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3   **Ozone and temperature decadal solar-cycle responses, and their relation to diurnal**
4   **variations in the stratosphere, mesosphere, and lower thermosphere, based on**
5   **measurements from SABER on TIMED.**

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12   **Abstract.** There is evidence that the ozone and temperature responses to the solar cycle of ~11
13   years depend on the local times of measurements. Here we present relevant results based on
14   SABER data over a full diurnal cycle, not available previously. In this area, almost all satellite
15   data used are made at only one or two fixed local times, which can be different among various
16   satellites. Consequently, estimates of responses can be different depending on the specific data
17   set. Also, over years, due to orbital drift, the local times of measurements of some satellites have
18   also drifted. In contrast, SABER makes measurements at various local times, providing the
19   opportunity to estimate diurnal variations over 24 hrs. We can then also estimate responses to the
20   solar cycle over both a diurnal cycle and at the fixed local times of specific satellite data for
21   comparison. Responses derived in this study, based on zonal means of SABER measurements,
22   agree favorably with previous studies based on data from the HALOE instrument, which
23   measured data only at sunrise and sunset, thereby supporting the analysis of both studies. We
24   find that for ozone above ~ 40km, zonal means reflecting specific local times (e.g., 6, 12, 18, 24
25   hrs) lead to different values of responses, and to different responses based on zonal means that
26   are also averages over the 24 hours of local time, as in 3D models. For temperature, effects of
27   diurnal variations on the responses are not negligible even at ~30 km and above. We also have
28   considered the consequences of local-time variations due to orbital drifts of certain operational
29   satellites, and for both ozone and temperature, their effects can be significant above ~30 km.
30   Previous studies based on other satellite data do not describe their treatment, if any, of local
31   times. Some studies also analyzed data merged from different sources, with measurements made
32   at different local times. Generally, the results of these studies do not agree so well among
33   themselves. Although responses are a function of diurnal variations, this is not to say that they
34   are the major reason for the differences, as there are likely other data-related issues. The effects
35   due to satellite orbital drift may explain some unexpected variations in the responses, especially
36   above 40 km.

37
38   **1.0 Introduction**
39   The understanding of the response of atmospheric ozone and temperature to the solar cycle of
40   ~11 years is important for both scientific and practical reasons. Global responses in the
41   stratosphere, mesosphere, and lower thermosphere have been investigated over decades based on
42   a variety of satellite data.
43   There is evidence that the magnitude of responses to decadal solar cycles depend on the local
44   times at which the measurements are made. For example, Beig et al,.[2012] in analyzing data
45   from the Halogen Occultation Experiment (HALOE), found that derived responses are different
46   at sunrise (6hrs) and sunset (18hrs).

47   However, with few exceptions, the instruments on satellites measure at only one or two local
48   times, which are fixed for the entire mission.
49   Generally, previous studies do not address in detail the issue of diurnal variations of the
50   responses, and there have been no studies describing the variations of the responses over the 24
51   hrs of local time. In the following, we provide estimates of the diurnal variations of the responses
52   over a 24 hrs, which has not been available previously.
53   As noted in Huang et al. [2016b], previous global responses to the 11-year solar cycle based
54   on measurements have been largely based on data from the NOAA operational satellites (which
55   include the Stratosphere Sounding Unit (SSU), the Microwave Sounding Unit (MSU), and the
56   Solar Backscatter Ultraviolet (SBUV) instruments), from the Stratospheric Aerosol and Gas
57   Experiment (SAGE I, II), on the Explorer and Earth Radiation Budget (ERB) satellites, from the
58   Halogen Occultation Experiment (HALOE) on the Upper Atmosphere Research Satellite
59   (UARS), and from the Sounding of the Atmosphere using Broadband Emission Radiometry
60   (SABER) instrument on the Thermosphere-Ionosphere-Mesosphere-Energetics and Dynamics
61   (TIMED) satellite, among others. The advantage of the operational satellites is that they can
62   provide global measurements covering decades, being replaced as needed. However, issues of
63   instrument offsets, stability, and continuity over many years and decades can be problematic.
64   Except for SABER (and UARS), instruments on these satellites make measurements at only
65   one or two local times, which are fixed for the mission duration. The NOAA operational
66   satellites are sun-synchronous, in which case the measurements are made at two fixed local
67   times, one for the ascending orbital mode, and one for the descending mode. HALOE and SAGE
68   make solar occultation measurements, only at instrument sunrise and sunset. Consequently, used
69   as is, responses based on zonal means of the above measurements reflect long term variations at
70   the fixed local times, and could be a source of differences among the various studies.
71   They could also be a source of differences with 3D models, whose ozone amounts and
72   temperature vary with local time around a latitude circle, and whose zonal means are averages
73   over both longitude and 24 hrs of local time. When comparing results of responses based on
74   zonal means from measurements with models, Austin et al. [2008] point out that "The model
75   results are strictly zonal average values, which is an average over local time, whereas the
76   observations are typically made at fixed local times. Therefore, in the mesosphere, where the
77   diurnal variation of ozone is large, some of the differences between model results and
78   observations may have arisen from a diurnal variation in the actual solar response". See also
79   Beig et al. [2012].
80   In addition, the orbits of some operational satellites have drifted, so that the local times at
81   which the measurements are made have also drifted over several hours or more (see McPeters et
82   al. [2013], Frith et al. [2014], Remsberg [2008], Randel et al. [2009], Tummon et al. [2015],
83   Hood et al. [2015]). Tumman et al. [2015] summarizes some of the data processing methods
84   taken by various groups. Generally, they report that diurnal variations are either neglected, or are
85   assumed to be negligible below ~ 45-50 km. See also Davis et al. (2015).
86   Previous results have not generally agreed so well with one another in their details. A major
87   reason for these differences may be the conditions and constraints under which the various
88   measurements were made. For details, see Austin et al., [2008], Crooks and Gray [2005], Gray et
89   al. [2005], Huang et al. [2016b].
90   In addition, previous studies generally have not described how they treat diurnal variations, so
91   that comparisons related to responses as a function of local times are problematical. We are also
92   not aware of studies based on orbital drift.

93   In contrast to most other measurements, SABER provide additional information which allows
94   us to estimate daily ozone and temperature diurnal variations, and then also the dependence of
95   their responses to the decadal solar cycle on local time. In the following, we focus on zonal
96   means of ozone and temperature, either at various specific local times, or averaged over local
97   times (as in 3D model), and the effects of their diurnal variations on their responses to solar
98   variability over a solar cycle of ~11 years (2002-2014), from 20 to 100 km.
99   In this study, we find that not only do the values of the responses depend on the local times at
100   which the measurements are made, but they can be significant even at altitudes as low as 30 km.
101   In Section 2, we review our previous analysis and derivation of diurnal variations and zonal
102   means that are averages of both longitude and local time around a latitude circle, based on
103   SABER measurements. We also describe how we can estimate new results of zonal means
104   corresponding to specific local times, and new results in estimating effects of orbital drift on
105   diurnal variations.
106   In Section 3 we describe our new results of responses to the solar cycle at the specific local
107   times of sunrise (6hrs) and sunset (18hrs), and compare with results from HALOE. This gives an
108   indication of the quality and reality of our and HALOE's results.
109   In Section 4 we describe our new results of responses to the solar cycle over a diurnal cycle of
110   24 hrs.
111   In Section 5 we describe our estimates of responses in situations where the local times have
112   'drifted' due to satellite orbital drifts. We also describe some previous studies.
113   In Section 6 we discuss the issue of data length.
114
115   **2.0 SABER data characteristics and analysis.**
116   The SABER/TIMED instrument [Russell et al., 1999] was launched in December 2001 with
117   an orbital inclination of~74º. SABER views the Earth's limb to the side of the orbital plane, and
118   vertical profiles, corresponding to the line-of-sight tangent point, are retrieved from
119   measurements of the CO_2 15 and 4.3 μm emissions for kinetic temperature, and from the 9.6μm
120   channel for ozone. About every 60 days, TIMED is yawed by 180º, so that the SABER
121   measurement footprint of SABER spans latitudes ~83ºN to 52ºS or ~83ºS to 52ºN on alternate
122   yaw periods. Over a given day and for a given latitude circle, measurements are made as the
123   satellite travels northward (ascending mode) and again as the satellite travels south-ward
124   (descending mode). Data at different longitudes are sampled over 1 day as the Earth rotates
125   relative to the orbit plane.
126   SABER scans altitude (~10-105 km for temperature, 15-100 km for ozone) every 58s with an
127   altitude resolution of ~2km, with ~96 scans per orbit, and ~14 longitudes per day.
128   The orbital characteristics of the satellite are such that, over a given day, a given latitude
129   circle, and a given orbital mode (ascending or descending), the local time at which the data are
130   measured is essentially the same, independent of longitude and time of day. For a given day,
131   latitude, and altitude, we work with data averaged over longitude: one for the ascending orbital
132   mode and one for the descending mode, each corresponding to a different local solar time,
133   resulting in two data points for each day. Each can be biased by the local time variations and is
134   therefore not a true zonal mean. True zonal means are averages made at a specific time over
135   longitude around a latitude circle, with the local solar time varying by 24 h over 360° in
136   longitude. The local times of the SABER measurements decrease by about 12 min from day to
137   day, and it takes ~60 days to sample over the 24 hrs of local time.
138

2.1 Previous analysis

The data are provided by the SABER project (version 2.0, level2A). They are interpolated to 4-degree latitude and 2.5 km altitude grids, after which zonal averages are taken for analysis.

In contrast to other satellite measurements, those from SABER (Russell et al., 1999) contain information to estimate the diurnal variations of ozone and temperature, and the results are described in Huang et al. [2010a, 2010b].

As noted in Huang et al. [2016b], SABER ozone and temperature measurements have been analyzed with success for more than a decade. We have derived variations with periods from one day or less (diurnal variations) up to multiple years (semiannual oscillations (SAO) and quasi-biennial oscillations (QBO)), and one decade or more (trends, responses to solar cycle). See Huang et al. [2008a,b, 2010a,b, 2014, 2016a,b]. Zhang et al. [2006] and Mukhtarov et al. [2009] have derived temperature diurnal tides using SABER data, and Nath and Sridharan [2014] have also derived responses to solar variability using SABER data.

For both ozone and temperature, these studies show that, for variations that are deviations from a mean state (e.g., diurnal variations, tides, semiannual and quasi-biennial oscillations, responses to solar variability, trends), SABER measurements are robust and precise. For example, zonal mean tidal temperatures can agree with other measurements to within ~ 1°K (Huang et al., 2010a), and our zonal mean ozone diurnal variations can agree with other diurnal measurements to less than a few percent (Huang et al., 2010b).

These previous results contain

1) diurnal variations of ozone and temperature for each day of the year, and

2) zonal means that are averages over both longitude and local time in a consistent manner, which can then be compared directly with 3D models.

Using these, we can then estimate the goals of this study, which is to

3) reconstruct the zonal means to reflect specific local times.

4) calculate responses to solar variability over a solar cycle at specific local times

5) estimate local time variations of responses as a result of orbital drifts of NOAA satellites, as noted above.

We can therefore find the variation of responses to the solar cycle over the 24hrs of local time, including at 6 and 18hrs for comparison with responses based on HALOE data at sunrise and sunset for comparison (see Beig et al. [2012], Fadnavis and Beig [2006]).

Compared to the stratosphere, diurnal variations of ozone and temperature themselves are more prominent in the mesosphere and lower thermosphere. Even in the stratosphere, they may not be negligible (Huang et al. 2010a, 2010b). Between ~30 and 80 km, ozone diurnal variations are due mainly to photochemistry (Brasseur and Solomon, 2005), while temperature diurnal variations are mainly a result of thermal tides (Chapman and Lindzen, 1970). For diurnal variations, our results for both ozone and temperature (Huang et al. 2010a, 2010b) show that they can be systematic from the lower thermosphere down to 25 km. This is consistent with results by Sakazaki et al. [2015] for ozone, and Oberheide et al.[2000] and Gille et al. [1991] for temperature.

As discussed below, for responses due to the solar cycle, our results show that the effects of local time variations can be non-negligible for altitudes even below 40 km, especially for temperature.

2.1.1 Diurnal variations

185   As noted above, and in Huang et al. [2016b], unlike other satellites mentioned above (except
186   UARS), the orbital characteristics of TIMED are such that SABER samples over the 24 hrs of
187   local time, which can be used to estimate diurnal variations of ozone and temperature. A
188   complication is that it takes SABER 60 days to sample over the 24 hrs of local time. Over 60
189   days, the variations with local time are embedded with the seasonal variations, and need to be
190   separated from them. The method we use estimates both the diurnal and mean variations (e.g.,
191   seasonal, semiannual, annual) together, by performing a least squares fit of a two-dimensional
192   Fourier series, where the independent variables are local time and day of year. The algorithm is
193   discussed further in Huang et al. [2010a,b].
194   The top row of Figure 1 shows zonal mean ozone diurnal variations (percent deviation from
195   midnight) for day 85 of 2005, at the equator, from 25 to 40 km (left panel), 45 to 60 km (right
196   panel), based on SABER data. See Huang et al. [2010b] for details, and references. It can be seen
197   that diurnal variations can be significant even at 25 km. Since the study of Huang et al.,[2010b],
198   Sakazaki et al.,[2013] have derived comprehensive ozone diurnal variations based on
199   observations from the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES)
200   on board the International Space Station (ISS).
201   The bottom row of Figure 1 corresponds to the top row, but for temperature. See Huang et al.
202   [2010a] for details. Even at altitudes near 30 km, the diurnal variations are systematic and, as
203   seen below, can affect results in estimating decadal responses. Although small, at 30 km, the
204   diurnal variations of temperature compare well with Zeng et al. [2008], Oberheide et al.[2000],
205   Gille et al.[1991], based on different types of measurements.
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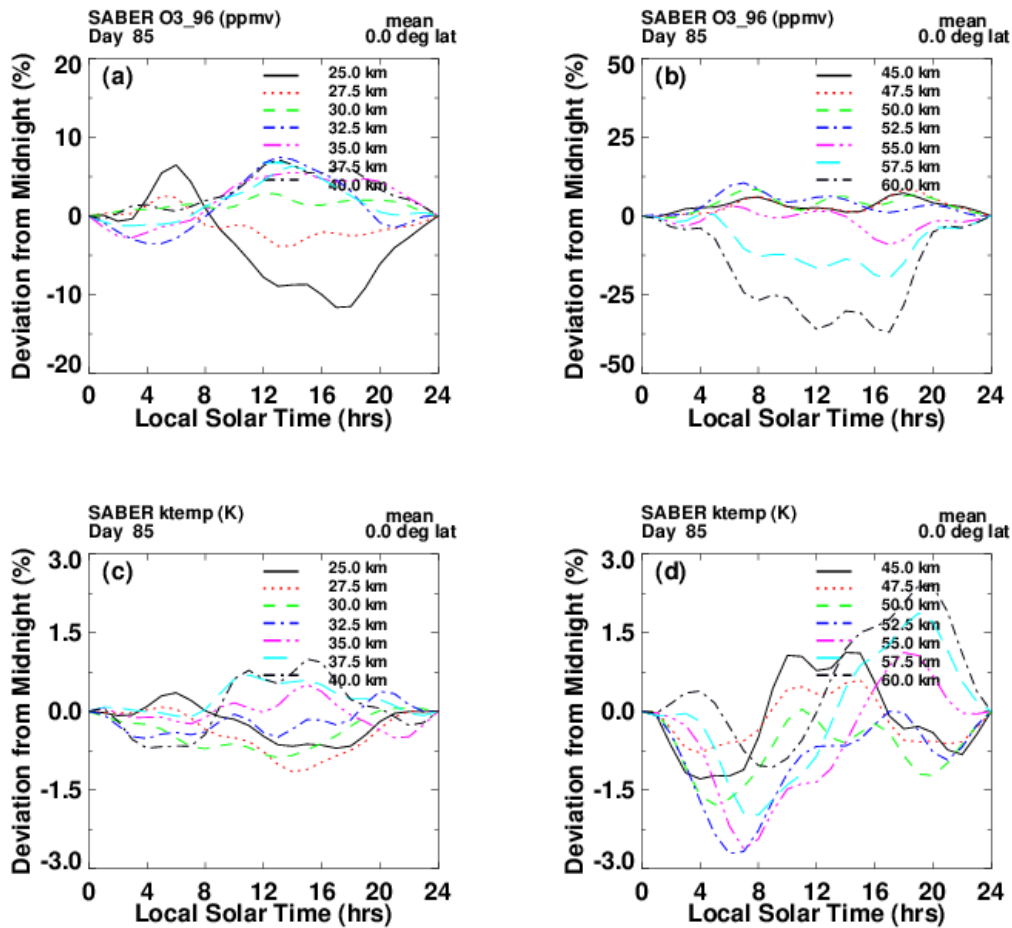


Figure 1. Top row: ozone zonal mean mixing ratios (ppmv) versus local time for day 05085 at the Equator. Left panel (a): 25 to 40 km (percent deviation from midnight), right panel (b): 45 to 60 km. Bottom row: as in top row, but for temperature (K).

2.1.2 Mean variations.

Once the diurnal variations are known for each day, the zonal mean variations, which are averages over longitude and local time, consistent with 3D models, can be obtained.

Based on these zonal means, our earlier results of decadal responses to solar activity, as represented by the 10.7 cm solar flux, had been presented in Huang et al. [2016a, 2016b].

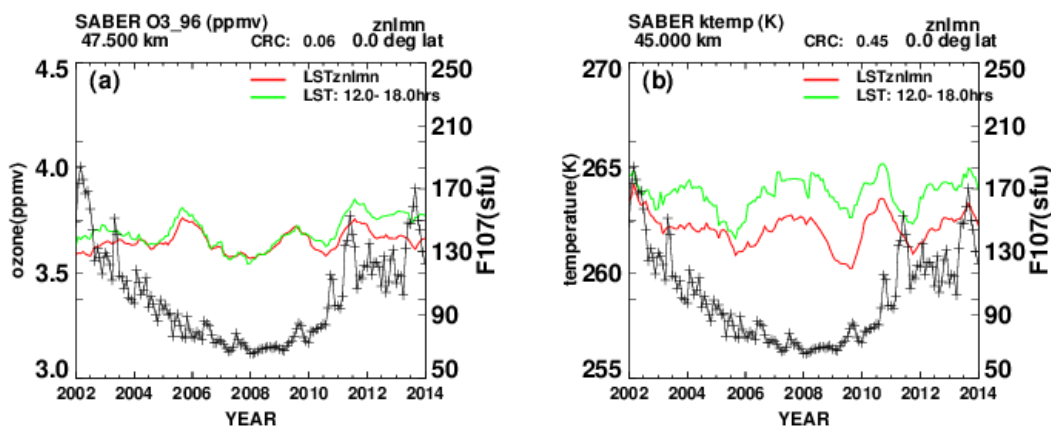
2.2 Current analysis

2.2.1 Multiple regression

For the current study, as for the previous analysis, we generate diurnal variations and mean variations as well, from which we generate the following:

a) monthly zonal means that are averaged over longitude, but at specific local times. These correspond to those satellite measurements which sample at specific local times

b) zonal means with local times that vary from month to month, to simulate the situation caused by satellite orbital drifts, as described earlier.

229   c) estimates of responses to the solar cycle, based on a) and b), and compare with responses
230 based on zonal means that are also averaged over local time.
231   As an example, in Figure 2, the left panel (a) shows our ozone monthly mean mixing ratios
232 (red line, parts per million by volume, ppmv) at 47.5 km and the Equator, from mid 2002 to mid
233 2014, with seasonal and local time variations removed. The green lines represents how the data
234 would vary if we simulated the variations with local time due to orbital drifts of the NOAA
235 operational satellites. We have varied the local times such that from 2002 to 2014, they progress
236 from 12 to 18 hrs. Also shown is the corresponding 10.7 cm flux (black lines, right axis, units in
237 sfu). As can be seen, year 2002 was near solar maximum; the middle of solar cycle 23, and 2014
238 is some years into cycle 24, which began ~2008. The right panel (b) corresponds to the left
239 panel, but for temperature (K) at 45 km. The labels 'CRC' denote the correlation coefficients
240 between the respective ozone and temperature zonal means and the 10.7 cm flux.
241   The estimates of responses to the solar cycle are made using Equation (1), in a similar manner
242 as previously done by others, and by us, using a multiple regression analysis (e.g., Keckut et al.
243 [2005], Soukharev and Hood [2006], Huang et al. [2016b]) that includes solar activity, trends,
244 seasonal, quasi biennial oscillations (QBO), and local time terms, among others, on monthly
245 values. Specifically, the estimates are found from the equation
246
247      $$M(t) = a + b*t + d*F107(t) + c*S(t) + l*lst(t) + g*QBO(t) \qquad (1)$$
248
249 where t is time (months), a is a constant, b is the trend , d the coefficient for solar activity (10.7
250 cm flux), c is the coefficient for the seasonal *(S(t))* variations, l the coefficient for local time *(lst)*
251 variations, and g the coefficient for the QBO. As is often done, the seasonal and local time
252 variations are removed first, but we include them in Equation (1) for completeness. The F107
253 stands for the solar 10.7 cm flux, which is commonly used as a measure of solar activity, and the
254 values used here are monthly means provided by NOAA.
255   M(t) stands for the input ozone or temperature zonal means described in a) and b), above.
256   The algorithm is applied to the monthly zonal-mean values from June 2002 through June 2014
257 (as in Figure 2), from 48°S to 48°N latitude, and from 20 to 100 km.
258

259
260 **Figure 2.** Ozone zonal mean mixing ratios (left panel, red line, ppmv) from mid 2002 to mid 2014, 47.5 km, 0º lat;
261 right panel, as in left panel, but for temperature (K) at 45km. The green lines represent how the data would vary if
262 we simulated the variations with local time due to simulated orbital drifts of the NOAA operational satellites. Black
263 lines (+, right scale) show the corresponding monthly 10.7 cm flux (sfu) provided by NOAA.

2.2.2 Statistical and error considerations

The analysis of uncertainties is the same for the current study as for the previous study of the mean variations just described. It is only the input data that are different. Previously, the input consisted of zonal means that are averaged over both longitude and local time, as in 3D models. Here the zonal mean reflect measurements made at specific local times. Details of the statistical analysis are given in Huang et al.,[2106a, 2016b].

The studies use a least squares fit of the multiple regression of Equation (1). Uncertainties in the responses are found from the sample variance (Bevington and Robinson, 1992, Huang et al., 2016a) of the fit. The curvature matrix and its inversion are quite stable due to the excellent sampling of SABER, as there are essentially no significant data dropouts to speak of. So the standard errors are quite stable and reasonable, as can be seen in the error bars in Figures 6, 7, 8, and A1 and A2, in the Appendix. Although very stable in our case, the inversion of the curvature matrix does not explicitly or definitively address potential aliasing among the various terms of the multiple regression, unless the matrix is diagonal.

In Section 6 (Data length and aliasing) below, we show that the derived responses are essentially the same whether we use all the terms in Equation (1) or only the term containing the solar flux to obtain the responses. So aliasing is not an issue here.

3.0 Results: Ozone and temperature responses to solar cycle at 6, 18hrs (sunrise and sunset)

Specifically, we use the term 'response to solar activity (solar cycle)' generally to refer to the term d*F107 in Equation (1), and in particular to ozone or temperature responses at solar maximum minus those at solar minimum, per 100 solar flux units (sfu). For ozone, it is also in terms of percentage differences. A positive response means that the response at solar maximum is larger than that at solar minimum (Huang et al.,2016b).

For the new results of this study, we focus on the following:

1) Responses to the solar cycle at 6 and 18 hrs (sunrise, sunset). Comparisons with responses based on HALOE data (Beig et al. [2012], Fadnavis and Beig [2006]), which measure only at sunrise and sunset.

2) Responses based on zonal means at specific local times.

3) Responses with local times changing due to satellite orbital drifts.

4) Comparison with results based on zonal means that are averages over both longitude and local time simultaneously, as in 3D models.

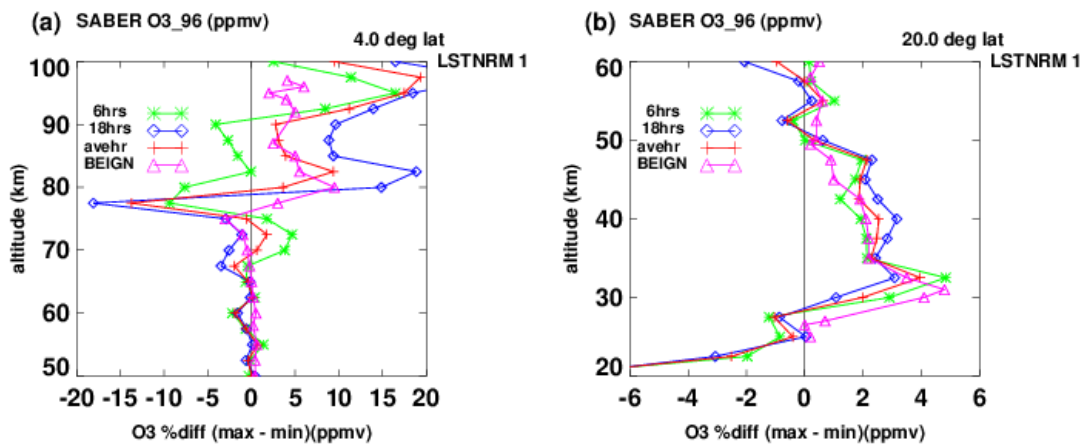
3.1 Ozone responses at 6, 18hrs (sunrise and sunset)

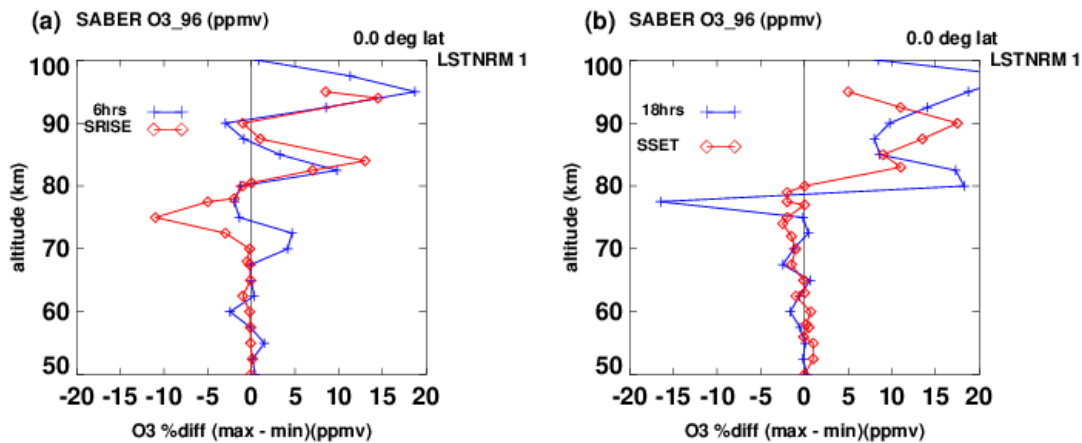
We consider first sunrise and sunset (6, 18hrs) because there are direct empirical results with which to compare, by Beig et al., [2012] and Fadnavis and Beig [2006], based on HALOE data from January 1992 to November 2005. Importantly, unlike other studies, they describe how they treat variations with local times, although they have results only at 6 and 18hrs.

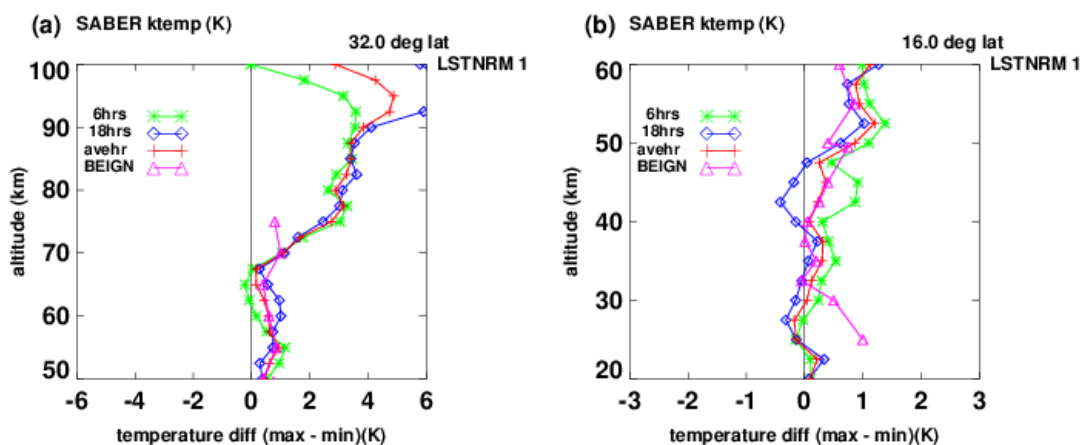
The comparisons will indicate the quality of our results at 6 and 18hrs, and also over the 24 hrs of local time.

In Figure 3 and applicable other figures, we have manually transferred values of plots from other studies for comparison, so they are not exact, but should be adequate for our purposes.

In comparisons with results based on HALOE data, uncertainties should be considered. According to Beig et al., [2012] and Fadnavis and Beig [2006], due to the sparse sampling inherent in solar occultation measurements, there are only 8 to 12 data points (sometimes less)

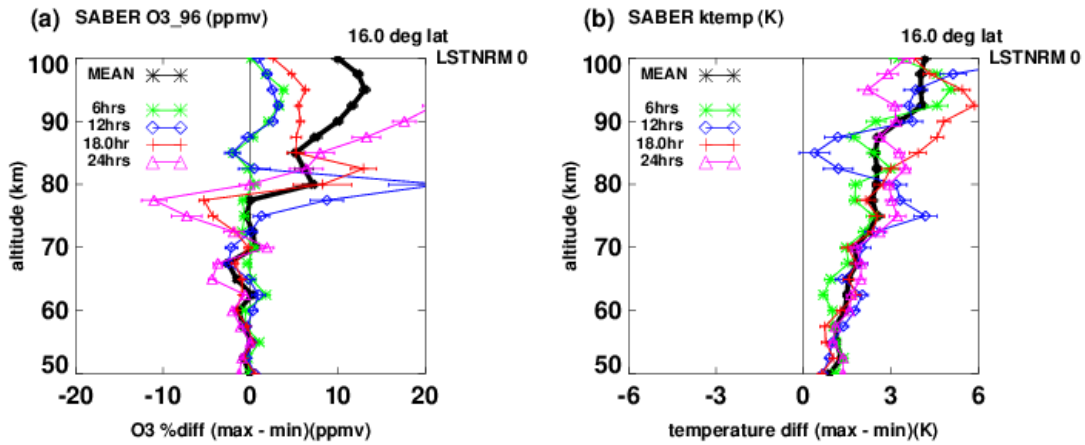
310   per month for each latitude. So they generally present responses that are based on data
311   composited over 30-degree latitude bins (e.g., 0-30ºS, N) and averages of responses at sunrise
312   and sunset. We get results at 4-degree intervals. Even if we composite the SABER data into 30º
313   bins, the distribution within the bins would be uniform, but quite different than that of HALOE
314   data, so we will present our results at specific latitudes. Our responses can vary significantly as a
315   function of latitude, so that is another consideration in the comparisons.
316   In addition, here and in the literature, ozone responses are normally given in terms of percent
317   changes, and the value of the ozone itself is needed to get percent values. Because absolute
318   values among various instruments can sometimes be offset, it is an added source of uncertainty.
319   Figure 3 (left panel) shows our and that of Beig et al.,[2012] ozone responses from 50 to 100
320   km, at 4ºN. The magenta triangles show responses based on HALOE data for ozone (composite,
321   0-30ºN, BEIGN), which are averages of sunrise and sunset responses, and should be compared
322   with the red plusses, which denote the average of our results at 6hrs and 18hrs. It can be seen that
323   the agreement of our averages (magenta triangles and red plusses) are very favorable, except for
324   our large negative value at 77.5 km, and above 90km. The green asterisks denote our results for
325   6hrs and the blue diamonds denote our responses at 18 hrs. The right panel corresponds to the
326   left panel, but for 20ºN and 20 to 60km, and the HALOE results are from Fadnavis and Beig
327   [2006], 0-30ºN composite. As in the left panel, the agreements of our averages (magenta
328   triangles and red plusses) are very favorable. It can be seen that even in the stratosphere, the
329   responses at 6hr are different from those at 18hrs.
330   Considering our discussion of uncertainties above, we believe that the results of Beig et al.
331   [2012] and Fadnavis and Beig [2006] (magenta triangles), agree very well with our estimates
332   (red plusses) in both altitude ranges (both panels of Figure 3). Note in particular the rapid change
333   from negative to positive values near 75-80 km. In Figure 3, the left panel at 4ºN was chosen in
334   part to compare further with Figure 4, and the right panel at 20ºN was chosen to compare with
335   Beig et al.,[2012] results based on composite data in the 0-30º latitude band. We note that our
336   results show that there can be significant differences of responses at various latitudes.
337

338
339   **Figure 3.** Ozone responses to solar decadal cycle versus altitude, at 4ºN, from 50 to 100 km (left panel), and 20ºN,
340   from 20 to 60km (right). Values are responses at solar max minus responses at solar min (% /100sfu). Magenta
341   triangles denote results by Beig et al. [2012], average of responses at 6 and 18 hrs local time, and 0-30ºN. Red
342   plusses denote our estimate (average at 6 and 18 hrs). Green asterisks denote our estimate at 6hrs, and blue
343   diamonds, estimate at 18hrs.
344

345   Figure 4 shows ozone responses to solar activity versus altitude, from 50 to 100 km, at the
346   equator for sunrise (left) and sunset (right). Values are responses at solar max minus those at
347   solar min (% /100sfu). Red diamonds denote responses found by Beig et al. [2012] at 6 hrs (left
348   panel) and 18 hrs (right), composite from 0-4ºN. Blue plusses denote our corresponding results
349   based on SABER data.
350   It is the only instance where Beig et al.,[2012] show responses separately for 6 and 18hrs.
351   Except for the large negative values (red diamonds) from Beig et al [2012] in the left panel
352   near 74 km, and the large negative value (blue plusses) by us at 77.5 km in the right panel, we
353   believe that the comparisons are mostly favorable, in view of uncertainties discussed earlier.
354   Although not shown, the half width of the error bars provided by Beig et al.,[2012] between 80
355   to 90 km are ~± 10 ((% /100sfu)
356   This can be compared with our results in the left panel of Figure 3 at 4ºN. It is seen that
357   although there are sharp variations above 70km, the agreements are at least qualitatively good,
358   considering the caveats noted above.
359   The large excursions near 75 km are not isolated, but are systematic for both Beig et al.,
360   [2012] and us, as can be seen further in Figure 6 for 16ºN.

361
362   **Figure 4.** Ozone responses to solar activity versus altitude, from 50 to 100 km, at the equator. Values are responses
363   at solar max minus responses at solar min (% /100sfu). Red diamonds denote results based on HALOE data by Beig
364   et al. [2012] at 6 hrs (left panel) and 18 hrs (right) local time, composite from 0-4ºN. Blue plusses denote our results
365   based on SABER data at 6hrs and 0 deg (left panel) and 18hrs (right).
366
367   **3.2 Results: Temperature responses at 6, 18hrs (sunrise and sunset)**
368   Figure 5 corresponds to Figure 3, but for temperature. Values are responses at solar max minus
369   responses at solar min (ºK /100sfu).
370   The left panel shows our and Beig et al.,[2012] temperature responses from 50 to 100 km, at
371   32ºN. The magenta triangles show responses based on HALOE data, by Beig et al. [2012] for
372   temperature (composite, 0-30ºN, BEIGN), which are averages of sunrise and sunset responses,
373   and should be compared with the red plusses which denote the average of our results at 6hrs and
374   18hrs. It can be seen that the agreement of our averages (magenta triangles and red plusses) are
375   very favorable, except at 75km. Beig et al.,[2012] do not provide temperature responses above
376   75 km. The green asterisks denote our results for 6hrs and the blue diamonds denote our
377   responses at 18 hrs. Beig et al,.[2012] do not provide results separately for 6 and 18hrs.

378 The right panel corresponds to the left panel, but at16ºN and 20 to 60km, and the HALOE
379 results are from Fadnavis and Beig [2006], 0-30ºN composite. Above 30km, the agreements of
380 our averages (magenta triangles and red plusses) are very favorable. We note that according to
381 Fadnivas and Beig [2006] and Remsberg et al. [2002], that at altitudes below ~35km (~5hPa),
382 HALOE uses temperatures from the National Center for Environmental Prediction (NCEP).
383 This could be the reason for the differences between the magenta triangles and our red plusses
384 below 35 km.
385 It can be seen that even in the stratosphere, the responses at 6hr are different from those at
386 18hrs. We note that the left panel represents results at 32ºN, instead of 16ºN, as the agreement
387 with results by Beig et al. [2012] is somewhat better.
388
389

390
391
392 **Figure 5.** Corresponds to Figure 3, but for temperature responses to solar activity versus altitude, from 50 to 100 km
393 (left panel), and 20 to 60 km (right). Values are responses at solar max minus responses at solar min ºK /100sfu.
394 Magenta triangles denote results by Beig et al. [2012], averaged of 6 and 18 hrs local time (composite 0-30ºN). Red
395 plusses denote our estimate (average of 6 and 18 hrs, at 32ºN (left panel)) and 16ºN, right panel), based on SABER
396 data. Green asterisks denote our estimates at 6hrs, and blue diamonds are estimates at 18hrs.
397

4.0 Ozone and temperature responses over a diurnal cycle.

399 In this section, we extend our results to other local times. Although the figures show responses
400 only at 6, 12, 18, and 24 hrs, we have generated hourly responses, and can do so at any local
401 time. We do not believe that plots at additional local times would add important information for
402 purposes here, and would make other details less discernible.
403 Generally, previous studies based on other satellite measurements do not describe how they
404 treat data with respect to local times, and we cannot make comparisons as with HALOE.
405 Some studies use different data from various instruments, which mix data measured at different
406 local times. See Section 5.2 and the discussion in reference to Figure 9, for details.
407 Figure 6 shows our ozone (left panel) and temperature (right panel) responses from 50 to 100
408 km, at 16ºN over a diurnal cycle (6, 12, 18, 24hrs). The black line denotes our responses based
409 on SABER data where the zonal means are averages over both longitude and 24 hrs of local
410 time. The green asterisks denote responses for 6hrs, blue diamonds (12hrs), red plusses (18hrs),
411 and magenta triangles (24 hrs).

412   Up to this point, ozone values are responses at solar max minus responses at solar min
413 (percent/100sfu). In the following, note that unlike the situation above at 6 and 18hrs for ozone at
414 specific local times, the normalizing values used to obtain responses in percent are now averaged
415 over local time, to be consistent with responses based on zonal means that are averages over both
416 longitude and local time (black line in Figure 6).
417
418

419
420 **Figure 6.** Ozone (left panel) and temperature (right) responses from 50 to 100 km at 16ºN. Values are responses
421 at solar max minus responses at solar min (% /100sfu) for ozone and ºK/100sfu for temperature. Black asterisks
422 denote responses based on zonal means that are averages over both longitude and local time. Green asterisks denote
423 our responses based on zonal means fixed at 6hrs, blue diamonds fixed at 12hrs, red plusses at 18 hrs, and magenta
424 triangles at 24hr, based on SABER data.
425
426   Figure 7 shows the ozone (left panel) and temperature (right panel) responses to solar activity
427 versus altitude, at the Equator, from 20 to 60 km, at 6hrs (green asterisks), 12hrs (blue
428 diamonds), 18hrs (red plusses), 24 hrs (magenta triangles), and based on zonal means that are
429 averages over local times (black asterisks). For ozone, below about 40 km, diurnal variations
430 have relatively little effect on responses. For temperature, the effects can be larger, even at
431 altitudes as low as 30 km.
432
433

434

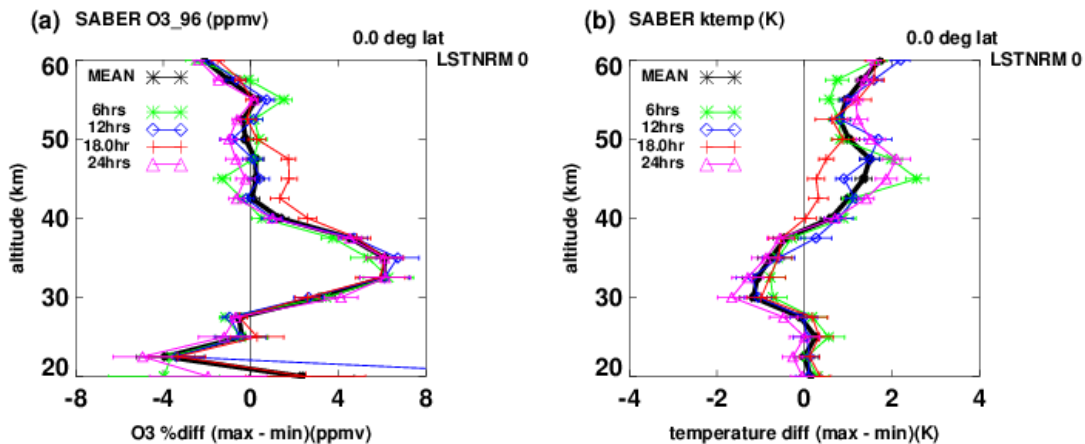



Figure 7. As in Figure 6, but from 20 to 60 km. Ozone (left panel) and temperature (right) responses at 0º. Values are responses at solar max minus responses at solar min (% /100sfu) for ozone and ºK/100sfu for temperature. Black asterisks denote our responses based on zonal means that are averages over both longitude and local time. Green asterisks denote our responses of zonal means at 6hrs, blue diamonds at 12hrs, red plusses at 18 hrs, and magenta triangles at 24hrs, based on SABER data.

  Figures A1 and A2 of the Appendix present corresponding plots to Figure 7, but at 32º and 44º.

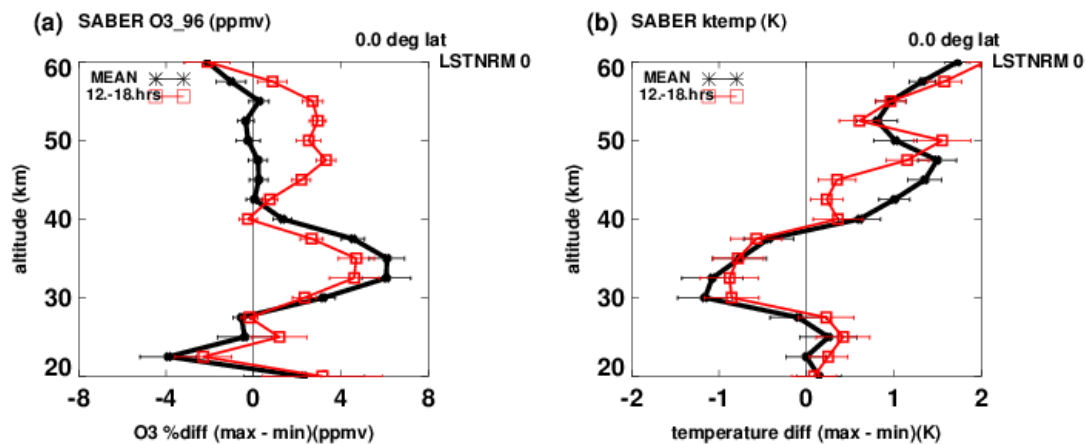
5.0 Comparisons with responses based on operational satellite measurements (fixed or drifting local times).

   In the stratosphere and lower mesosphere, previous global results of responses to the decadal solar cycle have been largely based on data from the NOAA operational satellites (including the Stratosphere Sounding Unit (SSU), the Microwave Sounding Unit (MSU), and the Solar Backscatter Ultraviolet (SBUV) instruments). An advantage of the operational satellites is that they can provide global measurements covering decades, being replaced as the instruments degrade. However, issues of calibration, instrument offsets, stability, and continuity, can be problematical. The satellites are generally polar orbiters and sun-synchronous, and make measurements at two fixed local times, one for the satellite ascending mode, and one for the descending mode.

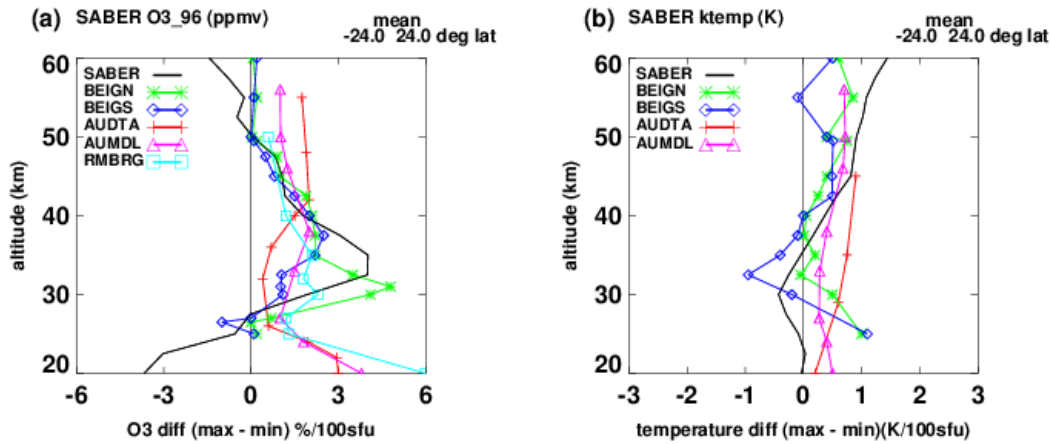
   As noted above, in merging data from different satellites, consistency in local times needs to be considered. Tumman et al. [2015], in reviewing some of the data processing methods taken by various groups, report that generally, diurnal variations are either neglected, or are assumed to be negligible below ~ 45-50 km. See also Davis et al. (2015).

5.1 Effects of local time variations due to satellite orbital drift

   As noted earlier, over years, the orbits of some satellites have drifted, so that the local times at which measurements are made have also drifted by several hours, as described by McPeters et al.[2013].

   To study the effects of local time changes due to orbital drift, from our estimates of diurnal variations, we can simulate their effects on responses to solar variability. As a simple example, Figure 8 shows our results for ozone (left panel) and temperature (right panel) responses to solar activity versus altitude, at the Equator, from 20 to 60 km. Values are responses at solar max minus responses at solar min in percent/100 sfu for ozone, and K/100 sfu for temperature. The red squares denote results where local times increased linearly from 12 to 18 hrs from 2002 to 2014, to simulate orbital drift. Black asterisks denote responses based on zonal means that are averages over both longitude and local time. It can be seen that there are significant differences between them, especially above 40 km. We have also run tests with the local time varying at different hours and durations, and the differences can be smaller or more pronounced than that shown in Figure 8.

475
476 **Figure 8.** Ozone (left panel) and temperature (right panel) responses to solar activity versus altitude, at the Equator,
477 from 20 to 60 km. Values are responses at solar max minus responses at solar min in % per 100 sfu for ozone, and
478 K/100 sfu for temperature. Black asterisks denote responses based on zonal means that are averages over both
479 longitude and local time. Red squares denote corresponding results, but with local times increasing linearly from 12
480 to 18 hrs from 2002 to 2014.
481

5.2 Comparisons with operational satellite data

482
483 Unlike the above comparisons with results by Beig et al.,[2012], based on HALOE data, other
484 studies, such as those based on operational satellites, generally did not describe how they
485 approached the issue of diurnal variations in detail. So we will not then attempt to make
486 comparisons, but only present some previous findings. In addition to issues related to local times,
487 there have been reports based on data-related issues in general. Details can be found in Austin et
488 al., [2008], Crooks and Gray [2005], Gray et al. [2005], and Huang et al. [2016b].
489 Figure 9 is taken from our previous analysis (Huang et al. [2016b], Figure 3). It compares
490 results from previous studies done by others, which were manually transferred by us, so they are
491 not exact. Our ozone responses (black line, SABER) are shown in the left plot (a), versus altitude
492 from 20 to 60 km, averaged from 24°S to 24°N, to better conform to results by others. The light
493 blue squares represent results of Remsberg (2008, RMSBRG), the green asterisks are from
494 Fadnavis and Beig (2006, BEIGN, 0-30°N), and the blue diamonds are from Beig et al.,(2012,
495 BEIGS, 0-30°S), all based on HALOE data.
496 The red line (plusses) in Figure 9(a) show ozone responses from Soukharev and Hood [2006]
497 (AUDTA, data from1979-2003), as reported by Austin et al. [2008], and from models (AUMDL,
498 magenta lines and triangles), also reported by Austin et al. [2008], representing composite results
499 from 25ºS to 25ºN latitude. The Soukharev and Hood [2006] results (red plusses) are a
500 composite based on SBUV, HALOE, and SAGE data, that show a minimum near 30 km, and a
501 maximum above 40 km.
502 The right plot in Figure 9(b) corresponds to the left plot, but for temperature. The temperature
503 responses (AUDTA, data from 1979-1997) were taken by Austin et al. [2008] from Scaife et al.
504 [2000]. In Figure 9(b), the black line denotes our responses based on SABER data, averaged
505 from 24°S to 24°N, to conform to previous results by others.
506 The issue of local time effects is not discussed in detail in these studies. As noted above,
507 Austin et al.,[2008] note that zonal means of models are averages over local time in contrast to
508 those based on satellite measurements, which are typically at fixed local times.

509
510 **Figure 9.** Left panel (a): ozone responses versus altitude from 20 to 60 km; black line: SABER results averaged
511 from 24°S to 24°N; light blue squares: Remsberg (2008, RMSBRG); green asterisks: Fadnavis and Beig, [2006],
512 BEIGN, 0-30°N; blue diamonds :BEIGS, 0-30°S, HALOE data; red plusses: Austin et al. [2008] data AUDTA;
513 magenta triangles, Austin et al., [2008] model, AUMDL, 25°S to 25°N latitude composite. Right panel (b):
514 temperature responses corresponding to left panel.

515

516   Nath and Sridharan [2014] have also analyzed the same SABER data as we did and derived
517 responses at 10–15° latitude. Plots comparing with our results are given in Figure 10 (taken from
518 Figure 5 of Huang et al. [2016a]). Black lines denote our results and red asterisks denote that by
519 Nath and Sridharan [2014]. For both ozone and temperature, their responses agree better with
520 ours up to ~45km, but not so well at higher altitudes. We believe that the differences of the
521 responses at higher altitudes are due to the local time variations in the SABER data, as discussed
522 in Section 2. Nath and Sridharan (2014) do not appear to have considered diurnal variations.
523 Note that in Figure 10 the ozone responses are not in percent differences, as in other plots, so that
524 differences between 45 and 80 km are not readily discernible, due to their small values.

525
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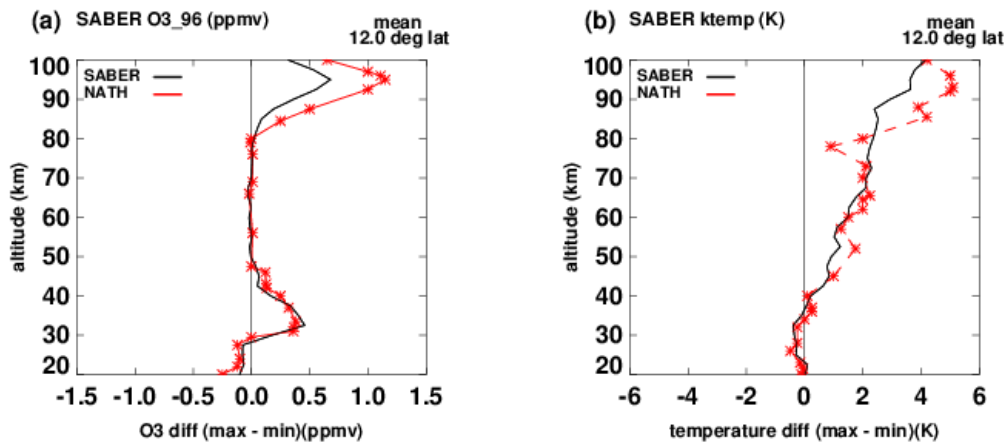

527
528 **Figure 10.** Ozone (left) and temperature (right) responses to solar activity vs. altitude, from 20 to 100 km. Values
529 are responses at solar max minus responses at solar min in ppmv /100 sfu for ozone and K/100 sfu) for temperature.

530 Black lines denote SABER responses at 12º lat; red color denotes results of Nath and Sridharan (2014), for 10–15º
531 lat, also based on SABER data.
532

6.0 Data length and aliasing

534   In Section 2.2.2, we noted that in the application of Equation (1), possible aliasing among the
535 different terms are not definitively addressed. In addition, it has been argued that more than one
536 solar cycle of data is more advantages. Following our analysis given in Huang et al.,[2016b], we
537 address these issues in this section.
538   Figure 11 is a scatter diagram plot of monthly values versus the 10.7 cm flux. The top row
539 shows ozone at 47.5 km at the Equator, the bottom row shows temperature at 45 km and the
540 Equator. The left panels represent the monthly zonal means that are averaged over both longitude
541 and local time, and the right panels use zonal means where the local times simulate orbital drift
542 as discussed in reference to Figure 8. The red lines in Figure 11 represent linear fits between the
543 monthly values and the 10.7 cm flux, which corresponds to using only the solar term (F107) of
544 the multiple regression (Eq. 1). For ozone (top row), the values 0.28 percent/100sfu (left header
545 label, left panel) and 3.24 percent/100sfu at 47.5 km (right panel) compare well with the
546 regression results which uses all terms of Eq. (1), seen in Figure 8 (left panel). For temperature
547 (bottom row), the values 1.23K/100sfu and 0.32K/100sfu at 45 km also compare well with the
548 right panel of Figure 8. Consequently, aliasing from other terms in Equation (1) is not
549 significant.
550   As for issues of data length, unlike time series data, where time increases monotonically with
551 data length, the 10.7 cm flux values remain within a fixed interval between solar minimum and
552 solar maximum (~70 and 200 sfu). In Fig. 11, the values span about one solar cycle. But even
553 over more solar cycles, the 10.7 cm flux values would only repeat and backfill in with values in
554 the same general area in Figure 11, effectively providing a more average result but not
555 necessarily reducing the uncertainty much otherwise.
556   It can be argued that even with more than one solar cycle of data available, analysis over
557 individual cycles should be made to analyze differences among solar cycles.
558
559

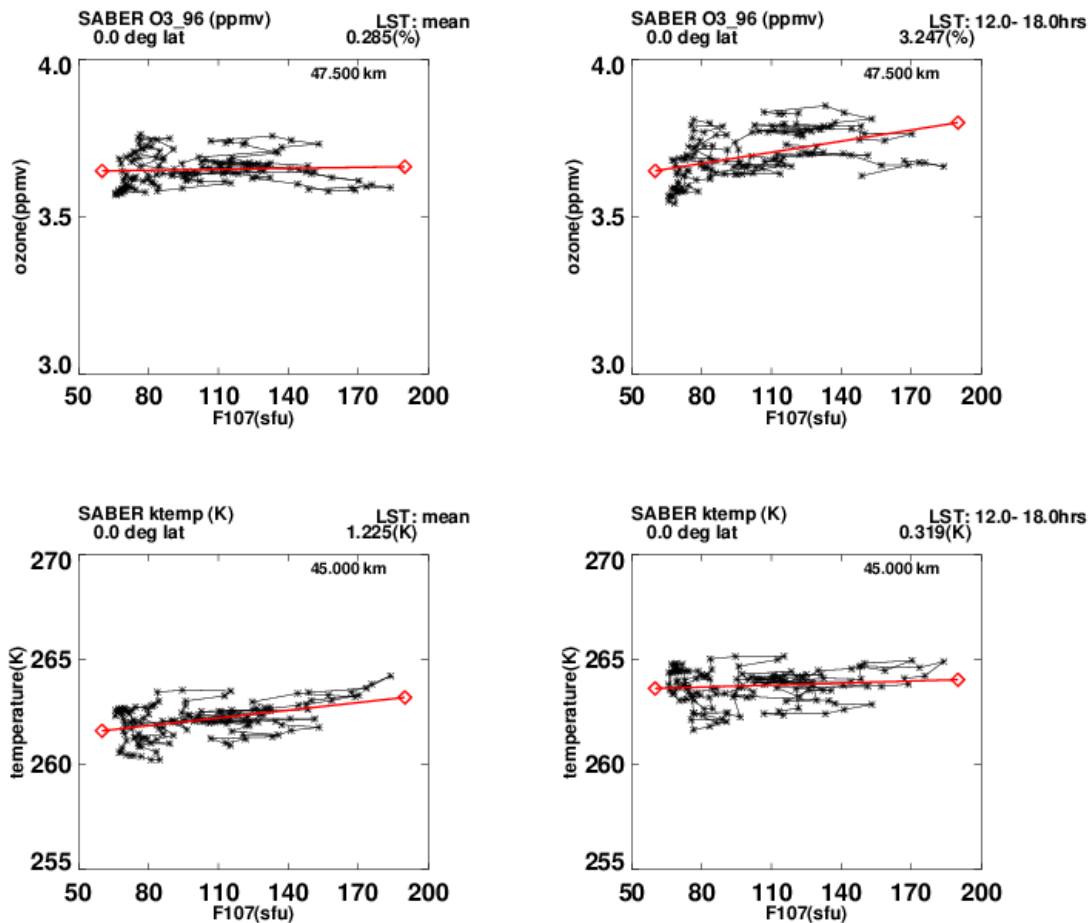



Figure 11. Top row: scatter plot of ozone monthly values versus 10.7 cm flux (sfu) at 47.5 km and the Equator. Left: monthly values are zonal means, including average over local time. Right: as in left panel, but zonal means include simulated local time variations of orbital drift. Bottom row: as in upper row, but for temperature monthly values. Red lines: linear fit between monthly values and 10.7 cm flux. Compare with Figure 8.

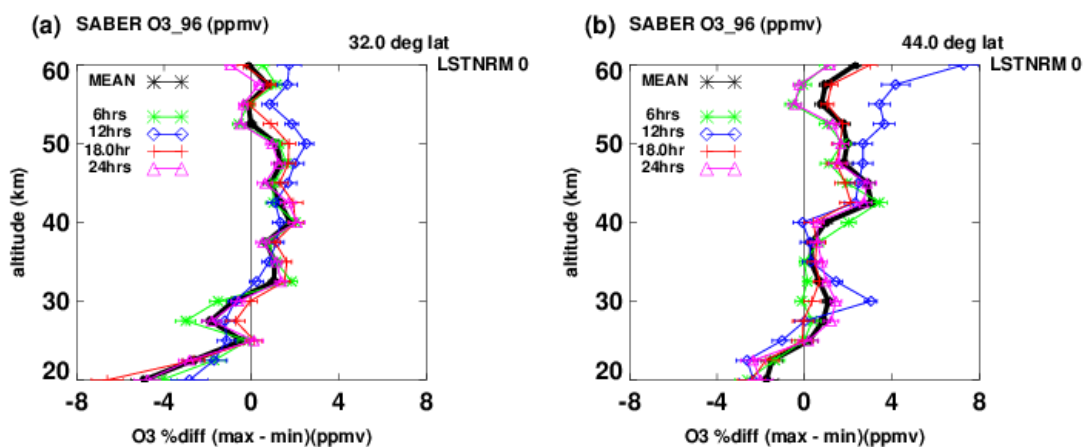
7.0 Summary and discussion.

Using SABER data, we have investigated the effects of ozone and temperature diurnal variations on their responses to the solar cycle, from 2002 to 2014, and 20 to 100 km.

We find that for ozone, above ~ 40km, zonal means reflecting specific local times (e.g., 6, 12, 18, 24 hrs) lead to different values of responses compared to each other, and compared to responses based on zonal means that are averaged over the 24 hours of local time (Figures 6,7). For temperature, effects of diurnal variations are not negligible at ~30 km and above.

We also have considered the variations of local times themselves due to orbital drifts of certain operational satellites, and their effects on responses to the solar cycle (Figure 8). The differences can be significant above ~35 km.

The quality and validity of our analysis are shown in comparisons with responses found by Beig et al., [2012], and Fadnavis and Beig, [2006], based on HALOE data, which made measurements only at sunrise and sunset. Comparisons with our corresponding results, based on SABER measurements, are favorable, both at sunrise and sunset separately, and combined. Our analysis is robust in that the average of responses at specific local times over a diurnal period of

581 24 hrs is the same as responses based on zonal means that are averages over longitude and local
582 time together.
583   Previous studies based on other satellite data generally do not describe their treatment, if any,
584 of local times, so we cannot compare as for HALOE. Some studies also analyzed data merged
585 from different sources, with measurements made at different local times. As discussed in Section
586 5.2 in reference to Figure 9, the results of these studies do not generally agree very well among
587 themselves.
588   We do not believe that diurnal variations are the major reason for the discrepancies, as there
589 are likely other data-related issues. Other reasons for differences may be the conditions and
590 constraints under which the various measurements were made. Details can be found in Austin et
591 al., [2008], Crooks and Gray [2005], Gray et al. [2005], and Huang et al. [2016b].
592   However, diurnal variations should be included as part of the analysis of the differences
593 among various results.
594   The effects due to satellite orbital drift (discussion in reference to Figure 8) may explain some
595 unexpected variations in the responses, especially above 40 km.
596
597
598 **Appendix**
599
600

601
602 **Figure A1.** As in Figure 7, Ozone responses at 32º (left panel) and 44º from 20 to 60 km. Values are responses at solar
603 max minus responses at solar min (% /100sfu) . Black asterisks denote our responses based on zonal means that are
604 averages over both longitude and local time. Green asterisks denote our responses of zonal means at 6hrs, blue
605 diamonds at 12hrs, red plusses at 18 hrs, and magenta triangles at 24hrs, based on SABER data.
606

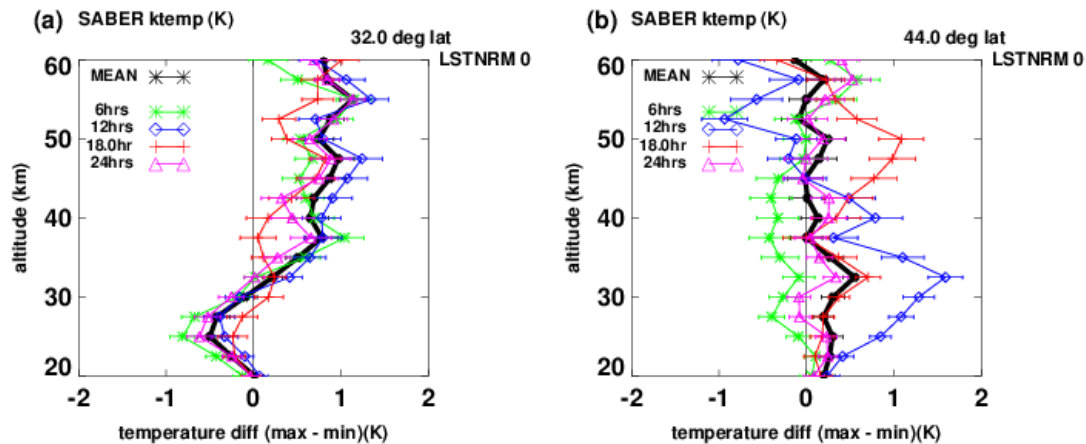



Figure A2. As in Figure A1, but for temperature responses at 32º (left panel) and 44º, from 20 to 60 km. Values are responses at solar max minus responses at solar min (ºK/100sfu). Black asterisks denote our responses based on zonal means that are averages over both longitude and local time. Green asterisks denote our responses of zonal means at 6hrs, blue diamonds at 12hrs, red plusses at 18 hrs, and magenta triangles at 24hrs, based on SABER data.

Data availability

The SABER data are freely available from the SABER project at http://saber.gats-inc.com/.

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