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Comparison of ozone retrievals from the Pandora spectrometer system and Dobson spectrophotometer in Boulder, Colorado

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Abstract

A comparison of retrieved total column ozone amounts TCO between the Pandora #34 spectrometer system and the Dobson #061 spectrophotometer from direct-sun observations was performed on the roof of the Boulder, Colorado NOAA building. This paper, part of an ongoing study, covers a one-year period starting on 17 December 2013. Both the standard Dobson and Pandora total column ozone TCO retrievals required a correction $TCO_{corr} = TCO (1 + C(T))$ using the effective climatology derived ozone temperature T to remove a seasonal difference caused by using a fixed temperature in each retrieval algorithm. The respective corrections $C(T)$ are $C_{Pandora} = 0.00333(T - 225)$ and $C_{Dobson} = -0.0013(T - 226.7)$ per K. After the applied corrections removed the seasonal retrieval dependence on ozone temperature, TCO agreement between the instruments was within 1 % for clear-sky conditions. For clear-sky observations, both co-located instruments tracked the day-to-day variation in total column ozone amounts with a correlation of $r^2 = 0.97$ and an average offset of 1.1 ± 5.8 DU. In addition, the Pandora data showed 0.3 % annual average agreement with satellite overpass data from AURA/OMI (Ozone Monitoring Instrument) and 1 % annual average offset with Suomi-NPP/OMPS (Suomi National Polar-orbiting Partnership, the nadir viewing portion of the Ozone Mapper Profiler Suite).

1 Description of ground-based instruments (PANDORA spectrometer system and Dobson spectrophotometer)

This paper compares ground-based total column ozone retrievals TCO obtained by two very different technologies: (1) the Dobson #061 spectrophotometer is designed to utilize a spectral differential absorption technique by making measurements of solar ultra violet radiation through three pairs of spectrally separated slits and (2) the Pandora #34 spectrometer system TCO algorithm is based on spectral fitting of the attenuated Solar spectrum using a modern small symmetric Czerny–Turner design spectrometer.

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The Pandora TCO is further compared with satellite retrieved TCO overpass data over Boulder, Colorado.

The Dobson spectrophotometer was developed in the mid-1920s to measure stratospheric ozone, and to assist investigations of atmospheric circulation (Dobson, 1957, 1968b). The Dobson time series of TCO measurements date back as far as 1926 for the Arosa, Switzerland station. Knowledge of global stratospheric ozone levels prior to satellite instruments is based primarily on measurements with these instruments (Dobson, 1957, 1968). A world-wide network developed after the instrument re-design in 1947 and the International Geophysical Year in 1957. Measurements made with the Dobson spectrophotometer can be analyzed for total column content of ozone, or for ozone vertical profiles (Umkehr technique, Mateer and DeLuigi, 1992), depending on the light source observed (direct-sun or sky radiances). The Dobson instrument calibration is a prime example of using the “classical” Langley plot method to determine an effective extraterrestrial solar constant (Langley, 1884; Shaw, 2007), and is unique to each instrument.

A complete description of the Dobson operation, principles of measurement, and use is available elsewhere (Komhyr and Evans, 2008). Briefly, the instrument measures the difference between the intensity of selected wavelength pairs in the range 300–350 nm (Eq. 1).

A -Pair (A_1 : 305.5/ A_2 : 325.0 nm)

C -Pair (C_1 : 311.5/ C_2 : 332.4 nm),

D -Pair (D_1 : 317.5/ D_2 : 339.9 nm) (1)

A spectra is produced by a prism spectrograph and projected onto a slit board containing two slits S_2 and S_3 , with the intensity of the wavelength at S_3 being stronger than that at S_2 , since light at S_2 is more strongly absorbed by ozone. A calibrated variable neutral density filter (“attenuator”) is used to reduce the intensity of the stronger wavelength (S_3) to that of the weaker (S_2). The light from the two slits is collected in a photomultiplier tube (PMT), the current is amplified and differenced in an external

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meter so that when the intensities from the slits are equal at the PMT, the meter reads zero. During the measurement, the variability in the PMT readings is recorded and used as a quality control of the measurements and to detect optically thin clouds.

A measurement with the Dobson spectrophotometer with a defined wavelength pair (A , C or D) is recorded as the position of the attenuator when the meter reads zero. When the instrumental Extra-Terrestrial Constant (I_{ETC}) is combined with the measurement I_{meas} , the result is then expressed as an N value. Based on Beer's Law, an N value is defined as (Eq. 2)

$$N = \text{Log}[I_{ETC}(S_2)/I_{ETC}(S_3)] - \text{Log}[I_{meas}(S_2)/I_{meas}(S_3)] \quad (2)$$

where N is the relative logarithmic attenuation caused by ozone and aerosols for the wavelength pair. The N values are converted to total column ozone TCO values through the use of standardized effective ozone cross sections and Rayleigh scattering optical depths determined through convolution with the standard Dobson spectral bandpasses (Komhyr et al., 1993).

For normal measurements designed to determine the total column content of ozone TCO, the measurements are taken using multiple pairs ($A + D$, or $C + D$), and combined to minimize the effects of aerosols and other absorbers, and corrected for Rayleigh scattering. The retrieval algorithm uses ozone absorption coefficients determined from the Bass and Paur (Bass and Paur, 1985) laboratory measurements of the ozone cross-section. The effective ozone cross sections are applied to process measurements at all Dobson stations and to use a fixed effective stratospheric temperature of -46.3°C , and thus do not reflect seasonal and meridional variability in stratospheric temperatures.

The Dobson spectrophotometer can be used for direct-sun, zenith-sky, or lunar measurements to determine total column ozone or ozone profiles (Umkehr method). Ozone measurements from the Dobson spectrophotometer are usually made with an operator present just a few times during each "good weather" day. The derived ozone values are only weakly affected by the presence of aerosols, since differential aerosol or attenuation usually affects both wavelengths in a pair almost equally.

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Dobson instrument calibrations are maintained by comparison with the World Standard Dobson #083 that is carefully maintained with regular Langley plot calibration at the Mauna Loa Observatory in Hawaii by ESRL (NOAA's Earth System Research Laboratory, Boulder, CO). The Boulder station instrument Dobson #061 is formally compared to Dobson #083 approximately once a year since 1982. Informal (without time synchronization) comparisons were also performed at various occasions whenever Dobson #083 was operated in Boulder. The calibration of Dobson #061 is changed to match Dobson #083 only when the results of the intercomparison are consistently different by more than 1%. Over the last 5 years, the difference between total column ozone derived from these two instruments was found to be within $\pm 1\%$ for airmasses smaller than 2.5 when using the AD-DSGQP type measurement (*A-D* pair wavelengths Direct Sun using a Ground Quartz Plate for clear sky conditions). Based on the last two formal intercomparisons (2013 and 2014), Dobson #061 results are estimated to be $\sim 0.5\% \pm 1\%$ lower than Dobson #083 results.

Recently, a small spectrometer system, Pandora, has become available based on commercial spectrometers having the stability and stray light characteristics that make them suitable candidates for direct-sun measurements of total columns of ozone and other trace gases in the atmosphere. Sky observations are also made for deriving trace gas altitude profiles. The Pandora spectrometer system uses a temperature stabilized (1°C) symmetric Czerny–Turner system from Avantes over the range 280–525 nm (0.6 nm resolution with $4.5\times$ oversampling) with a 2048×64 backthinned Hamamatsu CCD, 50 micron entrance slit, 1200 lines per mm grating, and fed light by a 400 micron core diameter fiber optic cable. The fiber optic cable obtains light from the sun, moon, or sky from front-end optics with a 2.2° field of view (FOV) for direct-sun observations using a diffuser and 1.6° FOV for sky observations without a diffuser. The optical head uses a double filter wheel containing 4 neutral density filters, a UV340 filter, a diffuser, and a blocked position. When combined with the variable exposure time (4–4000 ms), Pandora has a dynamic range of 10^7 to 1, which is sufficient for viewing both direct sun and sky, and for measuring the dark current in between each

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measurement. The laboratory calibrated Pandora TCO retrieval algorithm uses an external solar reference spectrum derived from a combination of the Kurucz spectrum (resolution 500 000) radiometrically normalized to the lower resolution shuttle Atlas-3 SUSIM spectrum (Thuillier et al., 2004; Bernhard et al., 2004). Ozone absorption cross sections are from Malicet et al. (1995). The use of a well calibrated top of the atmosphere TOA spectrum convoluted with the spectrometer slit function permits derivation of ozone amounts without resorting to either a Langley calibration approach or calibration transfer from a standard instrument.

The Pandora system has been extensively described in several publications (e.g., Herman et al., 2009; Tzortziou et al., 2012). For the purpose of deriving ozone, a visible light blocking filter (UV-340) is employed to greatly reduce stray light in the ozone sensitive range 305–340 nm. The algorithm for deriving ozone amounts differs from Dobson or Brewer instruments in that spectral fitting is used to cover the entire 310 to 330 nm range with a weighting system that measures the noise as a function of wavelength for each single spectrum and inversely weights the significance of the fitting to the amount of noise. On a typical clear-sky day, about 4000 direct-sun measurements are taken in 20 s at low to moderate solar zenith angles (SZA), which are averaged together to improve the single measurement signal to noise ratio by a factor of 60. TCO retrievals can be made under moderately cloudy conditions and at high SZA, but with the noise level increasing because of decreased amount of UV sunlight reducing the number of measurements possible in 20 s while continuing to fill the CCD wells to about 80 %. Aerosols without spectral absorption features have little effect on the TCO value retrieved, and are mostly removed by use of a low order polynomial in the retrieval algorithm. Both clouds and aerosols increase the retrieved TCO amount slightly because of multiple scattering within the cloud or aerosol layer.

Thick clouds reduce the number of available photons to the point where practical measurements are not possible because of decreased SNR. Since Pandora also measures total column NO₂ amounts using visible wavelengths (400–440 nm), a second cycle of measurements lasting 20 s is used without the UV340 filter. The result is that

TCO is measured every 80 s, since each 20 s measurement with light input is followed by 20 s dark count measurements.

The algorithms and calibration techniques for the Dobson spectrophotometer (Komhyr and Evans, 2006) are carefully documented in available documents or open literature. The documentation for Pandora, PanSoftwareSuite1.5_Manual.pdf, is available at <http://avdc.gsfc.nasa.gov/pub/tools/Pandora/install> and in Herman et al. (2009).

The retrieved Pandora TCO amounts have been successfully compared to a carefully calibrated double grating Brewer spectrometer #171 (Tzortziou et al., 2012) that uses a six-wavelength algorithm (an improvement over the standard 4-wavelength method) as described by Cede et al. (2005). The key results show good correlation between the Pandora and Brewer TCO amounts, even at high SZA, but with a clear seasonal difference caused by the assumption of a constant effective stratospheric temperature for the ozone absorption cross section, 225 K, in the Pandora algorithm. The Brewer wavelengths were selected to minimize the retrieval temperature sensitivity effect.

This paper will focus on one year's worth of data collected to perform direct comparison between the Dobson instrument (#061) in Boulder, Colorado located on the roof of the NOAA building and a Pandora (#34) adjacently located since 17 December 2013. All of the Dobson TCO comparisons in the following sections use retrieved clear-sky AD-DSGQP (*A-D* pair wavelengths Direct Sun using a Ground Quartz Plate for clear sky conditions). The Pandora retrieved TCO data are matched to the Dobson AD-DSGQP data times t_o and averaged over the interval $t_o \pm 8$ min. A temperature correction is applied based on a standard temperature climatology appropriate for 40° N (Wellemeyer et al., 1997). A future paper will discuss Pandora retrieved temperatures compared with balloon sonde temperatures and their effect on retrieved ozone amounts.

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2 TCO: Dobson spectrophotometer #061 compared with Pandora spectrometer #34

Both Pandora and Dobson ozone column retrievals depend on the choice of the spectroscopic ozone absorption datasets, its spectral temperature dependence, and selection of the stratospheric temperature for daily data processing. The current Pandora spectral fitting algorithm uses ozone cross sections derived from Malicet et al. (1995), while the standard Dobson wavelength pair algorithm uses Bass and Paur ozone cross sections (Bass and Paur, 1985). The standard retrieval algorithms for both instruments use fixed effective TCO retrieval temperatures (Dobson: 226.7 K and Pandora: 225 K), even though there is known seasonal variation in stratospheric temperature. Pandora data averaged over $t_o \pm 8$ min centered on the time t_o of the Dobson data acquisition shows that the two instruments track the ozone amount equally well (Fig. 1).

Figure 1a shows TCO data uncorrected for temperature from 17 December 2013 to 18 December 2014. The difference $\text{TCO}(\text{Dobson}) - \text{TCO}(\text{Pandora})$ shows a seasonal dependence (Fig. 1b) that appears to approximately track the seasonal change in stratospheric ozone weighted effective temperature (Table 1 and Fig. 2). However, taking the difference between the two time matched data sets (Fig. 1b) shows that the net difference in temperature sensitivity causes a small systematic seasonal difference between Pandora and the Dobson spectrophotometers (-5 DU or -2% Winter and $+10$ DU or $+3\%$ summer). The seasonal difference is significant at the level of 1 standard deviation ± 5 DU of the observed data about the Loess(0.5) curve (Fig. 1b). The Loess(f) procedure is based on local least squares fitting using low order polynomials applied to a specified fraction f of the data (Cleveland and Devlin, 1988).

A compiled climatology of ozone and temperature (Table 1) was used to generate the ozone weighted effective temperature for the location of Boulder, Colorado at 40° N latitude. The tables are given as a function of latitude, ozone amount, and height for each month. The ozone climatology has been described by McPeters and Labow (2011) and the temperatures by Wellemeyer et al. (1997). For this study, only

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the monthly data for latitudes of 40 and 50° N are used. The data are available from (ftp://toms.gsfc.nasa.gov/pub/ML_climatology/).

All Dobson TCO values for the WMO GAW network (including data from the Boulder Dobson #061) are derived based on procedures in the Dobson operational manual (Evans and Komhyr, 2008). Temperature sensitivity of the Dobson effective ozone cross sections for direct-sun measurement is based on the Bass and Paur ozone cross section spectroscopy dataset (Bass and Paur, 1985) and respective spectral band-passes measured for Dobson #083 instrument (Komhyr et al., 1993). Recent analysis (Redondas et al., 2014, and references therein) shows that temperature dependence in the Dobson and Brewer derived total column ozone is based on the choice of the spectroscopic dataset, its spectral temperature sensitivity, and specific selection of spectral bandpasses. Since total column ozone from Dobson #061 is processed with the Bass and Paur ozone cross sections, we use $-0.13\% \text{ } ^\circ\text{C}^{-1}$ (Komhyr et al., 1993) to correct the results for seasonal variability in stratospheric temperatures over Boulder, CO. Moreover, calculations recently published by Redondas et al. (2014) find very similar temperature sensitivity for Dobson #083 of $-0.133\% \text{ } \text{K}^{-1}$ for Bass and Paur ozone cross-section dataset, and very different sensitivity based on the Malicet data.

The temperature dependence for Pandora, $+0.33\% \text{ } \text{K}^{-1}$, is determined by applying retrievals at a series of different ozone temperatures from 215 to 240 K for the ozone cross sections of Malicet et al. (1995) (see also http://satellite.mpic.de/spectral_atlas) and obtaining a linear fit to the percent change. The temperature corrections are shown in Table 2 and Fig. 2. A similar figure could be made for the Dobson instrument based on the data in Table 3.

Applying both respective corrections based on the effective ozone temperatures T (Month, TCO), where $\text{TCO}_{\text{corr}} = \text{TCO} (1 + C(T, \text{TCO}))$ gives the results shown in Fig. 3. After removing the seasonal temperature effect from both Pandora and Dobson TCO retrieval algorithms, the average bias is reduced by a factor of 2 (-2.5 DU or $\sim 1\%$ in winter and $+5 \text{ DU}$ or 1.5% in summer) and is within a standard deviation of 5 DU about the Loess(0.5) curve. Based on the standard deviation from the mean ($1.1 \pm 5 \text{ DU}$ or

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$\pm 1.7\%$), the mean difference of 1.1 DU is statistically not different than zero. While there is significant scatter for the entire temperature corrected data set (Fig. 3b), the day to day agreement is good as shown in Fig. 3a.

The scatter plots (Fig. 4a and b) for Pandora vs. Dobson TCO confirms the high correlation ($r^2 = 0.96$ and 0.97) and near agreement (slopes 1.05 and 1.02) between the two data sets. Including the temperature correction for both Dobson and Pandora retrievals almost removes the seasonal bias and improves the correlation and agreement slightly.

3 Pandora vs. OMI and NPP satellite overpass TCO

A similar comparison with Pandora can be made using satellite TCO overpass data from AURA/OMI (Ozone Monitoring Instrument) and from Suomi-NPP/OMPS (Suomi National Polar-orbiting Partnership, the nadir viewing portion of the Ozone Mapper Profiler Suite). The data used is derived using the TOMS (Total Ozone Mapping Spectrometer) OMTO3 discrete wavelength algorithm with a temperature correction applied based on a monthly zonal mean temperature climatology (Bhartia and Wellemeyer, 2002). The Pandora data are matched to the either the OMI or NPP overpass times within ± 8 min and averaged over the 16 min interval (see Figs. 5 and 6).

If the time dependent ozone change is not too rapid, longer averaging intervals can be used. Temperature corrected Pandora ozone compared to OMI TCO overpass data set (Fig. 5) shows no seasonal bias and has a mean difference of 1.1 ± 8 DU. A similar comparison between Pandora and Suomi NPP/OMPS TCO overpass data (Fig. 6) shows an offset of 3.8 ± 8 DU. For both OMI and NPP the Pandora temperature correction has mostly removed any seasonal dependence. The small residual seasonal dependence is not statistically significant. Figure 7 shows that there is high correlation ($r^2 = 0.95$) between OMI and NPP ozone compared with Pandora ozone measurements. The Pandora TCO closely tracks the daily variations observed from OMI and NPP.

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A similar comparison for OMI and NPP is shown in Figs. 8 and 9 based on the TCO overpass data for Boulder Colorado (see Table 4) for the year starting in 17 December 2013. The two independent retrievals of satellite TCO show reasonably good agreement even though the ground location of each satellite's field of view is different by up to 50 km. The correlation is given by $r^2 = 0.96$ in Fig. 9, but with a slope of 0.9 suggesting a small bias between OMI and NPP TCO. This is also shown by the average of the difference in $\text{TCO}_{\text{NPP}} - \text{TCO}_{\text{OMI}} = 3.6 \text{ DU}$, but with a standard deviation of 9.8 DU. Given the scatter in the points, the difference is not significant.

For the comparison of Pandora #34 and the Dobson #061 the TCO data were filtered for the presence of clouds using the Dobson AD-DSGQP criteria for cloud-free observations. When comparing Pandora ozone measurements with OMI and NPP partial cloud filtering was used based on an estimate of the Pandora ozone retrieval uncertainty ($< 2\%$) and DOAS fitting residual of < 0.1 for each measurement. In addition, 12 measurements are averaged together over $\pm 8 \text{ min}$ about the Dobson, OMI, or NPP measurement times increasing the Pandora signal to noise ratio by a factor of 3. For OMI and NPP comparisons there is still residual scatter in the presence of light clouds even though the ozone retrieval is acceptable.

4 Pandora TCO data

Pandora retrieved TCO data are obtained every 80 s throughout the sunlit day except during periods of thick cloud cover or high SZA. The Pandora spectral data contains a clear measure of the occurrence of clouds and clear scenes during each day within its field of view, 2.2° surrounding the sun, by saving the output in counts from one pixel (# 2000) at approximately 520 nm. Cloudy (Fig. 10) and clear (Fig. 11) situations are easily distinguished. Moderately cloudy conditions, such as depicted in Fig. 10, will reduce the spectral signal and increase the retrieval error to greater than 2%. In contrast, the day depicted in Fig. 11 is nearly cloud free.

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The average effect of moderate cloud cover on 19 December 2013 reduced the average observed intensity at all wavelengths (by a factor of 2 at 520 nm). The effect on the retrieved ozone is to increase the apparent noise level of the ozone retrieval (Fig. 12: $SD = 2 DU$, where $SD =$ standard deviation from the mean of the difference between the ozone data and a Loess fit) as compared to the clear-sky case (Fig. 13: $SD = 0.8 DU$). For thin-cloud conditions, direct-sun observations have very few scattered photons in Pandora's 2.2° FOV and negligible multiple scattering effects. The ozone retrieval for 19 December also has missing cloud-filtered data for short periods when the clouds were thick in the Pandora FOV. Data before 09:00 MST and after 15:00 are not reliable in December at $40^\circ N$ because of increasing stray light effects for $SZA > 75^\circ$. For the Boulder site, there are obstructions for direct-sun observations (a building and the mountains) in the early morning and late afternoon as shown by the counts dropping to nearly zero (Figs. 10 and 11).

All of the Pandora TCO values have had a retrieval filter applied that limits the formal retrieval noise to 2 DU (about 0.5 to 1 % error). During December, the noon SZA was about 63.5° . Good retrievals of TCO can be obtained up to SZA of about 75° , if the Pandora field of view is not obstructed. At large SZA, the spectrometer retrieval can be affected by stray light as the direct contribution of photons in the 305–320 nm range is diminished by the large ozone absorption airmass factor AMF. For days or locations with high total column ozone values, the SZA cutoff can be smaller. The Pandora ozone spectral fitting retrieval algorithm inversely weights the contribution of each wavelength by its increased standard deviation from the mean caused by reduced count rate with increasing AMF. The effect of shifted wavelength retrievals is taken into account in the temperature corrections shown in Table 2 and Fig. 3.

Figure 14 shows a sample of Pandora ozone retrievals throughout 13 consecutive days. For the Boulder, Colorado location there are substantial TCO variations during most days, which are only partially detected in the Dobson measurements obtained at a few times during each day. Because of this variation, the Pandora time interval selected for the Pandora–Dobson comparison must be kept fairly short (e.g., ± 8 min)

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without causing under sampling of the coincident time series. Note that each daily graph has a vertical axis range of 60 DU to visually show the different daily daytime variation in retrieved TCO. Based on the set of observations, the morning to afternoon change is almost as likely to show increases or decreases over an extended range of days.

When Pandora TCO daily time series are formed at 10:00, 13:30, and 15:00 (Fig. 15), and fit with an approximately 28 day smoothing Loess(0.1), the seasonal dependence shows maxima (361 DU) at approximately 8 April with a minima (253 DU) on approximately 11 October. Peak TCO in March–April can go over 400 DU on single days as shown in Fig. 3 and the inset of Fig. 15. At 13:30 the day to day variation in TCO about the Loess 28 day curve with an annual average standard deviation of ± 18 DU. In the winter and spring (days 351–465; 17 December 2013–10 April 2014) the standard deviation is ± 23 DU that corresponds to the more active weather systems compared the relatively quiet summer and autumn conditions (days 500–650; 15 May 2014–12 October 2014) with a standard deviation of ± 12 DU.

The TCO time series shows the size of the 28 day average diurnal variation that is a function of season (Figs. 15 and 16). Figure 16a shows the differences TCO (10:00)–TCO (13:30) and TCO (15:00)–TCO (13:30) relative to a reference time (approximate OMI overpass time of 13:30). As shown in Fig. 16b, during the winter and spring, the morning values of TCO are generally larger (6 DU) than the afternoon values, while during the summer and autumn months the afternoon values are larger (4 DU). These 28 day morning to afternoon changes are much smaller than the changes on individual days (30–40 DU) as shown in Fig. 14.

5 Summary and conclusion

A 1 year long comparison (17 December 2013 to 18 December 2014) between collocated and time matched TCO derived from the Pandora #34 and Dobson #061 instruments (limited to clear-sky AD-DSGQP data), shows agreement with a small residual

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1.1 ± 5.8 DU bias after correction for ozone-weighted temperature climatology appropriate for Boulder, Colorado at 40° N. Before the temperature correction is applied to both Pandora and Dobson ozone values, there is small (−5 to 10 %) seasonal dependence in the difference between Pandora and Dobson TCO. After the climatologically-derived and total ozone adjusted temperature correction for each instrument is applied to the retrieved TCO values, the comparisons show reduction in the seasonal bias by a factor of two. Some of the differences between the Dobson and Pandora TCO may be associated with day-to-day variability in the stratospheric ozone and temperature not accounted for in the climatological temperature data set. Similar comparisons with both AURA/OMI and NPP/OMPS satellite data show very good agreement for the day-to-day variations and seasonal dependence even in the presence of light to moderate cloud cover. The comparison showed average Pandora TCO agreement with OMI to within 0.3 % (1.1 DU) with 2 % variability about the mean. A similar comparison with OMPS showed 1 % offset (3.8 DU, OMPS > Pandora) with 2 % scatter. The nearly continuous Pandora TCO retrieval shows that on any given day there can be strong diurnal variation, but when averaged over 28 days, the average diurnal variation is small (±5 DU). The year-long comparisons with the Dobson, OMI, and OMPS show that the Pandora system is stable and reliable with almost no operator intervention. The results of the Dobson comparison and a previous Brewer comparison (Tzortziou et al., 2012) suggests that the automated Pandora spectrometer system may be suitable as a replacement for older more expensive ozone monitoring instruments with the additional benefit of Pandora also measuring other trace gas amounts. Additional comparison campaigns with Brewers and Dobson instruments will be carried out in the future.

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Table 1. Ozone weighted average effective temperature (K) vs. ozone amount (DU) and month appropriate for Boulder, Colorado.

Mon/TCO	225 DU	275 DU	325 DU	375 DU	425 DU	475 DU	525 DU	575 DU
Jan	224.2	223.2	222.5	221.9	221.4	221.0	220.7	220.4
Feb	225.6	224.5	223.6	222.9	222.3	221.9	221.5	221.2
Mar	226.9	225.6	224.6	223.8	223.1	222.6	222.1	221.7
Apr	229.5	228.0	226.7	225.7	224.8	224.1	223.5	223.0
May	232.7	230.9	229.4	228.1	227.0	226.1	225.3	224.5
Jun	235.0	233.0	231.4	229.8	228.5	227.5	226.6	225.9
Jul	235.1	233.3	231.6	230.0	228.7	227.6	226.7	225.9
Aug	234.0	232.1	230.3	228.8	227.6	226.6	225.8	225.2
Sep	230.6	229.1	227.6	226.4	225.4	224.5	223.8	223.2
Oct	226.5	225.2	224.0	222.9	222.1	221.5	221.1	220.7
Nov	223.3	222.2	221.4	220.8	220.3	219.8	219.4	219.1
Dec	222.8	221.9	221.1	220.6	220.1	219.7	219.4	219.1

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Table 4. Location of OMI and NPP overpass data sets.

OMI: <http://avdc.gsfc.nasa.gov/index.php?site=1593048672&id=28>

NPP: http://avdc.gsfc.nasa.gov/pub/data/satellite/Suomi_NPP/OVP/TC_EDR_TO3/

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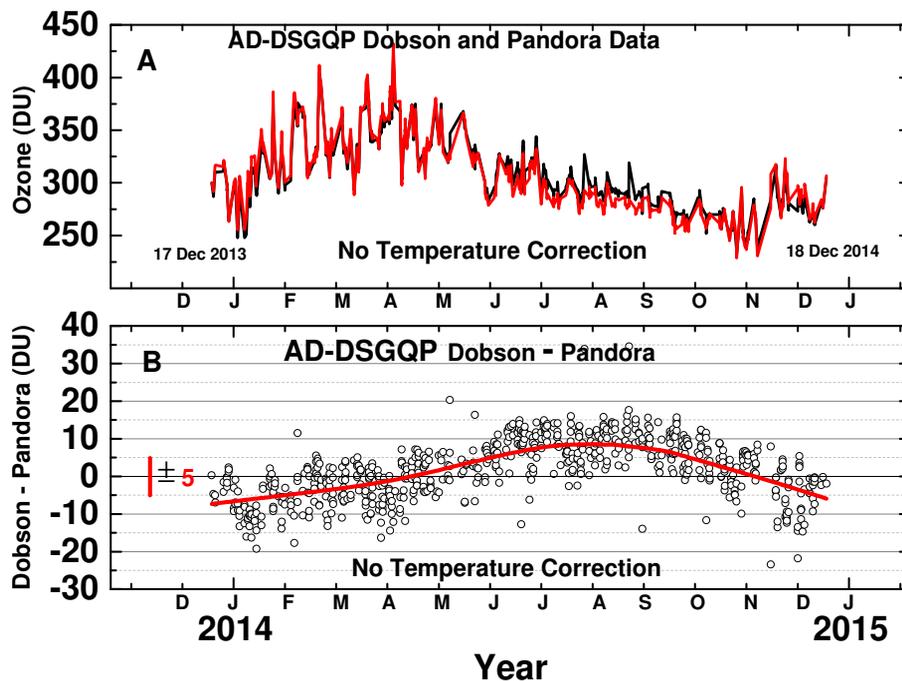


Figure 1. (a) Retrieved AD-DSGQP TCO data obtained from Dobson 61 and Pandora 34 atop the NOAA building in Boulder Colorado for ± 8 min average of TCO(Pan) about the Dobson measurement time. (b) The difference TCO(Dobson)–TCO(Pandora) showing a change in bias as a function of season without temperature correction. The standard deviation from the red Loess(0.5) curve is ± 5 DU. In this and subsequent graphs, the abscissa labels are for the first day of each month from 1 December 2013 to 1 January 2015.



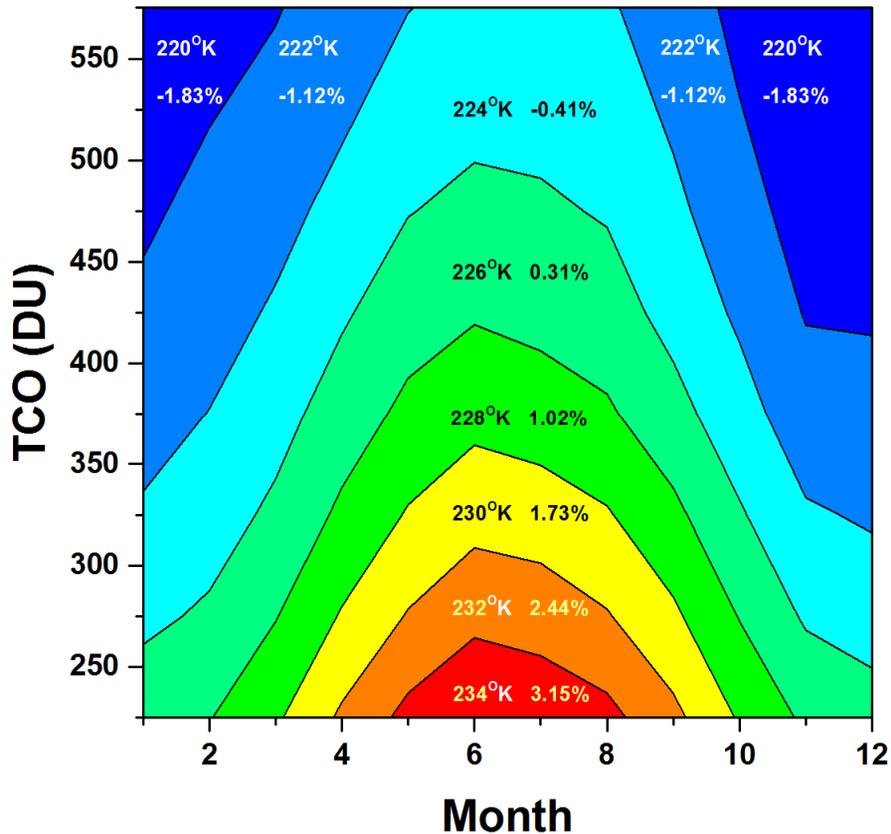


Figure 2. Ozone effective weighted temperatures T (K) and the percent Pandora ozone correction function $C(T)$ (in %) based on a fixed retrieval temperature of 225 K for the latitude of Boulder Colorado 40° N as a function of total column ozone amount TCO and month. $C_{\text{Pandora}} = 0.00333(T - 225)$, where $\text{TCO}_{\text{corr}} = \text{TCO} (1 + C(T))$. The number pairs $(T, C(T))$ represent the average values temperature and percent correction for the colored area, not the contour boundaries.

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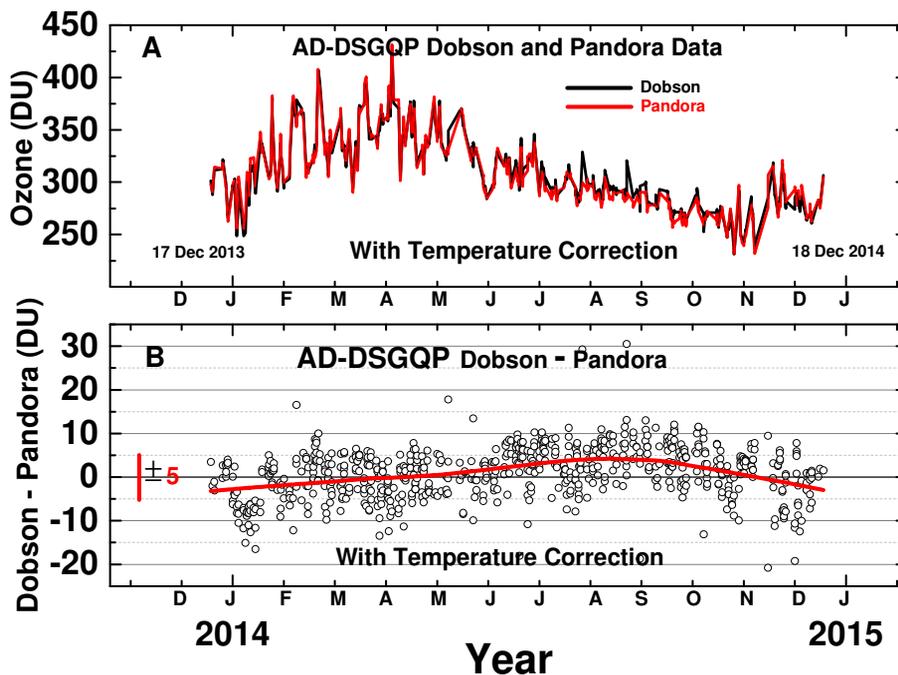


Figure 3. (a) Temperature corrected retrieved TCO data obtained from the Dobson #061 instrument and Pandora #34 spectrometer. (b) The difference TCO(Dobson)–TCO(Pandora) with temperature corrections removing most of the seasonal bias. The standard deviation from the red Loess(0.5) curve is ± 5 DU.



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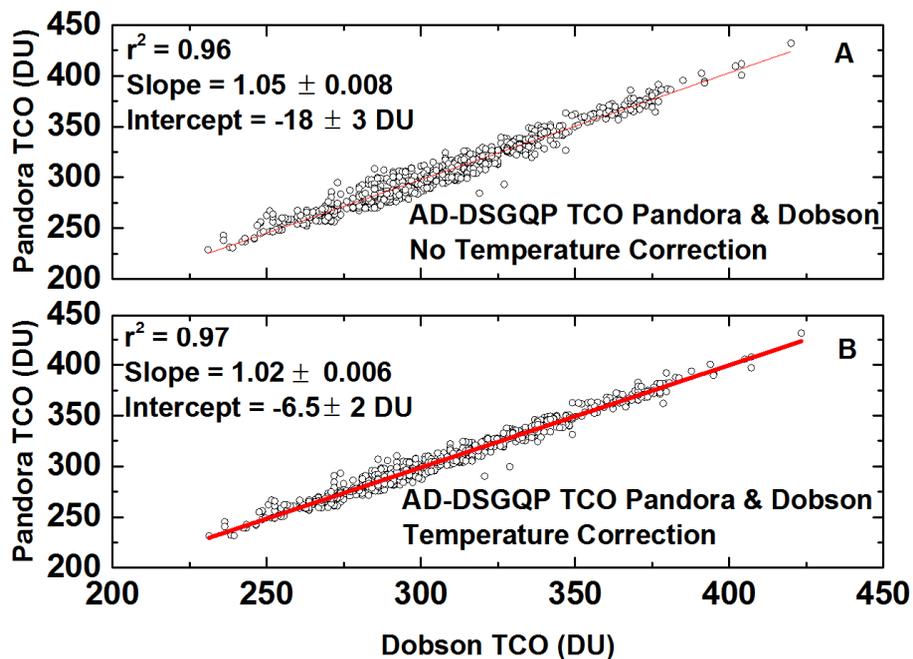


Figure 4. Scatter plot of Pandora TCO vs. Dobson TCO for clear-sky AD-DSGQP conditions: **(a)** no temperature correction and **(b)** with temperature correction.

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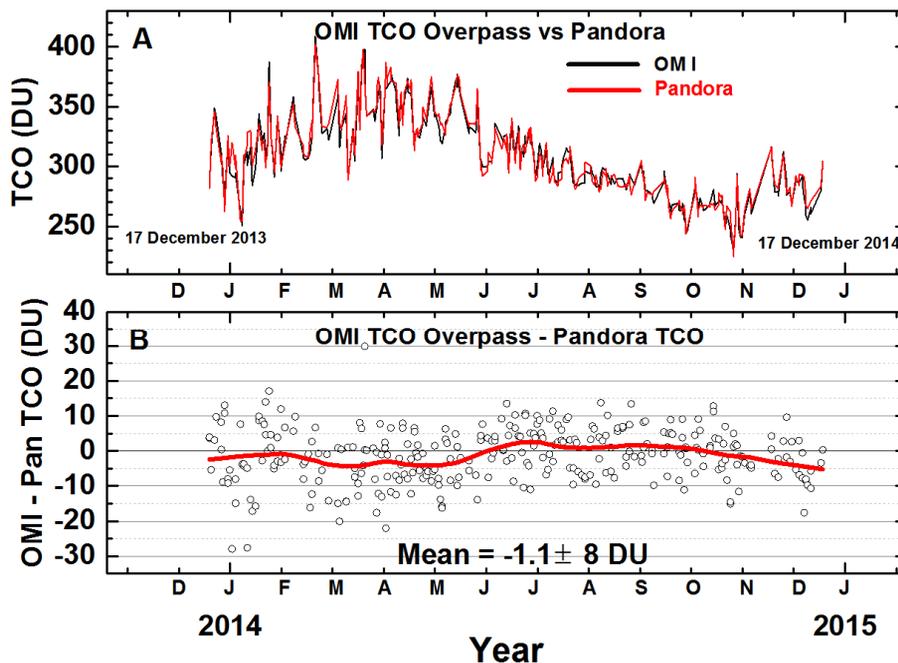


Figure 5. (a) OMI Overpass TCO data for Boulder, Colorado compared to Pandora TCO data averaged over a 16 min interval centered on the OMI overpass time. (b) OMI TCO–Pandora TCO and a Loess(0.2) fit (red curve).



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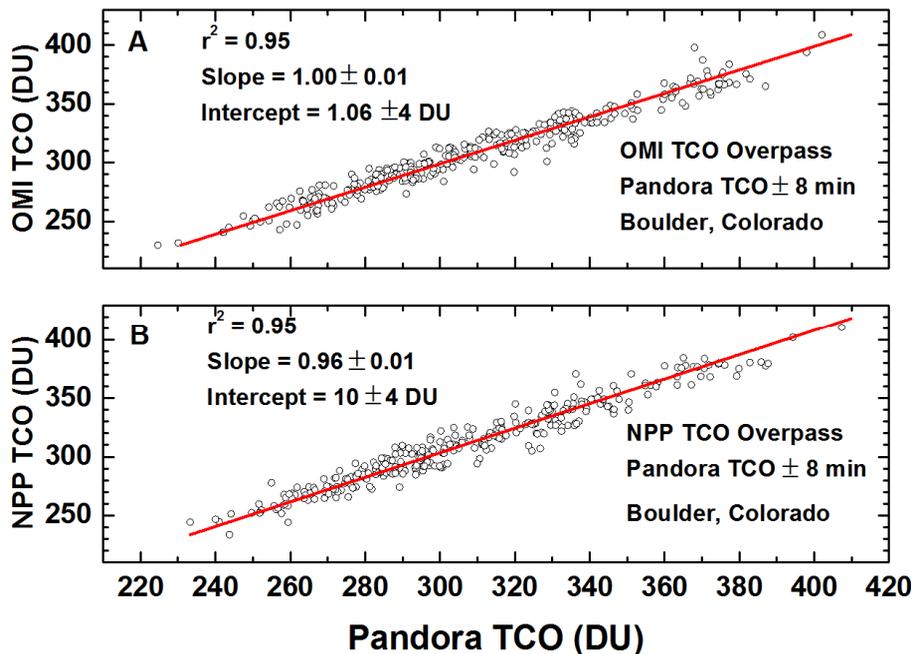


Figure 7. Scatter plot comparisons **(a)** between Pandora TCO measurements and those from OMI and **(b)** comparison with those from NPP. Shown are the correlation coefficient r^2 , slope, and y intercept.

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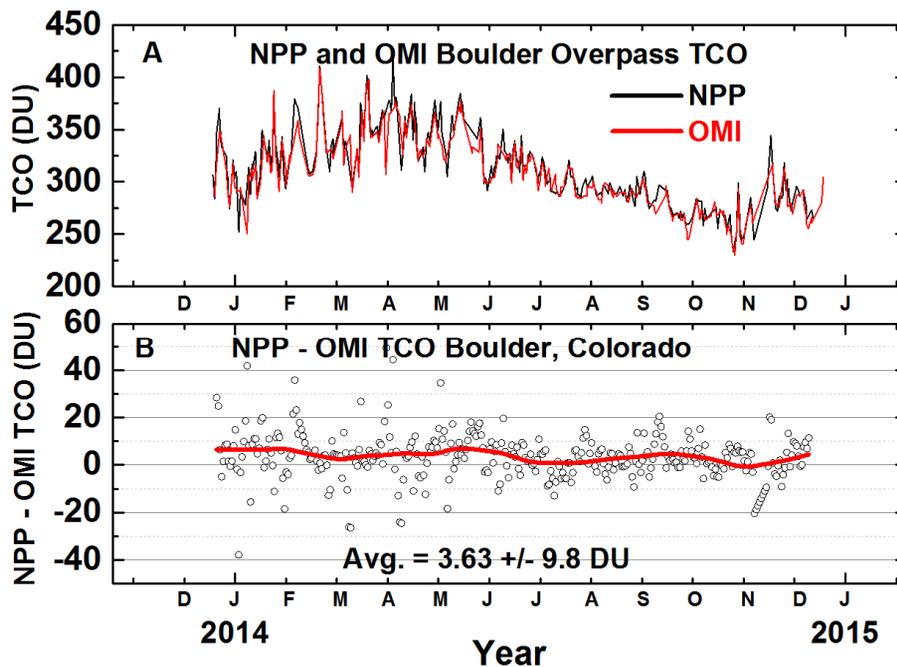


Figure 8. (a) Comparison of retrieved Boulder Colorado overpass TCO; (b) difference NPP–OMI TCO.

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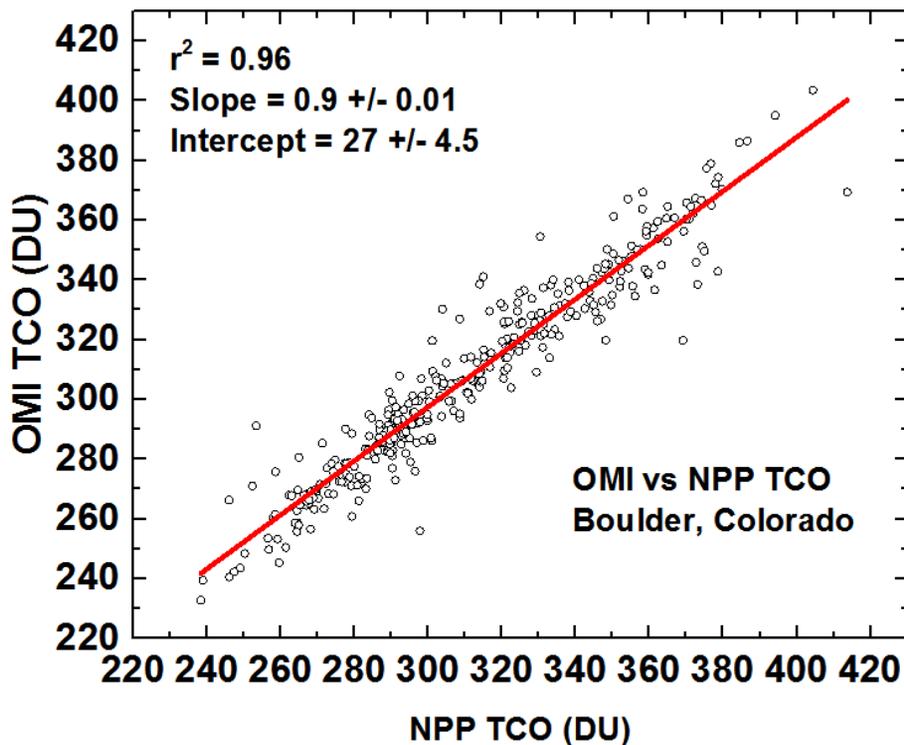


Figure 9. Scatter plot of NPP OMPs vs. AURA OMI TCO.

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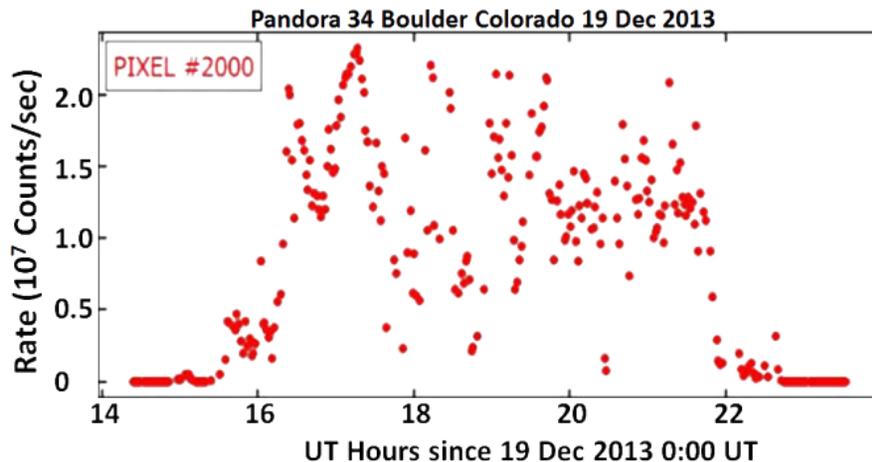


Figure 10. Pixel 2000 (about 520 nm) in counts per second vs. time of day (UT) for a cloudy day (Thursday 19 December 2013).

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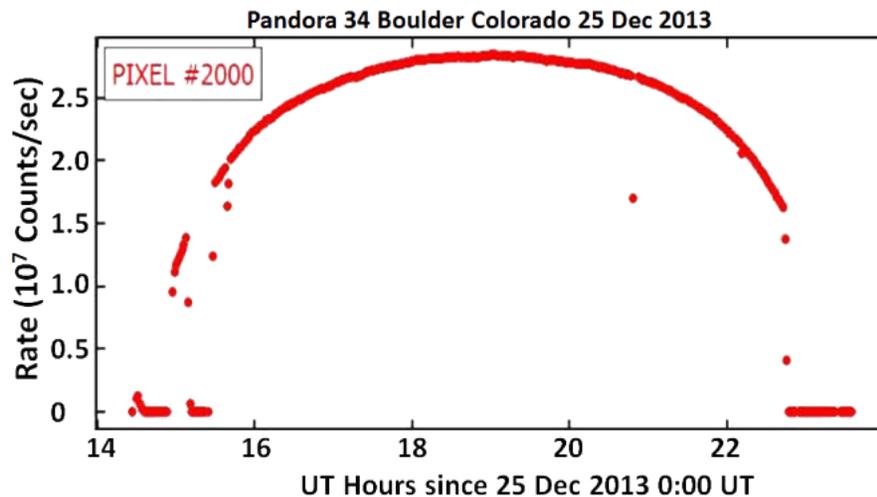


Figure 11. Pixel 2000 (about 520 nm) in counts per second vs. time of day (UT) for a clear day (Wednesday 25 December 2013).

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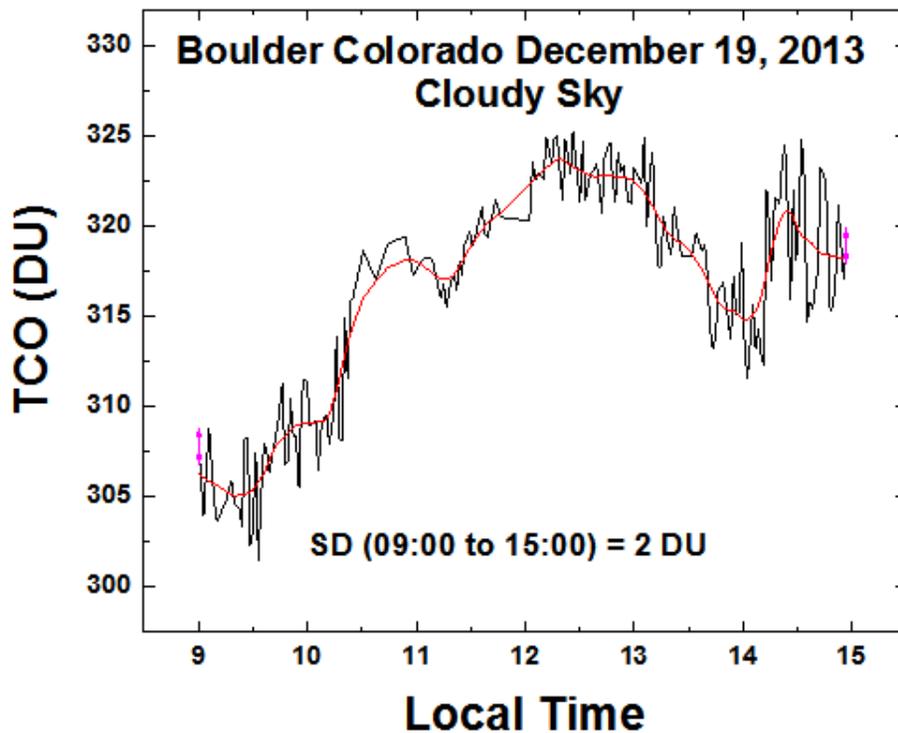


Figure 12. Pandora retrieved TCO under cloudy conditions as shown in Fig. 7 and a Loess(0.2) fit (red curve) to the TCO data.

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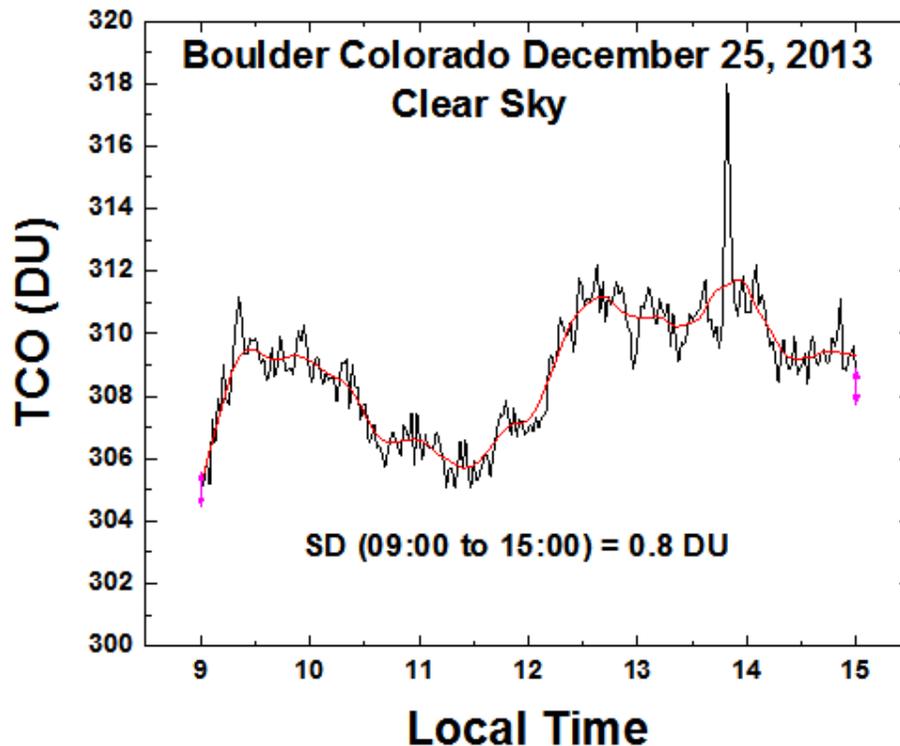


Figure 13. Pandora retrieved TCO under clear-sky conditions as shown in Fig. 8 and a Loess(0.2) fit (red curve) to the TCO data.

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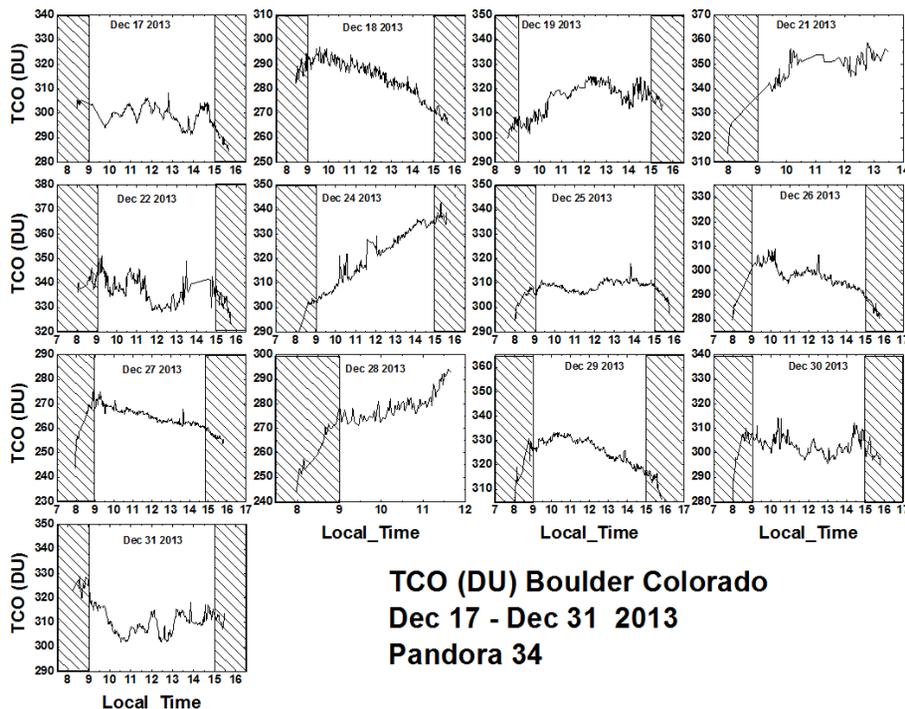


Figure 14. The variation of Pandora retrieved TCO throughout each day in Boulder Colorado from 17 December 2013 to 31 December 2013. The time scale is local standard time (GMT – 7). Times before 09:00 and after 15:00 are shaded. All vertical scales encompass 60 DU.

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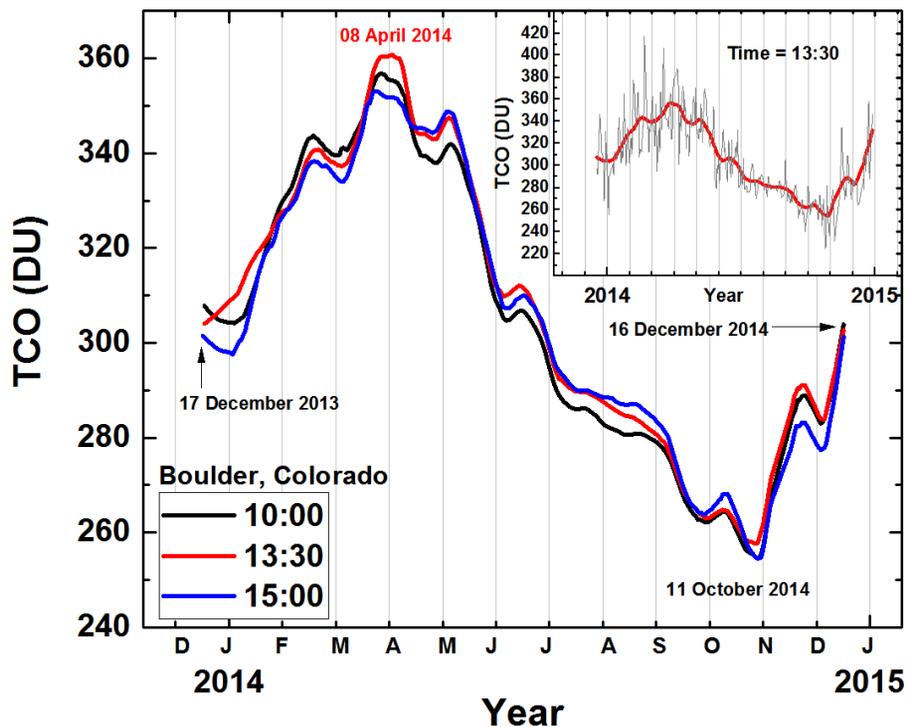


Figure 15. Loess(0.1) 28 day smoothing fit to the annual TCO cycle measured by Pandora at 10:00, 13:30, and 15:00LT (GMT -7). The inset (upper right) shows the daily TCO data for 13:30 h and the corresponding Loess(0.1) fit (red curve).

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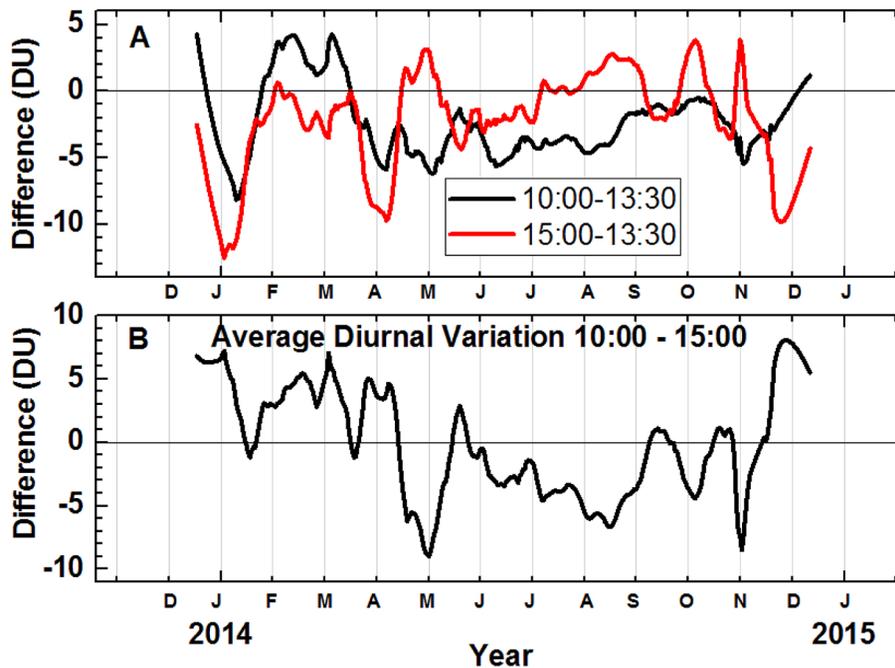


Figure 16. (a) The 28 day average TCO difference in morning (10:00) and afternoon (15:00) from the near-noon OMI overpass time (13:30). (b) 28 day average TCO difference morning-afternoon.

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