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Re-evaluation of the 1950–1962 total ozone record from Longyearbyen, Svalbard

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Abstract

The historical total ozone measurements taken with Dobson Spectrophotometer #8 at Longyearbyen, Svalbard, Norway, in the period 1950–1962 have been re-analyzed and homogenized based on the original measurement logs, using updated relevant parameters. In lack of sufficient calibration information, an empirical quality assessment was performed, based on a climatological comparison with ozone measurements in Tromsø, using TOMS data at both sites in the period 1979–2001, and Dobson data in the period 1950–1962. The assessment revealed that, as in the case of the Tromsø measurements, the C wavelength pair direct-sun measurements are most trustworthy (and most frequent), while the WMO standard reference mode AD direct-sun has a systematic bias relative to this data set. Zenith-blue (ZB) measurements at solar zenith angles (SZA) <80° were homogenized using two different polynomials before and from 1957; also ZB measurements at larger SZAs were homogenized by means of a normalization function derived from days with measurements over a wide range of SZAs. CC′ zenith-cloudy measurements, which are particularly frequent during the summer months, were homogenized by applying correction factors for only two different cloud types: high thin clouds and medium/low/thick clouds; a further diversification of corrections reflecting cloud conditions did not prove significant. The combination of all measurements yields a total of 4837 single values, covering 1676 days from September 1950 to September 1962; moon measurements during the polar night add another 137 daily means. The re-evaluated data show a convincing agreement with measurements since 1979 (TOMS, SAOZ, Dobson) as well as with the 1957–1962 data stored at the World Ozone and UV Data Centre (WOUDC).

1 Introduction

Two decades after the discovery of the Antarctic ozone hole (Farman et al., 1985) and global ozone layer reduction, the chemical and dynamical processes causing ozone

depletion are, to a large degree, understood and reproduced in chemical transport models (e.g., Chipperfield et al., 2005). An important tool to validate such models is to apply them to long time series of ozone and related stratospheric parameters, both in the "CFC" age and prior to it. This is also of great importance in order to make reliable predictions about the expected recovery of the ozone layer in the decades to come. For these reasons, much emphasis has been put into the re-evaluation of historical ozone data series during the last 10 years (Staehelin et al., 1998; Vanicek et al., 2003; Svendby, 2003; Hansen and Svenøe, 2005). At the same time, efforts have been taken to extend meteorological data records back in time, which can be used in order to investigate the natural variability of the ozone layer in pre-CFC periods (Brönnimann, 2003; Brönnimann et al., 2004). There exist, however, only few data series suitable for these purposes, especially at high latitudes, where the largest natural and human-induced ozone variations are observed.

The measurements presented here started in Longyearbyen, Spitzbergen (the biggest island of the Svalbard archipelago, see Fig. 1) in September 1950, after Dobson Spectrophotometer #8, which until then had been used for ozone measurements at the Norwegian sites Dombås and Oslo (Svendby, 2003), had undergone a major technical upgrade at Oxford. With several interruptions, the instrument has been in use until today, but the earliest data have never been digitised. The purpose of this work was to re-evaluate the Svalbard total ozone data from 1950 to 1962 and merge the new dataset with the data already stored in the World Ozone and UV Data Center (WOUDC), from the period 1957–1968. This data series is the only one from poleward of 70° before the International Geophysical Year (IGY) 1957/58. It, thus, can provide valuable information about the state of the Arctic ozone layer (natural variability, trends) before anthropogenic influences, e.g., CFC emissions, became noticeable. Combined with the recently re-evaluated ozone series from Tromsø, and the world's longest ozone series from Arosa, Switzerland, it also yields a unique latitudinal chain of ozone measurements over almost two decades.

In Sect. 2 of this paper, the measurement principle is outlined. More details about

the instrument history are given in Sect. 3, while the re-evaluation of the different measurement modes is discussed in the subsequent sections. The final data are shown in Sect. 8, followed by an outlook to future work.

2 Measurement principle

Dobson spectrophotometers were the first standardised ozone monitoring instruments; the manufacturing started in the 1920s. In the 1940s and early 1950s, the instruments were re-constructed to allow measurements with additional wavelength combinations; moreover, they were equipped with photo-multipliers. For details about the early history of Dobson measurements see Dobson (1968). Although more modern methods, e.g., the Brewer technique and satellite measurements, are available today, Dobson AD direct-sun measurements are still WMO's total ozone reference measurement mode, and Dobson measurements were, until recently, the only technique which gave satisfactory results under cloudy conditions.

The measurement principle is to determine the intensity ratio of light at two wavelengths (wavelength pair) in the Huggins band of ozone absorption, one of which is strongly absorbed by ozone, the other less so. Different wavelength pairs were in use, denoted A, B, C, and D. C was the standard pair prior to the IGY 1957/58; since then the use of a dual wavelength pair (AD) was recommended in order to reduce interference with aerosol scattering. For the case of Svalbard, however, the aerosol interference is expected to be only of minor importance, except during episodes with severe volcanic aerosol loading.

The light source can be direct sunlight (DS), light from the blue zenith (ZB), from the cloudy zenith (ZC), or moonlight. For the calculation of ozone values based on measurements using direct sunlight (DS) one needs the N value (a function of the intensity ratio of the two wavelengths), the airmass (geometrical path length of the light through the atmosphere), the path length through the ozone layer, and the ozone absorption coefficients for the respective wavelengths. The N value is obtained by conversion from

the dial reading (R value), which is the value read on the instrument. The conversion table is established and maintained by regular calibration measurements with artificial light sources.

From measurements made at the zenith (ZB or ZC), ozone cannot directly be calculated. Instead, empirical relations have to be found, based on simultaneous DS measurements. For ZC observations, an additional wavelength pair (denoted C′) is used. Both wavelengths of this pair are only weakly absorbed by ozone, so that their ratio contains information about the wavelength dependence of the attenuation by clouds. Also here, empirical methods have to be used to obtain ozone from these measurements.

Details about the instrument, the measurement techniques, the physical theory and the calculation of ozone values are given in, e.g., Dobson (1957), Komhyr et al. (1980), Komhyr (1993), Vanicek (2003) and Vanicek et al. (2003).

3 Instrument history and calculation of DS measurements

Ideally, detailed information about the instrument and the calibration history should be available for an accurate re-analysis. An example of this kind of good practice is found in Vanicek (2003) and Vanicek et al. (2003). In the original data sheets and documents of the 1950–1962 Svalbard data series there is not much information about the calibration of the instrument so that a related statement would be speculative. However, since the same instrument was used in Dombås and Oslo in the period 1940–1949 (Svendby, 2003), one can state that the original registration and calculation forms prove that the observers showed great care in their work. There are basically only two sources in the literature which can provide information about the instrument for the required period (Langlo, 1952; Larsen, 1959), one of which also served as source for Svendby (2003). In 1950, the Tromsø instrument (Dobson #14) was sent to Oxford for recalibration and technical upgrading with a photomultiplier; it was returned to Norway together with Dobson #8 later the same year. This coincidence provides strong evidence that

also #8 was re-calibrated and equipped with a photomultiplier before it was installed in Svalbard. During the first year, S. H. H. Larsen was the responsible observer, followed by H. Welde, the superintendent of the coal mines at Spitzbergen.

Based on this information about the operators, the information in Svendby (2003) and the well-known contacts with G. M. B. Dobson in Oxford, we assume that the instrument was in good condition and was regularly checked for its stability. It will be very challenging to recover additional information on the issue, after S. H. H. Larsen passed away in the late 1990s. The only calibration information in the original data are mercury lamp tests for 1 July 1958, 1 November 1958, and 20 April 1959. In this period the instrument appears to have been stable. However, the information from this short period does not allow to draw conclusions for the whole 13-year period of the re-analysis.

The original measuring protocols were available, containing date, time, dial reading (R value) and weather information, as well as sheets on which the ozone values were calculated. A noticeable part of the work was the digitisation of the data, before they were ready for re-evaluation. Unfortunately, we have no information about the original R–N conversion tables, either. Therefore, the conversion relation was derived by linear regression from the R and N values, which are available in the original calculation protocols. These results were then applied to those R values where no N value was available. In the course of this procedure it became clear that the conversion must have changed between 1956 and 1957. For this reason we decided to apply two different conversions for the time before and after 1956/57. Although this is a purely empirically motivated procedure, we regard it as the only reasonable way to handle the obvious change of instrument set-up.

At the time of the measurements the airmass was calculated with the help of tables. Today this can be done more easily by computer programmes. The solar zenith angle (SZA), which is the base of computing the airmass, was calculated by means of the LibRadtran scheme (Blanco-Muriel, 2001). For this tool, only the exact date and time of the measurement, together with longitude and latitude, are needed.

The ozone absorption coefficients used in 1950 differ significantly from the ones used today. These coefficients, defined as standard values by WMO, are taken from Komhyr (1993). In other total ozone re-analysis projects, e.g., Brönnimann et al. (2003), total ozone correction factors, based on the different absorption coefficients at different times, were used to transfer ozone values from original values to updated values.

The Svalbard original data from the 1950s and 1960s have never been published as a whole, but parts of it. At the World Ozone and UV Data Center (WOUDC) data base, data from 1957–1968 are stored, but compared to the original documents there are gaps, and a careful comparison revealed that the stored ozone data are sometimes based on less reliable measuring modes. Sub-sets of the data were published by Larsen (1959) and the data were also compiled by the International Ozone Commission (archived at the UK Met Office, see Normand, 1961).

In all of these subsets of published data, there are uncertainties about which measuring modes were used for the calculation of the values, and none of these publications yields the same amount of information as the original data set re-analysed here. In order to use all information available today, including additional information in the original measurements protocols and more recent information on reliability of measurement modes and updated cross sections, we re-calculated the ozone values starting from the R readings.

In agreement with other ozone measurement series we first established a basic data set in the standard direct-sun (DS) mode. For this data set, only measurements with an airmass of less than 6 (solar zenith angle $<\sim 81^{\circ}$) were accepted. In addition, we sorted out measurements, which showed obviously unrealistic values, and measurements, which already by the observer were flagged as unreliable. As a result of this selection process, we were left with 1337 single measurements from 609 days. The distribution of the days of the year covered is partially determined by illumination conditions, which are sufficient approximately from mid March until end of September, and, secondly, by weather conditions, since DS observations require clear sky. However, also observer availability and engagement seem to have played an important role for observation

statistics.

4 Quality assessment of the 1950–1962 Svalbard DS data by comparing with Tromsø data

Since there was no information available about the absolute calibration status of Dobson #8 in the time period investigated, the quality assessment of the Dobson total ozone record from Svalbard between 1950 and 1962 could only be made by an empirical quality check. For this purpose we assumed that the re-evaluated Tromsø series in the same time period could be used as a reference line. The distance between the sites is about 800 km, but Tromsø is the only available data series from high latitudes.

In order to establish a multi-annual (climatological) relation between the Tromsø and the Svalbard series, we first compared the datasets from the TOMS instruments (Version 7) on board the satellites Nimbus-7, Meteor-3 and Earth Probe at the two sites. These data are available since 1979, with missing information for 1995 and 1996, when no TOMS instrument was operational. For Tromsø, data are available on almost all days from early February to early November, while for Svalbard there are data only from early March until early October. Since we, in the historical dataset from Svalbard, have no direct-sun measurements before March and after September, we made the comparison only for the period March-September. We also chose to limit the data to the time period 1979 until 2001, since the newest TOMS data, according to information at the TOMS homepage (http://toms.gfsc.nasa.gov/news/news.html\#nov18), suffer from degradation of the instrument with a latitude-dependant signature. As the measurement statistics of TOMS is very good for both sites, we calculated monthly means, from which we calculated monthly mean ratios $x_i = \frac{\text{Svalbard}_i}{\text{Tromsø}_i}$, (where i denotes the month) and used these values as reference ratios. As to be expected from geophysical conditions, the values for the early months, like March and April, turned out to have a larger variation than the summer and autumn months. The monthly mean ratios of the period March–May are slightly larger than 1, while the ratios in the other months

are found to be between 0.94 and 1.00. The monthly ratios, averaged over the 23-year period are shown in Fig. 2 as a black curve (standard deviation: black dashed lines).

In a second step, similar ratios were derived for the (Dobson) data from 1950–1962. However, since the data coverage is much poorer in the case of the Svalbard measurements (in contrast to Tromsø, where the coverage was very high in this period), we decided to calculate the ratio between Tromsø and Svalbard data on a daily basis and then to calculate monthly averages of the daily ratios. Before calculating ratios, we also raised the question about which DS wavelengths should be taken as a standard and base of comparisons. In principle, this question is answered by the number of available data in the different modes as given in Table 1.

According to WMO, the measurements at the AD wavelength pairs are the standard to which the other types need to be adjusted. However, in the case of the Svalbard measurements (as well as in the re-evaluated Tromsø series), AD is not the first choice for a standard data set due to the scarcity of measurements in this mode; from this aspect, the C direct sun measurements should be used as reference dataset.

A second – and more important – reason to take C direct sun measurements instead of AD as the reference dataset, was given by the result of the Svalbard-Tromsø comparison as shown in Fig. 2. The annual variations of x_i in all modes are approximately the same as in the comparison based on TOMS data, except for September, when the statistics is much worse than in other months. However, both the AD_DS (yellow curve) and the CD_DS (blue curve) show a significant negative bias relative to the TOMS references ratios, about 4% in the case of the AD mode and 10% in the case of the CD measurement mode. The C-mode derived values, on the other hand, agree with the TOMS reference ratios to within ±1 standard deviation in all months except August.

One could, of course, "normalise" the AD and the CD measurements empirically to the C measurements. However, this procedure would introduce further uncertainties, because the correlation between the different types is not very compact. Moreover, they would not add any new information to the total dataset; both AD and, trivially, CD measurements are only made on days when there are also C measurements, which

are most reliable.

5 Zenith-blue (ZB) measurements

For zenith blue (ZB) observations, one uses scattered light, instead of direct sun light, from the zenith during clear sky conditions. The calculation of ozone values for this measurement type is different from the one for DS. It is not based on relationships that exactly describe physical processes, but it is calculated by establishing empirical relations between airmass (or solar zenith angle, SZA) and N-value (derived from dial reading) for ZB measurements and a reference ozone value from a quasi-simultaneous DS measurement (less than 15 min time offset).

To establish this empirical relation we used a 3rd degree polynomial, which already has proven to yield good results at other sites (Svenøe, 2000; Vanicek et al., 2003):

$$O_{3ZB} = a_0 + a_1 \cdot \mathrm{sza} + a_2 \cdot \mathrm{N} + a_3 \cdot \mathrm{sza}^2 + a_4 \cdot \mathrm{N}^2 + a_5 \cdot \mathrm{N.sza} + a_6 \cdot \mathrm{sza}^2 \cdot \mathrm{N} + a_7 \cdot \mathrm{sza.N}^2 + + a_8 \cdot \mathrm{sza}^3 + a_9 \cdot \mathrm{N}^3 \quad (1)$$

This regression model was calibrated using quasi-simultaneous DS measurements, if available. The relative deviations of the residuals $(O_{3,ZB}\text{-}O_{3,DS})\cdot 100/O_{3,DS}$ are shown in Fig. 3. The yellow lines denote the mean and ±2 standard deviations. As one can see, the results are mostly within ±5%.

In a first approach, one polynomial was used for the whole dataset. But similar to the establishment of the R-N conversion, there seems to have been a shift between 1956 and 1957. In the upper plot of Fig. 3 the blue asterisks denote the mean value for every year, using this approach. By using two different polynomial regressions (before and after 1957), a much better agreement with DS measurements can be achieved (red asterisks in Fig. 3).

The procedure was, in a second step, applied to all ZB measurements, also those without a quasi-simultaneous DS measurement, but only when solar zenith angles

were less than 80°. At higher SZA values, the derived ozone values seemed to converge to a constant value, which is not realistic. Obviously, the polynomial was not suited for extrapolation.

Due to the geographical location of the site, there are, however, a lot of ZB measurements with SZA values between 80° and 96°. These measurements were mostly made during the early (late February, March) or late season (September–October), when there are no DS measurements. A utilisation of these measurements, if properly corrected, would add significantly to the data set as a whole. For this purpose we applied a method, which already was used by Svenøe (2000). The basic idea is to establish a relation between a reference DS value and ZB measurements at all SZA values up to 90 degrees on the same day. The pre-assumption is that the ozone value is constant throughout the day, which is a very crude, but acceptable approach in lack of more detailed information. When comparing all ZB measurements (with varying SZA values) of the respective day with the reference DS value, one finds that this ratio for SZA >80° is strongly dependent on SZA, as shown in Fig. 4 (black dots). The resulting ratio curve is then used to normalise the "high-SZA" measurements also in periods when no reference measurements with SZA <80° exist. This procedure implies another pre-assumption, namely that the normalisation function is not dependent on other factors, e.g. total ozone and ozone vertical distribution.

Most ZB measurements with high SZAs in Fig. 4 were made in 1950 and 1951. The occasional data from other years do not appear in the figure, because in these periods there were no DS reference measurements. To utilise these data we had to assume that the relationship for 1950 and 1951 is also valid for the other years. The correction function was limited to SZA<90°, as the data scatter too much at larger SZAs due to worsening illumination conditions. We developed the polynomial regression for 77°<SZA<90° and applied it for 78°<SZA<90°. The blue dots in Fig. 4 indicate the result of this correction.

By extending the upper limit for SZA to 90°, but at the same time eliminating obviously erroneous outliers, 1482 single ozone values could be derived, from which 717 daily

means were calculated. Thus, by including ZB, more than 100 daily values were added, compared to the 609 values available from the DS mode. These days are mostly found in the early or late months of the year when DS measurements are not possible.

6 Zenith-cloudy measurements

Under cloudy conditions the zenith-cloudy measurement mode (ZC) is applied. For this purpose, besides the C wavelength pair, one measures another pair, C′, which is close to the C wavelength pair. This second pair is used to correct for the light extinction by clouds; for details see, e.g., Vanicek et al. (2003). The ZC measurements (more than 2500) can improve the data coverage considerably, as they are mostly taken on days without the possibility to take DS and ZB measurements. However, the treatment of ZC measurements is much more intricate, as it usually requires detailed weather information and information about cloud properties at a site.

During cloudy conditions, the N-value (derived from the dial reading) is too high compared to clear sky conditions, and one has to reduce it empirically to clear-sky values. This empirical correction, ΔN, depends on cloud height and/or thickness, SZA and N_C′ (the N-value from the second wavelength pair). It is calibrated using an ozone reference value for the same day from DS and/or ZB data. Also here, the ozone value has to be assumed to be constant throughout the day. After the correction of the N-value further data processing is exactly the same as in the case of ZB.

For about 500 ZC measurements a reference (DS, ZB) value was available on the same day. The corrections turned out to be independent of SZA for values of up to 80°. For higher SZA there is a strong dependency. For this reason and due to the fact that there were not enough data for a satisfactory correction for high SZA, only ZC data with SZA<80° were considered. With these limitations, 406 ZC measurements remained for the development of a cloud correction. Further investigations showed that the correction is independent of the ozone column. Thus the remaining dependent variables are N_C′ and cloud/weather information. The dependence of the correction

on N_C′ is shown in Fig. 5 (asterisks and diamonds).

The next step is to group the data according to different weather/cloud conditions. The most straightforward way is to classify into low (strong extinction), middle and high (weak extinction) clouds. This task is challenging, as the weather information was not systematic and with a highly varying degree of detail. More than 80% of the data in Fig. 5 are characterized with the attributes “partly cloudy”, “overcast” or “light clouds”. The most frequent type is “partly cloudy”, which is diffuse but also has the largest probability of reference DS or ZB measurements.

Various tests using different classes of cloud characteristics finally resulted in the decision to make just two different groups of cloud types: high (light) clouds and middle and low clouds. From a linear least-square fit the following correction functions (see Fig. 5) were derived:

$\Delta N = 23.133 - 0.10381 \cdot N_C'$ for high (light) clouds (solid line)

$\Delta N = 37.941 - 0.18055 \cdot N_C'$ for middle and low clouds (dotted line)

These corrections were applied to all the ZC measurements. In some cases, such as in autumn 1954, there was uncertainty about which group a measurement should belong to or there was no information about the clouds. In these cases the mean of the two corrections was applied. For some measurements between June and August 1956 the weather information indicated clear sky, which means that they can be considered as ZB measurements. Only very few of them, with a N_C′ smaller than 200, have been corrected as above.

Due to the empirical correction, ZC data inherently have a higher uncertainty than DS and ZB data. Assuming a mean correction for some measurements does not introduce more uncertainty than guessing a certain cloud type and using the corresponding correction.

The ZC data could then be processed in the same way as ZB data. In this way 2018 single ozone values, corresponding to 1117 daily means, could be calculated and added to the dataset.

7 Moon measurements

This measuring mode is the only one which can provide data during the polar night (about 4 months in Svalbard), when the sun is not above the horizon anymore. Only around full moon the light is sufficient for moon observations. A part of this data has already been published in 1959 (Larsen, 1959). It is well known that moon measurements are difficult to perform and thus less reliable than day measurements. For this reason, overlap periods between moon and daylight measurements were used for quality assessment of the moon measurements, but only daylight measurements were used for daily means on these days. The measurement and the derivation of ozone values follow the same procedure as in the case of DS.

8 Final data set and quality check

The statistics for the daily mean values based on DS and ZB is given in Table 2 (DS only in parantheses). It is obvious that the monthly measurement number distribution varies considerably from year to year. The years 1951–1955 have a rather good coverage from March to July, while in the years 1958–1960 only June and July contain a sufficient number of measurements; in 1961 and 1962 again the early months are covered best. This variation in the observation coverage is mainly caused by weather conditions, but also the presence of operators may have played a role. The combination of DS and ZB data yields in total 2819 single ozone values, from which 821 daily means can be derived. If one adds the ZC data, (2018 single ozone values), one arrives at a total of 4837 single values covering 1676 days (Table 3). The doubling of daily means more than compensates the introduction of the larger single-value uncertainty which is inherent to the ZC measurements. In fact, the inclusion of ZC measurements does not result in many more monthly means, but the number of days per month is rising significantly. Figure 6 shows, as an example, all daily means for 1954. Red squares mark daily means from DS and ZB. On days with a black asterisk only the daily mean

is solely based on ZC observations. If moon measurements are included, another 137 daily means can be added. The final data set of monthly means and number of daily means per month are given in Table 4.

Because we, in the course of the data analysis, suspected that there was a change in the instrument set-up around 1956/57, we checked the stability of the total data set. As in the initial quality check described in Sect. 4, this investigation was based on a comparison between TOMS data and the re-analysed historical data, but now using the combination of DS, ZB and ZC measurements. The resulting Svalbard – Tromsø ratios are denoted by the dotted red line in Fig. 2. To investigate the stability of this parameter over time, the following procedure was applied: Ratios of daily mean values (DS+ZB) at Svalbard and Tromsø were averaged within each year over the period April to July. These were compared with means and standard deviations of the ratios of April-to-July averaged total ozone at Svalbard and Tromsø from TOMS data. As a reference period from TOMS we chose the period 1979–1989, during which only one TOMS instrument was in operation; in addition, geophysical conditions were relatively stable compared to the 1990s. Results are shown in Fig. 7.

They reveal that the historical-data ratios increase apparently systematically with the years, but remain within the $\pm 1\sigma$ range of the TOMS-based ratios until 1960. If ZC data are included in the historical data set (diamonds), the values get closer to the TOMS Svalbard/Tromsø ratio range, especially in the years 1961 and 1962. If one takes into consideration standard deviations of the reference values and data statistics of the Dobson data set (e.g., missing July data in 1962), there is no clear evidence for a change or a drift; the trends found are in the order of about 2–3% over a 12-year period, which is not significant and maybe also explainable with intermediate geophysical trends.

9 Outlook and conclusions

The re-evaluation of the historical Svalbard ozone data is only the first, but most important step towards the establishment of a complete multi-decadal total ozone dataset for the European Arctic. More recent Dobson measurements from Svalbard are stored in the WOUDC database, both from the period 1963 to 1968, and from 1984 to 1997. While the data from the 1960s seem to agree well with the re-evaluated dataset (no obvious biases), there is more doubt about the measurements in the 1980s and early 1990s. These show significant (positive) biases relative to TOMS measurements from the same period.

In 1994, the instrument was moved to Ny-Ålesund, where measurements performed by staff from the Norwegian Polar Institute have continued until today. These data appear again more reliable and will be used, together with other ground-based and satellite measurements, to establish an as complete as possible ozone data series from Svalbard. As a final step, it is envisaged to combine these data with further measurements from the region, e.g., Hornsund in the south of the archipelago and from Heiss Island in the Franz-Josef-Land archipelago east of Svalbard into one European Arctic ozone series.

Figure 8 shows a series of April and June monthly means comparing the Dobson measurements with both TOMS and DOAS (type SAOZ) at Svalbard, and measurements at Heiss Island. Obviously, the 1980s Dobson data are too high compared to TOMS, but the offset varies significantly with month. On the other hand, as to be expected from the validation procedure described in this work, the agreement between TOMS and the post-1994 Dobson data is good until about 2000, but also the agreement of the Dobson with the SAOZ data.

The Heiss Island Brewer data in the 1990s agree surprisingly well with the Svalbard TOMS and DOAS data, taking into account the distance between the sites, while the filter (M-83, M-129) data from the 1970s and 80s seem to have a non-negligible positive offset to Svalbard TOMS. Hence, before the establishment of an Arctic ozone series

these biases have to be investigated in more detail.

The final data set will be analysed by multi-linear regression methods in a similar way as the Tromsø (Hansen and Svenøe, 2005) and the Arosa series (Appenzeller et al., 2000) in order to identify the parameters determining long-term variability of total ozone in the Arctic.

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References

Appenzeller, C., Weiss, A. K., and Staehelin, J.: North Atlantic Oscillation modulates Total Ozone Winter Trends, Geophys. Res. Lett., 27, 1131–1134, 2000.

Blanco-Muriel, M., Blanco-Muriel, M., Alarcon-Padilla, D. C., Lopez-Moratalla, T., and Lara-Coira, M.: Computing the solar vector, Solar Energy, 70, 431–441, 2001.

Bojkov, R. D., Komhyr, W. D., Lapworth, A., and Vanicek, K.: Handbook for Dobson Ozone Data Re-evaluation, WMO/GAW Global Ozone Research and Monitoring Project, Report No. 29, WMO/TD-no. 597, 1993.

Brönnimann, S.: A historical upper-air data set for the 1939–1944 period, Int. J. Climatol., 23, 769–791, 2003.

Brönnimann S., Cain, J. C., Staehelin, J., and Farmer, S. F. G.: Total ozone observations prior to the IGY. II. Data and quality, Quart. J. Roy. Meteorol. Soc., 129, 2819–2843, 2003.

Brönnimann, S., Luterbacher, J., Staehelin, J., Svendby, T. M., Hansen, G., and Svenøe, T.: Extreme climate of the global troposphere and stratosphere in 1940–42 related to El Nino, Nature, 431, 971–974, 2004.

Chipperfield, M. P., Feng, W., and Rex, M.: Arctic ozone loss and climate sen-

sitivity: Updated three-dimensional model study, Geophys. Res. Lett., 32, L11813, doi:10.1029/2005GL022674, 2005.
Dobson, G. M. B.: Observers' handbook for the ozone spectrophotometer, Ann. Int. Geophys. Year, Part 1, 5, 46–89, 1957.
Dobson, G. M. B.: Forty years' research on atmospheric ozone at Oxford: A history, Appl. Opt., 7, 387–405, 1968.
Farman, J. C., Gardiner, B. G., and Shanklin, J. D.: Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interaction, Nature, 315, 207–210, 1985.
Hansen, G. and Svenøe, T.: Multilinear regression analysis of the 65-year Tromsø total ozone analysis, J. Geophys. Res., 110, D10103, doi:10.1029/2004JD005387, 2005.
Komhyr, W. D., Mateer, C. L., and Hudson, R. D.: Operations handbook – Ozone observations with a Dobson spectrophotometer, Ozone Proj. Rep. 6, 125 pp., World Meteorol. Org., Geneva, Switzerland, 1980.
Komhyr, W. D.: Effective Bass-Paur absorption coefficients for use with Dobson spectrophotometers, J. Geophys. Res., 98, 20 451–20 465, 1993.
Langlo, K.: On the amount of atmospheric ozone and its relation to meteorological conditions, Geofys. Publ., 18, 6, 5–44, 1952.
Larsen, S. H. H.: Measurements of atmospheric ozone at Spitzbergen (78 N) and Tromsö (70 N) during the winter season, Geofys. Publ., 21, 5, 1959.
Normand, C. W. B.: International Ozone Commission. Report of the Bureau for the years 1951–1954. 5 August 1954, in: Air Ministry Branch, Ozone values (International Ozone Commission), Unpublished Report MO 19/3/9 Part I (formerly MO 15/90) of UK MetOffice, 31 January 1961, 1954.
Staehelin, J., Renaud, A., Bader, J., McPeters, R., Viatte, P., Hoegger, B., Bugnion, V., Giroud, M., and Schill, H.: Total ozone series at Arosa (Switzerland): Homogenization and data comparison, J. Geophys. Res., 103, 5827–5841, 1998.
Svendby, T.: Reanalysis of total ozone measurements at Dombås and Oslo, Norway, from 1940 to 1949, J. Geophys. Res., 10(D24), 4750, doi:10.1029/2003JD003963, 2003.
Svenøe, T.: Re-evaluation, statistical analysis and prediction based on the Tromsø total ozone record, PhD Thesis, Faculty of Science, Department of Physics, The Auroral Observatory, Tromsø, October 2000.
Vanícek, K.: Calibration history of the Dobson 074 and Brewer 098 ozone spectro-photometers, Czech Hydrometeorol. Inst., Prague, ISBN 80-86690-08-3, 2003.

Vanícek, K., Stanek, M., and Dubrovsky, M.: Evaluation of Dobson and Brewer Total Ozone Observations from Hradec Králové, Czech Republic, 1961–2002, Czech Hydrometeorol. Inst., Prague, ISBN 80-86690-10-5, 2003.

Table 1. Availability of the different types of direct sun measurements.

	Single measurements	Daily means	Years
C-DS	1337	609	1950–1962
AD-DS	431	210	1951, 1957–1962
CD-DS	558	264	1951, 1957–1962

Table 2. Number of daily means for DS+ZB (DS).

	Feb	March	April	May	June	July	Aug	Sep	Oct
1950	0	0	0	0	0	0	0	13 (12)	8 (0)
1951	3 (0)	19 (6)	22 (13)	18 (8)	10 (8)	13 (12)	9 (8)	1 (1)	0
1952	4 (0)	21 (6)	18 (18)	14 (14)	12 (12)	10 (9)	6 (4)	3 (1)	1 (1)
1953	1 (0)	17 (0)	14 (12)	17 (16)	11 (11)	18 (18)	5 (3)	0	0
1954	1 (0)	13 (0)	18 (18)	15 (13)	9 (9)	1 (0)	9 (0)	2 (0)	5 (0)
1955	0	6 (3)	17 (16)	22 (22)	21 (18)	4 (4)	7 (0)	8 (1)	5 (0)
1956	0	4 (4)	25 (20)	20 (14)	0	0	0	12 (6)	3 (0)
1957	0	6 (6)	20 (18)	15 (15)	9 (7)	5 (5)	5 (5)	5 (0)	2 (0)
1958	0	0	0	0	10 (10)	8 (7)	16 (13)	9 (8)	0
1959	0	0	0	2 (0)	6 (6)	13 (11)	8 (8)	11 (7)	0
1960	0	0	0	0	9 (9)	18 (16)	5 (3)	0	0
1961	0	12 (6)	27 (27)	17 (16)	5 (5)	0	0	0	0
1962	0	15 (13)	27 (27)	14 (14)	9 (9)	0	0	3 (3)	0

Table 3. Number of daily means for DS+ZB+ZC.

	Feb	March	April	May	June	July	Aug	Sep	Oct
1950	0	0	0	0	0	0	0	25	8
1951	3	23	27	27	26	27	30	7	0
1952	4	28	27	27	30	31	26	17	1
1953	1	17	21	26	28	25	23	0	0
1954	1	19	25	30	25	25	30	26	5
1955	0	6	29	28	30	30	28	25	5
1956	0	4	27	30	29	31	26	25	3
1957	0	6	29	28	27	23	23	17	2
1958	0	0	0	0	23	23	29	22	0
1959	0	0	0	6	10	21	16	23	0
1960	0	0	0	0	16	30	12	0	0
1961	0	16	30	27	16	13	10	0	0
1962	0	16	29	23	20	0	0	13	0

Table 4. Monthly total ozone means derived from the re-evaluated Svalbard Dobson measurements, including number of daily means contributing to monthly means.

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
1950									267 (25)	285 (8)	309 (5)	316 (7)
1951	367 (5)	418 (5)	441 (23)	431 (27)	401 (27)	368 (26)	325 (27)	303 (30)	311 (7)			334 (4)
1952	322 (3)	459 (7)	474 (28)	433 (27)	404 (27)	355 (30)	326 (31)	302 (26)	288 (17)	270 (1)		375 (8)
1953	408 (7)	366 (1)	395 (19)	430 (21)	396 (26)	342 (28)	317 (25)	287 (23)			235 (4)	403 (1)
1954	386 (3)	341 (2)	437 (19)	447 (25)	392 (30)	371 (25)	340 (25)	293 (30)	258 (26)	285 (8)		288 (3)
1955	402 (4)	463 (5)	398 (7)	402 (29)	397 (28)	367 (30)	325 (30)	302 (28)	265 (25)	278 (7)	311 (4)	296 (4)
1956		397 (2)	400 (5)	434 (27)	393 (30)	356 (29)	308 (31)	283 (26)	254 (25)	269 (3)	305 (2)	277 (3)
1957	334 (2)	523 (6)	473 (7)	414 (29)	384 (28)	363 (27)	313 (23)	287 (23)	275 (17)	295 (2)		
1958						371 (23)	352 (23)	304 (29)	298 (22)			
1959					400 (6)	360 (10)	345 (21)	310 (16)	274 (23)	291 (1)		
1960						366 (16)	331 (30)	301 (12)				363 (9)
1961	376 (8)	395 (2)	464 (16)	467 (30)	413 (27)	360 (16)	312 (13)	285 (10)				326 (5)
1962	336 (6)	410 (8)	373 (16)	399 (29)	425 (23)	370 (20)			284 (13)			

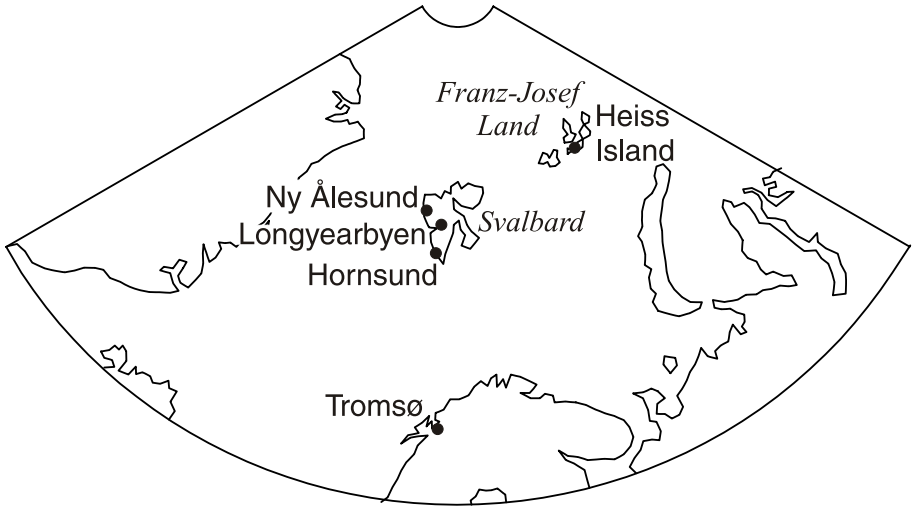

Fig. 1. Map showing the locations mentioned in the text.

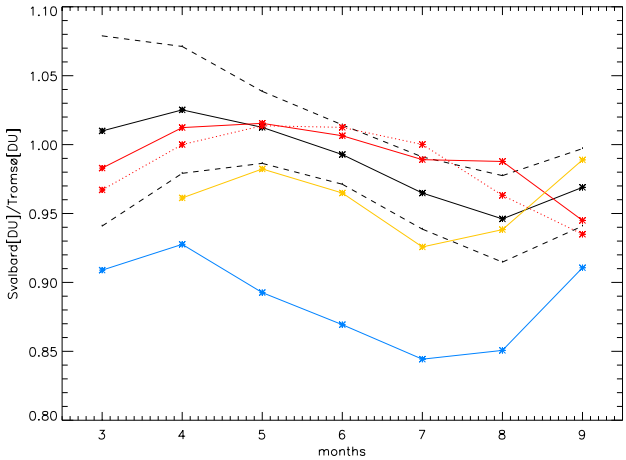

Fig. 2. Ratios between Svalbard and Tromsø total ozone monthly means: TOMS 1979–2000 (black) with standard deviation (dashed lines), Svalbard Dobson 1950–1962 C-DS (red solid line), AD-DS (yellow), CD-DS (blue). Red dotted line: DS, ZB and ZC data on CC′ wavelengths. TOMS: ratios of monthly means at both sites; Svalbard Dobson: monthly means of ratios of daily means from both sites (reduced statistics).

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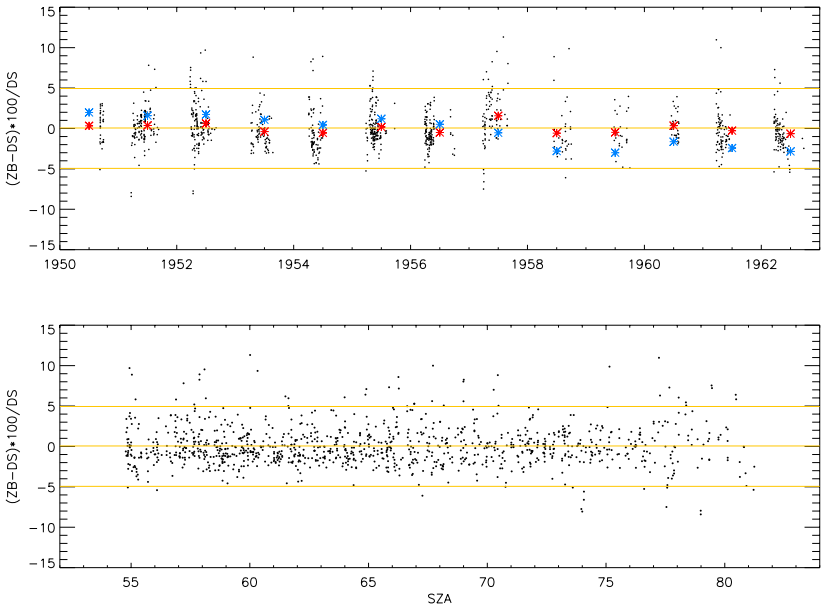

Fig. 3. Ratio between quasi-simultaneous zenith-blue and direct-sun measurements sorted chronologically (upper panel) and as a function of solar zenith angle (lower panel). Annual means using one polynomial: blue asterisks, and using different polynomials before and from 1957: red asterisks. Dots: single ratios based on two-function approach.

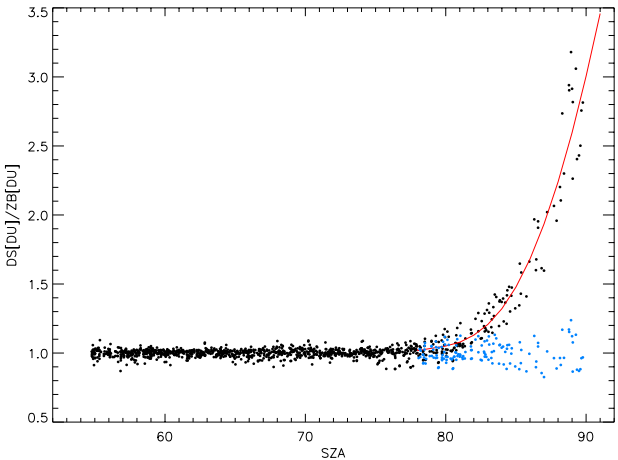

Fig. 4. Ratio between direct-sun and zenith blue measurements on days with measurements over a wide range of solar zenith angles: single values (black dots) and fit (red) used to normalise ZB measurements at SZA values >80°. Blue dots: ZB data after normalisation.

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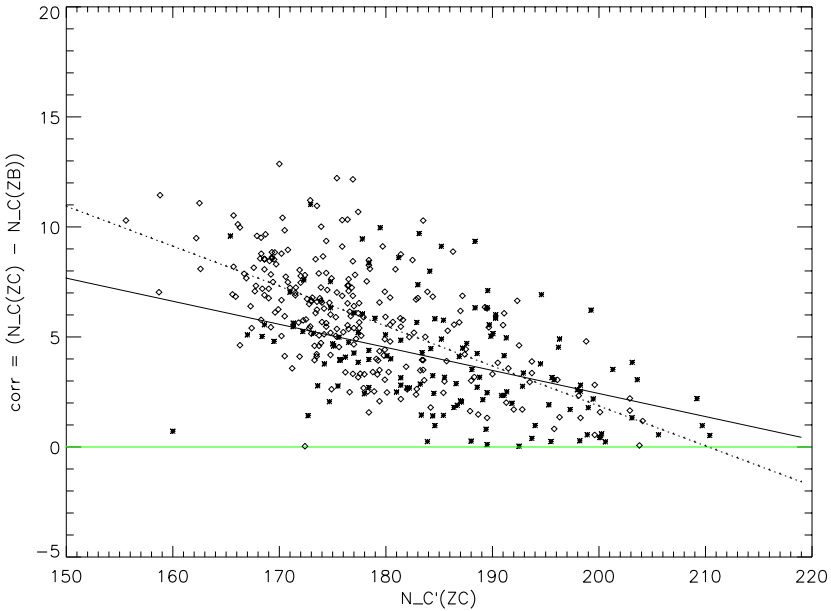

Fig. 5. Deviations of N values between quasi-simultaneous ZB and ZC N values, as a function of ZC N(C′) values, sorted according to cloud characteristics: high/thin clouds (asterisks, linear fit: solid black line), middle and low clouds (diamonds, linear fit: dotted line).

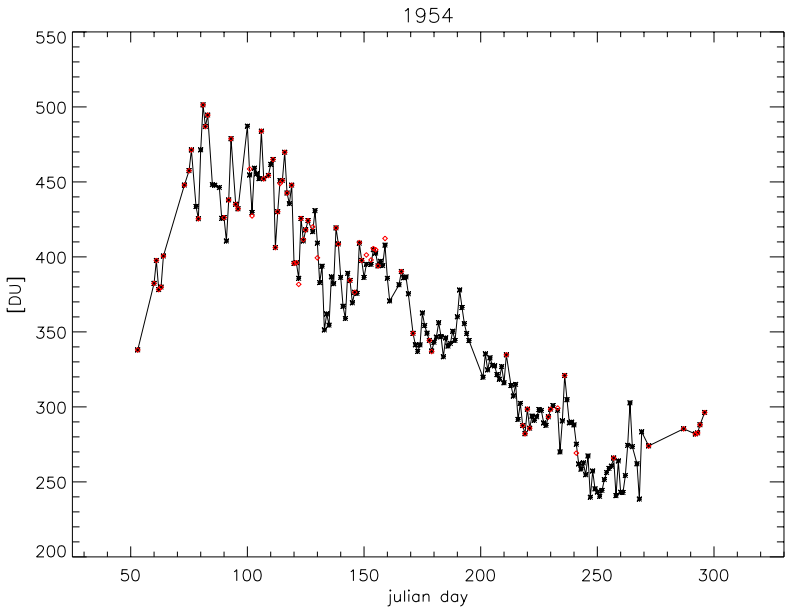

Fig. 6. Total ozone values from Svalbard Dobson in 1954: Red diamonds: DS+ZB measurements; black asterisks: dataset including ZC mode.

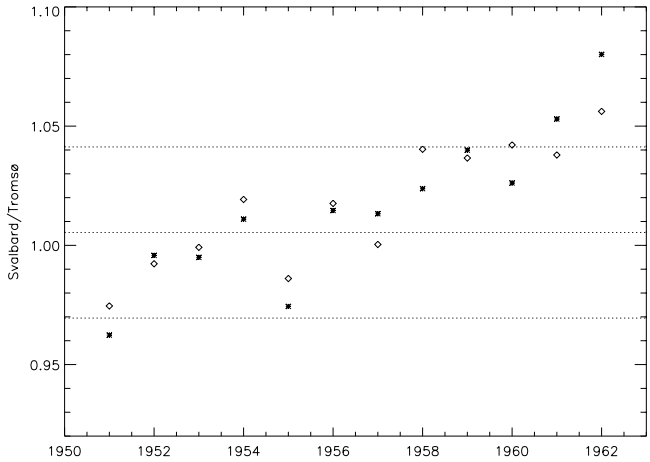

Fig. 7. Ratios of daily mean total ozone at Svalbard and Tromsø, averaged from April to July in each year (asterisks: DS+ZB; diamonds: DS+ZB+ZC). The dashed lines represent the long-term mean (±1 standard deviation) of the ratio of April-to-July averaged total ozone at Svalbard and Tromsø based on TOMS data (1979–1989).

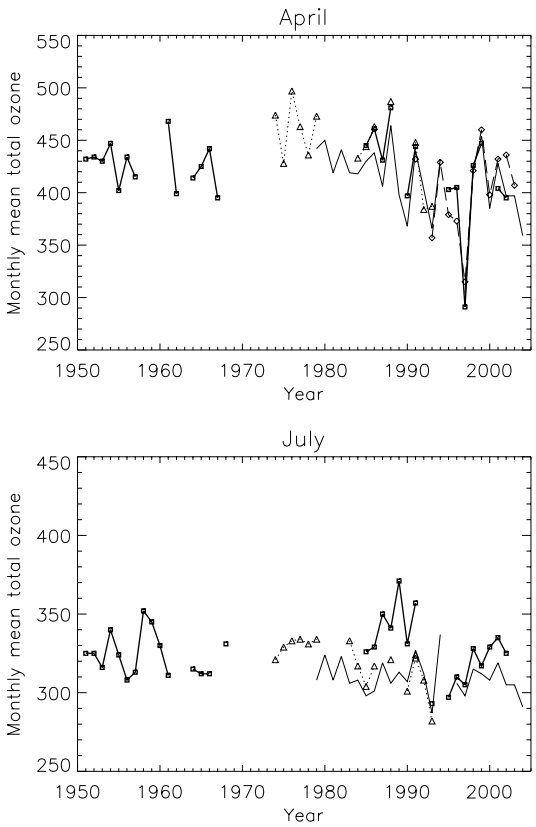

Fig. 8. Total ozone monthly means for April (upper panel) and July (lower panel): Bold solid line/squares: Dobson measurements at Longyearbyen (before 1994) and Ny-Ålesund (after 1994); thin solid line: TOMS data close to Ny-Ålesund; dashed line/diamonds (only April, since 1991): Ny-Ålesund DOAS; dotted line/triangles: Heiss Island M-83 (before 1990) and Brewer (after 1990).