Global structure and long-term variations of zonal mean temperature observed by TIMED/SABER

Jiyao Xu,1 A. K. Smith,2 W. Yuan,1 H.-L. Liu,3 Qian Wu,3 M. G. Mlynczak,4 and J. M. Russell III5

Received 14 February 2007; revised 9 August 2007; accepted 17 September 2007; published 25 December 2007.

[1] In this paper, we present a method of extracting zonal mean temperature and tides from TIMED/SABER satellite and discuss the features of the zonal mean temperature. The global temperature structure is presented, and the mean variations at each latitude and altitude are decomposed into semiannual (SAO), annual (AO), and quasi-biennial (QBO) components. The SAO is strong in the tropical upper stratosphere, mesosphere, and lower thermosphere. The SAO phase (measured by the time of the maximum) is at the equinox at 85 km and at solstice at 75 km. The amplitude is large compared to the annual mean temperature structure, which leads to a mesospheric inversion layer (MIL) in the zonal mean temperature around the equator at equinox. The AO is most evident at middle latitudes and displays a clear hemispheric asymmetry at solstices. The QBO in temperature is strongest in the tropical lower stratosphere; its period there is 26.6 months. There are also weak QBO signals near the mesopause and throughout the middle atmosphere at midlatitudes. The analysis of longer-term variations of the zonal mean temperature, probably affected by the solar cycle but also containing any other trends, indicates that in most regions, the zonal mean temperature decreases during the period of 5 years and is positively correlated with the solar radiation. These results use version 1.06 of the SABER temperature data, which have some known biases in the vicinity of the mesopause.


I. Introduction

[2] Observations indicate that the temperature in the middle atmosphere varies on all timescales that can be measured. Many aspects of the variability have not been described in a comprehensive way. For example, the detailed structure of the longer-period variations (months to interannual) of the zonal mean temperature has not been well characterized because of a sparseness of global observations that extend over the full range from the tropopause to the mesopause. It is important to characterize this variability in order to provide a framework for investigating dynamical coupling between different regions on these timescales. In addition, a complete description of the observations is valuable for validating numerical models.

[3] Middle atmosphere temperature observations made using several ground-based techniques are routinely taken at numerous sites around the globe. Constructing a global picture from these data is, however, problematic because most have a limited altitude coverage, many do not sample a full 24 h in local time (LT), the stations are irregularly distributed in space, and there are major gaps over oceans. Satellite remote sensing is a very effective method for observing the global structure of temperature, although it also has some significant difficulties. Retrieving temperature from an observed signal (e.g., radiance) is complicated and involves a number of uncertainties. Satellite observations have poor sampling in local time; depending on the orbit and the measurement technique this can range from a single local time for all data to a slow progression through the full 24 h.

[4] There have been a number of studies using satellite temperature measurements to describe the global structure. The Limb Infrared Monitor of the Stratosphere (LIMS) on the polar-orbiting Nimbus 7 satellite during 1978–1979 observed the temperature in the stratosphere and lower mesosphere at two local times (about 1300 and 2300 LT at the equator) [Gille and Russell, 1984; Remsberg et al., 2004]. The Solar Mesosphere Explorer (SME) satellite measured the temperature below 90 km at a fixed local time (1400–1500 LT) [Clancy et al., 1994]. The Microwave Limb Sounder (MLS), Improved Stratospheric and Mesospheric Sounder (ISAMS) and Halogen Occultation Experiment...
(HALOE) on Upper Atmosphere Research Satellite (UARS) made observation of global temperature from about 20 km to about 90 km [Wu et al., 2003; Leblanc and Hauchecorne, 1997]; HALOE was limited to sunrise and sunset observations while the other instruments observed over the full range of local times. The Wind Imaging Interferometer (WINDII) [Shepherd et al., 2004] and High-Resolution Doppler Imager (HRDI) [Ortland et al., 1998], also on UARS, made observation of daytime temperature in the mesosphere.

[s] Most measurements to date cover only part of the vertical range of the middle atmosphere or have a limited sampling in local time. An exception is the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the TIMED (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) satellite, which measures global temperature at high vertical resolution from the lower stratosphere to the lower thermosphere. Huang et al. [2006] analyzed 2 years of SABER temperature and presented results showing the mean and the annual, semiannual and quasi-biennial variations of the mean. Now 5 years of SABER temperature data have been accumulated.

[s] This paper will focus on the global structure of the zonal mean temperature and its temporal evolution by using TIMED/SABER temperature data. Note that the analysis must separate tides and other waves in order to determine the zonal mean fields. In section 2, we describe the method of extracting tides and zonal mean from the temperature data and the fitting method for analyzing the zonal mean changes. In section 3, we present the global structure of the zonal mean temperature determined from TIMED/SABER observations. We compare the SABER temperatures with those in the empirical NRL-MSIS model. The long-term variation of the zonal mean temperature structure is given in section 4, including analysis of the semiannual oscillation (SAO), annual oscillation (AO) and quasi-biennial oscillation (QBO) and the interhemispheric asymmetry. The trend of zonal mean temperature during the 5 years and its possible relation to the declining solar flux are also presented. In section 5, we address the possible aliasing between the diurnal tide and the mesospheric semiannual oscillation in the mean temperature. Conclusions are given in section 6.

2. Analysis Method

2.1. Method of Extracting Tides and Zonal Mean From TIMED/SABER Temperature Data

[7] The TIMED satellite was launched on 7 December 2001. SABER began making observations in late January 2002. It measures CO2 infrared limb radiance from the tropopause to the lower thermosphere; kinetic temperature profiles are retrieved over these altitudes using a full non-LTE inversion [Mertens et al., 2001, 2004]. Mertens et al. [2001] calculated the retrieval uncertainty and found values that increase with altitude from 1.4 K at 80 km to 22.5 K at 110 km. Discussion of an error source due to the neglect of CO2 vibrational change in the current version of the SABER temperature (v1.06) is given by Kutepov et al. [2006]; the impact of neglecting this process leads to a bias in the retrieved SABER temperature. The bias is largest near the polar summer mesopause, where it results in a mesopause altitude that is too low and a mesopause temperature that is too cold, but important elsewhere as well.

[8] The latitude range of the observations is from 53° in one hemisphere to 83° in the other; about every 60 d, the latitude coverage of SABER flips to the opposite hemisphere. The SABER duty cycle is quite high so there is nearly continuous coverage of middle and lower latitudes. In this paper, we use version 1.06 temperature data from February 2002 through December 2006 to analyze the temperature in the middle atmosphere and lower thermosphere.

[9] The atmosphere temperature can be decomposed into zonal mean; migrating and nonmigrating tides with diurnal, semidiurnal, terdiurnal, and 6-h periods; and planetary waves. The zonal means and the amplitudes and phases of all the waves vary on a range of timescales. In this analysis, we will focus on the long-term variations, such as the SAO, AO, and QBO. The temperature at the latitude of φ and the altitude of z can be expressed as:

\[
T(t, \lambda) = T(t) + \sum_{m=-M}^{M} \sum_{s=1}^{S} T_{m,s}^{\text{pw}} \cos\left(\omega_{0} t + m \lambda + \beta_{s,m}\right) + \sum_{k=-K}^{K} \sum_{l=1}^{L} T_{l,k}^{\text{pw}} \cos\left(\frac{\omega_{0}}{D(l)} t + k \lambda + \alpha_{l,k}\right) \tag{1}
\]

where \(\omega_{0} = 2 \pi / 24\) (hour), \(\lambda\) is longitude (in radians) and \(t\) and \(t_{0}\) are the local and universal time, respectively. The 3 terms on the right hand side of equation (1) are the zonal mean, the tides, including migrating \((s = m)\) and nonmigrating \((s \neq m)\) tides, and the planetary waves respectively. \(T_{m,s}^{\text{pw}}\) and \(\beta_{s,m}\) are the amplitudes and phases of tides with \(s = 1, 2, \ldots, S\) corresponding to the diurnal, semidiurnal, terdiurnal and 6-h periods, \(m = -M, \ldots, M\) are the tidal zonal wave numbers. \(T_{l,k}^{\text{pw}}\) and \(\alpha_{l,k}\) are the amplitudes and phases of the planetary waves with zonal wave numbers \(k = -K, \ldots, K\) and wave periods \(D(l), (l = 1, 2, \ldots, L)\) (in days). There are \(1 + 2(2M + 1) S + 2(2K + 1) L\) parameters in equation (1).

[10] Ideally, all components above should be considered in the analysis. However, we will explore ways to simplify the analysis by using the features of the SABER observation. The height of the TIMED orbit is about 625 km and the inclination is 74.1° (near Sun-synchronous). The orbit period is about 1.6 h (about 15 orbits/d). The times of daily observations center at two local times, corresponding to the diurnal, semidiurnal, terdiurnal and 6-h periods. The zonal means and the amplitudes and phases of all the waves vary on a range of timescales. In this analysis, we will focus on the long-term variations, such as the SAO, AO, and QBO. The temperature at the latitude of φ and the altitude of z can be expressed as:

\[
T(t, \lambda) = T(t) + \sum_{j=1}^{J} T_{j}^{\text{pw}} \cos\left(\omega_{j} t - \phi_{j}\right) + \sum_{m=-M}^{M} \sum_{s=1}^{S} T_{m,s}^{\text{pw}} \cos\left(\omega_{0} t + m \lambda + \beta_{s,m}\right) + \sum_{k=-K}^{K} \sum_{l=1}^{L} T_{l,k}^{\text{pw}} \cos\left(\frac{\omega_{0}}{D(l)} t + k \lambda + \alpha_{l,k}\right) \tag{2}
\]
Now, we discuss the effect of zonal mean on equation (2). It is obvious that the first and second terms on the right hand side of equation (2) are invariant under the zonal mean, and the zonal mean of the third term is zero for $m \neq s$ (if $m = s$, it becomes the migrating tide). The zonal mean of the fourth term of equation (2), the planetary waves, is not zero unless the wave is stationary ($D = \infty$). For an arbitrary wave period, the zonal mean is as follows:

$$\frac{1}{2\pi} \int_{0}^{2\pi} \left\{ \sum_{k=-K}^{K} \sum_{l=1}^{L} T_{jk}^{pw} \cos \left( \frac{\omega_0}{D(l)} t + (k - \frac{1}{D(l)}) \lambda + \alpha_{l,k} \right) \right\} d\lambda$$

$$= -\sum_{l=1}^{L} \sin \left( \frac{\pi}{D(l)} \right) \times \left\{ \sum_{k=-K}^{K} T_{jk}^{pw} \frac{1}{k - \frac{1}{D(l)} \pi} \cos \left[ \frac{\omega_0}{D(l)} t + \alpha_{l,k} - \frac{\pi}{D(l)} \right] \right\}$$

From this equation, we can see that the amplitude of the longer period and quasi-stationary planetary waves are attenuated by the factor $1/D$. Here we redefine the planetary wave amplitude and phase; the right side of equation (3) can then be written as $\sum_{l=1}^{L} T_{jk}^{pw} \cos \left[ \frac{\omega_0}{D(l)} t + \alpha_{l} \right]$. Therefore the zonal mean of equation (2) becomes

$$\frac{1}{2\pi} \int_{0}^{2\pi} T(t, \lambda) d\lambda = T_0(t) + \sum_{j=1}^{J} T_j^{pw} \cos \left[ \frac{\omega_0}{D(l)} t - t_0 \right]$$

$$+ \sum_{l=1}^{L} T_{jk}^{pw} \cos \left[ \frac{\omega_0}{D(l)} t + \alpha_{l,k} - \frac{\pi}{D(l)} \right]$$

(4)

Because the TIMED satellite processes slowly, it takes more than 60 d to complete a full 24-h coverage of local time. High latitudes (poleward of 55°) are sampled only on alternate yaw cycles. To avoid gaps introduced by the yaws, our analysis focuses on the latitude range between $-55^\circ$ and $55^\circ$. In order to extract migrating tides effectively, we use 70-d windows of data in the calculation. When estimating the zonal mean temperature $T(t)$ in equation (4), we consider its seasonal variation within the 70-d window period to avoid possible aliasing to other components. Therefore, in order to consider the seasonal variation of $\overline{T}(t)$ in the window, the linear trend variation over the 70 d is included, which is:

$$\overline{T}(t_0, t) = T_0(t_0) + \eta(t - t_0)$$

where $t_0$ is the center day of the 70-d window and $\eta$ describes the linear trend variation in the window. Therefore equation (4) becomes:

$$\frac{1}{2\pi} \int_{0}^{2\pi} T(t, \lambda) d\lambda = T_0(t_0) + \eta(t - t_0)$$

$$+ \sum_{j=1}^{J} T_j^{pw} \cos \left[ \frac{\omega_0}{D(l)} t - t_0 \right]$$

$$+ \sum_{l=1}^{L} T_{jk}^{pw} \cos \left[ \frac{\omega_0}{D(l)} t + \alpha_{l,k} - \frac{\pi}{D(l)} \right]$$

(5)

From equation (6), we can see that there are only $2 + 2\ell + 2\ell'$ parameters, which is much simpler than equation (1). From equation (6), we can determine the mean components, migrating tidal components and the frequency spectra of planetary waves by conducting temporal fitting. Note that the parameters $T_0$, $\eta$, $T_j^{pw}$, $T_{jk}^{pw}$ and $\alpha_l$ of equation (6) are functions of $t_0$, which is the center day of the 70-d window.

Before beginning the analysis, the temperature profiles are sorted into overlapping latitude bins that are 10 degrees wide with centers offset by 5° extending from 60°S to 60°N. Profiles are interpolated in the vertical with 1 km spacing from 20 km to 135 km. At each latitude $\phi$ and altitude $z$, the analysis steps through the 70-d windows with a resolution of 1 d. It is repeated with the window offset in 1 d intervals to give overlapping analyses.

The first step is to divide the daily data into two groups by local time corresponding to the ascending and descending phase. Then interpolate each group onto 36 longitude grids, each 10° wide, by fitting with a cubic spline. This ensures that all 36 longitude points are populated even when the data are irregularly spaced in longitude.

The second step is to calculate the zonal mean for each day to eliminate the nonmigrating tides and also the stationary planetary waves.

The third step is to calculate the zonal mean temperature, migrating tides and the temporal spectra of the planetary waves by the nonlinear least squares techniques using data from 70-d windows.

Eighteen parameters are extracted by our method: the average zonal mean temperature, its linear trend over the 70-d window, and the amplitudes and phases of four tidal periodicities (diurnal, semidiurnal, terdiurnal, and 6-h) and four traveling planetary waves. For the planetary waves, previous observations indicate that there is a broad range of periods of traveling planetary waves in the atmosphere, such as the quasi-2-d planetary wave in the mesosphere/lower thermosphere (MLT) region [e.g., Pancheva et al., 2004; Harris and Vincent, 1993; Gurubaran et al., 2001; Ward et al., 1996; Wu et al., 1993; Lima et al., 2004], 5–8 d wave [e.g., Kishore et al., 2004; Wu et al., 1994; Talaat et al., 2002; Clark et al., 2002], as well as 10-16, and 23-d waves. These waves are all considered in our analysis although, as discussed above, those components with relatively long periods are attenuated by the analysis. The waves are included in the analysis for a complete separation of the zonal mean from other signals in the data but are not considered further in this paper.

From the above discussion, we can see that the zonal mean temperature, the tides and the planetary waves can be effectively separated by this method. The technique was tested by applying a statistical $F$ test to the fitting; the results from this indicate that the separation of the mean from the waves is reliable to the 95% confidence level. In this paper, we discuss the global structure and the variation of zonal mean temperature $T_0(t, \phi, z)$ in equation (6). The global structure of tides will be discussed in a separate paper.
2.2. Temporal Variations of the Zonal Mean Temperature

[21] Previous studies indicate that the variations of the zonally averaged middle atmosphere contain prominent semiannual (SAO), annual (AO) and quasi-biennial (QBO) periodicities. In addition, there are longer-period variations in the temperature associated with the 11-year cycle in solar flux and changes in the composition of radiatively active gases.

[22] We now consider the global structures of the SAO, AO and QBO of the zonal mean temperature \( T_0 \) extracted using equation (6). A long-term trend term is also considered in our calculations; the solar cycle response is included in the trend. Although the solar cycle is quasi-periodic, the SABER data now available all fall in the declining phase of solar cycle 23. As discussed in more detail below, the data record is not sufficiently long for separating the atmospheric solar response from any other source of multiyear trend. In this study, we do not fit the mean temperature to actual measured solar flux because we do not have enough information to verify that the solar variations are the cause of the temperature variations. We thus solve for three periodic variations, each with an amplitude and phase, and a linear trend.

[23] In addition to the amplitudes and phases of the various oscillations, the period of QBO is also an unknown. The observed period in the equatorial stratosphere varies from 22 to 34 months, with an average of about 28 months [Baldwin et al., 2001]. In this analysis, we will solve for the period to get the best match to the QBO during this period.

For simplicity, the subscript of zero of \( T_0 \) calculated by equation (6) is omitted.

[24] In equation (7), \( \overline{T}_0 \) is the average zonal mean temperature and \( \mu_T (K) \) is the trend in the mean temperature. \( t_c \) is the center day of the of SABER 5-year observations. \( T_{SAO}, T_{AO} \) and \( T_{QBO} \) are the amplitudes of the SAO, AO and QBO over the 5 years and \( t_{SAO}, t_{AO} \) and \( t_{QBO} \) are the phases. The period of the QBO is also a variable, \( P_{QBO} \). The long-term variation of the temperature and the SAO, AO and QBO are determined simultaneously using a nonlinear least squares fitting method.

3. Comparison Between the Zonal Mean Temperature and the NRL-MSIS Model

[25] Figure 1 compares the zonal mean temperature at the vernal equinox (day 80) in 2003 from the TIMED/SABER measurements with the temperature from the empirical NRL-MSIS model (http://nssdc.gsfc.nasa.gov/space/model/atmos/nrlmsise00.html) for the same time. The global temperature structure derived from TIMED/SABER observations is similar to that from the empirical model except in the mesopause region. A blowup of the temperature at the mesopause can be seen in Figure 2. With a minimum at about 75 km and a maximum at about 85 km in the tropics, the temperature increases by about 15 K over these altitudes and shows an apparent inversion. A mesospheric inversion layer (MIL) or mesosphere temperature inversion (MTI) at similar altitudes and latitudes was also reported by Leblanc and Hauchecorne [1997].

[26] Figure 3 gives the variation of the zonal mean temperature at the equator over 5 years. At about 85 km there are temperature peaks at every equinox, while at 75 km the temperature minimizes at the same time. The temperature inversions start about 40 d before equinox and last for a total of about 100 d, although those at vernal equinox last slightly longer than those at autumnal equinox. Proposed mechanisms for the formation of MIL include tidal disturbances if limited local times are observed, photochemical heating, tide and/or gravity wave mean flow interaction,
inertial instability and the semiannual oscillation [Leblanc and Hauchecorne, 1997]. Although we have nearly complete local time coverage from SABER, the possibility of tidal aliasing cannot be easily dismissed because of the slow precession of the TIMED orbit. We must be cautious because both the vertical scale of the inversion, about half of the vertical wavelength of the migrating diurnal tide, and the equinox extreme values suggest possible aliasing from diurnal tide. This is further investigated in sections 4 and 5. After careful analysis, we find convincing evidence that these repeating temperature inversions are induced by a SAO in the mesospheric mean temperature. The SAO in temperature is associated with an SAO in mesospheric zonal mean wind that is believed to be forced primarily by gravity waves interacting with the mean flow [Dunkerton, 1982].

[27] The SAO in temperature is similar to the SME observations at a fixed local time (1400–1500 LT) [Clancy et al., 1994]. Leblanc and Hauchecorne [1997] used HALOE/UARS temperature observations to study the mesospheric temperature inversion (MTI) and they found there was a semiannual cycle in the amplitude of MTI. This is again consistent with the SABER results. Figure 3 also shows that the zonal mean mesopause in the equatorial region is located at about 98 km during all seasons.

**Figure 2.** SABER zonal mean temperature in the upper mesosphere at the vernal equinox (day 80), 2003. Contour interval is 3 K.

**Figure 3.** Variation of the zonal mean temperature at the equator with time.
Figure 4 gives the mean temperature structure for June solstice (day 170) in 2003. The zonal mean temperature distribution of TIMED/SABER at June solstice has many similarities to the MSIS result for the same time, although the temperature near the mesopause is again different. In particular, a two level mesopause is clearly apparent in the SABER temperature structure (Figure 5). The June SABER temperature distribution resembles that from observations by HRDI/UARS [Ortland et al., 1998]. A detailed discussion of the SABER mesopause structure and its variation with season is given by Xu et al. [2007]. The SABER observations give similar zonal mean temperature structures at equinox and solstice during all 5 years. However, it should be noted that the lower of the two mesopause altitudes in midlatitudes (Figure 5) is about 83–84 km, which is 2–3 km lower than seen in lidar observations. Lidar observations show that at midlatitudes in summer, the mesopause altitude is at about 86 km [States and Gardner, 2000; Chen et al., 2000; Chu et al., 2005; Fricke-Begemann et al., 2002]. Comparisons for 2003 also indicated that there is about a 2–3 km difference between the SABER temperature and ground-based observations at Ft. Collins [Xu et al., 2006]. The next version of the SABER data (version 1.7; processing to begin in 2007) will include the CO$_2$ vibrational exchange and will likely retrieve more accurate temperatures at the mesopause and therefore more accurate mesopause altitudes.

4. Long-Term Variations of the Zonal Mean Temperature

4.1. SAO, AO, and QBO

We first show the results of $P_{QBO}$ determined from the fitting method. Figure 6 shows the results of the calculation at the equator and 25 km, at the peak amplitude of the QBO. It is evident that, with the limited data record available, the goodness of the fit does not depend strongly on the period itself. Figure 7 shows the optimal QBO period as a function of altitude at the equator. We get some differences in the optimal period determined by the analysis when we calculate the period at different altitudes. This cannot be sustained as a characteristic of the QBO over long periods but, instead, is a result of the relatively short data record available from SABER. The QBO is strong in the tropical lower stratosphere, so we use the value calculated for 25 km at the equator as the best guess of the QBO period; that period is 26.6 months. Figure 7 also shows that the amplitude of the QBO has two peaks: one of about 3.2 K near 25 km and the other of 2.7 K near 37 km. The QBO period derived from the analysis is much shorter at the location of the upper peak in amplitude. For comparison, Figure 7 also includes the SAO amplitude; above 37 km, the SAO is the dominant oscillation of the temperature in the equator region. The AO in equatorial stratospheric temperature is very weak.
The global distributions of the amplitudes of the SAO, AO and QBO are given in Figure 8. Figure 8 also shows the relative amplitudes of the SAO, AO and QBO in percent, which are:

\[
\frac{T_{SAO}}{T_{SAO} + T_{AO} + T_{QBO}} \times 100\% \quad \frac{T_{AO}}{T_{SAO} + T_{AO} + T_{QBO}} \times 100\% \quad \frac{T_{QBO}}{T_{SAO} + T_{AO} + T_{QBO}} \times 100\%
\]

respectively. The SAO is strong in the stratosphere and mesosphere from 20°S to 20°N. There are three peaks of the tropical SAO: one in the upper stratosphere (45 km) and two in the mesosphere (75 km and 86 km). The global structure of the SAO amplitude is similar to the results of Huang et al. [2006], even though the methods used and the data periods are different (2002–2003 SABER data were used there). The temporal variations of temperature at the altitudes where the SAO is largest are shown in Figure 9. The relative amplitude of the SAO in the upper stratosphere reaches 70% and its phase indicates that the temperature maxima are near the equinoxes. At 75 km, the amplitude of the SAO is 6.5 K and the phase is near the solstices. At 86 km, the amplitude of the SAO is 4.5 K, and its phase is again near the equinoxes. Figure 9 indicates that the SAO constitutes 60–70% of the oscillations in these regions. From comparison with Figure 3, it is evident that the tropical MIL near the equinox is associated with the SAO in the mesosphere. There are also some signatures of the SAO in the midlatitude mesosphere although they are not the dominant oscillation there.

Figure 10 (top) shows vertical profiles of the amplitude and phase of the SAO at the equator. From 80 to 100 km, the phase of the SAO is near equinox (day 90–100). Below this, the phase undergoes a rapid shift in the
Figure 8. Global distribution of the (left) amplitude (K) and (right) relative magnitude (%) of the SAO, AO, and QBO.
Figure 9. Time series of zonal mean temperature at the equator at 45 km, 75 km, and 86 km.
Figure 10. Amplitudes and phases of the SAO and AO at (top) the equator, (middle) 20°N and (bottom) 40°N.
altitude range 75–80 km. At 75 km, the phase of SAO is near solstice (day 181), which is out of phase with that at the mesopause. The altitude of the phase reversal is similar to that found by Shepherd et al. [2004]. They analyzed the UARS/WINDII daytime temperature data of 1991–1997 and found that the phase reversal takes place around 82 km. Figure 10 also indicates that below 75 km, the SAO phase propagates downward at a speed of about 0.3 km per day or 9 km per month. The phases of the SAO at 75 and 86 km are also consistent with those from SME temperature [Clancy et al., 1994].

The vertical scale of the SAO in the tropical mesosphere is similar to that of the diurnal tide, which has maximum amplitude at low latitudes and also has a semi-annual variation. Because of these coincidences and the difficulty in separating zonal mean from migrating tides in satellite data, extra care must be taken to ensure that the SAO found in the analysis is actually a variation of the mean temperature rather than tidal aliasing. This is addressed in section 5.

Figure 8 (middle) indicates that, at latitudes poleward of 20°, the annual oscillation is the dominant temperature variation. The relative amplitudes of the AO near the stratopause and the mesopause regions are almost 100%. The AO in the Southern Hemisphere (SH) is out of phase with that in the Northern Hemisphere (NH). The AO in the mesopause region reaches maximum in winter, which is out of phase with that near the stratopause. Figure 8 shows a pronounced interhemispheric asymmetry in the AO amplitude; the AO of the SH stratosphere has a larger amplitude than that in the NH. Figure 11 gives the temperature variations at 40°N and 40°S at the altitude of 50 km. The amplitude of the AO at 40°S is more than 9.1 K, while that at 40°N is 5.81 K. At the stratopause, the southern midlatitude summer is warmer than that in the north and the southern midlatitude winter is colder. The situation is just the opposite in the mesopause region (Figure 12). The amplitude of the AO at 40°N is larger than that at 40°S by 3.3 K. The minimum temperature at 85 km and 40°S at the time of the December solstice is not as cold as that at
40°N around the June solstice. This is similar to the observations at the South and North Poles from Chu et al. [2003]. Extensive observational evidence indicates that the hemispheric asymmetry in the stratosphere is caused mainly by the asymmetry in planetary wave activity and the strength of the polar vortex. Possible causes of the hemispheric asymmetry in the mesosphere include the annual variation in solar flux due to the Earth’s eccentric orbit and gravity wave differences due either to tropospheric sources or to filtering by stratospheric winds. See Xu et al. [2007] for additional discussion.

Leblanc et al. [1998] and She et al. [1995] analyzed the SAO and AO in stratospheric and mesospheric temperature using long-term measurements made by Rayleigh and sodium Lidar at four sites between 19.5°N and 44°N [see Leblanc et al., 1998, Plate 4; She et al., 1995, Figure 4]. For comparison, the amplitudes and phases of the SAO and AO at 20°N and 40°N from SABER observation are given in Figure 10. For the SAO of the mean temperature, the phases in all three latitude regions have downward propagation below about 70 km; there is no downward propagation of the phase at 40°N. These features are very similar to the observations at Mauna Loa, Hawaii (19.5°N, 155.6°W) and at midlatitudes [Leblanc et al., 1998; She et al., 1995]. The amplitude of the AO at 40°N has two peaks, one near 80 km (about 17 K) and the other in the stratosphere (about 6 K), and has minima near 65 and 100 km. The AO phases at 40°N are at summer solstice below 65 km and at winter solstice above 65 km. The AO is weak in low latitudes. These features are also consistent with the observations of Leblanc et al. [1998] and She et al. [1995]. For comparison with airglow observation, Table 1 gives quantitative comparisons of the SAO and AO amplitudes and phases with ground-based airglow observations by Buriti et al. [2004], Takahashi et al. [1995], and Taylor et al. [2005]. The SAO amplitude determined from SABER is smaller than that of the ground-based data at all four sites although the phases are similar. For the annual cycles, the agreement with the amplitude is better and the phases are similar for most cases. The one case of extremely divergent AO phases

![Figure 12. Time series of temperature at 40°N and 40°S at 85 km.](image-url)
occurs close to the equator, where the AO amplitude is small and the latitudinal gradient in its phase is large, and is therefore not a cause for concern. Several factors could contribute to the amplitude differences: (1) The observation periods are different. (2) The ground-based observations were at night, so the contribution of the tides may influence the results. An SAO or QBO in diurnal tide in the mesosphere, along with sampling with partial local time coverage (e.g., night time observation), may lead to aliasing from tides to the SAO or QBO in zonal mean temperature. (3) The spatial resolutions of the two observation techniques are different. (4) There could be longitudinal structures in the oscillations.

Figure 8 shows that the QBO is the main oscillation in the lower stratosphere from 20°S to 20°N, where its relative amplitude reaches about 70%. As discussed above, the period used in the analysis is that calculated from the data at 25 km and the equator. Additional testing shows that, for these 5 years, the analyzed QBO structure is not sensitive to the exact QBO period within a reasonable range (24–30 months). The QBO is not confined to the tropical lower stratosphere; it extends into the tropical upper stratosphere and mesosphere and into midlatitudes, although its amplitude there is smaller than those of the AO and SAO. Huang et al. [2006] calculated the QBO in SABER temperature using 3 years of data (2002–2004; a subset of what was used in the present study). They found two QBO peaks in the mesosphere: one at 70 km with an amplitude of 3.5 K and the other at 85 km with an amplitude of 2.5 K. Our results instead indicate a peak located at 73 km with an amplitude of 1.74 K. Although some differences could be due to the different analysis techniques, we found that the QBO analysis was quite sensitive to the length of the data period used. Numerical tests show that when we use the same 3 years of data as used by Huang et al. [2006], the amplitudes of the QBO peaks in the equatorial mesosphere are larger than when we use the longer analysis period. By comparison with the situation in the stratosphere, the mesospheric QBO in mean temperature is fairly weak, and is therefore difficult to distinguish from other sources of interannual variability. The sensitivity of the analyzed QBO to the data period indicates that the data currently available spans too short of a time to determine the structure or even the existence of a QBO in zonal mean temperature in the middle mesosphere.

4.2. Long-Term Trend and Its Relation to the Solar Cycle

There have been a number of studies showing that the temperature in the middle atmosphere responds to the varying ultraviolet flux of the 11-year solar cycle. [e.g., Huang and Brasseur, 1993; Hood et al., 1993; McCormack and Hood, 1996; She and Krueger, 2004; Cleshena et al., 2005; Schmidt et al., 2006; Marsh et al., 2007]. The solar radio flux \( \mathcal{R} \) at 10.7 cm, referred to as the F10.7 flux, has been used as a representation of solar radiation variations (http://spird.nascom.nasa.gov/spird/index.jsp); its magnitude from 2002 to 2006 is shown in Figure 13, along with a linear fit. The solar radiation decreased from about 180 W m\(^{-2}\) Hz\(^{-1}\) in 2002 to about 80 W m\(^{-2}\) Hz\(^{-1}\) at the end of 2006. It is evident from Figure 13 that the 2002–2006 TIMED/SABER observations fall in the declining phase of solar cycle 23.

Previous analyses using satellite data indicate that the observed temperature in the upper stratosphere is in phase with solar cycle effects of ultraviolet radiation variations [Hood et al., 1993; McCormack and Hood, 1996]; that is, the lag time of the temperature response is negligible. Observations of mesospheric temperature from OH rotational bands by Cleshena et al. [2005] show that temperature variations in the mesosphere are also consistently in very close synchronization with the F10.7 flux.

Our fitting method (equation (7)) can determine the net changes in SABER temperature over this period but cannot determine how much of that change is due to the response to the solar cycle. Figure 14 gives the global distribution of the temperature change. From Figure 14 we can see that the temperature decreased in most regions; the exception is an increase in the tropical lower stratosphere.

The average temperature change between 20°S to 20°N is given in Figure 15. This period spans an interval from quite high solar activity just after solar maximum to low solar activity characteristic of solar minimum. The actual solar minimum has probably not been reached as of the end of 2006. For comparison with other studies, we will assume that this period encompasses a full solar cycle and therefore the magnitude of the change should be comparable.

<p>| Table 1. Comparison of SABER Temperature Oscillations With Those Diagnosed From Ground-Based Observations |
|---------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Position</th>
<th>Altitude, km</th>
<th>Semiannual Amplitude, K</th>
<th>Semiannual Phase, day</th>
<th>Annual Amplitude, K</th>
<th>Annual Phase, day</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{QBO}} )</td>
<td>7.4°S, 36.5°W</td>
<td>87</td>
<td>6.2</td>
<td>96</td>
<td>2.3</td>
</tr>
<tr>
<td>SABER</td>
<td>5°S</td>
<td>87</td>
<td>4.3</td>
<td>95</td>
<td>1.94</td>
</tr>
<tr>
<td>( T_{\text{QBO}} )</td>
<td>3.9°S, 38.4°W</td>
<td>87</td>
<td>8.5</td>
<td>97</td>
<td>1.7</td>
</tr>
<tr>
<td>SABER</td>
<td>5°S</td>
<td>87</td>
<td>4.3</td>
<td>95</td>
<td>1.94</td>
</tr>
<tr>
<td>( T_{\text{QBO}} )</td>
<td>22.7°S, 45°W</td>
<td>87</td>
<td>3.5</td>
<td>100</td>
<td>0.3</td>
</tr>
<tr>
<td>SABER</td>
<td>20°S</td>
<td>87</td>
<td>2.2</td>
<td>110</td>
<td>0.3</td>
</tr>
<tr>
<td>( T_{\text{QBO}} )</td>
<td>20.8°N, 56.2°W</td>
<td>87</td>
<td>5.8</td>
<td>95</td>
<td>–</td>
</tr>
<tr>
<td>SABER</td>
<td>20°N</td>
<td>87</td>
<td>2.84</td>
<td>108</td>
<td>2.97</td>
</tr>
<tr>
<td>( T_{\text{QBO}} )</td>
<td>20.8°N, 156.2°W</td>
<td>94</td>
<td>5.7</td>
<td>95</td>
<td>–</td>
</tr>
<tr>
<td>SABER</td>
<td>20°N</td>
<td>94</td>
<td>2.06</td>
<td>109</td>
<td>1.46</td>
</tr>
</tbody>
</table>

\( ^a \) Buriti et al. [2004] at Sao Joao do Cariri (7.4°S, 36.5°W), \( ^b \) Takahashi et al. [1995] at Fortaleza (3.9°S, 38.4°W), \( ^c \) Takahashi et al. [1995] at C. Paulista (22.7°S, 45.0°W), \( ^d \) Taylor et al. [2005] at Hawaii (20.8°N, 156.2°W).
to that from solar maximum to minimum. The SABER temperature changes in the tropical stratosphere are consistent with the solar cycle analysis of McCormack and Hood [1996], based on 14 years (1980–1995) of National Meteorological Center (NMC) temperature data. Note, however, that there are concerns about the separation of the solar cycle response from the QBO variations even for time series substantially longer than that available from SABER.

Figure 14 indicates that the temperature variation has two regions of maximum decrease of more than 4 K in the midlatitude upper mesosphere. No clear maximum shows up at this location in analysis of solar maximum minus solar minimum model integrations in the state-of-the-art HAMMONIA [Schmidt et al., 2006] and WACCM [Marsh et al., 2007] numerical models. These two models also do not simulate a maximum in the solar response in the middle mesosphere at the equator that would correspond to the largest magnitude change seen in Figure 15. However, overall the magnitudes of the temperature change in the 5 years of SABER data are closer to the HAMMONIA and WACCM model simulations than they are to some other analyses of mesospheric observations. For example, analysis of OH rotational temperature measurements from 1987 to 2000 at 23°S by Clemesha et al. [2005] show an amplitude for the 11-year oscillation in rotational temperature of 6 K (see Table 1 of their paper) or a peak-to-peak variation between solar maximum and minimum of 12 K. The magnitude of the net temperature variation of SABER is 2.7 K at 25°S, much smaller than seen by Clemesha et al. From midlatitude lidar measurements over Fort Collins (41°N, 105°W) from 1990 to 2001, She and Krueger [2006]...
[2004] found a temperature variation over one solar cycle of about 7 K; once again, the SABER temperature shows a smaller net change of only about 4.6 K.

[41] It is very important to keep in mind that this work cannot confirm that the change of temperature over this period is due to solar variation. The 5 years of available data is too short for reliable statistics. Also, since the change in solar forcing is approximately monotonic, it is not possible to distinguish the solar response from any other sources of long-term change. Other known changes in the mesosphere that could contribute to a trend are ongoing increases in CO₂ concentration [e.g., Schmidt et al., 2006] and long-term changes in water and, as a result, ozone [Marsh et al., 2003]. As discussed above, as of now there is not an agreement of the solar cycle response taken with different observation techniques or over different periods. Our discussion has been based on the hypothesis that the solar variations are the dominant influence on the atmospheric temperature structure over a timescale of 5 years. The comparison of the results with previous studies supports the assumption that the long-term trend of temperature may be dominated by the response of temperature to solar variation.

5. SAO and Tidal Aliasing

[42] As pointed out by Garcia and Clancy [1990], Garcia et al. [1997], and Smith [1997], one cannot rule out the possibility that aliasing from tides to the zonal mean temperature or wind affects the apparent mesospheric SAO found in satellite data. There is a general problem with the possibility of aliasing between the tides and zonal mean components for satellite data analysis [e.g., Salby, 1982; Palo et al., 1997; Forbes et al., 1997; Zhu et al., 2005]. The problem is particularly prominent for the mesospheric SAO because it has some features in common with the diurnal tide. The temperature maxima of both the tide and the SAO occur at the equator. The seasonal tidal amplitude maxima near the equinoxes correspond in time to the maxima of the SAO. The altitudes of the apparent SAO peaks (negative at 75 km and positive at 86 km) at equinox are separated by about 11 km; the distance between the two out-of-phase peaks is about half vertical wavelength of the migrating diurnal tide.

[43] Figure 16 gives the amplitude and phase of temperature variations due to the diurnal tide at the equator at 75, 85, and 95 km. The diurnal tide has large amplitude around equinoxes and the phase is relatively stable in the mesosphere over the 5 year period. During these years, the temperature amplitude of the diurnal tide in the upper mesosphere is much larger than the amplitudes of the semidiurnal and terdiurnal tides. Table 2 summarizes the 5-year averaged parameters of diurnal and semidiurnal tides at six altitudes in the mesosphere at the equator. From Figure 16, the vertical wavelength of the diurnal tide is consistently at about 20 km, while that of the semidiurnal tide (Table 2) is much longer. This confirms our earlier assumption that it is the diurnal tide that is more likely to contaminate the SAO analysis.

[44] In the current analysis, about 60 d are needed to accomplish 24-h local time coverage. Since this is a significant portion of a cycle, and since the diurnal tide can change significantly during a period of this length, we need to examine the data carefully to determine whether the apparent SAO shown in section 4 is caused or altered by tidal aliasing. It is also possible that changes in the mean temperature are affecting the analyzed diurnal tide.

[45] We can take advantage of the local time coverage of SABER to determine if the tides have been separated from the mean temperature in the analysis. The basic idea is as follows: First, we assume that tidal aliasing affecting the SAO analysis would come only from the diurnal migrating tide. The short vertical structure of the analyzed SAO (Figure 8) is similar to the wavelength of the diurnal tide but much shorter than that of the semidiurnal tide. The feature analyzed in this paper is zonally symmetric so nonmigrating tides do not contribute (see section 2). Second, if aliasing from the diurnal tide is the main contributor to the SAO, then the signal we diagnose as the SAO would vary depending on which phase of the tide is being observed. Specifically, the apparent SAO would be strongest when the data are sampled at the two local times when the tide maximizes and minimizes (12 h apart in local time). On the other hand, when the data are sampled at the phases with zero tide perturbation (nodal points), the analysis would give no or only a very weak SAO. These may not be exactly true all the time because of tidal variability, but should be valid statistically, especially if the tidal phase is stable.

[46] At 75 km, the temperature of the diurnal tide reaches maximum at about 0112 LT, minimum at 2212 LT, and zero at 0412 and 1612 LT. Because the phase of the diurnal tide is relatively stable over the 5 year period, the local times of these key points (maximum, minimum, and the two zero points) are also relatively stable. The two zero points are of particular interest because a time series of data taken only at these local times should have no migrating diurnal tide. We redo the fitting of variations as in equation (7) (for the QBO, AO, SAO, etc.) except that the temperature is sampled only in a 2 h window around these two zero points (chosen for the particular altitude level). The results for two altitude levels at the equator, along with the fit using data from all local times, are given in Figure 17.

[47] If the phase of the diurnal tide were absolutely stable and there were no aliasing between the zonal mean and the diurnal tide, the curves based on using data from the two zero points (local time nodes of the diurnal tide) should lie exactly on top of that based on analysis of all local times. Figure 17 shows that at both 75 and 85 km the fit using data from all local times almost overlaps that using only data near the two zero points. At both altitudes, the SAO is the most prominent variation even in the fit based on data from tidal zero points. We also calculated the SAO fit using data only at local time near the tidal maximum or minimum. If tides alone were responsible for the variation, these two cases would give SAO phases that were exactly opposite but, instead, the SAO phases at both levels were similar to those shown in Figure 17. (Because of the very slow precession of the TIMED satellite, there are tens of days difference between the observations at the local times of the tidal minimum and those at the tidal maximum. As a result, there is a small phase difference between the curves shown in Figure 17.) From this analysis, we conclude that the SAO
determined from the analysis presented in section 4 is predominantly a phenomenon of the mean temperature and is not dominated by contamination by the diurnal tide. Additional evidence comes from comparison of the SAO phases at 85 and 95 km. The SAO phases at these two altitudes would be out of phase if diurnal tidal aliasing were the main cause of the SAO in the analysis but, instead, they are the same.

Associated with this analysis of the dependence of the SAO on the tidal aliasing, we can revisit the analysis of SME temperature by Clancy et al. [1994]. They found temperature minima at equinoxes at 80 km (Figure 5 in their paper). At the local time of the SME observations (1400–1500 LT), this altitude coincides with a minimum point of the diurnal tide (Table 2). We use SABER data to test the effect of a single local time on the analysis; results are shown in Figure 18. Using SABER zonal mean temperatures, we are not able to reproduce the equatorial vertical structure in the SME analysis. However, if we use the SABER zonal mean plus the diurnal tide, with the phase corresponding to the local time of the SME observations, the analysis gives a pronounced minimum at 80 km, just like that found by Clancy et al. [1994]. It is the addition of the tidal minimum that accounts for the equinoctial minimum in temperature at 80 km. Because of the relatively

![Figure 16. Time series of the (top) phases (units are hours) and (bottom) amplitudes (units are K) of the migrating diurnal tide at 75 km (solid), 85 km (dashed) and 95 km (dotted).](image)

Table 2. Five-Year Averaged Parameters of the Diurnal and Semidiurnal Tide at Five Altitudes at the Equator

<table>
<thead>
<tr>
<th>Altitude, km</th>
<th>Amplitude of Diurnal Tide, K</th>
<th>Phase of Diurnal Tide, LT</th>
<th>Amplitude of Semidiurnal Tide, K</th>
<th>Phase of Semidiurnal Tide, LT</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>7.0</td>
<td>1012</td>
<td>2.75</td>
<td>0139</td>
</tr>
<tr>
<td>80</td>
<td>8.55</td>
<td>0347</td>
<td>2.58</td>
<td>0052</td>
</tr>
<tr>
<td>85</td>
<td>10.73</td>
<td>2243</td>
<td>2.34</td>
<td>0938</td>
</tr>
<tr>
<td>90</td>
<td>10.35</td>
<td>1729</td>
<td>2.11</td>
<td>0932</td>
</tr>
<tr>
<td>95</td>
<td>13.14</td>
<td>1044</td>
<td>3.15</td>
<td>0715</td>
</tr>
<tr>
<td>100</td>
<td>12.65</td>
<td>0533</td>
<td>2.94</td>
<td>0428</td>
</tr>
</tbody>
</table>
weak diurnal tides at the solstices, the effect of aliasing from tides to zonal mean temperature is weaker than at the equinoxes. This is a confirmation of the importance of broad local time coverage for avoiding tidal aliasing in order to determine the variations of the equatorial upper mesosphere.

6. Summary

[59] In this paper, we describe a method for extracting zonal mean temperature and migrating tides from TIMED/SABER satellite observations and present results for the mean temperature variations on seasonal, annual, and interannual scales. The seasonal variation of the global structure is broken down into periodic variations on semiannual, annual and quasi-biennial timescales. Interhemispheric asymmetries of the zonal mean temperature are discussed. The longer-term trend temperature over these 5 years is discussed under the assumption that it is at least in part associated with the declining solar flux of the solar cycle (which has a monotonic decrease over this period) although we recognize that many other processes could also contribute to the trend.

[50] The SABER temperature data used in this study have a systematic offset in the upper mesosphere compared to lidar data. Specifically, SABER temperature is colder than lidar observations near the mesopause and the mesopause altitude itself is too low, particularly in high latitudes during summer when the mesopause is coldest. The cause is known to be a neglect of vibrational exchange in the non-LTE retrieval algorithm [Kutepov et al., 2006] and will be corrected in future versions (beginning with version 1.07). We do not expect that this systematic error has a large impact on the analysis presented in this paper although it may lead to an overestimate of the magnitude of the annual
cycle in the high-latitude upper mesosphere. Caution should be used when using the mean temperatures from the current study to validate numerical models.

[51] The global structure of the zonal mean temperature is generally consistent with the NRL-MSIS empirical model, though there are some differences between them. At equinox, a stable layer is seen in zonal mean temperature around the equator (between 20°S to 20°N) in the mesosphere, with the temperature increasing by 5–15 K from 75 to 85 km. Such features have been seen in other observations, and are known as mesospheric inversion layers (MIL). This temperature inversion starts 40 d before equinox and lasts for about 100 d. The inversion is associated with the SAO in mean temperature, which has large amplitudes at 86 km and 75 km and is out of phase between them. These features are consistent with observations from SME [Clancy et al., 1994] and HALOE [Leblanc and Hauchecorne, 1997]. One concern about the SAO in upper mesospheric temperature is the possibility of aliasing from the diurnal tide to the zonal mean. Thorough investigation of this question indicates that the SAO in zonal mean temperature determined from our analysis is predominantly a phenomenon of the mean temperature rather than contamination by the diurnal tide.

Figure 18. Simulation of SME observations at (top) day 80 and (bottom) day 170 using TIMED/SABER 5-year averaged results at the equator.
The AO is by far the dominant periodic variation in the midlatitude stratosphere and mesosphere. In some regions, the relative amplitude of the AO can be well over 90%. The TIMED/SABER zonal mean temperature exhibits an obvious interhemispheric asymmetry, especially for the AO; in the stratosphere, the AO of zonal mean temperature in the SH is stronger than that in the NH but in mesosphere, the AO in the NH is stronger than in that in the SH. As shown in previous studies, radiation could contribute to the asymmetry because of the timing of the annual variation in the distance to the Sun [Chu et al., 2003] and dynamics could contribute because of differences in gravity wave sources [e.g., Vincent, 1994; Dowdy et al., 2001; Xu et al., 2007] and/or in filtering of gravity waves by stratospheric winds [e.g., Siskind et al., 2003]. The differences in the amplitudes of the annual oscillations between the two hemispheres found here are much larger than the annual variation of 6.6% of energy input from the Sun and indicate that a dynamical cause is also needed.

The SABER zonal mean temperature has a strong quasi-biennial oscillation (QBO) in the tropical lower stratosphere; the optimal fit gives a period of 26.6 months. The observations cover only two cycles of the QBO so the determination of the period is subject to significant uncertainty. Over much of the middle atmosphere away from the tropical lower stratosphere, the period of the QBO is not well constrained by the available data; analysis indicates it varies with location and with the length of the data record (up to 5 years) used in the calculation. At the lower stratospheric maximum, the relative amplitude of the QBO is about 50–60%. There are also weak indications of a QBO signal in the temperature in the upper mesosphere and in middle latitudes throughout the middle atmosphere but these are not robust when the analysis time period changes.

The global structure of the change in temperature over the 5 year period is presented. The data currently available cover most of the declining phase of solar cycle 23. In most of the middle atmosphere, the zonal mean temperature decreases during the period, in other words it is positively correlated with the solar radiation. The zonal mean temperature in the lower equatorial stratosphere has a small increase. The results and the consistency with a number of previous observational and modeling studies of the atmospheric response to the solar cycle suggest that the bulk of the temperature variation is associated with the solar variation. A longer period of observations is needed before definitive conclusions and reliable magnitudes of the solar response can be obtained.

Acknowledgments. This research was supported by the National Science Foundation of China (40621003, 40674088, and 40523006) and the National Important Basic Research Program (2001CB806036). This work was also supported in part by the CAS International Partnership Program for Creative Research Teams. The National Center for Atmospheric Research is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation. Additional support was provided by NASA Division of Space Science. Yue Deng (NCAR/HAO) and Hauke Schmidt (Max Planck Institute for Meteorology) gave many useful comments on an earlier version of this paper.

References
XU ET AL.: SABER MEAN TEMPERATURE


H.-L. Liu and Q. Wu, High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO 80307, USA.

M. G. Mlynczak, NASA Langley Research Center, Hampton, VA 23681, USA.

J. M. Russell III, Center for Atmospheric Sciences, Hampton University, Hampton, VA 23668, USA.

A. K. Smith, Atmospheric Chemistry Division, National Center for Atmospheric Research, Boulder, CO 80307, USA.

J. Xu and W. Yuan, Key Laboratory for Space Weather, Chinese Academy of Sciences, Beijing 100080, China.