Troposphere-Thermosphere Tidal Coupling as Measured by the SABER Instrument on TIMED during July-September, 2002

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ABSTRACT

Coupling between the troposphere and lower thermosphere due to upward-propagating tides is investigated using temperatures measured from the SABER instrument on the TIMED satellite. The data analyzed here are confined to 20-120 km altitude and ±40° latitude during 20 July – 20 September, 2002. Apart from the migrating (sun-synchronous) tidal components, the predominant feature seen (from the satellite frame) during this period is a wave-4 structure in longitude with extrema of up to ±40-50 K at 110 km. Amplitudes and longitudes of maxima of this structure evolve as the satellite precesses in local time, and as the wave(s) responsible for this structure vary with time. The primary wave responsible for the wave-4 pattern is the eastward-propagating diurnal tide with zonal wavenumber s = 3 (DE3). Its average amplitude distribution over the interval is quasi-symmetric about the equator, similar to that of a Kelvin wave, with maximum of about 20 K at 5°S and 110 km. DE3 is primarily excited by latent heating due to deep tropical convection in the troposphere. It is demonstrated that existence of DE3 is intimately connected with the predominant wave-4 longitude distribution of topography and land-sea difference at low latitudes, and an analogy is drawn with the strong presence of DE1 in Mars atmosphere, the predominant wave-2 topography on Mars, and the wave-2 patterns that dominate density measurements from the Mars Global Surveyor (MGS) spacecraft near 130 km. Additional diurnal, semidiurnal and terdiurnal nonmigrating tides are also revealed in the present study. These tidal components are most likely excited by nonlinear interactions between

their migrating counterparts and the stationary planetary wave with s = 1 known to exist in the Southern Hemisphere during this period just prior to the austral mid-winter stratospheric warming of 2002.

1. Introduction

Except for occasional intervals of extreme planetary wave activity, atmospheric tides represent the dominant dynamical component of the 80-120 km height region (hereafter referred to as the MLT, or mesosphere-lower thermosphere region). Many of the prevalent tidal oscillations originate from periodic variations in troposphere and stratosphere heating due to daily variations in the absorption of solar radiation. These waves propagate into the MLT and reach relatively large amplitudes in the 100-150 km region, where they undergo molecular viscous dissipation. The excitation of diurnal and semidiurnal tides due to solar radiation absorption by tropospheric H_2O and stratospheric O_3 are the most well-known sources of tidal excitation (Chapman and Lindzen, 1970; Groves, 1982a,b; Forbes and Garrett, 1979) and are mainly responsible for the sun-synchronous or "migrating" components of the MLT tides, although in-situ absorption of UV and EUV radiation and perhaps even chemical heating (Mlynzack and Solomon, 1993; Smith et al. 2003) at these altitudes cannot be overlooked. Forbes et al. (1997a) also demonstrate that latent heating connected with deep tropical convection contributes to the migrating tidal fields at these altitudes.

It is now recognized, through relatively recent observational analyses (e.g., Lieberman 1991; Hagan et al. 1997b; Talaat and Lieberman 1999; Oberheide and Gusev 2002; Forbes et al. 1995; 2003; Huang and Reber 2004; Manson et al. 2002, 2004) and modeling studies (e.g., Ekanayake et al. 1997; Miyahara et al. 1999; Forbes et al. 2001; Grieger et al. 2002; Hagan and Forbes 2002, 2003; Hagan et al. 1997a; Oberheide et al. 2002: McLandress and Ward, 1994) that there is a whole spectrum of tides propagating from the troposphere to the MLT, that are related to longitudinal variations in the heating rates due to variations in absorbing gas concentrations, land-sea differences and their influence on latent heat release, topography, and other factors. Non-linear tide-tide interactions (Teitelbaum and Vial 1991; Smith and Ortland 2001) and tide-planetary wave interactions (Hagan and Roble 2001; Yamashita et al. 2002; Angelats i Coll and Forbes 2002; Lieberman et al. 2004; Grieger et al. 2004) in the stratosphere and mesosphere are also known to play a role in explaining the spectrum of waves observed in the MLT region. Of particular importance is the recognition that interannual variability of low-latitude MLT tides is correlated with the El Nino-Southern Oscillation (ENSO) (Gurubraran et al., 2005). These authors provide evidence that large-scale convective systems originating over the western Pacific region in response to the El Nino Southern Oscillation (ENSO) facilitate excitation of nonmigrating tides through latent heat release or large-scale redistribution of water vapor. Thus, observations of MLT tides may provide new constraints on convective parameterizations and hydrologic cycles in general circulation models used for weather and climate predictions. At the same time, MLT tidal variability induced by tropospheric processes may have important impacts on ionospheric variability (Forbes et al., 2000), with interesting scientific and practical space weather (i.e., communications and navigation) implications. These perspectives provide the underlying motivation for the present paper, which focuses on troposphere-MLT tidal coupling.

The SABER instrument was launched onboard the TIMED satellite on December 7, 2001. Among other parameters, SABER provides measurements of kinetic temperature from approximately 20 km to 120 km altitude, during both day and night, and extending to latitudes as high as ±82° with close to 100% duty cycle. This type of coverage provides unprecedented opportunities for the study of tides and planetary waves, and their roles in coupling the troposphere, stratosphere, mesosphere and thermosphere. In this paper we explore the capabilities of SABER to elucidate solar thermal tides in the 20-120 km height regime, focusing on the 20 July to 20 September time period, and particularly on those waves thought to originate in the troposphere. This period covers a complete yaw cycle for the TIMED spacecraft, wherein SABER made measurements from approximately +53° to -83° latitude. This interval of time is of particular interest since mid- to late summer is thought to be a period of strong troposphere-thermosphere coupling, as suggested by the relatively large amplitudes of the eastward-propagating diurnal tides uncovered in previous studies (Talaat and Lieberman, 1999; Forbes et al., 2003; Huang and Reber, 2004; Manson et al., 2004). The consequences of this coupling on the lower thermosphere constitutes the primary focus of this paper, although aspects of other tidal oscillations during this period are also examined.

Before proceeding further, we now define the nomenclature utilized throughout this paper. The global temperature, density and wind fields induced by the daily cyclic absorption of solar energy in an atmosphere are referred to as solar thermal tides. Assuming continuity in space and time around a latitude circle, solar thermal tidal fields are represented in the form

$$A_{n,s} \cos(n\Omega t + s\lambda - \phi_{n,s}) \tag{1}$$

where t = time (days), Ω = rotation rate of the earth = 2π day^{-1}, λ = longitude, n (= 1, 2, ...) denotes a subharmonic of a solar day, s (= .... -3, -2, ...0, 1, 2, ...) is the zonal wavenumber, and the amplitude $A_{n,s}$ and phase $\phi_{n,s}$ are functions of height and latitude. At any height and latitude the total tidal response is obtained as a sum over n and s. The phase is defined as the time of maximum at zero longitude; in other words, the local time at Greenwich. (The alternative definition of longitude of maximum at t = 0 is not used for tides, since the phase is undefined for $s = 0$). In the above context, n = 1,2,3 represent oscillations with periods corresponding to 24 hours, 12 hours, 8 hours, and hence are referred to as diurnal, semidiurnal and terdiurnal tides, respectively. From (1) a zonal phase speed can be derived: $C_{ph} = d\lambda/dt = - n\Omega/s$. Eastward (westward) propagation corresponds to $s < 0$ ($s > 0$). Note that when s = n, $C_{ph} = - \Omega$, i.e., westward migration with the apparent motion of the Sun (to an Earth-fixed observer). Historically, these sun-synchronous components are referred to as 'migrating' tides, and the components corresponding to $s \neq n$ are referred to as 'non-migrating tides'. It is simple to show that local time dependences of atmospheric fields (i.e., temperature, winds, etc.) associated with migrating tides are independent of longitude. Local time structures that are longitude-dependent can be represented mathematically as a sum of terms (1) with various values of s and n, and hence as a superposition of solar thermal tides propagating to the east ($s < 0$), to the west ($s > 0$), or standing ($s = 0$) (Chapman and Lindzen, 1970). The non-migrating tides that give rise to longitude-dependent local time structures can arise either from (a) a zonally-asymmetric excitation source, such as latent heating associated with deep tropical convection (Hagan et al., 1997a; Forbes et al., 2001; Hagan et al., 2002, 2003); (b) by propagation of migrating tides through a zonally-asymmetric stationary background atmosphere (Angelats i Coll, 2002; Hagan and Roble, 2001); (c) via tide-tide nonlinear interactions (Teitelbaum and Vial, 1991); or (d) interactions between a zonally-asymmetric distribution of gravity waves, and the migrating tidal field (McLandress and Ward, 1994).

Throughout the remainder of this paper we utilize the notation and DWs or DEs to denote a westward or eastward-propagating diurnal tide, respectively, with zonal wavenumber s. For semidiurnal and terdiurnal oscillations 'S' and 'T' replaces 'D'. The standing oscillations are denoted D0, S0, T0, and stationary planetary waves with zonal wavenumber m are expressed as SPWm.

The eastward-propagating diurnal tide with zonal wavenumber s = 3 (hereafter referred to as DE3) is one of several nonmigrating tides recently found to exhibit fairly large amplitudes (~10-15 ms^{-1}) in the 90-110 km altitude range from wind measurements by the High Resolution Doppler Imager (HRDI) instrument on the Upper Atmosphere Research Satellite (UARS) (Talaat and Lieberman, 1999; Forbes et al., 2003; Huang and Reber, 2004; Manson et al., 2004). Analyses of lower-atmosphere heating rates from the NCEP-NCAR Reanalysis Project (Forbes et al., 2001) demonstrate that the predominant forcing mechanism for this wave is condensation or latent heating in the tropical troposphere, with secondary excitation resulting from radiative forcing. Furthermore, Forbes et al. (2001) calculate the global response of that atmosphere to these DE3 heating rates during July. They obtain more than a factor of two larger lower thermosphere wind amplitudes than those noted by the aforementioned observational studies, and predict temperature oscillations approaching 40 K over the equator between 120-150 km altitude. Current evidence indicates that DE3 and other tides excited in the troposphere may have a significant impact on the dynamics of the MLT, and the SABER measurements offer an opportunity to gain further insight into troposphere-MLT tidal coupling. It is the purpose of this paper to provide this deeper perspective.

In the following, we briefly describe the SABER data and method of analysis. Depictions of the SABER data are then provided to gain insight into the longitudinal variations in the local time structures of the temperature field that results from the presence of nonmigrating tides. In Section 3 we provide a typical frequency-zonal wavenumber decomposition of the tidal field, and discuss the possible origins of these components. Section 4 is devoted to DE3, wherein it is found to be nearly as large as the migrating (sun-synchronous) component, DW1. The abilities of current models to predict DE3 are also assessed in Section 4. DE3 is also examined from the viewpoint of a wave-4 longitude structure, and its connection with the predominant wave-4 content of the land-sea/topographic distribution of the surface. In this connection, we draw an analogy to the strong presence of DE1 in Mars atmosphere, the predominant wave-2 topography on Mars, and the wave-2 patterns that dominate density measurements from the Mars Global Surveyor (MGS) spacecraft near 130 km. In the final Section 5, we utilize a numerical model, calibrated with current observations, to estimate the effects of DW1 and DE3 on the zonal mean circulation of the thermosphere due to dissipation of this wave.

2. The experimental data and method of analysis

The method of deriving kinetic temperatures from CO_2 emissions is detailed in Mertens et al. (2001). One of the main difficulties is the determination of kinetic temperatures under conditions of non-local thermodynamic equilibrium (non-LTE), which pertains above about 70 km altitude. In the SABER version V1.04 temperatures analyzed here, non-LTE retrievals of T_k incorporate simultaneous determinations of CO_2 densities from the CO_2 15μm emission. This eliminates a major source of uncertainty since CO_2 is not well mixed above 75 km and therefore cannot be specified in terms of a volume mixing ratio. The CO_2 determinations, however, contain uncertainties connected with knowledge of atomic oxygen densities and the rate of CO_2 vibrational quenching. These errors, in addition to those associated with instrumental noise are estimated in Mertens et al. (2001), and *in toto* range between 1.4% at 80 km and 22.5% at 110 km. However, what is primarily important for the present application is the fidelity with which temperature *variations* can be determined. In this connection, apparent variations introduced into the SABER temperatures by un-modeled variability in the assumed atomic oxygen densities is of prime concern. The [O] densities in the retrieval are obtained from msise90 between 80 and 120 km. Specifically, if there are variations in [O] that are not modeled by msise90, then these oxygen variations can effectively introduce variations into the retrieved SABER temperatures. Given our uncertainty of atomic oxygen variability apart from those included in msise90, these effects are difficult to estimate for any particular phenomenon under investigation (i.e., any given nonmigrating tidal component). Our results at the upper altitude of 110-120 km should therefore be viewed with due caution, and at this point their acceptability is assessed qualitatively by examining the continuity of amplitude and phase relationships within the 80-120 km height regime. We hope in the future to derive atomic oxygen densities from other SABER data, and to utilize these in the temperature retrievals to reduce uncertainties accordingly.

SABER views the atmosphere 90° to the satellite velocity vector in a 550 km and 73° inclination orbit, so that latitude coverage on a given day extends from about 53° latitude in one hemisphere to 83° in the other. This viewing geometry alternates once every 60 days due to 180° yaw maneuvers required for the TIMED satellite. Within a yaw period, data from the ascending and descending portions of the orbit can include up to about 22 hours of local time (data are not acquired by SABER near noon). During 20 July – 20 September, 2002, TIMED was observing between +53° and –83° latitude; however, during this period high latitudes in the Southern Hemisphere experienced extreme planetary wave activity throughout the vertical extent sampled by SABER (i.e., see Kruger et al., 2005). As shown by Forbes et al. (2005), temporal variations in stationary planetary waves alias into many of the nonmigrating tides relevant to the present study. Therefore, data poleward of –53° in the Southern Hemisphere were rejected. In addition, in order to maintain 22 hours local time coverage at all latitudes, only data between ±40° was considered (some local time coverage is lost near the yaw boundaries at ±53°). These restrictions do not have a serious impact on the present study.

To extract the tidal oscillations, the following procedure was used. Temperature measurements between 20 June 2002 and 20 October 2002 were averaged in bins spanning 24° longitude, 5° latitude, and 1 hour in U.T. at increments of 2 km altitude from 20 to 120 km. A standard deviation was computed for each hourly data point, primarily providing a measure of geophysical variability. Sixty-day running means were obtained for each longitude bin, and then subtracted from the measurements to obtain a set of temperature residuals. This step was performed in order to remove long-term trends that could potentially alias into the tides (see Forbes et al., 1997b). At each altitude, latitude and longitude, Fourier least-squares fits were performed on the temperature residuals with respect to U.T. to determine amplitudes and phases of diurnal, semidiurnal and terdiurnal tidal components. Each frequency component was then subjected to Fast Fourier Transform (FFT) to perform the zonal wavenumber decomposition for $s = -6$ to $s = +6$. Uncertainty estimates were computed for each zonal wavenumber component, taking into account the frequency-component uncertainties from the previous stage of analysis. Average temperatures in the longitude and U.T. bins were also subjected to a two-dimensional FFT, determining the frequency and zonal wavenumber decompositions simultaneously, with little change in the results.

3. Local time structures

In this section we provide some perspective on how local time structures vary with longitude. This view is relevant, for instance, to interpreting differences in temperatures measured by ground-based sites at the same latitude, but different longitudes. The point is illustrated in Figure 1, which depicts temperatures as a function of latitude and local time at longitudes 108° and 276°, and at altitudes of 70 km, 86 km, and 110 km. At a given height, differences in these structures between longitudes is a measure of the relative importance of nonmigrating versus migrating tides. At 70 km, temperature perturbations are of order ±2-6 K, and the broad, salient features are similar at the two longitudes. At both longitudes, structures are predominantly semidiurnal at the higher latitudes. However, while the local time variation at the equator is clearly diurnal at 108° longitude, a strong semidiurnal component is still present at 276° longitude.

At 86 km, a diurnal oscillation still prevails near the equator at 108° longitude, with ±14 K temperature excursions approximately out of phase with those at 70 km. This is consistent with a ≈ 32 km vertical wavelength for the diurnal tide. A significant semidiurnal oscillation exists near –30° to –40° latitude, and persists at 276° longitude. At 276° longitude some mixture of diurnal and semidiurnal components combine to produce the observed structures. At 110 km, the patterns at the two longitudes actually begin to look more similar, with semidiurnal features clearly evident at all latitudes, and temperature excursions of ±20-30 K. However, this particular separation of longitudes may not be optimum for revealing the impact of DE3, which has an equatorial amplitude of ≈16 K at 110 km, but with 4 maxima in longitude (hence separated by 90°) in the local time reference frame (see following sections). From the above, we conclude that the relative importance of nonmigrating tides is highly dependent upon the relative phasing of the various individual components comprising the tidal field, and changes significantly with latitude, longitude and altitude within the MLT.

4. Overview of spectral components

The variation of local time structure with longitude as depicted in Figure 1 is embodied in a spectrum of zonal wavenumbers (i.e., s-values in Equation 1) for each *nth* harmonic (i.e., diurnal, semidiurnal, etc.). While in theory an infinite sum is required to capture the longitude variation of each harmonic, in practice relatively few harmonics are found to dominate. To illustrate, consider Figure 2, which depicts the latitude versus zonal wavenumber *amplitude* spectra of diurnal, semidiurnal and terdiurnal nonmigrating tides measured by SABER at 106 km. Migrating tides are omitted from this figure in order to highlight the generally smaller-amplitude nonmigrating components. Also shown are similar results from the Global Scale Wave Model (GSWM, Hagan and Forbes, 2002, 2003). The GSWM only includes nonmigrating tidal perturbations due to latent heat release by tropical convection, and thus may be used to assess plausibility of this source of excitation to explain the SABER results. To understand the specific zonal wavenumber content of the spectra, refer to previous works (i.e., Conrath, 1976; Zurek, 1976; Tokioka and Yagai, 1987; Yagai, 1989; Hendon and Woodberry, 1993; Williams and Avery, 1996; Forbes et al., 2001, Teitelbaum and Vial, 1991) that demonstrate the following principle: Zonal asymmetries in surface or atmospheric properties characterized by zonal wavenumber m modulate absorption of the nth harmonic of diurnally-varying solar radiation to excite the "sum and difference" thermal tides with frequency $n\Omega$ and zonal wavenumbers $n \pm m$. For instance, existence of SW1 and SW3 in Figure 2 is consistent with nonlinear interaction between SW2 and SPW1 (Forbes et al., 1995; Angelats i Coll and Forbes, 2002). These components can in principle also be excited by latent heating in the troposphere, wherein a similar interaction between the SW2 component of solar radiation and the s = 1 component of topography/land-sea contrast exists (Hagan and Forbes, 2003). However, this does not appear to be the case, based on the small GSWM amplitudes for these waves in Figure 2. A similar interaction between TW3 and SPW1 likely produces the TW2 signal in Figure 2, although the TW4 component of this wave pair is missing. No GSWM latent heating results are available for the terdiurnal tide.

A comparison between GSWM results for SW2 and SW3 and those derived from the SABER temperature measurements is provided in Figure 3. The solid lines represent fits to the SABER temperature amplitudes using the first two Hough modes for these wave components, which capture most of the latitudinal variability quite well; deviations between the fit and the data indicate the presence (in the measurements) of higher-order Hough modes. For SW2, the first two Hough modes have vertical wavelengths of > 200 km (symmetric) and ≈ 82 km (first antisymmetric). Some difference between the fit and data between 20-40° latitude is indicated, suggesting presence of higher-order modes. For SW3, superposition of the first two modes reproduces the latitude structure, indicating dominance of the first symmetric and antisymmetric modes, with vertical wavelengths of ≈ 105 km and ≈ 62 km, respectively. (N.B. restriction of the Hough mode fits to ±40° latitude precludes scrutinizing the above results too much.) The dotted lines in Figure 3 correspond to the GSWM results (Hagan and Forbes, 2003). Reasonable data-model agreement is obtained for the SW2 amplitude distribution and the phase shift near 10-20° latitude, but the model indicates much stronger phase gradients with latitude than the observations. Concerning SW3, it is clear that the model significantly underestimates the observed amplitudes, especially at low latitudes, indicating that latent heat release is insufficient to serve as the main excitation source for this wave. The modeled phase distribution is also unlike the observed one. As noted in the previous paragraph, it is more likely that SW3 is generated by nonlinear interaction between SW2 and SPW1. During this period of time, a large SPW1 existed in the Southern Hemisphere, as part of the wave field preceding the first recorded midwinter austral stratospheric warming (i.e. Kruger et al., 2005).

Returning to Figure 2, an obvious point revealed therein is that DE3 is the largest nonmigrating oscillation observed by SABER during this time period. Although the only known source of significance for DE3 is latent heating (Forbes et al., 2001), the GSWM underestimates the observed maximum of DE3 (≈ 16 K) by a factor of two. Comparison with other model results for DE3 are provided below. GSWM similarly underestimates DE2 by about a factor of 2. In addition to DE3, DE2 and DE1 also appear to be predominantly generated by latent heating in the tropical troposphere (Miyahara and Miyoshi, 1997; Miyahara et al., 1999; Ekanayake et al., 1997; Forbes et al., 2003). DE3 and DW5 comprise the wave pair due to interaction between the DW1 component of solar radiation interaction with the m = 4 component of topography/land-sea contrast (see Section 4), which is dominant at low latitudes (Yagai, 1989). Both of these waves are clearly evident in spectra of tropospheric condensation (latent) heating (Forbes et al., 2001), but the amplitude of DE3 is much stronger than that of DW5 in Figure 2. This is because DE3 possesses a much larger vertical wavelength (≤ 60 km) than DW5 (≤ 25 km). Since the time constant for eddy dissipation in proportional to the square of the vertical wavelength, DE3 penetrates much more effectively into the MLT than DW5. The degree to which the above differences occur also depends on how the vertical and latitudinal structures of heating project onto the different Hough modes comprising DE3 and DW5.

Similar arguments for the existence of DE2 and DE1 can be made with respect to the DW1 component of solar radiation interacting with the m = 1 and m = 0 components of topography, respectively. These tidal components have significantly longer vertical wavelengths than their westward-propagating counterparts, are thus less susceptible to dissipation, and hence more likely to penetrate to the upper mesosphere/lower thermosphere (Ekanayake, et al., 1997). Similarly, since the GSWM reveals that latent heating is only able to account for a ~2 K contribution to DW2 at the equator, it is likely that DW2 and D0 in Figure 2 arise from nonlinear interaction between DW1 and SPW1, as studies by Hagan and Roble (2001) and Lieberman et al. (2004) indicate that such amplitudes are easily achievable through this mechanism. As noted previously, the Southern Hemisphere experienced significant planetary wave activity at high latitudes during this period. Thus, it is possible that DW2 and D0 achieved much higher peak values during the 20 July – 20 September 2002, analysis period than the averages depicted in Figure 2.

A few wave components in Figure 2 remain that have not been discussed. SW6 and SE2 exist in the GSWM due to interaction between the SW2 component of radiation and the m = 4 component of topography. SABER reveals similar power at SE2, but not at SW6. This reason for this is not understood, since SW6 has a fairly long vertical wavelength (≤ 46 km). It is also possible that SE2 can be generated via nonlinear interaction between DW1 and DE2, but its wave counterpart, SPW4, was not observed. Of course, there are numerous tide-tide primary and secondary interactions that could be followed to explain the existence of energy at one frequency-zonal wavenumber pair or another (cf. Angelats i Coll and Forbes, 2002). Some of these might occur at lower altitudes, where the tidal spectra are different than those in Figure 2. However, given the small amplitudes involved, and potential uncertainties in the measurements, these possibilities are not pursued here. SE3, though, might be an exception given its comparatively 4 K amplitude and symmetric structure about the equator. Mathematically, interaction between the SW2 component of solar radiation and the m = 5 component of topography is a possibility, but it is unlikely that this combination would yield a tidal perturbation larger than the more likely SW6-SE2 pair noted previously. Nonlinear interaction between DE3 and D0 is another mathematically consistent option, but D0 amplitudes do not exceed 4 K during this time interval. The question regarding SE3 remains open.

Finally, height versus latitude structures for the migrating tides DW1, SW2, TW3, and the three nonmigrating tidal components DE3, SW3 and TW2, are illustrated Figure 4. DW1 reveals distinctive signatures of (a) trapped components between 40-60 km and above 100 km, due to in-situ excitation by O_3 absorption of UV solar radiation, and O_2 and N_2 absorption of EUV solar radiation, respectively; and (b) the main propagating tide between 60 and 100 km, with maxima at the equator and between ±20-30° latitude. The latter wave is mainly excited by H_2O solar radiation absorption in the troposphere, but tropospheric latent heating (Forbes et al., 1997a) and ozone absorption (Hagan, 1996) make non-negligible contributions. Note that DE3 is as large as DW1 below about 110 km. This tidal component is discussed in detail in the following section. SW2 and TW3 are also comparable to DW1 throughout most of the height regime accessible by SABER. Above 100 km, SW2 probably consists in part of an in-situ component due to EUV solar radiation absorption. TW3 is surprisingly large ($\approx$ 32 K) at tropical latitudes in the Southern Hemisphere. This tidal component is thought to originate both directly by solar radiation absorption, and indirectly by nonlinear interaction between DW1 and SW2 (Teitelbaum and Vial, 1991; Smith and Ortland, 2001). Vertical propagation of TW3 into the upper thermosphere may be relevant to explaining existence of the midnight temperature anomaly. As noted previously, SW3 and TW2 are probably excited by nonlinear interaction between their migrating counterparts, and SPW1 known to exist at high latitudes in the Southern Hemisphere during this period (i.e. Kruger et al., 2005). In this connection, it is not understood why the amplitudes of SW3 are larger in the Northern than Southern Hemisphere, but on the other hand, it must be remembered that we are only obtaining a glimpse of this wave structure between ±40° latitude.

5. The eastward-propagating diurnal tide with zonal wavenumber s = 3 (DE3)

DE3 is a prominent oscillation in the spectra of Figure 2. Modeling studies (Forbes et al., 2001; Hagan and Forbes, 2002) show that this oscillation is forced primarily by latent heat release due to deep tropical convection. DE3 was found to be the largest of all the non-migrating diurnal tidal components in the tidal analysis of UARS winds at 95 km by Talaat et al. (1999), Forbes et al. (2003), Huang and Reber (2004) and Manson et al. (2004). In this section we evaluate the capabilities of several models to reproduce the SABER DE3 amplitudes in Figure 3, and present alternative depictions of the SABER temperature measurements that focus on the role of topography/land-sea differences in influencing lower thermosphere structure. In addition, an analogy is provided with respect to similar troposphere-thermosphere coupling effects occurring in Mars' atmosphere.

We begin by comparing in Figure 5 the height versus latitude amplitude distribution of DE3 derived from TIMED/SABER, with three model results. The model denoted 'GSWM' corresponds to Global-Scale Wave Model (GSWM) results from Hagan and Forbes (2003), and includes forcing exclusively due to latent heating due to deep tropical convection. The GSWM predicts amplitudes with very similar latitude-height distribution as SABER, but approximately a factor of 2 too low in amplitude. The model result labeled 'GSWM/NCEP' utilizes heating rates from the NCAR/NCEP Reanalysis Project (Forbes et al., 2001), consisting of a combination of condensation heating, deep and shallow convective heating, vertical diffusion heating and short and longwave radiative heating. Of these, the combination of condensation and convective heating is by far dominant for DE3, and is roughly comparable in definition to the latent heating derived in Hagan and Forbes (2003). These results again yield global structures similar in shape to those of SABER, but are a factor of 2 *too large in amplitude*. The model labeled 'Kyushu GCM' is described in Miyahara and Miyoshi (1997) and Miyahara et al. (1999), and contains full tropospheric physics with heating rates of the type in the NCEP/NCAR Reanalysis. This model yields similar structures and amplitudes to those of "GSWM'. Note that the SABER temperatures peak at about 110 km, whereas GSWM peaks closer to 115 km, and Kyushu GCM at a higher altitude. These differences are attributable to variations between the DE3 vertical wavelengths and molecular viscosity profiles in the models and the atmosphere.

Figure 6 presents an alternative depiction of lower thermosphere temperature structure that is strongly influenced by the presence of DE3. Here we utilize 5 days of data at 110 km centered on day 238 of 2002, and calculate residuals from the mean values over this 5-day period. Figure 6 illustrates the mean residuals over this period for the ascending (LST ≈ 18.1 h) and descending (LST ≈ 3.08 h) portions of the orbit. Note that the extrema in Figure 6 are of order ±30 K, i.e. greater than the 10-20 K amplitudes for the DE3 averaged over the observation interval (cf. Figure 5). This means that wave components other than DE3 are contributing to the structures in Figure 6, and/or DE3 is changing with time during the interval. Although the local times along the orbit change slightly with latitude and time, for purposes of this discussion the local times of ascending and descending portions of the orbit can be assumed constant over days 236-240. We note that the predominant feature in this depiction is a wave-4 structure that tends to be opposite in phase for the ascending and descending portions of the orbit. The origin of this structure is now discussed.

Starting with Equation (1), and converting from universal time to local solar time using $t = t_{LT} + \lambda/\Omega$ where $\Omega = 2\pi/24\ \mathrm{h}^{-1}$, we obtain:

$$A_{n,s} \cos\left(n\Omega t_{LT} + (s-n)\lambda - \phi_{n,s}\right) \tag{2}$$

For days 236-240, local time is constant in the satellite frame for either the ascending or descending branch of the orbit. For t_{LT} = constant in (2), we see that the wave-4 structure is consistent with any values of s and n for which $|s-n| = 4$; in other words, a stationary planetary wave with s = 4; a diurnal tide (n = 1) with s = -3 or s = +5; a semidiurnal tide (n = 2) with s = +6 or s = -2; and so on. The fact that SABER observes two local times provides additional information that helps to resolve the ambiguity. If the ascending and descending orbits were 180° apart and if the structures in Figure 6 were exactly in antiphase, then it would be reasonable to assume that they corresponded to a diurnal tide since $n\Omega t_{LT}(\text{ascending}) - n\Omega t_{LT}(\text{descending}) = \pi$. However, mathematically a terdiurnal tide (n = 3) would also be an admissible solution for s = -1 or s = +7. Under these ideal conditions other mathematical possibilities would of course exist. As we will see below, evolution of these structures with respect to local time will provide the additional information necessary to make an unambiguous determination of DE3.

As alluded to previously, the DE3 and DW5 tidal components are connected with the predominance of wave-4 topography and land-sea difference in the tropics. The basic idea is that as the migrating diurnal harmonic of solar radiation (proportional to cos(Ωt+sλ)) passes over the surface of the Earth, characteristics of the surface (or overlying atmosphere) proportional to cos4λ *modulate* the surface heating so as to generate the "sum and difference" waves, DW5 and DE3:

$$\cos 4\lambda \cos(\Omega t + \lambda) \rightarrow \cos(\Omega t + 5\lambda) + \cos(\Omega t - 3\lambda) \qquad (3)$$

Similarly, wave-1 modulation of the diurnal component of heating gives rise to DW2 and D0:

$$\cos \lambda \cos(\Omega t + \lambda) \rightarrow \cos(\Omega t + 2\lambda) + \cos(\Omega t) \qquad (4)$$

As illustrated by Forbes et al. (2001), all four of the diurnal waves in (3) and (4) are prominently evident in the space-time decomposition of NCEP/NCAR Reanalysis heating rates, consistent with similar features seen in previous works (Tokioka and Yagai, 1987; Yagai, 1989; Hendon and Woodberry, 1993; Williams and Avery, 1996) and similarly interpreted.

Note also that wave-4 modulation of the *semidiurnal* component of solar heating yields

$$\cos 4\lambda \cos(2\Omega t + 2\lambda) \rightarrow \cos(\Omega t + 6\lambda) + \cos(\Omega t - 2\lambda) \qquad (5)$$

Again, and referring back to the discussion in connection with Equation (2), the wave-4 topography yields tides with |s-n| = 4 structures from sun-synchronous orbit, in this case with semidiurnal period. This result was generalized by Forbes and Hagan (2000) in connection with interpretation of lower thermosphere densities measured from Mars Global Surveyor in a quasi-sun-synchronous orbit. They showed that "*for any tidal frequency, the wavenumber m component of topography yields nonmigrating tidal structures which appear as wavenumber m stationary features from sun-synchronous orbit.*" In this connection, it is interesting to compare the result in Figure 6 with an analogous result for Mars, whose dominant topographic wavenumber at low latitudes is s = 2, as opposed to s = 4 for Earth. The Mars result is illustrated in Figure 7, and is based on identical data displayed in Forbes et al. (2004); namely, thermosphere density residuals (from the zonal mean) normalized to 125 km during Phase I aerobraking of the Mars Global Surveyor satellite from September, 1997, to March, 1998. It is obvious that Figure 7 is dominated by a wave-2 structure with respect to longitude, as opposed to the wave-4 structure indicated by SABER. However, there are some differences to note concerning the manner in which Figures 6 and 7 are constructed. First, Figure 6 depicts a latitude versus longitude structure averaged over only 5 days, and thus represents a quasi-instantaneous view. In contrast, the structure in Figure 7 was built up over nearly seven months, as the periapsis of MGS precessed in latitude. As such, it likely contains temporal variations that are mixed with latitude-longitude variations. Also, the data in Figure 6 were collected at two distinct local times, whereas the average local times for the Mars data evolved slowly from about 1530 LST at 30°N to about 1130 LST at 60°N.

Despite the above differences, the wave-2 structure in Figure 7 is quite evident, and as demonstrated by Forbes and Hagan (2000), is probably associated with the DE1 oscillation in Mars atmosphere, which is known to be near resonance. This wave originates from topographic wave-2 modulation of solar heating near Mars' surface, along with DW3:

$$\cos 2\lambda \cos(\Omega t + \lambda) \rightarrow \cos(\Omega t + 3\lambda) + \cos(\Omega t - \lambda) \tag{6}$$

In contrast to DW3, DE1 has a long vertical wavelength and is not very susceptible to eddy or molecular dissipation as it propagates from the troposphere to the thermosphere. The situation is thus similar to that of DW5 and DE3 in connection with wave-4 modulation of near-surface heating in Earth's thermosphere.

An alternative depiction of SABER temperatures somewhat more allied with that of Figure 7 is provided in Figure 8. This figure illustrates temporal evolution of the *equatorial* wave-4 structures illustrated in Figure 6 during the complete yaw cycle. In the way that this depiction is constructed, it excludes the zonal mean and migrating tides, The scale on the right-hand side indicates the local times sampled by the ascending and descending segments of the orbit for any given day. The tilt in the displayed structures can be used to identify the dominant underlying oscillation as follows. From (2), the longitude-local time dependence of the wave maxima is given by:

$$n\Omega t_{LT} + (s-n)\lambda - \phi_{n,s} = \text{constant} \tag{7}$$

Taking the derivative, we have

$$\frac{dt_{LT}}{d\lambda} = \frac{n-s}{n\Omega} = \gamma \tag{8}$$

Recall the previous ambiguities that existed in determining which values of s and n satisfied |s-n| = 4. Now consider some of these in connection with (8) and Figure 8: For DW5 (n = 1, s = 5), γ =-24h/90°; for DE3 (n = 1, s = -3), γ =+24h/90°; for SW6 (n = 2, s = 6), γ =-12h/90°; and for SE2 (n = 2, s = -2), γ =+12h/90°. Of these, only the slope for DE3 matches that of the structures in Figure 8, and therefore we conclude that DE3 is the predominant oscillation at the equator. Note also that Figure 8 provides information on the temporal evolution of DE3, which is substantial and likely connected with similar variability in the latent heating responsible for excitation of this wave. In addition, referring back to Figure 6, latitudinal structures associated with the equatorial amplitudes in Figure 8 are not symmetric about the equator. Assuming DE3 to be the dominant oscillation, this implies that DE3 consists of other components other the symmetric Kelvin mode, i.e., inertia gravity waves. This is also true with respect to the 2-month average structure for DE3 depicted in Figure 3, although less pronounced.

6. Impacts of tidal dissipation on MLT zonal mean zonal winds

In this section, we seek to understand the impact of dissipation of DE3 on the mean temperature and wind structure of the MLT region. As shown by Miyahara and Wu (1989), DW1 is capable of inducing a zonal mean westward jet in the equatorial MLT of order 20 ms^{-1} vis-à-vis molecular dissipation and deposition of momentum into the mean flow. Low-latitude mean meridional winds are also generated that are of potential significance to minor constitutent transport. Angelats i Coll and Forbes (2002) similarly demonstrate the importance of dissipation of SW1, SW2 and SW3 on the zonal mean circulation of the 100-170 km region at middle latitudes. In this section we will employ a numerical model to obtain similar estimates for DE3, and compare them to those of DW1 during late summer of 2002.

The numerical model employed here is a quasi-non-linear time-dependent global numerical model that simulates the propagation of one or more linearly independent waves (forced within the model) interactively with the zonal mean flow (Miyahara and Wu, 1989). All of the equations and boundary conditions for this model are fully detailed in Miyahara and Wu (1989), and thus are not repeated here. Briefly, the model consists of a zonal mean equation system and a perturbation equation system, obtained from a second-order perturbation analysis of the primitive equation system in log-pressure coordinates. The nonlinear zonal mean equations are coupled to the perturbation equations through zonally-averaged eddy flux terms in the zonal and meridional momentum equations, and in the thermodynamic equation. For instance, the eddy flux divergence term in the zonal mean zonal momentum equation appears as follows:

$$\bar{F}_u = -\frac{1}{a}\frac{\partial \overline{u'v'}}{\partial \theta} - \frac{2\cot\theta}{a}\overline{u'v'} - \frac{1}{p}\frac{\partial p\overline{w'u'}}{\partial x} \tag{9}$$

where a = planetary radius, θ = colatitude, u', v', w' are zonal, meridional and vertical velocities obtained by solving the tidal perturbation equation system, p is pressure, and $x = -\ln(p/p_o)$. Coefficients in the perturbation equation system are, in turn, functions of the zonal mean winds and temperatures. The two equation systems are integrated interactively until a steady state is achieved. The wave solution is affected not only by the zonal mean temperatures and winds induced by the solar heating, but also by the zonal mean field induced by momentum deposition due to the waves themselves. It is also possible to impose a zonal mean wind system and calculate the wave propagation through it, with or without feedback from the wave to the mean flow. The zonal-mean quantities solved for in this system are actually departures from the global mean. For present purposes, the global mean atmosphere (i.e., temperature, density, pressure) is approximated using MSISE90 (Hedin, 1991) for average solar conditions during August. The numerical model employed here has recently been exercised to simulate the interaction between the solar semidiurnal tide and the zonal mean circulation in the atmosphere of Mars (Forbes and Miyahara, 2005).

The model-data comparisons in Figure 5 suggest that our knowledge of forcing of DE3 may be deficient. Therefore, for the current numerical simulations, we *calibrate* a heat source so that the amplitudes of DW1 and DE3 approximate that of the SABER observations. In this way, the zonal mean zonal winds to be calculated may be viewed as credible. Vertical structure of the heat source is Gaussian-like, mainly confined to 0-13 km with a peak near 6.5 km. Further details are, for all practical purposes, irrelevant. Latitude structures for the heat sources are assumed to conform to the first symmetric diurnal Hough functions for DW1 and DE3. These are commonly known as the first symmetric propagating diurnal tide, and the diurnal Kelvin wave with zonal wavenumber equal to 3. Figure 9 demonstrates that the computed latitude structures of DW1 and DE3 represent a good approximation to the SABER determinations. The slight asymmetries in the computed structures about the equator are due to mean wind interactions at lower altitudes.

The model was run with latitude and vertical resolutions of 5° and 0.1 scale heights, with lower and upper boundaries at the surface and approximately 250 km. The tidal forcing was ramped up to its steady-state value by day 15 of the integration. The model was integrated with a time step of 300 s, and converged within 30 days. For the present computations, we have imposed a fixed climatological zonal mean wind model based on Hedin et al. (1993). The model was run with and without the addition of zonal mean winds produced by dissipation of the tide, and the two results were found to differ negligibly for present purposes. This is due to the fact that the maximum zonal mean winds induced by the tide exist, by definition, in a region of high dissipation, and it is dissipation that exerts the dominant influence on the tidal behavior at these altitudes.

Figure 10 illustrates the height versus latitude distributions of DW1 and DE3 temperature amplitudes, and the zonal mean winds produced by dissipation of these waves. For these results, the waves were computed in separate model simulations, independent of each other. Note that dissipation of DW1 gives rise to a westward jet over the equator, with maximum of order 15 ms^{-1} at 105 km. This result is similar to that published by Miyahara and Wu (1989) using an earlier version of this same model. Wave-generated mean meridional winds and temperatures due to DW1 (not shown) are of order ±2 ms^{-1} and -1 to -2 K, respectively. Dissipation of DE3 produces an eastward jet with maximum of about 25 ms^{-1} at 120 km over the equator. The higher altitude of the DE3 jet reflects the longer vertical wavelength of DE3 (≈ 60 km) as compared with DW1

(≈30 km), which causes it to dissipate at higher altitudes. DE3-generated mean meridional winds and temperatures (not shown) are of order -.5 to +1.5 ms^{-1} and -2 to -4 K, respectively

When both DW1 and DE3 are present, the zonal mean winds produced by both waves are not simply a superposition of the two zonal mean wind distributions in Figure 10. Therefore, a simulation was performed with both linearly independent waves simultaneously interacting with the zonal mean flow. These results are illustrated in Figure 11. The left panel shows zonal acceleration of the mean flow (i.e., $\overline{F_u}$ in (3)), which attains values of 10-15 ms^{-1}day^{-1} in the MLT at low latitudes. The right panel illustrates the zonal mean wind, which is characterized by a net *eastward* maximum of about 15 ms^{-1} near 110 km over the equator. Until now, based mainly on Miyahara's work (Miyahara and Wu, 1989; see references therein; see also Forbes et al., 1993) it has generally been accepted that a zonal mean westward jet ought to exist over the equator due to dissipation of the migrating diurnal tide. By extension, given the well-known semiannual variation of the diurnal tide, one might expect a semiannual variation in the westward zonal jet to occur as well. The present results show that at least during July-August, this jet is more likely eastward in direction. Moreover, throughout the year the relative importance of zonal mean winds generated by DW1 and DE3 is likely to change. Of course, there are other tidal components (i.e., DE2, DW2, etc.) that may also contribute to the zonal mean wind distribution in the equatorial lower thermosphere. The main point is, that tidal components other than the migrating diurnal tide are likely to have a significant impact on the zonal mean wind distribution, and that the character of this impact is likely to change over various time scales (intra-seasonal, inter-seasonal, inter-annual) in concert with the changing mixture of tides propagating into the MLT.

7. Summary and Conclusions

Temperatures measured from the SABER instrument on the TIMED spacecraft are analyzed to reveal migrating (sun-synchronous) and nonmigrating diurnal, semidiurnal and terdiurnal solar tides between 20-120 km and ± 40° latitude during 20 July – 20 September, 2002. The following results and conclusions emerge from this study:

- Nonmigrating tides induce significant longitudinal variations in the local time variation of temperature between about 80 and 120 km. At lower altitudes the temperature structure is dominated by the sun-synchronous (migrating) tidal components, and hence is nearly independent of longitude.

- Diurnal (D0, DW2), semidiurnal (SW1, SW3) and terdiurnal (TW2) nonmigrating tidal components exist that probably have their origin in nonlinear interactions between the respective migrating components (DW1, SW2, TW3) and the stationary planetary wave with s = 1 (SPW1). A significant SPW1 is known to exist in the Southern Hemisphere stratosphere during this period that is intimately connected with the austral midwinter stratospheric warming of 2002 (i.e. Kruger et al., 2005).

- The eastward-propagating diurnal tide with zonal wavenumber s = 3 (DE3) exists during this period with maximum amplitudes of similar order (8-20 K) as the migrating diurnal tide (DW1) propagating upwards from the lower thermosphere.

- DE3 is primarily excited by latent heating due to deep tropical convection in the troposphere. Independent model simulations reproduce the height versus latitude structure of this wave, with maximum amplitudes within a factor of two.

- Existence of DE3 is intimately connected with the predominant wave-4 longitude distribution of topography and land-sea difference at low latitudes. An analogy is drawn with the strong presence of DE1 in Mars atmosphere, and the wave-2 low-latitude topographic distribution on Mars.

- Model simulations are conducted that investigate impact of DW1 and DE3 on zonal mean winds in the lower thermosphere due to molecular dissipation of these waves. Independently, DW1 and DE3 produce zonal mean westward and eastward jets between 100-120 km over the equator of about –20 ms^{-1} and +30 ms^{-1}, respectively. Acting together, an eastward jet of about +20 ms^{-1} is produced. This result is expected to vary significantly in time, as the relative contributions of DW1 and DE3 vary. In addition, other waves (i.e., DW2, DE2, DE1) may make non-negligible contributions during some months of the year.

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Figure Captions

Figure 1. Latitude versus local time temperature structures at 108° longitude (top) and 276° longitude (bottom) at altitudes of 70 km (left), 86 km (center) and 110 km (right).

Figure 2. Latitude versus zonal wavenumber (positive for westward-propagating) amplitude spectra (K) for diurnal (left), semidiurnal (center), and terdiurnal (right) tidal temperature components from SABER measurements (top) and Global-Scale Wave Model (GSWM, Hagan and Forbes, 2002, 2003) results (bottom) at 110 km. The only non-migrating tidal source in the GSWM is latent heating due to deep tropical convection. No terdiurnal results are available for the GSWM.

Figure 3. Height versus latitude temperature amplitudes for the migrating diurnal, semidiurnal and terdiurnal tides (DW1, SW2, TW3) (top), and the non-migrating tides DE3, SW3 and TW2 (bottom). Contour intervals are 0.5, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0 K.

Figure 4. Horizontal amplitude (left) and phase (right) structures of SW2 (top) and SW3 (bottom) tidal temperatures at 116 km. Dashed lines correspond to GSWM results from Hagan and Forbes (2003), wherein latent heating due to deep tropical convection is the only source for non-migrating tides (i.e., SW3). Vertical bars represent 1-σ uncertainty estimates.

Figure 5. Comparison of height versus latitude amplitude structures of DE3 tidal temperature from various sources. Upper left: TIMED/SABER (this analysis). Upper right: GSWM results using NCEP/NCAR Reanalysis heating rates (Forbes et al., 2001). Lower left: GSWM results from Hagan and Forbes (2003). Lower right: Results from the Kyushu University Middle Atmosphere General Circulation Model (Miyahara and Miyoshi, 1997; Miyahara et al., 1999).

Figure 6. Mean residuals from the five-day mean of temperatures at 110 km centered on day 238 of 2002. Top: ascending portion of the orbit (mean local solar time = 18.1 h). Bottom: descending portion of the orbit (mean local solar time = 3.08 h).

Figure 7. Density residuals about the zonal mean at 130 km versus latitude and longitude, derived from accelerometer measurements on the Mars Global Surveyor spacecraft during Phase I of aerobraking (Forbes et al., 2004). Local times are provided on scale to the right. The figure is based on re-analysis of the same data discussed and displayed in Forbes et al. (2004).

Figure 8. Temperature residuals from 5-days means as in Figure 6, slipped once per day, plotted versus time and longitude over the equator for the ascending (top) and descending (bottom) portions of the orbit. This method of analysis removes the zonal mean and migrating tides from the data, leaving only the longitude-dependent structures. Local times are provided on scale to the right.

Figure 9. Comparison between model values (solid lines) for DW1 (top) and DE3 (bottom) and SABER temperature amplitudes (solid circles) as a function of latitude at 96 km. Vertical bars represent 1-σ uncertainty estimates for the SABER amplitudes.

Figure 10. Height versus latitude distributions of model temperature amplitudes (right) and wave-driven zonal mean winds (left) for DW1 (top) and DE3 (bottom).

Figure 11. Zonal mean eastward acceleration (left) and wave-driven zonal mean winds (right) from a model simulation that included both DW1 and DE3.