Reply to comments by Reviewer #2

Thank you very much for useful suggestions which greatly helped us to improve the manuscript.

In the followings, black letters show your comments and blue letters show our reply.

This paper represents a careful comparison of various satellite and model estimates of sunrise/sunset differences in (SSD) equatorial ozone. It is well written and considering the number of satellites compared and the inclusion of a model comparison, a remarkably consistent picture emerges of the SSD. My major concern is the attribution of this variation primarily to vertical transport by the migrating diurnal tide.

General comment:

Sakazaki et al. [2012] show the vertical structure of the DW1 (their Figure 5). In the tropics around 40 km the phase of the tide (time of maximum in T) is 1200 – which would imply zero diurnal temperature variation and vertical wind at 0600 and 1800. For a constituent with a vertical gradient and relatively long chemical lifetime we would expect it to roughly be in (or 180 degrees out of) phase with temperature variations (depending on the sign of the constituent vertical gradient – from eqn. 1). Why then do we see a maximum in the transport term when we expect there to be no difference in SR and SS from the DW1? In addition, the authors note that the ozone profile has a relative maximum at 32km (see eqn. 7), which implies the sign of the gradient changes below this level. The vertical wavelength of the tide is about 25 km (again Sakazaki et al. [2012]), so below this relative peak we would expect the same sign in the SR/SS difference - both gradient and wind direction have changed sign, but in Figure 5 we see the sign of SSD has changed. The paper would be far more convincing if it showed both the amplitude and phase of the SD-WACCM DW1 vertical wind (identical to MERRA presumably) and the mean profile of ozone. In addition, the authors have compared these to SABER measurements (16066/12) so it would add to their case if they included those comparisons.

We would appreciate your very careful review and useful suggestions.

Figure B1 shows the vertical profile of amplitude and phase of diurnal migrating tide (DW1) in vertical wind (black curves) and (red curves) averaged at 10°S-10°N, as derived from SD-WACCM data during 2008-2010. As you suggested, the phase basically shows a downward progression but it is almost constant in the middle and upper stratosphere. The constant phase is possibly due to the trapped mode which maximizes in the upper stratosphere (e.g., Sakazaki et al., 2013). This is why the phase of vertical wind similar between ~20 km and ~40 km; consequently, the sign of SSD is determined by that of vertical gradient of the background ozone profile only.

Next, we consider the phase relationship between the O_3 variations by tidal vertical transport and the temperature variations (Sakazaki et al., 2012). Equation (1) in the text is re-written here:

$$\frac{\partial[O_3]'}{\partial t} = -w'\frac{\partial\overline{[O_3]}}{\partial z} + S' . \quad (B1)$$

We assume that you consider the following linearized, thermodynamic equation:

$$\frac{\partial T'}{\partial t} = -w'(\frac{d\overline{T}}{dz} + \frac{g}{c_p}) + Q , \quad (B2)$$

where T', w' and Q are DW1 component of temperature (K), vertical wind (m s) and diabatic heating (K s^{-1}), respectively; $\overline{T}$ is zonal-mean, daily-mean temperature; g is gravity constant; c_p is the specific heat at constant pressure.

From Equations (B1-2), we can derive the relationship between T' and $[O_3]'$. Here it should be noted that the O_3 variations caused by vertical transport are in (or 180 degrees out of) phase with temperature variations only when diabatic heating is negligible (Q = 0 in Equation B2). In this case (Q = 0), the phases of T' and w' should be apart by a quarter cycle. In SD-WACCM, however, the phases of T' (red curve) and w' (black curve) are almost in phase in the upper stratosphere (Figure B1), indicating that $Q \neq 0$. This will be further discussed in the following paragraph. Note that the phase of T' is ~1200 LT, being consistent with the result by Sakazaki et al. (2012).

Figure B2 shows the diurnal temperature variations at ~40 km from SD-WACCM output. Again, it is seen that the phase is ~1200 LT, as you pointed out. Figure B2 also shows the temperature variations due to adiabatic processes (blue curve; first term on r.h.s. of Eq.B1) and diabatic heating (red curve; second term on r.h.s. of Eq. B1). The sum of the two terms is shown by solid dashed curve; the agreement between solid and dashed curves indicates that the Equation B2 is valid for the present case. It is seen that at this altitude, the two terms with different phases equally contribute to the diurnal variations. Note that the phase of adiabatic processes (i.e., phase of w') is 0600—0900 LT, being out of phase with the O_3 variations caused by vertical transport (Figure 7a in the manuscript); this phase relationship is consistent with your prediction. Note that the phase of ~1200 LT in temperature variations is achieved by the additional variations due to diabatic heating (the phase is ~1700 LT: red curve in Figure B2).

To summarize, diabatic heating in the upper stratosphere makes the issue complicated; the phases of vertical wind and temperature do not show clear progressions. For the phase relationship between temperature variations and O_3 variations due to vertical transport, it follows your prediction as far as the temperature variation due to adiabatic processes is concerned.

In the revised manuscript, Figure B1 will be added (for vertical wind only). We would not show SABER results for temperature to avoid the complexity.

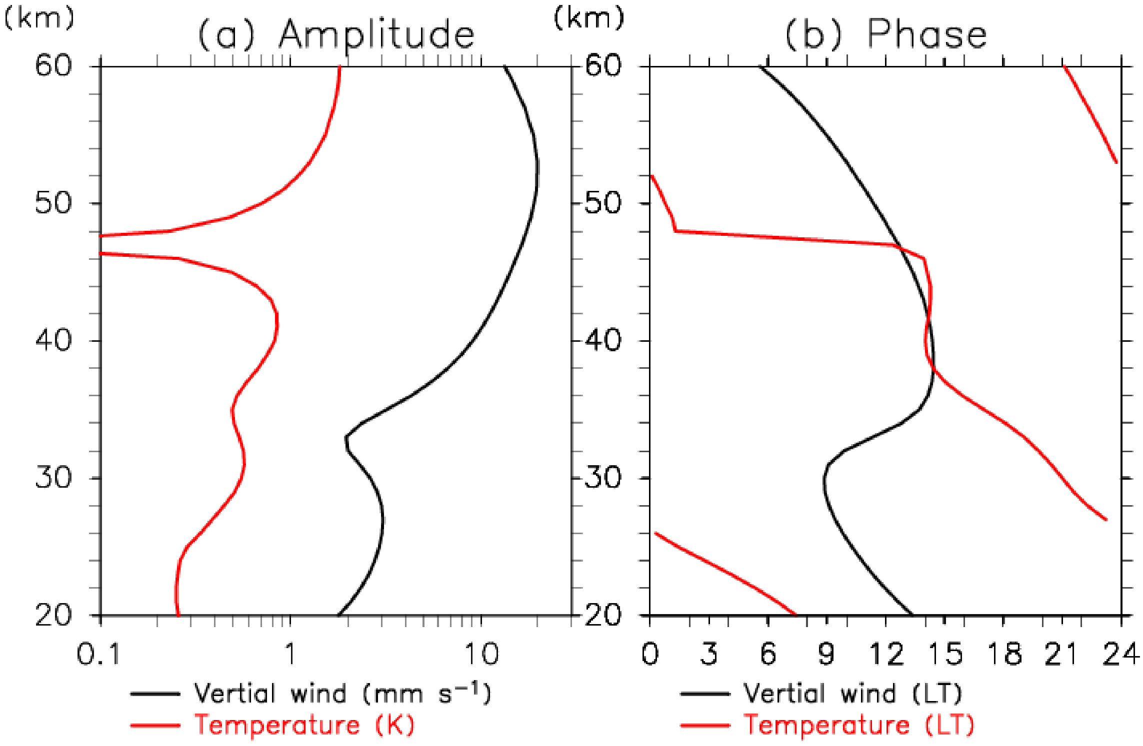

Figure B1: Vertical profiles of (a) amplitude and (b) phase for diurnal migrating tide in (black curves) vertical wind and (red curves) temperature, averaged between 10°S and 10°N, as derived from SD-WACCM data during 2008-2010.

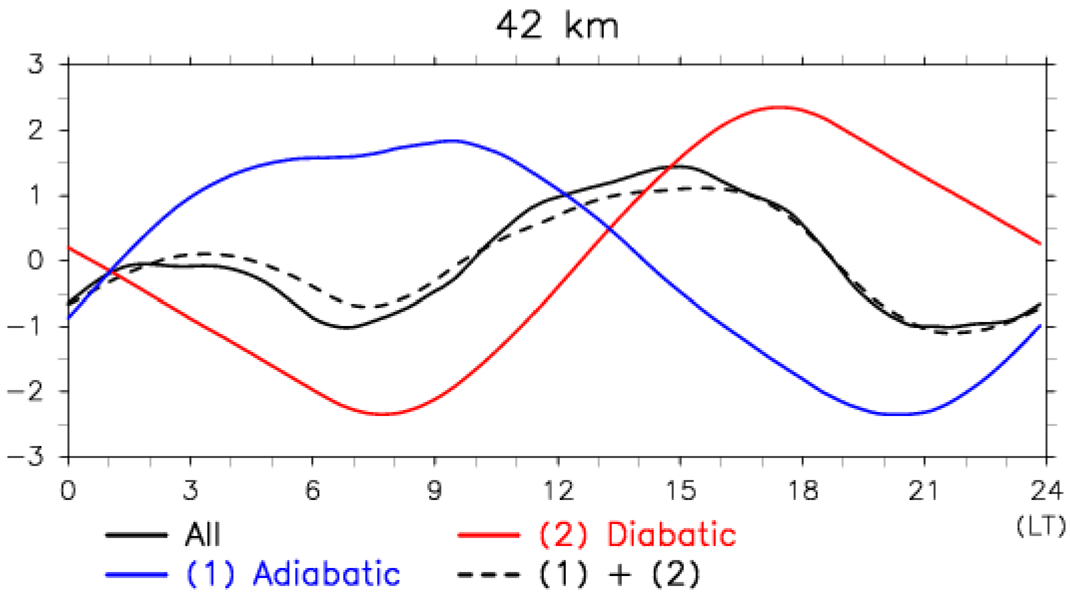

Figure B2: Diurnal temperature variations (K) averaged between 10°S and 10°N at 42 km level, as derived from SD-WACCM data during 2008-2010 (black solid curve). Blue and Red curves denote the contributions from the first and second terms (i.e., temperature variations due to adiabatic processes and diabatic heating), respectively, on the r.h.s. in Equation A2. Black dashed curve shows the sum of the two terms.

Specific comments:

1. 16047/8: "the diurnal migrating tide...is dominant over other higher-order harmonics": This is only true at certain seasons, latitudes and heights. For example, the diurnal tide in temperature and vertical wind is nearly zero at 20 N/S.

   Thank you for the suggestion. The expression will be changed as,
   "the diurnal migrating tide in upper air… is basically dominant over other higher-order harmonics in the tropical stratosphere."

2. 16047/18: It is true that the vertical wind is small and difficult to measure, but the temperature signal is and has been easily observed and could also be used to infer the vertical wind. It might be worth noting the proposed method is only practical when there is a vertical gradient in the constituent.

Thank you for the suggestion. The expression will be revised as,

"We suggest that in the presence of vertical gradient of ozone, the ozone SSD could be used to obtain quasi-observational evidence of tidal vertical winds in the tropical stratosphere."

The temperature tide may be difficult to use for estimating the vertical wind in the presence of diabatic heating ($Q \neq 0$). Please see our reply to the general comment.

3. 16053/25: Can the authors estimate an uncertainty in the geometric altitude determination?

The following description will be added in the revised manuscript:

"The uncertainty in altitude registration for SMILES is considered to be in the same order as that for other datasets. Note that there is no systematic difference in the altitude registration between SR and SS."

The above description will be included in the revised manuscript.

4. 16054/10: what is the frequency of the MERRA data used to nudge SD-WACCM? Enough to resolve the diurnal tides?

6-hourly data are used in this study. In the revised manuscript, the corresponding sentence will be revised as,

"Here specified dynamics (SD)-WACCM is a chemical transport model (CTM) that uses WACCM4 temperature, horizontal winds, and surface pressure nudged towards 6-hourly time series from MERRA reanalysis (Rienecker et al., 2011)."

Please also see Figure A1 (on the reply to Reviewer #1) which compares the diurnal temperature variations at 42 in SD-WACCM and MERRA. The two results are in good agreement.

5. 16060/24: Without error bars on these differences, it is difficult to say how similar these results are. Can the authors estimate the uncertainties in SSD based on simple propagation of errors?

We have added error bars (95% confidence interval) to the SAGE II, HALOE and ACE-FTS results in Figure 5. Please see Figure B3 for the revised version. The procedure to obtain the confidence interval is as follows. First, the 'error' is defined as the standard deviation from the monthly composite value. Then the error for the annual-mean has been derived such that the errors for each month propagate into the annual mean. Finally, the statistical test (*t*-test) has been made with the degrees of freedom being the total number of SS-SR pairs (128 for SAGE II, 86 for HALOE and 25 for ACE-FTS).

Accordingly, we have added error bars for Figure 9 (seasonal variation of SSD). Please see Figure B4 below for the revised version.

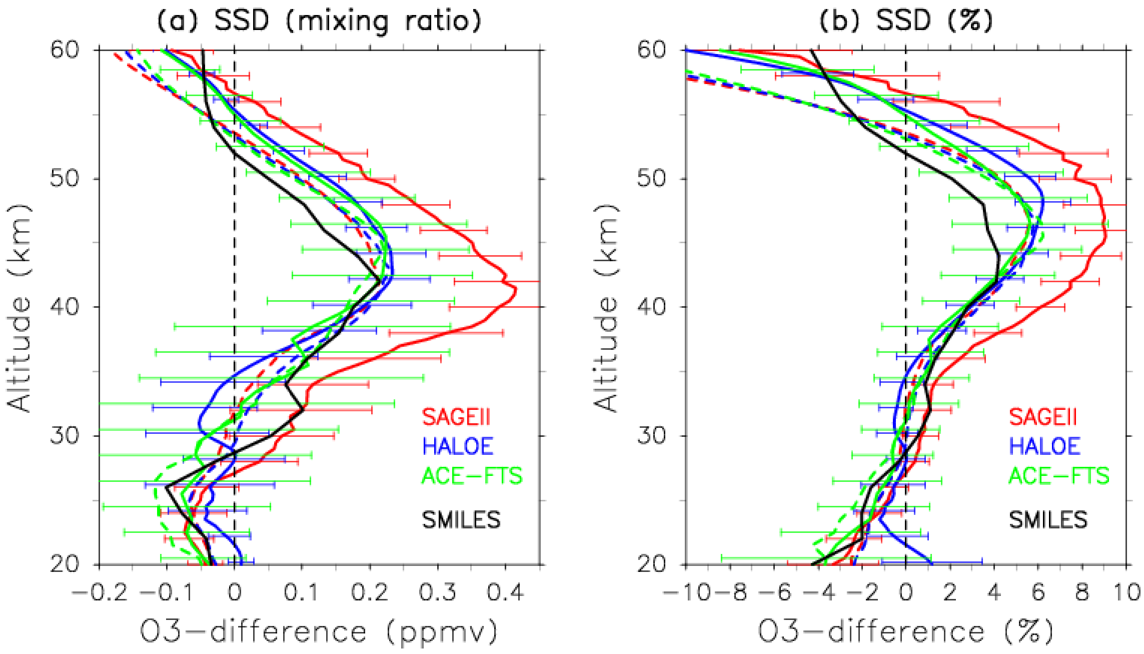

Figure B3: Revised Figure 5. SSD for 10°S–10°N in (a) ozone mixing ratio (ppmv), 2 and (b) SSD ratio to the daily mean (%), derived from SAGE II (red solid curves), HALOE (blue solid curves), and ACE– FTS (green solid curves). Red, blue, and green dashed curves denote SD–WACCM results at SAGE II, HALOE, and ACE–FTS coincidence, respectively. Black solid curves show the SMILES result (SR and SS are defined by those profiles with a solar zenith angle between 80° and 100°). Black dot-dashed curves show the difference between 18:00 and 06:00 LT, calculating using SMILES data and based on 1 hourly diurnal variations. Horizontal bars for SAGE II, HALOE and ACE-FTS show 95% confidential levels in *t*-test. For the statistical test, the error is defined as the standard deviation for the monthly SSD; this quantity has been propagated to the error in annual-mean. Then, the *t*-test has been made with the degrees of freedom being the total numbers of SS-SR pairs for each dataset.

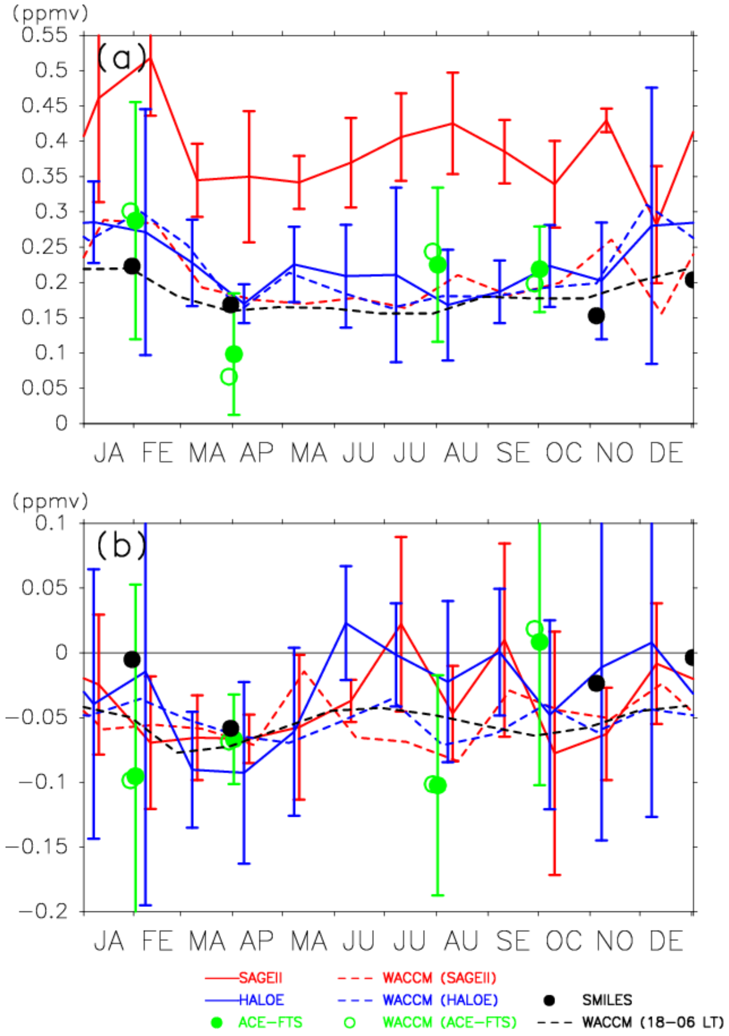

Figure B4: Revised Figure 9. Seasonal variation of O3 SSD at altitudes of (a) 40–45 km and (b) 22–28 km, obtained from (red solid curve) SAGE II, (red dashed curve) SD–WACCM at SAGE II locations, (blue solid curve) HALOE, (blue dashed curve) SD–WACCM at HALOE locations, (green closed circles) ACE–FTS, (green open circles) SD–WACCM at ACE–FTS locations, and (black closed circles) SMILES. The black dashed curve shows the difference in ozone between 18:00 and 06:00 LT, as deduced from diurnal variations in ozone concentration based on full-grid SD–WACCM between 2008. Vertical bars for SAGE II, HALOE and ACE-FTS show 95% confidential levels with *t*-test.

6. 16062/27: Again, "quasi-observation evidence of seasonal variations in stratospheric vertical tidal winds" can be obtained directly from temperature observations – simply replace dO3/dz with dT/dz.

The term of *"for the first time"* will be removed from the text to soften the expression.

7. 16065/13: see general comment - how can the sign change when the gradient in ozone changes sign but the 15 km difference in altitude is less than the vertical wavelength of the DW1 tide?

The phase of vertical wind does not show a downward progression in the upper stratosphere possibly due to the trapped mode. This is why the sign of SSD is only determined by that of vertical gradient of background of O_3.

Please see the discussion above on your general comment and Figure B1 for details.

8. 16066/12: How do the authors explain the good agreement in SSD between SDWACCM and observations, when the tidal amplitudes in SD-WACCM/MERRA are a factor of two low?

We had this description because it might be possible that observations which depend on reanalyses and SD-WACCM in the altitude registration and/or retrieval process show small SSD. But this paragraph seems confusing to the readers so that we will try to shorten it and avoid detailed discussion.

"Another related issue may be the reproducibility of tides in SD-WACCM and reanalyses. Satellite measurements use, more or less, (re)analysis data for the altitude registration and/or the retrieval process. It is found that the amplitude of diurnal tide in SD-WACCM and reanalyses is up to ~50% smaller in the upper stratosphere compared to than in data from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) measurements (version 2.0 data) (not shown; see Sakazaki et al. 2012 for the comparison between SABER and reanalyses). This could affect any of the satellite datasets, but a further study is needed for a more quantitative discussion."

9. 16077/Figure 5: If this is SSDcorr the caption should reflect that.

Will be corrected. Thank you.

10. 16083/Figure 11: This only shows the amplitude, but to understand the transport, the phase of the migrating tide needs also to be shown.

The vertical profile of amplitude and phase of diurnal migrating tide in vertical wind (black curves in Figure B1), will be added in the revised manuscript with the following description:

“Figure # shows the amplitude and phase of diurnal migrating in vertical wind averaged between 10°S and 10°N, as derived from SD-WACCM data. The amplitude exponentially increases with altitude. The phase basically shows the downward progression but it is almost constant around 40 km possibly due to the presence of trapped modes excited by ozone heating (e.g., Sakazaki et al., 2013b). Consequently, the phase of vertical wind is similar in the whole stratosphere; thus, the sign of SSD (minus at 20-30 km and plus at 35-50 km) is determined by that of vertical gradient in the background ozone concentration.”

Thank you very much again for your suggestions. Please also refer our reply to Reviewer #1 for further revisions.

Reference

Sakazaki, T., M. Fujiwara, and X. Zhang (2013), Interpretation of the vertical structure and seasonal variation of the diurnal migrating tide from the troposphere to the lower mesosphere. *Journal of Atmospheric and Solar-Terrestrial Physics*, 105-106, 66-80, doi:10.1016/j.jastp.2013.07.010.