Large-Scale Waves in the Mesosphere and Lower Thermosphere Observed by SABER

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ABSTRACT

Observations made by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on board NASA’s Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics (TIMED) satellite have been processed using Salby’s fast Fourier synoptic mapping (FFSM) algorithm. The mapped data provide a first synoptic look at the mean structure and traveling waves of the mesosphere and lower thermosphere (MLT) since the launch of the TIMED satellite in December 2001. The results show the presence of various wave modes in the MLT, which reach largest amplitude above the mesopause and include Kelvin and Rossby–gravity waves, eastward-propagating diurnal oscillations (“non-sunsynchronous tides”), and a set of quasi-normal modes associated with the so-called 2-day wave. The latter exhibits marked seasonal variability, attaining large amplitudes during the solstices and all but disappearing at the equinoxes. SABER data also show a strong quasi-stationary Rossby wave signal throughout the middle atmosphere of the winter hemisphere; the signal extends into the Tropics and even into the summer hemisphere in the MLT, suggesting ducting by westerly background zonal winds. At certain times of the year, the 5-day Rossby normal mode and the 4-day wave associated with instability of the polar night jet are also prominent in SABER data.

1. Introduction

A number of studies over the last couple of decades have documented the presence of fast (period ≤5 days) traveling planetary-scale waves in the mesosphere and lower thermosphere (MLT) (e.g., Hirota, 1978, 1980; Salby et al. 1984; Canziani et al. 1994; Lawrence and Randel 1996; Limpasuvan and Wu 2003; Pancheva et al. 2004) in addition to the quasi-stationary waves common at lower altitudes. The increasing prominence of fast waves at high altitudes is expected because, as a spectrum of waves propagates from the lower atmosphere, damping and absorption at critical levels will remove lower frequency components most effectively (see, e.g., Garcia and Salby 1987). Although high-frequency, planetary-scale waves have been detected in the MLT by both ground-based instrumentation and polar-orbiting satellites, the latter have the advantage that they can provide a global view of the phenomena.

We report here on preliminary studies of large-scale waves observed by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on board the National Aeronautics and Space Administration (NASA) Thermosphere–Iono-
sphere–Mesosphere Energetics and Dynamics (TIMED) spacecraft, which was launched on 7 December 2001. We use SABER observations from several continuous data segments currently available (typically about 30 days long), which are particularly well suited for processing using Salby’s (1982a,b) fast Fourier synoptic mapping (FFSM) technique (see section 3).

The SABER data reveal the presence of a rich spectrum of large-scale motions in the MLT. In addition to stationary Rossby waves, several planetary-scale waves with period \( \leq 5 \) days are identified. These include Kelvin and Rossby–gravity waves, eastward-propagating diurnal oscillations, the 4- and 5-day waves, and several spectral components associated with the “2-day wave,” all of which are discussed in detail in section 4. Westward-propagating diurnal oscillations, including the sun-synchronous tides, are not resolved synoptically by the SABER sampling pattern and are not discussed here.\(^1\)

2. SABER data

SABER uses limb-scanning, broadband infrared radiometry to measure temperature, ozone, water vapor, carbon dioxide, nitric oxide, and airglow emissions over a broad range of altitude from near-tropopause levels to the lower thermosphere (Mlynczak 1997; Russell et al. 1999). The method used for retrieving SABER temperatures is described by Mertens et al. (2001). Observations are made during both ascending and descending portions of the orbit. In this study we use “level 2A” retrievals of temperature, which are publicly available as version 1.04 (v1.04) from late January 2002 through August 2004 (more information available online at http://saber.larc.nasa.gov/).

The v1.04 data consist of vertical profiles registered in pressure as functions of longitude, latitude, and universal time. Aside from yaw maneuvers and instrument downtime, SABER has made almost continuous observations since launch. However, processed v1.04 data are available as continuous sequences only for certain periods of varying length, ranging from a few days to over one month. From January 2002 to February 2004 there are several data sequences of between 25 and 40 days suitable for synoptic mapping via Salby’s FFSM method. Observations taken during the following periods are used in the analyses presented here:

- 25 January–24 February 2002,
- 31 March–10 May 2002,
- 15 June–14 July 2002,
- 14 June–14 July 2003, and

Each of these periods comprises approximately one month, so their synoptic spectra have approximately the same bandwidth and thus are directly comparable. Furthermore, they cover four solstice seasons (two boreal and two austral summers) plus one equinox, which helps illustrate the interhemispheric and interannual variability of the 2-day wave. For each period we use SABER observations spanning the altitude range \( 15–120 \) km.

3. Fast Fourier synoptic mapping

As with any polar-orbiting satellite, observations made by TIMED are asynoptic; that is, global coverage is not instantaneous because measurements at different locations are made at different universal times. However, Salby (1982a,b) has proven an “asynoptic sampling theorem” that guarantees that the information content of combined-node asynoptic observations is equivalent to that of twice-daily synoptic sampling within the Nyquist limits common to both. In particular, the theorem implies that, if an observed field contains negligible variability beyond the Nyquist limits of asynoptic sampling, it is possible to reconstruct from the latter the full, instantaneous synoptic evolution of the field. This property of asynoptic sampling is desirable because it allows a straightforward but rigorous assessment of the information content of observations made from polar orbit, and their limitations due to aliasing.

Salby (1982a,b) has used these results to develop a mapping algorithm that can be used to obtain synoptic spectra from asynoptic observations. The utility of FFSM has been demonstrated by a number of recent applications (e.g., Lieberman 1991; Lait and Stanford 1988; Canziani et al. 1994; Manney et al. 1998; Sassi and Salby 1999). In spite of its power, FFSM has not been used very widely because it requires sampling at regular intervals in space and time for extended periods, something that is not often available from satellite observations. During the design of SABER, emphasis was placed from the outset on regularity and continuity of the sampling pattern; as a result, archived SABER products provide observations that are particularly well suited for analysis via FFSM.

Most of the planetary-scale waves documented in this study have wavenumbers and frequencies that fall well within the Nyquist limits of asynoptic sampling. In zonal wavenumber, these limits range from 0 (the zonal mean) to 7. In frequency, they range from slightly less
Eastward-propagating diurnal oscillations do, in fact, migrate

than 1 cycle per day (cpd) to slightly more (i.e., more negative) than −1 cpd, where positive (negative) frequencies denote westward (eastward) propagating oscillations. SABER sampling is unable to resolve westward-propagating diurnal oscillations (including the diurnal sun-synchronous tide and its harmonics). On the other hand, it is possible to resolve eastward-propagating diurnal oscillations (non-sun-synchronous, or “nonmigrating” tides) because −1 cpd falls just within the Nyquist limit for frequency. Nevertheless, reconstruction of oscillations near −1 cpd must be interpreted with caution because they may be contaminated (aliased) by unresolved oscillations at +1 cpd and beyond. In general, an unresolved wave at the zonal wavenumber/frequency pair \((m, +1 \text{ cpd})\) will alias onto \((m - 1, 0)\), the time mean at \(m - 1\), and \((m - 2, -1 \text{ cpd})\), the eastward-propagating diurnal component at \(m - 2\). These considerations are brought to bear below (section 4c) when attempting to characterize eastward-propagating diurnal oscillations found in the data.

4. Results

4a. Zonal-mean state and quasi-stationary wave field

Figure 1 shows the time-mean, zonal-mean temperature distribution for the data segment 15 June–14 July 2002 to illustrate the fact that SABER is able to observe accurately all the principal features of the zonal-mean temperature structure from the tropopause [2 scale heights (sh), or about 14 km assuming a uniform scale height of 7 km] to the lower thermosphere (17 sh, or about 120 km). In particular, the figure shows a cold tropical tropopause (\(-195 \text{ K near } 2.4 \text{ sh, or } -17 \text{ km}\)), a warm summer stratopause ranging between 280 K at the summer pole and 250–260 K in the Tropics, a very cold summer mesopause (<130 K poleward of 75°N), and a rapid temperature rise in the thermosphere above 15 sh. The quality of SABER temperature data has been demonstrated in detail by Remsberg et al. (2003), who compared an earlier version of SABER temperature against the Met Office analyses. More recently, Mertens et al. (2004) have carried out comparisons of SABER temperatures at polar latitudes with falling-sphere measurements. Retrieval of nonlocal thermodynamic equilibrium (NLTE) temperatures in the cold summer mesopause is perhaps the most stringent test of the SABER retrieval algorithm; the comparisons with falling-sphere data yield rather good agreement and increase our confidence in the quality of SABER v1.04 temperature retrievals.

Figure 2 shows the amplitude and phase structure of the quasi-stationary planetary wave field at zonal wavenumber \(m = 1\) for the period 25 January–24 February 2002. The amplitude/phase plot is constructed using the coherence method of Hayashi (1971)\(^3\) applied to the \(m = 1\) component of the synoptic spectrum obtained via FFSM over the frequency range ±0.03 cpd (i.e., periods of about 30 days eastward to 30 days westward, encompassing the time mean). The planetary wave amplitude is very large in the northern (winter) hemisphere, reaching 18 K in the upper stratosphere, with a second, out-of-phase maximum of ~15 K in the mesosphere. The westward phase tilt (decreasing phase) with altitude indicates vertical propagation throughout the entire middle atmosphere. There is also evidence of penetration into the Tropics and into the summer hemisphere above 10 sh, the tropical signal reaching a maximum of over 6 K near 13 sh at the equator. This suggests that the Rossby wave is being ducted from the winter into the summer hemisphere, presumably by the

\(^2\) Eastward-propagating diurnal oscillations do, in fact, migrate but they do not follow the motion of the sun. The term “nonmigrating” is misleading and, indeed, often confusing to readers not familiar with the literature. In this paper we use the term “non-sun-synchronous,” which, although awkward, accurately describes the nature of these diurnal oscillations.

\(^3\) A base point is chosen at a location where the wave amplitude is expected to be large, and the coherence is computed between this base point and all other points in the latitude–height plane. The amplitude is estimated as twice the square root of the local power, and the phase (relative to the base point) is calculated as the inverse tangent of the ratio of the quadrature spectrum to the cospectrum. The results are plotted only where the local coherence exceeds 0.6.
presence of westerly winds in the Tropics in the range of altitude 10–14 sh (cf. McLandress et al. 1996). Apparent tropical ducting of midlatitude Rossby waves is also found in other SABER data segments (not shown). It is largest in Northern Hemisphere winter (as in Fig. 2, and also in the period 27 January–22 February 2004), but it is also present in Southern Hemisphere winter (15 June–14 July 2002 and 14 June–14 July 2003), and even in the single equinox segment analyzed (31 March–10 May 2002), albeit with amplitudes about one-half of that seen in Fig. 2.

b. Tropical waves

The quasi-stationary waves documented above are among the largest amplitude wave features in the mapped SABER temperature in several of the periods analyzed in this study. This can be appreciated from Fig. 3, which shows the rms temperature spectrum as a function of scale height and frequency for $m = 1$ at the equator for 15 June–14 July 2002. Between 10 and 15 sh the quasi-stationary component dominates the spectrum. This appears to be the result of Rossby wave ducting into the Tropics, as discussed in connection with Fig. 2. Nevertheless, higher-frequency components are also in evidence. In the MLT (above 10 sh) these include concentrations of variance at frequencies between $-0.2$ and $-0.4$ cpd (eastward periods of 2.5–5 days), and between 0.5 and 0.7 cpd (westward periods of 1.5–2 days). A local variance maximum is also seen in the stratosphere (below 8 sh) in the frequency range $-0.05$ to $-0.15$ cpd ($\sim$7–20 days eastward). It is shown next that all of these signals are associated with recognizable tropical waves.

Figure 4 is an amplitude phase plot for wavenumber $m = 1$ in the MLT in the frequency range $-0.27$ to $-0.34$ cpd (eastward periods of about 3–4 days). The wave has an intrinsic phase velocity of about $132 \text{ m s}^{-1}$ eastward at the central period of 3.5 days, and a very long vertical wavelength, $\lambda_z$, of about 6 scale heights (42 km). According to equatorial Kelvin wave theory, the meridional $e$-folding scale for such a wave is $\sqrt{\left(\frac{\lambda_z N}{\beta \pi}\right)} = 3400 \text{ km} \left(\pm 30^\circ \text{ of latitude}\right)$, which is consistent with the amplitude structure shown in the figure. Similar Kelvin waves have been identified in satellite observations by Salby et al. (1984) and by Canziani et al. (1994). Salby et al. used data from the Nimbus-7 Limb Infrared Monitor of the Stratosphere (LIMS), which extended to 0.05 mb (70 km), while Canziani et al. used data from the Microwave Limb Sounder (MLS) on board the Upper Atmospheric Research Satellite (UARS), which covered a somewhat smaller range of altitude (up to 0.2 mb, or 60 km). These studies showed the presence of $m = 1$ Kelvin waves at periods of 3.5–4.5 days in the mesosphere, with typical amplitudes at 60–70 km of about 1–1.2 K, in good agreement with the SABER results of Fig. 4. The broader altitude coverage of SABER shows, furthermore, that these waves continue to grow in the lower thermosphere and attain much larger amplitudes (4–6 K) than previously observed in the mesosphere.

It is important to bear in mind that, because of the very long vertical wavelength of these Kelvin waves, an amplitude of 4–6 K, as shown in Fig. 2, implies a large horizontal velocity perturbation. For example, taking $|T'| = 4 \text{ K}$ gives a geopotential perturbation $\rho' \sim 1000 \text{ m}^2 \text{s}^{-2}$, by the hydrostatic equation; this, in turn, implies a zonal wind perturbation of $|u'| = (k/\omega)\rho'$ $\sim 10 \text{ m s}^{-1}$ for the Kelvin wave.

Table 1 summarizes the largest tropical oscillations identified in each of the five SABER data segments analyzed. In addition to the fast oscillations predominant in the MLT, like the Kelvin wave shown in Fig. 4, slower Kelvin waves of relatively small amplitude are
found in the stratosphere (below about 50 km). The transition from waves of longer period in the stratosphere to faster waves in the MLT reflects selective absorption/dissipation of the slower waves as they propagate upward (Salby and Garcia 1987), and is consistent with the findings of Salby et al. and Canziani et al. cited above. It should be noted that the summary presented in Table 1 is not meant to be exhaustive, but rather illustrative of the largest amplitude, most easily identifiable, wave modes found in the data. Identification of individual modes is often difficult because of the sporadic appearance of the waves, which may be present for only part of the period of analysis. As an example, Fig. 5 shows the evolution of the Kelvin wave in Fig. 4 as a function of altitude and time at the Greenwich meridian at the equator. Even though this wave dominates the eastward-propagating spectrum near 3.5 days in the MLT, its amplitude is by no means uniform in time but occurs in two main bursts, one at the beginning of the period and a second, stronger one about 2 weeks later.

The horizontal structures of all of the eastward-propagating waves listed in Table 1 exhibit a fair degree of equatorial symmetry and little phase change with latitude, indicating that they are mainly Kelvin waves. At westward periods, several clear cases of equatorially antisymmetric Rossby–gravity waves were also found in the data, as in the example shown in Fig. 6. With a central period of 1.55 days, this \( m = 1 \) oscillation has extremely large phase velocity, about 300 m s\(^{-1}\), a vertical wavelength of 40–45 km, and a correspondingly broad meridional structure. Note that, while the vertical wavelength and meridional scale are similar to those of the Kelvin wave discussed above, its frequency is more than twice as large, as expected from the dispersion relation for Rossby–gravity waves (Andrews et al. 1987, their chapter 4).

c. Non-sun-synchronous tides

The rms spectrum in Fig. 3 also contains significant variance near \(-1\) cpd, the eastward diurnal period, above 8 sh. Similar concentrations of variance are found at higher wavenumbers as well in this and other SABER data segments analyzed. Closer inspection reveals the presence of coherent oscillations in the MLT, some of which may be identified as eastward-propagating, non-sun-synchronous tides. Interpretation of these waves requires caution because of the possibility of aliasing by unresolved, westward-propagating diurnal signals, as previously discussed in section 3.
have tentatively interpreted these signals as properly sampled, eastward-propagating tides if they meet the following criteria:

- The signal is coherent over a broad range of latitude and altitude in the MLT.
- The coherent signal has a structure such that phase increases with altitude (eastward phase tilt), as expected for upward and eastward propagating oscillations.

On the basis of these criteria we have compiled Table 2, which summarizes the occurrence of eastward-propagating, diurnal oscillations at zonal wavenumbers 1–6 for all SABER data segments analyzed here. Signals with amplitude up to 10 K are found at \( m = 2 \)–6 during most periods. On the other hand, we could not find any \( m = 1 \) oscillation that met our phase structure criterion; there were coherent \( m = 1 \) signals in most data segments, but in all cases their phase was found to decrease with altitude over broad regions, raising the possibility of aliasing by westward propagating variability at \( m = 3 \). For those oscillations identified as eastward-propagating tides, the largest amplitudes occurred in the lower thermosphere, above 14 sh (\( \approx 100 \) km); below this altitude, amplitudes were usually one-half or less than the maxima in the lower thermosphere.

Figures 7 and 8 show the structures of four of these eastward-propagating diurnal waves, at \( m = 2, 3, 5, \) and 6. The waves reach amplitudes of as much as 10 K in the lower thermosphere and exhibit a variety of latitudinal structures. For example, the \( m = 3 \) oscillation shown is mostly equatorially symmetric, the \( m = 2 \) and \( m = 6 \) waves have predominantly antisymmetric structure, and the \( m = 5 \) wave exhibits a mixture of symmetric and antisymmetric behavior. In reality, it is unlikely that any single wave mode dominates any period of analysis, so the structures of Figs. 7 and 8 can be expected to reflect a superposition of different wave modes. This can be appreciated from Fig. 9, which shows the evolution of the \( m = 2 \) wave field at 12.4 sh over the frequency interval \((-1.04, -0.91)\) cpd during the one-week period 23–30 June 2002. For the first half of the period, the wave field is dominated by a predominantly equatorially symmetric structure that gradually gives way to a mainly antisymmetric structure toward the end of the period.

Lieberman (1991) has previously documented the presence of eastward-propagating diurnal waves in LIMS data, with amplitudes <0.5 K in the mesosphere (comparable to those shown in Fig. 7 in the same altitude range). The present results are consistent with these findings and show, furthermore, that eastward-propagating diurnal oscillations occur over the entire range of wavenumber resolved by SABER and extend into the lower thermosphere with much greater amplitudes than observed in the mesosphere.

d. The 2-day wave

In addition to the tropical oscillations discussed above, SABER data show another major source of variability in the MLT that occurs at periods near 2 days and is associated with the so-called 2-day wave, which has been the subject of numerous previous investigations (see, e.g., Limpasuvan and Wu 2003, and references therein). Because of their global, multiyear coverage of the MLT, SABER observations offer an excellent opportunity for studying the structure and variability of the 2-day wave. Figure 10 shows ampli-

† At \(-1\) cpd, zonal wavenumber 7 is not resolved by SABER sampling.
January–February 2004. The 2-day wave is evident in both periods from the concentration of variance at $m = 3$ and $-0.5$ cpd, although the rms amplitude is about three times larger in 2002 than in 2004.

There is also an indication in Fig. 10 that the variance peak at 2 days is accompanied by smaller concentrations of variance at other wavenumber–frequency pairs, especially ($m = 2$, 0.3 cpd) in 2002 and ($m = 1$, 0.15 cpd) in 2004. This variance, together with that at ($m = 3$, 0.5 cpd), tends to lie along a line of constant phase velocity ($c = 70$ m s$^{-1}$; denoted by the red line in the figure). This is even more evident in Northern Hemisphere (NH) summer, as illustrated in Fig. 11, which shows spectra at 40 N, 11 sh for 15 June–14 July 2002 and 14 June–14 July 2003. In NH summer the distribution of variance is more uniform along the line of constant phase velocity. Furthermore, the largest variance occurs at ($m = 4$, 0.56 cpd) rather than at ($m = 3$, 0.5 cpd), especially in 2002. This behavior is broadly consistent with the notion that the 2-day wave arises from

Table 1. Tropical waves in SABER temperature data: “range” denotes altitude range where waves are found (S: stratosphere, 3–8 sh; MLT: mesosphere/lower thermosphere, 8–14 sh; “type” identifies waves as Kelvin or RG: Rossby gravity).

<table>
<thead>
<tr>
<th>SABER data segment</th>
<th>$m$</th>
<th>Period (days)</th>
<th>Amplitude (K)</th>
<th>Range</th>
<th>Type</th>
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</thead>
<tbody>
<tr>
<td>25 Jan–24 Feb 2004</td>
<td>1</td>
<td>2.6–3.1 Eastward</td>
<td>4.0</td>
<td>MLT</td>
<td>Kelvin</td>
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<td>2.4</td>
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<td>RG</td>
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<tr>
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<td>2</td>
<td>1.8–2.1 Eastward</td>
<td>3.5</td>
<td>MLT</td>
<td>Kelvin</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>5.3–8.3 Eastward</td>
<td>1.2</td>
<td>S</td>
<td>Kelvin</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5.5–8.3 Eastward</td>
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<td>S</td>
<td>Kelvin</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.7–4.8 Eastward</td>
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<td>Kelvin</td>
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<tr>
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<td>Kelvin</td>
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<tr>
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<td>1.9–2.1 Eastward</td>
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<td>MLT</td>
<td>RG</td>
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<td>1.9–2.1 Westward</td>
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<td>4.5–5.9 Eastward</td>
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<td>Kelvin</td>
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<td>Kelvin</td>
</tr>
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<td></td>
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<td>4.5–7.1 Eastward</td>
<td>0.9</td>
<td>S</td>
<td>Kelvin</td>
</tr>
</tbody>
</table>

FIG. 5. Evolution of the $m = 1$ Kelvin wave temperature field in the frequency range (-0.34, -0.27) cpd (2.94–3.7 days westward) at the Greenwich meridian at the equator during the period 15 Jun–14 Jul 2002. The contour interval is 2 K.
baroclinic instability of the summertime jet, as first proposed by Plumb (1983), who calculated from a midlatitude, beta plane model that a typical summertime mesospheric wind profile is most unstable to a wave of $m=3$ with phase velocity of $-60 \text{ m s}^{-1}$. Note also that, based upon the limited sample presented here (two NH and two SH summers), there appears to be a systematic interhemispheric difference in the manifestation of the 2-day wave, such that in SH summer the wave corresponds more nearly to the conventional idea of a single, $m=3$ oscillation, whereas in NH summer the variance is more evenly distributed along the line $c=70 \text{ m s}^{-1}$ and actually tends to be largest at $m=4$ (cf. Limpasuvan et al. 2000).

The hypothesis that baroclinic instability is an important factor in the excitement of the 2-day wave is further supported by the finding that, outside the solstice seasons, SABER observes negligible variance associated with the 2-day wave. In particular, the spectrum for 31 March–10 May (not shown) exhibits negligible variance at the locations where such maxima are present in Figs. 10–11. This result is corroborated by examination of a second SABER data segment for 19–29 September 2003. Because of its short length this segment was not included in the other analyses presented here. However, it too shows no indication of enhanced variance anywhere near 2 days.

Figure 12 shows the structure of the $m=3$ and $m=4$ components of the 2-day wave during the NH summer of 2002. The waves attain large amplitude (5–6 K) in the summer mesosphere and have very long vertical wavelengths (about 10 sh, or 70 km). Limpasuvan and Wu (2003) have retrieved very similar structures (and amplitudes) from UARS/MLS data. The very long vertical wavelength supports the idea that the waves are quasi-normal modes, as does their amplitude structure, which is antisymmetric about the equator and resembles the Rossby–gravity normal modes calculated from the linearized equations with realistic background winds (e.g., Salby 1981). Taken together, the results shown in Figs. 10–12 may be interpreted as an indication that the 2-day wave arises from excitation via baroclinic instability of the set of atmospheric normal modes that lie closest to the locus of the instability in the wavenumber–frequency domain. This suggestion has been made before on the basis of observations (Randel 1994) and numerical modeling (Norton and Thuburn 1996; Salby and Callaghan 2001); it is consistent with all of the SABER data analyzed in the present study.

e. The 5- and 4-day waves

SABER data show the presence of certain wave modes at $m=1$ that are also prominent in other datasets. The most significant of these are the 5-day Rossby normal mode and the 4-day wave associated with instability of the wintertime polar vortex (see, e.g., Lawrence and Randel 1996).

The 5-day wave is the gravest symmetric Rossby normal mode and has been the subject of numerous theoretical and observational studies (e.g., Salby 1981; Garcia and Salby 1987; Madden 1979; Prata 1989; Venne 1989; Randel 1993; Hirooka 2000). In SABER data, the 5-day wave is clearly identifiable in the near-equinox period 31 March–12 May 2002. As shown in Fig. 13, the wave exhibits the classical normal mode structure, with little phase change below 10 sh; it has maximum amplitude of 1.5 K in the stratosphere and 3.5 K in the mesosphere. The signal is coherent over a very wide range of altitude: from 3 to 14 sh ($\sim 20$–100 km) in both hemispheres. Between 10 and 14 sh the phase varies more rapidly than at lower altitudes (where it changes by...
slightly more than one-quarter wavelength from 3 to 10 sh, an altitude range of nearly 50 km). The more rapid phase change above 10 sh may be indicative of dissipation in that region.

The structure and amplitude of the 5-day wave observed by SABER is consistent with the findings of Lawrence and Randel (1996), who documented the wave in **Nimbus-6 Pressure Modulator Radiometer** (PMR) data. The main features seen in Fig. 13 are present in Lawrence and Randel’s analysis, including the two maxima in the stratosphere and mesosphere, the slow phase change with altitude in the stratosphere and lower mesosphere, and the more rapid phase change above. Also in common with Lawrence and Randel’s findings is the fact that no clearly identifiable 5-day wave was found in any of the other (nonequinox) SABER data segments analyzed. Presumably, forcing of the 5-day wave is not limited to the equinoctial seasons, but the background wind configuration during the solstices is not conducive to setting up a global normal mode structure.

It is tempting to use SABER data to search for other planetary-scale atmospheric normal modes; in particular, the gravest antisymmetric and second symmetric Rossby modes of \( m = 1 \) have theoretical periods of 10 and 16 days, respectively (see, e.g., Salby 1981). How-

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**Table 2. Amplitudes (K) of coherent, eastward-propagating diurnal oscillations found in SABER data for zonal wavenumber, \( m = 1-6 \), in the altitude range 6–17 sh. Letters in parentheses denote the predominant symmetry with respect to the equator as S: symmetric, AS: antisymmetric, and M: mixture of symmetric and antisymmetric.**

<table>
<thead>
<tr>
<th>Data segment</th>
<th>( m = 1 )</th>
<th>( m = 2 )</th>
<th>( m = 3 )</th>
<th>( m = 4 )</th>
<th>( m = 5 )</th>
<th>( m = 6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Jan–24 Feb 2002</td>
<td>—</td>
<td>7.0 (AS)</td>
<td>7.5 (AS)</td>
<td>3.0 (M)</td>
<td>2.0 (M)</td>
<td>—</td>
</tr>
<tr>
<td>31 Mar–10 May 2002</td>
<td>—</td>
<td>4.8 (M)</td>
<td>8.0 (M)</td>
<td>3.0 (M)</td>
<td>3.0 (M)</td>
<td>5.0 (AS)</td>
</tr>
<tr>
<td>15 Jun–14 Jul 2002</td>
<td>—</td>
<td>9.0 (AS)</td>
<td>10.0 (S)</td>
<td>—</td>
<td>1.2 (M)</td>
<td>4.5 (AS)</td>
</tr>
<tr>
<td>14 Jun–14 Jul 2003</td>
<td>—</td>
<td>6.0 (M)</td>
<td>10.0 (M)</td>
<td>5.0 (AS)</td>
<td>5.0 (M)</td>
<td>—</td>
</tr>
<tr>
<td>7 Jan–22 Feb 2004</td>
<td>—</td>
<td>—</td>
<td>4.0 (AS)</td>
<td>2.7 (AS)</td>
<td>4.0 (AS)</td>
<td>5.0 (S)</td>
</tr>
</tbody>
</table>

**Fig. 7.** As in Fig. 2 but for eastward diurnal oscillations of (left) \( m = 2 \) and (right) \( m = 3 \), for 15 Jun–14 Jul 2002. The amplitude contour interval is 0.5 K.
ever, the longest continuous SABER data segments available to us are not much longer than one month, as already noted, so the spectral bandwidth is too coarse to be able to differentiate variance associated with these modes from the quasi-stationary continuum.

In addition to the 5-day wave, SABER observations reveal the presence of a 4-day wave at \( m = 1 \) in the Northern Hemisphere winter 2004 (cf. Venne and Stanford 1979; Lawrence et al. 1995). Lawrence and Randel (1996) have pointed out that this wave, which is apparently associated with instability of the winter polar night vortex, is much more robust in the Southern than in the Northern Hemisphere winter and is confined to the polar regions. Unfortunately, the attitude of the TIMED spacecraft during the two southern winter seasons that we have examined was such that the field of view extended only to \( 54^\circ S \), precluding observation of the 4-day wave. For the data segment of 22 January–22 February 2002, no 4-day wave could be identified, but during 27 January–22 February 2004 a strong, distinct spectral peak was found at high northern latitudes, as shown in Fig. 14. The peak is centered at \( 0.23 \) cpd (4.3 days eastward) and is clearly separated from the large peak centered at zero frequency, which corresponds to the quasi-stationary Rossby wave field (cf. Fig. 2).

The amplitude/phase structure of the 4-day wave is shown in Fig. 15, where the range of latitude is limited to the Northern Hemisphere since the wave is a high-latitude phenomenon, not present equatorward of \( 40^\circ \).

**Fig. 8.** As in Fig. 2 but for eastward diurnal oscillations of (left) \( m = 5 \) (14 Jun–14 Jul 2003) and (right) \( m = 6 \) (31 Mar–10 May 2002). The amplitude contour interval is 0.25 K.

**Fig. 9.** Evolution of the \( m = 1 \) eastward diurnal temperature wave at the Greenwich meridian and 12.4 sh, synthesized over the frequency range \((-0.91, -1.04)\) cpd (0.96–1.1 days), during 23–30 Jun 2002. The contour interval is 1 K.
Fig. 10. Wavenumber–frequency rms temperature amplitude spectrum at 11 sh and 40°S for (top) 25 Jan–24 Feb 2002 and (bottom) 27 Jan–22 Feb 2004. The red lines correspond to constant phase velocity $c = 70 \text{ m s}^{-1}$. Positive (negative) frequencies denote westward (eastward) propagation; the color bar shows amplitude in K. Note the larger amplitude scale in the top panel.
The structure consists of two lobes, in the upper stratosphere and mesosphere, with a nearly 180° phase jump between them at about 9 sh (~63 km) and little phase variation elsewhere. This structure is very similar to that calculated by Manney and Randel (1993) using a linearized model with a specified, climatological basic state. In particular, the out of phase, double-node structure seen in Fig. 15 is reproduced in Manney and Ran-
del’s calculations, where it is found to be associated with instability-related potential vorticity fluxes. The amplitude of the wave is much larger (4–5 K) than calculated by Manney and Randel (0.5–0.8 K), perhaps because these authors used a climatological, time-mean background state, whereas the actual temperature and wind distribution may be considerably more unstable at certain times.

4. Summary

We have carried out a preliminary survey of planetary-scale waves observed by SABER in the MLT by mapping v1.04 data for some of the continuous observational periods currently available. Aside from the quasi-stationary planetary wave field in winter, variability in the MLT is dominated by fast equatorial waves in the Tropics, including Kelvin and Rossby–gravity waves that propagate from the lower atmosphere, and a spectrum of modes associated with the 2-day wave that appear to be forced in situ during summer.

The quasi-stationary component of the wave field is due to vertically propagating Rossby waves that attain very large amplitude (15–20 K) in the winter hemisphere. An interesting feature of the quasi-stationary wave field is its tendency to extend into the deep Tropics and even into the summer hemisphere with significant amplitude (3–6 K), which suggests ducting by local background westerly winds. Although SABER does not measure winds, earlier results from the UARS High Resolution Doppler Imager (HRDI) and Wind Imaging Interferometer (WINDII) instruments (McLandress et al. 1996) do show the presence of westerly zonal-mean zonal winds in the upper mesosphere and lower thermosphere, just where SABER data suggest that wave ducting is occurring.

Eastward-propagating Kelvin waves and westward-propagating Rossby–gravity waves are clearly present in SABER data, reaching amplitudes of 6 K in the MLT. Short-period Kelvin waves are thought to play a role in the forcing of the semiannual oscillation (SAO) in both the stratosphere and mesosphere. The eventual availability of long-term, continuous SABER observations will allow a fresh assessment of the contribution of these waves to the SAO. In addition, Kelvin waves, through their motion field and temperature perturbations, should influence the behavior of chemical con-

Fig. 12. As in Fig. 2 but for the components of the 2-day wave at \( m = 3 \) and \( m = 4 \) for 15 Jun–14 Jul 2002. The amplitude contour interval is 0.5 K.
constituents throughout the middle atmosphere. The simultaneous availability of data on temperature and chemical composition (in particular, ozone) in forthcoming versions of the SABER dataset will provide an opportunity to advance our understanding of the interplay of dynamics and photochemistry in the middle atmosphere.

Significant concentrations of eastward propagating variance are also found at the diurnal period over the range of zonal wavenumber \( m/100 \approx 5 - 6 \) in most of the data segments analyzed here, with amplitudes ranging up to several kelvin. These eastward, non-sun-synchronous tides can be resolved by the combined-node sampling pattern of SABER. Westward-propagating diurnal oscillations (including the sun-synchronous tides) are not resolved synoptically by SABER and were not considered in this study. Eastward-propagating diurnal waves may also play an important role in mesospheric tropical dynamics, as argued by Sassi and Garcia (1997) and Garcia and Sassi (1999). It is believed that these waves are forced, at least in part, by diurnal variability of convective heating in the Tropics (see Riciardulli and Garcia 2001).

Outside the Tropics, variability in the MLT is dominated by the “2-day wave,” which attains large amplitudes during the solstices in the summer hemisphere. SABER observations indicate that the phenomenon is

![Figure 13](image1.png)  
**Fig. 13.** As in Fig. 2 but for the 5-day Rossby normal mode, over the frequency range \((0.15, 0.20)\) cpd (5–6.6 days westward) during 31 Mar–10 May 2002. The amplitude contour interval is 0.25 K.

![Figure 14](image2.png)  
**Fig. 14.** Rms temperature amplitude vs frequency spectrum for \( m = 1 \) at 68°N and 11.45 h during 27 Jan–22 Feb 2004. A spectral peak at \(-0.23\) cpd (4.3 days eastward) is clearly distinct from the large peak centered about the zero frequency.

![Figure 15](image3.png)  
**Fig. 15.** As in Fig. 2 but for the 4-day wave, over the frequency range \((-0.18, -0.26)\) cpd (3.8-5.5 days eastward), during 27 Jan–22 Feb 2004. The amplitude contour interval is 0.5 K.
not limited to the \( m = 3 \), 2-day oscillation, but instead comprises a spectrum of waves that cluster along a line of constant, westward phase velocity, \( c = 70 \text{ m s}^{-1} \), with maximum amplitude of \( \approx 6 \text{ K} \) at \( (m = 3, 0.5 \text{ cpd}) \) and \( (m = 4, 0.56 \text{ cpd}) \). This behavior, together with the observed structure of the waves and the fact that they are present with high amplitude only during the solstice seasons, is consistent with excitation of a collection of atmospheric normal modes by baroclinic instability of the easterly summer jet in the mesosphere (cf. Norton and Thuburn 1996). The availability of SABER data over several seasonal cycles will be invaluable for understanding the climatology of this wave and for evaluating the importance of baroclinic instability as a forcing mechanism.

SABER observations also reveal the presence of 4- and 5-day waves at \( m = 1 \), albeit only at certain times of the year. The 4-day wave, which is associated with instability of the polar night jet, is found in one of the Northern Hemisphere winter data segments analyzed (2004), but not in the other (2002). During the southern winters of 2002 and 2003, the attitude of the TIMED spacecraft was such that it could not view the polar latitudes where the wave occurs. The structure of the 4-day wave observed by SABER closely resembles that obtained in linear instability calculations (Manney and Randel 1993) and supports the idea that the wave arises from unstable configurations of the winter polar night jet.

The 5-day Rossby normal mode is found in SABER data for spring 2002, the only near-equinox data segment available to us, but is not clearly identifiable as a global mode in any of the northern or southern winter solstice periods analyzed. Nevertheless, during the period when it is present in SABER data, the 5-day wave attains large amplitude (2.5–3.5 K) and is globally coherent. Availability of longer SABER data sequences in the future should help establish the climatology of this and other normal modes, and their dependence on the background state.

This survey of traveling waves observed by SABER highlights the power of combined-mode remote sensing for elucidating the transient dynamics of the MLT. In addition to confirming the presence of wave modes that have been well documented in the past, SABER data shed new light upon, or reveal for the first time, planetary-scale variability at shorter periods and at altitudes hitherto inaccessible to space-based remote sensing. Sorting out the sources of these waves, and their effects on the dynamics and chemical composition of the MLT will require processing of more extensive, continuous data segments for both temperature and chemical constituents. Ancillary datasets for winds, either derived geostrophically from SABER temperature data (outside the Tropics) or measured by the Timed Doppled Interferometer (TIDI) instrument on board TIMED, will also be necessary for more quantitative evaluations of the role of these transient motions in the MLT.

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