No change detected on Earth’s mid-latitude atmospheric ozone by the 2017 Total Solar Eclipse

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Six high altitude balloon flights were completed during the summer of 2017 to measure the effect of the total solar eclipse on Earth’s ozone over the eastern Snake River Plain in Idaho. The stratospheric ozone layer undergoes a noisy diurnal pattern driven primarily by photochemistry above 30 km and by atmospheric dynamics for altitudes below 30 km. The flights for this project rarely exceeded that boundary and were an attempt to detect photochemistry effects in the lower stratosphere. The first five flights determined a baseline for the distribution of ozone from ground level to the mid-stratosphere. The sixth flight was done during the total solar eclipse and was compared to the baseline. These data were also compared to multiple years’ data taken in the Uintah Basin in northeast Utah. All measurements were consistent with each other and show spatial and temporal variations in the ozone column that are expected. The balloon’s instrumentation payload was at the tropopause during eclipse totality and no change in either temperature or ozone was detected that was above the normal noise level in the previous data sets. The conclusion is that no photochemical processes are strong enough to clearly modify Earth’s ozone in the lower stratosphere on timescales shorter than three hours. This is consistent with previously reported satellite data of total column ozone.

I. Introduction

One of the great scientific and political triumphs of the last century has been the “healing” of Earth’s ozone layer by International cooperation through the Montreal Protocol and banning substances that were causing the ozone hole. This also led to extensive studies of Earth’s ozone layer in the stratosphere resulting in a significant improvement in our understanding of how the ozone layer grows and ebbs. While ground level ozone is a monitored pollutant, stratospheric ozone protects life on Earth from the Sun’s ultraviolet radiation. A better understanding of ozone at various altitudes is important for human health.

There is a well-established daily pattern to ground level ozone. Fig. 1 shows ozone measured by the Utah Division of Air Quality and verified by our ozonesonde collocated for comparison. Ozone formation begins the moment sunlight starts to interact with pollutants such as nitrogen oxides (NO_x) and volatile organic compounds.

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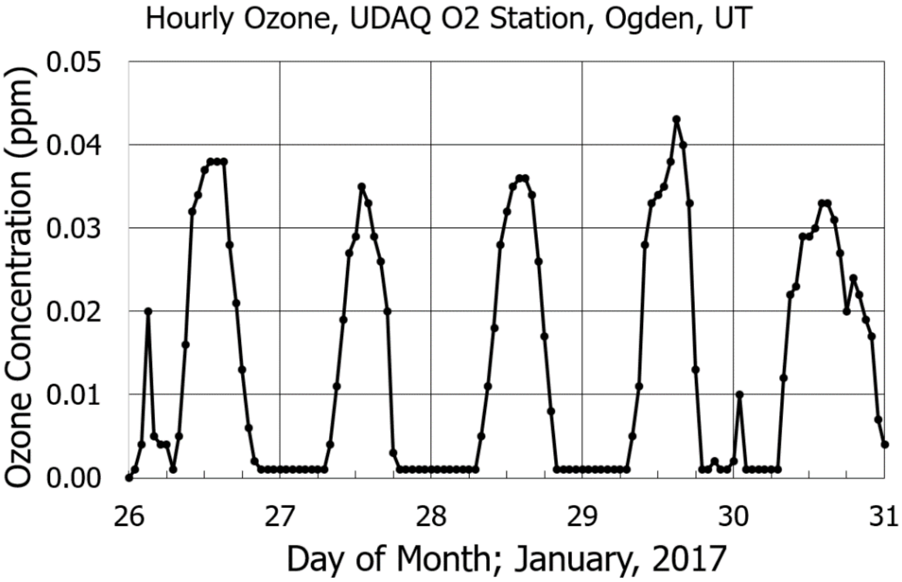

Fig. 1 Example of the diurnal pattern in ground level ozone as measured by the Utah Division of Air Quality. The vertical lines are local standard time midnight.

Since there is a clear ground level relationship between ozone and sunlight, it is reasonable to ask if this pattern is also found in the stratosphere. Ozone in the stratosphere is caused by interactions between the allotropes (O, O_2, and O_3) of oxygen and ultraviolet light from the Sun. Diatomic oxygen is broken up into atomic oxygen by the absorption of an ultraviolet photon. The resulting oxygen atoms are highly reactive and combine with other diatomic oxygen molecules to form ozone. The process can be summarized as

$$3O_2 + \gamma \rightarrow 2O + 2O_2 \rightarrow 2O_3. \tag{1}$$

Subsequent exposure to ultraviolet radiation breaks up the ozone into atomic and diatomic oxygen, which then quickly reforms ozone. The result is a reasonably stable layer of ozone, but more importantly for human life is the fact that the process consumes a considerable number of ultraviolet photons with the effect of protecting life on Earth below from this harmful radiation.

The infamous ozone hole is caused by chlorine atoms acting as a catalyst to break up ozone back into diatomic oxygen molecules. Unfortunately, this process is dramatically faster than the photochemical process that changes the diatomic oxygen back into ozone. Since it is a catalyst, the chlorine does not get consumed in the chemical reaction and is immediately available to convert another ozone molecule into diatomic oxygen. A similar catalytic reaction occurs with bromine. While other molecules can destroy ozone (for example, nitric oxide and hydroxyl radicals), the ones caused mostly by human activity are chlorine and bromine. Another problem is that ozone depletion happens 24 hours a day, whereas ozone production only happens when there is sunlight with a resulting seasonal variation of the size of the ozone hole. The research reported here is not directly related to ozone depletion, but is investigating the correlation between sunlight and total ozone in the lower stratosphere.

Ozone is measured in our atmosphere primarily from three platforms: ground based, satellite, and *in situ* measurements. The advantage to ground and satellite instrumentation is that it operates continuously. The disadvantage is that the primary result is a total column measurement. Some devices can determine altitude profiles, but the vertical resolution is modest, typically 1-3 kilometers. The *in situ* measurements are typically done with ozonesondes suspended under weather balloons. The advantage is high resolution in both amount of ozone and location in the air column. Ozonesondes can resolve concentration differences of a few parts per billion and the vertical resolution is better than 0.5 km. The vertical resolution of an ozonesonde is limited by the 2-minute response time combined with the vertical speed of the balloon system. The disadvantage of ozonesondes is the lack of a continuous data set as measurements happen only one-flight-at-a-time.

Most of Earth's ozone is in the lower stratosphere. A typical ozonesonde measurement is shown in Fig. 2. While ozone concentration remains high in the upper stratosphere, the amount of ozone drops with the dropping air density. Thus, measurements to altitudes of 30 to 35 km capture most of the total ozone. Likewise, satellite and ground-based total ozone column measurements are effectively measurements of the quantity of ozone in the lower stratosphere.

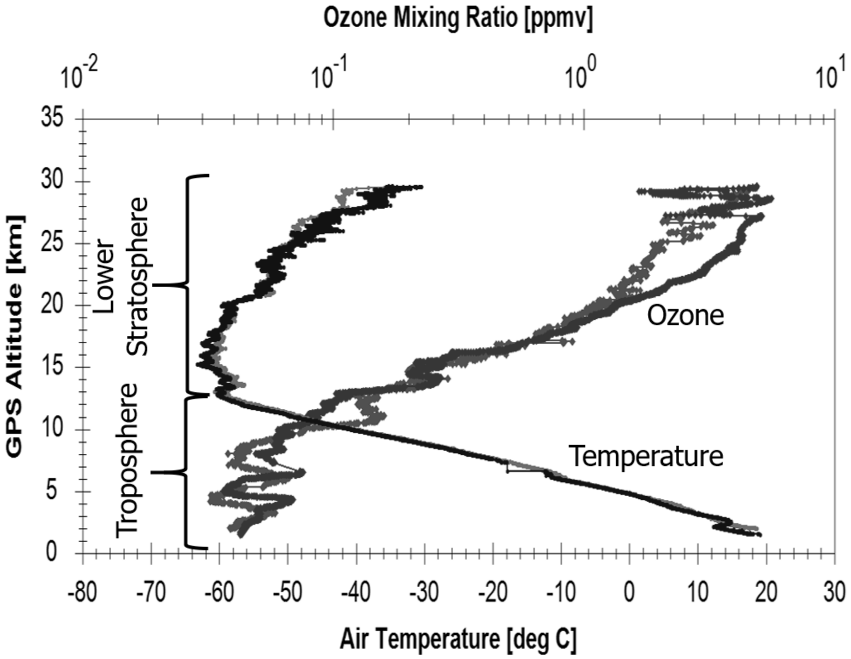

Fig. 2 A typical atmospheric profile. The end of the steady drop in temperature defines the top of the troposphere. The absorption of ultraviolet light heats the stratosphere, causing the increase in temperature.

Imai [1], have shown that there is a diurnal pattern to stratospheric ozone, although it is only a few percent. Sakazaki [2] used multiple instruments to detect a subtle daily pattern in ozone concentration. The strongest diurnal pattern is in the upper stratosphere as can be seen in Fig. 3, which is a region that is out of reach for high altitude balloons. The pattern gets weaker lower in the stratosphere as can be seen in Fig. 4, but could still be detectable by balloon borne ozonesondes. Similar diurnal patterns have been reported and modeled by other researchers, such as NASA’s Pandora program [3], Studer [4], and Schanz [5].

We attempted a novel approach to detect the effect of sunlight on the ozone layer by measuring the stratospheric ozone during the 21 August 2017 total solar eclipse. The launch of the ozonesonde was timed to position the ozonesonde at the bottom of the stratosphere right at the time of totality.

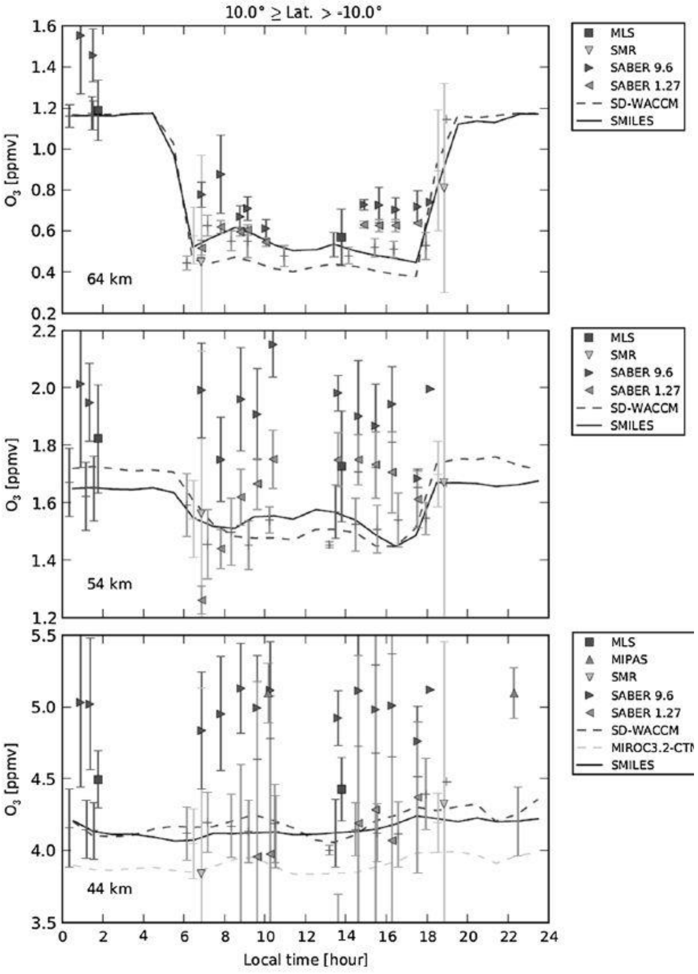

Fig. 3 Diurnal pattern in ozone in the upper stratosphere reported by Sakazaki. Note that the ozone actually drops during sunlight hours, the exact reverse of ground level ozone. Figure from Imai, page 5767 [1].

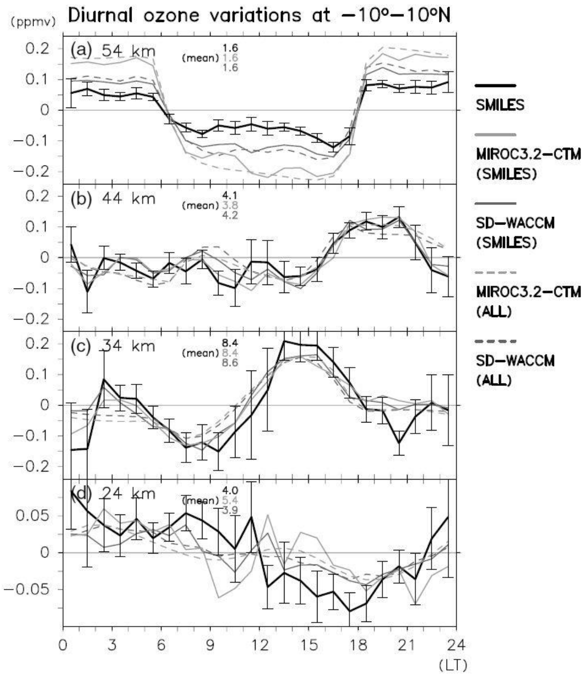

Fig. 4 Diurnal pattern in ozone in the lower stratosphere as reported by Sakazaki. The vertical scale is the change in ozone concentration, which is a small percent of the total ozone. Figure from Sakazaki, page 2996 [2].

Two other reports of ozone measurements can be found in the literature. Adams [6] used a ground-based UV-visible spectrometer during a 98% solar eclipse in Canada on 1 August 2008. They found no evidence of an effect on the total ozone column caused by the eclipse. Ratnam, [7] flew multiple ozonesondes during the 15 January 2010 annular eclipse, although at their location the maximum eclipse only reached 79.4% coverage. Ratnam's group found no significant changes during the eclipse, but did observe a surge of ozone after the eclipse that they attribute to horizontal advection in the lower stratosphere.

Holton [8] argues in a review paper that a large fraction of stratospheric ozone evolves from a tropical stratosphere-troposphere exchange process. They propose that a global scale process transports ozone across an isentropic surface just above the tropopause. Hadley circulation would then be the predominant mechanism by which ozone is moved through the stratosphere to higher latitudes. The lack of evidence in our measurements for solar driven ozone levels seems to lead credence to ozone being produced by photochemistry in the tropics and then transported globally through the stratosphere.

II. Baseline Ozone Data

All data were taken with a balloon hoisted electrochemical cell (ECC) ozonesonde, EN-SCI model 2ZV7-ECC, attached to an iMet model 1-RSB radiosonde. Ozone concentrations were calculated from the raw data using the NOAA SkySonde software with the standard data analysis settings. The ozonesonde was calibrated between flights and at the start of each flight. As noted above, the same ozonesonde used in flight was compared against the Utah Division of Air Quality ground station in Ogden, UT, as an independent calibration. The two instruments produced the same ozone concentration values to within the uncertainty of a few parts per billion that we normally see in ozonesonde data. The extra effort for insuring calibration was necessary because we are expecting any change in the ozone layer caused by the solar eclipse to be small.

Two sets of baseline data were obtained. The primary set was obtained over the three-month period preceding the total solar eclipse. These data were taken on flights over the Eastern Snake River Basin. The location was the same basin as the measurements that were taken during the eclipse. The secondary data set was taken at the same time of year (August) during the previous two years (2015 and 2016). The secondary baseline data set was collected from flights over Utah's Uintah basin. Based on the analysis by Sakazaki, the difference in latitude should have very little impact on the results. Since there is a known seasonal variation in the ozone layer we needed to have a set of baseline measurements taken at the same time of year.

The baseline results are shown in Fig. 5 and Fig. 6. The darker lines are when the ozonesonde is on the way up, the lighter lines are when it is under parachute on the way down. Fig. 5 a) is typical of the repeatability of the measurements in both directions. In fact, the flights never go up and down in the same place, the result is that sometimes there is a horizontal variation in the ozone concentration, as can be seen in Fig. 5 b). Data taken over Utah's Uintah Basin in the preceding two Augusts are similar to Fig. 5.

Overlaying the data runs shows the stability over time of the ozone layer and the instabilities in the ozone concentration close to the tropopause. The 2017 data are shown in Fig. 6 a) superimposed on each other with Fig. 6 b) showing the 2015, 2016, August baseline data.

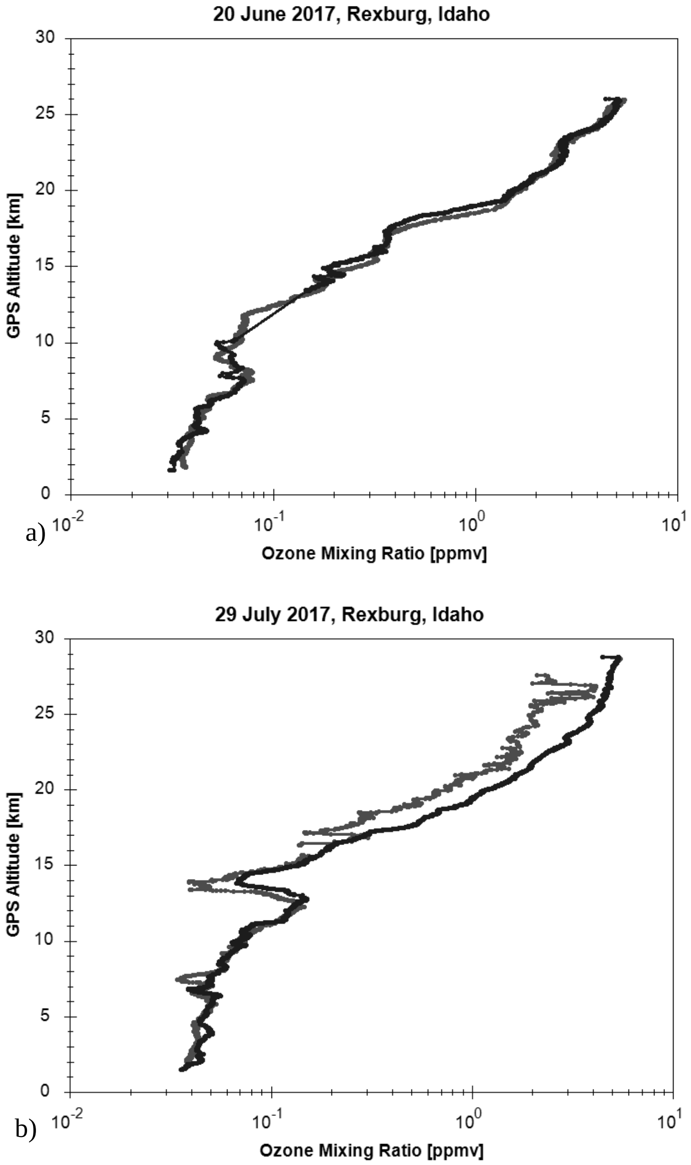

Fig. 5 Baseline data collected in 2017 over the Eastern Snake River Basin, Idaho. The data collected in 2015 and 2016 are similar.

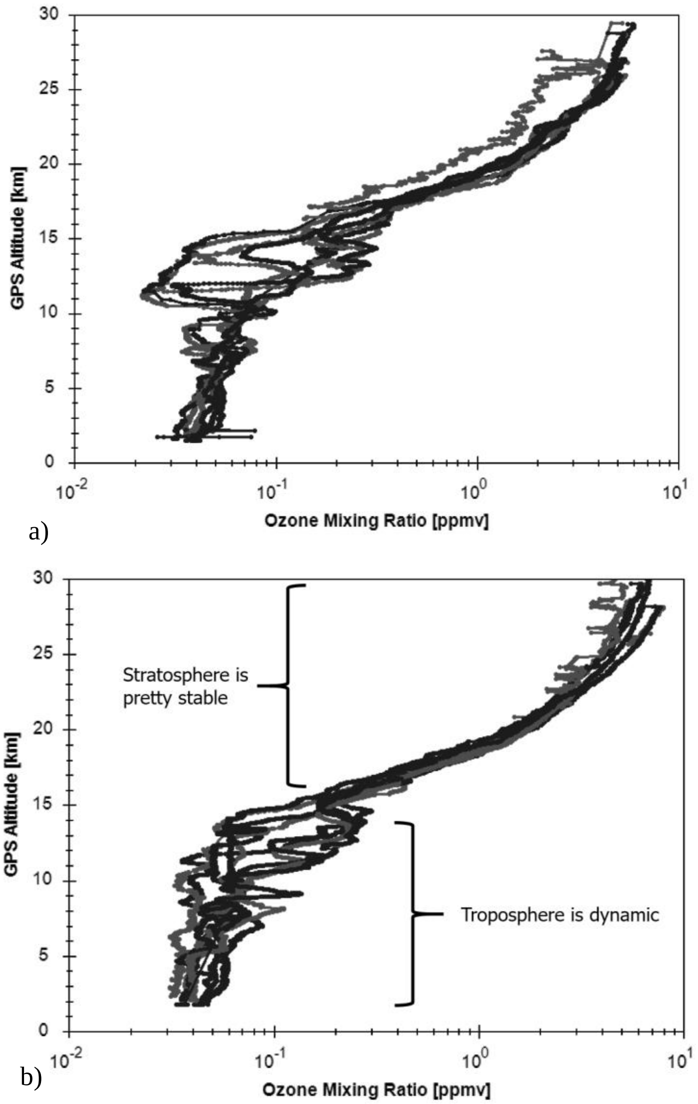

Fig. 6 Baseline data sets overlaid for comparison. a) Four data sets from 2017. b) Five flights from 2015 and 2016. In both cases the upper troposphere is the most unstable region.

III. Eclipse Ozone Data

The ozonesonde reached the bottom of the stratosphere almost exactly at the start of totality. Since totality was just slightly more than 2 minutes, the ozonesonde only covered about 0.5 km vertically during that time. However, the hope was that the hour before totality would start to impact the ozone layer in preparation for the arrival of the ozonesonde. After totality, as the eclipse faded it is assumed that there would be enough time with minimal sunlight that the ozone layer would not immediately respond before the ozonesonde could traverse that region of the stratosphere.

Fig. 7 shows the ozone concentrations during the eclipse. At first glance, one might think that the ozone changed during the time between launch (just before the eclipse) and landing (when the eclipse was nearly finished). However, these differences are common in ozonesonde data and can be a result of both time and location. In the case of Fig. 7 the descent was 15 to 20 km to the southeast of the path up.

Superimposing the eclipse day data on top of the aggregate 2017 baseline shows that the normal variation is larger than any change that could be claimed by changes in solar ultraviolet radiation flux. Referring to Sakazaki's data reproduced in Fig. 3 and Fig. 4, we see that the expected variation is at most a few tenths of a part per million in the region of the stratosphere that we are measuring. Since the horizontal axis in Fig. 8 is logarithmic, the size of 0.1 ppm changes, but it is small compared to the observed fluctuations in the ozone expected on a normal basis.

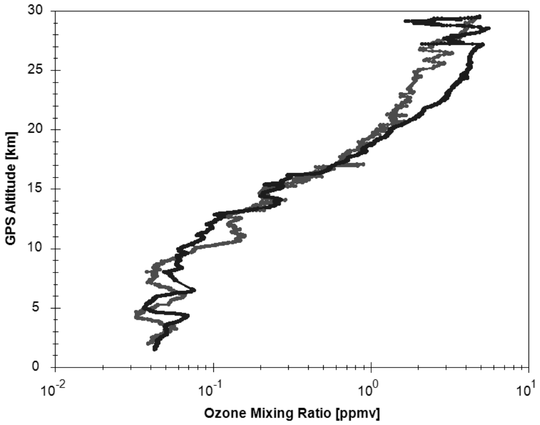

Fig. 7 The ozone measurements taken on the day of the 2017 total solar eclipse. The darker line is on the way up, the lighter line is on the way down.

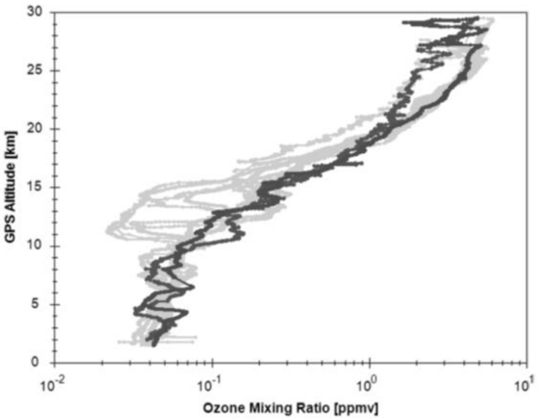

Fig. 8 Ozone measured during the 2017 total solar eclipse are the darker lines, superimposed on top of the four 2017 summer flights.

IV.Conclusion

We saw no evidence for a detectable change in ozone in the lower stratosphere that could be attributed to photochemistry. Any variations were small in comparison to normal daily fluctuations. This is consistent with the model that the lower ozone layer is driven more by dynamics than direct photochemistry. The upper stratosphere is predicted to be more sensitive to sunlight, but weather balloons do not routinely reach those altitudes and we did not capture any significant measurements beyond 30 km above sea level.

It is possible that this is the first time ozonesondes have been flown during a total solar eclipse. One ozonesonde mission has been reported during a non-total eclipse. That research was just outside the main path of the 15 January 2010 annular eclipse (at a location where the eclipse reached a maximum of 79.4%). They detected no significant change in ozone during the eclipse, but a flight shortly after the eclipse did detect an increase in ozone that they attribute to the eclipse. Ozone was studied with a ground based spectrometer during the 1 August 2008 solar eclipse which reached 98% at the location of the measurements. That group found no detectable changes beyond the expected normal fluctuations. Our results are consistent with both of these studies. Future work should plan to fly an ozonesonde shortly after the eclipse to determine if the post eclipse surge is actually associated with the eclipse.

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