosphere part of the profile (100 hPa to 50 hPa, grey dashed box) is expanded in the small inset in each graph.

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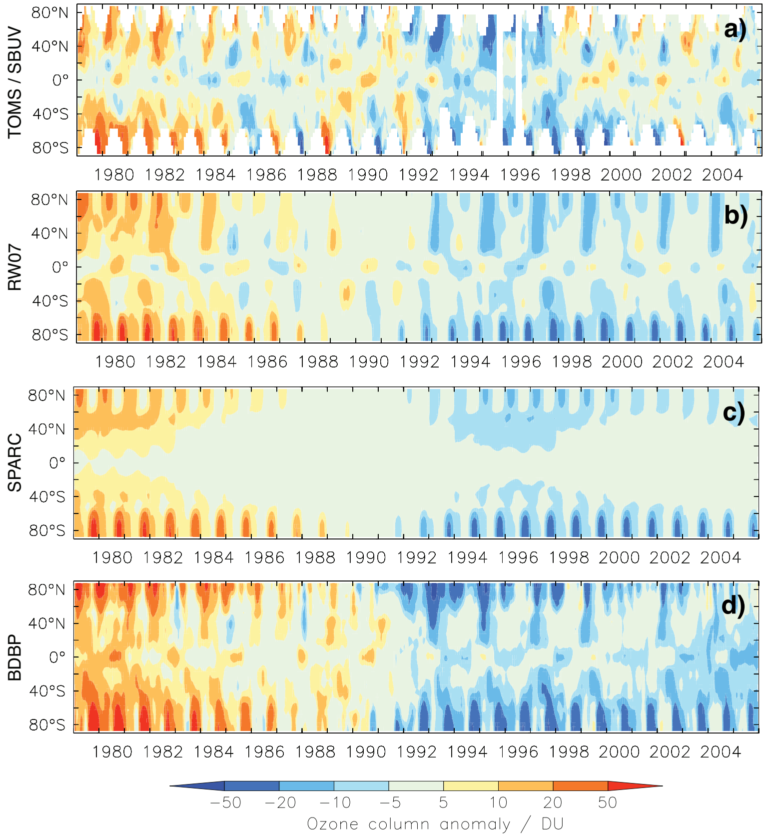

Fig. 3. Total column ozone anomalies (with respect to 1979 to 2005) as a function of time and latitude, for **(a)** TOMS/SBUV, and integrated ozone, from 250 hPa to 1 hPa, for the three datasets, **(b)** RW07, **(c)** SPARC, and **(d)** BDBP. White regions in **(a)** indicate where no TOMS/SBUV data were available. Blue colours indicate negative anomalies, red colours indicate positive anomalies.

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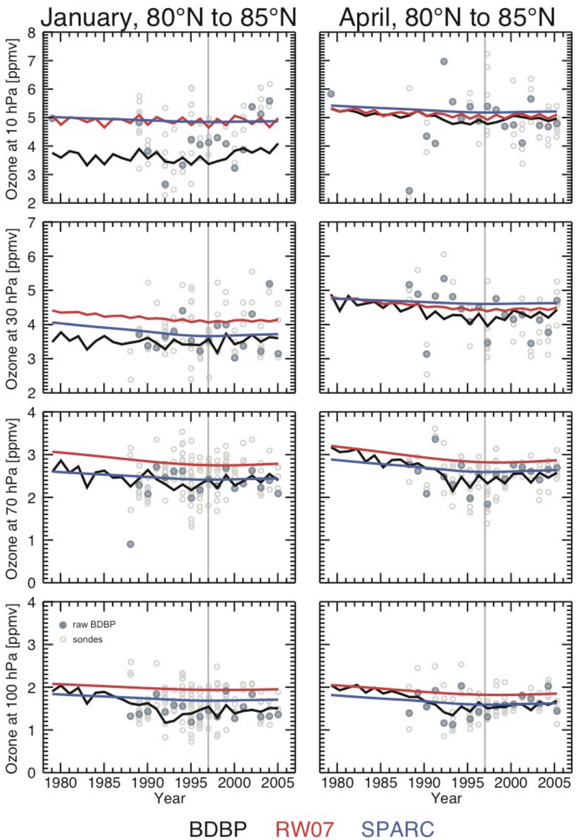

Fig. 4. January (left) and April (right) ozone time series 80° N to 85° N for four different pressure levels. Individual ozonesonde measurements available in this zone are shown for these months (grey open circles), together with BDBP raw monthly means (Tier 0, dark grey, filled circles), and the BDBP (Tier 1.4, black), RW07 (red) and SPARC (blue) time series. The vertical grey line denotes the inflection point selected for piecewise linear trend calculations (see Sect. 6).

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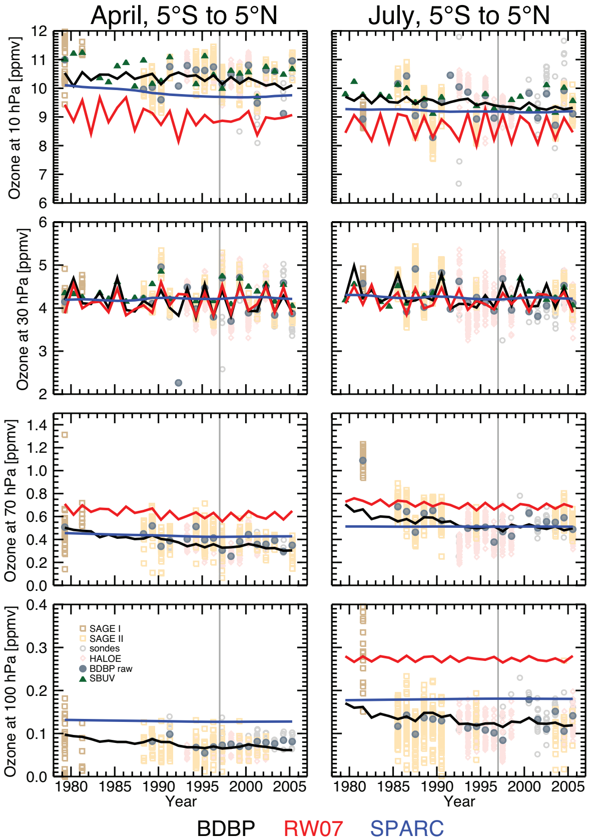

Fig. 5. April (left) and July (right) ozone time series between 5° S to 5° N for four different pressure levels. Individual ozonesonde (grey open circles), SAGE I and II (orange open squares), HALOE (red open diamonds), and SBUV/SBUV2 (dark green, filled triangles), BDBP raw monthly means (Tier 0, dark grey, filled circles), and the BDBP (Tier 1.4, black), RW07 (red) and SPARC (blue) time series are shown. The vertical grey line denotes the inflection point selected for piecewise linear trend calculations.

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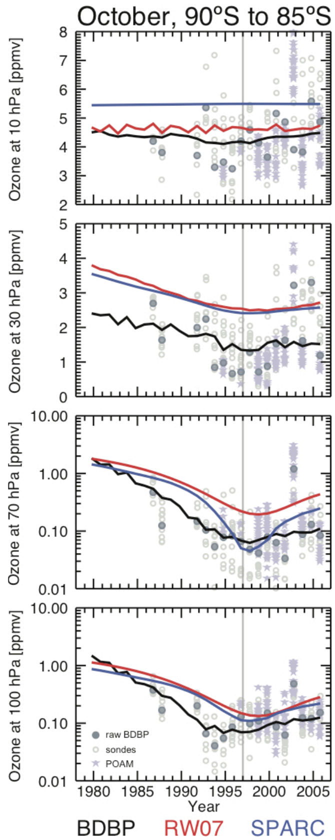

Fig. 6. October ozone time between 85° S and 90° S for four different pressure levels. Individual ozonesonde (grey open circles), and POAM II and III (violet starts), BDBP raw monthly means (Tier 0, dark grey, filled circles), and the BDBP (Tier 1.4, black), RW07 (red) and SPARC (blue) time series are shown. The vertical grey line denotes the inflection point selected for piecewise linear trend calculations.

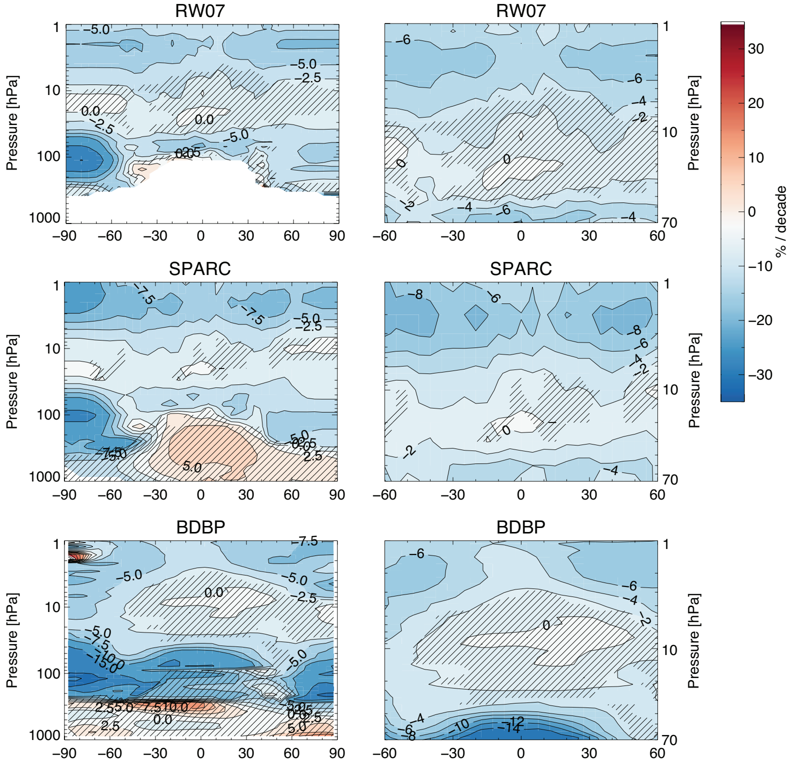

Fig. 7. Left column: Annual mean trend (% per decade) as a function of latitude and pressure for the time period 1979 to 1996, for the RW07 dataset, for the SPARC dataset, and the BDBP dataset. Hatched regions show trends that are not significantly different from zero at the 2σ level. Blue colours indicate negative trends, red colours indicate positive trends. Contour levels are: ±35, ±30, ±25, ±20, ±15, ±10, ±7.5, ±5, ±2.5, 0. Right column: same as left column, but enlarged to the region 60° S to 60° N, 70 hPa to 1 hPa. Contour levels are in increments of 2 % per decade. Note that no trend values are available for RW07 in the troposphere since RW07 is only defined in the stratosphere.

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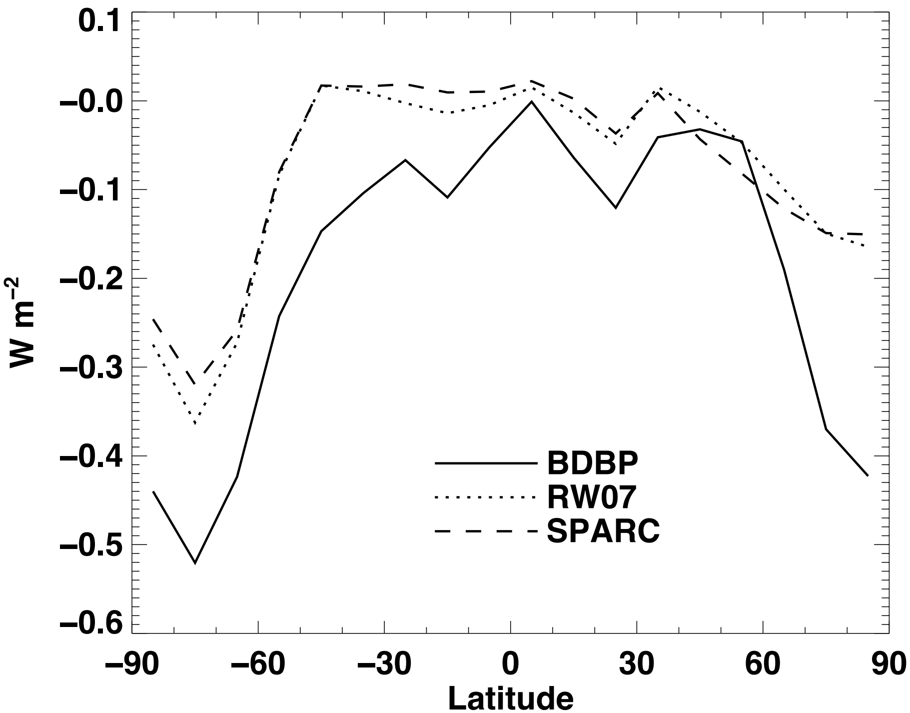

Fig. 8. Annual mean radiative forcing due to ozone changes between 1979–1981 and 1995–1997 averages for BDBP, RW07, and SPARC ozone databases. The global mean values from these calculations are given in Table 3 (column total).

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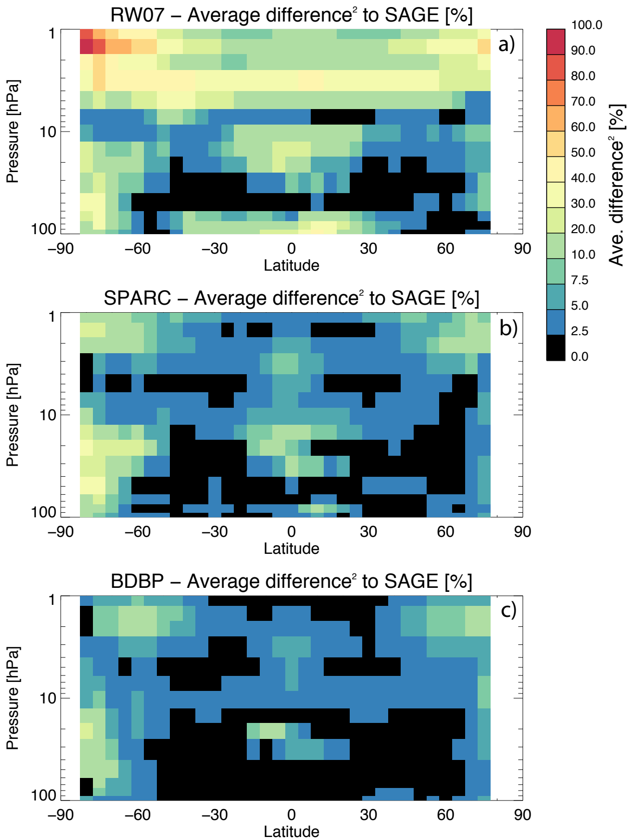

Fig. 9. Average squared difference between all available monthly mean SAGE II values for given latitude bands and pressure levels, and **(a)** the RW07 data set, **(b)** the SPARC data set, and **(c)** the BDBP data set, given in percent. Note, that for RW07 at 100 hPa some monthly means are not available between 20° S and 25° N due to missing tropospheric data. Colours changing from black to red indicate a change in average squared differences from 0 % to 100 %.

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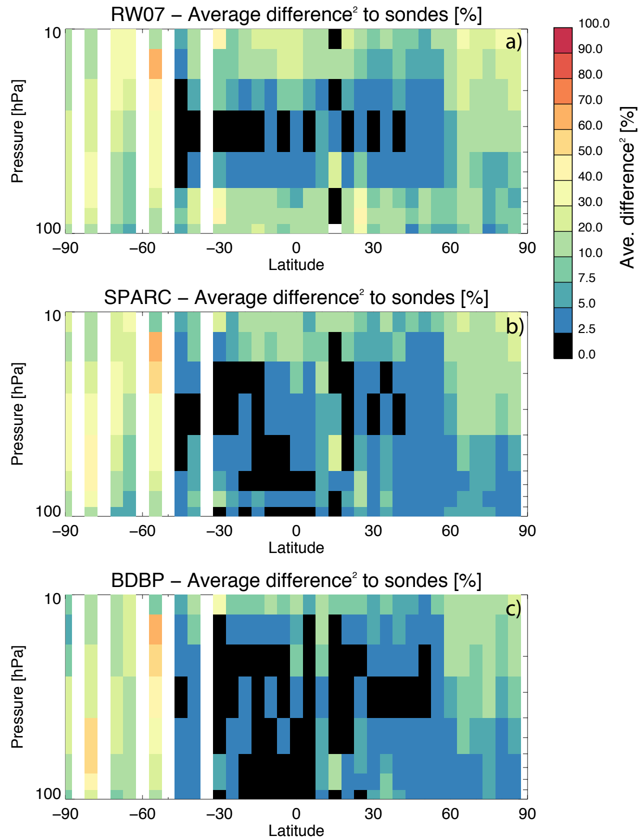

Fig. 10. Average squared difference between all available monthly mean ozone sonde values for given latitude bands and pressure levels (obtained from Hassler et al., 2009), and **(a)** the RW07 data set, **(b)** the SPARC data set, and **(c)** the BDBP data set, given in percent. Note, that for RW07 at 100 hPa some monthly means are not available between 20° S and 25° N due to missing tropospheric data. Colours changing from black to red indicate a change in average squared differences from 0 % to 100 %.

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