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Consistency of time series and trends of stratospheric ozone as seen by ozonesonde, SAGE II, HALOE, and SBUV(/2)

Yukio Terao[1] and Jennifer A. Logan[1]

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[1] We examined the consistency of time series for stratospheric ozone obtained by ozonesondes, SAGE II, HALOE, and SBUV(/2) in the northern extratropics and find excellent agreement for interannual variability and trends of ozone for 50–12.5 hPa over Europe. Ozonesonde, SAGE, and HALOE data agree well for ~200 hPa–12.5 hPa. Ozone in the past few years is ~6% below values in the early 1980s for 80–20 hPa, while values for 200–125 hPa are similar to those in the early 1980s. Small differences in monthly mean ozone and trends between ozonesondes and SAGE are caused by spatial and temporal sampling differences. The quality of SBUV(/2) Version 8 ozone data was evaluated by comparison to the homogeneous SAGE data. Most biases between SBUV(/2) and SAGE data are within ±10% except for large negative biases of SBUV(/2) at 50 hPa in the tropics. There is less homogeneity in the SBUV(/2) time series for the upper stratosphere, with negative biases for NOAA-11 after 1997 at 3–5 hPa and positive biases for NOAA-9 and 16 at 2–5 hPa, compared to earlier SBUV data, implying that the later data may lead to errors in calculated ozone trends. SBUV(/2) ozone trends agree well with SAGE trends in the midlatitude lower stratosphere for 1984–2000, but SBUV(/2) trends are as much as 4%/decade more positive than SAGE trends in the upper stratosphere. We find that SAGE sampling does not influence zonal mean trends, implying that SAGE/SBUV(/2) trend differences are related to data quality and to the different coordinate systems in which ozone is measured.

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1. Introduction

[2] Stratospheric ozone decreased at northern midlatitudes between the end of 1970s and the mid-1990s [e.g., *World Meteorological Organization* (*WMO*), 2003]. *Logan et al.* [1999] analyzed ozonesonde data for middle and high latitudes of the Northern Hemisphere and found a significant decrease of ozone from 1970 to 1996; −3 to −10%/decade for about 12–25 km with the largest decrease below 18 km. They noted regional differences in ozone trends: the largest decreases at the Canadian and northern Japanese stations and the smallest at European stations. *Randel et al.* [1999] analyzed vertical trends in ozone derived from satellite and ground-based measurements from 1979 to 1996, as well as from ozonesonde measurements. The ensemble estimate of the ozone trends for 40°–50°N from these measurements showed significant negative trends over all altitudes between 10 km and 45 km, with the largest decreases of −7.3 ± 4.6%/decade at 15 km and −7.4 ± 2.0%/decade at 40 km, and with the smallest decrease, −2.0 ± 1.8%/decade, at 30 km.

[3] Recently, several analyses have shown that the ozone values have leveled off for the last decade in the upper stratosphere at 35–45 km [*Newchurch et al.*, 2003], in the lower stratosphere at 12–25 km [*Yang et al.*, 2006], and for the total column of ozone [*Reinsel et al.*, 2005]. However, it is uncertain the extent to which the recent turnaround in stratospheric ozone is attributable to the decline in atmospheric halogen loading after the Montreal Protocol, to natural variability of the solar cycle, or to variability in atmospheric temperature and transport, possibly linked to climate change (see review by *Weatherhead and Andersen* [2006]). *Hadjinicolaou et al.* [2005] found, using simulations with a chemical transport model, that the upward trend in total ozone from 1994 to 2003 was forced only by transport changes. *Yang et al.* [2006] used a combination of regression analyses and model simulations to show that, above 18 km, the upward trend in ozone after 1997 was attributable to the decline in atmospheric halogen loading; however, they found that below 18 km, it was due to changes in atmospheric transport.

[4] The primary sources of information on ozone profile trends are ozonesondes, the Stratospheric Aerosol and Gas Experiment (SAGE) II, the Halogen Occultation Experi-

[1]School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, USA.

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ment (HALOE), and the series of Solar Backscatter Ultraviolet (SBUV) and SBUV/2 (referred to as SBUV(/2) together) instruments. Recently, the version 8 (V8) SBUV(/2) data set became available [*Bhartia et al.*, 2004]. This newly reprocessed data set is greatly improved from the former one that was used for previous international assessments [e.g., *Stratospheric Processes and Their Role in Climate* (*SPARC*), 1998; *WMO*, 1999, 2003]. A question of primary concern is whether these data sets, ozonesondes, and three satellite measurement systems are self-consistent.

[5] *Randel et al.* [1999] and *WMO* [2003] presented discrepancies in ozone trends as observed by ozonesonde and SAGE I/II instruments. The ozone trends in the lower stratosphere observed by ozonesondes over northern midlatitudes were more negative than SAGE I/II results, even though they agreed within the error bars. The vertically integrated annual ozone profile trends over northern midlatitudes derived from SAGE I/II (−1.7 DU/decade at 25–50 km) and ozonesondes (−8.2 DU/decade at 0–25 km) were significantly larger than the column ozone trends, −7.4 DU/decade, derived from the Total Ozone Mapping Spectrometer (TOMS) and SBUV(/2) data [*WMO*, 2003]. In the upper stratosphere, SBUV(/2) trends were more positive than SAGE I/II trends at almost all latitudes between 25 km and 45 km [*SPARC*, 1998; *Randel et al.*, 1999; *Cunnold et al.*, 2000].

[6] The purpose of this study is to examine the consistency of records of ozonesonde, SAGE II, HALOE, and the newest V8 SBUV(/2) measurements in terms of interannual variability and trends. Quantitative assessment of differences in ozone time series is crucial to improve our understanding of uncertainties in ozone trends.

[7] Our first focus is on comparisons of monthly mean time series obtained by the four independent measurements in different regions of northern midlatitudes. Most previous studies used profile-to-profile comparisons to validate satellite data sets or compared zonal mean values from different satellites: SAGE II and ozonesondes [*Wang et al.*, 2002]; SAGE II, HALOE, SBUV(/2), and Umkehr [*Cunnold et al.*, 2000]; SAGE II and HALOE [*Nazaryan et al.*, 2005]; SAGE II and SBUV/2 [*Nazaryan and McCormick*, 2005]; SBUV(/2) and Umkehr [*Petropavlovskikh et al.*, 2005]; SAGE II, SBUV/2, Umkehr, and ozonesondes [*Fioletov et al.*, 2006]. We address the effects of differences in spatial and temporal sampling on monthly mean ozone values.

[8] Our second focus is on evaluating the quality of the V8 SBUV(/2) ozone data by comparing zonal mean values with the self-consistent SAGE II data. The series of SBUV(/2) measurements consists of four sensors, so the differences in data quality of each sensor may affect derived trends. Our third focus is on comparisons of ozone trends derived from SAGE II, SBUV(/2), and from ozonesondes (in selected regions). Here we address the issue of the vertical coordinate system used in calculating biases and trends of upper stratospheric ozone, predicted by *Rosenfield et al.* [2005].

[9] The data and the analysis method are described in section 2. The time series of monthly mean ozone in the northern midlatitudes are compared in section 3, and we analyze spatial/temporal sampling issues. Results of regional ozone trends are shown in section 3. The zonal mean bias and trends of SBUV(/2) ozone data are compared with SAGE II data in section 4. We discuss and summarize the results in section 5.

2. Data and Analysis Method

2.1. SAGE II

[10] SAGE II was launched in October 1984 on board the Earth Radiation Budget Satellite and operated for more than 20 years, until August 2005. SAGE II is a solar occultation sensor which consists of a seven-channel Sun photometer; it measures atmospheric transmission profiles during each sunrise and sunset from the spacecraft [*Mauldin et al.*, 1985]. From the transmission profiles, vertical profiles of ozone, nitrogen dioxide, aerosol extinction, and water vapor are derived with vertical resolution of ∼1 km or less [*Chu et al.*, 1989]. SAGE II obtains profiles in two narrow latitude bands each day, 15 each at sunrise and sunset, separated by ∼25° in longitude. Latitude coverage of SAGE II varies between 70°S and 70°N from month to month.

[11] The SAGE II retrieval of trace gases is highly sensitive to levels of aerosol extinction, especially below 20 km [*Chu et al.*, 1989]. Thus the SAGE II ozone data below 25 km are contaminated after the eruption of Mount Pinatubo in June 1991 by high aerosol loadings. In this paper we use the filters proposed by *Wang et al.* [2002] (referred to as the Wang filter) to remove erroneous ozone data. This filter is based on observed amounts of aerosols which were most abundant in the lower stratosphere. The gap in SAGE II data after the Pinatubo eruption varies with altitude. At northern midlatitudes, the Wang filter removes measurements from June 1991 until January 1994 for 200 hPa and until January 1993 for 50 hPa, with no data gap above 30 hPa.

[12] SAGE II observations were temporarily interrupted from July 2000 to October 2000 by an instrument failure. After November 2000, SAGE II measured only one profile per orbit in a preset mode, either sunrise or sunset.

[13] In this analysis we used ozone data processed by the version 6.2 (V6.2) retrieval algorithm; these are very similar to the previous version, V6.1. The SAGE II data were obtained from ftp://ftp-rab.larc.nasa.gov/pub/sage2/v6.20. Comparisons of the SAGE II V6.1 ozone data with coincident ozonesonde measurements [*Wang et al.*, 2002] show that the agreement between SAGE II and ozonesonde data is ∼10% for 10–20 km and ∼5% for 20–30 km, SAGE II overestimates ozone between 15 and 20 km (<5%) and underestimates ozone below the tropopause (30% in the upper troposphere), and the precision of SAGE II ozone measurements is ∼10% at 20 km and ∼40% at 10 km.

2.2. HALOE

[14] HALOE was operational from September 1991 to November 2005, on board the Upper Atmosphere Research Satellite. HALOE also uses the solar occultation technique and measures profiles of ozone, aerosol extinction and many other trace gases using a broadband radiometer with vertical resolution of ∼2 km or less [*Russell et al.*, 1993]. Temporal and spatial coverage of HALOE observations are similar to those of SAGE II.

[15] In this analysis we used the HALOE version 19 (V19) ozone data (http://haloedata.larc.nasa.gov/download/index.php). Comparisons of the HALOE V19 ozone data

with the SAGE II V6.0 using the trajectory mapping approach showed a root-mean-square difference between the two data sets of 4–12% throughout most of the stratosphere except in the tropics [*Morris et al.*, 2002]. They also showed a low bias of HALOE ozone relative to SAGE II of 5–20% below 22 km between 40°S and 40°N. An analysis by *Nazaryan et al.* [2005] showed a low bias of HALOE V19 relative to SAGE II V6.1 of 5–10% at 20–30 km in the northern midlatitudes. The precision of HALOE V17 ozone measurements was estimated to be 8, 12, and 30% at 1, 10, and 100 hPa, respectively [*Brühl et al.*, 1996].

2.3. SBUV and SBUV/2

[16] SBUV(/2) measure global distributions of backscattered ultraviolet radiation at 12 wavelengths using a nadir-viewing double-grating monochromators with an instantaneous field of view (IFOV) on the ground of approximately 180 km by 180 km [*Heath et al.*, 1975; *Frederick et al.*, 1986; *Hilsenrath et al.*, 1995]. Total ozone column and ozone profiles are derived from the ratio of the observed backscattered spectral radiance to the incoming solar spectral irradiance [*Bhartia et al.*, 1996]. SBUV was launched on board NASA's Nimbus-7 spacecraft in October 1978. SBUV/2s, slightly improved versions of SBUV, were launched on board the National Oceanic and Atmospheric Administration (NOAA) satellites, NOAA-9 in December 1984, NOAA-11 in September 1988, NOAA-14 in December 1998, NOAA-16 in September 2000, and NOAA-17 in June 2002. By combining data from these instruments, the coverage is nearly continuous from late 1978 to the present.

[17] In our study we used vertical profiles of ozone from the version 8 (V8) SBUV on Nimbus-7 and SBUV/2s on NOAA-9, -11, and -16 [*Bhartia et al.*, 2004]. The data and descriptions of the V8 algorithm, data quality, and validation results are available on DVD-ROM media (SBUV Version 8 DVD, http://disc.sci.gsfc.nasa.gov/data/datapool/TOMS/DVD-ROMs/). Vertical profiles of ozone are provided in Dobson units (DU) in 13 layers; from 1000 to 63.1 hPa, 63.1–40.0 hPa, 40.0–25.1 hPa, 25.1–15.8 hPa, 15.8–10.0 hPa, 10.0–6.3 hPa,. . . . ., and 0.63–0.40 hPa (1 DU is defined as the column height of pure gaseous ozone in 1×10^{-3} cm at standard pressure and temperature and is equivalent to 2.687×10^{16} molecules cm^{-2}). Profiles of ozone are also provided in mixing ratio on 15 pressure surfaces, but we prefer to use the partial column ozone data because it is a better measure of the ozone value in each layer. Note that the vertical resolution of SBUV(/2) data is lower than the data grid, ~3 km above 63 hPa. At northern midlatitude (40°N), the averaging kernels show that the best vertical resolution is ~6 km near 3 hPa, degrading to ~11 km at 50 hPa (SBUV Version 8 DVD).

[18] The V8 SBUV(/2) algorithm is designed to provide an unbiased time series of ozone for studying interannual variability and trends [*Bhartia et al.*, 2004]. Degradation of the instruments [*Hilsenrath et al.*, 1995] and a priori assumptions in the retrievals [*Bhartia et al.*, 1996] can result in an apparent trend in ozone. In the V8 algorithm the same set of a priori profiles are used from year to year to remove any artificial trends due to the a priori [*McPeters et al.*, 2007]. The method to produce averaging kernels is improved and the vertical resolution of 6 to 8 km in the upper stratosphere in the V8 algorithm is better than that of 8 to 10 km in previous versions [*Bhartia et al.*, 2004]. The long-term calibration accuracy of each SBUV(/2) instrument is estimated to be ~3% [*DeLand et al.*, 2004]. The mean differences in ozone profiles between V8 data and ground measurements (microwave, lidar, and sonde) are within ±10% from 24 to 50 km (30 hPa and 1 hPa) [*Ahn et al.*, 2004; SBUV Version 8 DVD]. The anomaly differences between SBUV(/2) and Umkehr measurements at three stations in the northern midlatitudes are within ±5% from 30 to 40 km layers, and the slope of differences are up to −1.4% per decade at the 30 km layer [*Petropavlovskikh et al.*, 2005].

[19] We constructed an ozone time series using Nimbus-7 from January 1984 to November 1988; NOAA-11 from December 1988 to December 1993 (NOAA-11a below) and from July 1997 to December 2000 (NOAA-11b); NOAA-9 from January 1994 to June 1997 to fill in gaps in the NOAA-11 time series due to its orbit; and NOAA-16 after January 2001. We used the data of ascending and descending orbit measurements with a maximum solar zenith angle of 84°; these correspond to profile error codes of 0, 10, 100, and 110 given with the data (SBUV Version 8 DVD). Potential sources of error in the combined SBUV(/2) data set are significant spacecraft orbital drift and issues related to the grating drive position of NOAA-9 and NOAA-11 after 1996 [*Petropavlovskikh et al.*, 2005; SBUV Version 8 DVD]. *Petropavlovskikh et al.* [2005] found artificial upward trends of NOAA-9 data only at the 40 km layer, which could be caused by calibration errors at the shortest wavelengths of NOAA-9, and no artificial trends for NOAA-11.

2.4. Ozonesondes

[20] Ozonesonde data were obtained from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) for Uccle (51°N, 4°E), Hohenpeissenberg (48°N, 11°E), and Payerne (47°N, 7°E) in Europe; Tateno (36°N, 140°E) in Japan; Edmonton (53°N, 114°W) and Goose Bay (53°N, 60°W) in Canada; and Wallops Island (38°N, 76°W) in the United States. Recent data for Wallops Island were provided by F. Schmidlin (personal communication, 2005), and data for Boulder, Colorado (40°N, 105°W) by S. Oltmans (personal communication, 2005). Further information on the ozonesonde types and on data quality issues is given by *Logan* [1994] and *Logan et al.* [1999]. The data records for Uccle, Payerne, and Boulder have been reprocessed in recent years [*Lemoine and De Backer*, 2001; *Stubi et al.*, 1998; S. Oltmans, personal communication, 2005].

[21] Selection criteria for the sonde data are described by *Logan et al.* [1999], with the additional criterion that the sounding had to reach 20 hPa to be included in the analysis. The sonde data were processed to give monthly mean values of the column of ozone in 33 equally spaced layers in log-pressure from 1000 to 6.3 hPa (30 layers up to 10 hPa), and these layers were then grouped into 11 layers of ~3 km thickness [*Logan et al.*, 1999]. The vertical integration removes small-scale variations in ozone. These layers are centered at 800, 500, 300, 200, 125, 80, 50, 30, 20, 12.5, and 8 hPa; the SBUV(/2) data were provided for the same layers above 50 hPa. In this study we use ozonesonde

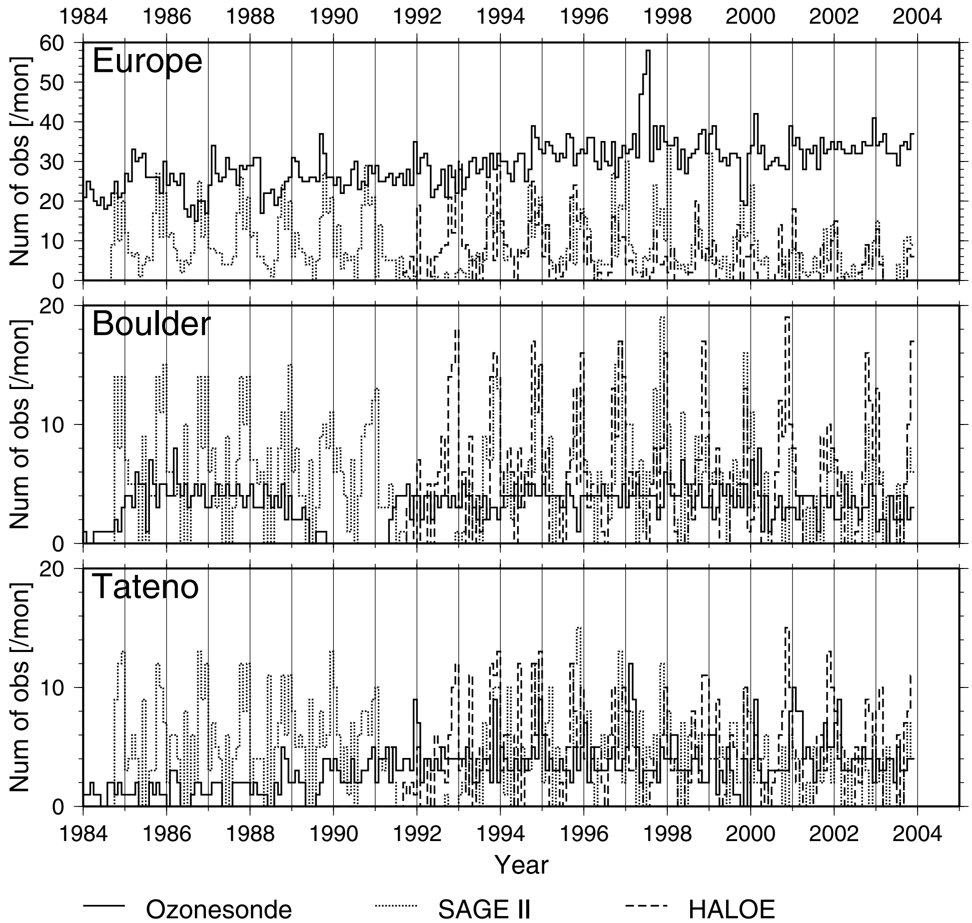

Figure 1. Number of observations per month made by ozonesonde (solid line), SAGE II (dotted line), and HALOE (dashed line) at 50 hPa for Europe (top), Boulder (middle), and Tateno (bottom).

data from 200 hPa to 12.5 hPa. The sonde errors become larger above 10 hPa, and many sondes do not reach the higher altitudes [*SPARC*, 1998]. Below 300 hPa, both SAGE II and HALOE provide few measurements and their measurement uncertainties become larger.

[22] The monthly mean values for the three European stations were averaged together and are referred to as Europe below. The number of observations per month is shown in Figure 1 for three ozonesonde locations, Europe, Boulder, and Tateno. Measurements are made 2–3 times a week at each European station, resulting in 20–35 profiles per month for Europe. Measurements are made weekly at the other stations, except for Tateno (1–2 per month before 1990). We selected Tateno because even fewer measurements were made before 1990 at the other long-term Japanese stations, Sapporo and Kagoshima.

2.5. Analysis Method

2.5.1. Comparison of Ozonesonde Data With SAGE II, HALOE, and SBUV(/2)

[23] We compared monthly mean time series of ozonesonde profile data for six locations with the SAGE II, HALOE, and SBUV(/2) data for seven layers from 12.5 hPa to 200 hPa. The SAGE II and HALOE data were integrated into partial ozone columns in DU for the same layers as the sonde data. We used pressure data from the National Centers for Environmental Prediction (NCEP) to convert the vertical coordinates of SAGE II and HALOE data from geometric altitude to pressure. The NCEP data are used for the SAGE II and HALOE retrieval for these altitudes and are distributed as a part of the data products. We discuss the quality of the NCEP data in section 2.5.2 and section 4 and show that there are no serious problems with the NCEP data for pressures >10 hPa. The SBUV(/2) data were used only between 12.5 hPa and 50 hPa in this part of the analysis.

[24] We selected SAGE II, HALOE, and SBUV(/2) measurements within a grid box of ±5° in latitude and ±20° in longitude around the location of the ozonesonde stations and then formed monthly mean values for the satellite data. For Europe, we employed a grid box from 45°N to 55°N and from 10°W to 30°E to sample the satellite data. We selected the box size as a compromise; if a smaller box is used, the number of satellite measurements is too few to construct a continuous time series, and if a larger box is used, differences between ozonesonde and satellite measurements increase.

[25] Figure 1 shows the number of observations per month for SAGE II and HALOE at 50 hPa. The gap in the SAGE II data is evident after June 1991, as is the decreased measurement frequency after 2000. The HALOE measurements are also degraded after 2000, especially in

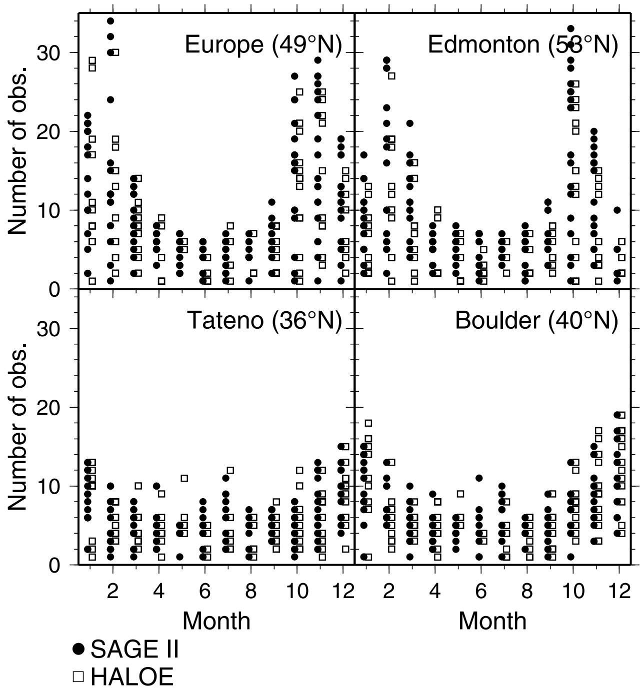

Figure 2. Seasonal variations of number of observations of SAGE II (closed circle) and HALOE (open square) for Europe, Edmonton, Tateno, and Boulder.

spring and summer. The number of satellite profiles is smaller than that of ozonesondes for Europe but is larger elsewhere.

[26] The SAGE II and HALOE measurement frequency varies seasonally (Figure 2), with more measurements from October to February than from March to September. There are also more measurements at the higher latitudes (Europe and Edmonton) than the lower latitudes (Boulder and Tateno) in late fall and winter. The converse is true in spring and summer, with more measurements at lower latitudes.

[27] Figure 3 shows that the difference in monthly anomalies (satellite–sonde) becomes smaller as the number of satellite measurements per month, n, increases. Clearly, the measurement frequency of satellite data influences the representativeness of the monthly mean values, and their uncertainty decreases as n increases. Differences in monthly anomalies over Europe are stable within ±25% for 125 hPa and ±10% for 50 hPa when n exceeds 10 for SAGE II and HALOE. They are largest for n less than 5. In this study we used monthly mean data for SAGE II and HALOE only if $n > 4$. Ozonesonde measurements are weekly outside Europe, often with $n \leq 4$ (Figure 1). We did not restrict the ozonesonde data to $n > 4$ as the weekly measurements may provide more reliable monthly mean values than a few SAGE II or HALOE profiles which are clustered in a few days in the month.

[28] The latitude of SAGE II and HALOE measurements in each grid box also varies seasonally, because of seasonal changes in the satellite orbit (Figure 4). For Europe and Edmonton, the latitude of the satellite measurements is north of that of the ozonesondes by up to 5° in winter and is to the south in spring and fall. These characteristics appear for stations north of 45°N, including Goose Bay (53°N). Conversely, for Tateno, Boulder, and Wallops Island, the satellite measures slightly south of the ozonesondes in winter. For SBUV(/2) data, the number of observation in each box is constant with ~250/month. There are no seasonal variations in measurement latitude.

[29] Time series are shown below as monthly means and anomalies. Monthly anomalies are the difference between a given monthly mean and the average of all monthly means for that calendar month over the data record; from January 1984 (SBUV(/2) and ozonesondes), October 1984 (SAGE II), and October 1991 (HALOE) to December 2003.

2.5.2. Zonal Mean Comparison of SBUV(/2) and SAGE II

[30] In section 4 we calculate zonal mean values of monthly mean ozone using SAGE II and SBUV(/2) data from 60°S to 60°N in 10° latitude bins. This analysis extends vertically from 50 hPa to the 1.25 hPa layer.

[31] SAGE II uses NCEP temperatures and pressures up to 0.4 hPa in its retrieval. The NCEP temperature data in the upper stratosphere are generated from the TIROS Operational Vertical Sounder (TOVS) data on NOAA satellites

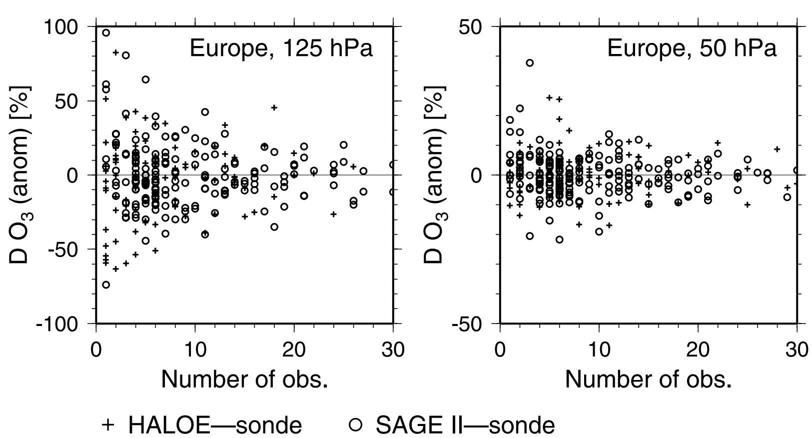

Figure 3. Scatter plots for number of observations and differences in monthly ozone anomalies from ozonesonde values for SAGE II (circle) and HALOE (cross) measurement. Results are plotted for Europe at 50 and 125 hPa.

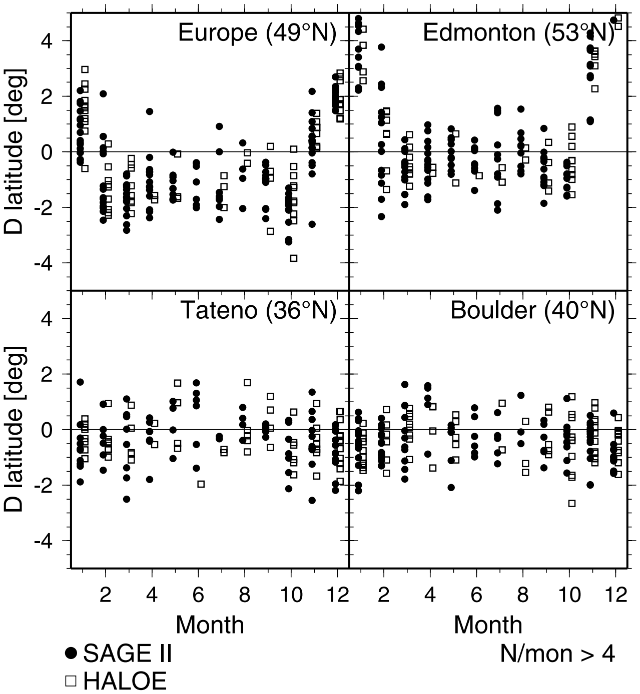

Figure 4. Seasonal variations of differences in measurement latitude between SAGE II and ozonesondes (closed circle) and between HALOE and ozonesonde (open square) for Europe, Edmonton, Tateno, and Boulder.

and a few rocketsonde profiles, and thus the time series of NCEP temperatures is influenced by the replacement of NOAA satellites and the measurement frequency of rocketsondes, potentially resulting in artificial trends [*Keckhut et al.*, 2001; W. Randel, personal communication, 2006]. This indicates that care is required for in analyzing SAGE II data on NCEP pressure levels in the upper stratosphere. As an alternative we also used the Committee on Space Research (COSPAR) International Reference Atmosphere 1986 (CIRA-86) [*Fleming et al.*, 1990] to convert SAGE II data from geometric altitude to pressure levels. We used the monthly mean CIRA-86 pressure data provided as zonal mean values in 10° bins as a function of altitude from 20 km to 120 km in 5 km intervals (ftp://nssdcftp.gsfc.nasa.gov/models/atmospheric/cira/cira86ascii). The CIRA data have no interannual trend.

[32] We also calculated SAGE II ozone trends on geometric altitude levels. The results of SAGE II trends on NCEP pressure, CIRA-86 pressure, and geometric altitude are compared and discussed in section 4. We note that recent comparisons of SAGE and SBUV(/2) data by *Fioletov et al.* [2006] and *Nazaryan and McCormick* [2005] used NCEP pressures to convert SAGE altitude levels to pressure levels.

3. Regional Analysis of Ozonesonde, SAGE II, HALOE, and SBUV(/2) Data

3.1. Comparison of Monthly Mean Time Series

[33] Time series of monthly mean ozone and monthly ozone anomalies are shown in Figures 5a and 5b for Europe at 50 hPa (~19–22 km), as three month running means. The ozonesonde, SAGE II, HALOE, and SBUV(/2) measurements are generally in good agreement in terms of interannual variability. The sonde, HALOE, and SBUV(/2) data show anomalously low ozone in the winter of 1992–1993, which is the lowest ozone in the entire record. The SAGE II, SBUV(/2), and sonde data show anomalously high ozone in the winters of 1985–1986, 1990–1991, and 1993–1994, as does HALOE for 1993–1994. The differences between ozonesonde and both SAGE II and HALOE become larger for the anomalously low ozone in the winter of 2001–2002 and for the anomalously high ozone in the winter of 2002–2003. This indicates that the reduced measurement frequency of SAGE II and HALOE after 2000 does not adequately represent the behavior of ozone on a regional basis.

[34] Figure 5c shows percent differences in monthly mean ozone between ozonesonde and satellite measurements ((satellite-sonde)/sonde $\times$ 100). The SAGE II data have a positive bias with respect to the ozonesonde data and the HALOE data have a negative bias, with mean differences (±1 sigma) of 3.4 (±4.4)% for SAGE II and −4.0 (±4.4)% for HALOE. This result agree quantitatively with the previous studies [*Morris et al.*, 2002; *Nazaryan et al.*, 2005]. The SBUV(/2) data generally agree with ozonesonde data within ±5%. No significant mean biases of SBUV(/2) data are observed during 1984–2004 (~0.1%). However, there are some small differences in each SBUV(/2) measurement period: a negative bias of −1.9 (±2.5)% for NOAA-9 (1994–1996) and a positive bias of 2.8 (±4.2)% for NOAA-11b (1997–2000).

[35] Differences in monthly ozone anomalies are shown in Figure 5d. The satellite and ozonesonde data generally agree within ±10% except after 2001 and often agree within ±6%. The differences in anomalies of both SAGE II and HALOE measurements with respect to ozonesondes often show similar seasonal or interannual variabilities, suggesting a common cause for sonde-satellite differences.

[36] Results for 125 hPa (13–16 km) are shown in Figure 6. There are no SBUV(/2) data for the lower levels. Here also the satellite measurements generally capture interannual variability as observed by ozonesondes. However, the differences between ozonesonde and SAGE II/HALOE anomalies are ±20%, larger than those at 50 hPa. The very low ozone given by HALOE during 1993 appears to be contaminated by high aerosols from the eruption of Mount Pinatubo. Ozone is much more variable in the lower stratosphere (~125 hPa) compared to 50 hPa, and the satellite data are less precise, so it is not surprising that the agreement is degraded in the lower level.

[37] Figures 7 and 8 shows time series of monthly ozone anomalies and differences in monthly mean ozone between ozonesonde data and satellite data at 50 hPa and 125 hPa for Boulder and Tateno. At 50 hPa, the sonde, HALOE, and SBUV(/2) data show anomalously low ozone in the winter of 1992–1993. They also show anomalously low ozone in the winters of 1994–1995 and 1998–1999, and high ozone in the winters of 1993–1994, 1995–1996, and 2002–2003. At 125 hPa, there is not a good correspondence between the interannual variabilities shown by the satellite and sondes. For Tateno, at both 50 and 125 hPa differences in ozone (satellite-sonde) are more positive than those for Boulder and Europe, indicating that the ozonesonde measurements

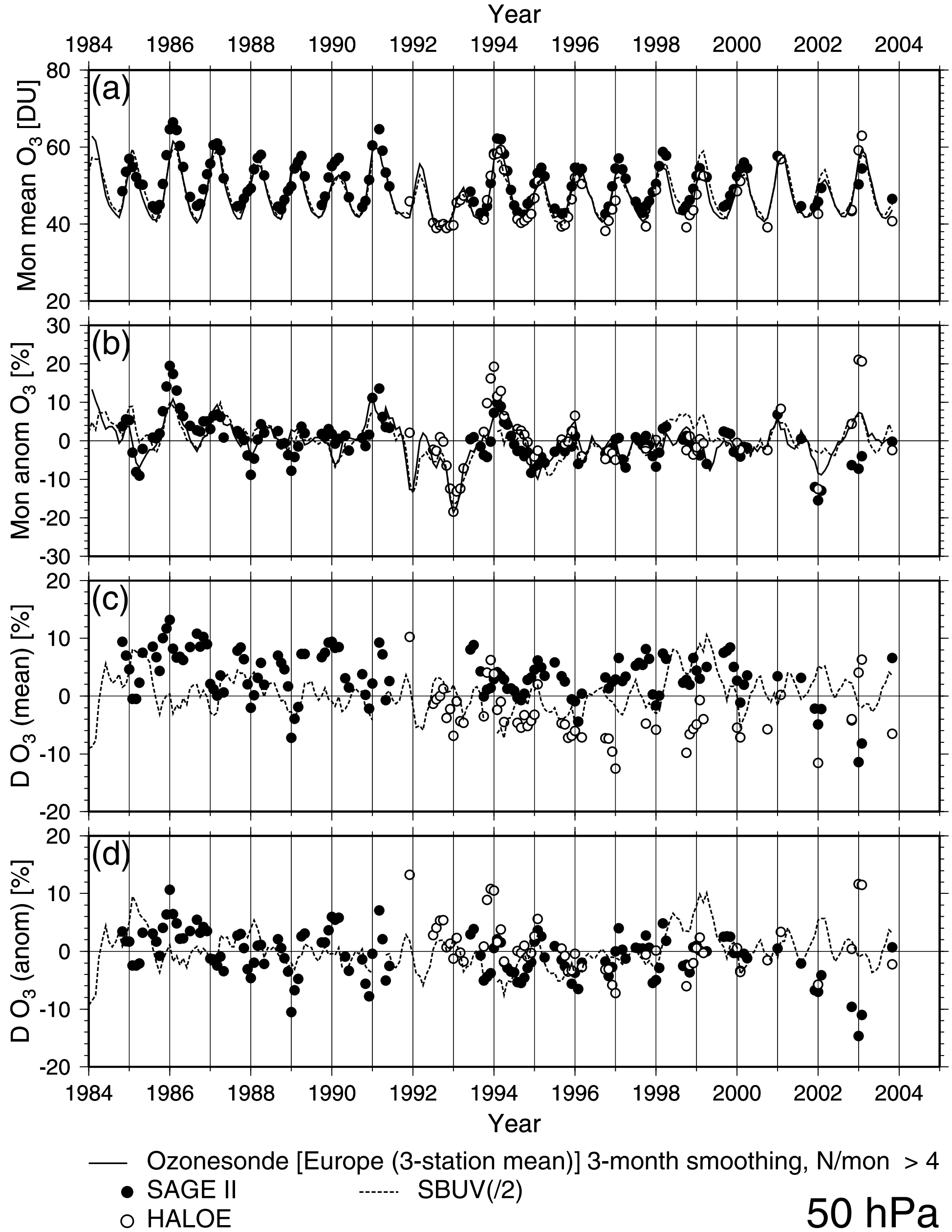

Figure 5. (a) Monthly mean ozone and (b) monthly ozone anomalies observed by ozonesonde (solid line), SAGE II (solid circle), HALOE (open circle), and SBUV(/2) (dashed line) for Europe at 50 hPa. (c) Differences in monthly mean ozone and (d) differences in monthly ozone anomalies between ozonesonde and satellite data ((satellite-sonde)/sonde $\times$ 100). A three month running mean was applied to the data.

at Tateno have a negative bias with respect to other stations, as discussed further below.

[38] The range of variations in monthly anomalies as seen by SBUV(/2) is smaller than that of the other measurements. The SBUV(/2) anomalies in the low ozone winters (e.g., -10% in 1992–1993 and -7% in 1998–1999 for Boulder) are clearly smaller than the other satellite and sonde anomalies ($\sim -20\%$). The converse is true for the anomalously high ozone in 1993–1994 and 1995–1996. These differences may result from the higher number of SBUV(/2) measurements, $\sim$250 per month, compared to $\sim$10 (in winter) for SAGE II and HALOE and $\sim$4 for sondes. The more frequent measurements may smooth out extreme events. The SBUV anomalies would be smaller than those of the other data sets by a factor of 5 ($\sqrt{n}$) if the reduction was caused simply by more measurements (250 verses 10). Variability of ozone within the region of $10° \times 40°$ could also contribute to the differences.

[39] The differences between sonde and satellite are larger and more variable for Boulder and Tateno than for Europe (Figure 6c). The larger differences are likely caused by the smaller number of sonde measurements, <5 per month. The smaller number of sonde profiles for stations outside Europe represents the monthly means better at 50 hPa than at 125 hPa where ozone is more variable. Also, at 50 hPa, the sonde-satellite differences are larger in winter

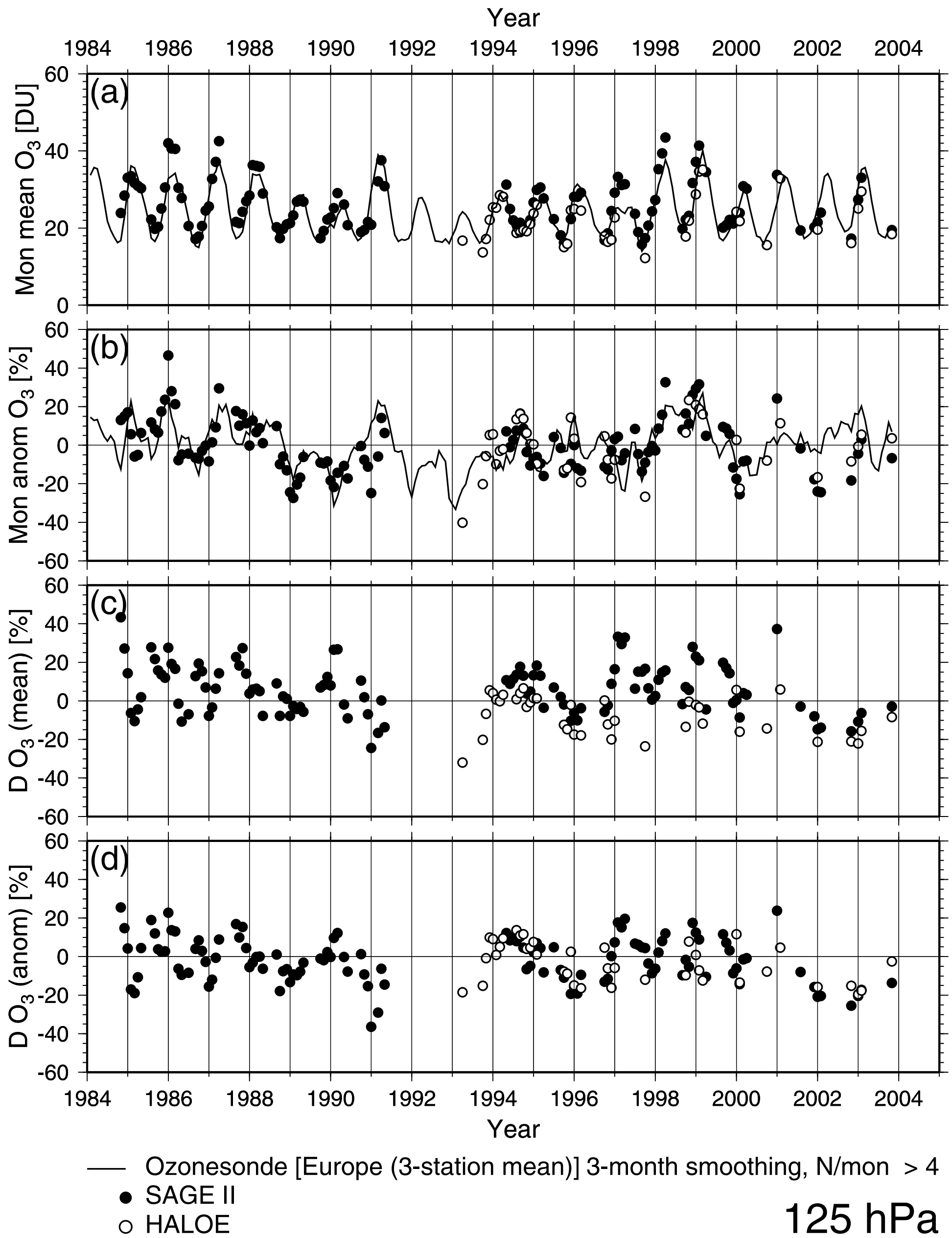

Figure 6. Comparison of sonde and satellite data for ozone over Europe at 125 hPa. See Figure 5 for details. Note that the different scales from Figure 5.

than in summer, especially over Tateno. Fewer than five sonde profiles represents the monthly means less well in winter than in summer, when ozone is less variable.

3.2. Bias of SAGE II, HALOE, and SBUV(/2) With Respect to Sondes

[40] Figure 9 shows the vertical distribution of the mean bias of SAGE II and HALOE with respect to ozonesondes. The values of biases and their standard deviations at 50 hPa and 125 hPa are given in Table 1. For all stations, we find either zero or small positive biases for SAGE II and zero or negative biases for HALOE from 80 to 12.5 hPa, except for Tateno. The biases are generally larger for 125 and 200 hPa than for higher altitudes.

[41] The mean biases in Figure 9 are very similar to those found by *Wang et al.* [2002] who made profile-to-profile comparisons using stricter spatial coincident criteria than we used (by 50%). *Wang et al.* [2002] found that the variability in SAGE/sonde differences became smaller if they required closer matches in space and time but that the biases did not change.

[42] There are regional differences in the biases. For the Canadian stations, Edmonton and Goose Bay, the biases for SAGE II are almost zero for altitudes above 125 hPa and increase toward 200 hPa. For the U. S. stations, Boulder and Wallops Island, and for Europe the biases for SAGE II increase gradually with decreasing altitude and increase still more at 200 hPa. For Tateno, Japan, the bias profile has a

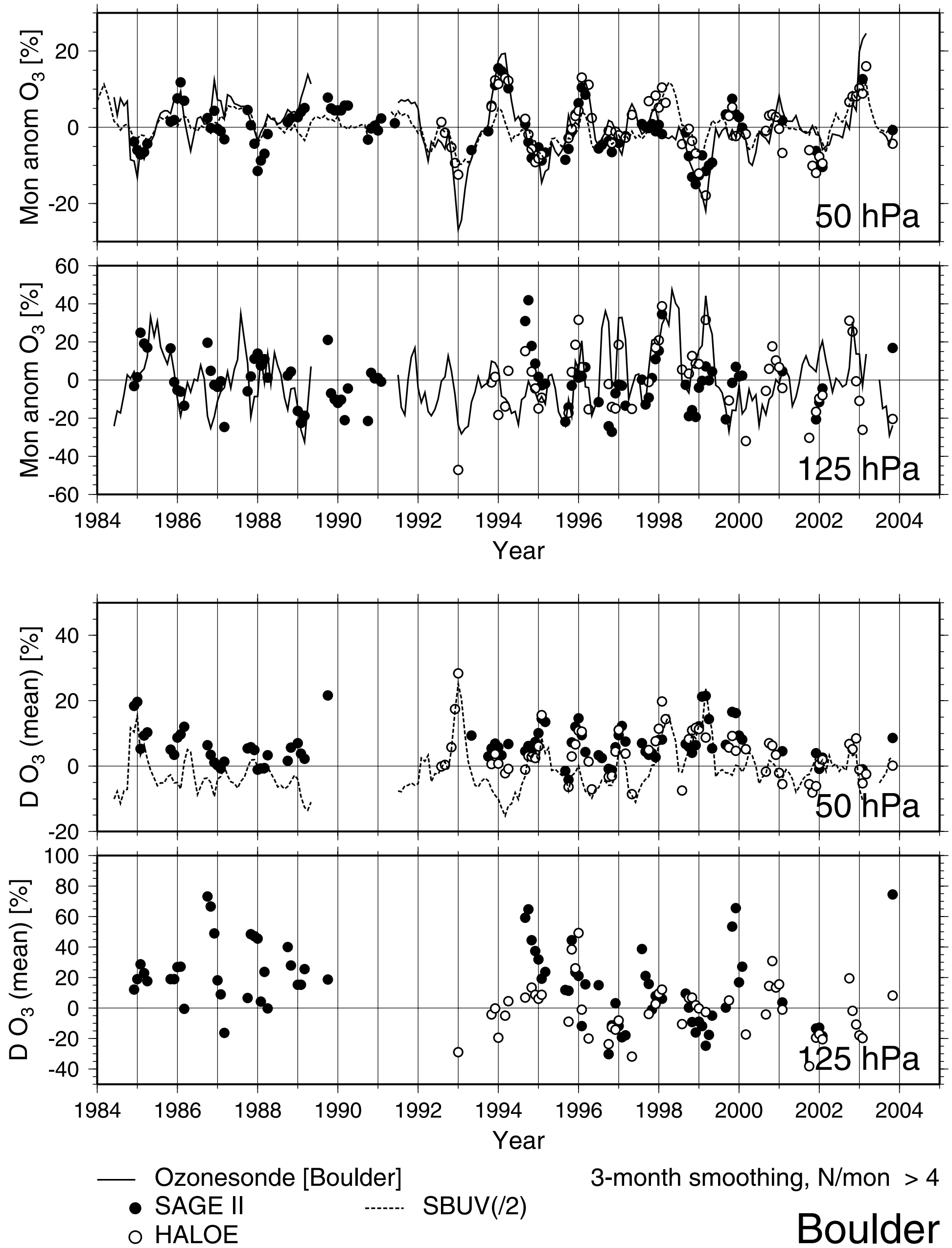

Figure 7. Monthly ozone anomalies and differences in monthly mean ozone between ozonesonde and SAGE II (solid circle), HALOE (open circle), and SBUV(/2) (dashed line) for Boulder at 50 hPa and 125 hPa. See Figure 5 for details.

different character, with SAGE II biased high below 50 hPa with a maximum bias of over 20% at 80 and 125 hPa. HALOE measurements also have relatively large positive biases between 30 and 100 hPa for Tateno. The results are similar for Sapporo but with smaller biases of 10–15% for SAGE II and 5–10% for HALOE between 50 and 200 hPa (not shown).

[43] The regional differences in the biases are likely caused by differences in the quality of ozonesonde measurements, since both SAGE II and HALOE provide data with homogeneous quality and similar measurement frequency until 2000. Different types of ozonesondes were used on each continent; electrochemical concentration cell (ECC) sondes for North America, primarily Brewer Mast (BM) sondes for Europe (ECC sondes after 1997 for Uccle and after 2002 for Payerne), and KC sondes for Japan. The results in Figure 9 imply that there is a significant difference in ozone as measured by KC sondes compared to BM and ECC sondes at pressures >50 hPa. Comparisons with UV-photometer measurements showed that KC sondes tended to underestimate ozone by up to 10% below 20–25 km, while biases of BM and ECC sondes were much smaller in the lower stratosphere [*Smit and Kley*, 1998; *Smit and Sträter*, 2004]. These results are qualitatively consistent with larger SAGE II biases below 50 hPa over Tateno. Note that at Tateno, the layers of 125 and 200 hPa are often near

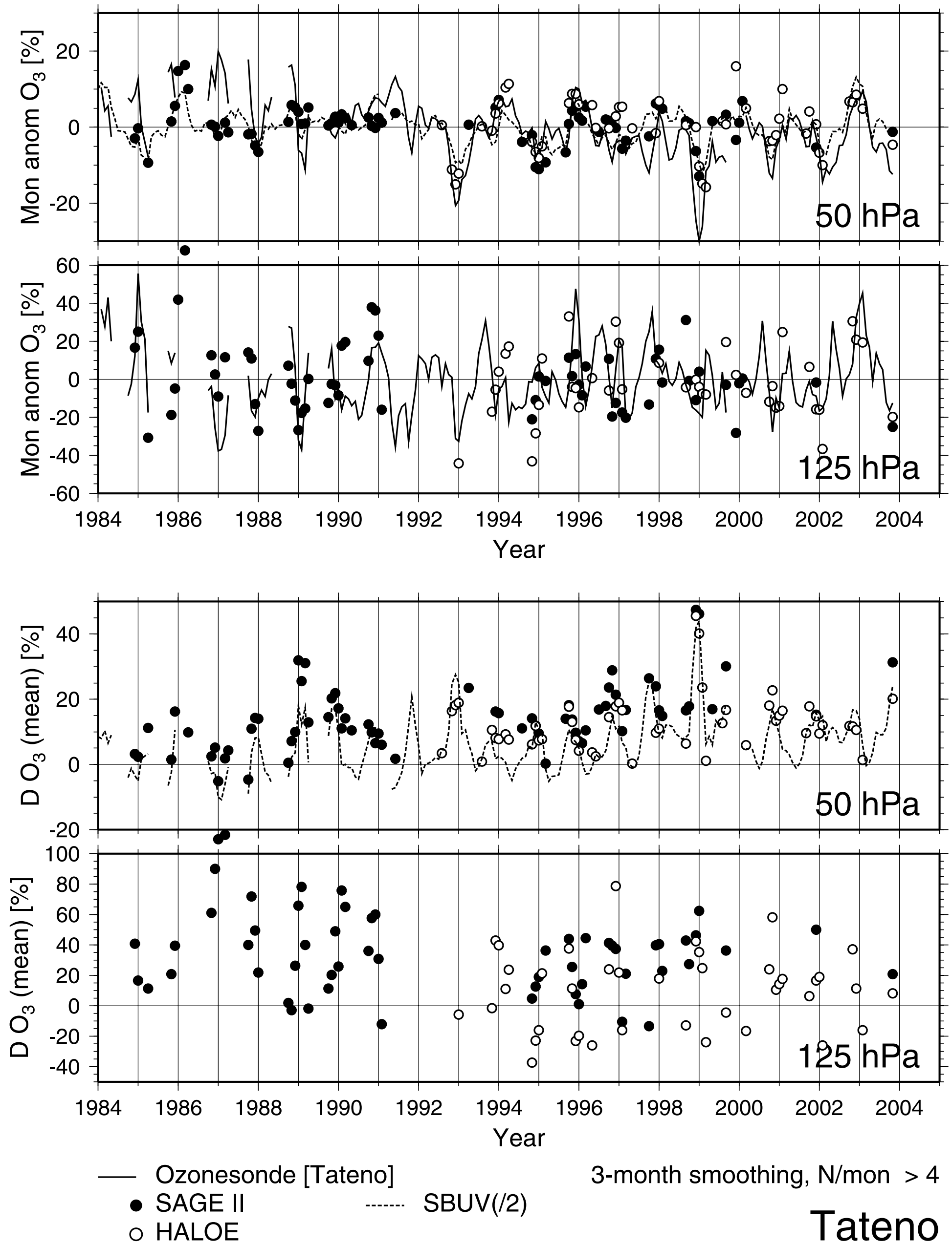

Figure 8. Monthly ozone anomalies and differences in monthly mean ozone between ozonesonde and satellite data for Tateno at 50 hPa and 125 hPa. See Figure 7 for details.

the tropopause where the vertical gradient and variability of ozone is large. This may also contribute to the larger differences between the ozonesonde and satellite measurements at Tateno.

[44] We investigated whether the use of potential temperature as a coordinate in the lower stratosphere might lead to smaller differences between satellite and sonde data, by removing some of the dynamical variability. We calculated monthly mean ozone for ozonesonde, SAGE II, and HALOE measurements for seven isentropic layers (centered at 350, 390, 445, 510, 590, 680, and 790 K) that correspond roughly to the seven pressure layers from 200 hPa to 12.5 hPa. The results for the average differences between ozonesonde and SAGE II/HALOE are shown in Table 2 for 390 K and 510 K, which correspond to 125 hPa and 50 hPa, respectively. For the SAGE II data at the lower layer (390 K), the differences, and especially their variabilities, become smaller by using isentropic coordinates. However, for the higher layer (510 K) and/or for the HALOE data, the differences are almost same and sometimes become larger than those on the pressure coordinate.

[45] Figure 10 shows vertical distributions of the average bias for each SBUV(/2) data set with respect to ozonesonde data. For Europe, all four SBUV(/2) data sets and ozonesonde data agree within ±4%, and the range among the SBUV (/2) data sets is ~6%. The SBUV(/2) biases are slightly positive at 30 hPa and slightly negative at 20 hPa. For other stations the differences between SBUV(/2) and

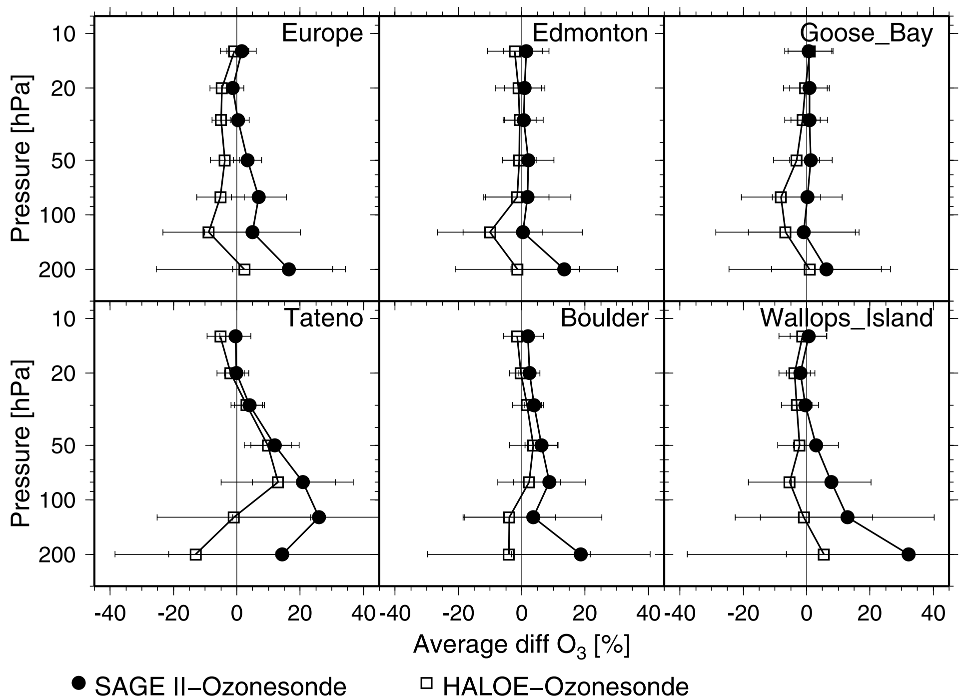

Figure 9. Vertical profiles of average bias of SAGE II and HALOE data with respect to ozonesondes for each sonde location. The biases were calculated by averaging the differences in monthly mean ozone over the data record. The horizontal lines show one standard deviation.

sondes are generally within ±5% except for NOAA-16, and the range among the SBUV(/2) data sets is 6–10%. The SBUV(/2) biases over Tateno are larger, ±10% and more positive at 30 and 50 hPa, which is consistent with the results from SAGE II and HALOE. The larger range of biases outside Europe is likely caused by the smaller number of sonde measurements each month. We examine the SBUV(/2) biases for Europe in more detail in the next section.

3.3. Sources of the Differences Between Sonde and Satellite Measurements

[46] Several issues could be causing the differences between time series of satellite and ozonesonde data, including measurement errors and different spatial and temporal sampling. Here we focus on the effects of differences in sampling using data for Europe, where the monthly mean values for ozone are well defined by the sonde data (>20/month). We required >5 satellite measurements per month in our analyses, as discussed in section 2.5.1. However, more than 10 SAGE II/HALOE profiles per month are needed for the difference in individual monthly means to be less than ±25% for 125 hPa and ±10% for 50 hPa (Figure 3), and these cases are in winter/spring (Figure 2) when ozone is most variable in the lower stratosphere.

[47] In our comparisons of sonde and satellite measurements it was necessary to use a relatively large region (10° × 40°) to ensure that there were adequate satellite data. Variability within this region could contribute to differences in ozone measured by satellite and sondes, as well as differences in temporal sampling. We explored this issue using SBUV (/2) data, which are available daily with resolution of 180 km, to define the spatial and temporal variability in ozone. The analysis also provides insight into the self-consistency of the SBUV (/2) record.

[48] We selected daily SBUV(/2) measurements that coincided with ozonesonde or SAGE II measurements and processed the SBUV(/2) data into time series of monthly mean ozone using coincidence criteria of ±2.5° in latitude, ±10° in longitude, and ±1 day in time. We refer to these coincident SBUV(/2) measurements as sonde-sampled SBUV and SAGE-sampled SBUV, respectively. For Europe, SBUV(/2) data coincided with ~92% of ozonesonde and SAGE II data, and ~4 SBUV(/2) profiles were sampled around each ozonesonde or SAGE II profile.

[49] Figure 11 shows time series of ozone at 50 hPa as seen by ozonesonde and sonde-sampled SBUV data, along with their differences. The sonde-sampled SBUV data agree with sonde data within ±10% and the differences in mean biases for each SBUV(/2) instrument vary from −3.2% for NOAA-9 to 0.7% for NOAA-16. Figure 12 shows comparisons of SAGE II with SAGE-sampled SBUV. The SAGE-sampled SBUV data have negative biases of −1.2% to

Table 1. Average Differences and One Standard Deviation (1σ, Inside Parentheses) Between Ozonesonde and SAGE II/HALOE at 125 hPa and 50 hPa (in %)

Station	SAGE II		HALOE	
	125 hPa	50 hPa	125 hPa	50 hPa
Europe	4.7 (15.8)	3.4 (4.4)	−9.1 (13.5)	−4.0 (4.4)
Boulder	5.0 (21.1)	6.3 (5.2)	−3.1 (15.5)	3.5 (7.7)
Tateno	21.9 (29.8)	11.9 (7.7)	−0.5 (26.2)	9.9 (7.6)
Edmonton	0.1 (19.0)	1.8 (8.1)	−9.8 (17.4)	−0.6 (5.8)
Goose Bay	−1.4 (17.9)	1.7 (6.8)	−7.6 (20.6)	−2.9 (7.4)
Wallops Island	8.4 (27.8)	2.3 (6.9)	−5.6 (24.6)	−2.5 (7.2)

Table 2. Same as Table 1 but for 390 K and 510 K Using the Isentropic Coordinate

	SAGE II		HALOE	
Station	390 K	510 K	390 K	510 K
Europe	3.1 (13.3)	3.3 (5.2)	−9.8 (11.3)	−4.2 (4.2)
Boulder	0.7 (16.7)	7.7 (5.6)	−6.6 (13.8)	5.2 (7.8)
Tateno	7.7 (20.9)	17.1 (9.2)	−5.4 (21.4)	12.9 (7.5)
Edmonton	−0.9 (16.2)	0.2 (7.1)	−9.9 (15.0)	−1.7 (6.1)
Goose Bay	−3.4 (18.5)	2.7 (8.2)	−6.8 (17.1)	−3.2 (8.0)
Wallops Island	2.3 (21.6)	5.2 (8.4)	−11.3 (22.3)	−0.2 (8.5)

−5.6% for the different SBUV(/2) instruments, and larger monthly differences.

[50] Table 3 summarizes of comparisons of SBUV(/2) with sonde and SAGE II data for 50 to 12.5 hPa. The biases of SBUV(/2) data are within ±5% and the differences in biases among the SBUV(/2) data subsets are within 1–4%, except for the SAGE-sampled SBUV at 50 hPa. The larger differences between SBUV(/2) and SAGE II at 50 hPa are likely caused by the lower vertical resolution, and hence poorer quality, of the SBUV(/2) data at 50 hPa compared to higher altitudes. There is an evolution of the bias from NOAA-11a (December 1988 to December 1993) to NOAA-11b (July 1997 to December 2000) for both sondes and SAGE II in all layers, indicating a small drift to higher ozone values of ~1–4% over ~9 years. Since NOAA-11 moved from an afternoon orbit to a morning orbit between the NOAA-11a and NOAA-11b data periods, this could also affect the overall change.

[51] Figure 13 shows that the differences in SBUV(/2) sampled at the SAGE II and sonde locations and times are very similar to the differences in monthly mean ozone given by SAGE II and sonde measurement themselves. We find a high degree of correlation between the SAGE–sonde differences in ozone and the differences seen by coincident SBUV(/2) data, with R^2 of 0.64–0.76 for 50 to 12.5 hPa (Figure 14). This implies that a large fraction of the SAGE–sonde differences is caused by differences in spatial/temporal sampling.

3.4. Comparison of Trends Derived From Sondes, SAGE II, and SBUV(/2)

[52] Trends in monthly mean ozone for 1984–2000 were calculated using a linear regression model that includes terms for the seasonal cycle of ozone, four seasonal linear trends, the quasi-biennial oscillation (QBO), and the solar cycle. The model is similar to that in the work of *Logan et al.* [1999], except that the seasonal cycle of ozone is treated as six sin/cos terms, and two QBO terms are derived from the principal components of the Singapore zonal winds as described by *Logan et al.* [2003]. We omitted the data after 2000 because of the sparseness of the SAGE II data. We omitted Tateno from the analysis because of the sparseness of measurements before 1990 and concerns over data quality (section 3.1 and 3.2). For SBUV (/2) trends, we used all measurements in each 10° × 40° region.

[53] Figure 15 shows trends in the vertical distribution of ozone in % per decade for sondes, SAGE II, and SBUV (/2). There are insufficient SAGE II data to calculate trends in the lower levels. For Europe the sonde and SAGE II trends agree well at all levels, while for other stations, the agreement is best at 50 hPa. The trends agree within their

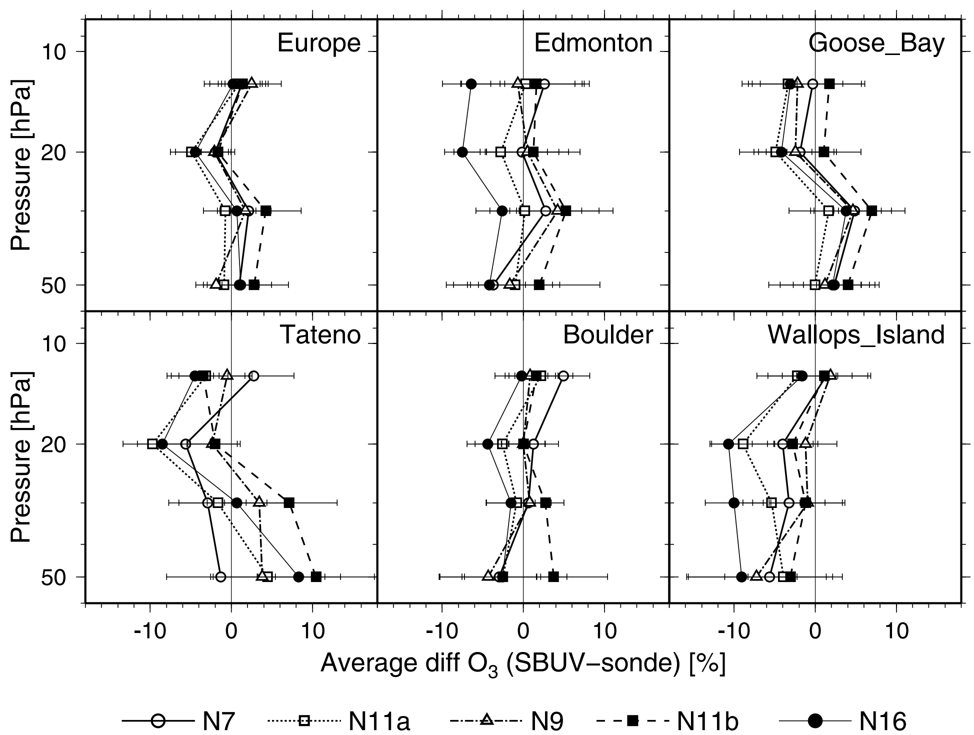

Figure 10. Vertical profiles of average bias of SBUV(/2) data with respect to ozonesondes for each ozonesonde station. The biases were calculated by averaging the differences in monthly mean ozone for the measurement period of each SBUV(/2) sensor (section 2.3). The horizontal lines show one standard deviation.

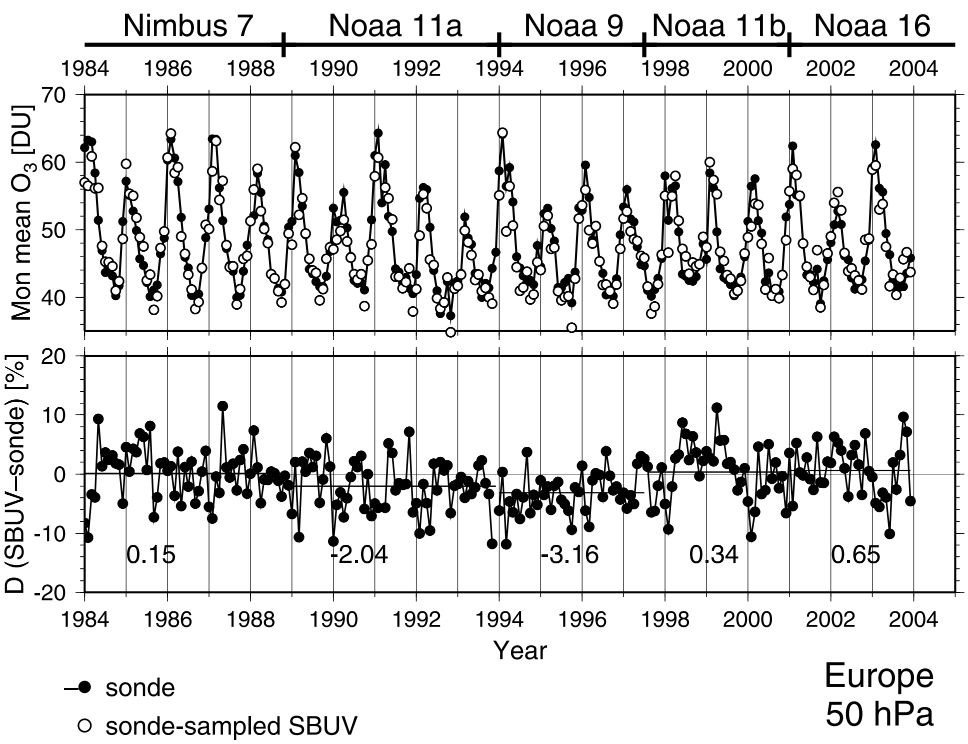

Figure 11. (top) Monthly mean ozone observed by ozonesonde (closed circle) and by SBUV(/2) sampled for the same date and location (open circle) for Europe. (bottom) Differences in monthly mean ozone and between ozonesonde and coincident SBUV(/2) ((SBUV − sonde)/sonde × 100). Results are shown for the 50 hPa layer. Horizontal lines and numbers show mean differences (in %) averaged over the measurement period of each SBUV(/2) sensor.

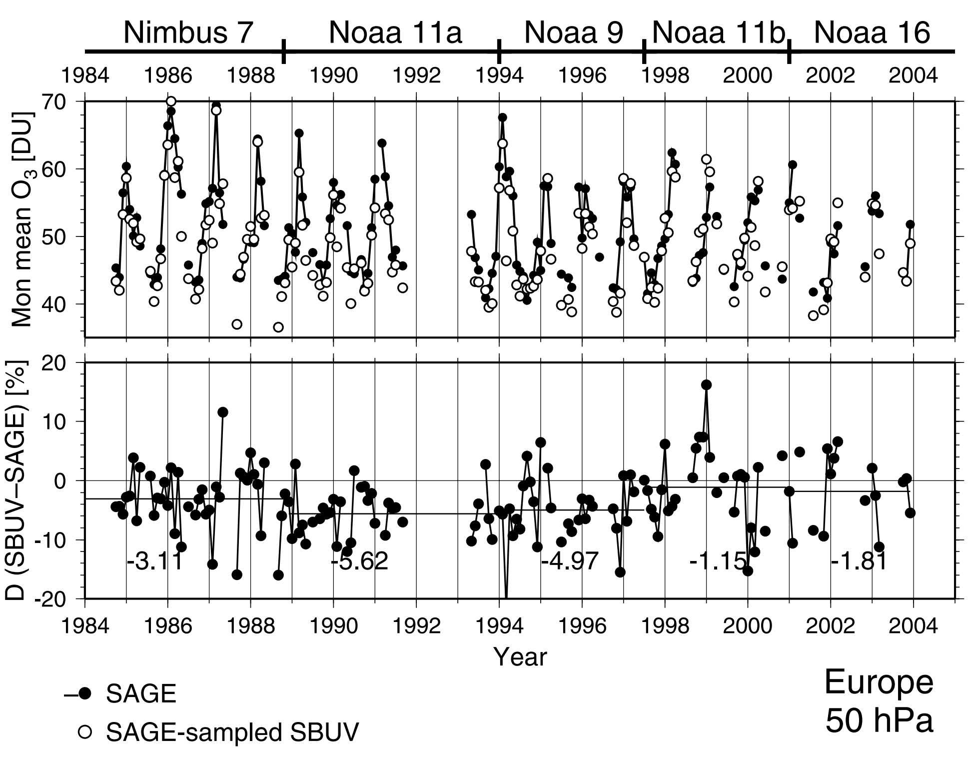

Figure 12. Comparison of SAGE II and SBUV(/2) sampled for the same date and location. See Figure 11 for details.

Table 3. Summary of Mean Differences Between SBUV(/2) Aboard Nimbus-7, NOAA-9, NOAA-11, and NOAA-16, and Ozonesonde or SAGE II Over Europe (in %)[a]

	Layer, hPa	Nimbus-7	NOAA-11a	NOAA-9	NOAA-11b	NOAA-16
ozonesonde	12.5	4.22	2.17	4.34	3.58	2.06
	20	−0.00	−3.65	−0.77	0.07	−2.67
	30	2.77	−0.60	2.08	4.09	1.43
	50	0.15	−2.04	−3.16	0.34	0.65
SAGE II	12.5	−0.30	−0.80	−1.34	−0.21	−1.66
	20	−0.86	−2.96	−2.09	−0.56	−2.55
	30	0.94	−0.90	−0.50	2.32	1.40
	50	−3.11	−5.62	−4.97	−1.15	−1.81

[a]The average biases of sonde-sampled SBUV and sondes, and SAGE-sampled SBUV and SAGE II, were calculated from averaging the differences in monthly mean ozone over the measurement period of each SBUV(/2) sensor.

errors for the Canadian stations, but this is not the case for the upper levels at Boulder and Wallops Island. The SBUV(/2) and SAGE II trends agree well for the higher latitude regions, Europe, Edmonton, and Goose Bay, but the SBUV (/2) trends are systematically more positive, by 1–3% per decade, for Boulder and Wallops Island.

[54] Figure 16 shows trends derived from sonde- and SAGE-sampled SBUV for Europe. The ozone trends derived exclusively from the SBUV data agree very well with those from the SAGE II and ozonesonde data. These results imply that the differences in ozone trends derived from sondes and from SAGE II are caused primarily by sampling differences. The effect of sampling differences on ozone trends is expected to be even larger for the other regions, where the sonde data are less frequent.

[55] We also calculated ozone trends on isentropic coordinate (not shown). The results using potential temperature are very similar to those using pressure, although the differences between ozonesonde and SAGE II trends are slightly smaller for lower layers for some stations.

3.5. Time Series Over Europe From 1979

[56] We conclude the regional analysis by using the four data sets to show how ozone has changed since 1979. Trends in the vertical distribution of ozone usually are calculated starting in 1979 or 1980 because of the availability of satellite measurements since then [e.g., *WMO*, 1999, 2003].

[57] We show in Figure 17a that there is excellent agreement in the interannual variability of ozone since 1979 as seen by ozonesondes, SBUV(/2), SAGE II, and HALOE over Europe. The sonde, SAGE, and HALOE data also agree well down into the lowermost stratosphere (Figure 17b, note change in scale). The ozone anomalies

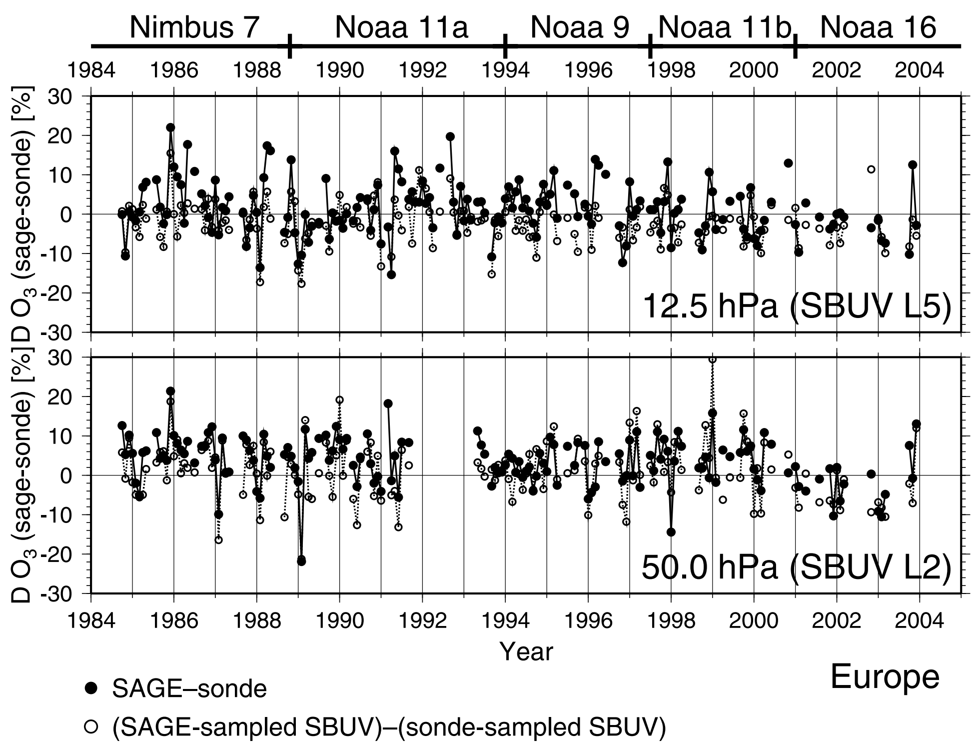

Figure 13. Differences in monthly mean ozone between ozonesonde and SAGE II (closed circle with solid line) and between sonde-sampled SBUV and SAGE-sampled SBUV (open circle with dashed line) for Europe at 12.5 hPa and 50 hPa.

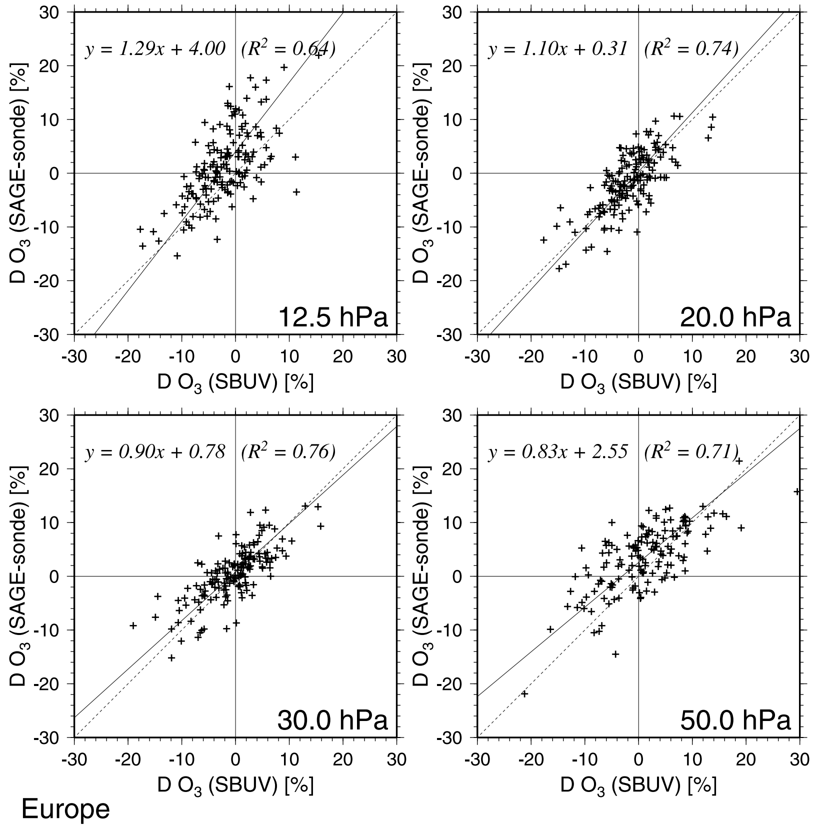

Figure 14. Scatterplots of differences in monthly mean ozone between ozonesonde and SAGE II (vertical axis) and between sonde- and SAGE-sampled SBUV (horizontal axis) for 12.5, 20, 30, and 50 hPa layers. The equation shows the result of reduced major axis (RMA) regression analysis. R^2 is coefficient of determination. The solid line shows a RMA regression fit and the dashed line shows a nominal 1:1 relationship.

in these figures were calculated with respect to 1985–1990 as a common base period, except for HALOE where 1994–1999 was used. The average of the ozonesonde anomalies for 1979–1981 was then subtracted from each time series to normalize them to a common initial time.

[58] Figure 17a shows the overall downward trend in ozone from 1979 to the mid-1990s, with minimum values in the winter of 1992–1993 at and below the ozone maximum (50 hPa). Ozone values have been relatively constant since 1998 from 80 to 20 hPa, and values in the past few years are about 6% below those in the early 1980s. There is now no evidence for a downward trend in ozone in the lowermost stratosphere, with ozone values since the mid-1990s similar to those in the first half of the 1980s (Figure 17b).

4. Zonal Mean Analysis of SAGE II and SBUV(/2) Data

[59] SAGE II and SBUV(/2) data have been used to determine zonal mean trends in ozone [e.g., *SPARC*, 1998; *WMO*, 2003; *Cunnold et al.*, 2000; *Wang et al.*, 2002; *Newchurch et al.*, 2003; *Nazaryan and McCormick*, 2005]. Here we extend our analysis of the biases of the SBUV(/2) instruments with respect to SAGE to all latitudes and to the upper stratosphere, and we compare zonal mean trends of SBUV(/2) and SAGE II data.

[60] The recommendation of a major international assessment of ozone trends was to compute the trends from different instruments in their native coordinate system, and then compare profile trends using a standard atmosphere [*WMO*, 1999]. Temperatures are decreasing in the upper stratosphere [*Ramaswamy et al.*, 2001]. In the presence of such a trend, the altitude of pressure surfaces and the air density of pressure surfaces will change with time, and consequently the trends calculated for ozone will depend on the coordinate system used, as discussed by *Rosenfield et al.* [2005]. We address this issue below.

4.1. Bias of SBUV(/2) With Respect to SAGE II

[61] Here we evaluate the self-consistency of the SBUV(/2) time series using the self-consistent SAGE data set. To calculate the bias of SBUV(/2) with respect to SAGE II, we convert the SAGE data from altitude to pressure layers using the CIRA-86 standard atmospheres (section 2.5.2) in addition to NCEP data because of concern over discontinuities and trends in the NCEP temperature data in the upper stratosphere [e.g., *Keckhut et al.*, 2001].

[62] The biases between SAGE II and SAGE-sampled SBUV for each SBUV(/2) sensor are shown in Figure 18. The biases are generally within ±5% from 50 hPa to 5 hPa at 40°–60° and from 30 hPa to 5 hPa for 40°N–40°S, using the NCEP data. Results are similar for the CIRA atmos-

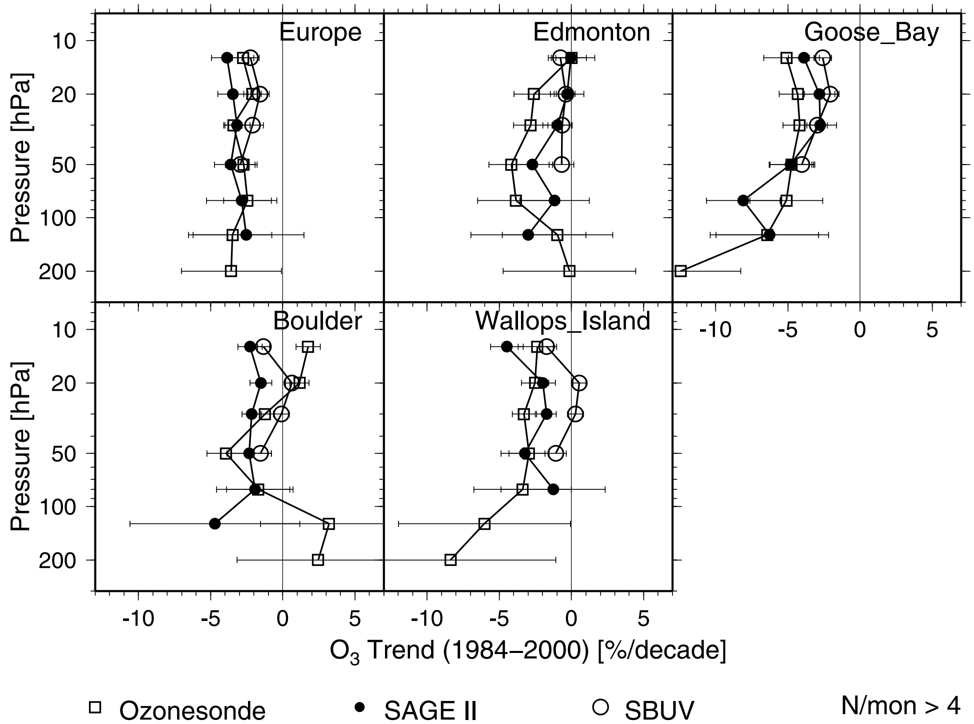

Figure 15. Trend in the vertical distribution of ozone in % per decade from 1984 to 2000 for each ozonesonde location. The open squares, closed circles, and open circles show results obtained by using the ozonesonde, SAGE II, and SBUV/2 data, respectively. The horizontal lines show the trend ±1 standard error.

pheres, but the biases exceed ±5% for some latitudes at 20 hPa and 8 hPa, particularly for NOAA-16. Differences in biases among the SBUV(/2) sensors are smallest between 30 hPa and 12.5 hPa, indicating that the SBUV(/2) time series are most homogeneous there.

[63] There are large negative biases for SBUV ozone relative to SAGE at 50 hPa for 40°N–40°S. The 50 hPa level is well below the partial pressure maximum in the vertical distribution of ozone in the tropics and subtropics, and errors of the SBUV(/2) retrieval become larger below the ozone maximum; the data are more influenced by the a priori climatology at 50 hPa than higher levels [*Bhartia et al.*, 1996]. These factors can lead to large enhancements of the SBUV(/2) biases. Providing the SBUV product with 3 km resolution at 50 hPa for latitudes <40° has introduced a much larger bias than for higher latitudes, where 50 hPa is closer to the ozone maximum [e.g., *Logan*, 1999].

[64] The biases at 2–3 hPa on the CIRA levels are more positive than those on NCEP levels by 2–6%, with largest differences for NOAA-9 and NOAA-16. The differences

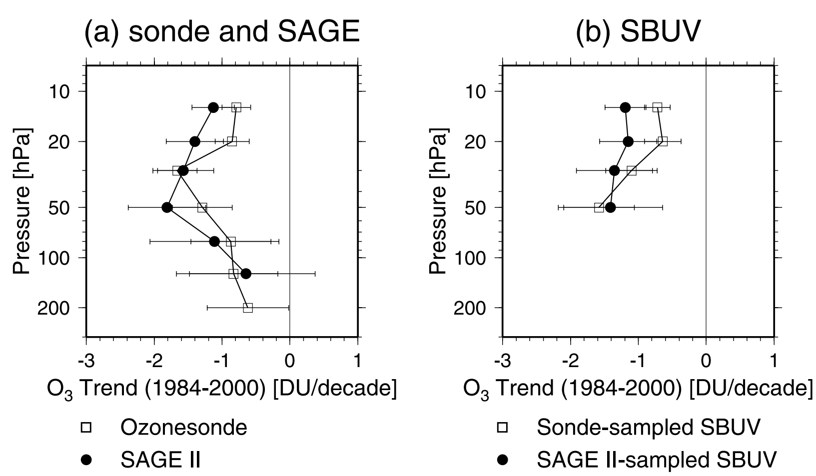

Figure 16. (a) Ozone trends over Europe as derived from ozonesonde (open square) and SAGE II (closed circle). These are the trends in Figure 15 plotted in DU/decade. (b) Ozone trends as derived from sonde-sampled SBUV (open square) and SAGE-sampled SBUV (closed circle). The horizontal lines show the trend ±1 standard error.

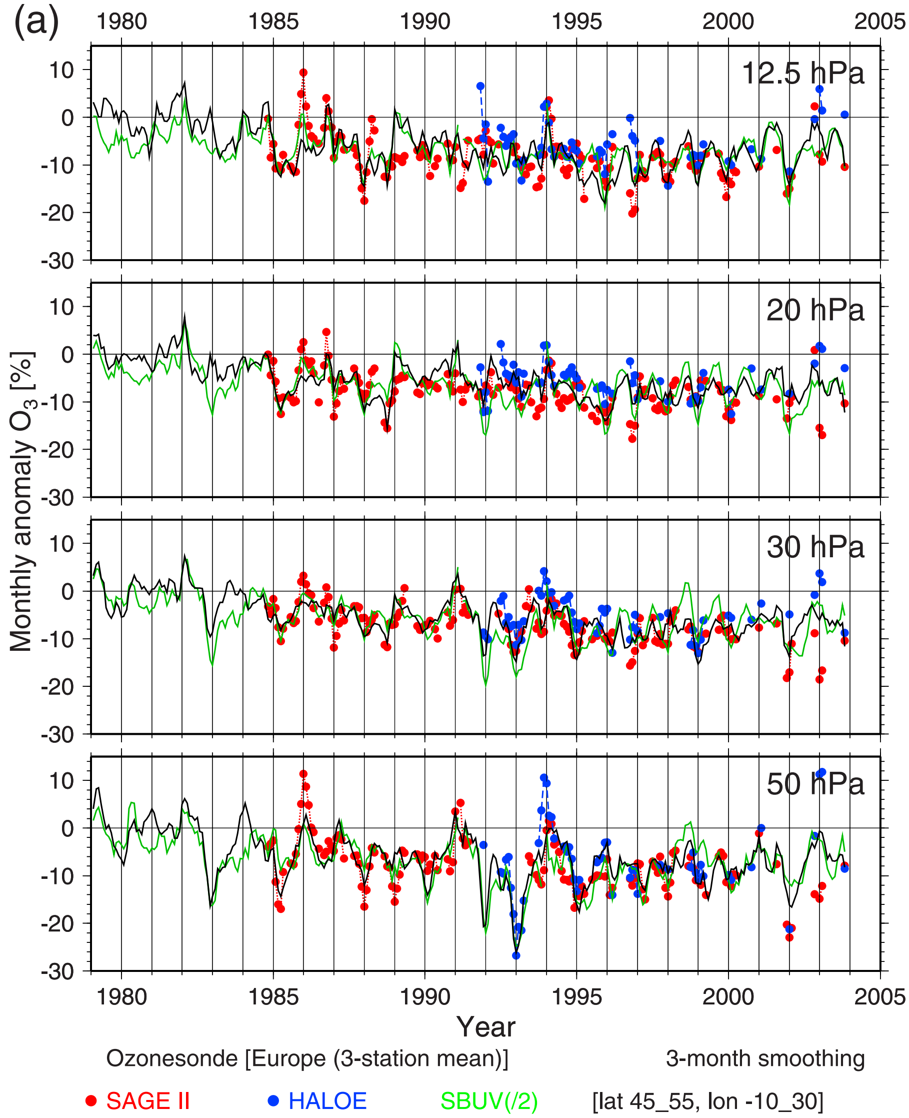

Figure 17. Monthly ozone anomalies for Europe as measured by ozonesondes (black line), SAGE II (red circles), HALOE (blue circles), and SBUV(/2) (green line) at seven layers; (a) from 12.5 hPa to 50 hPa and (b) from 80 hPa to 200 hPa. The monthly anomalies were calculated as the difference between a given monthly mean and the average of monthly means for 1985–1990 for each data set, except for HALOE where 1994–1999 was used; the average of the monthly mean ozonesonde anomalies for 1979–1981 was then subtracted from each anomaly time series.

between CIRA and NCEP pressures likely are caused by discontinuities in the NCEP temperature record in the upper stratosphere and an offset between CIRA and NCEP pressure data. NOAA-9 SBUV data have the largest biases relative to SAGE at 2–3 hPa for both the NCEP and CIRA atmospheres. Our results agree with a previous validation analysis that showed higher values and a upward drift of NOAA-9 SBUV/2 for the 40 km layer (~3 hPa) with respect to Umkehr measurements [*Petropavlovskikh et al.*, 2005]. The large spread in the SBUV(/2) biases at 2–3 hPa implies that there are inhomogeneities in the time series, with likely effects on the reliability of trends derived from these data.

[65] The vertical shape of the bias profiles are similar for all latitudes, except that NOAA-11b is an outlier, with the most positive biases at 30 hPa, and negative biases from 8 to 3 hPa, where the other NOAA data sets show positive biases. The specific biases of NOAA-11b and the high bias of NOAA-9 at 2–3 hPa could be caused by issues with the spacecraft orbital drift of NOAA-9 and NOAA-11 after 1996 [*SBUV Version 8 DVD*, *Petropavlovskikh et al.*, 2005]. Some of the zigzag structure in the bias profiles may result from difficulties in the wavelength-dependent calibration of SBUV(/2) [*Petropavlovskikh et al.*, 2005].

4.2. Zonal Mean Trends of SAGE II and SBUV(/2)

[66] Figure 19 shows trends in the vertical distribution of zonal mean ozone calculated from the SAGE II data, the SAGE-sampled SBUV data, and the complete SBUV data set. The latter contains several thousand measurements each month in each 10° zonal band. For SAGE II and the SAGE-sampled SBUV data, there are zero to hundreds of measure-

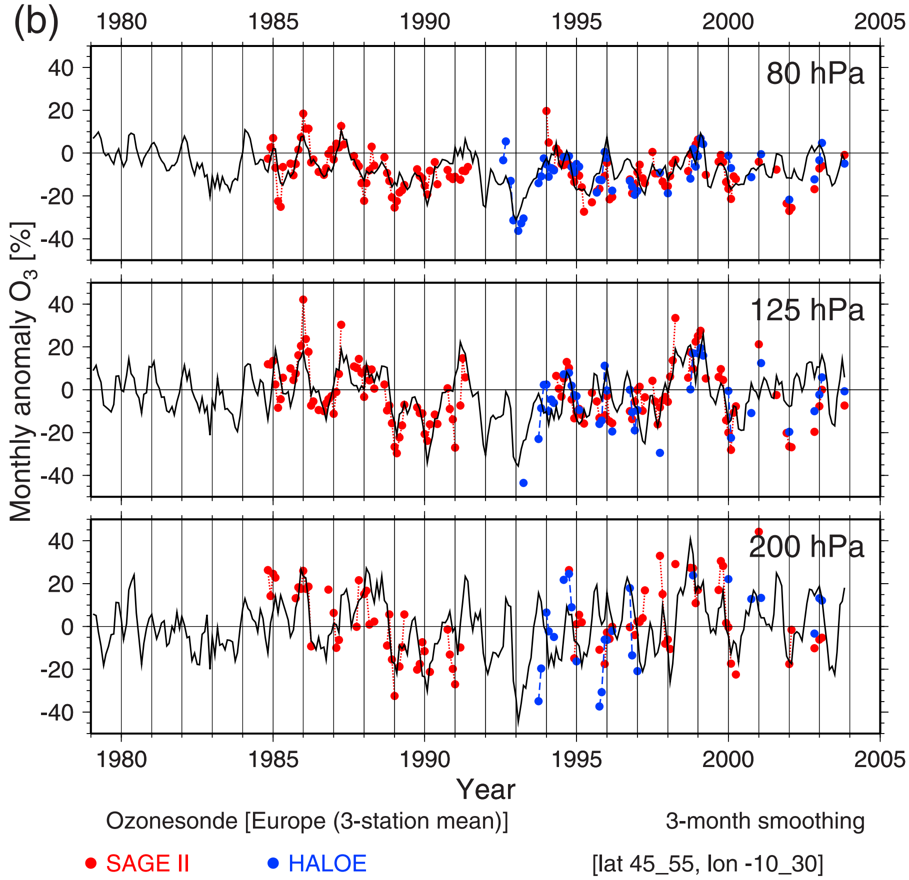

Figure 17. (continued)

ments each month, and the mean measurement latitude varies seasonally. The SAGE II trends were calculated using three different vertical coordinates: (1) on geometric altitude levels, with the results plotted on U.S. Standard Atmosphere 1976 pressure levels (referred as SAGE(alt)); (2) on NCEP pressure levels (SAGE(NCEP)), and (3) on CIRA-86 pressure levels (SAGE(CIRA)).

[67] The SAGE-sampled SBUV trends are very similar to the complete SBUV trends, with differences almost always less than 1% per decade. This indicates that the sparse sampling of SAGE II compared with SBUV(/2) does not affect zonal mean trends and that differences in trends derived from SAGE II and SBUV(/2) are caused by differences in data quality or by issues related to the coordinate system in which the trends are calculated [*Rosenfield et al.*, 2005].

[68] We now consider the effect on SAGE trends of changing the data from ozone number density on an altitude scale to partial ozone columns on pressure levels. SAGE-(NCEP) trends are very similar to the SAGE(alt) trends below 10 hPa for all latitude bands, indicating that the change of vertical coordinate has no effect on the trends in the lower stratosphere. Above 10 hPa, the SAGE(NCEP) and SAGE(alt) trends are similar for 40°–60° with differences in trends of <1.5%/decade. However, for lower latitudes the SAGE(NCEP) trends are more positive than those for SAGE(alt), with differences as high as 4%/decade above 3 hPa in the tropics.

[69] *Rosenfield et al.* [2005] quantified the effects of changing the coordinate system in which ozone trends are calculated, in the presence of a temperature trend, using results from an interactive two-dimensional model. They found that the ozone decrease at 3 hPa is larger for trends calculated from the ozone number density on geometric altitudes than for trends calculated on pressure levels, by 1%/decade in the tropics, and 1.5–2%/decade in midlatitudes. *Li et al.* [2002] estimated that the observed temperature trend of −1 K/decade would reduce the ozone trend by 1%/decade at 1.8 hPa, 45°S, using a chemical box model. Their results indicated that SAGE trends on altitude levels should be more negative than SBUV trends on pressure levels by 1%/decade. The trend in ozone that we calculate for SAGE(alt) is indeed more negative than that for SAGE(NCEP) at 2–3 hPa, but by 2–3%/decade in the tropics and by about 1%/decade in the midlatitudes. The SAGE(NCEP) trends are likely influenced by discontinuities and artificial trends in the NCEP temperatures in the upper stratosphere, and we do not consider these trends to be reliable. The NCEP temperatures in the upper stratosphere are derived from satellite data and are influenced by changes in the NOAA satellites [*Keckhut et al.*, 2001], while in the lower stratosphere the NCEP temperatures are influenced by radiosondes as well and appear to have fewer artifacts in terms of trends.

[70] The SAGE(CIRA) trends are almost same as SAGE(alt) for all regions. This is expected, as the CIRA-

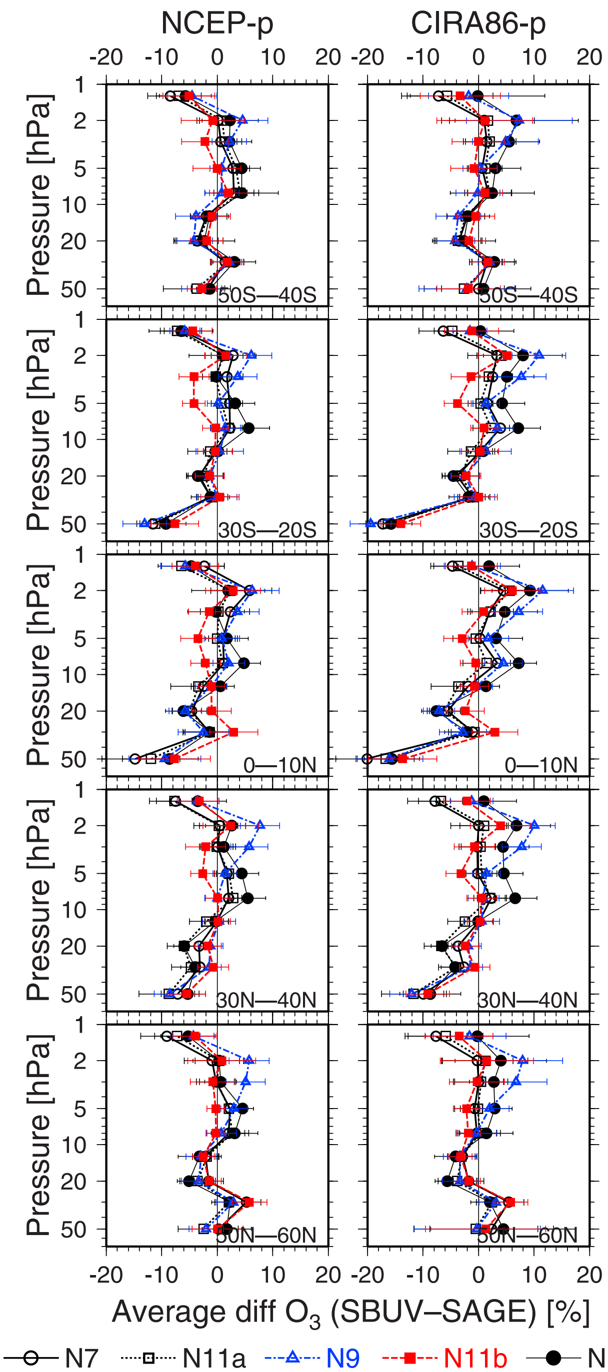

Figure 18. Average difference of zonal mean ozone between SAGE II and SAGE-sampled SBUV during the NOAA-7, NOAA-11a, NOAA-9, NOAA-11b, and NOAA-16 measurement periods (open circles, open squares, blue triangles, red squares, and closed circles, respectively). These were calculated by averaging the differences in monthly mean ozone as (SBUV − SAGE)/SAGE × 100 over the measurement period of each SBUV(/2) sensor. The SAGE II data were converted to pressure levels using NCEP data (left) and CIRA-86 data (right). Results are shown for selected regions: 40°–50°S, 20°–30°S, 0°–10°N, 30°–40°N, and 50°–60°N. The horizontal lines show one standard deviation.

86 temperature and pressure data are for a fixed time, so changing the coordinate system before calculating the trend does not affect the results.

[71] The SAGE(alt) trends and SBUV trends are most similar in the lower stratosphere for 40°–60°N and 40°–50°S. Both show a decrease in ozone of 2–3%/decade for 30–50 hPa, with SAGE usually giving a larger decrease than SBUV, by at most 1%/decade. This is consistent with the results from our local analysis for midlatitude sonde stations (shown in Figure 15). For lower latitudes, the SBUV data given trends that are typically 2%/decade more positive than the SAGE trends, and indicate an increase, rather than a decrease, in ozone in the lower stratosphere.

[72] In the upper stratosphere the differences between the SAGE(alt) and SBUV trends are as much as 4%/decade. The decrease in ozone derived from the SBUV data is largest at 5 hPa, while that derived from SAGE data is largest at 2–3 hPa. Thus the SBUV trends are more negative than SAGE trends for 5–8 hPa but are more positive at 1–2 hPa, with similar trends in between.

[73] Several previous studies investigated zonal mean ozone trends as observed by SAGE II and SBUV(/2). The largest negative SAGE(alt) trends in this work are −5 to −7%/decade at 2–3 hPa at the higher latitudes for both hemispheres (40–60°S and 50–60°N) and up to −4%/decade at 50 hPa for other latitudes. These negative trends agree quantitatively with the results of *Wang et al.* [2002]. *SPARC* [1998] and *Cunnold et al.* [2000] reported that Nimbus-7 SBUV and NOAA-11 SBUV/2 (V6) trends were more positive than SAGE I/II (V5.96) trends at almost all latitudes between 25 km (∼30 hPa) and 45 km (∼2 hPa) during 1979–1996. Our results show that, by contrast, SBUV(/2) trends are more negative than SAGE II trends between 3 hPa and 8 hPa. *Nazaryan and McCormick* [2005] used V8 NOAA-11 SBUV/2 data and showed that SBUV/2 trends were more positive at 15 hPa and more negative at 5 hPa than SAGE II trends, similar to our results, although their analysis period was different from ours (1988–2001) and they used only NOAA-11 SBUV/2 data. Model simulations give maximum negative trends around 42 km (∼2 hPa) for 35°N–60°N and 35°S–60°S [*WMO*, 2003]. The height of largest downward trend agrees very well with the results from SAGE II data.

5. Discussion and Conclusions

[74] We conducted an in-depth analysis of the consistency of time series for ozone obtained by ozonesondes, SAGE II V6.2, HALOE V19, and V8 SBUV(/2). Our focus first was on northern midlatitudes, where questions had been raised about whether trends derived from ozonesondes and SAGE data were self-consistent [*WMO*, 2003]. Our second focus was on evaluating the quality of the newly reprocessed V8 SBUV(/2) data set [*Bhartia et al.*, 2004]. The self-consistency of the SAGE II data was essential to this analysis.

[75] Our analysis of measurements over Europe showed that there is no inconsistency between the sonde and SAGE trends. We explored the causes of the SAGE–sonde differences in interannual variability using coincident SBUV(/2). Our analysis showed that 64–76% of the variance of the SAGE–sonde differences in monthly mean ozone are

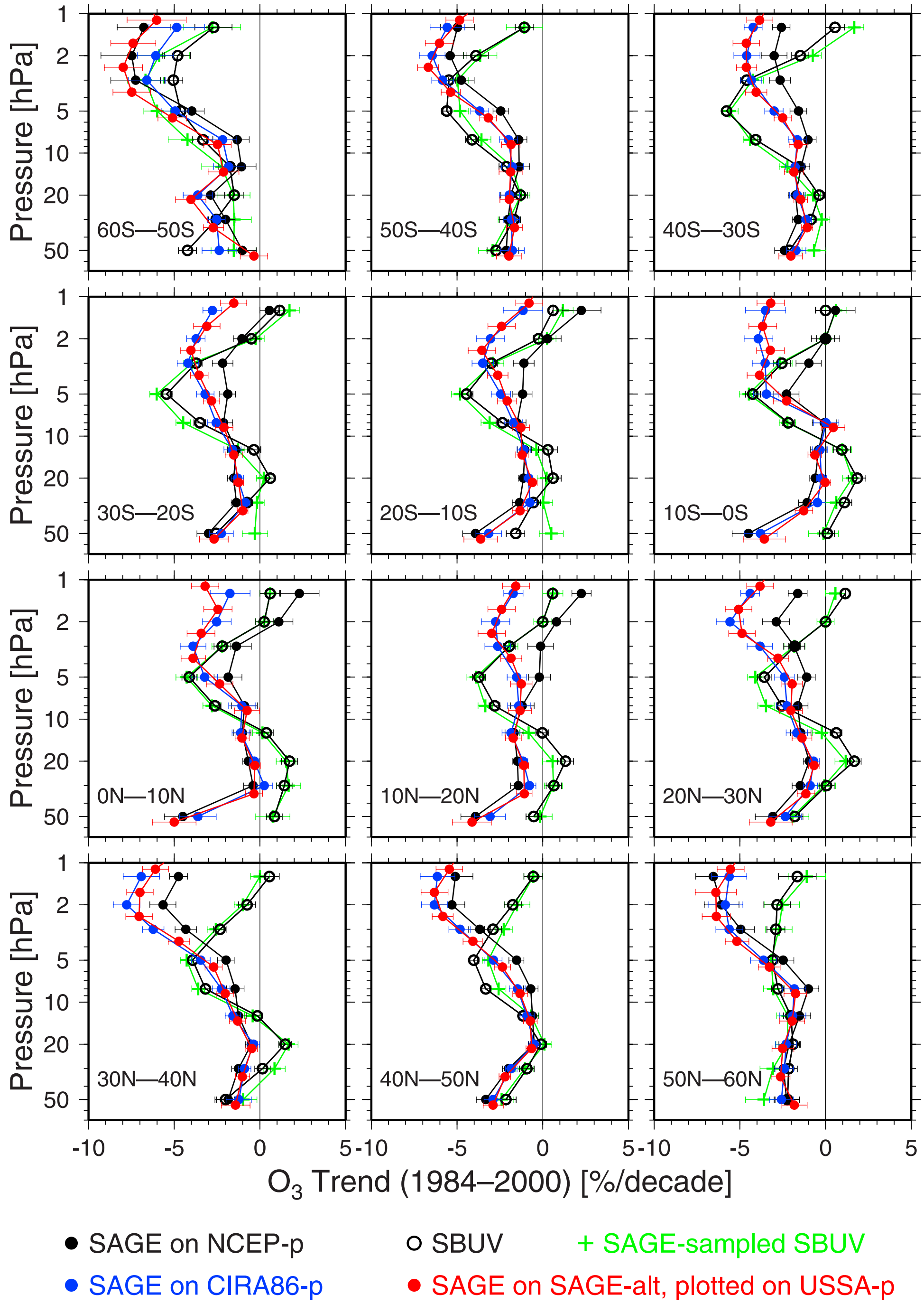

Figure 19. Trend in the vertical distribution of zonal mean ozone in % per decade from 1984 to 2000. The black circles show results obtained by using the SAGE II data on NCEP pressure levels, the blue circles by the SAGE II data on CIRA-86 pressure levels, and the red circles by the SAGE II data on geometric altitude levels then plotted on U. S. Standard Atmosphere pressure levels (see text). The open circles show results from the complete SBUV(/2) data and the green crosses from the SAGE-sampled SBUV data. The horizontal lines show the trend ± one standard error.

caused by differences in spatial/temporal sampling. We also found, by comparison to sonde and SAGE II data, that the V8 SBUV(/2) record is homogeneous (within 2–4%) at midlatitudes from 50 to 12.5 hPa.

[76] Trends derived for midlatitudes from ozonesondes and SAGE II agree within their errors for most regions, and the differences in trends are caused primarily by differences in sampling. The regional and zonal mean SBUV(/2) trends in the lower stratosphere agree well with the SAGE II trends at 50°–60°N and are slightly less negative than the SAGE trends at 40°–50°N.

[77] We used the sonde, SBUV(/2), SAGE, and HALOE data sets to show how ozone in the lower stratosphere has changed over Europe since 1979. There is excellent agree-

ment in the interannual variability of ozone as seen by the different data sets, and they reveal the overall downward trend in ozone from 1979 to the mid-1990s, with minimum values in the winter of 1992–1993 at and below the ozone maximum (50 hPa). The relatively constant ozone values evident since 1998 from 80 to 20 hPa have been attributed to the turnaround in the amount of effective chlorine in the stratosphere in 1996–1997 [*Yang et al.*, 2006]. Ozone values in recent years are about 6% below those in the early 1980s (Figure 17a).

[78] There is now no evidence for a downward trend in ozone in the lowermost stratosphere, with ozone values since the mid-1990s similar to those in the first half of the 1980s (Figure 17b). Earlier analyses gave a substantial downward trend in ozone [*Logan et al.*, 1999] because those trends were calculated up to 1996 and were strongly influenced by the low values of ozone in the 2 years after the Pinatubo eruption.

[79] Ozone is measured weekly at ozonesonde stations outside Europe. We found that for these stations there was fairly good agreement in the monthly ozone anomalies for sondes, SAGE II, HALOE, and SBUV(/2) near the ozone maximum at midlatitudes (~50 hPa). However, the agreement is poorer in the lowermost stratosphere where ozone is more variable. Our analysis implies that more frequent measurements than weekly are required to capture the monthly variability in ozone in the lowermost stratosphere. Similarly, if the SAGE II data are to be used for regional analysis, more than 10–15 profiles per month are needed in winter/spring to capture monthly variability at pressures greater than 100 hPa.

[80] The SAGE II V6.2 data have a positive bias and the HALOE V19 data have a negative bias with respect to the ozonesonde data, in agreement with previous studies [*Morris et al.*, 2002; *Nazaryan et al.*, 2005]. We found regional differences in the biases between sonde and SAGE II data that are related to the type of ozonesonde used. The comparisons with the self-consistent SAGE data showed that the Japanese KC sondes are biased low compared to BM and ECC sondes in the lowermost stratosphere. A similar conclusion was reached in a laboratory study but our analysis showed a larger bias than that reported by *Smit and Sträter* [2004].

[81] We examined the homogeneity of the V8 SBUV(/2) ozone record by comparing the bias with respect to SAGE II data for each subset of the SBUV(/2) data. This analysis required that we convert the SAGE data from geometric altitude to pressure levels. Because of concern over inconsistencies in the NCEP temperature/pressure data in the upper stratosphere [*Keckhut et al.*, 2001], we used the CIRA-86 standard atmospheres as well as the NCEP data to convert the SAGE data to pressure levels.

[82] The similarity of the SBUV(/2) biases calculated with the CIRA and NCEP atmospheres for 50–10 hPa implies that the use of the NCEP atmospheres to convert the SAGE data to pressure levels causes no problems in the lower stratosphere. Conversely, the differences of the SBUV(/2) biases calculated with the CIRA and NCEP atmospheres in the upper stratosphere confirms that the use of the latter data to convert the SAGE data to pressure levels introduces errors into the SAGE time series. Further evidence for this is provided by the erroneous trends that result when SAGE data are first converted to pressure levels using NCEP atmospheres.

[83] The similarity in the biases of SBUV(/2) to SAGE II for different SBUV(/2) data subsets indicates that the SBUV(/2) time series are most homogeneous for 50 to 12.5 hPa at midlatitudes. We found a small drift to higher ozone values of ~1–4% in the NOAA-11 data between the NOAA-11a and -11b periods.

[84] There is less homogeneity in the SBUV(/2) time series for 8 to 1.25 hPa, as shown by the negative biases of NOAA-11b at 3–5 hPa and the positive biases of NOAA-9 and -16 at 2–5 hPa, compared to the biases for Nimbus 7 and NOAA-11a. Previous validation analyses showed that the quality of NOAA-9 data is relatively poor compared to the other sensors at ~40 km (~3 hPa) [*Ahn et al.*, 2004; *Petropavlovskikh et al.*, 2005]. The high bias of NOAA-16 at 8–1.25 hPa is of particular concern, as NOAA-16 is at the end of the time series. A high bias in ozone values after 2000 will influence assessments of ozone recovery in the upper stratosphere using SBUV(/2) data.

[85] Most biases between SBUV(/2) data and SAGE II data are within ±10%. Exceptions are the positive NOAA-9 and -16 data in the upper stratosphere, and the large negative biases of SBUV(/2) data at 50 hPa from 40°N to 40°S, from −5% to −20%. The SBUV(/2) instruments cannot give reliable information on the vertical distribution of ozone below the ozone maximum (in partial pressure), and 50 hPa is well below the ozone maximum for these latitudes. We argue that the SBUV data set that we analyzed here (~3 km resolution) should be used with great caution below the ozone maximum. Above the ozone maximum, a wavelength-dependent calibration problem of SBUV(/2) [*Petropavlovskikh et al.*, 2005] is the likely cause of the zigzag structure seen in the SBUV biases with respect to SAGE II.

[86] We investigated whether the relatively sparse sampling of SAGE data affected zonal mean trends by comparing trends calculated using all the SBUV data with those derived from SBUV data coincident with SAGE profiles. Our results showed that the SAGE sampling does not influence the zonal mean trends, implying that differences in trends derived from SAGE II and SBUV(/2) are caused by differences in data quality and by the different coordinate systems in which ozone is measured [*Rosenfield et al.*, 2005].

[87] For SAGE II trends calculated on an altitude scale we find good agreement with SBUV(/2) trends in the midlatitude lower stratosphere for 1984–2000. Both data sets show a decrease of 2–3%/decade for 50–30 hPa, with the SAGE II data giving a slightly larger decrease than SBUV(/2), by at most 1%/decade. The SAGE II data give a decrease in ozone at lower latitudes that is largest at 50 hPa (3–5%/decade), while the SBUV(/2) data give either no trend or an small increase in ozone.

[88] In the upper stratosphere the SAGE II data give a decrease in ozone of 5–7%/decade in the extratropics and 3–5%/decade in the tropics, in agreement with prior studies for similar time periods [*Wang et al.*, 2002; *Nazaryan and McCormick*, 2005]. However, the SBUV(/2) trends are as much as 4%/decade more positive than the SAGE II trends in the tropics, with smaller differences in the extratropics. According to the results of *Rosenfield et al.* [2005], trends in

temperature could explain only 0.5%/decade of the difference in the tropics between SAGE II trends (on altitude) and SBUV(/2) trends (on pressure) and about half of the 2–3%/decade difference in the extratropics.

[89] The SBUV(/2) data imply a decrease in tropical ozone of 4–5%/decade at 5 hPa, larger than that derived from SAGE II data by 2–3%/decade. The SBUV(/2) trends derived here are influenced by the NOAA-11b data (July 1997 to December 2000) that are biased low by about 4–8% compared to the other SBUV(/2) data subsets (Figure 18). Our analysis of the biases in the SBUV(/2) data relative to SAGE imply that the later NOAA data (both 11b and 16) can lead to errors in calculated ozone profile trends.

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J. A. Logan and Y. Terao, School of Engineering and Applied Sciences, Harvard University, 29 Oxford Street, Cambridge, MA 02138, USA. (yterao@nies.go.jp)