Investigating the Temperature Variability of the Middle and Upper Atmosphere over the Equator using SABER and NCAR TIME-GCM

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ABSTRACT

The National Center for Atmospheric Research (NCAR) Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIME-GCM) simulated diurnal tides also observed in National Aeronautics Space Administration (NASA) Thermosphere Ionosphere Mesosphere Energetic Dynamics (TIMED) satellite measurements of the middle and upper atmosphere at the equator. This study examined the temperature structure and day to day temperature perturbations between 40 and 120 kilometers over the equator during 2002 using the Sounding of the Atmosphere using Broad-band Emissions Radiometry (SABER) instrument of the TIMED satellite and NCAR TIME-GCM. We also quantified the diurnal tide as it propagates upwards into the middle and upper atmosphere. The performance of the TIME-GCM was assessed by comparing its analysis to the SABER analysis. The SABER atmospheric tides are analyzed in terms of ascending and descending orbit nodes. The TIME-GCM atmospheric tides were sampled along the SABER instrument measurement track and analyzed in terms of ascending and descending orbit nodes. Contour plots of two times the equatorial mean temperature profile for the SABER temperature measurements and TIME-GCM temperature predictions were constructed. IDL programs also generated contour plots of the estimated diurnal tide amplitude for the SABER temperature measurements and TIME-GCM temperature predictions. During this study we assumed the difference between the ascending local solar time and descending local solar time is approximately 12 hours. This research also assumed that the ascending and descending temperature profiles consist of a diurnal mean and perturbation. We find from observing the contour plots day to day diurnal tidal variability, but no seasonal variability. We also discovered a vertical wavelength of 25 kilometers in the estimate of the diurnal tide amplitude contour plots.
1. INTRODUCTION

The Earth’s atmospheric structure consists of different layers defined according to the temperature gradients throughout the atmosphere (see figure 1). Each layer of the atmosphere is important and plays significant roles. For instance, the region from the surface to about 11 kilometers (km) is known as the troposphere and it is the area where the majority of our weather occurs. The stratosphere, mesosphere, and thermosphere make up the middle and upper atmosphere. The middle and upper atmosphere plays a vital role in the protection of life from the dangerous nature of outer space. Specifically, the middle and upper atmosphere shields all life-forms from ultraviolet radiation and meteorites. Thus, the study of the middle and upper atmosphere is extremely important because it will develop our understanding of the chemical and dynamical processes that govern this region of the atmosphere.

![Figure 1: Temperature profile of the Earth’s atmosphere](http://royal.okanagan.bc.ca/mpidwirn/atmosphereandclimate/atmslayers.html)

We advance our knowledge of the middle and upper atmosphere by investigating the diurnal temperature perturbations, which are greatest at the equator, using the SABER (Sounding of the Atmosphere using Broad-band Emission Radiometry) instrument on the TIMED (Thermosphere Ionosphere Mesosphere Energetic Dynamics) satellite and the NCAR TIME-GCM (Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model). Specifically, we examine the equatorial mean temperatures and the diurnal temperature variability between 40 and 110 kilometers during.

An important feature of this region is atmospheric tides, which are global-scale waves or oscillations in temperature, wind, density, and pressure with periods that are harmonics of a solar day. A solar day is the length of time which passes between the Sun reaching its highest point in the sky two consecutive times. Migrating diurnal
atmospheric tides are westward propagating waves with zonal wave number 1 (i.e., one maxima/minima along a latitude circle) and a 24-hour period. These tides are excited by water vapor absorption of infrared solar radiation, stratospheric ozone absorption of ultraviolet radiation, and latent heat release related to deep convection in the tropics (Hagan, 1996; Hagan et al., 1997; Forbes et al., 1997; Hagan and Forbes, 2002; 2003). Because the atmospheric density decreases with altitude, these tidal waves grow in amplitude as they propagate upward into the increasingly less dense upper atmosphere and conserve energy, causing increasingly large perturbations in the middle and upper atmosphere.

Figure 2: A diagram of a wave with its amplitude (maximum perturbation) and phase (time of maximum perturbation).

Figure 2 gives us an idea of how an atmospheric tide would look if it was observed from a place on the ground, but atmospheric tides occur globally. Two features of atmospheric tides are its amplitudes and phases. The amplitude measures the maximum magnitude of an oscillation and the phase is the local time where the wave is at its maximum peak (see figure 2). This work allows us to quantify the growth of the diurnal tide as it propagates upward into the middle and upper atmosphere.

Our analyses are important for various reasons. One reason is that it grants us the opportunity to study and examine the part of the atmosphere that plays a fundamental task in the security of human life. Understanding the temperature variability in the middle and upper atmosphere will enhance our knowledge of the dynamical coupling processes of this region of the atmosphere. This work is also of inherent interest since investigating the day-to-day temperature variability over the equator using SABER and TIME-GCM has never been done before. One of the objectives of the TIMED mission is the quantification of tidal variability and its impact on the global mean state of the atmosphere. Thus, this work will also contribute to the objectives of the TIMED mission.

1.2 TIME-GCM

The TIME-GCM is a simulation model of the thermosphere, ionosphere, and mesosphere, with coupled electrodynamics. It is used to calculate winds, temperature,
and compositional structures between 30 and 500 km. The TIME-GCM is a part of a series of general circulation models developed at NCAR, which includes the Thermosphere General Circulation Model (TGCM), the Thermosphere/Ionosphere General Circulation Model (TIGCM), and the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM). The TIME-GCM is an extension of the TIE-GCM by expanding the lower boundary from 97 km to 30 km. NCAR TGCM’s are three-dimensional, time-dependent models of the Earth’s upper atmosphere. The TIME-GCM, particularly, is three-dimensional in latitude, longitude, and pressure. The latitude begins at -87.5 degrees south to +87.5 degrees north with 5-degree resolution. The model uses a finite differencing technique to obtain a solution for the coupled, nonlinear equations of hydrodynamics, thermodynamics, continuity of the neutral gas, and for the coupling between the dynamics and composition. The Global-Scale Wave Model (GSWM) tidal results (Hagan and Forbes, 2002; 2003) at 30 kilometers are included at the lower boundary to account for tropospheric tidal sources. The TIME-GCM runs on IBM supercomputers of NCAR. It has 44 fields of output, but this research is confined to its temperature results.

1.3 SABER INSTRUMENT

The National Aeronautics Space Administration’s (NASA) TIMED satellite is a slowly precessing satellite that it orbits the earth 15 times per day and makes measurements at all longitudes, but at very limited local times which evolve at a rate of less than 20 minutes per day (see figure 3).

![Figure 3: The SABER instrument is illustrated at the lower left of the TIMED satellite](image-url)
The TIMED satellite has four instruments, namely, the TIMED Doppler Interferometer (TIDI), Solar Extreme Ultraviolet Experiment (SEE), Global Ultraviolet Imager (GUVI), and SABER. The SABER instrument is a 10-channel infrared radiometer that measures Earth limb emissions from the TIMED satellite. The SABER measurements on any given day are made at two specific local times at specified latitude (see figure 4). These local times are associated with the ascending and descending orbit nodes and are longitude independent. Ascending orbit nodes are the trajectories of the instrument as the satellite moves from south to north and descending orbit nodes are the trajectories when the satellite moves from north to south (Oberheide et al., 2003). The latitudinal coverage depends on the yaw cycle. The TIMED satellite yaws (i.e., changes its orbital flight direction) every 60 days from forward to backward and vice versa (Oberheide et al., 2003).

![SABER measurement footprints as a function of local solar time on April 15, 2002 (Maura, 2002).](image)

SABER measures height profiles of temperatures at specific latitudes from 10 km to 180 km. It also makes day and nighttime measurements. Its goal is to explore the mesosphere and lower thermosphere globally and improve our understanding of the essential processes governing the dynamics and transport of the middle and upper region of the atmosphere.

2. METHODOLOGY

A tidal oscillation at a specific latitude is described mathematically by

\[
\tilde{T} = \sum \delta T_{s,n} \cos(\omega_n (t_{UT} - t_{s,n}) - s\lambda) \tag{1}
\]

, where

Tamara Singleton, SOARS® 2004, 5
\( \tilde{T} = \text{tidal oscillation} \)
\( t_{\text{UT}} = \text{universal time} \)
\( \delta T_{s,n} = \text{tidal amplitude} \)
\( \omega_n = \text{frequency} \)
\( t_{s,n} = \text{time of maximum amplitude} \)
\( s = \text{zonal wavenumber} \)
\( \lambda = \text{longitude in radians} \)
\( n = \text{the wave period} \)

The frequency for a tidal oscillation is given by
\[
\omega_n = \frac{2\pi n}{24 \text{ hours}}
\]
, where \( n = 1 \) denotes the diurnal tidal component and \( n = 2 \) denotes the semidiurnal tidal component. The relationship between local solar time \( (t_{LT}) \) and universal time \( (t_{UT}) \) is given by
\[
t_{LT} = t_{UT} + \frac{\lambda}{15^\circ} \frac{360^\circ}{2\pi}
\]
thereby converting (1) to
\[
\tilde{T} = \sum \delta T_{s,n} \cos[\omega_n (t_{LT} - t_{s,n}) - \lambda (s + n)]
\]
Note that the wavenumber \( s \) is positive eastward, so \( s=-1 \) for the migrating diurnal tide, and \( s=-2 \) for the migrating semidiurnal tide. Thus, the second term on the right hand side of the above equation vanishes for migrating tides, which are longitude independent.

For our SABER equatorial measurement analysis we assume that the ascending and descending zonal mean temperature profiles consist of a diurnal mean and a tidal oscillation. They are described mathematically [Oberheide, 2002] as a function of altitude by the following equations
\[
\tilde{T}_{\text{up}} = T + \delta T \cos\left[\frac{2\pi}{24} (t_{\text{up}} - \varphi)\right] \quad (2)
\]
and
\[
\tilde{T}_{\text{dn}} = T + \delta T \cos\left[\frac{2\pi}{24} (t_{\text{dn}} - \varphi)\right] \quad (3)
\]
, where

\[\bar{T}_{\text{up}} = \text{ascending zonal mean temperature}\]
\[\bar{T}_{\text{dn}} = \text{descending zonal mean temperature}\]
\[\bar{T} = \text{zonal and diurnal mean (longitudinal and 24-hour average)}\]
\[\delta T = \text{amplitude of a migrating diurnal tide}\]
\[\phi = \text{phase}\]
\[\frac{2\pi}{24} = \text{diurnal tidal frequency}\]
\[t_{\text{dn}} \text{ and } t_{\text{up}} = \text{local solar times of the descending and ascending orbits}\]

Before analyzing the SABER temperature measurements, we assumed the ascending and descending zonal mean temperature profiles consist of a diurnal mean and perturbation. We also assumed that the difference between the ascending local solar time and descending local solar time is approximately 12 hours apart. If \(t_{\text{up}} - t_{\text{dn}} = 12\), then summing the profiles results in two times the equatorial mean temperature profile.

\[
\bar{T}_{\text{up}} + \bar{T}_{\text{dn}} = \bar{T} + \delta T \cos\left(\frac{2\pi}{24} (t_{\text{up}} - \phi)\right) + \bar{T} + \delta T \cos\left(\frac{2\pi}{24} (t_{\text{dn}} - \phi)\right)
\]
\[= 2\bar{T} + \delta T \cos\left(\frac{2\pi}{24} (t_{\text{up}} - \phi)\right) + \cos\left(\frac{2\pi}{24} (t_{\text{dn}} - \phi)\right)\]
\[= \text{two times equatorial mean temperature profile}\]

Taking the difference of the profiles results in two times the diurnal mean temperature profile which provides an estimate of the diurnal tide amplitude.

\[
\bar{T}_{\text{up}} - \bar{T}_{\text{dn}} = \bar{T} + \delta T \cos\left(\frac{2\pi}{24} (t_{\text{up}} - \phi)\right) - \bar{T} - \delta T \cos\left(\frac{2\pi}{24} (t_{\text{dn}} - \phi)\right)
\]
\[= 2\delta T \cos\left(\frac{2\pi}{24} (t_{\text{up}} - \phi)\right)\]
\[= \text{two times the diurnal mean temperature profile}\]
\[= \text{estimate of the diurnal tide amplitude}\]

We analyzed SABER temperature measurements for day 25 through day 302 for the year 2002 at altitudes of 30 km – 120 km. For each observed day, we used Interactive Data Language (IDL) to visualize the longitudinally averaged ascending temperature profile, descending temperature profile, two times the equatorial mean temperature profile, and an estimate of (i.e. twice) the diurnal tide amplitude (see Appendix A).

The TIME-GCM temperature predictions were sampled along the SABER instrument track and were identically analyzed in terms of the ascending and descending

Tamara Singleton, SOARS® 2004, 7
orbit nodes. We analyzed the ascending and descending orbit nodes using a modified version of the IDL program that was used to analyze the SABER ascending and descending orbit nodes (see Appendix B).

4. RESULTS AND DISCUSSION

For each observed day between day 25 and day 302 of the year 2002, we developed line plots of the ascending temperature profiles, descending temperature profiles, the summation of the profiles and the difference of the profiles. Below is the 40-110 km result for day 90.

![Figure 5: Line plots for SABER temperature measurements for day 90](image)

We also plotted the longitudinal average ascending and descending temperature profiles at altitudes of 40 km – 110 km denoted by the bold line.

Using IDL we also constructed similar line plots of the ascending and descending profiles of the TIME-GCM temperature predictions. The figure below displays these line plots for day 90.
When comparing the two figures we see that the TIME-GCM temperature predictions generally agree with the SABER temperature measurements. However, the TIME-GCM ascending temperature profiles are warmer than the SABER ascending temperature profiles. We see that the diurnal perturbation gets larger with increasing altitude which is consistent with the behavior of an upward propagating tide. We also noticed that the estimated diurnal amplitude is smaller for the TIME-GCM than for SABER. We also see an unexpected temperature increase in both the SABER and TIME-GCM mean temperature estimates near 85 km. We note that this occurs at the same altitude where the diurnal perturbation is large and positive. These features were consistent throughout most of our line plots.
An IDL program was constructed to produce contour plots for the summation and difference of the ascending and descending temperature profiles. The contour plot below (see figure 7) illustrates the summation profiles for the entire year of 2002 of the SABER temperature measurements.

![Contour plot of two times the equatorial mean temperature profile for the SABER temperature measurements](image)

Figure 7: Contour plot of two times the equatorial mean temperature profile for the SABER temperature measurements

This contour plot illustrates the various layers of the atmosphere, where blue denotes cooler temperatures and red warmer temperatures that are approximately twice as big as expected (Figure 1). We see increasing temperature from about 40 km to 60 km indicating the location of the stratosphere. The temperature then begins to decrease dramatically around 70 km representing the mesosphere. It then reaches a coldest temperature of about 375 K at about 100 km signifying the mesopause region of the atmosphere. The temperature begins to increase dramatically again beyond 100 km. One feature not evident in this contour plot is seasonal variability. The gaps that are seen in the contour plots are missing data, i.e. missing observed days of SABER temperature measurements. The days missing are day 1 through 24, day 61, day 131 through 133, day 145 through 165, day 200 through 203, and day 303 through 365.

We produced a contour plot of two times the equatorial mean temperature profile for the TIME-GCM predictions below (see figure 8).
Figure 8: Contour plots of two times the equatorial mean temperature profile for the TIME-GCM temperature predictions.

From observing this contour plot, we see the various layers of the atmosphere like in the observed data. Increasing temperature occurs from about 40 km to around 60 km identifying the stratosphere. Then the temperature begins to decrease at 60 km reaching its coldest temperature of about 375 K around 100 km signifying the mesopause region. In this contour plot we are not seeing much seasonal variability.

Thus when comparing the SABER contour with the TIME-GCM contour we see that the TIME-GCM contour generally agrees with that of the observed data. We do observe more variability in the SABER measurements than the TIME-GCM predictions.

The IDL program also produced a contour plot of the estimated diurnal tide amplitude, i.e. the difference between the ascending and descending temperature profiles. The contour plot below (see figure 9) is for the SABER measurements for the year 2002.
In this contour plot, red denotes warmer temperature and blue denotes cooler temperature. Recall this is a contour plot of twice the diurnal tide amplitude. Hence, for the SABER temperature measurements the amplitude of the diurnal tide is ranging from -12.5 to about 25 K. We are also observing at each altitude warm and cold temperatures. This is because TIMED is a slowly precessing satellite making temperature measurements at local times that are fixed on any given day, but vary over 24 hours in about 72 days (i.e., yaw cycle). Thus, if the ascending time leads the descending time at the beginning of a yaw cycle, it will lag the descending time at the end, and vice versa. We observe warm then cold temperatures at each altitude, which is consistent with the behavior of an upward propagating diurnal tide (described above). The observed vertical wavelength is about 25 km (figure 9).
Below is the contour plot of the estimated diurnal amplitude for the TIME-GCM temperature predictions. The temperature predictions below in this contour plot generally agree with the observed data in figure 9. The diurnal amplitude for the predictions range from -12.5 to 25 K. In this contour plot, we observe warm then cold temperatures at each altitude, which is consistent with the behavior of an upward propagating diurnal tide. The vertical wavelength in the predicted data is about 25 km (figure 10).

![Contour plot of estimated diurnal amplitude](image)

**Figure 10:** Contour plot for the SABER data of the difference between the ascending and descending temperature profiles.

This research assumed that the ascending local times and descending local times are approximately 12 hours apart. We also assumed that the ascending and descending temperature profiles consist of a diurnal mean and tidal perturbation only. These assumptions may be one reason why we are not observing seasonal variability. The composition of the ascending and descending temperature profiles did not account for any residuals such as the semidiurnal tidal component. We expect semidiurnal temperature variability to affect our results above 100 km in the observed and predicted data.

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