Earth Syst. Sci. Data Discuss., 5, 445–473, 2012
www.earth-syst-sci-data-discuss.net/5/445/2012/
doi:10.5194/essdd-5-445-2012

Earth System Science Data Discussions
Open Access

Dobson, Brewer, ERA-40 and ERA-Interim original and assimilated total ozone data sets – evaluation of differences: a case study, Hradec Králové (Czech), 1961–2010

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Received: 26 April 2012 – Accepted: 8 May 2012 – Published: 30 May 2012

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Published by Copernicus Publications.

Abstract

Homogenized data series of total ozone measurements taken by the regularly and well calibrated Dobson and Brewer spectrophotometers at Hradec Králové (Czech) and the data from the re-analyses ERA-40 and ERA-Interim were assimilated and combined to investigate differences between the particular data sets over Central Europe, the NH mid-latitudes. The Dobson-to-Brewer transfer function and the algorithm for approximation of the data from the re-analyses were developed, tested and applied for creation of instrumentally consistent and completed total ozone data series of the 50-yr period 1961–2010 of observations. The assimilation has reduced the well-known seasonal differences between Dobson and Brewer data below the 1 % calibration limit of the spectrophotometers. Incorporation of the ERA-40 and ERA-Interim total ozone data on days with missing measurements significantly improved completeness and reliability of the data series mainly in the first two decades of the period concerned. Consistent behaviour of the original and assimilated data sets was found in the pre-ozone-hole period (1961–1985). In the post-Pinatubo (1994–2010) era the data series show seasonal differences that can introduce uncertainty in estimation of ozone recovery mainly in the winter-spring season when the effect of the Montreal Protocol and its Amendments is expected. All the data sets confirm substantial depletion of ozone also in the summer months that gives rise to the question about its origin. The assimilated and completed data series of total ozone will be further analyzed to quantify chemical ozone losses and contribution of natural atmospheric processes to the ozone depletion over the region. This case study points out importance of selection and evaluation of the quality and consistency of the input data sets used in estimation of long-term ozone changes including recovery of the ozone layer over the selected areas. Data are available from the PANGAEA database at doi:10.1594/PANGAEA.779819.

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1 Introduction

Long-term observations of total ozone (X) are the key sources of information for evaluation of condition of the ozone layer and for estimation of trends including identification of the recovery of stratospheric ozone. Multi-decadal observations of X usually cover periods of measurements taken with different instruments and with modified operation procedures. This is why several separate data series or their versions exist at stations with the long records.

The Solar and Ozone Observatory (SOO) of the Czech Hydrometeorological Institute (CHMI) at Hradec Králové (Czech Republic) started regular measurements of total ozone in 1961 and thus its record completed the 50-yr data series in 2010. In this period the Dobson and Brewer spectrophotometers were operated at the SOO. Both instruments have created independent data sets of total ozone related through international intercomparisons to calibration scales of the world reference standards. After homogenization of the Dobson (X_D) and the Brewer (X_B) measurements for calibration and test histories of the instruments both data series showed significant seasonal differences. To avoid this instrumental signal in the merged data set and make representative statistical analyses possible a transfer function between X_D and X_B observations had to be developed and applied in assimilation of both data series.

As the Dobson observations are taken only on days with suitable weather condition there are quite a lot of days without measurements, mainly in the first two decades since 1961. The highest numbers of the missing days appeared usually in the winter months under specific weather (circulation) situations. This can influence trend analyses of total ozone over the region. Filling in the gaps by data from other sources e.g. from external re-analyses therefore could contribute to the completeness of the assimilated data sets and their application for investigation of changes of the ozone layer. But first an algorithm for integration the external data is to be developed and tested.

The above specified steps of assimilation of the datasets X_D and X_B should influence timing and magnitude of log-term changes of the ozone layer over this typical NH mid-latitude region. Such impacts have been investigated and evaluated for Hradec Králové and are presented in the last chapter. The outputs of this case study are expected to contribute to management of the different total ozone data sets prior their application in scientific studies.

2 Data and methods

2.1 Dobson data series

The Dobson spectrophotometer is a double monochromator that measures X_D by the technique of the Differential Optical Absorption Spectroscopy (DOAS). The instrument selects by slits and compares spectral irradiances of solar radiation at three wavelength pairs A, C, D in the UV part of the spectrum with strong and weak absorption by ozone (A: 305.5/325.4, C: 311.5/332.4, D: 317.5/339.9 nm). The values of X_D are then derived by the retrieval algorithm based on the Beer's law (Dobson, 1957) which supposes that any particular instrument has its slits adjusted exactly in the same pre-defined positions and that the ozone cross sections at all wavelength pairs are fixed to the ozone effective temperature $T_\text{eff} = -46.3\,^\circ\text{C}$. The total ozone values calculated from the linear combination of the double pair AD are taken as the representative X_D data with the highest priority (Komhyr, 1980; Basher, 1982).

Total ozone observations have been taken with the Dobson spectrophotometer No. 074 (D074) at the SOO since 1961. The instrument is operated and the measurements are processed according to the international standard operation procedures (Komhyr, 1980; Evans, 2008). Since 1986 the spectrophotometer has been regularly intercompared towards the international references (Fig. 1) linked to the World Standard Spectrophotometer No. 083 (Komhyr et al., 1989) with the uncertainty below 1 % (DS_AD) and tested every month by the standard and spectral lamps. Complex reconstruction of the calibration history of the D074 was performed and the calibration constants re-defined for the period 1961–2002 (Vaníček, 2003) and then continuously

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updated afterwards. Currently the D074 is maintained as the secondary Dobson standard instrument for the European region.

Re-definition of the calibration constants and digitalization of all historical records allowed homogenization and re-evaluation of quality of the whole X_D data series originated by the D074 at SOO. This included re-processing of all individual observations taken both on the Direct Sun (DS) and Zenith Sky (ZS) solar radiation, updating of the zenith polynomials and application of the Bass-Paur ozone absorption coefficients (Komhyr et al., 1993). A detailed analyses has confirmed that precision of the D074 instrument was 1–2 % for the period 1962–1979 and 1 % from 1980 onwards for DS_AD measurements and the range of the relative optical air mass of the ozone layer μ below 3.2 (Vaníček et al., 2003). The homogenized X_D data series was re-deposited into the WOUDC as a new representative Dobson data set from Hradec Králové.

2.2 Brewer data series

In January 1994 the Brewer spectrophotometer No. 098 (B098) model MK-IV (single monochromator) was installed and observations of total ozone started at the SOO. The B098 is fully automated, self-testing and PC controlled instrument constructed for permanent outdoor exposition. The principle of total ozone measurements also comes of the DOAS technique. In comparison with the Dobson algorithm the Brewer values X_B are derived from the weighted linear combination of spectral irradiances measured at five wavelengths (306.3, 310.0, 313.5, 316.8, 320.0 nm) that makes separation of total SO_2 possible (Kerr et al., 1981). As the above selected wavelengths can be re-adjusted according to the actual condition of the instrument and their ozone absorption coefficients re-defined according to the new slit functions the X_B values calculated by the Brewer algorithm are significantly less T_{eff} dependent than the Dobson X_D observations (Kerr, 2002).

The B098 instrument is intercompared and its calibration constants checked and re-defined every two years by the international travelling etalons directly linked to the World Brewer Reference Triad (Kerr et al., 1998). For the whole period of 1994–2010 the calibration offsets of the B098 were below 1 % as documented in Fig. 1. After investigation of the operational lamp tests and updating of the zenith polynomials the B098 data series X_B was re-evaluated (Vaníček, 2003; Vaníček et al., 2003) and re-deposited into the WOUDC.

2.3 Total ozone from re-analyses

Several global re-analyses of total ozone data have been produced for different time periods. The comprehensive total ozone data base 20th Century Reanalysis V2 (20CRV2 hereafter) is available at NOAA/OAR/ESRL PSD that covers period I/1871 onwards with resolution 2 × 2°. The European Centre for Medium-Range Weather Forecasts (ECMWF) created the ERA-40 re-analyses (IX/1957–VIII/2002, 2.5 × 2.5°) that is followed by the ERA-Interim (I/1979–XII/2010, 1.5 × 1.5°), see Uppala et al. (2005) and Dee et al. (2009). The above re-analyses can be exploited as external data sources to fill in missing periods/days of ground observations by interpolation from the grid points to the location of Hradec Králové (Fig. 2) and thus to fully complete the long-term total ozone data series on the daily base if more accurate statistical parameters are required. The years 1961–1975 is the most topical period for such completing at SOO. Though it covers the era of pre-satellite monitoring of stratosphere and it is out from the space observations of the ozone layer the existing Dobson and Brewer data make investigation and evaluation of methods for filling-in the gaps mainly in the 60-ties to 70-ties possible.

2.4 Transfer function of Dobson to Brewer total ozone observations

Soon after introduction of the Brewer spectrophotometers in the global network the experiences showed that substantial differences could appear between X_D and X_B measurements at stations with collocated instruments (Kerr et al., 1988; Koehler et al., 1986). As replacement of the Dobson spectrophotometers by the Brewer instruments

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can affect homogeneity of simply combined long-term records of total ozone (X_{DB}):

$$X_{DB} = X_D(\text{I}/1961\text{–XII}/1993) \cup X_B(\text{I}/1994\text{–XII}/2010) \quad (1)$$

it has been recommended to study this phenomenon more extensively and to apply proper transfer functions between both types of data series (Staehelin et al., 2002).

The first attempt to explain and quantify offsets between the X_D and X_B observations at Hradec Králové was made after 10-yr operation of B098 at SOO (Vaníček, 2006). The study confirmed a substantial seasonal cycle of the differences $X_D - X_B$ (hereafter the residuals) with the maximum offsets up to −3.5 % in the winter-spring months. These were supposed to be caused by the different temperature sensitivity of the Dobson and Brewer ozone absorption coefficients at their operational wavelengths. Nevertheless, after adjustments for the annual course of T_{eff} (Kerr, 2002) a certain seasonal amplitude of the residuals persisted and remained for analysis.

The need of assimilation of all available total ozone data series at Hradec Králové of the 50-yr period 1961–2010 initiated a more complex investigation of the differences between X_D and X_B data sets. This was made by means of 9269 simultaneous (±10-min) individual X_D (DS_AD) and X_B (DS) measurements from 1997 to 2009. The period 1997–2009 was selected due to implementation of the 1-point calibration method of B098 and after the ∼1 % shift of the calibration level of the D074 in 1997, see Fig. 1. Relative differences between the original X_D and X_B observations are displayed in percents in Fig. 3 by the black curve that shows a regular seasonal cycle exceeding the 1 % limits of the precision of measurements every winter-spring season. A detailed investigation of the Dobson versus Brewer differences that was performed at Arosa, Switzerland (Scarnato et al., 2009) showed that besides the influence of the T_{eff} also the stray light effects significantly contribute to the seasonality of the residuals. The authors therefore decided to reduce the $X_D - X_B$ differences using the transfer function of the Dobson to Brewer total ozone data defined as a second-order multi-regression polynomial (Scarnato et al., 2010):

$$X_B = a_1 X_D + a_2(k_{TD} X_D) + a_3(\mu X_D) + a_4(\mu X_D)^2 + \varepsilon \quad (2)$$

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where X_B and X_D are simultaneous Brewer and Dobson total ozone measurements, $a_1 \ldots a_4$ are regression coefficients, k_{TD} is correction factor for the T_{eff} influence, μ is relative optical air mass of the ozone layer that reflects the stray light effects and ε is the residual. To keep the same approach at both stations the relation (2) was applied as the transfer function between D074 and B098 observations at Hradec Králové too. The k_{TD} factor was defined according to Kerr (2002) by Eq. (3)

$$k_{TD} = 0.00130(-46.3 - T_{eff}) \quad (3)$$

Application of the transfer function (2) includes creation of the data set of T_{eff} that depends on the geographical location and can be calculated correctly if vertical ozone profiles are available for the station. In the Czech Republic the ozone sonde profiles have been measured at the aerological station Praha-Libuš about 100 km apart Hradec Králové since 1978 three times per week from January to April. As the data series of T_{eff} is not complete for all months and for the whole period of 1961–2010 the best estimation of T_{eff} by temperature measured at some of the standard pressure level was investigated. The analysis of the long-term records of the aerological data sets from Praha-Libuš showed that temperature at the 20 hPa level T_{20} gives the best fit both with stratospheric T_{eff} (800–10 hPa) measured in the winter-spring months and with reference Dobson calibration temperature −46.3 °C (Vaníček et al., 2011). Therefore, the merged T_{eff} and T_{20} data sets from Praha-Libuš were used for calculation of the parameter k_{TD} (Eq. 3) and for estimation of the regression coefficients: $a_1 = 1.004$, $a_2 = 2{,}2$, $a_3 = -0.0066$, $a_4 = 0.000009$.

The above regression coefficients and temperature data set were used to correct the original Dobson X_D (DS_AD) observations for temperature (X_{TEFF}) and for the full regression (Eq. 2) (X_{REGR}). The residuals of these particular Dobson data sets towards the Brewer observations $X_D - X_B$, $X_{TEFF} - X_B$ and $X_{REGR} - X_B$ are viewed in percents by slightly smoothed curves in Fig. 3. It is evident that only the temperature corrections (transfer function without stray light components) somewhat reduce the seasonal cycle of the residuals, but the amplitude of $X_{TEFF} - X_B$ still exceeds 1 % precision of the instruments in the winter-spring season in all years. On the other hand application of the full regression gives substantial decrease of the residuals $X_{REGR} - X_B$ below the precision limit almost in the whole period concerned. The effects are demonstrated in Fig. 4 by curves of relative density distribution of the residuals and in Table 1 by basic statistics. It can be concluded that the transfer function (2) fits the Dobson observations to the Brewer once with the average accuracy of 0.2 % and with the lower and upper quartiles below 1 % comparing to 1.2 % and 2.1 % respectively for the residuals$X_D - X_B$ of the uncorrected X_D values. For X_{REGR} 78 % of the residuals occur in the ±1 % limits of the calibration precision of the instruments while only 38 % and 49 % of the residuals can be found in this range for X_D and for X_{TEFF}, respectively. Moreover, the $X_{REGR} - X_B$ residuals are more symmetrically distributed around zero. With regards to the above results the transfer function (2) and the regression coefficients derived for the instruments D074 and B098 and the location of Hradec Králové were used for conversion of the whole X_D data series of 1961–2010 to the level of the total ozone data set created by the instrument B098.

2.5 Assimilation of Dobson and Brewer total ozone data series

Though the Dobson measurements cover the whole period 1961–2010 and the Brewer observations only the years 1994–2010 the assimilation of both data series was carried out on the calibration/measurement level of the B098 spectrophotometer. The reason was that the observation capacity of B098 is ten to twenty times higher comparing to D074 and that the Brewer instrument can measure total ozone (DS or ZS) under any weather condition. This is important mainly in the winter/spring months when variability of total ozone is very high and linked with typical circulation patterns. Moreover, the assimilated data series (X_{ASIM}) of total ozone related to B098 (B189) can be continuously extended on the same calibration scale of this perspective instrumentation at Hradec Králové in the coming decades.

The process of assimilation was comprised of the following particular steps.

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– The data set of daily noon temperatures T_{eff} and T_{20} from Praha-Libuš was extended for the period 1971–2010.

– The data set of daily noon temperatures T_{20} of the period 1961–1970 was created for Praha-Libuš from the re-analyses ERA-40 by means of a special interpolation algorithm developed and tested by the aerological measurements (Vaníček et al., 2011).

– All individual Dobson observations of the period 1961–2010 were corrected by the transfer function (2) using the actual values of μ and the temperature factor k_{TD} calculated by Eq. (3) using the aforesaid T_{eff} and T_{20} data sets. The ZS measurements were corrected in the same way like the DS observations as the zenith polynomials of D074 kept the relation between DS and ZS total ozone values unaffected. The daily averages X_{REGR} were then calculated for each particular day with measurements by Eq. (2).

– On days with available X_{REGR} and X_{B} values the priority was given to the Brewer daily averages. On days with missing Brewer observations the X_{REGR} values were included into the X_{ASIM} data series. Creation of the X_{ASIM} data set then can be expressed by the formula:

$$\begin{aligned} X_{\mathrm{ASIM}} = {} & X_{\mathrm{REGR}}(1961\text{–}1993) \cup X_{\mathrm{B}}(1994\text{–}2010) \\ & \cup X_{\mathrm{REGR}}(1994\text{–}2010) \text{ on days without } X_{\mathrm{B}} \end{aligned} \tag{4}$$

After detailed data quality check several tens of suspicious observations were cancelled. Finally the assimilated data series X_{ASIM} includes 14 916 daily averages of total ozone. This represents 82 % of days of 1961–2010. Nevertheless, numbers of days with observations is not equally distributed over the whole period. Mainly in the 60-ties there are quite a lot of days (~70 % in winter and ~50 % in summer months) when the in situ observations were not taken due to the personal capacity Fig. 5. To strengthen

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statistical weight of the assimilated data set in the first decade of measurements an attempt was made to fill in the missing days by external total ozone data from the ERA-40 and ERA-Interim re-analyses.

2.6 Integration of ERA-40 and ERA-Interim total ozone data

Several interpolation models were tested by cross-validations to evaluate the best method of filling-in the missing daily averages in the X_{ASIM} data set from the 20CRV2, ERA-40 and ERA-Interim re-analyses. Re-analyzed total ozone values from the grid-point(s) close to the center of the Czech Republic as well as to the position of Hradec Kralove observatory (Fig. 2) were used: 15° E, 50° N for ERA-40 re-analysis, 49.5° E, 50° N for ERA-Interim re-analysis and the average value from 14° E, 50° N and 16° E, 50° N grid points for 20CRV2 re-analysis. In the first step, the differences between the re-analyzed (X_{REA}) and observed X_{D} daily total ozone values were investigated. The results indicated larger spread for 20CRV2 differences than for ERA-40 especially since 1979. Prior 1979 the spreads were comparable. For this reason, the ERA re-analyses were selected for the data integration. Despite of some large values the autocorrelation analysis indicates that the differences between the X_{REA} values from different days retain useful signal for the shifts of several days. It makes possible to apply relatively simple method of filling-in the missing data by estimated values ($X_{\mathrm{E}d}$) calculated from the ERA re-analyses by the linear interpolation:

$$X_{\mathrm{E}d} = X_{\mathrm{REA}d} + [a(X_{\mathrm{ASIM}(d-b)} - X_{\mathrm{REA}(d-b)}) + b(X_{\mathrm{ASIM}(d+a)} - X_{\mathrm{REA}(d+a)})]/(a+b) \tag{5}$$

where d is day with missing observed value, $X_{\mathrm{E}d}$ is total ozone estimate for the day d, $X_{\mathrm{ASIM}i}$ is the assimilated value for the day i, $X_{\mathrm{REA}i}$ is the reanalyzed value for the day i, a is number of days from the day d to the nearest next day with both $X_{\mathrm{ASIM}(d+a)}$ and $X_{\mathrm{REA}(d+a)}$ available, b is number of days from the day d to the nearest previous day with both $X_{\mathrm{ASIM}(d-b)}$ and $X_{\mathrm{REA}(d-b)}$ available.

The accuracy of the estimates of $X_{\mathrm{E}d}$ by the algorithm (5) was evaluated by means of cross-validation. This was based on samples from different years when both observed

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and reanalyzed values are available for the calendar day d (the ±10 days window was applied to increase the number of validation cases) as well as for the day a days after and b days before that day. Estimated values X_{Ed} were compared with the observed ones from X_{ASIM}. The means and standard deviations of differences gave information about the uncertainty of the estimation (Eq. 5). Systematic errors of estimated values X_{Ed} were mostly found to be small if compared with their uncertainty and were neglected. As the total ozone values in ERA-40 are clearly less accurate in 1961–1978 than in 1979–2002 the cross-validation characteristics for the estimated values X_{Ed} prior 1979 were calculated from 1961–1978 data while for estimates after 1978 the data sets from the 1979–2002 were used. For the period of 1 January 1989–31 August 2002 the estimates X_{Ed} were available both from ERA-40 and ERA-Interim. Comparison of cross-validated characteristics indicates that application of the ERA-Interim reanalysis gives slightly better results than ERA-40 in this period though the differences are quite small. Finally the assimilated X_{ASIM} and the estimated X_{Ed} data sets were merged and the all-days data series of total ozone values X_{ALL} was created according to the relation:

$$X_{ALL} = X_{ASIM} \cup X_{Ed}(1961\text{–}2010) \text{ on days without } X_{ASIM} \qquad (6)$$

Altogether 3345 daily values of total ozone from ERA-40 and ERA-Interim have been included into the assimilated data series to cover all missing days of 1961–2010. This represents 18 % of the whole data series and 42 % of the period 1961–1978.

Monthly averages of total ozone derived from the X_{ALL} and X_{ASIM} data series were compared to evaluate the above process of completing the all-days data set. It was found that filling-in the missing days gives well pronounced systematic shifts of monthly means of total ozone calculated from both data series that occur especially in the period of measurements taken only with D074. The Dobson observations were not performed on days with adverse weather condition (rain, snowfall, fog) that occurs usually during cyclonal situations. On the contrary, under anti-cyclonal periods the measurements were more frequent. As a result selection of the days with/without Dobson

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measurement is not random with respect to the total ozone values. It may consequently lead to some errors in calculation monthly averages of total ozone from the non-filled-in data series.

The magnitude of the errors depends primarily on the number and distribution of the missing values within the months. For this reason the differences are highest at the beginning of the time series X_{ASIM} when the days with in situ measurements are sparse than in the later decades (Fig. 6). In some months prior 1978 (the ERA re-analyses without satellite measurements) the differences of monthly means reach more than ±5 % (about +11/−14 % in extreme cases) with slight underestimation on average. Then they decrease onwards down to ±2 % till 1993 and mostly up to ±1 % afterwards. Differences of the annual means are up to +1/−2 % in the 60-ties, then up to ±1 % till 1993 (Dobson period) and negligible since 1994 (Brewer period).

3 Results and discussion

Investigation of recovery of the ozone layer is a topical subject of the ozone research. The recent studies showed that though depletion of the layer has stopped the second stage of the recovery (ozone increase) has not been clearly documented by real observations yet (World Meteorological Organization, 2007). The process of recovery is expected to be different in time and geographical locations and it will be closely tied both with impacts of the Montreal Protocol and with the climate change (World Meteorological Organization, 2011). Evaluation of the actual depletion of stratospheric ozone over the particular regions depends on the knowledge of condition of the ozone layer in the pre-ozone-hole period that serves as a benchmark of its natural state. This chapter is focussed on a simple assessment of relation between the data series defined in the Sect. 2 by means of differences between long-term overall changes of total ozone. The main goal is to evaluate impact of application of the particular data sets on the seasonal behaviour of total ozone in the post-Pinatubo period 1994–2010 in the geographical region of Central Europe.

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3.1 Pre-ozone hole references and post-Pinatubo offsets

In the NH mid-latitudes seasonal and year-to-year variations of total ozone are well pronounced. Therefore, information about total ozone prior the 80-ties and investigation of relation between the original Dobson X_D, combined X_{DB}, assimilated X_{ASIM} and completed X_{ALL} data series on the monthly basis was carried out. It has been found that some months have very similar long-term behaviour of monthly averages of X_{ALL} that makes grouping the months into three seasons: winter-spring (DJFMA), summer (MJJA) and autumn (SON) possible. For the above data sets the seasonal averages of total ozone were calculated for each year of the post-Pinatubo period 1994–2010 and then compared with the reference R_D, R_{DB}, R_{ASIM}, R_{ALL} values (averages) of the pre-ozone-hole period 1961–1985. The relative differences in percents:

$$\Delta X_D = 100(X_D - R_D)/R_D \quad (7)$$

$$\Delta X_{DB} = 100(X_{DB} - R_{DB})/R_{DB} \quad (8)$$

$$\Delta X_{ASIM} = 100(X_{ASIM} - R_{ASIM})/R_{ASIM} \quad (9)$$

$$\Delta X_{ALL} = 100(X_{ALL} - R_{ALL})/R_{ALL} \quad (10)$$

were then calculated (Table 2) and analyzed.

It has been found that in the DJFMA and SON months the combined data series X_{DB} reduces seasonal depletion of total ozone in the post-Pinatubo period comparing to the original Dobson data set X_D by about 1.5–2 % while insignificant change appears in MJJA. This is evidently due to combination of the seasonally different X_D and X_B data before the transfer function was applied (Fig. 3). For the data series of the homogeneous Dobson (X_D) and Brewer (X_{ASIM}, X_{ALL}) calibration scales the offsets in 1994–2010 are almost the same in all seasons.

It can be concluded from Table 2 that equivalent depletions of total ozone for all data sets occur both in the DJFMA and in MJJA months. This is surprising finding as the effect of ODS chemistry is expected to be dominant in the winter-spring than in the summer season. Conclusion can be made that together with the impact of Effective

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Equivalent Stratospheric Chlorine (EESC) concentrations also other processes significantly contribute to long-term changes of total ozone in the NH mid-latitudes concerned (Harris et al., 2008; Wohlman et al., 2008; Rieder et al., 2011).

3.2 Post-Pinatubo tendencies

In the second step the relative differences defined by Eqs. (6)–(9) for the data sets concerned in the post-Pinatubo period (1994–2010) were investigated on the seasonal basis. For this yearly ΔX values were approximated by linear regressions (Fig. 7a, b, c). From the graphs and according to the slopes of lines SL given in percents per decade in Table 2 it is evident that substantial differences exist between particular data sets mainly in the most topical winter-spring season. In DJFMA all data series show increasing tendencies that can be taken as a partial influence of decrease of EESC concentrations due to effect of the Montreal Protocol. But value of the gradient $\mathrm{SL_D}$ of the original Dobson data series is only one-third of the slopes of other data sets. This can be explained by higher sensitivity of the Dobson observations to more frequent occurrence of the low ozone extreme events in the post-Pinatubo period (Rieder et al., 2011) and by the fact that the Brewer observations cover almost all days in the concerned months while in the winter-spring season the Dobson measurements are available only on about 10 days per month of specific weather and circulation condition suitable for observations. The higher shift of the ΔX_{DB} line in the DJFMA season (Fig. 7a) appears due to the lower reference R_{AD} value of this data set calculated from the Dobson not assimilated data of 1961–1985. If linear approximation is taken for estimation of the full recovery ($\Delta X = 0$) then the assimilated data reach this level about 2020 while the single Dobson data series gives the date around 2060. This is an example how risky is to apply input data sets for simple statistical trend analyses without previous critical evaluation of their origin.

In the MJJA season (Fig. 7b) the gradients were mostly below 1 % per decade and thus no significant tendencies have been found for all data sets. But it is interesting that the ΔX_{D} values unlike the others indicate a negative tendency that was explained by lower numbers of the Dobson DS observations in summer months of several years of the period concerned. This gives an example how sampling of the input data (in this case by unfavourable weather condition) can influence general tendencies. Similar conclusions can be stated for the autumn months SON (Fig. 7c).

4 Conclusions

Influence of the input data characteristics on evaluation of long-term changes of the ozone layer over Central Europe was investigated by means of total ozone measurements taken at Hradec Králové in the 50-yr period 1961–2010. Substantial differences between Dobson D074 and Brewer B098 simultaneous observations were confirmed in the winter-spring months. Simple continuation/combination of the data records created by D074 (1961–1993) and B098 (1994–2010) would introduce an instrumental signal into the combined data series X_{DB} of the period 1961–2010 that is up to three times higher than precision of the spectrophotometers.

Contribution of the instrumental fraction to the total ozone changes was eliminated below 1 % by assimilation of both data sets using the Dobson-to-Brewer transfer function. The merged data series X_{ASIM} was filled-in on missing days from the re-analyses. Comparison of the datasets with and without filled-in values indicated that the lack of measurement on days with adverse weather condition may lead to non-random selection effect and to less accuracy in estimation of the monthly means of total ozone in order of several percent with slightly prevailing underestimation. This impact is discernible especially in years (months) with sparse Dobson measurement. For annual means this effect reaches 2 percents at the 60s (with prevailing underestimation again) and decreases to negligible values at the beginning of 21th century.

The completed all-days data set X_{ALL} was used to estimate attenuation of the ozone layer between the pre-ozone-hole (1961–1985) and post-Pinatubo (1994–2010) periods. The data series with consistent instrumental/calibration origin (X_D, X_{ASIM}, X_{ALL}) show almost the same ozone depletion both in winter-spring and summer seasons by

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about −6 %. In the winter months the ozone decrease is masked by about one-third in the combined data set X_{DB} due to the D074 versus B098 instrumental differences.

Creation of particular total ozone data sets and investigation of their relation was the first step in evaluation of the long-term changes of ozone by observations from Hradec Králové. In the second stage total ozone variability will be investigated by statistical models to identify the key predictors that influence the ozone layer over Central Europe with the outlook to its evolution in the coming decade(s). For this task the completed data series X_{ALL} that is instrumentally linked to the Brewer calibration scale and B-P ozone cross sections will be applied. The data set is now free available also to other users as a pilot output of the Project P209/10/0058 supported by the Czech Grant Agency at the PANGEA data base: doi:10.1594/PANGAEA.779819.

Acknowledgements. The Czech Grant Agency has provided support for the research that led to this paper in the framework of the Project No. P209/10/0058 "Long-term Changes of the Ozone Layer Over the Territory of the Czech Republic".

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Table 1. Statistical parameters of the Dobson to Brewer residuals of total ozone in percents.

Residuals	Average	Median	Lower quartile	Upper quartile	Standard Deviation	Residuals below 1.0	Residuals below 1.5
$X_D - X_B$	−1.2	−1.3	−2.1	−0.4	1.3	38 %	56 %
$X_{TEFF} - X_B$	−0.9	−1.0	−1.7	−0.2	1.1	49 %	68 %
$X_{REGR} - X_B$	−0.2	−0.3	−0.8	0.3	0.9	72 %	90 %

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Table 2. Seasonal values of the pre-ozone hole (1961–1985) references R (Dobson Units), the relative differences ΔX (%) and slopes SL (%/decade) of the linear approximation of ΔX values in the post-Pinatubo (1994–2010) period for particular X_D, X_{DB}, X_{ASIM} and X_{ALL} total ozone data sets.

Season	R_D (DU)	R_{DB} (DU)	R_{ASIM} (DU)	R_{ALL} (DU)	ΔX_D (%)	ΔX_{DB} (%)	ΔX_{ASIM} (%)	ΔX_{ALL} (%)	SL_D (%/dec)	SL_{DB} (%/dec)	SL_{ASIM} (%/dec)	SL_{ALL} (%/dec)
DJFMA	366.4	366.4	371.3	371.6	−5.9	−3.9	−5.1	−5.1	+1.0	+2.8	+2.7	+2.9
MJJA	350.9	350.9	352.3	354.7	−5.3	−4.8	−5.2	−5.8	−0.9	+0.2	+0.2	+0.4
SON	294.4	294.4	298.1	299.6	−1.8	−0.2	−1.4	−1.9	−0.5	+0.9	+0.9	+1.1

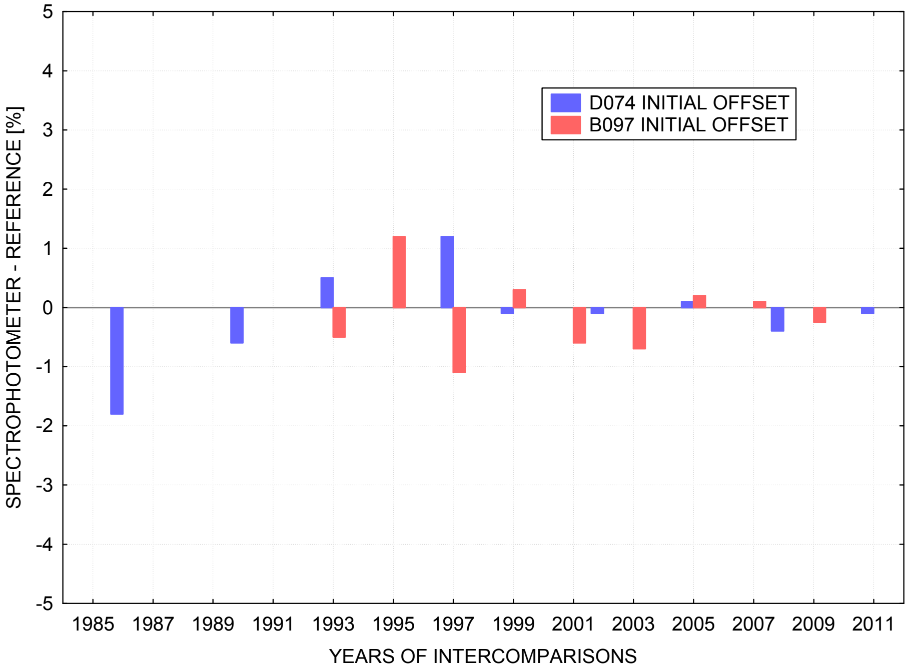

Fig. 1. Calibration offsets of the D074 and B098 spectrophotometers towards the international etalons. The initial offsets document calibration stability of the instruments.

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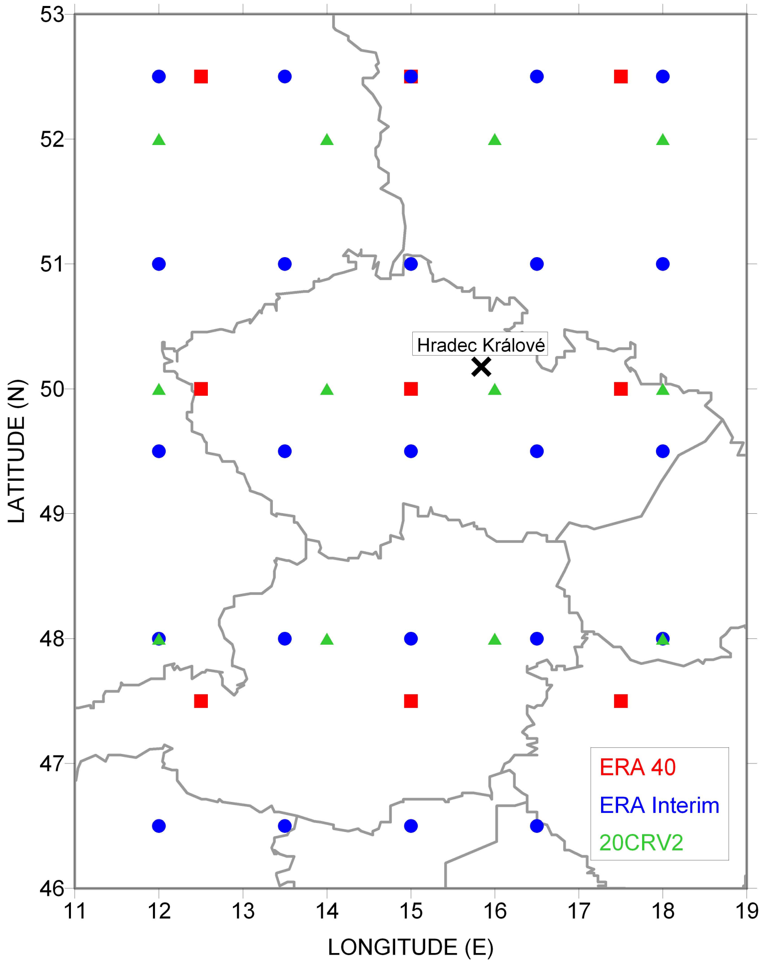

Fig. 2. The grid points of 20th Century Reanalysis V2, ERA-40 and ERA-Interim re-analyses surrounding the location of Hradec Králové.

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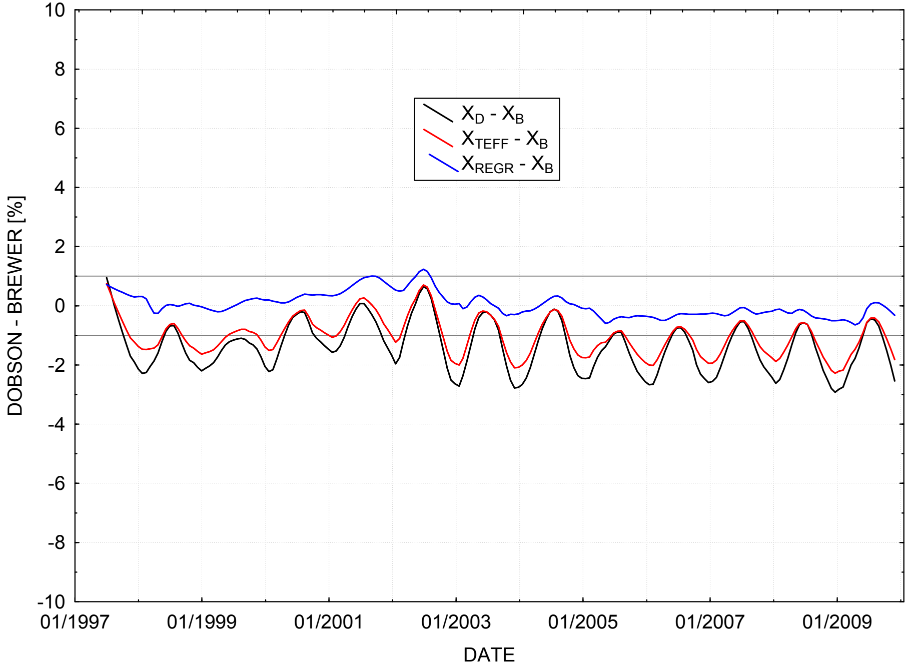

Fig. 3. Residuals between simultaneous Dobson and Brewer total ozone observations (smoothed by the Robust Locally Weighted Regression), Hradec Králové, 1997–2009.

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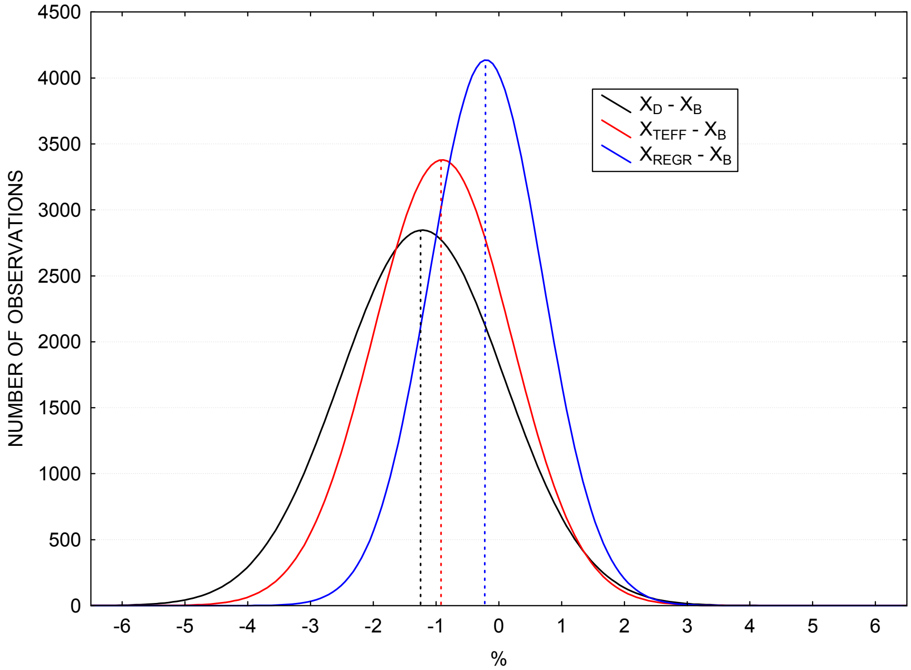

Fig. 4. Relative density distribution of the Dobson-Brewer total ozone residuals, Hradec Králové, 1997–2009.

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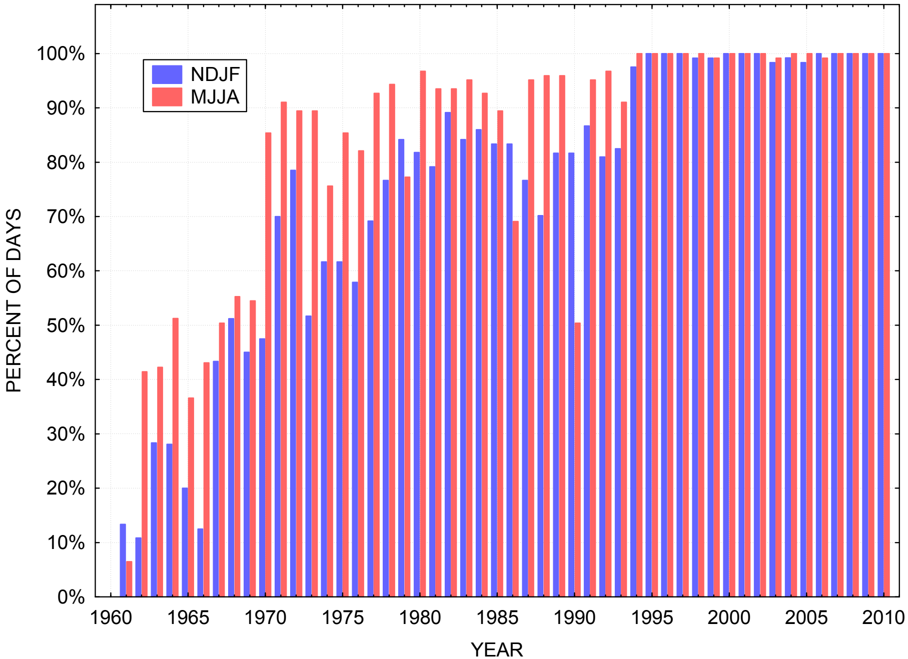

Fig. 5. Average numbers of days with total ozone observations per month in the assimilated data series X_{ASIM} in the winter (NDJF) a summer (MJJA) seasons, Hradec Králové, 1961–2010.

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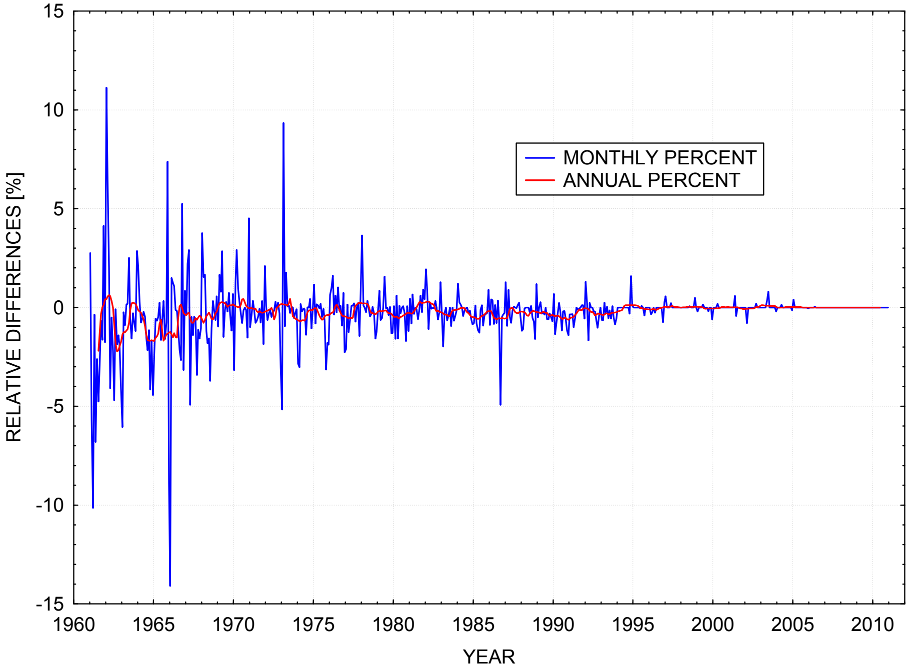

Fig. 6. Relative differences between monthly averages of total ozone calculated from the data sets X_{ASIM} and X_{ALL} in percents, Hradec Králové, 1961–2010, months and years.

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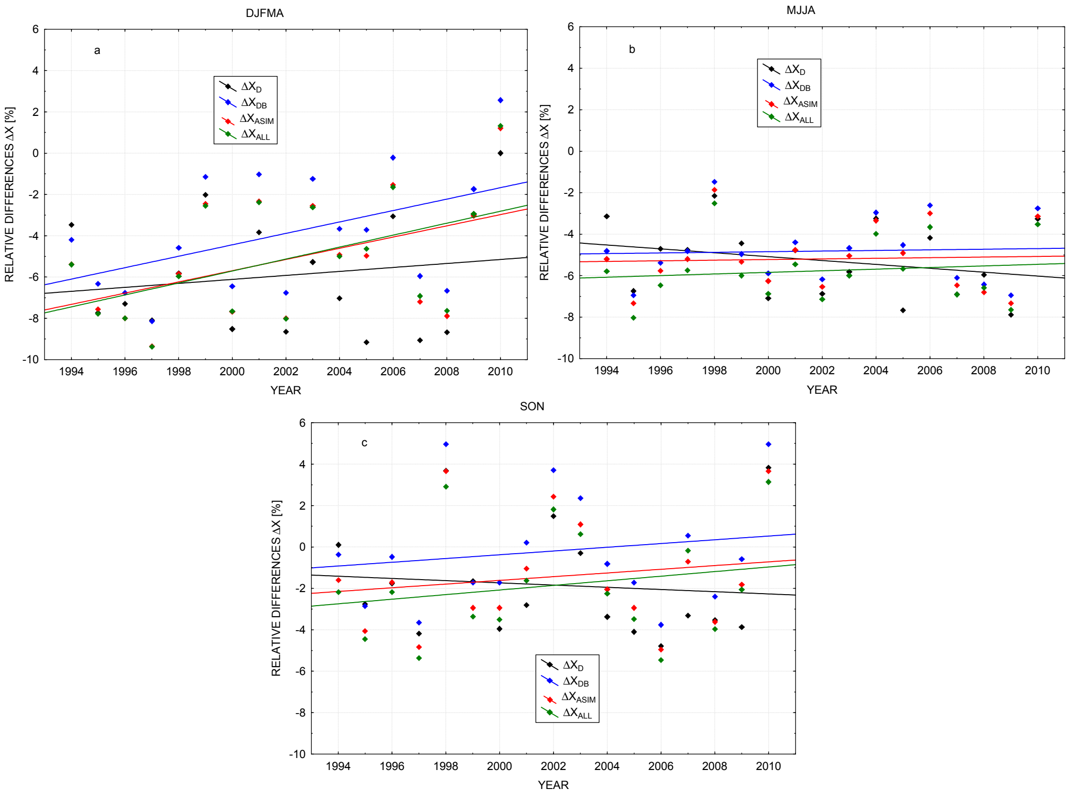

Fig. 7. Linear approximations of the relative differences ΔX_D, ΔX_{DB}, ΔX_{ASIM}, ΔX_{ALL} in the Post-Pinatubo period in particular seasons DJFMA **(a)**, MJJA **(b)** and SON **(c)**, Hradec Králové, 1994–2010.

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