Atmos. Chem. Phys. Discuss., 12, 15597–15638, 2012
www.atmos-chem-phys-discuss.net/12/15597/2012/
doi:10.5194/acpd-12-15597-2012

Atmospheric Chemistry and Physics Discussions

On the use of the correction factor with Japanese ozonesonde data

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Received: 26 April 2012 – Accepted: 31 May 2012 – Published: 22 June 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

In submitting data to the World Meteorological Organization (WMO) World Ozone and Ultraviolet Data Center (WOUDC), numerous ozonesonde stations include a correction factor (CF) that multiplies ozone concentration profile data so that the columns computed agree with column measurements from co-located ground-based and/or overpassing satellite instruments. We evaluate this practice through an examination of data from 4 Japanese ozonesonde stations: Kagoshima, Naha, Sapporo, and Tsukuba. While agreement between the sonde columns and Total Ozone Mapping Spectrometer (TOMS) or Ozone Mapping Instrument (OMI) is improved by use of the CF, agreement between the sonde ozone concentrations reported near the surface and data from surface monitors near the launch sites is negatively impacted. In addition, the agreement between the mean sonde columns without the CF and the ground-based Dobson instrument columns is improved by ~1.5 % by using the McPeters et al. (1997) balloon burst climatology rather than the constant mixing ratio assumption for the above burst height column estimate. Limited comparisons of coincident ozonesonde profiles from Hokkaido University with those in the WOUDC database suggest that while the application of the CFs in the stratosphere improves agreement, it negatively impacts the agreement in the troposphere. Finally, unexplained trends and changing trends in the CFs appear over the last 20 yr. The overall trend in the CFs for the four Japanese ozonesonde stations from 1990–2010 is $(-0.157\pm0.032)\times10^{-2}\,\mathrm{yr}^{-1}$; but from 1993–1999 the trend is $(-2.21\pm0.14)\times10^{-2}\,\mathrm{yr}^{-1}$ and from 1999–2009 is $(1.180\pm0.059)\times10^{-2}\,\mathrm{yr}^{-1}$, resulting in a statistically significant difference in CF trends between these two periods of $(3.39\pm0.15)\times10^{-2}\,\mathrm{yr}^{-1}$. Given our analysis, we recommend the following: (1) use of the balloon burst climatology is preferred to a constant mixing ratio assumption for determining total column ozone with sonde data; (2) if CFs are applied, their application should probably be restricted to altitudes above the tropopause; (3) only sondes that reach at least 32 km (10.5 hPa) before bursting should be used in data validation and/or ozone trend studies; and (4) all ozone trend studies employing Japanese sonde data

should be revisited after a careful examination of the impact of the CF on the calculated ozone trends.

1 Introduction

Ozonesondes have been a stalwart technology in atmospheric chemistry analyses for many decades. The original ozonesonde instrument is described in (Komhyr, 1969), with numerous follow-up studies examining the reliability, accuracy, and precision of ozonesonde data (e.g. Komhyr et al., 1995a,b; Smit et al., 2007). Ozonesonde data have also been used in numerous validation campaigns for satellite instruments, including the Stratospheric Aerosol and Gas Experiment (SAGE), SAGE II (e.g. Cunnold et al., 1989), SAGE III (e.g. Rault and Taha, 2007), the Halogen Occultation Experiment (HALOE) (e.g. Bruehl et al., 1996), the Microwave Limb Sounder (MLS) (e.g. Froidevaux et al., 1996; Jiang et al., 2007) the Tropospheric Emission Spectrometer (TES) (e.g, Nassar et al., 2008; Worden et al., 2007), the Atmospheric Infrared Sounder (AIRS) (e.g. Bian et al., 2007), the Global Ozone Monitoring Experiment (GOME) (e.g. Liu et al., 2006), the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) (e.g. Brinksma et al., 2006) and the Ozone Mapping Instrument (OMI) (e.g. Kroon et al., 2011).

Integrated ozone profiles have been used to validate estimates of tropospheric column ozone (TCO) (e.g. Fishman et al., 1990; Thompson and Hudson, 1999; Ziemke et al., 2005; Osterman et al., 2008). And numerous studies have provided an analysis of trends in tropospheric ozone profiles (e.g. Hasebe and Yoshikura, 2006; Logan, 1994; Logan et al., 1999; Kivi et al., 2007; Krzyscin et al., 2007; Miller et al., 2006; Naja and Akimoto, 2004b; Oltmans et al., 2006; Logan, 1985). The reliability of the ozonesonde data sets is critical to our continued and developing understanding of ozone trends, transport, and tropospheric pollution studies.

In this paper, we examine carefully the ozonesonde data from four Japanese sounding stations: Sapporo, Tsukuba, Kagoshima, and Naha (see Table 1 for geographic and sampling information). These stations have provided long-term observations of ozone profiles since the late 1960's, primarily employing the carbon iodine (CI) electrochemical concentration cell (ECC) technology until December 2009 (Sapporo and Tsukuba) or November 2008 (Naha), noting that observations at Kagoshima ended in 2005 (see Table 1 for details). The CI approach is detailed in WMO (2011). This technology uses a single ECC with a platinum gauze cathode and activated carbon anode immersed in a potassium iodide solution. Phosphate buffers are added to keep the solution neutral, while potassium bromide is added to keep the solution from freezing. Ozone bubbled through the solution results in the redox-reaction with iodine. Contact with the platinum cathode causes the conversion of iodine back to iodide by the uptake of two electrons, which results in a reaction at the carbon anode. The electrical current so produced is directly related to the ozone concentration reported. This type of cell was first developed by Kobayashi and Toyama (1966).

All data presented in this paper have been retrieved from the World Ozone Ultraviolet Data Center (WOUDC, www.woudc.org) as submitted by the Japan Meteorological Agency (JMA), with file upload dates for all sites and date ranges listed in Table 2. Ozonesonde profiles in this archive, not just the Japanese sondes, most frequently apply a correction factor (CF) to the profiles that results in better agreement between total columns computed from the sonde profiles and correlated ozone measurements (e.g. Dobson and Brewer spectrophotometers, satellite overpass data). Data in the header of the downloaded WOUDC files indicate the value of the CF, the correlative observation type used to compute the CF, and whether or not the CF has been applied to the profile (in most cases, it has been applied). In the sections that follow, we examine the impact of the CF as applied to the Japanese soundings in comparisons with satellite, surface monitor, and coincident profile data, particularly noting trends in the CF itself as well as trends in the agreement with the column and surface ozone readings. The final section offers some conclusions derived from this study as well as some recommendations for the use of CF data with ozonesonde profiles.

2 Column measurements

In this section, we investigate the need for a correction factor (CF) as determined through comparisons of integrated ozonesonde profiles with satellite overpass data. In addition, we compare the CFs computed with columns that use a constant mixing ratio assumption for the above burst height column estimate to columns computed using the McPeters et al. (1997) balloon-burst climatology. Without the CFs, we find large (∼5–10 %) offsets in sonde columns as compared with satellite overpass data. Furthermore, we find trends in these offsets over the period of our study (1990–2009). The columns computed with the balloon-burst climatology result in CFs nearer to 1.0, suggesting this approach is preferred, as we demonstrate below.

Figure 1 shows histograms of the total column sonde data minus Total Ozone Mapping Spectrometer (TOMS, 1990–2004) or Ozone Mapping Instrument (OMI, 2004–2009) overpass columns as a percentage of the TOMS/OMI for the four Japanese ozonesonde stations. The solid (dashed) lines represent the differences between the sonde columns without (with) the CF applied and the satellite columns (note both the columns with and without the CFs applied appear in the header of the WOUDC data files). The sonde column with the CF is, by definition, the same as the correlative instrument column listed in the header of the same data file, as can be seen from the procedure used to calculate the CFs: the CFs are determined with the following approach: (1) integrate the raw ozonesonde profiles from the surface to burst altitude without the CF applied; (2) add on an above burst height column based on a constant mixing ratio assumption; (3) compare with the reference instrument (a ground-based Dobson instrument co-located at each ozonesonde station in the case of the Japanese sounding data); (4) the CF is the ratio of the reference instrument column to the sonde column. For all 4 Japanese stations, the histograms for the data without the CF are shifted to values greater than 0 with rather broad offset distributions. Sapporo and Tsukuba show the largest offsets while Naha shows the smallest offset. The corrected data from all four stations show very similar and much narrower distributions, with slight negative offsets. The better agreement between the ozonesonde columns with the CF and the satellite data is not surprising given the documented good agreement between ground-based Dobson instruments and satellite overpass data (McPeters and Labow, 1996; Balis et al., 2007; Fioletov et al., 2008).

Table 3 describes the statistical characteristics of the histogram data depicted in Fig. 1. We note that the standard deviations (in parentheses in the Table) are similar for all four sites, although the offsets vary. For the columns without the CF applied (again, as listed in the header of the WOUDC data files), the offsets range from a low of (3.7 ± 8.4) % at Naha to a high of (7.8 ± 7.9) % at Sapporo, with an overall mean over the four sites of (6.1 ± 8.7) %. With the CFs, the offsets range from (−0.3 ± 3.6) % at Tsukuba to (−0.9 ± 3.2) % at Sapporo, with a mean of (−0.7 ± 3.3) %. The data suggest that integrated ozonesonde profiles without CFs applied result in much larger columns than found from either the ground-based or satellite column observations.

The data in Table 3 also reveal trends in the differences between the sonde and satellite columns for the period 1990–2009 (1990–2005 for Kagoshima). Without the CF, these trends range from (2.36 ± 0.61) % decade^{-1} at Sapporo to (5.59 ± 0.84) % decade^{-1} at Kagoshima, with a mean trend over the 4 sites of (3.47 ± 0.31) % decade^{-1}. With the CF, the trends are smaller but generally significant, ranging from the insignificant (−0.09 ± 0.34) % decade^{-1} at Kagoshima to (2.19 ± 0.17) % decade^{-1} at Naha, with a mean of (1.49 ± 0.12) % decade^{-1}. The reason for the trends in the offsets is unknown, although we investigate several possibilities below.

Finally, Table 3 divides the period 1990–2009 in half, computing offsets and trends in the column differences for the sub-periods of 1990–1999 and 2000–2009 (the justification for the separation of the analysis into these two sub-periods lies in the trends in the CFs themselves, discussed below). For the sonde columns without the CF, we see the offsets are not statistically significantly different from 0 or each other during either sub-period. The trends in the offsets, however, show a statistically significant difference between the two sub-periods without the CF at every station and overall, with the overall trend during the 1990–1999 period being (16.00 ± 0.82) % decade^{-1} and during the 2000–2009 period being (−7.75 ± 0.74) % decade^{-1}, for a difference (latter minus former) of (−23.8 ± 1.1) % decade^{-1}.

The sonde columns with the CF again shown no statistically significant difference at any station during either period or between periods, nor do the overall offsets. The trends in the offsets, however, do show a statistically significant difference between the former and latter periods at all stations except Kagoshima (where the record ends in 2005). Overall, the trend shifts from (0.34 ± 0.34) % decade^{-1} during the 1990–1999 period to (3.07 ± 0.30) % decade^{-1}, with a difference (latter minus former) of (2.73 ± 0.45) % decade^{-1}.

Figure 2 provides a comparison of the histograms of the CFs at each ozonesonde station as given in the WOUDC file headers (which uses a constant mixing raido assumption for the column above the balloon-burst altitude) with those we compute by integrating the ozonesonde profiles and adding an above balloon-burst altitude column using a climatology based on Solar Backscatter Ultra-Violet (SBUV) satellite instrument data and developed by McPeters et al. (1997). The Dobson columns are divided by these "balloon-burst" columns to get the CFs, as described above. In each case, we see the CF distributions are shifted to values further from and less than 1.0 (where 1.0 indicates perfect agreement with the ground-based column measurement), though this shift is lessened when the balloon-burst approach is applied. Based on this analysis, therefore, we recommend using the balloon-burst climatology for computing ozonesonde columns.

We note that the practice of using a constant mixing ratio assumption for ozone above the balloon burst altitude appears to have been initiated in Dobson (1973). However, we also note that in that paper, the use of a constant mixing ratio to compute the above balloon-burst column is endorsed only for those balloons that burst above 20 hPa and is calculated only from the burst altitude up to ∼11 hPa (or ∼30 km).

Figure 3 shows the mean CFs at each ozonesonde station as a function of burst altitude (computed from the burst pressures) divided into 2 km increments. The figure also separates the 1990–1997 data (red) from the 1997–2009 data (blue). During the former period, the instruments were KC-79 type sondes, while during the latter period, they were KC-96 (except Naha, which in addition to this switch also switched from KC-96 to ECC sondes in 2008 – see Table 1). At all four stations, lower burst altitudes result in larger CFs. The CFs are typically lower for the 1997–2009 period as compared to the 1990–1997 period except for the Naha station, where the values are comparable. CFs for burst altitudes >32 km appear nearly constant.

We note that Logan et al. (1999) used a burst altitude criteria of 16 hPa (~29 km) in selecting sondes for use in their trend calculations using three Japanese stations (Sapporo, Tateno/Tsukuba, and Kagoshima) from late 1968/early 1969–1996. Based on our Fig. 3 for data from 1990–1997, it appears that the CFs at 29 km are slightly higher than those >32 km (10.5 hPa), although not by a statistically significant amount. For most of the remainder of this study, therefore, we present only ozonesonde data resulting from flights with burst altitudes >32 km. Furthermore, given the dependence of the CF on burst altitude, we recommend that satellite validation work use only those ozonesonde profiles that attain altitudes of at least 32 km (10.5 hPa).

We further examine the differences in CFs between the KC-79 and KC-96 sondes as compared with the findings from the Jülich Ozone Sonde Intercomparison Experiments in 2000 (JOSIE 2000 – Smit and Sträter, 2004) and 1996 (JOSIE 1996 – Smit and Kley, 1998). JOSIE 2000 found that the KC-96 sondes performed better in a controlled environmental chamber simulation than did the KC-79 sondes, with a resultant mean CF of 0.96±0.02 for the KC-96 versus the 0.91±0.10 found in JOSIE 1996 for the KC-79 sondes. Looking at the CFs for the Japanese sondes that were actually flown, we find a mean of 0.962±0.055 for the KC-79 sondes (1979–1997) and a mean of 0.901±0.038 for the KC-96 sondes (1997–2009), suggesting that the KC-96 flown sondes actually result in columns more different than correlative measurements. The smaller scatter in the KC-96 data, as indicated by the smaller standard deviation, is consistent with the finding of JOSIE 2000, but the mean CF value for the KC-96 sondes is more different from 1.0 than the KC-79 data. Even if we look at the CFs just in the years of the JOSIE studies, we find a mean CF in 1996 of 0.890 ± 0.040 for the KC-79 sondes and a mean CF in 2000 of 0.884 ± 0.039 for the KC-96 sondes, a result suggesting essentially no difference between the performances of the two types of sondes. The explanation for the differences between the CF results with the flown sondes and those of the JOSIE data is unknown at present but probably warrants further investigation.

Figure 4 shows the CFs as a function of time at all four ozonesonde stations for only those flights with burst altitudes >32 km. The data are divided into two groups: those prior to August 1997 (red, when the KC-79 sondes were retired) and those since August 1997 (blue, all KC-96 sondes). We note that the scatter in the CFs decreases after the switch from KC-79 to KC-96. Table 4 provides the CF trends and their uncertainties. All four stations show statistically significant decreases in the CF values as a function of time from 1990–1997. The mean trend over all four stations during this period is $(-1.82 \pm 0.15) \times 10^{-2}\,\mathrm{yr}^{-1}$. Since 1999, all four stations show increasing CFs, with a mean increase of the CF of $(1.180 \pm 0.059) \times 10^{-2}\,\mathrm{yr}^{-1}$. The mean difference in these trends (latter period minus former period) is a statistically significant $(3.00 \pm 0.16) \times 10^{-2}\,\mathrm{yr}^{-1}$.

Figure 5 shows the annual mean CFs at each of the Japanese stations using the data in Fig. 4. We can see that the trend toward CF values further away from and below 1.0 begins ~1993, about two years after the Mt. Pinatubo eruption, with a recovery toward CFs of nearer 1.0 beginning ~1999. Table 4 also shows calculated trends in the CFs at the four stations divided into the two periods that appear to have consistent trends: 1993–1999 and 1999–2010. As the values in this table demonstrate, a statistically significant change in CF trends appears between these two periods, with an overall negative trend of $(-2.21 \pm 0.14) \times 10^{-2}\,\mathrm{yr}^{-1}$ during the former period, an overall positive trend of $(1.180 \pm 0.059) \times 10^{-2}\,\mathrm{yr}^{-1}$, and a statistically significant difference in the CF trends of $(3.39 \pm 0.15) \times 10^{-2}\,\mathrm{yr}^{-1}$. Again, the cause of these trends has yet to be determined.

Previous works have alluded to the potential problems caused by trends in CFs. The analysis shown in Fig. 1 in Logan et al. (1999) shows CFs (as found in the WOUDC data file headers) for Tateno (Tsukuba) sonde launches from 1970–1996. It is apparent from their Fig. 1 that the CFs were decreasing at the end of the time series, after ~1993, as seen more clearly in our Fig. 4. Table 4 in Logan et al. (1999) summarizes trend analyses in % decade^{-1} for the periods 1970–1996 and 1980–1996. They found no statistically significant trends in the CFs at Sapporo or Kagoshima, but statistically significant negative CF trends of -1.3 ± 0.9 or -3.3 ± 1.7 % decade^{-1} for the two analysis periods respectively at Tateno (Tsukuba). Converting our results in Table 4 to the same units, we find a trend in the CF at Tsukuba of $\sim -27 \pm 3$ % decade^{-1} for the 1993–1999 period and of $\sim +18 \pm 1$ % decade^{-1} for the 1999–2009 period, much larger and more alarming than those found in Logan et al. (1999). We note, however, that the trend computed from 1990–2009 was only $\sim -1.0 \pm 0.5$ % decade^{-1}. The CFs at the end of the record had recovered to their values at the beginning. The portion of the record analyzed in their paper showed a great deal more consistency in the CFs at Tsukuba from 1980–1992, with only the last few years of their analysis including the period with the strong trend noted in our Fig. 4. They also used a lower burst altitude exclusion criteria (16 hPa) than recommended in our study, and they excluded any sonde profile associated with a CF <0.8 or CF >1.2. As seen in our Fig. 4, the latter criterion excludes very few profiles before 1995. However, given the real trend seen in the CF data in the mid 1990s, more profiles report CFs at or less than 0.8, particularly during the 1997–2009 time period. Such profiles would be excluded from the Logan et al. (1999) analyses, but probably should not be, since the entire data set appears to be drifting toward CFs further from but less than 1.0. We suggest an altered exclusion criterion: rather than using the absolute difference between the CF and 1.0, use the difference between the CF and a running mean CF (smoothed CF with time) of more than two standard deviations in the period extending from 6 months prior to 6 months after the profile in question.

Miller et al. (2006) examined ozone profile trends using WOUDC data from 12 ozonesonde stations in the Northern Hemisphere. In their study, they exclude any soundings with a CF <0.9 or CF >1.15, a tighter criteria than Logan et al. (1999), and one that becomes especially problematic from 1993–2008 for the Japanese sounding data. They note a statistically significant change in trend starting around 1996, nearly the same time the Japanese stations switched from KC-79 to KC-96 ozonesondes (Summer 1997) and corresponding to the minimum CFs in the 1990–2009 record examined in our paper. Miller et al. (2006) excluded the two years after the eruption of Mt. Pinatubo from their trend calculations. It is unclear the extent to which their results would change if the exclusion criteria based on the CFs was changed or the CFs not applied at all.

Solomon et al. (1998) discuss the impacts on stratospheric chemistry from the material injected into the upper troposphere and lower stratosphere by the eruption of Mt. Pinatubo (June 1991). They found decreases in ozone at mid latitudes (40°–60° N) as a result of heterogeneous chlorine chemistry, with a recovery by March of 1996. Keim et al. (1996) report significant reductions in the NO_x/NO_y ratio near the mid-latitude tropopause as measured by the NASA ER-2 high-altitude aircraft during the April 1993 Stratospheric Photochemistry, Aerosols, and Dynamics Expedition (SPADE), again the result of heterogeneous reactions with chlorine species on Pinatubo aerosols. An outstanding question is, what if any impact the volcanic effluence and the resulting altered chemistry might have had on the reactions in the carbon-iodine sondes used by the Japanese stations? We have examined ozonesonde data from 9 other stations in the WOUDC database that use the Brewer-Mast and ECC approach. None exhibit similar trends in the associated CFs in their header of the data files at the WOUDC as found for the Japanese sondes.

The fact that the CFs show trends with time is of some concern. Caution is recommended if the ozonesonde data is to be used in trend calculations of ozone profile shapes, tropospheric columns, and/or stratospheric columns (Logan, 1985, 1994; Miller et al., 1995). Below, we comment on a few such studies that may have seen impacts from the trends in CFs at the Japanese stations.

Ziemke et al. (2005) found their tropospheric column ozone computed with the cloud slicing technique from Version 8 TOMS data exceeded that found by integrating tropospheric profiles at Kagoshima and Naha. As we can see by examining Fig. 4, both stations have CFs <1.0, meaning that the ozone columns computed from the sounding data are less than the uncorrected tropospheric columns. Thus, the CFs may explain, at least partially, the bias observed in Ziemke et al. (2005).

Oltmans et al. (2006) examined ozone profile trends for stations with data at the WOUDC. In particular, they found statistically significant positive trends below 300 hPa for the three Japanese stations (Sapporo, Tsukuba, and Kagoshima) from 1970–2004, but negative trends below 700 hPa from 1990–2004 at Naha. The authors also report that since the early 1990's, the tropospheric trends have been negative at all four of these stations, despite growing emissions from China that probably should have led to increased ozone transport to Japan. Based on the analysis presented here, at least part of the explanation lies in the fact that the CFs were trending downward from 1993–1999, resulting in tropospheric values that were smaller with time. Despite the increasing trend in the CFs following 1999, the values by 2004 had not yet recovered to those seen in 1993, by which time the downward trend in CFs at the Japanese stations was clearly underway.

Hasebe and Yoshikura (2006) examined ozone trends using the data from the Japanese sounding stations for the periods 1968–1975 and 1990–2002 and a potential temperature/equivalent latitude analysis. They found losses of 5–20 %, mainly in the midlatitude stratosphere and of 30–50 % in the spring season in the lower stratosphere, with negative trends from the former to the latter analysis period throughout the profile (their Fig. 3). In Table 5, we show the mean and one standard deviation values for the CFs at each of the three stations used in their analysis for each of the two periods. While none of the differences between the CFs at any of the stations is statistically significant, both Sapporo and Tsukuba show a trend toward smaller CF values, which would lead to lower ozone amounts. No trend is apparent at Kagoshima when examined over the entire period, but recall that trends in the CFs during the latter period are found at all three stations. Thus it remains an open question how much of the ozone profile trends reported in Hasebe and Yoshikura (2006) are real and how much can be attributed solely to the trends in the CFs.

Finally, Hayashida et al. (2008) examined the agreement between GOME tropospheric ozone columns and the integrated Japanese sonde columns from 1996–2003 with the CFs applied. They found generally good agreement between the two instruments throughout this analysis period, although their Fig. 2 suggests that the tropospheric sonde columns were typically less than those determined from GOME, and their data show no discernable trends in the differences between them, as might be expected from our analysis. The former result is consistent with the fact that the Japanese sonde profiles have been multiplied by CFs of less than 1.0, which suggests that the application of the CFs are not appropriate for the tropospheric column computed from ozonesonde data.

Since the greatest uncertainties in the ozonesonde profiles arise in the stratospheric portion of the data as a result of pump inefficiencies in the low pressure, low temperature environment at and above the tropopause, it may be necessary to apply CFs to this portion of the profile (see Sect. 4 below). Application of the CFs to the tropospheric portions, however, may not be justified (see Sects. 3 and 4 below). For example, the study of Naja and Akimoto (2004a) computed tropospheric trends after removing the CFs from the tropospheric portion of the ozone profiles. This approach is the one we would endorse for all tropospheric trend studies. In fact, this approach is also the one recommended in the SPARC-IOC-GAW Report (1998, see page 170, second paragraph).

3 Surface measurements

In this section, we investigate the need for a CF as determined through comparisons of ozonesonde data gathered in the lowest 100 m above the surface of each flight with hourly averaged data from surface monitors near the launch sites. Ideally each ozonesonde station would have its own ozone monitor so that pre-launch ozone measurements from the sondes could be validated against the ground-based monitors. We use the long-term station database (available online at: http://www.nies.go.jp/igreen/td_disp.html) as a source for the surface monitor data, and note that the Japanese stations actually report "oxidant" mixing ratios. These data should closely reflect the ozone concentrations at the surface sites. This database contains only a subset of operational surface monitor stations in Japan. Table 6 lists information on the surface monitor data. For the Japanese ozonesondes stations, Sapporo and Tsukuba both have monitors nearby (<20 km from the launch sites) in the database, although the Tsukuba monitor record ends in 2002. The surface monitor nearest Kagoshima station is ∼160 km north, which can lead to large discrepancies between the balloon observations and the surface monitor data. The Hedo station is the nearest to Naha (∼92 km north-northeast), although the available record of data does not begin until 2001. It should be noted that the Naha ozonesonde station is located close to an urban area, so its ozone measurements will be affected by the urban plume, while the Hedo station is located at a remote site on the northern tip of the island. The differences in these locations are likely the primary cause of the larger offsets between the ozonesonde and surface monitor data shown in Fig. 6.

Figure 6 shows histograms of the differences between the sonde mean ozone concentrations in the lowest 100 m above the surface and the appropriately timed hourly surface monitor ozone concentrations near each launch site, both with and without the CFs applied to the sonde data. Table 7 provides a statistical summary of these differences. Looking at the overall data comparisons shown in Fig. 6, we see that for all four stations, the distributions of values shifts toward "0" with no CF applied to the sonde data. The overall statistical comparisons in Table 7 reveal a similar result: in each case, the overall mean offset at each site is closer to "0" without the CF applied, improving on average from an offset of −4.9 ± 8.0 with the CF to −1.5 ± 8.5 ppb without (note that Naha is excluded from the "overall" average and prior to 1997 analysis since Hedo data were not available before 2001).

We examined the sensitivity of these results to three different calculations of the near surface ozonesonde readings: (1) the ozone reading at the highest ambient pressure for each ozonesonde flight; (2) the ozone reading at 10 m above the surface; and (3) the average ozone concentration in the first 100 m above the surface. The third approach resulted in the smallest mean offsets for both the data with and without the CFs applied.

Given the trends in the CFs noted in Sect. 2 above, we decided to further divide our analysis of the sonde-surface monitor comparisons into two periods: before and after the switch from KC-79 to KC-96 sondes, which occurred August 1997 except at Tsukuba, where it occurred in June 1997. Figure 7 shows the histograms for the three ozonesonde stations active in 1997 divided into these two time periods and between data with and without the CFs applied. In both time periods at each station, the distributions of the differences (sonde minus surface monitor) shift toward more positive values if CFs are not applied. In general, the sonde data agree more closely with the surface monitor data when the CFs are not applied to the data.

Table 7 provides the statistical analyses of trends in the data appearing in Fig. 7. At each station, the overall trend is closer to "0" using data without the CFs applied, with an average change from $-0.823 \pm 0.099\,\mathrm{ppb\,yr^{-1}}$ with the CFs applied to $-0.46 \pm 0.10\,\mathrm{ppb\,yr^{-1}}$ without the CFs applied. In each case, without the CF applied, we see a statistically significant change in trends from the KC-79 period to the KC-96 period. Much of the trend appears to be attributable to the change in the sonde instrument type in 1997. Overall, the trends in the sonde-surface differences are smaller without the CF applied than with it applied. Furthermore, the agreement between the near surface readings and the surface monitors appears to have been somewhat better with the KC-79 than the KC-96 ozonesondes. At present, we do not have an explanation for these observations.

4 Sapporo ozonesonde intercomparison

ECC ozonesondes have been launched from the campus of Hokkaido University (41.07° N, 141.35° E) since 2003. This site is located ~2 km from the Sapporo station launches. To date, 58 such launches have occurred, with 35 of the payloads carrying a combination of ozonesondes and frost-point hygrometers, and the remaining payloads carrying only frost-point hygrometers. Of those 35 flights with ozonesondes, 8 occurred on the same dates as the standard Sapporo station carbon-iodide KC-96 ozonesonde flights, and 7 of those reached altitudes >29 km before bursting, with one reaching an altitude of 32 km. All of the Hokkaido University ozonesondes have used the NOAA configuration with an En-Sci ECC, TMAX-C interface board, and Vaisala RS80 radiosonde. Hokkaido University sondes are processed with the NOAA STRATO software (http://cires.colorado.edu/~voemel/strato/strato.html). The 10 flights in August 2008 and 12 flights in August/September of 2009 used 0.5 % buffered potassium iodide cathode solutions while the remaining flights used solutions 2 % unbuffered potassium iodide cathode solutions. No CFs are applied to the Hokkaido University data.

Table 8 summarizes the column ozone observations for each of the 7 coincident flights, including the ECC Hokkaido University sonde columns, the Earth Probe Total Ozone Mapping Spectrometer (EPTOMS) (2004 flights) or OMI (2005–2009 flights) columns over the Sapporo station (43.06° N, 141.33° E), and the Sapporo CI KC-96 ozonesonde columns, calculated both with and without the CFs. The mean differences in the agreement between the sondes and satellite columns are not statistically significantly different (see the second to last row of Table 8), due both to the scatter and the small number of coincident sondes, although the mean difference between TOMS/OMI columns and the columns from the Sapporo CI KC-96 sondes with the CFs applied shows the smallest standard deviation. This result is not surprising since the application of the CFs result in perfect agreement between the sonde columns and the collocated Dobson instrument at the Sapporo station launch site. Nevertheless, for two of the flights, the ECC and CI KC-96 ozonesonde columns agree with one another better than either agrees with OMI/EPTOMS or the Dobson instrument. In fact, the overall agreement between the ECC sonde columns and the Sapporo CI KC-96 sonde columns is slightly better for the uncorrected data, though not statistically significantly so (see the last row of Table 8). The explanations for these observations are unclear, but they enhance the case that caution must be used when applying the correction factors based on either satellite or ground-based column measurements.

Table 9 presents an overall comparison of the columns from the ECC and CI sondes (both with and without the CFs) to the satellite columns from EPTOMS (1996–2005) and OMI (2004–2009). The best agreement is found for the corrected CI sonde data, but that agreement is not statistically significantly different from the agreement seen between the ECC Hokkaido University sondes and satellite observations. The worst agreement and largest scatter is seen with comparisons of the CI sonde columns without the CFs applied and the satellite columns, indicating that some correction to the profiles is necessary.

To gain insight as to how best to correct the CI sonde profiles, we examine the mean percent differences between the ECC Hokkaido University ozonesonde profiles and those from the CI ozonesondes for the 7 coincident flights listed in Table 8. The overall comparison is shown in Fig. 8, with comparisons between the ECC sonde profiles and both the corrected (blue) and uncorrected (red) CI KC-96 sonde profiles. Data from each of the 7 comparisons appear as the black curves in Fig. 8. Here, the percent difference is calculated as the 100 × (CI − ECC)/ECC.

Again, we are limited by the small number of coincidences, which results in statistically insignificant differences. Nevertheless, we note that throughout the troposphere, the mean difference of the Sapporo CI KC-96 profiles without the CFs applied with Hokkaido University ECC sonde profile differences are closer to 0, while in the stratosphere (above 18 km), the mean difference of the Sapporo profiles with the CFs applied with the ECC sonde profiles is closer to 0. With the majority of the ozone present in the ozone layer between 20 and 30 km, the CFs are heavily influenced by the stratospheric concentrations. In looking at the mean profiles, however, we see in Fig. 8 that the tropospheric differences are negative while the stratospheric differences are positive, meaning that applying the CFs to the entire profile exacerbates the differences in the troposphere, though in the limited 7 cases that make up the data in Fig. 8, the differences between the mean profiles with and without the CFs applied are not statistically significant. These results are consistent with the findings in JOSIE 2000 (Smit and Sträter, 2004) and JOSIE 1996 (Smit and Kley, 1998).

We also note that the mean CF applied in the 7 matching cases is 1.028 ± 0.082, which is higher than the historical record suggests, with a mean of 0.927 ± 0.093, indicating that our sample may not be representative, with the profiles in the sample having smaller ozone concentrations than typical in the larger data set. This bias is apparent in the fact that three of the black curves from individual flights appearing in Fig. 8 remain negative from the surface through the ozone layer.

In summary, the profile data comparison, though not statistically significant, suggests that while applying CFs in the stratosphere is helpful for improving agreement with satellite and Dobson instrument columns as well as with the stratospheric portion of the ozone profiles observed in the correlated ECC sondes from Hokkaido University, the tropospheric comparisons may be improved without the application of the CFs, a result consistent with the findings of the SPARC-IOC-GAW Report (1998), as cited earlier. Furthermore, the ECC sonde agreement with the satellite observations is statistically similar to that found with the corrected CI sonde data, suggesting the ECC technology may well be the better approach. Since late 2009, all Japanese stations have switched from the CI KC-96 sondes to the ECC sondes, so the problems explored in this paper may well be moot now.

5 Conclusions and recommendations

This paper has provided an analysis of the application of the correction factor (CF) for ozonesonde profile data based on observations from the four Japanese ozonesonde stations, TOMS and OMI overpass column data, ground-based Dobson instrument column data (used to determine the CFs for the Japanese sounding in the WOUDC database), and surface monitor data from sites nearby to the ozonesonde stations. We find that while CFs based on sonde column to Dobson instrument column ratios result in better agreement with the satellite observations, the agreement between the sonde reported ozone concentration measurements and those of the nearby surface monitors deteriorates.

Comparisons of ozonesonde profiles from Hokkaido University (which employed the standard ECC technology) with those of the Sapporo station (which employed the CI KC-96 technology) indicate that while the application of CFs improves agreement with the ozone concentrations in the stratosphere (and with the total columns measured by other instruments), it may make agreement in the troposphere worse.

Disturbingly, we found the CFs at the Japanese ozonesonde stations exhibit trends over the period 1990–2009, with differing trends during the period 1990–1997 (when KC-79 sondes were flown) and the period 1997–2009 (when KC-96 sondes were flown). These trends are as yet unexplained, although given the consistency of the downward trend from 1993–1999 at all four Japanese stations and of the upward trend from 1999–2009, we wonder about the possibility of a chemical interference mechanism, perhaps resulting from the altered chemical composition of the stratosphere due to the eruption of Mt. Pinatubo. Our preliminary investigation of the CFs at 9 other ozonesonde stations with data in the WOUDC database suggests that similar trends in CFs are not present over the same periods. We intend to expand this investigation and analysis in future work.

Regardless of its cause, the presence of the CF trends at the Japanese stations warrants caution when employing ozonesonde data with CFs applied to the entire profile in trend calculations. Since the CFs do result in better agreement of the sonde columns with correlative measurements, and since most of the ozone is in the stratosphere, one possible approach to consider, which we recommend based on this study, which was suggested in the SPARC-IOC-GAW Report (1998), and which Logan et al. (1999) noted was suggested around the time of their paper (uncited reference) is only to apply

CFs to the stratospheric portion of the profiles. Such an approach would require a new method for calculating the CFs. Here would be our recommendation: (1) integrate the sondes to the tropopause; (2) add the balloon-burst climatological column to the tropospheric column; (3) subtract the sum of partial columns computed in #1 and #2 from the correlative column measurement (Dobson, Brewer, TOMS/OMI); (4) compute the sonde column above the tropopause; and (5) take the ratio of the correlative stratospheric column in #3 to the sonde stratospheric column in #4 – that is the new CF. Some iteration may be required so that a discontinuity between the tropospheric and stratospheric portions of the ozonesonde profile would not appear.

We also note that the CFs show a dependence on burst altitude below 32 km (10.5 hPa). We therefore recommend only using ozonesonde data from those profiles that extend to at least 32 km altitude. Finally, we found that using the McPeters et al. (1997) balloon-burst climatology rather than a constant mixing ratio assumption for calculating the above-burst height columns resulted in better agreement between the sonde columns and the ground-based Dobson instrument columns. We therefore recommend using the balloon-burst climatology for computing total columns with ozonesonde data. Again, all of our analyses should be expanded to other ozonesonde stations in the WOUDC database, since most stations in that database apply the CF to the entire profile, as has been done at the Japanese sounding stations.

Acknowledgements. Funding for this work was provided by a Fulbright Scholar Grant from the Japan-U.S. Educational Commission and NASA's Aura Data Validation Program (D. Considine and E. Hilsenrath, program managers). Special thanks to my hosts in Japan during my Fulbright.

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Table 1. Information for the Japanese ozonesonde stations used in this study.

Station	Latitude	Longitude	Date Range	Sonde Type
Sapporo	43.1° N	141.3° E	Jan 1990–Jul 1997 Aug 1997–Nov 2009 Dec 2009–present	KC-79 KC-96 ECC
Tsukuba	36.1° N	140.1° E	Jan 1990–May 1997 Jun 1997–Nov 2009 Dec 2009–present	KC-79 KC-96 ECC
Kagoshima	31.6° N	130.6° E	Jan 1990–Jul 1997 Aug 1997–Mar 2005	KC-79 KC-96
Naha	26.2° N	127.7° E	Jan 1990–Jul 1997 Aug 1997–Oct 2008 Nov 2008–present	KC-79 KC-96 ECC

Table 2. Information on the files downloaded from the WOUDC. Ozonesonde data supplied by JMA.

	Sapporo			Tsukuba			Naha	
Earliest Flight Date	Latest Flight Date	WOUDC File Creation Date	Earliest Flight Date	Latest Flight Date	WOUDC File Creation Date	Earliest Flight Date	Latest Flight Date	WOUDC File Creation Date
17 Jan 1990	29 Dec 1999	23 Sep 2004	13 Jan 1990	28 Dec 1999	24 Sep 2004	17 Jan 1990	28 Dec 1999	24 Sep 2004
5 Jan 2000	26 Dec 2007	12 Mar 2008	5 Jan 2000	30 Jan 2008	12 Mar 2008	6 Jan 2000	23 Jan 2008	12 Mar 2008
4 Jan 2008	9 Feb 2009	28 Apr 2009	7 Feb 2008	25 Feb 2009	28 Apr 2009	4 Feb 2008	29 Oct 2008	28 Apr 2009
3 Mar 2009	25 Mar 2009	20 May 2009	4 Mar 2009	26 Mar 2009	20 May 2009	13 Nov 2008	20 Nov 2008	3 Nov 2009
2 Apr 2009	30 Apr 2009	9 Jun 2009	1 Apr 2009	30 Apr 2009	10 Jun 2009	3 Dec 2008	3 Dec 2008	16 Nov 2009
7 May 2009	24 Jun 2009	9 Aug 2009	7 May 2009	25 Jun 2009	10 Aug 2009	14 Jan 2009	28 Jan 2009	3 Nov 2009
7 Jul 2009	30 Jul 2009	30 Aug 2009	1 Jul 2009	29 Jul 2009	31 Aug 2009	3 Feb 2009	3 Feb 2009	16 Nov 2009
4 Aug 2009	18 Aug 2009	5 Oct 2009	5 Aug 2009	26 Aug 2009	5 Oct 2009	10 Feb 2009	24 Jun 2009	3 Nov 2009
1 Sep 2009	30 Sep 2009	2 Nov 2009	2 Sep 2009	24 Sep 2009	2 Nov 2009	1 Jul 2009	1 Jul 2009	16 Nov 2009
7 Oct 2009	28 Oct 2009	4 Oct 2010	1 Oct 2009	28 Oct 2009	4 Oct 2010	8 Jul 2009	22 Jul 2009	3 Nov 2009
12 Nov 2009	17 Dec 2009	18 Oct 2010	12 Nov 2009	22 Dec 2009	18 Oct 2010	29 Jul 2009	12 Aug 2009	16 Nov 2009
4 Jan 2010	27 Jan 2010	20 Sep 2010	15 Jan 2010	27 Jan 2010	20 Sep 2010	26 Aug 2009	30 Sep 2009	3 Nov 2009
1 Feb 2010	24 Feb 2010	27 Sep 2010	3 Feb 2010	24 Feb 2010	27 Sep 2010	9 Oct 2009	28 Oct 2009	4 Oct 2010
4 Mar 2010	29 Mar 2010	14 Jun 2010	3 Mar 2010	31 Mar 2010	14 Jun 2010	4 Nov 2009	22 Dec 2009	18 Oct 2010
5 Apr 2010	19 Apr 2010	16 Jun 2010	8 Apr 2010	21 Apr 2010	16 Jun 2010	7 Jan 2010	20 Jan 2010	20 Sep 2010
17 May 2010	17 May 2010	5 Jul 2010	6 May 2010	28 May 2010	5 Jul 2010	2 Feb 2010	24 Feb 2010	27 Sep 2010
10 Jun 2010	30 Jun 2010	27 Jul 2010	3 Jun 2010	30 Jun 2010	27 Jul 2010	3 Mar 2010	24 Mar 2010	14 Jun 2010
15 Jul 2010	15 Jul 2010	7 Sep 2010	8 Jul 2010	23 Jul 2010	7 Sep 2010	8 Apr 2010	21 Apr 2010	16 Jun 2010
2 Aug 2010	30 Aug 2010	4 Oct 2010	4 Aug 2010	24 Aug 2010	4 Oct 2010	5 May 2010	26 May 2010	5 Jul 2010
9 Sep 2010	30 Sep 2010	2 Nov 2010	1 Sep 2010	29 Sep 2010	2 Nov 2010	30 Jun 2010	30 Jun 2010	27 Jul 2010
6 Oct 2010	27 Oct 2010	29 Nov 2010	6 Oct 2010	27 Oct 2010	29 Nov 2010	14 Jul 2010	21 Jul 2010	7 Sep 2010
17 Nov 2010	24 Nov 2010	4 Jan 2011	4 Nov 2010	24 Nov 2010	4 Jan 2011	4 Aug 2010	25 Aug 2010	4 Oct 2010
2 Dec 2010	27 Dec 2010	31 Jan 2011	1 Dec 2010	22 Dec 2010	31 Jan 2011	8 Sep 2010	22 Sep 2010	2 Nov 2010
	Kagoshima					6 Oct 2010	13 Oct 2010	29 Nov 2010
17 Jan 1990	22 Dec 1999	24 Sep 2004				4 Nov 2010	24 Nov 2010	4 Jan 2011
6 Jan 2000	20 Mar 2005	12 Mar 2008				1 Dec 2010	22 Dec 2010	31 Jan 2011

Table 3. Trends in the differences between sonde and satellite ozone columns, and the mean offsets in those column ozone differences (Japanese ozonesonde columns minus TOMS/OMI columns) for the period 1990–2009 (* for Kagohsima station, the data record ends in 2005) as computed with and without the CF applied. The calculations are based only on those sondes that reach a minimum altitude of 32 km (10.5 hPa) before bursting. The numbers in parenthesis in this and the following tables represent one standard deviations.

No CF	Overall		1990–1999		2000–2009	
Station	Offset (%)	Trend (% decade^{-1})	Offset (%)	Trend (% decade^{-1})	Offset (%)	Trend (% decade^{-1})
Sapporo	7.8 (7.9)	2.36 (0.61)	5.9 (8.3)	11.1 (1.7)	8.8 (7.4)	−8.7 (1.4)
Tsukuba	7.4 (9.0)	3.73 (0.53)	5.6 (10.3)	18.8 (1.4)	9.2 (7.4)	−12.4 (1.1)
Kagoshima*	4.2 (8.4)	5.59 (0.84)	3.0 (9.5)	15.7 (1.8)	5.5 (7.0)	−8.3 (2.8)
Naha	3.7 (8.4)	2.47 (0.60)	3.1 (9.9)	16.7 (1.7)	4.2 (7.1)	−4.5 (1.4)
Overall	**6.1 (8.7)**	**3.47 (0.31)**	**4.5 (9.7)**	**16.00 (0.82)**	**7.3 (7.6)**	**−7.75 (0.74)**
w/CF	Overall		1990–1999		2000–2009	
Station	Offset (%)	Trend (% decade^{-1})	Offset (%)	Trend (% decade^{-1})	Offset (%)	Trend (% decade^{-1})
Sapporo	−0.9 (3.2)	1.23 (0.24)	−1.4 (3.0)	−0.10 (0.67)	−40.5 (3.2)	1.23 (0.61)
Tsukuba	−0.3 (3.6)	1.69 (0.21)	−1.3 (4.0)	−0.33 (0.66)	0.5 (3.0)	1.69 (0.48)
Kagoshima*	−0.7 (3.2)	−0.09 (0.34)	−0.4 (3.3)	1.03 (0.71)	−0.9 (3.1)	−0.09 (1.28)
Naha	−0.6 (2.7)	2.19 (0.17)	−2.0 (2.4)	0.96 (0.48)	0.4 (2.5)	2.19 (0.48)
Overall	**−0.7 (3.3)**	**1.49 (0.12)**	**−1.4 (3.5)**	**0.34 (0.34)**	**−0.1 (3.1)**	**3.07 (0.30)**

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 4. Trends in the CFs for the Japanese ozonesonde stations. The calculations are based only on those sondes that reach a minimum altitude of 32 km (10.5 hPa) before bursting. * For Kagohsima station, the data record ends in 2005. The "Delta" column represents the difference in the trends of the 1999–2009 period and the 1993–1999 period.

Site	1990–2010 (10^{-2} yr^{-1})	(KC-79) 1990–1997 (10^{-2} yr^{-1})	1993–1999 (10^{-2} yr^{-1})	(KC-96) 1999–2009 (10^{-2} yr^{-1})	Delta (10^{-2} yr^{-1})
Sapporo	−0.198 (0.058)	−0.76 (0.30)	−2.43 (0.25)	1.14 (0.11)	3.57 (0.27)
Tsukuba	−0.089 (0.053)	−2.15 (0.22)	−2.45 (0.24)	1.62 (0.084)	4.07 (0.25)
Kagoshima	−0.85 (0.10)*	−2.50 (0.37)	−2.02 (0.34)	0.59 (0.24)*	2.61 (0.42)
Naha	0.084 (0.065)	−1.77 (0.34)	−1.84 (0.30)	1.02 (0.12)	2.81 (0.32)
Overall	**−0.157 (0.032)**	−1.82 (0.15)	−2.21 (0.14)	**1.18 (0.059)**	**3.00 (0.16)**

Table 5. Comparison of CFs at three Japanese stations for the periods 1968–1975 and 1990–2002, after (Hasebe and Yoshikura, 2006).

Station	CFs 1968–1975	CFs 1990–2002
Sapporo	0.97 (0.11)	0.92 (0.09)
Tsukuba	0.97 (0.11)	0.90 (0.10)
Kagoshima	0.94 (0.14)	0.94 (0.11)

Table 6. Information for ground-monitors near Japanese ozonesonde stations used in this study.

Ozonesonde	Surface Monitor Information				
Station	Station	Latitude	Longitude	Distance (km)	Data record used
Sapporo	Kokusetsu	43.082° N	141.333° E	~3 km	1993–2007
Tsukuba	Kokusetsutsukuba	36.164° N	140.183° E	~12 km	1990–2002
Kagoshima	Kokusetsuoomuta	33.030° N	130.446° E	~160 km	1992–2007
Naha	Hedo	26.856° N	128.262° E	~92 km	2001–2008

Table 7. Trends in the differences between sonde and surface measurements, and the mean offsets in those differences (Japanese ozonesonde average from the surface to 100 m above the surface minus surface monitor hourly oxidant average) for the period 1990–2007 as computed with and without the CF applied. The average means and offsets are computed using a Monte Carlo method.

Site	Sonde w/out CF		Sonde w/CF	
Overall	Trend (ppbv yr^{-1})	Mean Offset (ppbv)	Trend (ppbv yr^{-1})	Mean Offset (ppbv)
Sapporo	**−0.129 (0.091)**	**−4.3 (9.0)**	**−0.306 (0.090)**	**−6.8 (9.1)**
1993–1997	0.93 (0.55)	−3.2 (9.5)	0.33 (0.59)	−4.2 (10.1)
1997–2007	−0.05 (0.16)	−4.8 (8.8)	0.07 (0.15)	−8.0 (8.3)
Tsukuba	**−0.71 (0.19)**	**0.3 (16.0)**	**−1.39 (0.18)**	**−4.2 (16.1)**
1990–1997	−2.85 (0.44)	1.6 (16.2)	−3.92 (0.42)	−0.8 (16.4)
1997–2002	1.15 (0.67)	−1.3 (15.8)	1.21 (0.62)	−8.0 (14.8)
Kagoshima	**−0.54 (0.22)**	**−0.7 (17.9)**	**−0.78 (0.22)**	**−3.8 (17.9)**
1992–1997	0.80 (0.91)	5.4 (18.3)	−0.38 (0.91)	3.4 (18.2)
1997–2005	2.19 (0.43)	−4.2 (16.7)	2.27 (0.41)	−8.0 (16.3)
Naha	**	**	**	**
1992–1997	**	**	**	**
2001–2008	0.36 (0.32)	−7.7 (9.4)	0.61 (0.30)	−9.5 (9.1)
Average*	**−0.46 (0.10)**	**−1.5 (8.5)**	**−0.823 (0.099)**	**−4.9 (8.6)**
1990–1997*	−0.36 (0.38)	1.3 (8.7)	−1.32 (0.39)	−0.5 (8.8)
1997–2007*	0.92 (0.22)	−3.4 (8.2)	1.04 (0.20)	−8.0 (7.8)

*Naha data are not included in averages.

** No data for Hedo station is available to compare with Naha sonde until 2001, so overall average trend form early 1990's to 2007 is also not presented.

Table 8. Column ozone amounts for Earth Probe TOMS (EPTOMS) or Ozone Mapping Instrument (OMI), electrochemical concentration cell (ECC) ozonesondes launched at Hokkaido University, and the Carbon Iodine (CI) ozonesondes launched at Sapporo both without and with correction factors applied. Mean differences between the sonde columns and TOMS/OMI columns are shown, with 1σ in parenthesis. Mean differences of the CI columns with and without the correction factors (CF) applied are shown relative to the ECC columns, with 1σ in parenthesis. For the flight of 12 August 2009 (marked *), no OMI overpass is available, so the overpasses from the prior and next day are averaged.

Date of Flights	TOMS/OMI (DU)	ECC (DU)	CI, KC-96 w/out CF (DU)	CI, KC-96 w/ CF (DU)
10 Feb 2004	403.4	412.2	444.6	417
26 May 2004	346.4	318.6	328.3	353
25 Jan 2005	401.2	379.0	426.7	397
6 Sep 2006	268.8	281.7	275.5	280
29 Jul 2008	306.8	261.9	260.2	303
12 Aug 2009	276.4*	275.4	269.2	273
18 Aug 2009	291.8	307.7	283.1	300
Mean difference w/TOMS/OMI	N/A	−8 (23)	−1 (29)	4.0 (7.7)
Mean difference w/ECC	N/A	N/A	−7 (25)	−12 (19)

Table 9. Differences in column ozone amounts between ozonesondes and Earth Probe TOMS (EPTOMS) and Ozone Mapping Instrument (OMI). Data from electrochemical concentration cell (ECC) ozonesondes launched at Hokkaido University (which use the En-Sci two cell KI technology) and the Carbon Iodine (CI) ozonesondes launched at Sapporo both without and with correction factors (CF) applied. The data include the mean differences, 1σ in parenthesis, and the number of flights compared after the comma.

Satellite	ECC Hokkaido Univ. Sondes (2003–2009) DU (DU), #	CI Sapporo Sondes w/out CF (1996–2009) DU (DU), #	CI Sapporo Sondes w/CF (1996–2009) DU (DU), #
EPTOMS (thru 2005)	−12 (15), 11	34 (29), 342	−5 (13), 342
OMI (since 2004)	6 (16), 25	26 (24), 157	1.4 (8.7),157

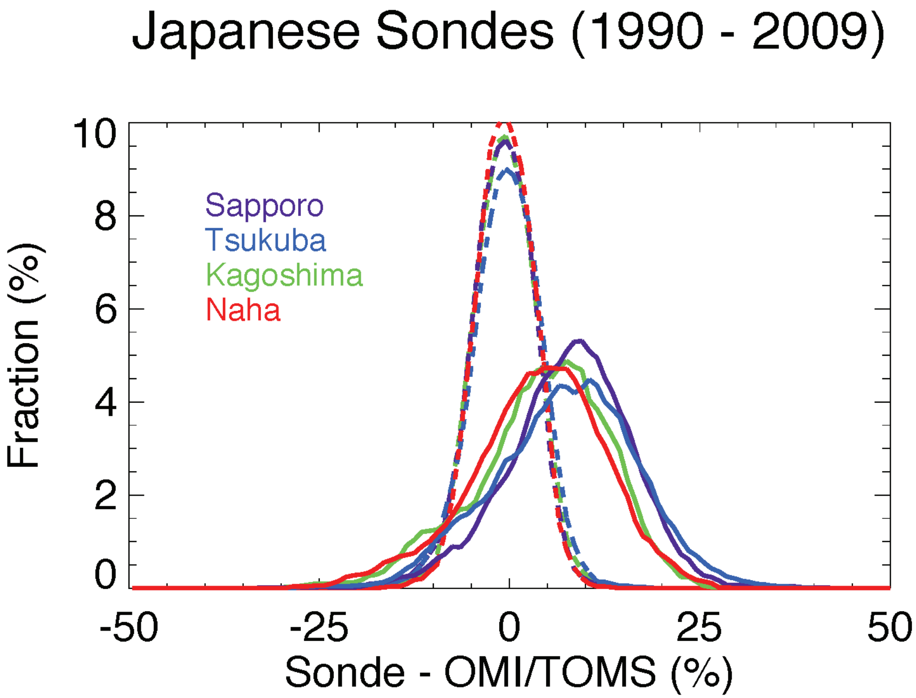

Fig. 1. A comparison of column ozone between integrated ozonesonde profiles from and the TOMS/OMI overpass data for the four Japanese stations. The thick lines represent data without the CF, while the dashed lines represent the data multiplied by the CF as applied and cited in the WOUDC data files. Kagoshima data cease in 2005.

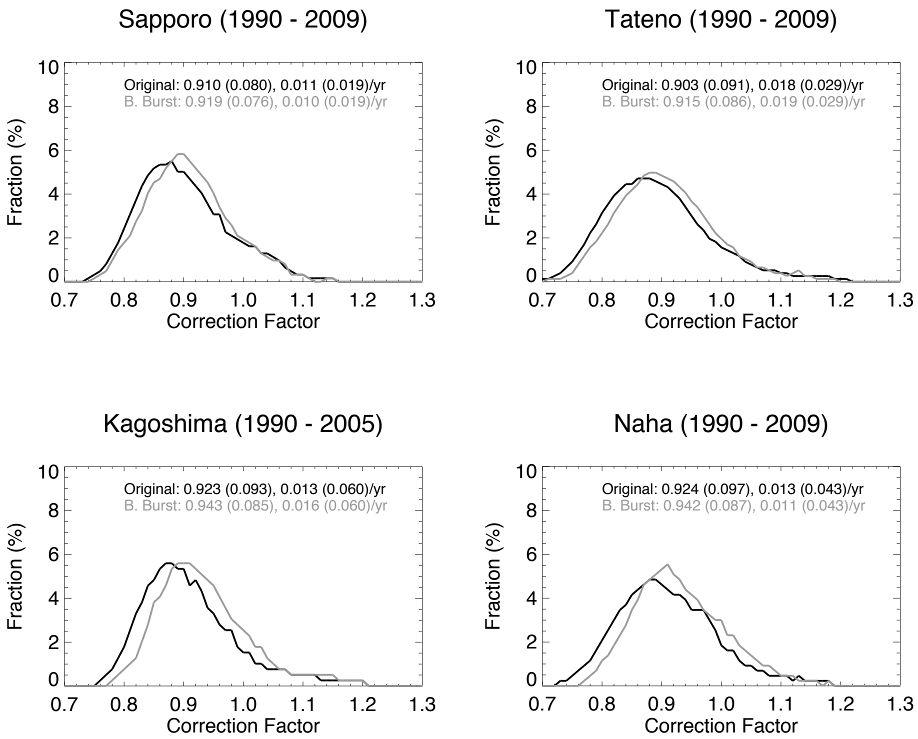

Fig. 2. Histograms showing a comparison of the corrections factors applied and listed in the WOUDC data files with those calculated in this study using a balloon-burst climatology. For all stations, the balloon-burst CFs are nearer to 1.0. The numbers in parenthesis represent one standard deviations.

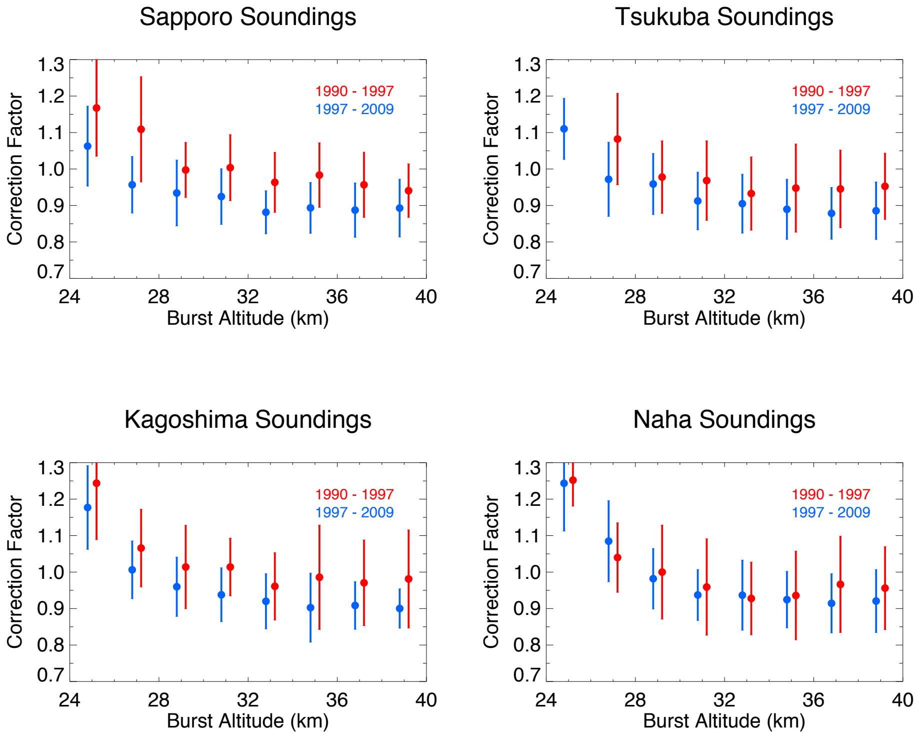

Fig. 3. CFs reported in the WOUDC data files as a function of burst altitude for ozonesonde profiles and columns at the Japanese stations. Data are divided in 2-km bins by burst altitude and divided temporally from 1990–1997 (KC-79 sondes) and 1997–2009 (KC-96 sondes). The error bars represent one standard deviations.

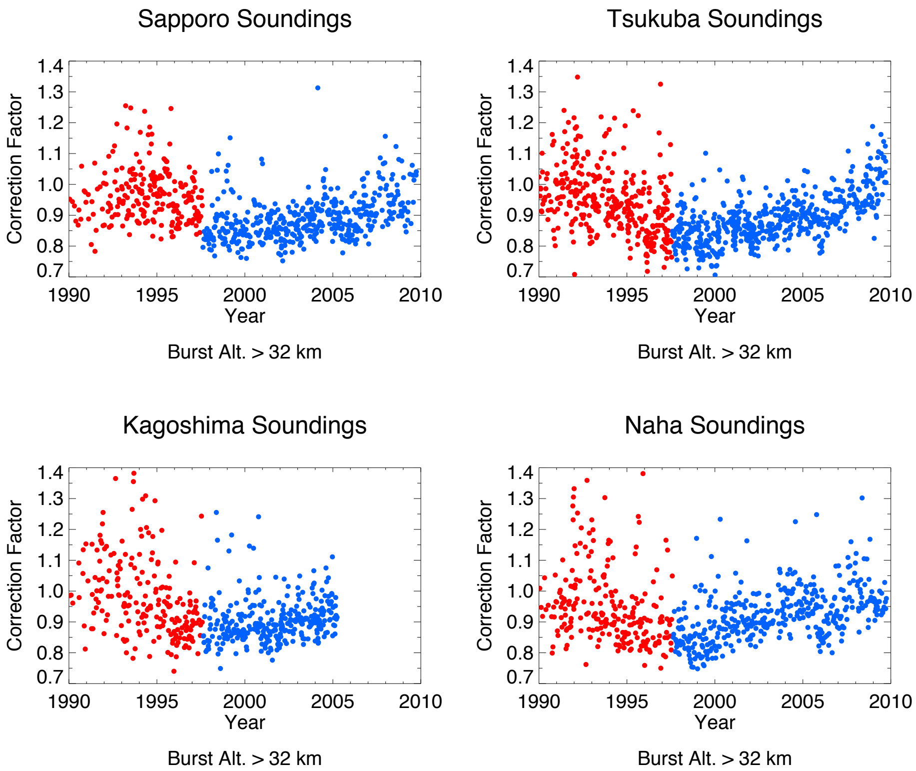

Fig. 4. CFs reported in the WOUDC data files as a function of time for all soundings from the Japanese stations that reach a burst altitude of at least 32 km (10.5 hPa). For Sapporo, Kagoshima, and Naha, ozonesondes changed from KC-79 to KC-96 in August 1997, while for Tsukuba, the change occurred in June 1997. CFs reached a minimum around the time of the change, were trending downward before the change, and have trended upward since the change at all four stations. See also Table 4 for calculations of these trends.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

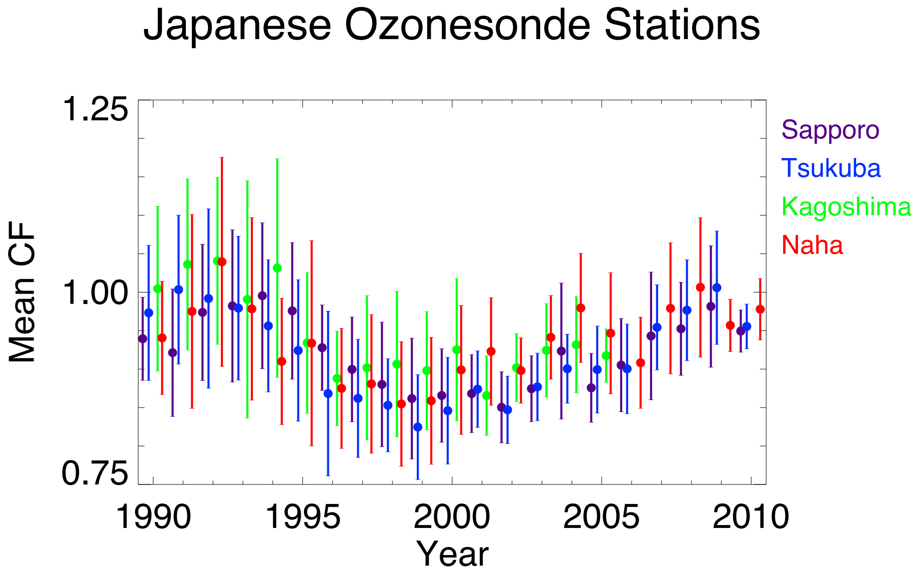

Fig. 5. Annual mean CFs for the data plotted in Fig. 4, with slight horizontal offsets for each station for clarity. The error bars represent one standard deviations.

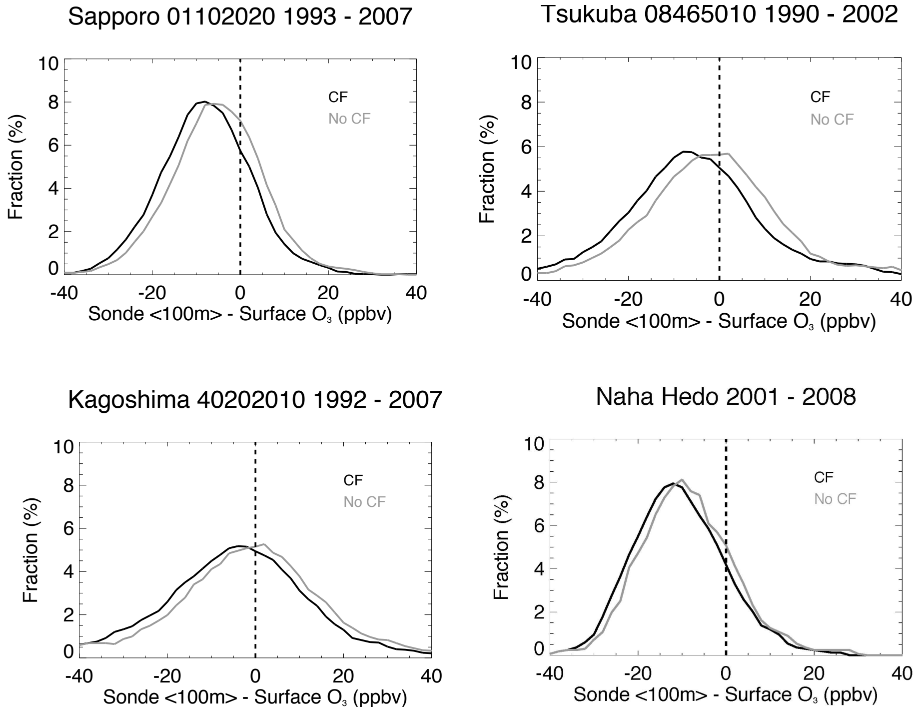

Fig. 6. Histograms of the offsets between mean ozonesonde profile data between the surface and 100 m above the surface with hourly-average oxidant data from the nearest surface monitor available in the long-term data base (www.nies.go.jp/igreen/td_disp.html), both with and without the recommended CF applied. All stations show better agreement without the CFs applied. See also Table 6 for a statistical analysis.

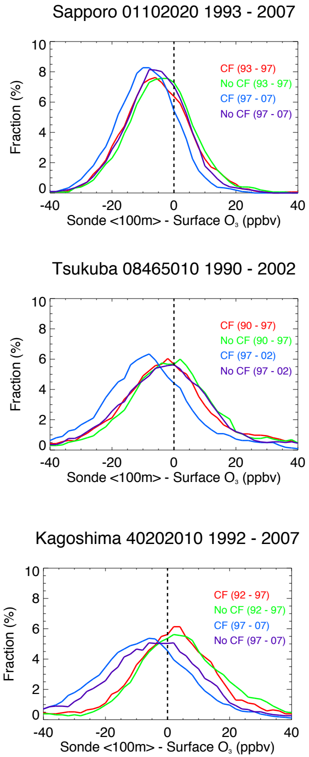

Fig. 7. As in Fig. 6, but with data separated into periods before and after 1997. See also Table 6 for a statistical analysis.

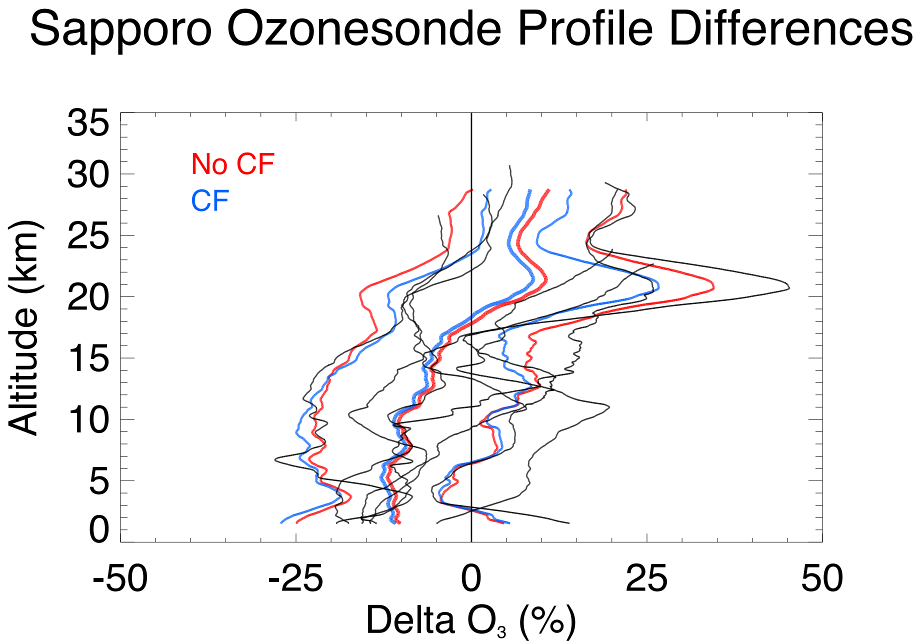

Fig. 8. A comparison of the mean (thick) and mean ±1σ percent differences (thin) between the En-Sci ECC sondes launched from Hokkaido University and the CI sondes from the Sapporo station (CI – ECC)/ECC), both with (blue) and without (red) the CFs applied for the 7 launches that occurred on the same days. Only the ECC sondes reaching least 29 km altitude before bursting (10 February 2004, 26 May 2004, 25 January 2005, 6 September 2006, 29 July 2008, 12 August 2009, and 18 August 2009) are shown. The percent differences for the individual flights appear as the black lines. A 3-km boxcar smoothing function is applied to the percent difference data due to the limited number of coincidences.