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Total column ozone in New Zealand and in the UK in the 1950s

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Abstract

Total column ozone measurements reach back almost a century. Historical column ozone data are important to obtain a long term perspective of changes of the ozone layer, but arguably also as diagnostics of lower stratospheric or tropopause-level flow in time periods of sparse upper-air observations. With the exception of few high quality records such as that from Arosa, Switzerland, ozone science has almost exclusively focused on data since the International Geophysical Year (IGY) in 1957, although earlier series exist. In the early 2000s, we have digitised and re-evaluated many pre-IGY series. Here we add a series from Wellington, New Zealand, 1951-1959. We re-evaluated the data from the original observation sheets, performed quality control analysis and present the data. The day-to-day variability can be used to assess the quality of reanalysis products, since the data cover a region and time period with only few upper-air data. Comparison with total column ozone in the reanalyses ERA-PreSAT (which assimilates upper-air data), 20CRv3 and CERA20C (which do not assimilate upper-air data) shows high correlations with all three. Although trend quality is doubtful (no calibration information and no intercomparisons are available), combining the record with other available data (including historical data from Australian locations) allows a 70-year perspective of ozone changes over the southern midlatitudes. The series is available from the World Ozone and Ultraviolet Data Centre. Finally, we also present a short series from Downham Market, UK, covering November 1950 to October 1951, and publish it with further historical data series that were previously described but not published.

1 Introduction

Regular total column ozone measurements reach back almost a century (Fabry and Buisson, 1921; Dobson and Harrison, 1926). While interest first arose from its close relation to

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tropopause flow, which seemed promising as a meteorological diagnostic prior to the invention of the radiosonde, the focus then shifted towards understanding stratospheric circulation and monitoring of the ozone layer. Historical data were not considered particularly important until the onset of ozone depletion and the discovery of the Antarctic ozone hole. Even then, the focus was on ozone changes since the International Geophysical Year (IGY) in 1957/58, when a global network was initiated and a new measurement protocol (double wavelength pair) was introduced, leading to higher quality measurements (Dobson, 1957a,b; Dobson and Normand, 1957). Only few, long records such as the one from Arosa were re-evaluated (Staehelin et al., 1998), providing an important basis for trend assessments (see also Müller, 2009 and Bojkov, 2012, for a history of ozone measurements).

In the early 2000s, the first author compiled and digitised a considerable number of pre-IGY series in order to exploit their relation to tropopause flow and the stratospheric meridional circulation (Brönnimann et al., 2003a,b). Trend quality is not necessarily required for such applications since the day-to-day variation at mid-latitudes is much larger than the trend. The data were digitised, homogenised if possible and some (but not all) were delivered to the World Ozone and Ultraviolet Data Centre (WOUDC). Not all existing series could however be found. Here we add further series to this collection, namely from Wellington, New Zealand, 1951-1959 (the data from the IGY onward are already in the WOUDC data base) and a short and patchy series from Downham Market, UK, from November 1950 to October 1951. In this paper we present the series, their quality control and show selected analyses. The data are used to independently assess reanalysis data sets, and the long term changes of ozone over the southern midlatitudes since the 1950s is presented.

The paper is organised as follows. Section 2 presents the instrument history and Section 3 describes the data re-evaluation. Comparisons with upper-air data and reanalysis data sets are presented in Section 4. In Section 5 we provide an assessment of the data quality and compare the results with literature. Conclusions are drawn in Section 6.

2. Ozone data and instrument histories

2.1. Wellington (D#17)

Already during Dobson's first (photographic) global ozone network in the late 1920s (Dobson et al., 1930), New Zealand participated by hosting a spectrophotometer in Christchurch (Fig. 1). When Dobson built the new photoelectric instruments in the 1930s (Dobson, 1931) and planned a global network with these instruments, New Zealand was approached again and in

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1937 eventually placed an order (see Nichol, 2018; Farkas, 1954). However, delays occurred, and the designated instrument (Dobson #17) was only finished shortly before the war. When the war started, the UK approached New Zealand and asked to withhold the delivery of D#17 in order to use it in the UK. The instrument operated in the UK until 1947. It was then decided that a recalibration and improvement was necessary before the instrument could be shipped to New Zealand, therefore, the instrument was sent to Oxford. The photoelectric cell and amplifier were replaced by a photomultiplier (Farkas, 1954). In Dobson's original observation sheets from Oxford (Vogler et al., 2007) we found measurements performed with D#17 on 24 Feb and 1 Mar 1940 and then again on 21 and 22 Nov 1946. This was presumably before the upgrade. Note, however, that these observation sheets are incomplete. No sheets from Oxford could be found for the period from January 1947 to October 1949, which might have contained the calibration information (together with other measurements from Oxford, which are lost).

The instrument was sent from the UK only in late 1949 and arrived in New Zealand in 1950. The instrument was first tested, and it was found that the setting of the quartz plates had altered during the transport (Farkas, 1954). As a consequence, a new table of plate settings was produced for operations. Then the instrument was put in operation in Kelburn, Wellington (Fig. 1).

The first measurements are dated 1 August 1951. In the first years, Elizabeth Porter was in charge of the measurements. After her unexpected death in 1953, Edith Farkas took over and was in charge of operations until the mid-1980s. The instrument underwent another major rehaul in 1963/4. At this occasion it was also compared with D#105 (Nichol, 2018).

For all observations, the shorter wavelength was 311.2 nm (C pair) and measurements were taken in direct sun (DS) mode as well as at the blue (ZB) or cloudy zenith (ZC, using an additional wavelength that is not strongly absorbed by ozone; the pair formed by the two longer wavelengths, sometimes termed C', allows addressing the attenuation by clouds). The relative path length through the ozone layer, μ, was calculated from a nomogram. The altitude of the ozone layer was assumed to be 22 km. For DS measurements, an atmospheric correction was added, which was assumed to be 0.095 m atm. cm for clear days and 0.1 for slightly hazy days and more (usually 0.11) for very hazy days.

Observations at the blue or cloudy zenith require calibration using quasi-simultaneous observations. In 1954, when the report was published, only a limited set of such observations was available, values were described as somewhat doubtful (Farkas, 1954). For this paper, we thus recalibrated these measurements.

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Farkas (1989) and Nichol (2018) consider the data prior to 1964 unreliable, as no intercomparison had been made. For the sake of completeness, Nichol (2018) shows data from the IGY onward, though noting their inferior quality. These data, from July 1957 onward, are available from the WOUDC. However, the data prior to 1957 have so far not been available electronically. The earliest data have been published by Farkas (1954), where in addition to the reduced ozone amount also the observation mode, wavelength pair used, and observation time was indicated. Reduced values were sent to the International Ozone Office, where the communication was stored and later sent to Environment Canada. It was scanned and recently sent to the first author as a PDF file (Bais, personal communication).

We digitised the total column ozone data from both sources, the PDF file from the International Ozone Office as well as from Farkas (1954). Upon inquiry, the original data sheets (covering 1951 to 1960) were found at NIWA, scanned, and sent to the first author (Fig. 2). The original readings were then also digitised. The main source of information in this paper are the original sheets; the reduced values from the other two sources were used for cross-checking. Note that we do not have calibration information or intercomparison data. However, the data sheets contain many notes that provide additional information on the instrument history. This information will be given in Sect. 3.

2.3. Downham Market

The scans from the Ozone Office also contained data from Downham Market, though almost illegible. These are daily averaged, reduced total column measurements with no additional information. They covered the year 1951 (January to October). We supplemented these data with values printed on a graph (incidentally, this was a New Year's card sent out by the International Ozone Office, Fig. 3), such that we could extend the series backward to late November 1950. Note that both sources of information are secondary sources and thus inherently unreliable. Nevertheless, as will be shown, the quality of the data seems unexpectedly high.

Sometimes monthly means were indicated on the sheet, which we could use to cross check our digitisation. Additionally, monthly data from Downham Market (November 1950 to October 1951) were found in the communication of the International Ozone Office, stored at the UK Met Office (Normand, 1961). These data were also used to cross-check where there were no monthly means in the other source, although there were also sometimes differences between the monthly means from both sources. This second source (Normand, 1961) also

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showed us that the record would have continued into November 1951 for at least 17 days, and that 15 and 26 daily values are missing in our source for November and December 1950, respectively.

Nothing is known about the instrument or the history of the measurements. We assume that the instrument (the number remains unknown) was relocated to Hemsby in November 1951. Brönnimann et al. (2003b) digitised the Hemsby total column ozone data and found a good quality (in terms of day-to-day changes) apart from an unplausible (flagged) period. The context of the measurements remains also unknown. Scrase (1951) mentions the testing of radiosondes at Downham Market in approximately the same period.

3. Re-evaluation and analysis methods

3.1. General procedure

The processing of Dobson data is described in Komhyr and Evans (2006); the standard procedure to re-evaluate the data is given in Bojkov et al. (1993). We followed the two guidelines as closely as possible. Note, however, that no calibration information and no intercomparison data were available. The standard equation for calculating total column ozone X (in atm. cm at standard pressure) from a single wavelength pair (with short and long wavelengths λ and λ') is:

$$X = \frac{N - (\beta - \beta')\frac{mp}{p_0} - (\delta - \delta')\sec(SZA)}{(\alpha - \alpha')\mu} \qquad \text{(Eq. 1)}$$

where β is the molecular scattering coefficient (primes denote the longer wavelength), α is the absorption coefficient, δ is the aerosols scattering coefficient, m is the relative air mass, μ is the relative path length through the ozone layer, and SZA is the solar zenith angle. The relative intensity N is the actual measurement:

$$N = \log\left(\frac{I_0}{I_0'}\right) - \log\left(\frac{I}{I'}\right) \qquad \text{(Eq. 2)}$$

where I and I_0 are the intensities at the surface and outside the Earth's atmosphere, respectively. N is obtained from the dial reading at the instrument, R, via a conversion table (R-N table). No unique value can be given for the aerosol scattering coefficient (δ-δ') as it depends on the haziness of the atmosphere.

For double wavelength pairs such as AD or BD, the following equation is used:

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$$X_{12} = \frac{(N_1 - N_2) - [(\beta - \beta')_1 - (\beta - \beta')_2]\frac{mp}{p_0} - [(\delta - \delta')_1 - (\delta - \delta')_2]\sec(SZA)}{[(\alpha - \alpha')_1 - (\alpha - \alpha')_2]\mu} \quad \text{(Eq. 3)}$$

Aerosol scattering can then be neglected.

When re-evaluating historical data, the procedure is to first process the DS data (the double pair data can be processed directly, while the single pair data require assumptions concerning aerosol scattering). The ZB observations are then calibrated against quasi-simultaneous (typically within minutes) DS observations by fitting N and μ using third order polynomials (Vanicek et al., 2003):

$$X = c_0 + c_1 N + c_2 \mu + c_3 N^2 + c_4 \mu^2 + c_5 N^3 + c_6 \mu^3 + c_7 N \mu + c_8 N \mu^2 + c_9 N^2 \mu \quad \text{(Eq. 4)}$$

Vanicek et al. (2003) recommend to split the data into seasons and fit polynomial functions separately.

In a second step, ZC observations are processed. This is done by adjusting N by adding a term ΔN in such a way that they can be processed similar to ZB observations. For the C pair, ΔN is determined by means of an additional wavelength pair, C', the shorter wavelength of which corresponds to the longer wavelength of the C pair. Both wavelengths of the C' pair are very little absorbed by ozone and thus allow assessing the aerosol and cloud scattering. The correction additionally depends on the cloud type and altitude. Vanicek et al. (2003) use cloud attenuation tables for the correction; constructing such a table however requires a lot of parallel measurements. Vogler et al. (2006) uses linear regressions of the form

$$\Delta N = c_0 + c_1 N_{C'} \quad \text{(Eq. 5)}$$

separately for situations with high clouds and situations with middle or low clouds. Here, ΔN is the difference between N of a quasi-simultaneous ZB measurement and N of the ZC measurement (both for the C pair), while $N_{C'}$ refers to the C' pair of the ZC measurement.

If original observations sheets are not available, all that can be used are the calculated total column ozone values as well as, if available, the time of day (which allows calculating SZA). Changes in the absorption scale can be corrected by scaling the data (see Brönnimann et al., 2003b) and statistical corrections must be used otherwise. Assessing the dependence of, e.g., differences to a neighbouring station, on SZA or on the annual cycle can give some hints on possible causes for biases. Statistical corrections can be made dependent on the seasonal cycle or SZA, although series processed in this way are likely to be of a lower quality.

In this paper we followed the former, detailed approach for Wellington and the latter approach for Downham Market. The following sections describe the details of the processing.

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193 *3.2. Wellington*

194 All observations, 2500 in total, were digitised. Zenith observations were noted on the sheet
195 but the distinction between ZB and ZC is not made on the sheets until 1954 (however, prior to
196 that time the observations and calculations indicate whether a zenith observations was
197 performed at the clear or cloudy zenith, and some of the measurements could be double
198 checked with Farkas, 1954). ZC observations were performed from the beginning, often in
199 pairs (ZB and DS, ZC and DS). Observation pairs of ZB/ZC or observation triplets only
200 follow later. From 1955 onward, there are occasional observations of the A pair, and from
201 1957 on of the AD pair. In 1957 numerous quasi-simultaneous observations of AD and C
202 pairs were performed, then AD measurements were no longer performed, while BD
203 measurements became frequent.

204 There are almost no measurements from July 1956 to February 1957, which is also confirmed
205 in the data from the Ozone Office. The second half of 1958 was missing entirely from the data
206 sheets, but in that case daily data were sent to the Ozone Office and are today found at
207 WOUDC, indicating that data sheets have been lost. Our material continues in January 1959.
208 From September 1959 onward, various problems seemed to have occurred, according to notes
209 on the observation sheets. One note reads: “While putting lid back after battery change on 8
210 October 1959, the quartz plates must have moved. From standard lamp readings the estimated
211 correction for dial readings is as follows: b + 9, c+c’ + 6, d + 10”. Another note in October
212 1959 speculated that “Quartz plates might have moved at beginning of September at one of
213 the occasions when silica gel was changed”. From October 1959 onward, data sheets become
214 relatively messy, with black ink, red pencil, and many strike throughs. It is hard to follow if
215 and which corrections were done. A deterioration was also found in terms of correlation and
216 was visually apparent when plotting the data. Problem with the quartz plates are also
217 mentioned later on (e.g., an adjustment in February 1960 is mentioned). We therefore only
218 consider data prior to September 1959.

219 From the original observations we basically used only the dial readings *R* and the time of
220 observations as well as information on the haziness and cloud cover, but all other calculations
221 were nevertheless digitised and provided important information. For instance, we checked the
222 averaging of the different *R* readings, we reassessed the *R*-*N* conversion (which is a linear
223 function per wavelength) and found that the relation has not changed over the period under
224 study. In this way we checked all steps of the original calculations, where possible.
225 Inconsistencies led to the correction of digitisation errors, of typos on the original sheets, or of
226 miscalculations; however, some could not be resolved and led to the flagging of observations.

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From the time we calculated the solar zenith angle SZA using the MICA software. The variables m and μ (assuming an ozone layer height h of 22 km) were calculated from SZA following Komhyr and Evans (2006). We extracted sea-level pressure from the Twentieth Century Reanalysis version 3 (20CRv3, Slivinski et al., 2019) and calculated station pressure p assuming a gradient of 0.125 hPa m^{-1}. Note that we could also have used the original μ calculations and neglected the pressure dependence. The effect of each of these factors is ca. 1-2 DU (referring to the standard deviation; this is much smaller than the observation error). Our procedure allowed further checks and thus further corrections of erroneous data, though it might also have introduced further errors (e.g., digitisation errors of the time of day).

According to Farkas, the shorter wavelength of the C pair was 311.2 nm, which slightly deviates from the nominal value of 311.45 nm for the C wavelength pair. Therefore, we tested two sets of absorption coefficients: the standard Bass-Paur absorption coefficients (Komhyr et al., 1993) as well as modified coefficients. Using the standard coefficients can be justified by the fact that we do not know the slit function for this specific instrument. Furthermore, the full width-at-half-maximum is typically larger than 1 nm, such that effects are likely small. Modified coefficients can be motivated by the work of Svendby (2003), who adjusted coefficients for D#8 with a centre wavelength of 311.0 nm (she could actually measure the slit function of D#8). As an approximation, we can interpolate between her value and the Bass-Paur coefficient, yielding $\alpha = 0.891$. Assuming that the long wavelength was the same, we get $(\alpha-\alpha')$ of 0.851. Similarly, the Rayleigh scattering coefficient was adjusted and $(\beta-\beta')$ was set to 0.111.

In the calculation sheet sent to observers in the 1950s, molecular and aerosol scattering were not distinguished. Only the first term of the equation, $N / (\alpha - \alpha') \mu$, was evaluated. From this, Dobson suggested to subtract 95 DU on clear days and 100 DU (occasionally more) on hazy days. Using Eq. 1 we can calculate molecular scattering and find that it amounts to ca. 95 DU, leaving 0 to 15 DU to aerosols, depending on haziness. Svendby (2003), for a site in Norway, found aerosol scattering contributions of 0 to 4% using direct sun C' observations. In order to determine aerosol scattering we analysed all CC' observations performed in DS mode. Only 23 observations were found, and using the method of Svendby (2003) we found inconsistent results (negative coefficients), indicating that the longer wavelength of the C' pair might have been different from that in D#8. We therefore assumed an aerosol scattering coefficient $(\delta-\delta')$ for the C pair of 0.001 for clear days (the vast majority of days), 0.005 for hazy days and 0.01 for very hazy days. This is less than indicated in the tables that came with the instrument D#42 in College, Alaska, for which we have the numbers (0.006, 0.018, 0.029 for slightly

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hazy, hazy, and very hazy days, respectively; see Brönnimann et al. 2003b). However, the coastal station Wellington might be less affected by aerosols than Oxford or College. Our correction corresponds to aerosol effects of ca. 1.2, 6, and 12 DU which is consistent with Svendby (2003) and also yields consistent results between C and double-wavelength pair measurements (see below).

We then processed all DS data. AD DS measurements have become the standard with the IGY. However, the correlation of AD DS total ozone with the C DS data was very low (around 0.5) and the seasonal cycle of AD DS measurements was unrealistic. Obviously there was a problem with the A wavelength pair, and this must have been the reason why AD measurements were discontinued and BD measurements were performed later on. Therefore, we did not further pursue A and AD measurements.

We then compared the BD DS data with quasi simultaneous (<3 hr time difference) C DS data (Fig. 4a). We identified 136 pairs, and their correlation was 0.85. The C DS measurements are slightly lower than the BD DS measurements (by 1.8%) when adjusted coefficients are used, slightly higher (1.0%) when Bass-Paur coefficients are used.

In the next step we compared the C DS data with quasi simultaneous (<3 hrs) C ZB data. We identified 429 pairs and applied Eq. 4, stratifying the data into May to October and November to April, respectively. We found an overall good fit (Fig. 4b), with explained variances of 87% and 95% for the two seasons, respectively (numbers are the same for Bass-Paur or adjusted coefficients). The standard deviations of the residuals were 12 DU for the winter and 9 DU for the summer season.

Next we compared C ZB with C ZC data. We found only 65 quasi-simultaneous observations (Fig. 4c). Separating them into different cloud types was impossible as almost all measurements were for cumulus. We therefore fit only one function, but rather than a linear function as in Vogler et al. (2006) we used a second order polynomial function. The explained variance of the fit R^2 was 0.58. The corrections for N that were obtained in this step were then applied to the Z ZC data and they were then reduced with the same equation as the C ZB data. As a further test we then selected quasi-simultaneous (<3 hrs) observations of C DS and C ZC and found 178 pairs (Fig. 3d). The correlation was 0.96 and the standard deviation of the differences amounted to 13 DU, but a mean bias of 5.8 DU (5.7 DU for the case with adjusted coefficients) is apparent. We therefore subtracted 5.8 DU (5.7 DU) from all ZC observations.

In this way all data could be processed. During the process we discovered sometimes inconsistences (e.g., errors in the calculation performed in the 1950s, or typos), and some

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values were marked with question marks on the sheets. While some of the problems (e.g., miscalculations or typos) could be resolved, in other cases such values were flagged in our data set, though we still reduced the ozone amount. We also flagged other suspect values, e.g., cases where *N* values were not reduced at all on the sheets. In total, of the 2500 observations digitised, 2253 values were reduced, of which 56 were flagged. By definition of the procedure, DS data are the reference, while ZB data and ZC data are fitted to the DS data in two steps and thus a somewhat lower quality is expected.

Finally, we compared our reduced values to those digitised from the Ozone Office files as well as to those stored at WOUDC. This revealed further important information. For instance, January and February 1959 are missing in the Ozone Office data but not in our data sheets. The non-reporting could be due to low quality. In fact, many values in January 1959 had question marks on the original sheets and there is a note that the battery was extremely low; on 4 February battery and spring were replaced and the rhodium plate was fixed to position "opaque". In our series, however, only a sequence of values in January 1959 was flagged.

For further comparisons we averaged our values (not considering flagged values) to daily means using New Zealand dates as well as UTC dates and then compared with the two daily data sets. Both sources (Ozone Office, WOUDC) used New Zealand dates, although both are shifted by one day after February 1959. We found a generally good agreement; discrepancies were checked, which led to the flagging of two additional values, while most checked values were not flagged.

Finally, for the daily data set, we supplemented the missing half year in 1958 with the data from the Ozone Office, scaled with 1.041 to account for the change in absorption coefficients. All processed original observations as well as the supplemented daily values are shown in Figure 5 (here we show the version with Bass-Paur coefficients). No obvious discrepancies are found, although the scatter in the C ZC data is visibly larger than for C DS or C ZB data. In this way the data set is used in the following.

3.3. Downham Market

In the case of Downham Market, our data are only daily mean, reduced total column measurements. All that can be done is to adjust them to account for the change in the absorption cross sections used. At the time of the measurement, the so-called Ny-Choong scale was in use. With the IGY, the Vigroux (1953) scale was adopted, but a few years later was found to provide inconsistent results and was replaced by an updated Vigroux scale.

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Finally, the Bass-Paur scale was adopted as standard (Komhyr et al., 1993). To convert directly from the Ny-Choong to the Bass-Paur scale, we multiplied the all values with 1.416, as recommended in Brönnimann et al. (2003b).

Several daily values were illegible, and two were marked with a question mark on the sheet and were correspondingly flagged. The monthly mean values were used to cross-check the numbers. The digitised raw data were then compared with the data from Oxford (Vogler et al., 2007). Using linear regression with Oxford total column ozone as an independent variable, days with exceedingly large residuals (outside ±3 standard deviations) could be flagged and further checked (e.g., checking for digitising errors or by comparing the value with the days before and after). Only one suspect measurement was found; it was flagged correspondingly.

A very high correlation of 0.91 was found between the series. Although the data only cover one year, the difference series showed a clear seasonal cycle, with largest differences approximately around summer solstice. Offsets that include a seasonal cycle are possible due to effects that either depend on the solar zenith angle (e.g., due stray light in the instrument), on temperature, on the ozone amount, or on the tropopause height. The data amount is not sufficient to decide between different seasonalities. However, given the very high correlation between the data from Downham Market and Oxford, pointing to a high day-to-day accuracy, we adjusted the Downham Market data by subtracting a seasonal cycle based on fitting the first harmonic to the difference series. Corrections are between 13 (winter) and 58 (summer) DU.

Repeating the regression approach on this series we found one additional potential outlier (outside ±3 standard deviations) that was correspondingly flagged. In this format the series is used further in our paper.

3.4. Comparison with other data sets

In addition to Oxford total column ozone, which was used for flagging outliers and debiasing the Downham Market record, we used additional historical total column ozone data for several analyses. Specifically, we used total column ozone from various locations in Europe (Brönnimann et al., 2003b) as well as a historical series from Canberra, (1929-1932), which were digitised from daily values in Brönnimann et al. (2003a) and converted to the Bass-Paur scale. While the European data, which were assumed to be of higher quality than some of the other series, are available from the WOUDC, the other series described in Brönnimann et al. (2003a) were only made available via an ftp site, which no longer exists. We therefore publish

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all historical series used in this paper, together with all other series described in Brönnimann et al. (2003a), in an electronic supplement to this paper (Table S1).

We also use a series from Aspendale near Melbourne, Australia, from the 1950s. Observations with Dobson spectrophotometer #12 began in July 1955. Measurements were taken near noon. Standard observational and calibration procedures were used (Funk and Garham, 1962). The data since the IGY are today found in the WOUDC data base. Concerning the earlier data, monthly means are found in various sources (Normand 1960, Funk and Garham, 1962, as well as the scans from the Ozone Office), but the individual values have so far not been published (the original data sheets are held at the National Archives of Australia). We converted the data to the Bass-Paur scale using a scaling factor of 1.041.

For comparison with later periods (1990s and 2010s), we used total column ozone from the WOUDC data base, namely from Lauder, NZ as well as Melbourne (measurements were performed in the city in the 1990s and at the airport in the 2010s). All locations of the sites are shown on Figure 1.

Further, we also used zonally averaged total column ozone data sets in order to embed the Wellington series from the 1950s into a long term and global context. For the 1950s we use the HISTOZ assimilated ozone data set (Brönnimann et al., 2013), which is based on an off-line assimilation of historical total column ozone series into an ensemble of chemistry climate model simulations (note that the monthly Aspendale data from 1955 onward have been assimilated). For the 1990s we use the Zonal Mean Ozone Binary Database of Profiles (BDBP, Bodeker et al., 2013) and for the 2010s we use the MOD7 release of the SBUV (Version 8.6) merged total and profile ozone data set (Frith et al., 2014).

Comparisons were also performed with radiosonde and other upper-level data. We used radiosonde data from IGRA2 (Durre et al., 2018) originating back to TD54 (see Stickler et al., 2010). We used data from Auckland (1949-1957) for comparison with the Wellington ozone data (at 490 km distance) and from Invercargill airport (1950-2020) for comparison with Lauder ozone data for the period (1987-2010). Radiosonde data from Norfolk Island (1943-2020) were also used for analysing spatial patterns. For the Downham Market data, no nearby radiosonde station was available. We compared the total column ozone data with geopotential height and temperature at all levels from the surface to the lower stratosphere. All three stations were used to check the flow field for individual days. The locations of the stations are also shown in Fig. 1.

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Total column ozone data provide an excellent opportunity to assess the quality of upper-air data sets. Brönnimann and Compo (2012) use total column ozone from the 1950s and 1960s to assess the quality of the Twentieth Century Reanalysis data set version 2 (Compo et al., 2011). This data set does not assimilate any upper air information, so it is interesting to know how good the data agree with total column ozone observations. Additional data sets became available in later years, including ERA20C (Poli et al., 2016). Hersbach et al. (2017) produced a reanalysis for the period 1939-1963 assimilating historical upper-air data, termed ERA-PreSAT, and compared it with 20CRv2 and ERA20C with respect to their correlation with historical total ozone data in the period 1939-1963. Best correspondence was found with ERA-preSAT, but no historical ozone data over Australia or New Zealand were used.

In the meantime, further data sets have become available, including CERA-20C (Laloyaux et al., 2018) and 20CRv3 (Slivinski et al., 2019). Here we compare both historical total column ozone data series with the three reanalysis data sets ERA-PreSAT, 20CRv3, and CERA20C. For the processing, as in Brönnimann and Compo (2012) and Hersbach et al. (2017), all data were deseasonalised by subtracting the first two harmonics of the seasonal cycle, and then Pearson correlations were calculated. For the case of Downham Market, which only covers one year, we fitted only the first harmonic function.

4. Results

4.1. Downham Market

We start the results with the shorter series of Downham Market, which is simpler as it allows fewer comparisons. We first analysed correlations. Table 1 lists the correlations between the re-evaluated Downham Market data (without the flagged values) and other total column ozone series before and after deseasonalising. Note that for the reanalyses 20CRv3 and CERA-20C, we used the ensemble mean.

Correlations are generally high. Even with the series of Arosa (at almost 1000 km distance), a correlation of 0.78 was found (not shown). For the nearby Oxford series as well as for ERA-preSAT, correlations exceed 0.90 on the absolute values and 0.75 on the anomalies. The corresponding scatter plot (Fig. 6) for these two cases shows a linear relation with no apparent deviations for high or low values. The 20CRv3 reanalysis, which in contrast to ERA-PreSAT does not assimilate upper-level variables, also shows very high correlations. Slightly lower correlations are found for CERA-20C.

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We also analysed ozone fields for individual days. For this we supplemented the Downham Market ozone observations with other observations from Europe, as given in Brönnimann et al., 2003b). Five days were selected with good data coverage and pronounced positive or negative anomalies of observed total column ozone over Downham Market. For these days, observed ozone is plotted together with ozone from ERA-PreSAT (Fig. 7). We find a good agreement between Downham Market and neighbouring stations as well as with ERA-PreSAT total column ozone fields in all cases. In fact, most of the stations show a good agreement, in this sense confirming the value of historical total column ozone data.

4.2. Wellington

For Wellington, in addition to similar analyses as for Downham Market, we also analysed the series in a longer term context. Furthermore, we also compare the series with radiosonde data from the stations displayed in Fig. 1.

Results of the correlation between Auckland radiosonde data and total column ozone in Wellington are given in Table 2. For comparability purposes, we performed the same analysis for a more recent period (1987-2010), with Invercargill radiosonde data and total column ozone measurements in Lauder. From all series, the first two harmonics of the seasonal cycle were subtracted, then the anomalies were correlated. As expected for a midlatitude site, we find negative correlations with geopotential height at all levels, but strongest near the tropopause and decreasing towards the surface and towards the stratosphere. For temperatures, correlations change sign at the tropopause, i.e., high total column ozone is related to a low tropopause altitude and to a cold upper troposphere and a warm lower stratosphere.

Correlations are lower for the historical period than for the recent period. Differences could be explained by the shorter spatial distance between Lauder and Invercargill (180 km) than between Wellington and Auckland (490 km) and also the shorter temporal distance (in the historical period radiosondes were launched once per day, first at 11 UTC, later at 0 UTC, whereas in the second period we have twice daily soundings of which we chose the closer), but also due to a lower quality of both data sources (ozone measurements and radiosonde). Nevertheless, with correlations approaching -0.5 at the tropopause-level, results show that day-to-day variability in total column ozone is likely to be well captured.

Next we compared Wellington ozone with ozone from reanalysis data sets (Table 3). Absolute values of the reprocessed Wellington observations are 5.5% (adjusted coefficients) or 8%

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(Bass-Paur) higher than those from the reanalyses. This is not due to outliers or specific periods, but seems to be a feature of the bulk data. Correlations are lower than for Downham Market, as expected since in the area of New Zealand, the reanalyses are not well constrained. Nevertheless, we find correlations of around 0.6 to 0.8 for absolute values and of 0.45 for anomalies. Lowest correlations on the anomalies are again found for CERA-20C. There is no clear difference between the observation modes, except that the "infilled" daily data from the Ozone Office are slightly worse (pointing to the value of working with original material).

As for Downham Market, we analysed some specific cases for Wellington. Figure 8 shows a day with particularly high total column ozone in the series of Wellington. High ozone values at midlatitudes are mostly due to upper-level troughs. The reanalyses ERA-PreSAT and 20CRv3 both reproduce higher ozone values related to an upper trough (100 hPa geopotential height is also indicated), but do not reproduce the absolute value. 20CRv3 shows stronger gradients in both fields.

4.3. The long-term view

Finally, we also put the reanalysed series from Wellington in a long term context (Fig. 9). We compared the decadally averaged seasonal cycle for the 1950s (both for the Bass-Paur coefficients and the adjusted coefficients) with that from Lauder from the 1990s (corresponding to the peak of ozone depletion) and the 2010s. At least ten days were required to form a monthly average from which decadal averages were then taken. Also shown on the same figure are data from Aspendale/Melbourne for the three periods, and to the plot of the first period we also added the Canberra, 1929-1932 series. Note that Canberra and Melbourne are further north than Wellington, Lauder is further south. To make ozone at the different latitudes comparable, we added offsets that were calculated from MOD7 zonal averaged data (differences between the corresponding latitudes).

For the same three periods we also show zonal average total column ozone as a function of latitude and calendar month in the assimilated total ozone data set HISTOZ (Brönnimann et al., 2013; note that this data set does not assimilate the Wellington data) for the 1950s, together with corresponding data from Bodeker et al. (2013) for the 1990s and from the MOD7 SBUV merged data set for the 2010s. Note that the latitude-calendar month plots are based on three different data sets. However, HISTOZ is by construction consistent with BDBP, and the difference between MOD7 and BDBP is marginal.

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For the 1950s, the shape of the curves agrees well, but there are considerable differences in the levels, reflecting the uncertainty in absolute values. The Wellington curve with adjusted coefficients is the lowest the Canberra series is (on average) the highest. Comparing the figures for the 1950s and the 1990s, we find a large decrease between the two time periods. This decrease is much stronger than the uncertainty between the data sets. Both in the station data as well as in the global data set the change from the pre-ozone depletion climatology to the maximum decade of ozone depletion, the 1990s, is thus clearly visible. Ozone depletion is not just visible over Antarctica in spring, but also year round at southern midlatitudes and in the subtropics. From the 1990s to the 2010s, a slight increase is seen at most latitudes in MOD7, but hardly near 40° S. Likewise, only a faint increase is seen in the Lauder observations.

5. Discussion

The re-evaluated total column ozone series from Wellington is internally consistent, although its absolute level remains difficult to assess in absence of calibration information. From the comparisons in Fig. 3 and assuming that in any comparison both series contribute roughly equally to the error of the difference, a standard deviation of 13 DU in the difference between two series is equivalent to a random error (standard deviation) of 9 DU in each of the two series. We can therefore assume that in the reprocessed Wellington series the random error (in terms of a standard deviation) is better than 10 DU. The systematic error is of approximately the same magnitude. The choice of the absorption coefficients leads to a difference of 8.8 DU, however, other uncertainties add to this. Comparisons with reanalysis data but also HISTOZ suggest that the Wellington data are too high, but comparisons with Aspendale and Canberra data (which are of a still lower quality, though) suggest that the data are too low. Too high values could be due to calibration errors, or due to a too small aerosol correction. However, high values are also possible for dynamical reasons such as a negative phase of the Southern Annular Mode (SAM). In fact, pressure reconstructions indicate a sequence of years with negative SAM in the 1950s (Fogt et al., 2011, 2016). In any case, we recommend using the Wellington data with the adjusted coefficients, which best uses all information present to the authors, although important pieces of information are lacking.

The Downham Market data are surprisingly precise, with a much higher correlation with independent data than that data from Wellington. Also the absolute level is arguably better determined as this series is statistically adjusted while the Wellington data are completely independent from any other series. However, despite the good statistical performance, the

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524 Downham Market data is of a different quality merely based on the fact that we do not have
525 raw data.

526 Both the Downham Market, UK, and Wellington, NZ, data well depict day-to-day variability,
527 which is closely related to the flow near the tropopause (Steinbrecht et al., 1998). This is
528 evidenced by the high correlation with radiosonde data in the case of Wellington and points to
529 a good quality of the ozone data. Note that lower correlations between total ozone and upper-
530 level variables are expected in the southern midlatitudes than at northern midlatitudes (see
531 Brönnimann and Compo, 2012). However, as we have no calibration information and no
532 intercomparison data, the series may not have trend quality.

533 For Downham Market, a large correction was necessary, but correlation with Oxford ozone
534 observations likewise suggests a high quality with respect to short-term changes, which is
535 surprising given the almost illegible data sheet. However, both the Oxford series and the
536 Donwham Market series might have been affected by tropospheric aerosols. This was the
537 reason why Dobson did not consider the Oxford series as very valuable for science, and the
538 same might also be the case for Downham Market.

539 Once the reliability of day-to-day variations in the ozone data is established, they can be used
540 to assess historical reanalysis products. In Brönnimann and Compo (2012), anomaly
541 correlations between observed and 20CRv2 ozone in Christchurch (in the 1920s) was found to
542 be around 0.5 (a similar value as for Wellington); for Europe anomaly correlations exceeding
543 0.6 were found. Hersbach et al. (2017) found anomaly correlations of 0.6 to 0.8 for total
544 column ozone in ERA-PreSAT, which is similar to what we find for Downham Market. We
545 find even higher correlations in our case, which might be due to better data but more likely
546 also reflect improvements in the reanalysis products.

547 Note that the quality of the Wellington data has not been tested for use in trend studies, and
548 we recommend not to use the data for trend analysis given the reported problems with the
549 instrument. Together with other data sources, the series nevertheless provides a glimpse at
550 ozone variability in the pre-ozone depletion era, which can be compared to later periods. All
551 data sources together illustrate a decrease in total column ozone from the 1950s to the 1990s,
552 approximately the time of minimum ozone (Solomon, 1999; Staehelin et al., 2001). An
553 increase is found in some data sets and stations since then and interpreted as a sign of ozone
554 recovery (Solomon et al., 2016). In the case of the southern midlatitude, an increase from the
555 1990s to the 2010s is hardly detectable. Historical data such as those from Wellington are
556 valuable as they depict ozone at southern mid-latitudes prior to the onset of ozone depletion.

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Taken together, the data indicate that recovery is still far from complete. Values have not nearly returned to the 1950s state.

6. Conclusions

Historical total column ozone data are relevant not just for analyses of long term changes in the ozone layer, but also as a diagnostic of day-to-day atmospheric dynamics near the tropopause. In this paper we present historical series from Wellington, New Zealand, 1951-1959 and Downham Market, UK, November 1950 to October 1951. The data are re-evaluated and analysed with respect to their quality. The former series will be made available via the World Ozone and Ultraviolet Data Centre. Both series are published in the electronic supplement, together with other historical total column ozone series used in this paper and described in Brönnimann et al. (2003a).

The analyses reveal a good depiction of day-to-day variability, a fact which can be used to assess the quality of reanalysis products, since the data cover a region and time period with only few upper-air data. We show comparisons with the three reanalyses ERA-PreSAT (which assimilates upper-air data), 20CRv3 and CERA20C, all of which show high correlations, particularly over Europe, but also over New Zealand. Eventually, historical total column ozone data could also be assimilated into historical reanalysis products.

The Wellington data were combined with other data sources to assess long-term ozone changes over New Zealand. The 1950s in this context represent the era prior to the onset of ozone depletion. Together, the data suggest that the recovery of the ozone is underway, but is still far from the state it had in the 1950s. It should be noted, however, that the historical Wellington data arguably do not have trend quality.

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References

Bodeker, G. E., Hassler, B., Young, P. J., and Portmann, R. W.: A vertically resolved, global, gap-free ozone database for assessing or constraining global climate model simulations, Earth Syst. Sci. Data, 5, 31–43, doi:10.5194/essd-5-31-2013, 2013.

Bojkov, R. D.: International Ozone Commission: History and activities. IAMAS Publication Series No. 2, 2012.

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.

https://doi.org/10.5194/acp-2020-654
Preprint. Discussion started: 28 July 2020

Atmospheric Chemistry and Physics Discussions

592 Brönnimann, S., Bhend, J., Franke, J., Flückiger, S., Fischer, A. M., Bleisch, R., Bodeker, G., Hassler, B.,
593 Rozanov, E., and Schraner, M.: A global historical ozone data set and signatures of El Niño and the 11-yr
594 solar cycle, Atmos. Chem. Phys., 13, 9623-9639, 2013.

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

597 Brönnimann, S. and Compo, G. P.: Ozone highs and associated flow features in the first half of the twentieth
598 century in different data sets, Meteorol. Z., 21, 49-59, 2012.

599 Brönnimann, S., Staehelin, J., Farmer, S. F. G., Cain, J. C., Svendby, T. M., and Svenøe, T.: Total ozone
600 observations prior to the IGY. I: A history, Q. J. Roy. Meteorol. Soc., 129B, 2797–2817, 2003a.

601 Brönnimann, S.: Climatic changes since 1700, Springer, Advances in Global Change Research Vol. 55, xv + 360
602 pp., doi:10.1007/978-3-319-19042-6, 2015.

603 Dobson, G. M. B. and Normand, C. W. B.: Determination of constants used in the calculation of the amount of
604 ozone from spectrophotometer measurements and an analysis of the accuracy of the results, Ann. Int.
605 Geophys. Year, 16, 161– 191, 1957.

606 Dobson, G. M. B., Kimball, H. H., and Kidson, E.: Observations of the amount of ozone in the Earth's
607 atmosphere and its relation to other geophysical conditions, Part IV, Proc. Phys. Soc. London, Ser. A,
608 129(811), 411–433, 1930.

609 Dobson, G. M. B.: A photoelectric spectrophotometer for measuring the amount of atmospheric ozone, Proc.
610 Phys. Soc. London, 43, 324–339, 1931.

611 Dobson, G. M. B.: Adjustment and calibration of ozone spectrophotometer, Ann. Int. Geophys. Year, 5, 90– 114,
612 1957b.

613 Dobson, G. M. B.: Observers handbook for the ozone spectrophotometer, Ann. Int. Geophys. Year, 5, 46–89,
614 1957a.

615 Durre, I., Yin, X., Vose, R. S., Applequist, S., and Arnfield, J.: Enhancing the Data Coverage in the Integrated
616 Global Radiosonde Archive, J. Atmos. Oceanic Technol., 35, 1753–1770, 2018.

617 Fabry, C., and Buisson, H.: Etude de l'extremit´e ultra-violette du spectre solaire, J. Phys. Rad., Série 6, 2, 197–
618 226, 1921.

619 Farkas, E.: Measurements of Atmospheric Ozone at Wellington, New Zealand. New Zealand Meteorological
620 Service, Technical Note 114, 1954.

621 Farkas, E.: Ozone observations and research in New Zealand–A historical perspective. Current Science, 63, 722-
622 727, 1992.

623 Fogt, R. L., Perlwitz, J., Monaghan, A. J., Bromwich, D. H., Jones, J. M., and Marshall, G. J.: Historical SAM
624 variability, part II: 20th century variability and trends from reconstructions, observations, and the IPCC AR4
625 models, J. Clim., 22, 5346– 5365, 2009.

626 Fogt, R. L., Jones, J. M., Goergens, C. A., Jones, M. E., Witte, G. A., and Lee, M. Y.: Antarctic station ‐ based
627 seasonal pressure reconstructions since 1905: 2. Variability and trends during the twentieth century, J.
628 Geophys. Res. Atmos., 121, 2836– 2856, 2016.

629 Frith, S. M., Kramarova, N. A., Stolarski, R. S., McPeters, R. D., Bhartia, P. K., and Labow, G. J.: Recent
630 changes in total column ozone based on the SBUV Version 8.6 Merged Ozone Data Set, J. Geophys. Res.
631 Atmos., 119, 9735-9751, doi:10.1002/2014JD021889, 2014.

632 Funk, J. P. Garham, G. L.: Australian ozone observations and a suggested 24 month cycle, Tellus, 14, 378–382,
633 1962.

634 Hersbach, H., Brönnimann, S., Haimberger, L., Mayer, M., Villiger, L., Comeaux, J., Simmons, A., Dee, D.,
635 Jourdain, S., Peubey, C., Poli, P., Rayner, N., Sterin, A. M., Stickler, A., Valente, M. A. and Worley, S. J.:
636 The potential value of early (1939–1967) upper-air data in atmospheric climate reanalysis, Q. J. Roy.
637 Meteorol. Soc., 143, 1197–1210, 2017.

638 Komhyr, W. D. and Evans, R.: Operations handbook – Ozone observations with a Dobson Spectrophotometer,
639 Tech. Rep. 51, Global Ozone Res. and Monitor. Proj., World Meteorol. Org., Geneva, 2007.

640 Komhyr, W. D., Mateer, C. L., and Hudson, R. D.: Effective Bass-Paur absorption coefficients for use with
641 Dobson spectro-photometers, J. Geophys. Res., 98, 20,451– 20,465, 1993.

642 Komhyr, W. D.: Operations handbook—Ozone observations with a Dobson Spectrophotometer, Global Ozone
643 Res. and Monitor. Proj., World Meteorol. Org., Geneva, 1980.

644 Laloyaux, P., de Boisseson, E., Balmaseda, M., Bidlot, J. ‐ R., Brönnimann, S., Buizza, R., Dalhgren, P., Dee,
645 D., Haimberger, L., Hersbach, H., Kosaka, Y., Martin, M., Poli, P., Rayner, N., Rustemeier, E., and

https://doi.org/10.5194/acp-2020-654
Preprint. Discussion started: 28 July 2020

Atmospheric Chemistry and Physics Discussions

Schepers, D.: CERA‐20C: A coupled reanalysis of the Twentieth Century. J. Adv. Model. Earth Syst., 10, 1172–1195, doi:10.1029/2018MS001273, 2018.

Müller, R.: A brief history of stratospheric ozone research, Meteorol. Z., 18, 3-24, 2009.

Nichol., S.: Dobson spectrophotometer #17: past, present and future, Weather & Climate 38, 16-26, 2018.

Normand, C. W. B.: Ozone data tables. In: Ozone values (International Ozone Commission). Report MO 19/3/9 Part I (formerly MO 15/90), Met Office, 1961.

Poli, P., Hersbach, H., Dee, D. P., Berrisford, P., Simmons, A. J., Vitart, F., Laloyaux, P., Tan, D. G., Peubey, C., Thépaut, J., Trémolet, Y., Hólm, E. V., Bonavita, M., Isaksen, L., and Fisher, M.: ERA-20C: An atmospheric reanalysis of the twentieth century, J. Climate, 29, 4083–4097, https://doi.org/10.1175/JCLI-D-15-0556.1, 2016.

Scrase, F. J.: Radiosonde and radar wind measurements in the stratosphere over the British Isles, Q. J. Roy. Meteorol. Soc., 77, 483-488, 1951.

Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., Allan, R., Yin, X., Vose, R., Titchner, H., Kennedy, J., Spencer, L. J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Crouthamel, R., Domínguez‐Castro, F., Freeman, J. E., Gergis, J., Hawkins, E., Jones, P. D., Jourdain, S., Kaplan, A., Kubota, H., Le Blancq, F., Lee, T., Lorrey, A., Luterbacher, J., Maugeri, M., Mock, C. J., Moore, G. K., Przybylak, R., Pudmenzky, C., Reason, C., Slonosky, V. C., Smith, C., Tinz, B., Trewin, B., Valente, M. A., Wang, X. L., Wilkinson, C., Wood, K. and Wyszyński, P.: Towards a more reliable historical reanalysis: Improvements to the Twentieth Century Reanalysis system, Q. J. Roy. Meteorol. Soc., 145, 2876– 2908, 2019.

Solomon, S.: Stratospheric ozone depletion: A review of concepts and history, Rev. Geophys., 37, 275–316, 1999.

Solomon, S., Ivy, D. J., Kinnison, D., Mills, M. J., Neely III, R. R., and Schmidt, A.: Emergence of healing in the Antarctic ozone layer, Science, 353, 269-274, 2016.

Staehelin, J., Harris, N. R. P., Appenzeller, C., and Eberhard, J.: Ozone trends – A review, Rev. Geophys., 39, 231–290, 2001.

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.

Steinbrecht, W., Claude, H., Köhler, U., and Hoinka, K. P.: Correlations between tropopause height and total ozone: Implications for long-term changes, J. Geophys. Res., 103, 19183–19192, 1998.

Stickler, A., Grant, A. N., Ewen, T., Ross, T. F., Vose, R. S., Comeaux, J., Bessemoulin, P., Jylhä, K., Adam, W. K., Jeannet, P., Nagurny, A., Sterin, A., Allan, R., Compo, G. P., Griesser, T., and Brönnimann, S.: The comprehensive historical upper-air network, Bull. Amer. Meteorol. Soc., 91, 741-751, 2010.

Vanicek, K., Dubrovsky, M., Stanek, M.: Evaluation of Dobson and Brewer total ozone observtaions from Hradec Králové, Czech Republic, 1961-2002, Publication of the Czech Hydrometeorological Institute, ISBN: 80-86690-10-5, Prague, 2003

Vigroux, E.: Contribution a l'étude expérimentale de l'absorbtion de l'ozone, Ann. Phys., Série 12, 8, 709–762, 1953.

Vogler, C., Brönnimann, S., and Hansen, G.: Re-evaluation of the 1950-1962 total ozone record from Longyearbyen, Svalbard, Atmos. Chem. Phys., 6, 4763-4773, 2006.

Vogler, C., Brönnimann, S., Staehelin, J., and Griffin, R. E. M.: The Dobson total ozone series of Oxford: Re-evaluation and applications, J. Geophys. Res., 112, D20116, doi:10.1029/2007JD008894, 2007.

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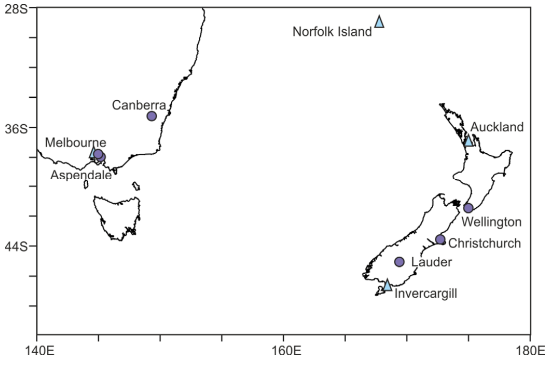
689 **Figures**



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692 **Fig. 1.** Map of the stations used (circles: ozone, triangles: upper-air).

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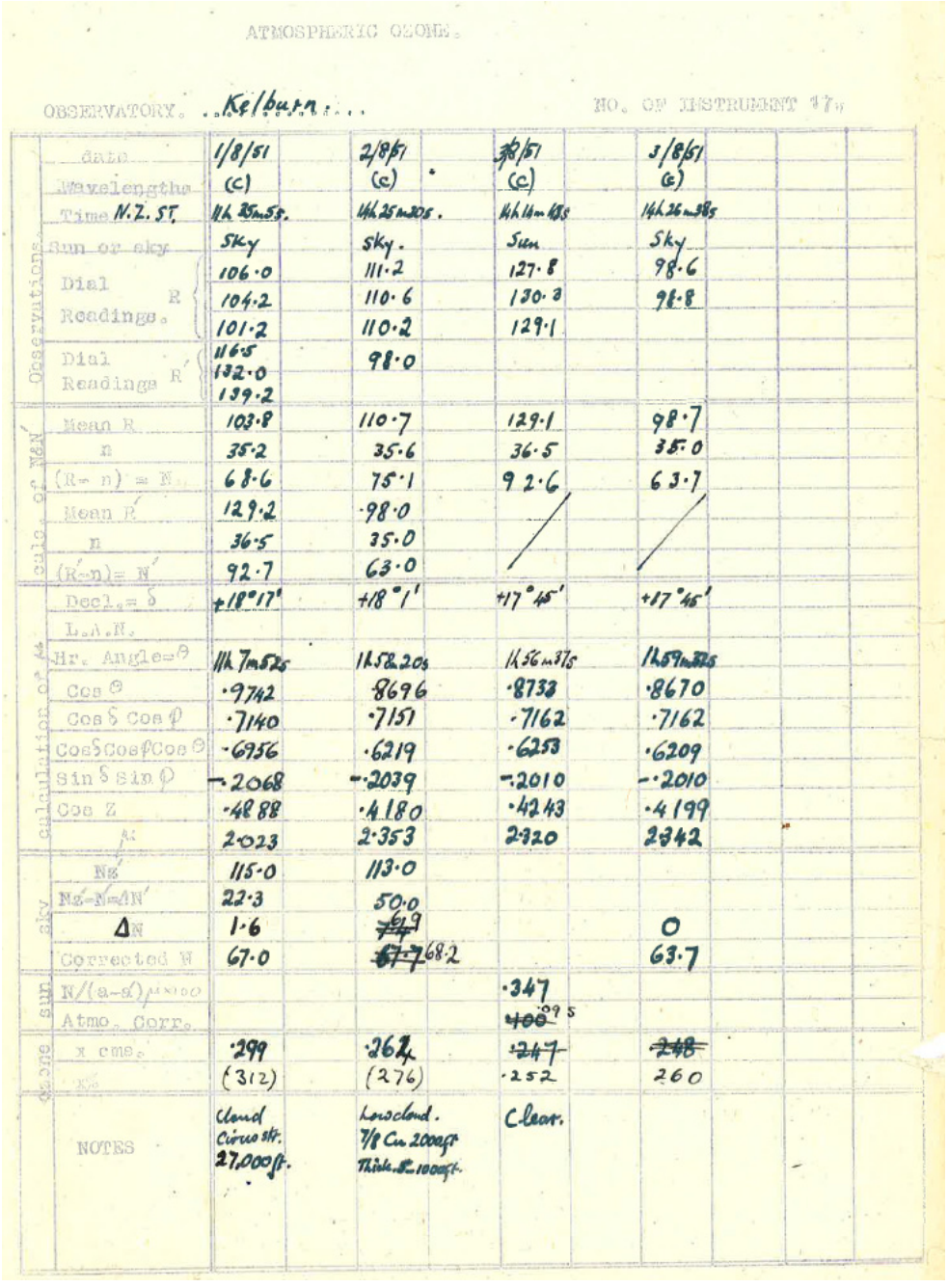

ATMOSPHERIC OZONE.

OBSERVATORY. Kelburn. NO. OF INSTRUMENT 47.

Observations	date	1/8/51	2/8/51	3/8/51	3/8/51
	Wavelengths	(c)	(c)	(c)	(c)
	Time N.Z.S.T.	11h 35m 5s.	14h 25m 30s.	14h 16m 43s	14h 26m 38s
	Sun or sky	Sky	Sky.	Sun	Sky
	Dial Readings. R	106·0	111·2	127·8	98·6
		104·2	110·6	130·3	98·8
		101·2	110·2	129·1	
	Dial Readings R′	116·5	98·0		
		132·0			
		139·2			
Calculation of N & N′	Mean R	103·8	110·7	129·1	98·7
	n	35·2	35·6	36·5	35·0
	(R − n) = N	68·6	75·1	92·6	63·7
	Mean R′	129·2	98·0		
	n	36·5	35·0		
	(R′−n)= N′	92·7	63·0		
Calculation of A	Decl.= δ	+18°17′	+18°1′	+17°45′	+17°45′
	L.A.N.				
	Hr. Angle=θ	11h 7m 52s	11h 58m 20s	11h 56m 37s	11h 59m 22s
	Cos θ	·9742	·8696	·8733	·8670
	Cos δ Cos φ	·7140	·7151	·7162	·7162
	Cos δ Cos φ Cos θ	·6956	·6219	·6253	·6209
	Sin δ Sin φ	−·2068	−·2039	−·2010	−·2010
	Cos Z	·4888	·4180	·4243	·4199
	A	2·023	2·353	2·320	2·342
Sky	Ng′	115·0	113·0		
	Ng′−N=ΔN′	22·3	50·0		
	ΔN	1·6	~~67·9~~		0
	Corrected N	67·0	~~67·7~~ 68·2		63·7
Sun	N/(a−d)			·347	
	Atmo. Corr.			~~400~~ 399 s	
Ozone	x cms.	·299	·262	~~·247~~	~~·248~~
		(312)	(276)	·252	260
	NOTES	Cloud Cirro str. 27,000 ft.	Low cloud. 7/8 Cu 2000 ft Thick. St. 1000 ft.	Clear.	

Fig. 2. Original data sheet from Wellington, NZ.

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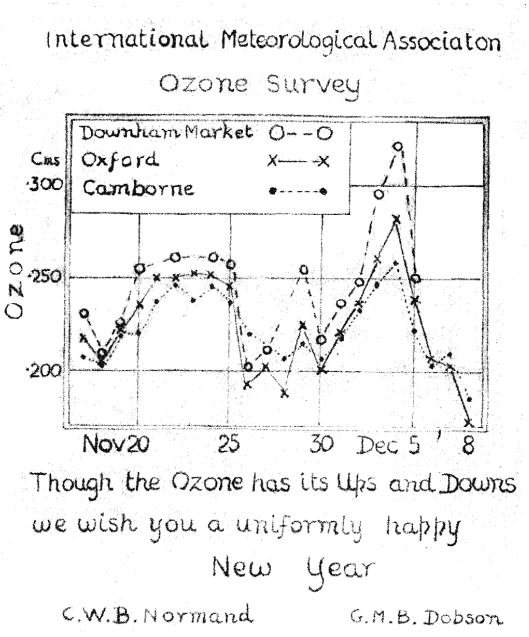

Fig. 3. New Years Card with data from Downham Market, 1950.

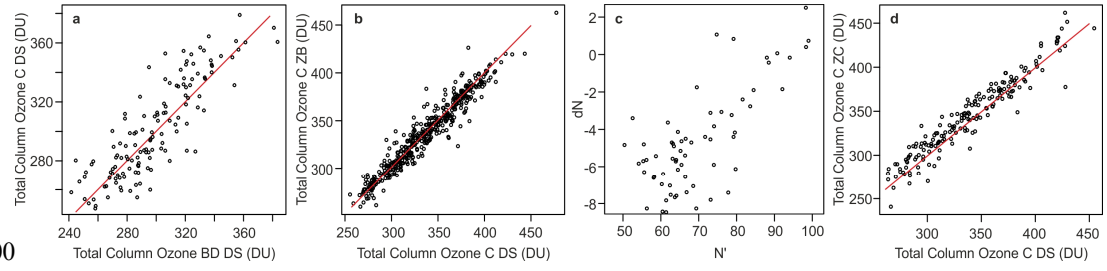

Fig. 4. Comparisons of (a) BD and C wavelength pair direct sun calculations, (b) fitted C ZB data against C DS observations, (c) *dN* versus *N'* for C ZC observations and (d) reduced C ZC observations versus quasi-simultaneous C DS observations. Here results are shown for the case with Bass-Paur absorption coefficients; plots for the adjusted coefficients are indistinguishable. One-to-one lines are shown in red.

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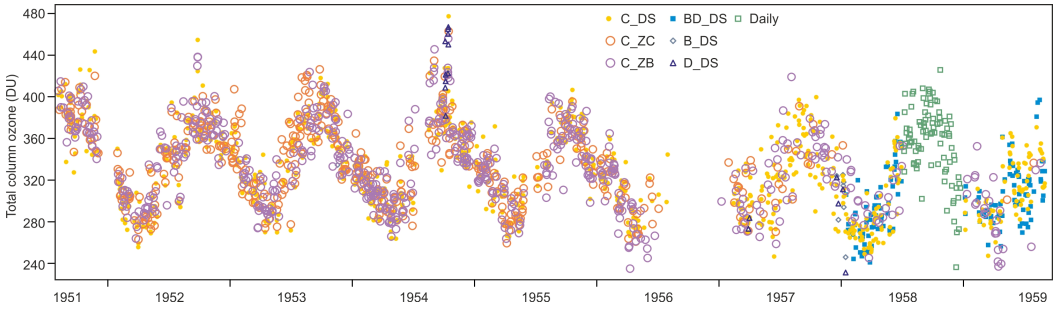

706

707 **Fig. 5.** Total column ozone at Wellington, 1951-1959 for different wavelength pairs and observation modes
708 (here for the case of Bass-Paur coefficients).

709

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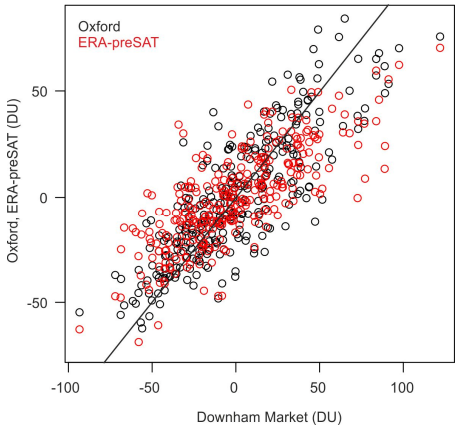

711

712 **Fig. 6.** Scatter plot of deseasonalised total column ozone data at Downham market against measurements
713 performed in Oxford as well as total column ozone data from the closest grid cell in ERA-PreSAT. The one-to-
714 one line is shown in black.

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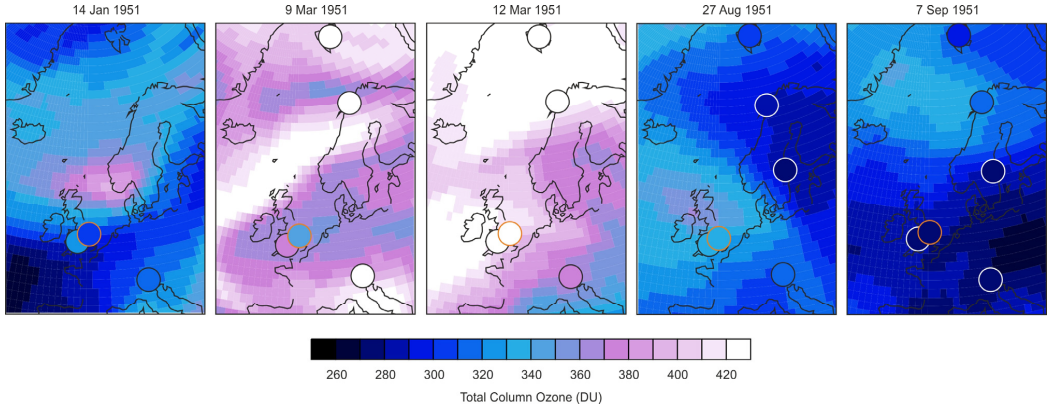
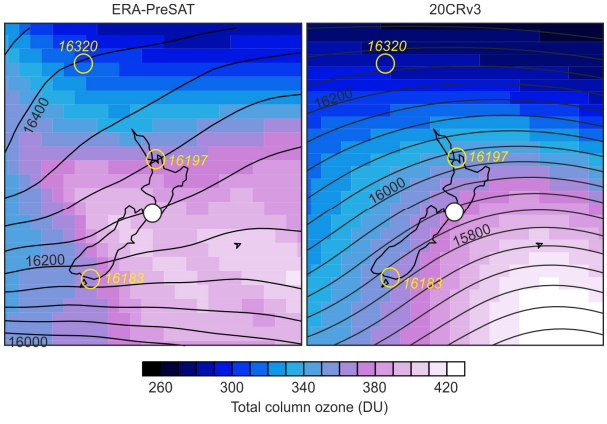


716

717 **Fig. 7.** Total column ozone in ERA-PreSAT as well as in observations from various stations on five days in the
718 year 1951 (Downham Market is marked with an orange outline of the circle).

719



720

721 **Fig. 8.** Total column ozone and 100 hPa geopotential height on 25 Sep 1952 in ERA-PreSAT (left) and 20CRv3
722 (right). The filled circle indicates the measured total column ozone value at Wellington (434.6 DU, adjusted
723 coefficients), open circles indicate geopotential height from radiosonde (taken 12 hours later).

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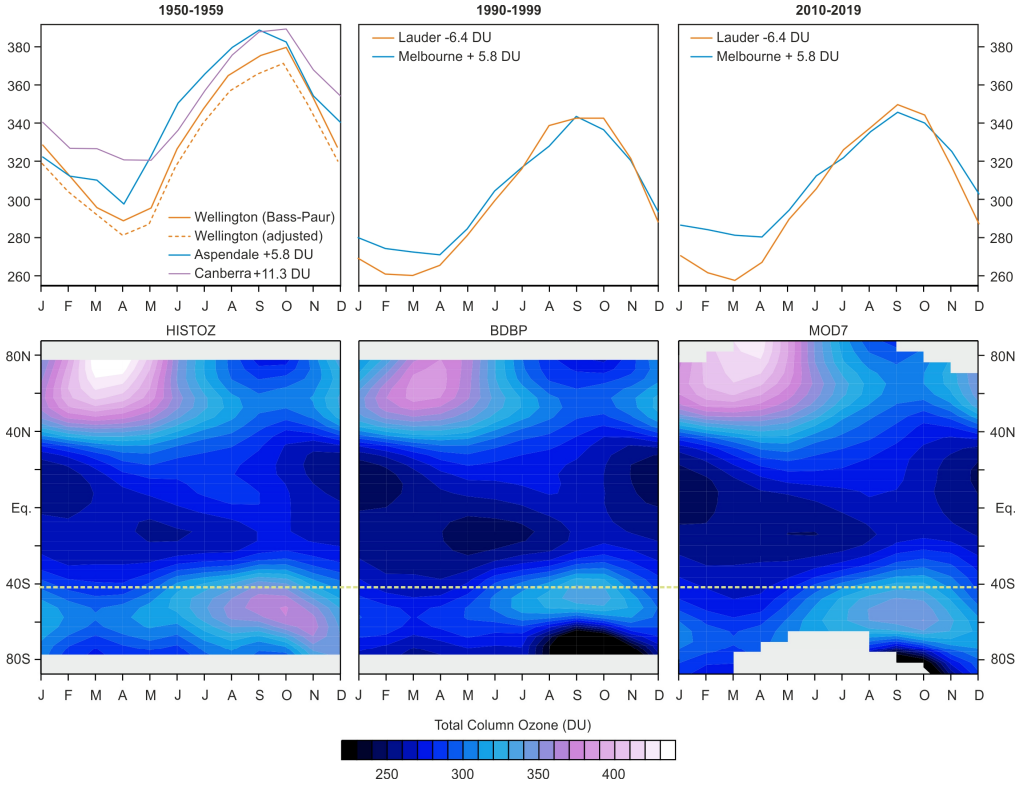

725

726 **Fig. 9.** Top: Decadally averaged annual cycle from total column ozone measurements in New Zealand and
727 Australia in the 1950s, 1990s, and 2010s. Note that the series are adjusted according to the annual mean offset
728 between the corresponding latitudes and that of Wellington in MOD7. Bottom: Zonally averaged total column
729 ozone as a function of calendar month and latitude in the data sets HISTOZ (1950s), BDBP (1990s) and MOD7
730 SBUV merge (2010s). The bottom left and middle panels are from Brönnimann (2015). Lauder and MOD7 data
731 end in 2018. The dashed line indicates the latitude of Wellington. Grey: No data.

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Tables

Table 1. Pearson correlation coefficients of the re-evaluated total column ozone series from Downham Market with other column ozone series. Anomalies refer to the values after subtracting the first harmonic function in terms of day of year.

Compared series	Absolute	Anomalies
Oxford	0.91	0.83
ERA-PreSAT	0.90	0.75
20CRv3 ens. mean	0.84	0.74
CERA-20C ens. mean	0.84	0.69

Table 2. Correlation coefficients (after deseasonalising) between total column ozone at Wellington and radiosonde geopotential height and temperature at Auckland (1951-1957) as well as total column ozone at Lauder and radiosonde data at Invercargill (1987-2010); see Fig. 1 for locations.

p (hPa)	GPH	T	GPH	T
	Wellington		Lauder	
1000	-0.22	-0.18	-0.17	-0.44
850	-0.28	-0.35	-0.34	-0.50
700	-0.35	-0.40	-0.43	-0.56
500	-0.42	-0.41	-0.53	-0.59
400	-0.44	-0.40	-0.56	-0.58
300	-0.46	-0.25	-0.59	-0.51
200	-0.45	0.16	-0.60	0.28
100	-0.33	0.42	-0.40	0.69

Table 3. Correlation coefficients (before and after deseasonalising) between total column ozone at Wellington and in other data sets (1951-1959) for different (the table relates to the case of Bass-Paur coefficient; results are almost indistinguishable for the adjusted coefficients).

		all	C-DS	C-ZB	C-ZC	BD	Daily
ERA-PreSAT	abs	0.65	0.66	0.65	0.68	0.71	0.66
20CRv3	abs	0.77	0.77	0.83	0.81	0.66	0.46
CERA-20C	abs	0.66	0.65	0.68	0.69	0.67	0.64
ERA-PreSAT	anom	0.44	0.45	0.45	0.48	0.51	0.36
20CRv3	anom	0.42	0.43	0.53	0.44	0.52	0.29
CERA-20C	anom	0.37	0.35	0.46	0.39	0.44	0.31