Response to comments by Forrest M. Mims III.

We thank Mr. Mims for his good comments, which have helped to improve our manuscript.

Comment by reviewer

While the results in this paper are certainly intriguing, there are significant differences between the instrument employed by the authors and the TOPS instrument employed by Mims and Mims. The author's instrument uses filters having a FWHM bandpass of 10 nm, while TOPS has filters with a 5-nm bandpass FWHM. TOPS also measured column ozone at 300nm and 305 nm, which is much more sensitive to ozone variations than the wavelengths used by the authors. TOPS is also a direct sun instrument that can provide measurements in a few seconds, while the author's instrument is a full-sky C1 device with an exceptionally long 2-minute scan time. As we have learned from comparisons with an EPA Brewer placed at our site, the much faster scan time provided by TOPS provides higher resolution results and avoids errors caused by aerosol changes that can occur during minute-duration scans. Moreover, TOPS often detects subtle changes in the ozone column missed by Dobson and Brewer instruments, which both require considerably more time for an ozone measurement. Before our findings are ruled out by this paper, we feel that the authors should point out the very significant instrumental differences, especially the filter wavelengths, the filter bandpasses and the time required per scan. In each of these cases, TOPS offers superior performance when compared with their instrument. Thus, the findings of subtle waves in the ozone layer by TOPS cannot be so quickly discounted by this paper. I close by observing that TOPS uncovered a calibration drift in the Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) (Satellite Monitoring Error, Nature 361, 1993). TOPS evolved into Microtops and then Microtops II. All these instruments provide results in close agreement with Brewers and Dobsons at the Mauna Loa Observatory. Thank you for considering the points made herein. Forrest M. Mims III fmimsiii@yahoo.com Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-1048, 2018.

Authors' Response

As described in Section 5.2. of the manuscript, the total ozone column (TOC) was derived from measurements of response-weighted global irradiance measured by the GUVis-3511. Specifically, ratios of measurement at 340 and 305 nm were compared with similar ratios in a look-up table that was calculated with a radiative transfer model as a function of SZA and TOC. The look-up table was calculated by taking the response functions of the instrument (Fig. 3 of manuscript) and observing conditions (e.g., aerosol optical depth, (AOD)) into account. The method of calculating TOC from measurements of global irradiance (instead of direct irradiance as it is typically done for Dobson, Brewer, TOPS, and Microtops instruments) was first proposed by Stamnes et al. (1991). We found that the accuracy of TOCs derived from global irradiance is similar to that of data from Dobson instruments or satellite (TOMS, OMI) observations if the look-up table takes local conditions into account (ozone profile, albedo, elevation, etc.) (Bernhard et al., 2005b). For example, this study uncovered systematic errors in Dobson measurements associated with approximations in the standard Dobson retrieval method, which subsequently helped to better understand the limitation of Dobson measurements. We have further validated the method for GUV instruments (Bernhard et al., 2005a). Based on this work we believe that our TOC measurements are not of inferior quality compared to TOPS measurements and provide further evidence below.

Ability to detect small changes in TOC

As described in the manuscript (P23, L26ff.), our data do not indicate oscillations in TOC that may have been triggered by bow waves from the Moon's shadow. In contrast, Zerefos et al. (2000) reported peak-to-peak variation in TOC of about 1 %. while Zerefos et al. (2007) reported a peak-to-peak amplitude of 2.0–3.5 %. Finally Mims and Mims (1993) describe a peak-to-peak amplitude of up to 5 DU (1.7 %). We show in the following that our method is capable of detecting fluctuations of this magnitude.

By analyzing the values of our ozone look-up table, we determined that a 1 % change in the ratio of the response-weighted global irradiance at 340 and 305 nm results in a TOC change of 1.1 DU at the start of the eclipse. At the end of the eclipse (when the SZA is smaller) a 1 % change in the ratio leads to a change of 1.6 DU. As described in the manuscript, ozone calculations are based on the average of 45 seconds (not 2 minutes as stated by the reviewer) of global spectral irradiance measurements that are sampled at 1 Hz. By calculating the standard deviation of these samples and using standard error propagation, we calculated an uncertainty (confidence interval of 95 %) for the ratio of measurements at 340 and 305 nm of 0.13 % for the start and 0.06 % for the end of the eclipse. By combining these uncertainty estimates with the sensitivity of the TOC to changes in this ratio, we determined that our measurements are able to detect changes in ozone of 0.14 DU at the start and 0.10 DU at the end of the eclipse. Since the average TOC on 21 August 2017 was about 298 DU, these absolute changes translate to relative changes of 0.05 % and 0.03 %, respectively. Our method is therefore well capable to detect changes of the magnitude of 1 to 3.5 % reported by Zerefos et al. (2000, 2007) and Mims and Mims (1993).

We agree with the reviewer that measurements at 300 nm are more sensitive to changes in ozone than measurements at 305 nm. However, measurements at 300 nm are also noisier than measurements at 305 nm because the irradiance at 300 nm is smaller than that at 305 nm by factors of 10 (end of eclipse) to 30 (start of eclipse). Moreover, small errors in the characterization (e.g., center wavelength) of the filters functions have a larger effect at shorter wavelength. Since we do not have access to a TOPS or Microtops, we cannot determine whether these instruments are really superior to the GUVis-3511 in determining the TOC as the reviewer asserts. (Of note, the shortest wavelength of a Dobson is 305.5 nm and if measurements at 300 nm would be of great advantage, these instruments would likely use a shorter wavelength.) In any case, our analysis above illustrates that our instrument is sensitive enough for detecting bow-waved induced TOC variations of the proposed magnitude.

<u>Effect of aerosols on ozone retrieval</u>

The look-up table for TOC retrievals was calculated with the same model parameters that were used to convert response weighted irradiance measurements to spectral irradiance as described in the Supplement to this publication. Specifically, aerosol extinction was parameterized with Ångström's turbidity formula by setting the Ångström coefficients α and β to 2.10 and 0.0394, respectively. These values were derived from the instrument's measurement of direct solar irradiance at 19:00:30 after the end of the eclipse. At the start (16:02:58; see Fig. 8b of manuscript), the Ångström coefficients were 1.96 and 0.0570, respectively. To quantify the effect of changing aerosol conditions on TOC retrievals, we modeled the global spectral irradiance for 16:02:58 using either the Ångström coefficients used for the TOC look-up table or the coefficients applicable to this time. The difference in AOD changed the ratio of global spectral irradiance at 340 and 305 nm by only 0.12 %. Using the same sensitivity factor discussed above, we determined that the resulting bias in TOC is 0.13 DU or 0.04 %.

Limb-darkening corrected AODs (Fig. 8a), suggest that the largest AOD during the eclipse occurred at 16:52 when the Ångström coefficients were 1.95 and 0.0788, respectively. (This estimate is somewhat uncertain due to the uncertainty of the limb-darkening correction.) We calculated the aerosol effect in a similar way as before and conclude that the elevated AOD at 16:52 increases the retrieved TOC values by 1.5 DU or 0.5 %. Again, this value is considerably smaller than the fluctuations reported by Zerefos et al. (2000, 2007). Yet, aerosols can explain 1.5 DU of the 5.0 DU increase in limb-darkening corrected TOC measurements that can be seen in Fig 8a of the manuscript between 16:00 and 17:00.

We also like to point out that TOC retrievals from global irradiance is less sensitive to changes in AOD than retrievals using the direct beam (such as those utilized by the TOPS instruments) because photos that are removed from the direct beam by aerosols contribute to the global irradiance. So direct measurements are not necessarily better.

Sampling frequency

TOC measurements discussed in the manuscript are available at a rate of one value every 2 minutes. It is therefore not possible to determine whether the moon's shadows resulted in fluctuations in TOC on a shorter time scale. However, oscillations reported by Zerefos et al. (2000) had a period of 20 minutes and those reported by Zerefos et al. (2007) had periods ranging between 30 and 40 minutes. Zhang et al. (2017) reported ionospheric bow waves, which manifested themselves as electron content disturbances, with a period of about 25 minutes during the solar eclipse of 21 August 2017. If these bow waves had also affected the ozone layer, these oscillations should have been detectable with our sampling frequency. Finally, Mims and Mims (1993) report that TOC measurements taken during the total solar eclipse of 11 July 1991 show three fluctuations, which began 700 seconds after the third contact with durations of 378, 270 and 432 seconds, respectively. It is curious that these oscillations had a much shorter duration than those reported by Zerefos et al., (2000, 2007) and Zhang et al. (2017). In any case, oscillations of this duration should still shown up in our 2-minute data considering the low noise in our data discussed above and illustrated in Fig. 9, in particular between the 3rd and 4th contact.

Concluding remarks

We did not "rule out" the findings of the paper by Mims and Mims (1993) as stated by the reviewer. Instead, we simply stated that our data do not support the observation by Zerefos (2000; 2007) and Mims and Mims (1993), and concluded that the question of whether or not bow waves from the Moon's shadow can lead to variations in TOC is still up for debate. We suggested that this debate could be settled by performing limb-darkening-corrected measurements of TOC with different instrument types during one of the upcoming solar eclipses. If such measurements were to show fluctuations in TOC with the same magnitude and timing, the effect of bow waves on TOC could be convincingly demonstrated. We still believe that this is a reasonable path forward and might stimulate future research.

Proposed changes to manuscript

The following text will be added to Sect. 5.2 of the manuscript:

> "By analyzing the sensitivity of TOC to changes in the irradiance ratio and by quantifying the noise in the measurements of the 305 and 340 nm channel we determined that our measurements are able to detect changes in ozone of 0.14 DU (0.05 %) at the start and 0.10 DU (0.03 %) at the end of the eclipse at 95 % confidence level for constant aerosol conditions. The additional uncertainty in TOC values due to changing AODs was determined to be 1.5 DU (0.5 %)."

In Sect. 7.1., the following sentence:

> "Results corrected for the LD effect (thick lines in Fig. 8a) indicate that the AOD was monotonically decreasing over the period of the eclipse (from 0.41 to 0.32 at 319 nm and from 0.05 to 0.04 at 1018 nm) without a spurious spike near the time of totality."

will be replaced with:

> "Results corrected for the LD effect (thick lines in Fig. 8a) indicate that the AOD was increasing between the 1st contact and 16:52 (from 0.41 to 0.58 at 319 nm and from 0.05 to 0.07 at 1018 nm) and then monotonically decreasing to 0.34 at 319 nm and 0.04 at 1018 nm at the end of the eclipse. Corrected results do not have a spurious spike near the time of totality."

In Sect. 7.2, the following sentence:

> "(We have no explanation for the increase in TOC of about 5 DU between 16:00 and 17:00 other than natural variability)"

will be replaced with:

> "The increase in TOC of about 5 DU between 16:00 and 17:00 can partly be explained by increasing AODs over this period, which cause a high-bias in the ozone retrievals."

In Sect. 8.3, the following sentence:

> "Bow waves with wavelengths between of 300 and 400 km and a period of about 25 minutes have indeed been observed during the solar eclipse of 21 August 2017 (Zhang et al., 2017)."

will be replaced with:

> "Ionospheric bow waves with wavelengths between of 300 and 400 km and a period of about 25 minutes, which manifested themselves as electron content disturbances, have indeed been observed during the solar eclipse of 21 August 2017 (Zhang et al., 2017). If these bow waves had affected the ozone layer, these

oscillations should have been detectable with our sampling frequency of one TOC value every two minutes."

Also in Sect. 8.3, the following sentence:

"These small variations are well within the natural variability of the TOC."

will be replaced with:

"These small variations are well within the natural variability of the TOC and the uncertainty of our TOC retrieval of 1.5 DU (0.5 %), which is mainly caused by the effect of changing aerosols on ozone calculations."

References

Bernhard, G., Booth, C. R., and Ehramjian, J. C.:. Real-time ultraviolet and column ozone from multichannel ultraviolet radiometers deployed in the National Science Foundation's ultraviolet monitoring network, Opt. Eng., 44(4), 041011-1, https://doi.org/10.1117/1.1887195, 2005a.

Bernhard, G., Evans, R. D., Labow, G. J., and Oltmans, S. J.: Bias in Dobson total ozone measurements at high latitudes due to approximations in calculations of ozone absorption coefficients and air mass, J. of Geophys. Res., 110, D10305, https://doi.org/10.1029/2004JD005559, 2005b.

Mims III, F. M. and Mims, E. R.: Fluctuations in column ozone during the total solar eclipse of July 11, 1991, Geophys. Res. Lett., 20(5), 367–370, https://doi.org/10.1029/93GL00493, 1993.

Stamnes, K., Slusser, J., and Bowen, M.: Derivation of total ozone abundance and cloud effects from spectral irradiance measurements, Appl. Opt., 30(30), 4418–4426, https://doi.org/10.1364/AO.30.004418, 1991.

Zerefos, C. S., Balis, D. S., Meleti, C., Bais, A. F., Tourpali, K., Kourtidis, K., K. Vanicek, K., Cappellani, F., Kaminski, U., Colombo, T., and Stübi, R.: Changes in surface solar UV irradiances and total ozone during the solar eclipse of August 11, 1999, J. Geophys. Res., 105(D21), 26463–26473, https://doi.org/10.1029/2000JD900412, 2000.

Zerefos C. S., Gerasopoulos E., Tsagouri I., Psiloglou B. E., Belehaki A., Herekakis T., Bais A., Kazadzis S., Eleftheratos C., Kalivitis N., and Mihalopoulos N.: Evidence of gravity waves into the atmosphere during the March 2006 total solar eclipse, Atmos. Chem. Phys., 7(18), 4943–4951, https://doi.org/10.5194/acp-7-4943-2007, 2007.

Zhang, S.-R., Erickson, P. J., Goncharenko, L. P.,. Coster, A. J., Rideout, W., and Vierinen, J.: Ionospheric bow waves and perturbations induced by the 21 August 2017 solar eclipse, Geophys. Res. Lett., 44(24), https://doi.org/10.1002/2017GL076054, 2017.