Local-Time Variabilities of March Equinox Daytime SABER CO₂ in the Upper Mesosphere and Lower Thermosphere Region

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Abstract This work reports the analysis of the local-time variations of daytime CO₂ in the Upper Mesosphere and Lower Thermosphere region as observed by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics satellite. Results show that daytime SABER CO₂ in the upper mesosphere between latitudes 30°S and 50°N is lower in the morning than in the afternoon. The same was found in the lower thermosphere but between latitudes 50°S and 50°N. The opposite was found in the upper mesosphere between 50°S and 30°S. These results are compared to simulations of CO₂ by the Whole Atmosphere Community Climate Model–eXtended. It was found that the local-time variations of Whole Atmosphere Community Climate Model–eXtended CO₂ are weaker than SABER CO₂. Model diagnostics indicated that these local-time variations in the model are driven primarily (secondarily) by strong vertical (meridional) gradients in Upper Mesosphere and Lower Thermosphere CO₂ volume mixing ratios and strong local-time variations in vertical (meridional) winds. This work concludes that SABER CO₂ shows significant local-time variations that are not well simulated by Whole Atmosphere Community Climate Model–eXtended, and we suggest that this is likely because of weaker tidal forcing in the model.

1. Introduction

Local-time variabilities in the Upper Mesosphere and Lower Atmosphere (UMLT) region are well known to be primarily driven by atmospheric tides. Atmospheric tides are sinusoidal oscillations along a geographic latitude circle with periods that are subharmonics of a solar day (Chapman & Lindzen, 1970; Forbes, 1995). They are further divided into migrating and nonmigrating tides. Migrating tides follow the apparent motion of the Sun. Their phase is the same over every longitude in the local frame. In contrast, nonmigrating tides do not follow the apparent motion of the Sun and so their phase differs with longitude. Tides are well known to be induced by heating due to latent heat release and by heating due to water vapor and ozone from the lower atmosphere. Their impacts on the UMLT region are known to also affect the Ionosphere/Thermosphere region (Jones et al., 2014; Jones et al., 2017; Jones et al., 2018). Thus, they are important in coupling the lower atmosphere with the middle and upper atmosphere (Hagan & Forbes, 2002, 2003; Immel et al., 2006).

Numerous observational studies have already been done to advance our understanding of tides in the UMLT region. The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite has provided us with a wealth of information on these tides in the region. SABER temperature observations have consistently shown that the migrating diurnal tide (DW1) is strongest during equinox seasons over the low latitudes while the migrating semidiurnal tide (SW2) is strongest during solstice seasons over the mid-latitude winter hemisphere (e.g., Gan et al., 2014; Mukhtarov et al., 2009; Pancheva et al., 2009; Zhang et al., 2006). These observations have also shown that nonmigrating tides tend to be strongest from June to September which are months of intense tropical convection (Forbes and Wu, 2005; Zhang et al., 2006;...
Oberheide et al., 2009; Xu et al., 2009; Sakazaki et al., 2012). These TIMED observations compare well with earlier Upper Atmosphere Research Satellite (UARS) temperature observations (Forbes & Wu, 2006; Svoboda et al., 2005; Talaat & Lieberman, 1999; Wu et al., 1998).

There have been recent concerns on how tides affect CO2 volume mixing ratio (VMR) in the UMLT region. Rezac, Jian, et al., 2015; Rezac, Kutepov, et al., 2015) simultaneously retrieved daytime CO2 and temperature in the region using SABER CO2 15- and 4.3-μm radiance. This provided daytime observational profiles of CO2 that span more than 1 solar cycle. Yue et al. (2015) then analyzed monthly global-mean SABER CO2 profiles and found that the linear trend above 100 km is around 10%/decade which is larger than the trend at the surface. Later, Qian, Burns, Solomon, & Wang (2017) and Rezac et al. (2018) found a different trend of ~5%/decade up to around 90 km, slowly increasing up to ~8%/decade at ~105 km. The differences were due to the consideration of asymptotic sampling in SABER measurements in more recent analyses. It was suggested that this is a result of a significant local-time variation in CO2 as illustrated in Figure 1 of Rezac et al. (2018). Unfortunately, the detailed analysis of these local-time variations is yet to be done. There were previous satellite-based observations of UMLT CO2 from the Michelson Interferometer for Passive Atmospheric Sounding and Atmospheric Chemistry Experiment–Fourier Transform Spectrometer. Unfortunately, they did not have enough local-time coverage to observe tides (LóPez-Puertas et al., 2000; Bernath et al., 2005; Beagley et al., 2010).

A significant local-time variation in CO2 over the UMLT region would also suggest that there might be local-time biases with the operational SABER v2.0 temperature profiles. These profiles were not simultaneously retrieved with CO2. Their retrieval algorithm assumed no local-time variations is yet to be done. There were previous satellite-based observations of UMLT CO2 from the Michelson Interferometer for Passive Atmospheric Sounding and Atmospheric Chemistry Experiment–Fourier Transform Spectrometer. Unfortunately, they did not have enough local-time coverage to observe tides (LóPez-Puertas et al., 2000; Bernath et al., 2005; Beagley et al., 2010).

In addition to its importance in the accurate evaluation of long-term trends and the accurate retrieval of temperature profiles, a significant local-time variation in CO2 over the UMLT region also suggests that CO2 can be used as a tracer for advection and diffusion due to tides because CO2 in this region has a photochemical lifetime of around 1,000 days (Garcia et al., 2014; LóPez-Puertas et al., 2000; Smith, Garcia, et al., 2011). Recently, Qian, Burns, Solomon, & Wang (2017) and Qian, Burns, & Yue (2017) used CO2 to characterize the general circulation pattern throughout the UMLT region which provided observational evidence of a winter-to-summer lower thermospheric circulation. One of the major challenges of tides in the UMLT region is observing tracer transport processes due to these tides (Gardner, 2018; Gardner & Liu, 2010; Gardner & Liu, 2016; Swenson et al., 2018).

Tidal transport plays a significant role in the dynamics and composition changes in the UMLT region and the Ionosphere/Thermosphere region (Jones et al., 2014; Jones et al., 2017; Jones et al., 2018). Since tides occur on a global scale, only satellite observations can completely cover them (Zhang et al., 2006). Both TIMED Doppler Interferometer and UARS High Resolution Doppler Imager or the Wind Imaging Interferometer have provided us with information on winds albeit these are limited to zonal and meridional winds (McLandress et al., 1994; Morton et al., 1993; Svoboda et al., 2005; Talaat & Lieberman, 1999; Wu et al., 2006; Wu et al., 2008b; Wu et al., 2008a; Wu et al., 2011). An alternative to wind observations are composition observations. Both TIMED and UARS have also provided us with composition observations. These are mostly observations of airglow emission rates, atomic oxygen, and ozone mass mixing ratio. Transport changes can be inferred from volume or airglow emissions rates because they are dependent on transport-induced changes in the mixing ratio of the atom or molecule important to the given emission rate (Burrrage et al., 1994; Marsh et al., 1999; Nischal et al., 2017; Oberheide et al., 2013; Oberheide & Forbes, 2008; Shepherd et al., 1995; Shepherd et al., 1997; Ward, 1999; Zhang et al., 1998). Similarly, transport changes can be inferred from ozone because ozone is dependent on transport-induced changes in atomic oxygen (Smith et al., 2010; Smith, Marsh, et al., 2011). However, crucial to the use of these chemically active species is accurate chemistry in the numerical models. A more advantageous approach in determining transport due to tides would be to observe a chemical species like CO2 that has a relatively long chemical lifetime.

These studies clearly show that it is very important to understand the local-time variation of CO2 in the UMLT region. Understanding these local-time variations of CO2 advances our understanding of climate change, remote sensing, and the overall dynamics of the region. In this paper, we take full advantage of the recently retrieved SABER daytime CO2 profiles to analyze the local-time variation of daytime CO2 in
the UMLT region during March equinox. We focus on March equinox because this is the season that is well known to have significant local-time variation over the low to middle latitudes due to the diurnal tides, particularly the migrating diurnal tide (DW1) which maximizes in amplitude during this time (Gan et al., 2014; Mukhtarov et al., 2009; Pancheva et al., 2009; Zhang et al., 2006). We then compare these observed local-time variations in daytime CO2 to those simulated by the Whole Atmosphere Community Climate Model–eXtended (WACCM-X) 2.0 simulations. Finally, we compare SABER temperatures retrieved with and without local-time variations in CO2.

2. Data Sets and Methodology

This work utilizes CO2 VMR observations from the SABER instrument onboard the TIMED satellite. A description of the SABER instrument can be found in Russell et al. (1999). Rezac et al. (Rezac, Kutepov, et al., 2015) used SABER measurements of limb radiances at 4.3 and 15 µm to simultaneously retrieve these daytime CO2 VMR and temperature. This data set is called SABER v2.0 Level-2C (SABER Level-2C CO2 or temperature hereafter).

When working on tides and local-time variabilities using satellites, it is important to fully characterize the orbit and data sampling of the satellite (McLandress & Zhang, 2007; Oberheide et al., 2003). SABER has alternating latitudinal coverage of 82°N–53°S and 53°N–82°S that occur due to the spacecraft yaw cycle every ~60 days. The mission has an orbital period of ~1.6 hr and a local-time precession of 12 min per day. It has been shown that for SABER, tidal studies require 60 days of observations to achieve full diurnal coverage (Zhang et al., 2006). However, SABER Level-2C is only available during the day. And so, our SABER CO2 profiles only show the local-time variations of CO2 only between approximately 0600 and 1800. This is better than observations by Michelson Interferometer for Passive Atmospheric Sounding and Atmospheric Chemistry Experiment-Fourier Transform Spectrometer because these two instruments cannot provide good local-time coverage (Beagley et al., 2010; Bernath et al., 2005; López-Puertas et al., 2000). However, this lack of complete local-time coverage hinders us from applying least squares fit decomposition to determine the tidal amplitudes of all tides.

The SABER CO2 profiles are binned by first grouping the CO2 profiles into latitude and local-time bins for each day. The latitude bin is between 50°S and 50°N with a 5° latitudinal spacing while the local-time bin

![Figure 1](https://www.agu.org/journal/pdfs/2019JA027039/1.png)
is from 0600 to 1800 with a 2-hr spacing. Then, they are averaged across all longitudes which yield a latitude and local-time profile clearly showing the local-time variations of the observed and modeled parameters. Since SABER CO₂ is available during daytime only, we limit the presentation to local-time variations between 0600 and 1800 and between latitudes 50°S and 50°N. This approach isolates the combined influence of different migrating tides between 0600 and 1800 because migrating tides have the same local-time variation across all longitudes, while nonmigrating tides have different local-time variation at different longitudes. Finally, all values between 80 and 85 km are averaged and referred to as upper mesosphere while all values between 95 and 100 km are averaged and referred to as lower thermosphere.

These observations are then compared with model outputs from WACCM-X 2.0. Utilizing elements of WACCM and Thermosphere-Ionosphere general circulation models, this model can simulate the middle and upper atmosphere while accounting for the coupling of the atmosphere with ocean, sea ice, and land. It extends the upper boundary up to around 700 km, depending on solar activity. It has a conventional latitude-longitude grid with horizontal resolution of 1.9° in latitude and 2.5° in longitude. The vertical resolution is the same as WACCM which is 2 points per scale height below ~50 km and increases to 4 points per scale height above ~50 km. For a detailed description of the model, see Liu et al. (2018). While a lot of research has been done to check the simulation of local-time variations in earlier versions of WACCM, the local-time variations in this recent version of WACCM have not been examined in detail. This work uses a WACCM-X March equinox run under solar minimum and geomagnetically quiet conditions ($F_{10.7} = 70$ and $K_p = 1$) because we will not consider solar cycle influences in this work. Also, all SABER CO₂ profiles are retrieved during geomagnetically quiet conditions (Rezac, Kutepov, et al., 2015). The model outputs are also binned into the same latitude and local-time grid as that used for the SABER measurements. Since WACCM-X was only ran for March equinox at solar minimum, we only utilized SABER CO₂ March equinox latitude-local time profiles averaged between solar minimum years 2007 and 2009.

The local-time variations of CO₂ can be decomposed into a first-order component which is its zonal-mean and a second-order component which is composed of the local-time variations primarily due to tides. Thus, a complete analysis of CO₂’s local-time variation requires us to first look at the zonal-mean profile of CO₂. This will involve comparing WACCM-X zonal-mean CO₂ and SABER zonal-mean CO₂. Unfortunately, SABER CO₂ is available during the daytime only. Thus, the best that we can do is to compare this daytime zonal mean of CO₂ as observed by SABER and as simulated by WACCM-X. We will then compare these modeled daytime zonal-mean results with the modeled daily averaged zonal mean. This gives us an idea of how far-off the daytime zonal mean is from the daily averaged zonal mean. After looking at the zonal mean of CO₂, we can now look at the local-time variations of CO₂ in the upper mesosphere (80–85 km) and lower thermosphere (95–100 km) as observed by SABER and as simulated by WACCM-X in March equinox.

After comparing the SABER observations with the WACCM-X simulations, we then determine the physical mechanisms by which WACCM-X simulates the local-time variations of CO₂. Knowing these mechanisms in the model will aid in improving the simulations of the model. We are specifically interested in determining and explaining the main transport processes behind these variations. This is done by diagnosing the model using a tendency analysis with the continuity equation. This is given by

$$
\frac{\partial \mu}{\partial t} + \left( \frac{u}{\cos \phi} \right) \frac{\partial \mu}{\partial \lambda} + \left( \frac{v}{\cos \phi} \right) \frac{\partial \mu}{\partial \phi} + \left( \frac{w}{\cos \phi} \right) \frac{\partial \mu}{\partial z} = \frac{1}{\rho_0} \frac{\partial}{\partial z} \left( \rho_0 K_{zz} \frac{\partial \mu}{\partial z} \right) - \frac{1}{\rho_0} \frac{\partial}{\partial \phi} \left( \rho_0 D_\phi \frac{\partial \mu}{\partial \phi} \right) + \frac{1}{\rho_0} \frac{\partial}{\partial \lambda} \left( \rho_0 \mu w_0 \right) = 0 \tag{1}
$$

where $\mu$ is the CO₂ volume mixing ratio (in parts-per-million volume), $t$ is the time, $\phi$ is the latitude, $\lambda$ is the longitude, and $z$ is the geopotential height. The variables $u$, $v$, and $w$ are the neutral zonal, meridional, and vertical winds, respectively; $K_{zz}$ is the eddy diffusion coefficient; $D_\phi$ is the molecular diffusion coefficient and $w_0$ is its corresponding diffusive separation velocity; $\rho_0$ is the atmospheric neutral density; and $a$ is the radius of the Earth which is $6.37 \times 10^6$ m. Note that the eddy diffusion coefficient is calculated from a gravity wave parameterization (Garcia et al., 2017; Richter et al., 2010). The molecular diffusion coefficient is as defined in Smith, Garcia, et al., (2011). Equation (1) states that CO₂ VMR is controlled by horizontal advection, vertical advection, eddy diffusion, and molecular diffusion. Calculating each of these terms determines the contribution of these different transport processes to the local-time
variations in CO₂. Previous research used the same approach but with the use of chemically active species such as atomic oxygen and simplified transport models (Akmaev & Shved, 1980; Angelats i Coll & Forbes, 1998; Marsh et al., 1999; Shepherd et al., 1995; Shepherd et al., 1997; Ward, 1998; Ward, 1999; Zhang et al., 1998).

Since the observed SABER CO₂ profiles used in this study were simultaneously retrieved with temperature, we can compare them with the SABER Level-2A operational temperature profiles (SABER Level-2A hereafter). The SABER Level-2C temperature profiles were binned in the same way as the Level-2C CO₂ profiles. The SABER Level-2A temperature profiles are not simultaneously retrieved with CO₂ and so, in contrast to the SABER Level-2C profiles, the SABER Level-2A retrieval algorithm utilized daily-mean and monthly-mean CO₂ profiles from WACCM (Remsberg et al., 2008). These comparisons will provide insight regarding the sensitivity of the SABER Level-2 temperature retrieval algorithms to the assumptions regarding CO₂.

The SABER Level-2A temperature profiles were sampled to match that of the SABER Level-2C profiles as closely as possible. A challenge to getting an exact match is that the SABER Level-2C profiles only provide the latitude, longitude, and UT of the profiles at 80 km, while Level-2A provides the tangent-point latitude, longitude, and UT for each data point in each profile. For example, given a SABER Level-2C temperature profile that has data points from ~30 to 120 km, the location of this profile is only provided by a single value of latitude, longitude, and UT at 80 km. On the other hand, given a SABER Level-2A temperature profile that has data points from ~30 to 120 km, the location of each data point from ~30 to 120 km has a different corresponding latitude, longitude, and UT (vertical profiles of latitude, longitude, and UT). We therefore had to perform our own interpolation of these location and time profiles of SABER Level-2A to 80 km to match that of SABER Level-2C. Hence, in this case, we used the following conditions for matching the profiles: For each day, a SABER Level-2A profile is within a Level-2C profile’s location if it is within 5° latitude, 10° longitude, and 1 hr UT of a given Level-2C profile. Grid sizes smaller than this were found to yield minimal matches such that the contour plots hardly show any filled regions. Grid sizes larger than this were found to show results that are not significantly different that this chosen grid size.

3. Daytime Zonal Mean of SABER CO₂ and WACCM-X CO₂

Figure 1 shows the daytime zonal-mean SABER CO₂ mixing ratio during March equinox averaged for the period between 0800 and 1600 local time (Figure 1a), daytime zonal-mean WACCM-X CO₂ volume mixing ratio (Figure 1b) for the same season and local time, daily (day and night) averaged zonal-mean WACCM-X CO₂ volume mixing ratio (Figure 1c), and the percent differences between the daytime and daily averaged zonal-mean WACCM-X CO₂ volume mixing ratio for March equinox (Figure 1d). Both SABER CO₂ and WACCM-X CO₂ show daytime zonal-mean values of around 380 ppmv between 80 and 85 km over latitudes 30°S to 30°N. Between 80 and 85 km, daytime SABER CO₂ exhibits higher values over latitudes 50°S to 30°N than over the latitudes 30°N to 50°N. Daytime WACCM-X CO₂ exhibits higher values over the low latitudes than the midlatitudes. Above 90 km, both daytime SABER CO₂ and daytime WACCM-X CO₂ exhibit higher CO₂ VMR over the midlatitudes than over the low latitudes, although the daytime SABER CO₂ exhibits a peak near approximately 30° latitude in both hemispheres. These peaks as well as the lower SABER CO₂ VMR poleward of latitudes 30°S and 30°N may be attributed to poor sampling in these latitudes (Rezac, Kutepov, et al., 2015). This poor local-time sampling will be shown in the next section. With regard to the vertical gradients, both SABER CO₂ and WACCM-X CO₂ between around 40°S and 40°N depart from their well-mixed state at around 85 km. Poleward of 40° latitude, both SABER and WACCM-X depart from their well-mixed states below 85 km.

The WACCM-X daily averaged zonal mean CO₂ VMR and percent difference of the daily averaged zonal mean and the daytime zonal mean in Figures 1c and 1d, respectively, show a pattern that is very similar to the diurnal migrating tidal (DW1) perturbations in temperature (Zhang et al., 2006). There is a dipole pattern over the low latitude with daily averaged zonal-mean CO₂ up to 10% lower than the daytime zonal-mean CO₂ between 85 and 90 km and 10% higher than the daytime zonal-mean CO₂ between 95 and 100 km. The presence of these DW1 signatures is consistent with what we would expect from a daytime zonal mean. A daytime zonal-mean averages out SW2 but will have DW1 aliased into it.
4. Local-Time Variations of SABER CO$_2$ and WACCM-X CO$_2$

The previous section characterized and compared the zonal-mean profile of SABER CO$_2$ and WACCM-X CO$_2$. They clearly show that there are some similarities and differences in the overall patterns of daytime SABER CO$_2$ and WACCM-X CO$_2$. It was identified that some of these differences may be due to inadequate sampling of SABER CO$_2$ profiles or may be due to deficiencies in the model's eddy diffusion. We now note these zonal-mean profiles as we proceed with determining and explaining the tide-induced local-time variations of CO$_2$.

Figure 2 shows the local-time variations of SABER CO$_2$ VMR in the upper mesosphere and lower thermosphere during March equinox. Figure 2a shows the local-time variations of SABER CO$_2$ VMR in the upper mesosphere during March equinox. White spaces denote lack of data. Since SABER cannot view the Sun directly, it cannot observe during noon local time. However, the grid employed in this work uses 2-hr spacing and so the 1200 noon local-time bin contains profiles between 1100 and 1300 local time. Figure 2a shows that, during March equinox, SABER CO$_2$ in the upper mesosphere region has higher VMR in the afternoon than in the morning between 20°S and 50°N. It shows peak values in the afternoon of around 370 ppmv or ~5% increase and minimum values in the morning of around 330 ppmv or ~5% decrease.

Figure 2b shows a similar variation for SABER CO$_2$ in the lower thermosphere with peak values of around 290 ppmv or ~7% increase and minimum values of around 240 ppmv or ~10% decrease.

The above SABER CO$_2$ observations are compared with WACCM simulations in Figures 2c and 2d which show the local-time variations of WACCM-X CO$_2$ in the upper mesosphere and lower thermosphere during March equinox, respectively. For easier comparison, contour-fill is only applied over latitude and local-time grid points with SABER CO$_2$ that have values. Figure 2c shows that most of the local-time variations in WACCM-X CO$_2$ in the upper mesosphere during March equinox are between 30°S and 30°N. This is characterized by higher CO$_2$ in the afternoon than in the morning. Peak CO$_2$ values in the afternoon are around 370 ppmv or ~2% increase while minimum values in the morning are around 350 ppmv or ~2% decrease. The pattern is similar with what SABER CO$_2$ observes but the morning-afternoon differences are clearly stronger in SABER CO$_2$ than in WACCM-X CO$_2$. Figure 2d shows the local-time variations of WACCM-X CO$_2$ in the lower thermosphere during March equinox and it exhibits minimum values of around 230 ppmv or ~5% decrease between 0800 and 1800 local time. There are minimal morning-afternoon differences. This is clearly different from SABER CO$_2$.

Comparing SABER CO$_2$ and WACCM-X CO$_2$ shows that the main differences are the phase of the local-time variations and the strengths of the local-time variations, likely corresponding to the amplitudes and phases of tides. With regards to the strengths of the local-time variations, the general discrepancy is that the model simulates weak local-time variations. As mentioned earlier, there have been no known analysis of tides and local-time variations of WACCM-X CO$_2$ but there have been studies that looked at other versions of WACCM. These studies showed that those older versions of WACCM underestimated the tidal amplitudes in the UMLT region, particularly in the case of the migrating diurnal tide (Chang et al., 2008; Lu et al., 2012). As for the phase differences, these may suggest differences in the simulation of the background atmosphere with the real atmosphere (Forbes & Vincent, 1989; Hays et al., 1994; Mukhtarov et al., 2009; Walterscheid, 1981). A future manuscript will be prepared that compares the amplitudes and phases of migrating tides in WACCM-X with the amplitudes and phases of migrating tides from observations.

5. Physical Mechanisms That Drive the Local-Time Variations of CO$_2$ in the Upper Mesosphere

To determine the transport processes behind these local-time variations in CO$_2$, we present the tendency analysis of the continuity equation of WACCM-X CO$_2$. Specifically, we determine which advective or diffusive transport process explains most of the variations in WACCM-X CO$_2$. Then, since each transport process is a product of the vertical or meridional gradient of CO$_2$ along with wind advection or the diffusion coefficient, we will further characterize the drivers and roles of these components. Finally, we use these to explain the local-time variation of SABER CO$_2$ as well as the differences in SABER CO$_2$ and WACCM-X CO$_2$. In this section, we first present the analysis in the upper mesosphere. This section will focus on Figures 3 and 4. Towards the end, Figure 2 will be referenced.
Figure 3 shows the tendency analysis of the continuity equation for WACCM-X CO₂ in the upper mesosphere during March equinox. Figure 3a shows the total time rate of change of WACCM-X CO₂. It shows variations of ±4 ppmv/hr. Figure 3b shows the tendency due to zonal advection. Figure 3c shows the tendency due to meridional advection. Figure 3d shows the tendency due to vertical advection. Figure 3e shows the tendency due to eddy diffusion. Figure 3f shows the tendency due to molecular diffusion. Comparing the tendency values, eddy and molecular diffusion contribute the least to the total changes in WACCM-X CO₂ since their magnitudes are less than ±0.1 ppmv/hr. Of the advection terms, the tendency due to vertical advection induces variations of ±4 ppmv/hr and has a pattern that resembles most of the total changes in WACCM-X CO₂ between latitudes 50°S and 20°N. In most of these areas, this corresponds to almost 90% of the overall variations. For latitudes between 20°N and 50°N, the tendency due to vertical advection...
explains the decreases between 1000 AM and 1400 PM. However, for the variations before 1000 AM and after 1400 PM, both meridional and vertical advection are significant. During these local times, vertical advection contributes around 60% of the overall variations while meridional advection contributes around 30% of the overall variations.

It has now been shown that vertical advection drives most of the local-time variations of WACCM-X CO2 while meridional advection plays a secondary role. Meridional advection contributes to the local-time variations of WACCM-X CO2 only over the midlatitudes. Figure 4 further explains how meridional and vertical advection drive the local-time variations of WACCM-X CO2 during March equinox in the upper mesosphere. Equation (1) shows that meridional advection \( \frac{\partial C}{\partial t} \) is dependent on the meridional gradient of WACCM-X CO2 and the meridional winds while vertical advection \( \frac{\partial C}{\partial z} \) is dependent on the vertical gradient of WACCM-X CO2 and the vertical winds. Figure 4a shows the local-time variations of the meridional gradient of WACCM-X CO2 in this season and altitude while Figure 4b shows the local-time variations of the vertical gradient. Figure 4c shows the local-time variations of meridional wind in this season and altitude while Figure 4d shows the local-time variations of vertical wind.

Looking first at the components of the meridional advection of CO2 in the upper mesosphere, the meridional gradient in Figure 4a shows a predominantly negative gradient in the northern hemisphere between latitudes 20°N and 50°N and a predominantly positive gradient in the southern hemisphere between latitudes 20°S and 50°S. A negative (positive) meridional gradient in the northern (southern) hemisphere suggests higher CO2 in the midlatitudes than in the high latitudes. However, between latitudes 20°S and 20°N and between 0600 AM and 1200 noon, the northern low-latitude (0–20°N) CO2 shows a positive meridional gradient while the southern low latitude (20°S–0) shows a negative meridional gradient. This signifies low CO2 around the equator relative to the midlatitudes. After 1200 local time, the meridional gradient completely becomes negative throughout the northern hemisphere and positive throughout the southern hemisphere. This meridional gradient of CO2 in the upper mesosphere during March equinox appears to be affected generally by the equinoctial meridional circulation which increases CO2 in the midlatitudes then transports it equatorward where it is then pushed down to lower altitudes (Garcia et al., 2014; Rezac, Jian, et al., 2015). The regions with strong meridional gradient over the midlatitudes coincide with regions of strong meridional advection tendency as shown in Figure 3c. Figure 4c shows the meridional wind and it exhibits a local-time variation over the northern hemisphere characterized by southward winds in the morning and northward winds in the afternoon. In the northern hemisphere, the southward winds and the negative meridional gradient in the morning coincide with the negative meridional advection tendency. This suggests that southward winds reduce CO2 over the midlatitudes by transporting them to the low latitudes. On the
other hand, the negative meridional gradient in the northern hemisphere and the northward winds in the afternoon coincide with positive meridional advection tendency. This suggests that northward winds increase CO₂ in the midlatitudes by transporting CO₂-abundant air from the low latitudes to the midlatitudes.

For the southern hemisphere, the local-time variations of meridional wind are characterized by northward winds in the morning and southward winds in the afternoon. The positive meridional gradient and the northward winds in the morning coincide with the negative meridional advection tendency. This indicates that northward winds further remove CO₂ over the southern midlatitudes by transporting them to the low latitudes. On the other hand, the positive meridional gradient and the southward winds in the afternoon coincide with the positive meridional advection tendency. This indicates that southward winds transport CO₂-abundant air over the low latitudes into the midlatitudes. These results suggest that the meridional advection of CO₂ is driven by a strong meridional gradient and strong meridional winds. Also, these results indicate that the meridional gradient controls whether the meridional winds increase or decrease CO₂ at a given latitude. The meridional winds appear consistent with variations due to the tides (McLandress et al., 1994; Morton et al., 1993; Svboda et al., 2005; Talaat & Lieberman, 1999; Wu et al., 2006; Wu et al., 2008b; Wu et al., 2008a; Wu et al., 2011). These facts suggest that tides primarily control the meridional advection of CO₂ through the meridional winds. However, they can only significantly influence the meridional advection of CO₂ in regions with strong meridional gradient of CO₂.

Looking at the components of the vertical advection tendency of CO₂ in the upper mesosphere, the vertical gradient of CO₂ mixing ratio in Figure 4b is negative throughout the upper mesosphere, and this is known to be due to increasing influence of photochemistry with height and decreasing Kzz (Garcia et al., 2014). Figure 4b further shows that the vertical gradient of CO₂ peaks over regions that coincide with a strong negative vertical advection tendency as shown in Figure 3d. Figure 4d shows the local-time variation of vertical wind that also exhibits strong downward wind over regions coinciding with a strong negative vertical advection tendency. This suggests that the regions of strong negative vertical advection tendency are driven by strong negative vertical gradient and strong downward wind. Figure 4d though also shows a strong upward wind over the region coinciding with a strong positive vertical advection tendency. The absolute magnitude of strong upward wind of this region is actually comparable to the absolute magnitude of strong downward winds over the midlatitudes. However, the vertical advection tendency shows an absolute positive magnitude slightly weaker than the absolute negative magnitudes. This may be due to slightly weaker vertical gradient in the region. These results suggest that the vertical advection of CO₂ is driven by steep vertical gradient and strong vertical winds. Also, since the vertical gradient of CO₂ is negative throughout, upwelling at a given altitude always induces an increase in CO₂ while downwelling always induces a decrease in CO₂.

Noting these inferred mechanisms from the tendency analysis, we may now suggest how WACCM-X can simulate local-time variations in CO₂ that would be consistent with SABER CO₂ in the upper mesosphere during March equinox as shown in Figure 2a. We first look at the local-time variations of SABER CO₂ in the upper mesosphere during March equinox. For regions between 20°S and 20°N, Figures 3a and 3d indicate that these regions appear predominantly driven by vertical advection. Figures 4b and 4d indicate that this first suggests that SABER CO₂ has significant vertical gradients in this region. Then, the higher SABER CO₂ in the afternoon may be simulated by an upwelling while the lower SABER CO₂ in the morning may be simulated by a downwelling. For regions between 20°N and 50°N, Figures 3a, 3c, and 3d suggest that these regions appear to be driven by both meridional and vertical advection. Specifically, it is shown that vertical advection explains the variations between 1000 and 1400 local time while both meridional and vertical advection explain the variations before 1000 and after 1400 local time. The highest variations in SABER CO₂ between 20°N and 50°N are located first between 0600 and 0800 local time and second between 1600 and 1800 local time. Since the meridional gradient here is known to be predominantly negative because of the meridional circulation, we suggest that the region of low SABER CO₂ between 0600 and 0800 local time may be simulated by southward winds and downwelling while the region of high SABER CO₂ between 1600 and 1800 local time may be simulated by northward winds and upwelling.

Comparing SABER CO₂ and WACCM-X CO₂ in the upper mesosphere, the overall weaker local-time variations of WACCM-X CO₂ in the upper mesosphere may be due to weak meridional circulation or weak tides.
The presence of weak tides in WACCM-X would be consistent with past studies indicating weak tides in models (Chang et al., 2008; Lu et al., 2012).

### 6. Physical Mechanisms Behind the Local-Time Variations of CO₂ in the Lower Thermosphere

In this section, we present the tendency analysis in the lower thermosphere. This section will focus on Figures 5 and 6. Toward the end, Figure 2 will be referenced. Figure 5 shows the tendency analysis of the continuity equation for WACCM-X CO₂ in the lower thermosphere during March equinox. Figure 5a shows the total time rate-of-change of WACCM-X CO₂. It shows overall variations of ±8 ppmv/hr. Figure 5b shows the tendency due to zonal advection. Figure 5c shows the tendency due to meridional advection. Figure 5d shows the tendency due to vertical advection. Figure 5e shows the tendency due to eddy diffusion. Figure 5f
shows the tendency due to molecular diffusion. Looking at all the values, eddy and molecular diffusion contribute the least to the total changes in WACCM-X CO₂ since their magnitudes are less than ±0.5 ppm/hr. Of the advection terms, the tendency due to vertical advection induces variations of ±8 ppm/hr and resembles most of the total changes in WACCM-X CO₂ between latitudes 20°S and 20°N and between local times 0600 AM and 1200 noon. In most of these areas, this corresponds to almost 90% of the overall variations. The total changes in WACCM-X CO₂ everywhere else require both meridional and vertical advection.

Figure 6 further explains the mechanisms behind the meridional and vertical advection tendencies behind WACCM-X CO₂ during March equinox in the lower thermosphere. Figure 6a shows the local-time variations of the meridional gradient of WACCM-X CO₂ in this season and altitude while Figure 6b shows the local-time variations of the vertical gradient. Figure 6c shows the local-time variations of meridional wind in this season and altitude while Figure 6d shows the local-time variations of vertical wind.

Looking first at the meridional advection in the lower thermosphere, the meridional gradient in Figure 6a shows a predominantly positive gradient in the northern hemisphere and a predominantly negative gradient in the southern hemisphere. The meridional gradient in the lower thermosphere exhibits an opposite pattern to the upper mesosphere. It was found that this pattern also reflects the equinoctial meridional circulation in the lower thermosphere (not shown). Figure 5c shows that the strongest meridional advection tendency occurs over the northern hemisphere low latitudes in the morning as well as over the southern hemisphere low to middle latitudes in the afternoon. Figure 6a shows that the regions of highest meridional gradients do not correspond to the regions of highest meridional advection tendency. On the other hand, Figure 6c shows the meridional wind in the lower thermosphere which exhibits strong southward winds over the northern hemisphere low latitudes in the morning. Since the meridional gradient here is positive, southward winds induce an increase in CO₂. These coincide with peak positive meridional advection tendency. In the southern hemisphere, strong northward winds occur over the low to middle latitudes in the afternoon. Since the meridional gradient here is negative, these induce an increase in CO₂. These also coincide with peak positive meridional advection tendency. These indicate that similar to the upper mesosphere, the meridional advection of CO₂ in the lower thermosphere is also driven by strong meridional gradient and strong meridional winds. The meridional gradient of CO₂ in the lower thermosphere also controls whether the meridional winds increase or decrease CO₂ in a given latitude. The meridional winds show local-time variations that are approximately 6 hr out of phase with the local-time variations in the upper mesosphere. These phase differences with height are consistent with typical altitude variations of tides in the UMLT region particularly that of DW1 (Mukhtarov et al., 2009; Pancheva et al., 2009; Zhang et al., 2006). These suggest that tides also primarily influence the meridional advection of CO₂ in the lower thermosphere through the meridional winds.

Looking now at the components of the vertical advection tendency of CO₂ in the lower thermosphere, the vertical gradient in Figure 6b is also negative throughout the region. Figure 6b further shows that the vertical gradient of CO₂ peaks over the low-latitude morning and these coincide with a strong negative vertical advection tendency as shown in Figure 5d. Figure 6d shows the local-time variation of vertical wind and it also exhibits strong downward wind over the low-latitude morning. This suggests that the strong negative vertical advection tendency over the low-latitude morning is driven by a strong negative vertical gradient and strong downward wind. These results suggest that, like the upper mesosphere, the vertical advection of CO₂ in the lower thermosphere is driven by a strong vertical gradient and strong vertical winds. Also, since the vertical gradient of CO₂ is negative throughout, upwelling at a given altitude always induces increase in CO₂ while downwelling always induces decrease in CO₂.

Noting these mechanisms from the tendency analysis, we may now determine how WACCM-X can simulate local-time variations in CO₂ that would be consistent with SABER CO₂ in the lower thermosphere during March equinox as shown in Figure 2b. For regions between 20°S and 20°N, Figures 5c and 5d indicate that the lower CO₂ in the morning may be attributed to downwelling while the higher CO₂ in the afternoon may be attributed to upwelling.

The differences between SABER CO₂ and WACCM-X CO₂ may be attributed to two factors. First, it may be due to weak meridional circulation or weak tides in WACCM-X. Second, SABER CO₂ suggests minimal phase difference in the tides between the upper mesosphere and the lower thermosphere. This is not the
case in WACCM-X. Since the phase of tides is sensitive to the background atmosphere, this may suggest that WACCM-X does not simulate the same background atmosphere that SABER CO₂ suggests. This is a common issue with models (Forbes & Vincent, 1989; Hays et al., 1994; Mukhtarov et al., 2009; Walterscheid, 1981). Checking this would require nighttime CO₂ data since, as shown in Figure 1, there is significant tidal aliasing in the daytime zonal mean profiles of CO₂.

7. Comparison of SABER Level-2C and SABER Level-2A Temperatures

We have shown that SABER CO₂ does have significant local-time variations than WACCM-X and that they are predominantly driven by meridional and vertical advection. These local-time variations need to be accounted for in long-term CO₂ trend calculations and temperature retrieval algorithms that rely on these local-time variations in CO₂. Rezac et al. (2018) have already determined the effects of including such local-time variations in long-term trend calculations. Here we show the differences between SABER Level-2C temperatures retrieved with local-time variations in CO₂ and SABER Level-2A temperatures retrieved without local-time variations in CO₂. This will allow us to check which of these differences can be attributed to the CO₂ assumptions in the Level-2A retrieval algorithm. Figure 7 shows March equinox the comparison between SABER temperatures retrieved with the local-time variations accounted for and SABER temperatures that do not account for them. Figure 7a shows the variations of SABER Level-2C temperatures as a function of latitude and local time in the upper mesosphere during March equinox. Figure 7b shows the variations of SABER Level-2A temperatures as a function of latitude and local time in the same season and altitude. Both show higher temperatures in the morning and weaker temperatures between 1200 and 1600 local time before slightly increasing again after 1600 local time. The % differences between them are shown in Figure 7c. Figure 7c shows that in the morning between approximately 20°S and 20°N, SABER Level-2C T_k is lower than SABER Level-2A T_k by approximately 3% while in the afternoon, SABER Level-2C T_k is higher than SABER Level-2A T_k by approximately 1%. Figure 7c also shows that over all other latitudes, SABER Level-2C T_k is lower than SABER Level-2A T_k by approximately 3 to 4%.

To understand these results, recall that these CO₂ and temperature profiles are retrieved from radiance measurements. Radiance results from a nonlinear combination of temperature and CO₂. Generally, both temperature and CO₂ are directly proportional to radiance (Rezac, Jian, et al., 2015). SABER Level-2A T_k was retrieved with daily-mean CO₂ profiles from WACCM. Thus, if there is a strong local-time variation in CO₂, this local-time variation would be compensated in the temperature profile which acts to increase the local-time variation of the temperature profile. Figure 7c does not show this. Figure 7c would indicate a stronger local-time variation in SABER Level-2C T_k over 20°S and 20°N if the morning (afternoon) variations of SABER Level-2C T_k were higher (lower) than the morning (afternoon) variations of SABER Level-2A T_k. This would indicate that for March equinox, the differences in SABER Level-2C and SABER Level-2A temperatures in the upper mesosphere may not be completely attributed to the lack of CO₂ local-time variations in the retrieval. It may be due to uncertainties in other retrieval parameters such as atomic oxygen. Past studies have ruled out local thermodynamics equilibrium or nonlocal thermodynamics equilibrium processes (Rezac, Kutepov, et al., 2015).

Figure 7d shows the local-time variations of SABER Level-2C T_k in the lower thermosphere during March equinox. Figure 7e shows the local-time variations of SABER Level-2A T_k in the same season and altitude. Both show higher temperatures in the morning and weaker temperatures in the afternoon. Figure 7f shows that in the morning between approximately 20°S and 20°N, SABER Level-2C T_k is higher than SABER Level-2A T_k by approximately 2% while in the afternoon, SABER Level-2C T_k is lower than SABER Level-2A T_k by approximately 1%. Figure 7f also shows that in the morning between 20°N and 40°N, SABER Level-2C T_k is higher than SABER Level-2A T_k by approximately 2% while in the afternoon, SABER Level-2C T_k is lower than SABER Level-2A T_k. This is exactly the case. Now these differences could possibly be attributed to the local-time variations in CO₂ if SABER CO₂ is lower in the morning and higher in the afternoon. Figure 2 already showed this to be the case. Thus, these differences in SABER
Level-2C $T_k$ and SABER Level-2A $T_k$ over the low-latitude lower thermosphere during March equinox may be attributed to the retrieval's inclusion of a local-time variation in CO$_2$. On the other hand, Figure 7f would indicate a stronger local-time variation in SABER Level-2C $T_k$ over the midlatitudes if the morning (afternoon) variations of SABER Level-2C $T_k$ were lower (higher) than the morning (afternoon) variations of SABER Level-2A $T_k$. This is not the case. Thus, these differences in SABER Level-2C $T_k$ and SABER Level-2A $T_k$ over the midlatitude lower thermosphere during March equinox may not be attributed to the retrieval's inclusion of a local-time variation in CO$_2$.

8. Discussion

This work has shown that there is a significant local-time variation in CO$_2$ in the UMLT region during March equinox. This proves the importance of considering the asynoptic sampling of SABER CO$_2$ measurements when calculating the linear trend of CO$_2$ in the region (Qian, Burns, Solomon, & Wang, 2017; Rezac et al., 2018). Apart from calculating trends, the presence of these significant local-time variations in CO$_2$ also suggests careful analysis when isolating SABER CO$_2$ variabilities with time scales less than 60 days. Averages of these SABER CO$_2$ profiles using observations that do not span at least 60 days will have tides aliased into them. For example, in the case of daily zonal-mean profiles (zonal mean calculated with incomplete local-time sampling), our analysis specifically indicates that these profiles will have diurnal tides aliased into them during March equinox over the low latitudes. The errors in these daytime zonal-mean profiles can reach around 10% because of these tidal aliases.

It was then shown that in WACCM-X, vertical advection plays a pivotal role in explaining these variations inducing almost 90% of the overall variation in most areas especially at the low latitudes. Meridional advection plays a secondary role in the midlatitudes where vertical advection contributes around 60% of the overall variation while meridional advection contributes around 30% of the overall variations. It was further characterized that tides induce meridional and vertical advection of CO$_2$ through tide-induced meridional and vertical winds, respectively. The meridional gradient of CO$_2$ is predominantly controlled by the residual circulation while the vertical gradient is predominantly controlled by photochemistry and the residual circulation.
Explaining these local-time variations in CO$_2$ allows us to use SABER CO$_2$ as a validation for the WACCM-X simulated local-time variations of meridional and vertical advection in the UMLT region. Consequently, since the local-time variations in the UMLT are driven by tides, this also allows us to validate tide-induced meridional and vertical advection in WACCM-X. This work showed that the local-time variations of SABER CO$_2$ are much stronger than WACCM-X CO$_2$. Results also show a phase difference in the local-time variations. These would thus indicate that the simulations of the tides in WACCM-X need improvement. Weaker tides may suggest that the lower atmospheric or in situ source of the tides may be weaker than observed. Weaker tides may also suggest that if these tides do originate in the lower atmosphere, the background atmosphere may be attenuating their strength as they propagate upward (Hagan & Forbes, 2002, 2003). The phase differences between observed and simulated may also be rooted in problems with the background atmosphere of the model. One common source of problem in the background atmosphere of the model is the eddy diffusion due to breaking gravity waves (Hays et al., 1994; Mukhtarov et al., 2009). The vertical propagation of tides is typically hindered by increases in eddy diffusion (Forbes & Vincent, 1989; Hays et al., 1994; Mukhtarov et al., 2009; Walterscheid, 1981). Since WACCM-X simulates weaker tides, it may suggest that the eddy diffusion in WACCM-X needs to be reduced. Apart from model physics, model resolution is another common model issue that induces weak tidal forcing.

After presenting and interpreting the local-time variations of CO$_2$ in the UMLT region, this work assessed the impacts of including these variations in SABER temperature retrieval algorithms. It was found that only the differences between SABER Level-2C and Level-2A temperatures in the lower thermosphere during March equinox could be attributed to the inclusion of CO$_2$ local-time variations in the retrieval algorithm. This may be due to the fact that the March equinox lower thermosphere did show the strongest local-time variations in CO$_2$ compared to the other seasons and altitudes analyzed in this work. However, the differences are generally less than 5%.

Apart from the UMLT region, weaker simulations of tides in models are also important in the Ionosphere/Thermosphere region. Yamazaki and Richmond (2013) and Jones et al. (2014) show that the presence of tides act as another form of “mixing” that reduces atomic oxygen in the upper atmosphere by pulling it down into its recombination area in the upper mesosphere. Oberheide et al. (2011) tried to improve the simulations of tides in the Ionosphere/Thermosphere region by constructing the Climatological Tidal Model of the Thermosphere. Climatological Tidal Model of the Thermosphere involved the use of satellite observations in the UMLT region including SABER Level-2A temperature observations. Since we have just shown that these SABER Level-2A temperature observations may be weaker than reality, this work suggests that there are also inaccuracies in our simulations of the effects of UMLT tides on the ionosphere and thermosphere.

**9. Summary and Conclusions**

This work used SABER CO$_2$ observations in the UMLT region to determine the local-time variations of CO$_2$ in the UMLT region during March equinox. Results indicate that during March equinox, SABER CO$_2$ is lower in the morning and higher in the afternoon between 30°S and 50°N. The opposite is found between 50°S and 30°S. It was then compared with WACCM-X CO$_2$ simulations. It was shown that WACCM-X does not fully reproduce the observed local-time variations in SABER CO$_2$. WACCM-X simulates weaker local-time variations in the upper mesosphere than observed while WACCM-X simulates local-time variations in the lower thermosphere with different phase than observed. Tendency analysis on WACCM-X simulations indicate that the local-time variations of CO$_2$ in the UMLT region are predominantly controlled by meridional and vertical advection. Vertical advection plays a primary role while meridional advection plays a secondary role. After analyzing the local-time variations of CO$_2$ in the UMLT region, the differences between SABER Level-2C and SABER Level-2A temperatures were analyzed to check if their differences may be attributed to the CO$_2$ assumptions in their retrieval algorithms. It was shown that only the lower thermosphere during March equinox showed differences between SABER Level-2C and SABER Level-2A temperatures that could be attributed to the inclusion of CO$_2$'s local-time variations in the SABER Level-2C $T_k$ retrieval algorithm.

This work first concludes that CO$_2$ does have a significant local-time variation driven by meridional and vertical advection. This is not well simulated by WACCM-X, likely due to inaccuracies in the local-time...
variations of meridional and vertical advection. This work also confirms that the differences between SABER Level-2C and SABER Level-2A temperatures may not necessarily be due to the CO2 assumptions in their respective retrieval algorithms. This suggests that more in-depth work needs to be done in understanding the differences between SABER Level-2C and SABER Level-2A temperatures. This work clearly demonstrated the need for more information on the local-time variations of CO2. And so, this work highly recommends retrieving nighttime CO2 in the near future (Panka et al., 2017).

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