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Brewer spectrometer total ozone column measurements in Sodankylä

Tomi Karppinen, Kaisa Lakkala, Juha M. Karhu, Pauli Heikkinen, Rigel Kivi, and Esko Kyrö

Finnish Meteorological Institute, Arctic Research Center, Sodankylä, Finland

Correspondence to: Tomi Karppinen (tomi.karppinen@fmi.fi)

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Abstract. Brewer total ozone column measurements started in Sodankylä in May 1988, 9 months after the signing of The Montreal Protocol. The Brewer instrument has been well maintained and frequently calibrated since then to produce a high-quality ozone time series now spanning more than 25 years. The data have now been uniformly reprocessed between 1988 and 2014. The quality of the data has been assured by automatic data rejection rules as well as by manual checking. Daily mean values calculated from the highest-quality direct sun measurements are available 77 % of time with up to 75 measurements per day on clear days. Zenith sky measurements fill another 14 % of the time series and winter months are sparsely covered by moon measurements. The time series provides information to survey the evolution of Arctic ozone layer and can be used as a reference point for assessing other total ozone column measurement practices.

1 Introduction

Ozone is a molecule consisting of three oxygen atoms (O_3). It is produced from oxygen molecules by photochemistry in the equatorial stratosphere, where the UV radiation is at its strongest. It is then transported to higher latitudes by the atmospheric circulation (e.g., Müller, 2012). Ozone is a strong absorber of ultraviolet (UV) radiation and thus an important constituent of the atmosphere enabling life on earth as we know it. Excessive exposure to UV radiation is known to have harmful biological effects. It is known to cause diseases of the eyes and skin, for example (Lucas et al., 2006), as well as having a negative influence on vegetation (Teramura and Ziska, 1996).

In 1984, it was found that the total ozone above Antarctica diminishes during Antarctic spring (Farman et al., 1985) and the discovery was later confirmed by analyzing satellite data (Bhartia et al., 1985). This showed in reality what a significant effect chlorofluorocarbons (CFC) had on the total amount of ozone – in theory, this concept had been suggested already by Molina and Rowland (1974). These findings caused a reaction in decision makers and led to The Vienna Convention for the Protection of the Ozone Layer in 1985, and to The Montreal Protocol in 1987, both aiming to decrease the amount of CFCs used widely as refrigerants and blowing agents at that time. The evolution of the global distribution of total ozone has been under close scrutiny since and the state of the ozone layer is revised regularly (WMO, 1985, 1988, 1989, 1991, 1995, 1998, 2003, 2007, 2011, 2014).

In the wake of The Montreal Protocol, ozone measurements were introduced at the Finnish Meteorological Institute Arctic Research Center (FMI-ARC) in Sodankylä comprising both the Brewer measurements and the regular ozone soundings starting in 1988. Even though the ozone depletion is more pronounced and regular in the Antarctic, the Arctic has witnessed some really low total ozone amounts in the cold winters and springs of 1990s and 2000s (Rex et al., 1997, 2002; Manney et al., 2011). The location of FMI-ARC (67.368° N, 26.633° E) is well suited for Arctic ozone studies as it often lies within or on the edge of the polar vortex during the time of ozone depletion in the spring.

Sodankylä is one of only seven Brewer stations north of the Arctic Circle (Kipp & Zonen, 2015). As the Arctic ozone is highly variable, these few measurement sites are extremely valuable for monitoring the evolution of the ozone layer. Also, the measurement techniques face challenges at high

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latitudes where the solar elevation angle is very low for long periods. The FMI-ARC has been active in evaluating the effect of low solar elevation angles on Brewer measurements. These studies are important because Brewer no. 037 has been serving as a reference instrument for satellite validation as well as validation for other ground-based measurement methods.

As a permanently staffed station north of the Arctic Circle, FMI-ARC is a rarity, and can produce data of high quality and with infrequent data gaps. In this paper the uniformly processed Brewer data set from 1988 to 2014 is presented. In Sect. 2 the instrument itself is described and the measurement procedure is explained. The means of maintaining the quality and continuity of the measurements are presented. In Sect. 3 the data flow is briefly described and the data processing algorithm is presented along with the rules applied to disregard inaccurate or erroneous data. In Sect. 4 the data set obtained is demonstrated and some features are highlighted. Some useful diagnostics and statistics of the availability of the data are presented.

2 Instrument operation

2.1 Instruments

The total ozone column over Sodankylä has been measured with Brewer spectrophotometer, serial number 037, since May 1988. In September 2012, a new Brewer, serial number 214, was acquired but is still in the comparison phase rather than in operational use.

The Brewer instrument stands on a tripod which can be leveled by adjusting the height of all three legs separately. On top of the tripod sits a tracker which maintains the azimuthal orientation of the entrance optics towards the Sun. Accurate tracking of the Sun requires the rotational axis of the tracker to be exactly vertical. The spectrometer itself is mounted on top of the tracker.

The light source is selected with a rotating prism inside the spectrometer. The input can be global radiation through the diffuser on top of the instrument, direct radiation from a point source, or radiation from either of two internal calibration lamps. Field of view for the direct radiation measurement is approximately 2–2.7° (Kazadzis et al., 2005).

The input light is dispersed in a monochromator, consisting of a spherical mirror and a grating. The grating can be rotated by a motorized micrometer to select the measured wavelength. In the more recent Brewer, serial number 214, there is a double monochromator with two sets of mirrors and gratings working synchronously. The double monochromator has significantly less light coming from outside the desired wavelength band.

In place of a single exit slit, there is a slit mask with eight different slit positions. The mask can be rotated fast to go through a set of predefined wavelengths without moving the grating. One of the positions has the exit slit completely shut for determining the dark current of the photomultiplier and one position allows light from two slits to enter the photomultiplier for characterization purposes. The wavelength resolution for the Brewers is roughly 0.6 nm (full width at half maximum of the instrument function), depending slightly on the individual instrument. The wavelength range is 290–325 nm for Brewer no. 037 and 286.5–365 nm for Brewer no. 214.

The photons are counted by a photomultiplier and the counts are recorded. To accommodate large variations in the intensity throughout the day, there is a filter wheel equipped with a set of neutral density filters. The attenuation needed is determined on an initial intensity check. Another filter wheel is deployed to choose a diffuser, a polarizer, or a clear opening depending on the measurement mode.

2.2 Measurement procedure

There are four measurement procedures to measure ozone with a Brewer instrument, each suited to different conditions. The direct sun (ds) measurement is suited to clear sky conditions with a solar elevation angle higher than 15°. Focused sun (fz) measurements are used for direct sunlight when the elevation angle is below 15°. Zenith sky (zs) measurements are used when the direct sunlight is blocked due to cloudy weather. During the polar winter when the sun elevation stays low for a long period, focused moon (fm) measurements are possible when the phase is close to full moon.

In the direct sun measurement, the azimuth tracker rotates towards the Sun and the zenith prism turns so that the direct light from the Sun is guided towards the entrance slit. A diffuser is used to smooth the input light to reduce the effect of slight misalignments. A further attenuation filter might be selected depending on the intensity in a pretest. The grating is kept stationary at a predefined ozone measurement position and the slit mask is rotated to rapidly to select the output wavelengths. The wavelengths are roughly 306.3, 310.1, 313.5, 316.8, and 320.1 nm. The wavelengths are more accurately defined for each individual instrument in the yearly or biennial calibration.

For low solar elevation angles, the procedure called focused sun is performed. To enhance the input light intensity, the diffuser is omitted but a neutral density filter may be applied to control the maximum counting rate. The forward scattered sky light entering the photomultiplier is estimated by measuring the intensity just beside the Sun, and subtracted from the intensities measured from the direct sunlight.

When the direct sunlight is blocked by clouds, the total ozone column is estimated by measuring scattered light from the zenith. The prism is directed at the zenith angle of 0° and the same wavelengths are measured as in the direct sun measurements. No diffuser is applied but neutral density filters are applied when needed. To be less affected by the clouds, light goes through a film polarizer that is fixed in the direction that rejects primary scattered light from the zenith (Brewer and Kerr, 1973; Muthama et al., 1995).

For high latitudes, there is a time when the Sun does not rise high enough for any of the measurement procedures mentioned above. For that time of the year, the only possibility is to measure using light from the moon. The routine is called focused moon (fm). There is no diffuser used. The intensities are rather low and usually no neutral density filter is needed.

The instrument operation is fully automated. The commands can be given manually but normally the instrument operates on a schedule written by the operator. The schedule consists of command strings set to start when a certain solar zenith angle is reached. In addition to the ozone measurement modes mentioned above, there are several commands to check the status of the motors and follow the changes of instrument characteristics as well as measurement mode for measuring global UV radiation.

2.3 Calibration

The instruments need to be calibrated regularly to keep track of possible changes in their characteristics and the effect of these changes on the ozone measurements. Calibration can be done at the instrument's home institute against a well-calibrated reference instrument or the instrument can be moved to take part in a calibration campaign where the instrument can be calibrated against a reference instrument or by using a Langley extrapolation method. The calibration history of the Brewer no. 037 is presented in Table 1. The main characteristics to be redefined are the extraterrestrial constant (ETC), the ratio of measurements from the internal calibration lamp at ozone measurement wavelengths, the wavelength setting for ozone measurements, the instrument function, and the differential absorption coefficient (α).

The ETC tells what the instrument would measure if there was no ozone between the instrument and the Sun. It is dependent on the spectral response of the instrument and the change in ETC is monitored by measuring the intensities at the same wavelengths from an internal calibration lamp. In the calibration campaign, the ETC and lamp reference value ($R6_{\mathrm{sl,ref}}$) are determined. If these values behave the same as in the last calibration, any change in the lamp intensity ratios is considered as a change in the instrument response and not a change in the lamp, and thus the time series between calibrations must be corrected for ETC changes as indicated by the changes in the lamp value.

The optimal grating position for ozone measurements is searched by measuring ozone with several positions close to the expected one. The wavelength scale for the micrometer positions is determined by measuring a set of known emission lines from different discharge lamps, for example mercury and cadmium lamps. From these lamp measurements the instrument function is also retrieved. The differential absorption coefficient is calculated for the exact operational wavelengths as a convolution between the instrument function and the ozone absorption cross section.

Table 1. Brewer no. 037 calibration history (partly adopted from IOS, 2015).

Year	Month	Location
1988	April	Sodankylä
1989	June	Sodankylä
1990	June	Sodankylä
1993	November	Izaña
1994	September	Jokioinen
1995	June	Sodankylä
1996	October	Izaña
1997	July	Sodankylä
1998	June	Jokioinen
1999	June	Jokioinen
2000	June	Tylosand
2001	June	Jokioinen
2002	June	Sodankylä
2003	June	Sodankylä
2004	June	Jokioinen
2005	June	Sodankylä
2006	June	Jokioinen
2007	May	Sodankylä
2008	June	Jokioinen
2009	June	Sodankylä
2009	December	Izaña
2011	November	Izaña
2013	November	Izaña

In addition to these annual or biennial checks, the dead time of the photomultiplier is constantly monitored. The temperature dependence has been characterized already at the factory by the manufacturer. The neutral density filter wavelength dependence has also been measured more frequently lately but no corrections have been applied this far.

Quality control

Quality control includes procedures to ensure the instrument is measuring in the ideal manner, the measurements are not stopped or obstructed, and all the changes in the instrument are recorded.

To ensure the view is not obstructed and the sunlight is transmitted ideally inside the instrument, the window is regularly manually cleaned using isopropyl alcohol. For the snow and rain, a blower has been installed that keeps the window clear except for the heaviest snowfalls. After heavy snowfall, a manual cleaning is required and the situation can be checked from a webcam installed to see the Brewer at all times.

Inside the instrument there are two calibration lamps, a mercury discharge lamp and a quartz–halogen lamp, called the standard lamp, with continuous spectrum. The emission lines of the mercury lamp are used for frequent checks of the wavelength selection for accurate measurements and for ensuring the correct behavior of the stepper motors moving the grating. In Sodankylä, the measurements are usually made before each spectral scan where the stepper motors make numerous small steps to scan a big wavelength range with 0.5 nm interval. This ensures the measurements are always made at the exact wavelengths that are expected.

The standard lamp is measured daily for the same wavelengths that are used in ozone measurements. This assures all the changes in the instrument response are recorded. Assuming the lamp does not change, the value measured from the lamp corresponds to a change in the solar measurements. In a calibration campaign, the lamp measurements are reviewed to check if the lamp measurement changes are due to a change in the lamp or due to a change in the instrument. Ozone measurements are corrected respectively.

Because the Brewer is also used for spectral UV measurements, the changes in the response are followed very carefully by measuring a 1000 W calibration lamp in a dark room every 6 weeks. After each calibration, before the instrument returns to the measurement site, the tracker is opened and the friction wheel rotating the tracker is cleaned to allow the maximum friction and to ensure there is no slipping and losing steps which would result in poor azimuthal pointing accuracy.

To ensure the maximum intensity and thus the maximum contrast in the measurements, the orientation of the tracker and the zenith prism need to be checked regularly. This procedure is called sighting. The instrument is oriented towards the Sun and the entrance slit is viewed from a view port on top of the instrument. If the instrument orientation is perfect, the picture of the Sun is centered around the entrance slit. If this is not the case, the azimuth tracker and zenith prism motors are commanded from buttons on the side of the instrument casing to turn the instrument to achieve perfect orientation.

For an accurate orientation check, a human eye is needed, but for a rough check, an automatic routine measurement has been developed. In this routine the intensity of the light through the entrance slit is measured in the original position and in positions a few motor steps away from the original one. The maximum intensity is regarded as the optimum orientation and changes are suggested if necessary by the operating software.

Since the beginning of 2015, a database system called IDEAS has been in use to enhance the continuity and quality of the data. The system parses the raw data files and updates in approximately 10 min intervals. Warnings are raised and sent by e-mail if there are signs in the data for misbehavior of the instrument, for example if the wavelength calibration is too much off of the reference value. This warning system ensures the erroneous behavior of the instrument is noticed as soon as possible and corrective action can be taken.

3 Data handling

3.1 Data flow and data storage

Data are collected by the operating computer controlling the Brewer. At this point the data consist of raw counts and preliminary data reduction including not only the measurements of ozone but also the wavelength calibration and stability check information. These data are retrieved to a local server once every 5 min. Another server hosting a database system IDEAS, collects the data from the primary local server every 5 min.

The processing of the final products that are sent to the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) and to the FMI-ARC database http://litdb.fmi.fi still require human interaction. The data are collected from the primary local server to a personal computer and processed with software described in Sect. 3.2. There are rules to assure the quality of the data (Sect. 3.3) but some erroneous measurements must still be filtered out by the human eye. At the moment, the data are available in the WOUDC database until May 2010 and the update for Sodankylä data will be made when the quality assurance is finished.

Finland is participating in Eubrewnet COST action (COST-ES1207, http://www.eubrewnet.org) and the Brewer data are sent from the primary local server to the Eubrewnet database every 20 min. The database is under development and not fully operational at this moment. When operational, the database will receive Brewer raw data from all the participating countries and the final products will be processed by a central computer. This way the data will be consistent through the whole network.

3.2 Algorithm

For all ozone measurement procedures, the raw data include total counts from the photomultiplier for seven positions of the slit mask, F0–F6. To retrieve vertical ozone columns, O3Brewer software written in Delphi language by Martin Stanek is used (Stanek, 2015). The retrieval process is described below.

Before the physical modeling of the absorption itself, the raw counts are first turned into photon count rates C (photons per second) (SCI-TEC Instruments Inc., 1999). First, the dark counts are removed and the integration time for each slit exposure is taken into account in term 2/IT, and CY is the number of slit exposure cycles. Dark counts F_1 are measured at slit mask position 1, where the exit slit is closed. The photon count rate C_i for slit mask position i becomes

$$C_i = \frac{2 \times (F_i - F_1)}{\mathrm{IT} \times \mathrm{CY}}, \text{ for position } i = 2 \ldots 6. \tag{1}$$

The photomultiplier has a dead time (DT), a time it takes it to recover from a hit by a photon to be able to count another photon. The effect is assumed to follow the Poisson statistics and hence the equation

$$C_{i,\mathrm{m}} = C_{i,\mathrm{t}} \times e^{-C_{i,\mathrm{t}} \times \mathrm{DT}}, \tag{2}$$

where $C_{i,\mathrm{m}}$ is the measured photon count rate and $C_{i,\mathrm{t}}$ is the true photon count rate. The first estimate for the true photon count rate is given by

$$C_{i,\mathrm{t},1} = C_{i,\mathrm{m}} \times e^{C_{i,\mathrm{m}} \times \mathrm{DT}}. \tag{3}$$

After this, a better estimate is calculated by plugging the first estimate in the original equation

$$C_{i,\mathrm{t},2} = C_{i,\mathrm{m}} \times e^{C_{i,\mathrm{t},1} \times \mathrm{DT}}. \tag{4}$$

This is repeated eight times and the result is expected to converge until then, making $C_{i,\mathrm{t},9}$ the final estimate for $C_{i,\mathrm{t}}$.

Later will be shown that, when calculating ozone, we are dealing with logarithms of irradiance ratios. For this reason the photon count rates are converted to logarithmic scale, $C_{i,\mathrm{l}}$

$$C_{i,\mathrm{l}} = 10^4 \times \log_{10}\left(C_{i,\mathrm{t}}\right). \tag{5}$$

The response of the instrument may change according to the change in temperature inside the instrument. The effect is assumed linear and has been characterized at the factory. Corrected photon count rate $C_{i,\mathrm{tc}}$ will be

$$C_{i,\mathrm{tc}} = C_{i,\mathrm{l}} + (\mathrm{TC}_i) \times T, \tag{6}$$

where T is temperature and TC_i is the wavelength-dependent temperature correction coefficient.

The final instrumental correction will be neutral density correction. This actually does not affect the ozone calculation as the attenuation is assumed to be wavelength independent. The effect of filter non-neutrality has been found very small in recent calibrations. The final photon count rate $C_{i,\mathrm{f}}$ will be

$$C_{i,\mathrm{f}} = C_{i,\mathrm{tc}} + NF, \tag{7}$$

where NF is the 10 000 times the 10-based logarithm of attenuation ratio of the filter.

The physical model of retrieval from final photon count rates to total ozone column, well described by Savastiouk (2006), is based on the Beer–Lambert law considering Rayleigh scattering and scattering by aerosols, as well as absorption by sulfur dioxide and ozone. The data from slit mask position 0 are not taken into account so using the other five (positions 2–6) wavelengths, a set of wavelength-dependent weighting coefficients are found such that the ozone calculus is, in theory, not affected by sulfur dioxide or aerosols. For ozone, the coefficients are such that only four wavelengths (positions 3–5) are needed. The final photon count rates are corrected for Rayleigh scattering according to equation

$$C_i = C_{i,\mathrm{f}} + \frac{BE_i \times \mu_r \times P}{1013}, \tag{8}$$

where BE_i is Rayleigh correction coefficient for slit mask position i. The BE_i used are the original ones calculated by the instrument designer based on Bates (1984). P is the pressure of the instrument location, set to 1000 mbar for Sodankylä. μ_r is the air mass factor for Rayleigh scattering, calculated from

$$\mu_r = \sec\{\arcsin[(6370/6375) \times \sin(A)]\}, \tag{9}$$

where A is the solar zenith angle at the time of the measurement. The double ratio $R6$ affected only by ozone is calculated from Rayleigh corrected photon count rates C_i as

$$R6 = -C3 + 0.5 \times C4 + 2.2 \times C5 - 1.7 \times C6. \tag{10}$$

Total ozone column $X_{\mathrm{O_3}}$, is retrieved from the ratio as

$$X_{\mathrm{O_3}} = (R6 - \mathrm{ETC} + \mathrm{SL}) / \left(\mu_{\mathrm{O_3}} \times \alpha\right), \tag{11}$$

where extraterrestrial constant ETC and differential absorption coefficient α are constants determined in calibration. SL is the change in $R6$ value measured from a calibration lamp. For this, a reference value $R6_{\mathrm{sl,ref}}$ is determined during calibration campaign and the changes are followed by measuring this ratio $R6_{\mathrm{sl}}$ several times per day. The lamp is assumed not to change and so the changes should reflect changes in the ETC. The assumption is then checked at the next calibration when also the new reference value is determined. The correction factor SL is based on daily mean value $\overline{R6_{\mathrm{sl}}}$ as

$$\mathrm{SL} = R6_{\mathrm{sl,ref}} - \overline{R6_{\mathrm{sl}}}. \tag{12}$$

Ozone air mass factor $\mu_{\mathrm{O_3}}$, describes the path length that the light has to travel compared to a thickness of the ozone layer right above us. For the calculation, ozone is considered to lie in a thin layer at the altitude of 22 km. This makes the air mass factor

$$\mu_{\mathrm{O_3}} = \sec\{\arcsin[(6370/6392) \times \sin(A)]\}, \tag{13}$$

where A is the solar zenith angle.

For the focused sun measurements fz, the algorithm is identical to that of the direct sun. Before calculating the R6 however, the photon count rate measured 0.5° off of the Sun is deducted from the photon count rate measured from the direct sun. This is made to counter the effect of multiply scattered light reaching the instrument from the same direction than the direct light (Josefsson, 1992).

For the moon measurements, the algorithm is identical to the direct sun algorithm. However, the accuracy and consistency of these measurements are much lower than for the direct sun measurements as the intensities are much lower and the tracking has been found to be more difficult than in the case of solar tracking. Also moon albedo could introduce a systematic error to the measurements. Lucke et al. (1976) reviewed some results on moon albedo showing either no wavelength dependency (Lebedinsky et al., 1967) or a linear dependency for the wavelength range used in the Brewer

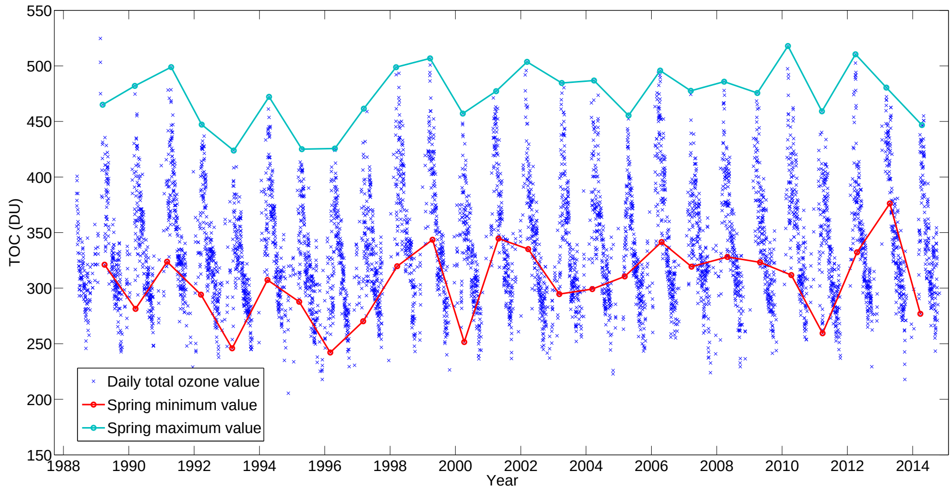

Figure 1. Total ozone column daily average time series with spring time extreme values highlighted for each year. For the spring, minima and maxima measurements from March and April are considered.

ozone retrieval. As the weighting coefficients in the algorithm have been chosen to disregard any absorption effects that are linear with wavelength, there should not be a remarkable difference between focused moon and direct sun measurements. After comparing solar and lunar measurements, Kerr (1989) concluded that the ETC and the differential absorption coefficient α are the same for both measurement types.

The processing of the zenith sky measurements is based on the comparison of zenith sky (zs) and direct sun measurements (ds) (Muthama et al., 1995). A polynomial will be fitted between a number of near-simultaneous zs and ds measurements so that using the X_{O_3} from ds measurements a best-possible set of coefficients a to i are found for relation

$$R6_{zs} - \mathrm{ETC} = a + b \times \mu + c \times \mu^2 + d \times X + e \times X\mu + f \times X\mu^2 + g \times X^2 + h \times X^2\mu + i \times X^2\mu^2. \quad (14)$$

These coefficients depend on the instrument and on the measurement location. For Brewer no. 037 the fitting of the coefficients, the so-called sky chart, has been done by Karhu (1995).

The daily value is calculated as an average of measurements that meet the filtering criteria (see Sect. 3.3). Only one type of measurement is used for one daily value. The measurement types are ranked by their expected quality so that the order is ds, fz, zs, fm. The measurements of lower rank are only used if there are no measurements at the higher level. The ranking is justified by the assumptions that focused sun and moon measurements are more prone to errors due to small deviations in pointing accuracy and zs is more prone to errors due to retrieval algorithm based on a non-physical model.

3.3 Quality assurance

To assure the quality of the data, some automatic data filtering rules have been obeyed. The measurement routine for one ozone value has five consecutive measurements. The standard deviation among these five measurements is not allowed to be more than 3 DU (Dobson units) in ds, zs, or fz measurements. For moon measurements the deviation is allowed to be 5 DU. The air mass factor has been limited to 3.8 for ds and to 3.0 for zs measurements to avoid the effects of stray light but to allow measurements to start as early as possible in the spring. For focused sun measurements, the air mass limit is set to 6 and for moon measurements to 3.5. Before submitting the data to the database, it is also inspected visually for obvious spikes or other suspicious behavior. The random errors of individual observations are within ±1 % in about 90 % of all measurements (Fioletov et al., 2005).

4 Demonstration of the data set

The daily values of total ozone column over Sodankylä are presented as a time series in Fig. 1. The yearly highest and lowest total ozone values of March and April are highlighted. Contrary to Antarctica the minimum values do not coincide with yearly minimum as the annual minima of ozone in the Arctic do not occur in spring but later in autumn because of strong modulation of ozone layer thickness by the Brewer–Dobson circulation. Ozone is build up at high latitudes during the wintertime, and even after the ozone loss inside the polar vortex, the total amount of ozone will be high after the vortex is broken up and the ozone-rich air is transported to polar areas. During the summer, the circulation of ozone-rich air from the equatorial region is weaker and the ozone is destructed by natural photochemistry as the solar elevation is

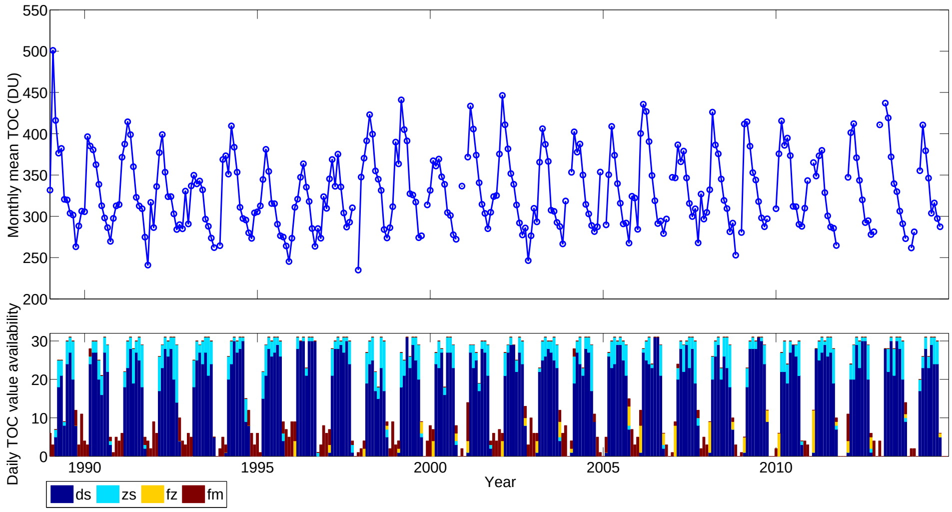

Figure 2. Upper panel shows the monthly mean ozone calculated from daily values. The amount of daily values available for each month is shown in the lower panel. Different measurement styles have been color coded to show which type of measurements have been used for monthly mean value.

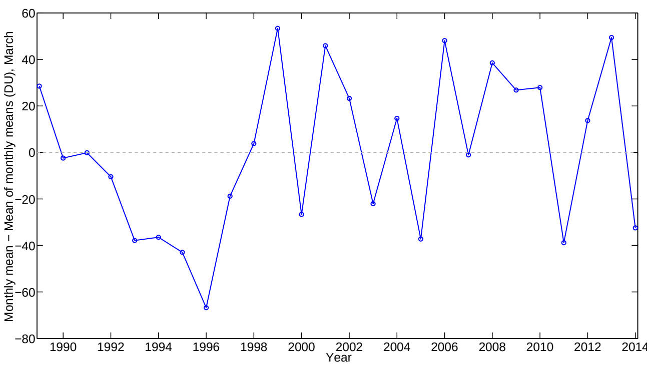

Figure 3. The difference of March monthly mean each year to the all-time March mean.

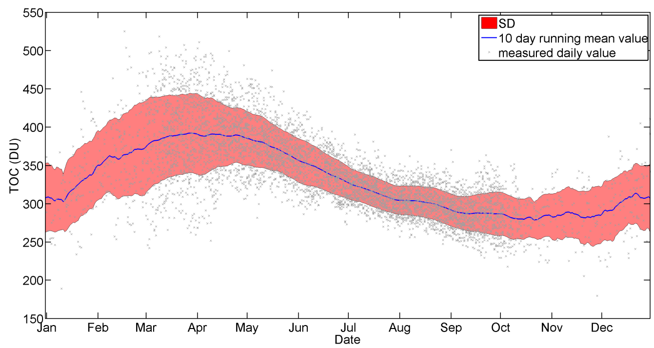

Figure 4. Ten days' running average of daily values 1988–2014 for each day of the year.

higher. As a result, the ozone reaches its minimum during late autumn before a new buildup begins. However, the spring minimum is still the best indicator for the extent of chemical destruction of the ozone layer. The high values of February 1989 stand out from the time series but the data from the same date from TOMS instrument aboard the Nimbus-7 satellite confirm the total amount of ozone was very high.

Monthly mean values have been presented in Fig. 2. In the figure, the number of daily values available for a particular monthly value is also presented. Overall, from all daily values, 77 % are based on ds measurements and 14 % on zs measurements. Winter months are sporadically covered by focused moon measurements. While no significant trend is observed in the monthly mean values, the March monthly mean plot (Fig. 3) suggests that in the beginning of the 1990s there was a period of strong spring ozone depletion and after 1997 there has been huge variability between cold and warm winters. The monthly mean of March is affected by the intensity of the chemical depletion and the persistence of the polar vortex and thus gives a bit more insight on the extent of the depletion than just the minimum total ozone column measured.

More in-depth trend and regression analysis is a matter for further study and some earlier work has been done. Kivi et al. (1999) analyzed Brewer total ozone time series. They found a trend of (-1.0 ± 0.1) % per year corresponding to the time period 1989–1997. At Sodankylä, vertically resolved ozone soundings have been performed since the late 1980s. Based on the ozonesonde data, Kivi et al. (2007) found that negative trends prior to 1997 can be attributed to a combined effect of dynamical changes, winters of relatively large chemical ozone depletion, and the impact of aerosols from Mt. Pinatubo eruption in 1991. The regression model used by Kivi et al. (2007) included a number of proxies account-

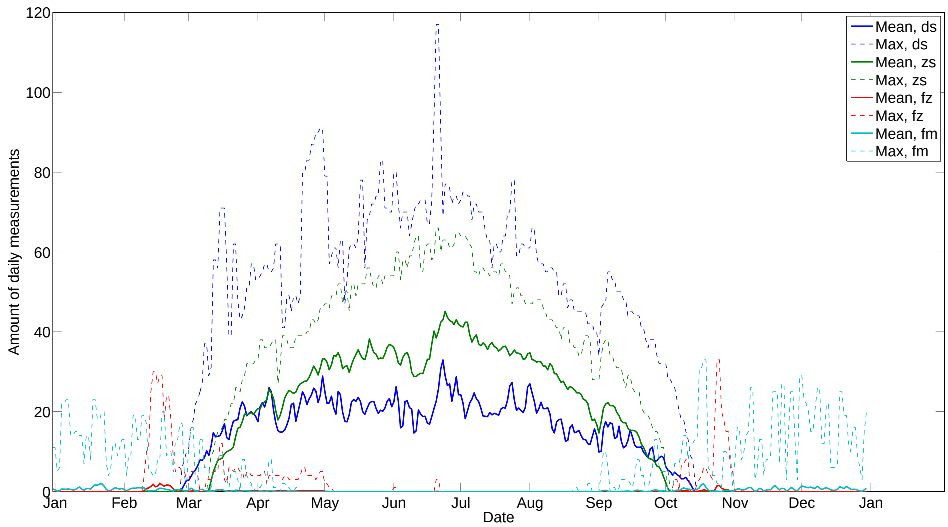

Figure 5. The seasonal variability of the amount of measurements. Solid lines represent the mean amount of measurements of each type for each day of the year. The maximum amount for any year for this certain day of year has been plotted in dashed lines in the color representing the measurement type.

ing for the dynamical and chemical variability. They found that total ozone amounts in the stratosphere correlate highly with proxies for the stratospheric circulation, polar ozone depletion, and tropopause height.

The daily ozone climatology is depicted in Fig. 4. The main features are the accumulation of ozone during the winter and early spring and the decline during the summer owing to the atmospheric circulation patterns and their seasonal changes (Weatherhead et al., 2005). The variability is very large in spring as the location, timing, and persistence of the polar vortex hugely affect the transportation and chemical loss of ozone. The uncertainties are larger for the deep winter months as the only measurement mode available is the focused moon procedure.

Figure 5 shows mean and maximum daily amounts of different types of measurements and gives another view on measurement availability. From the dashed lines depicting maximum amounts it can be seen that direct sun measurements are more frequent than zenith sky measurements when the sky is clear. However, because of clouds the mean amounts of zenith sky measurements are a bit higher during the summer. The peak in the maximum amounts at midsummer is from the calibration campaign in 2003. During the calibration, direct sun measurements are prioritized and UV scans are omitted. This permits over 100 direct sun measurements to be made during 1 day. Normally, a clear day with regular UV scans can have up to 75 direct sun measurements. Even though the clouds seem to obstruct on average one third of the possible ds measurements, a high portion of the daily values is based on them as there usually is a possibility during the day to get some successful direct sun measurements. The availability of ds and zs measurements in the spring and in the fall are affected by the air mass factor limits of 3.8 and 3.0, respectively. The focused sun and moon measurements are, on average, very rare but some days can give up to 20 good-quality measurements during the time when direct sun or zenith sky measurements are impossible or too unreliable.

In Fig. 6 is the comparison of Brewer no. 037 and the Ozone Monitoring Instrument (OMI) on board the NASA EOS-AURA satellite between the years 2004 and 2014, showing a systematic difference of about 1.9 %. Sodankylä Brewer data have been used in several satellite comparisons (e.g., Kyrö, 1993; Balis et al., 2007; Damiani et al., 2012) and in comparison to other ground-based instruments (e.g., Vigouroux et al., 2008). Sodankylä also hosted two total ozone column intercomparison campaigns in the springs of 2006 and 2007, aiming to characterize and tackle the measurement challenges caused by low solar elevation angles (McPeters et al., 2006). A follow-up CEOS Intercal Nordic campaign was arranged consisting of measurement periods at Sodankylä, for low solar elevation measurements, and at Izaña for high solar elevation measurements and laboratory characterization (Karppinen et al., 2015).

5 Conclusions

There is a data set of 26 years of uniformly processed Brewer ozone data from Sodankylä and the processing algorithm with the data acceptance rules have been described in this paper. The instrument has been well maintained and regularly calibrated during its time of operation. An automatic warning system has been built to allow fast response to any unexpected stops in the measurements and to follow that the instrument is operating in an ideal way. The quality-assured

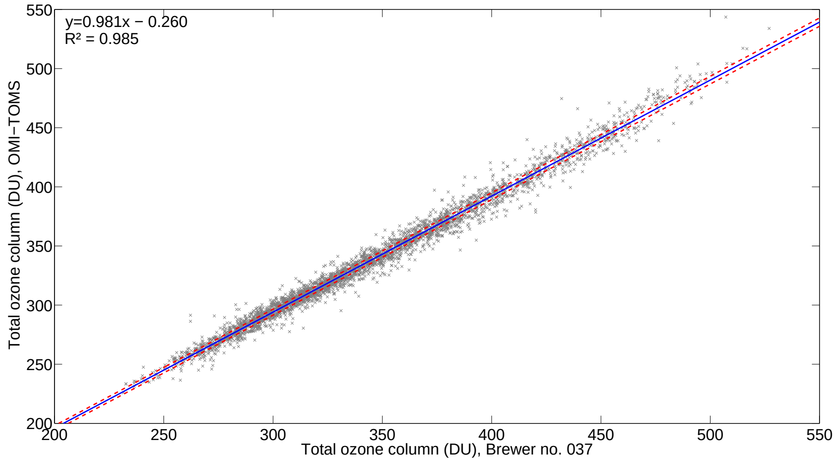

Figure 6. Comparison of Brewer no. 037 direct sun measurements and OMI satellite data using TOMS retrieval algorithm. The Brewer reference value was the closest direct sun measurement with a maximum limit of 1 h difference in the measurement times.

data will be available in WOUDC database as well as in http://www.litdb.fmi.fi. Data are also sent to the Eubrewnet database where the Brewer community will set up best possible data processing algorithm to achieve coherent total ozone data across the Eubrewnet network. Sodankylä data are valuable for Arctic ozone studies and for validating other ozone measurements at high latitudes.

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