Seasonal variation of diurnal perturbations in mesopause region temperature, zonal, and meridional winds above Fort Collins, Colorado (40.6°N, 105°W)

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On the basis of lidar observations from May 2002 through April 2003, covering both day and night, we performed a harmonic analysis to extract the diurnal perturbations in mesopause region temperature, zonal and meridional winds over Fort Collins, Colorado (40.6°N, 105°W), binned every 2 months. The results were compared to predictions of the 2000 and 2002 versions of Global-Scale Wave Model (GSWM00 and GSWM02). The diurnal tidal period oscillations showed a mixture of propagating and evanescent (trapped) modes, but the propagating modes dominated for most of the year. The agreement in temperature diurnal phases between observation and GSWM prediction is marginal. On the other hand, other than July-August meridional winds, the observed diurnal phases in both wind components are in good agreement with GSWM predictions for most of the altitude range reported. The diurnal amplitude predictions of GSWM00 were reasonably close to lidar observations, while other than January-February, the GSWM02 amplitude prediction overestimated the observations, typically by a factor of two. We also conducted comparisons on tidal perturbations in zonal wind between radar campaigns and our lidar observations. The lidar data agreed reasonably well with the MF radar data from 2000 to 2001 at nearby Platteville, Colorado (40.2°N, 104.7°W), but showed considerable differences with the data from other midlatitude stations from 1992 to 1993. The dominance of the evanescent mode in the temperature diurnal tidal oscillation during the early winter (November and December), which reached a peak value at midnight, was interesting and anomalous. By invoking the more recent data (November and December in 2003), as well as the diurnal temperature observations from December 1998, we report that the evanescent (trapped) diurnal tidal perturbations were robust and persisted from one year to the next.


1. Introduction

Atmospheric solar tides are global oscillations with periods that are subharmonics of a solar day. Migrating solar diurnal tides must have a westward phase velocity synchronized with the Earth’s rotation. These waves oscillate with the local sun time (LST). Global oscillations with periods of 24/n (n = integer) that are nonsynchronous with the sun are called nonmigrating tides; they may be stationary, eastward, or westward propagating. At a single station, we can only observe tidal period oscillations, but cannot distinguish whether they are migrating tides or nonmigrating tides, or local perturbations, which are not tides. To determine this, multistation observations are needed. Knowledge of solar tides in the mesosphere and lower thermosphere region (MLT) is essential for the testing of the dynamics and chemistry imbedded in global models, as their characteristics can impact thermal and dynamical structure in the region. Experimentally, tides may be deduced from zonal distributed observations that cover most local times, preferably over a full diurnal cycle (24 hours continuous). Short of such a complete global coverage, satellite observations, which provide partial local time global coverage, and ground-based observation at fixed locations, which provide fill local time coverage, may be combined to determine migrating and nonmigrating tides.

Tidal signatures in the mesopause region (80 and 110 km) have been reported for several decades from many ground-based radar stations, which measure zonal and meridional winds [Fellous et al., 1975; Stening et al., 1978; Clark, 1978; Roper, 1978; Tsuda et al., 1988;
2. Data Sets and Analysis Technique

The lidar data consist of altitude profiles of the returned photons from Na fluorescence at three specified Na D frequencies within the Doppler-broadened bandwidth of the returned photons from Na fluorescence at three specified Na D frequencies within the Doppler-broadened bandwidth of the sodium resonance absorption spectrum, yielding line-of-sight wind and temperature for each beam. By assuming that the hourly mean vertical wind was negligible, an hourly mean zonal wind profile was determined from the east beam observation and meridional wind from the north beam observation. Since the lidar signal from each beam gives a temperature, an hourly mean temperature profile for this study was determined from the mean of the two measured values. The measurement precisions for temperature and wind with 2 km spatial resolution and 1 hour integration were estimated under nighttime fair sky condition to be 0.5 K and 1.5 m/s, respectively, at the Na peak (92 km), and 5 K and 15 m/s at the edges (81 and 107 km) of the sodium layer. Because of the necessity of using the Faraday filter for observations under sunlit condition, the received signal was attenuated by a factor of 4 to 5. We degrade the spatial resolution to 4 km for these data, leading to a measurement uncertainty more than 1.5 times larger, depending on the residual sky background through the Faraday filter.

Although a total of 1219 hours of observation with good a signal-to-noise ratio was taken, only 927 hours of data corresponded to campaigns with longer than 24-hour continuous observation. These data were binned bimonthly with the number of hours in each campaign and each bimonthly period given in Table 1. Our earlier study of temperature tides [She et al., 2002], and the more recent study of July and August temperature and wind tides [She, 2004] employed only 24-hour continuous data to minimize the effects of data gaps within a 24-hour period. After more careful considerations, we believe that all data acquired continuously in excess of 24 hours should be included for periodogram analysis and tidal period harmonics analysis to improve statistics, and possibly reduce the aliasing of longer-period planetary waves. The present data set is well distributed throughout a year, but the coverage within each month was however still not long enough to form individual monthly means to compare with model predictions. As a compromise we grouped the data into bimonthly sets, with 165, 164, 134, 159, 100, and 205 hours of data, respectively for May–June, July–August, September–October, November–December, January–February, and March–April. The bimonthly set of July–August 2002 is interesting in that there were three 24-hour sets each month with the August observation made continuously. This bimonthly data set, consisting of two 3-day composites, was studied in detail and the result reported recently [She, 2004]. When diurnal period oscillations were investigated for individual days (full diurnal cycles), we find considerable variability from one day to the next, suggesting the possible modulation of diurnal tides by longer-period planetary waves, including 2-day waves or shorter-period perturbations (gravity waves). For the case reported, a minimum of 3 days of observation was needed for the coherence of solar forcing to prevail over the variability in diurnal mean as well as in diurnal tidal oscillations, leading to the expected convergence to “climatology” in the multiday composite observation. Though the amount of data shown in Table 1 is still not enough to claim a climatology, we assess the confidence level of harmonic fit to each bimonthly composites and found that overall they are fairly representative of diurnal perturbations over Fort Collins, Colorado (41°N, 105°W). Since our longest continuous
Table 1. Data Set Used for the Yearlong (Binned Bimonthly) Study of Mesopause Region Diurnal Tides in Temperature, Zonal and Meridional Winds Over Fort Collins, Colorado

<table>
<thead>
<tr>
<th>Campaign Sets (UT-Day)</th>
<th>Campaign Hours</th>
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<tbody>
<tr>
<td><strong>January to February (100-Hour Total)</strong></td>
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<tr>
<td>3019–3021</td>
<td>60-hour</td>
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<tr>
<td>3050–3052</td>
<td>40-hour</td>
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<tr>
<td><strong>March to April (205-Hour Total)</strong></td>
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<tr>
<td>3064–3065</td>
<td>25-hour</td>
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<tr>
<td>3066–3068</td>
<td>63-hour</td>
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<tr>
<td>3072–3073</td>
<td>37-hour</td>
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<tr>
<td>3100–3101</td>
<td>24-hour</td>
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<tr>
<td>3103–3104</td>
<td>30-hour</td>
</tr>
<tr>
<td>3106–3107</td>
<td>26-hour</td>
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<tr>
<td><strong>May to June (165-Hour Total)</strong></td>
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</tr>
<tr>
<td>2142–2143</td>
<td>39-hour</td>
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<tr>
<td>2145–2146</td>
<td>31-hour</td>
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<tr>
<td>2150–2151</td>
<td>37-hour</td>
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<tr>
<td>2159–2160</td>
<td>29-hour</td>
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<tr>
<td>2162–2163</td>
<td>29-hour</td>
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<tr>
<td><strong>July to August (164-Hour Total)</strong></td>
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<tr>
<td>2198–2199</td>
<td>24-hour</td>
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<tr>
<td>2210–2212</td>
<td>60-hour</td>
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<tr>
<td>2221–2224</td>
<td>80-hour</td>
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<tr>
<td><strong>September to October (134-Hour Total)</strong></td>
<td></td>
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<tr>
<td>2257–2260</td>
<td>61-hour</td>
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<tr>
<td>2280–2281</td>
<td>43-hour</td>
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<tr>
<td>2282–2283</td>
<td>30-hour</td>
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<tr>
<td><strong>November to December (159-Hour Total)</strong></td>
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<tr>
<td>2309–2311</td>
<td>49-hour</td>
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<tr>
<td>2320–2321</td>
<td>40-hour</td>
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<tr>
<td>2347–2349</td>
<td>42-hour</td>
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<tr>
<td>2353–2354</td>
<td>28-hour</td>
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*The above list gives data sets, longer than 24 hours continuous each from the first yearlong campaign (May 2002 to April 2003), and their duration in hours, totaling 927 hours of observation. The first digit of the UT-Day indicates the last digit of the year data were taken; for example, 2142 represents day 142 of year 2002.

observation during this period was 83 hours, in general, our data set was not long enough to evaluate the 2-day wave and our resulting tidal period perturbations may be contaminated by planetary wave modulations.

[7] The procedure for data analysis is fairly standard and was described previously [She, 2004]. Briefly, a bimonthly time series of hourly mean temperature and wind profiles, each consisting of several continuous data sets longer than 24 hours, are linearly fitted to a constant term plus the sum of the oscillations with diurnal, semidiurnal, terdiurnal and quatradiurnal periods at each altitude. Since our measurement errors were much smaller than the geophysical variability, we weigh each data point equally in the harmonic fitting process. The amplitude and phase (the time at which maximum value occurs) for each period with uncertainties are reported at 0.5 km intervals, oversampled to smooth the profiles. The resulting diurnal tidal period perturbations for each bimonthly interval are plotted along with GSWM00 and GSWM02 tidal predictions for reference. Our aim is neither to evaluate model prediction nor to seek agreement. We include both versions of GSWM to assess the extent of nonmigrating tidal contribution [Hagan and Forbes, 2002, 2003].

sets, longer than 24 hours each, we found that the fitted amplitudes and phases for the diurnal and semidiurnal components were independent of whether the 8- and 6-hour periods were included in the fit or not. We discuss only diurnal components here with a companion paper on semidiurnal components in preparation. The study of terdiurnal [Smith and Orland, 2001] and quatradiurnal tides may be a future project.

[8] Along with the least squares harmonic fitting, Lomb periodogram analysis was performed to calculate the dimensionless Lomb power [Press et al., 1992] spectrum including tidal periods, revealing the full frequency content in each data set. As expected, the resulting Lomb power at the tidal periods qualitatively mirrors the corresponding tidal amplitudes deduced from the harmonic analysis. A salient feature of the Lomb power lies in the fact that a Monte Carlo simulation with the same temporal structure may be used to assign a percent probability that a given Lomb power could be produced by random noise, thus giving an estimate of the significance level of the deduced Lomb power. In this connection, we will use the percent confidence of the Lomb power, defined as one minus the significance probability. For each data set, we typically evaluate the Lomb powers required for 50% and 95% confidence in the analysis. These powers may be compared to the deduced Lomb power of a tidal period for each altitude to provide a qualitative measure of the goodness of the reported tidal amplitude and phase. In addition, for each reported point on a tidal amplitude or phase profile, we also give the 1-σ uncertainty of the harmonic fitting. Both the 1-σ uncertainty and confidence level will be used to judge the quality of the tidal fits derived from the data set in discussions below. A comment can be made at this point on the difference between data whose length is an exact multiple of 24 hours and all data from campaigns longer than 24-hour continuous. In principle, with multiple 24-hour data sets, we have the same number of data points at each local time, so all local times are weighted equally in the fit and the deduced 4 tidal period perturbations are the same as the Fourier transform frequencies, which makes interpretation easier. With data sets longer than 24 hours, aliasing from longer periods will be reduced, but there might be some slight effects from repeating some local times more than others (effectively periodic gaps). We have organized the data both ways: exact multiple of 24 hours or all campaigns longer than 24 hours. We found that the outputs in tidal amplitude and phase are essentially the same except for the points with less than 50% confidence.

[9] Before we present and compare lidar observations to tidal models, there are a number of caveats. First, when tidal amplitude is comparable to its assessed uncertainty, it could induce a huge uncertainty (as much as half of the tidal period in question) into the tidal phase. Presumably, this could occur in both observation and numerical modeling, and we found that they typically occur when the confidence level of the analysis is lower than 50%. Second, observations at a single station are a superposition of both global and local tidal period perturbations. Depending on which one dominates, the observed results could be very different from the GSWM00 model predictions, which only consider global effects. Third, if the observation on a given day includes some transient event, local or global, it could greatly distort
the result, especially for tidal amplitudes, and thus cause a big difference between observation and model prediction. This last difficulty can be overcome by long-period extended lidar data acquisition [She et al., 2004].

3. Annual Variations of Observed Diurnal Oscillations and Comparison to Models

[10] We present the seasonal variation in diurnal phases and amplitudes for each bimonthly period in Figures 1–6, along with diurnal amplitudes and phase predictions from both GSWM00 [Hagan et al., 1999] and GSWM02 [Hagan and Forbes, 2002, 2003]. Here, we should point out that, in general, the altitude dependence (or shape) of phase by the GSWM00 and GWSM02 is the same. However, because of the inclusion of nonmigrating tidal sources, the amplitude predicted by GWSM02 is about a factor of 2 larger than that of GSWM00. In Figures 1–6, the diurnal phases and amplitudes are plotted as a function of altitudes between 80 and 105 km. In some cases the rate of downward phase progression (including model prediction) appears to change as a function of altitude,
indicating that the vertical wavelength may be height-dependent.

[11] The first impression of these diurnal period comparisons between models and the observations is the complexity of the lidar results. We should point out here that the large error bars in some diurnal phase plots, for example, the lidar data in Figure 1f below 90 km, and Figure 3b around 90 km, are due to the small diurnal amplitudes at the same altitude (see Figures 1e and 3a). Indeed, we found (not shown) the confidence level for January-February meridional wind below 90 km and that for May-June temperature between 89 and 91 km are lower than 50%.

[12] In most of the diurnal phase plots, lidar observations show downward phase progressions (upward wave propagation), meaning diurnal oscillations in this region receive more energy contribution from upward propagating components. However, possible mode transitions between propagating modes and evanescent (trapped) modes are seen during several data periods. For the purpose of this paper, we define a trapped mode as an observed phase propagation with a speed greater than 10 km/h (or vertical wavelength longer than 240 km), which could be due to comparable amplitudes of upward phase propagating and/or in situ excited components in the mesopause region during those periods. For example, the March-April zonal and meridional wind diurnal phases (Figures 2d and 2f) show the typical propagating behavior below 93 km, but transition to somewhat evanescent (trapped) behavior
higher up with little phase progression. Looking at the amplitudes for this period, we do not find obvious damping in the zonal wind amplitude at 93 km, but the decrease in the meridional wind amplitude above 90 km is evident, and it reaches the minimum at 93 km. The confidence level for meridional wind (between 93 and 101 km) varied between 50% and 95%. The wavy structure in the March-April temperature diurnal amplitude seems to have no obvious effect on its downward phase progression. Another case is the temperature diurnal phase in the January-February period (Figure 1b), where a near evanescent mode dominates below 88 km, but it appears to be propagating in the region from 88 km to 93 km. Then it changes back to evanescent mode over 93 km. The temperature amplitude at this time does not show such complicated features. It is slowly increasing (from 4 K to 7 K) with the altitude, and then takes a sharp turn at 96 km. Below 96 km the lidar observed temperature amplitude is in good agreement with GSWM02 prediction. A hint of similar diurnal phase behavior can also be found in Figures 3b, 3f, 5b and 5f.

The most mysterious diurnal phase behavior happens during the early winter months (November-December), when the temperature diurnal phase (Figure 6b) appear to be evanescent over the entire altitude range, whereas the models show propagating behavior with a ~30 km vertical wavelength. Zonal wind (Figure 6d) at this period show somewhat propagating characteristic, but the meridional...
wind (Figure 6f) phase is questionable because of small diurnal amplitudes. We discuss this interesting behavior more later. Similar tidal characteristics show up in July-August as well, but in a somewhat opposite way. In the July-August period, the temperature (Figure 4b) and zonal wind (Figure 4d) diurnal tides show downward phase progression, which are in agreement with GSWM, whereas the meridional wind diurnal phase (Figure 4f) shows almost no progression. At the same time, the temperature amplitude seems to stay constant along the altitude, but the zonal and meridional wind amplitude show wavy structures, and oscillate back and forth between two models’ predictions.

![Figure 4. Same as Figure 1 except for July-August (2002).](image)

[14] The wavy structure in the diurnal amplitude is quite common in our observations. This could be due to the interference between two tidal modes, as demonstrated in a simulation in which the (1, 1) tidal mode with 6-hour phase shift was combined with the (1, −2) mode [Forbes, 1982]. The GSWM predicts that the diurnal amplitudes will grow smoothly with altitude and reach its peak around 105 km, then decrease because of molecular thermal diffusion [Hagan et al., 1999] in the lower thermosphere. However, this is not usually seen in our observations. Also, unlike the lidar observations, the models predict apparent downward phase and upward group propagation for every diurnal tidal components during all of the
seasons. The damping of the diurnal amplitude at higher altitudes is another typical characteristic in our observations (Figures 1a, 1c, 1e, 2a, 2c, and 6c). The damping region extended from 95 to 100 km in many diurnal amplitude profiles. Similar damping above 90 km in the diurnal amplitude was also reported in TIDI data [Wu et al., 2004]. There have been numerical simulations [Forbes and Hagan, 1988] on the propagating tide in the mesopause region and the damping seems to be caused by mechanical and thermal dissipation, such as Rayleigh friction and Newtonian cooling.

Although the observed diurnal phase and amplitudes show complex vertical structure, the propagating component seems to be most common above Fort Collins, in agreement with the models. Since the models are global-scale climatological predictions, differences between observations from one local station and models are expected. Similarities between lidar observations and model predictions do show up in many of the periods and tidal components, i.e., the temperature diurnal phases in March-April (Figure 2b) from 87 to 98 km, in July-August (Figure 4b) from 85 to 95 km, and in September-October (Figure 5b) from 84 to 91 km. There are many similarities observed in the wind field too, such as zonal wind diurnal phase in March-April (Figure 2d) from 80 to 95 km, in September-October (Figure 5d) from 86 to 99 km. Similarity here refers to

Figure 5. Same as Figure 1 except for September-October (2002).
not only a similarity in vertical wavelength (phase progression rate), but also a small time offset between the observations and the model predictions within experimental error bars. The mixture of evanescent modes and propagating modes has been discussed in the early tidal numerical simulation and theory [Forbes, 1982, 1995; Forbes and Hagan, 1988]. Basically, the propagating modes with relatively shorter wavelengths, for example the (1, 1) mode with 30 km vertical wavelength, are quite sensitive to dissipation, especially eddy diffusion. The upward propagating modes then could have significant damping. In the MLT at midlatitudes, where the atmosphere has a large meridional gradient of temperature, eddy diffusion is stronger than in the equatorial region [Lindzen and Hong, 1974; Walterscheid and Venkateswaran, 1979; Walterscheid et al., 1980]. Thus the upward propagating component loses energy and the evanescent mode excited by an in situ source, for example the stratospheric ozone, could dominate the propagating mode at certain altitudes. However, it is easy to understand that, since the evanescent mode decays exponentially when it travels away from the source, it eventually will give the dominant role back to the propagating modes. Again, like GSWM, these theory and numerical simulations favor the propagating modes as well in the mesopause region (80–110 km) because there is not much heating in this region or the possible source is

Figure 6. Same as Figure 1 except for November-December (2002).
Seasonal variation of diurnal tidal amplitudes and phases in temperature (solid line with circles), zonal wind (dash-dotted line with squares) and meridional wind (dashed line with diamonds) at 91 km based on bimonthly fit. The altitude of 91 km was chosen because it is near the peak of the Na layer and it is an altitude used in radar tidal wind reports.

![Figure 7](image-url)

Figure 7. Seasonal variation of diurnal tidal amplitudes and phases in temperature (solid line with circles), zonal wind (dash-dotted line with squares) and meridional wind (dashed line with diamonds) at 91 km based on bimonthly fit. The altitude of 91 km was chosen because it is near the peak of the Na layer and it is an altitude used in radar tidal wind reports.

too weak to generate significant effects [Hagan, 1996]. The in situ source exciting the evanescent mode in our observation is unclear at this point. Mesospheric ozone might be the culprit, but its density is too low to excite such a big evanescent mode like that seen in the November-December temperature component and July-August meridional wind component. For example, the stratospheric ozone layer, which is about an order of magnitude higher in mixing ratio than the mesospheric ozone layer, causes the evanescent mode (1, −2) to dominate roughly from 40 to 60 km. Chemical heating in the MLT is another possible source [Mylniczak and Solomon, 1993].

It is worth noticing that the GSWM02 amplitudes are considerably larger than observation, and GSWM00 predictions seem to be closer to lidar data during most of the year, raising a question about the latent heat generated nonmigrating tidal contribution in the midlatitude region. Similar results are reported by radar wind data [Manson et al., 2004]. However, in January-February, the temperature and zonal wind amplitudes exceed the GSWM00 in most of the altitude range and agree well with GSWM02 results, resulting in the largest amplitudes measured during the year.

As we mentioned earlier, lidar observations are always limited by weather, and thus an average campaign lasts about 40 hours. So, in routine lidar tidal analysis, the time of observation of the campaign is usually not long enough to discuss planetary wave effects, and thus we do not include periods longer than 24 hours in our harmonic fitting, but we can discuss the planetary wave and tide interactions during our more limited number of long campaigns (>3-day), which revealed quasi 2-day wave modulations [She, 2004]. In fact, we have performed harmonic fits with and without the inclusion of a 2-day wave to the only campaign (UT day 221–224) in this data set that is longer than 3 days. We found basically no difference in tidal amplitudes and phases for this campaign. Because of the large day-to-day variability of the diurnal tide [Forbes, 1985], and our limited number of data sets, it is still too early to build a true tidal climatology. With this first yearlong diurnal cycle data set, the bimonthly variation of diurnal tidal amplitude and phase at 91 km for temperature, zonal and meridional  is shown in Figure 7. One evident feature in the amplitude plot is that temperature reaches its peak amplitude during the winter month (from November to February). The peak of the zonal wind amplitude in February is almost double the peak value of meridional wind amplitude in the summer months (from May to August). The meridional wind amplitude during the rest of the year is small, and stays almost constant. However, GSWM predicts that the diurnal tide is strongest during the equinox period, which we do not see in this data set. The zonal and meridional wind diurnal phases follow each other quite well, with the phase difference between the two varying from 8 hours to within a couple of hours. We could not find a correlation between the temperature and wind phases, suggesting that the structure (e.g., polarization relation) of the tide changes with season or that there exists a component of independent tidal period perturbations in temperature, such as local heating. Further investigations are needed on this subject.

While our lidar-measured wind tides will be compared to radar winds observed at midlatitudes in the following section, lidar temperature tides can only be compared with two existing yearly temperature observations [States and Gardner, 2000; She et al., 2002], which binned their tidal observations into 4 seasons. Although it is difficult to make comparisons because of the difference between seasonal binning and bimonthly binning, some comments on their difference and similarity can still be made. For example, Illinois lidar observed temperature diurnal amplitudes, Figure 3 in States and Gardner [2000], for nonwinter seasons are about ~3 K higher than Fort Collins measurement in Figure 2 of She et al. [2002]. However, Fort Collins measurements are ~2 K higher than those observed by Illinois lidar results during the boreal winter. In general, the earlier amplitudes are higher than the bimonthly amplitudes reported here by ~2 K. Observed diurnal phase during spring from the Illinois measurement shows evanescent mode dominance below 92 km, whereas Fort Collins lidar diurnal phases in Figure 2b of She et al. [2002] indicates propagating mode characteristic from 85 to 100 km, which is in good agreement with our current March-April measurement (Figure 2b). The diurnal phase behaviors during boreal winter were also quite different,
with some evanescent mode dominance behavior above 92 km in earlier Fort Collins measurement, Figure 2h of She et al. [2002], but propagating behavior in Illinois lidar results. Fall season diurnal phase behaviors of the two older data sets are similar, but significantly different from the current September-October result (Figure 5b), in which there was a mode transition event at 90 km. Summer diurnal phases of these three data sets are also considerably different, though we note that the earlier summer campaign was especially short.

4. Radar and Lidar Data Comparison

[19] We compared our bimonthly lidar zonal wind results at 91 km with the radar wind from stations in the midlatitude region of North America. These results include the MF radar in nearby Platteville, Colorado (40.2°N, 104.7°W), recently reported by Manson et al. [2003]; the Urbana (40°N, 88°W) MF radar; the Durham (42°N, 71°W) meteor wind radar; and the London (43°N, 81°W) MF radar [Thayaparan et al., 1995]. The comparison between the lidar observations and the multistation radar campaign conducted during 1992–1993 at 91 km and (c and d) between Na-lidar and Platteville MF radar (2000–2001) at 91 km and 85 km. Notice that the starting month in Figures 8a and 8b is November to conform with Thayaparan et al. [1995], and the starting month in Figures 8c and 8d is August to conform with Manson et al. [2003].
together with Platteville results measured from August 2000 to July 2001 (Figures 8c and 8d). At both altitudes, the zonal wind amplitude deduced from the radar and lidar data follow a similar seasonal variation, except for the sharp peak in lidar amplitudes for January-February at 91 km, which is almost double the value of radar measurement. For example, at 91 km, both stations show the peak zonal wind diurnal amplitude in February and September, and an amplitude minimum in November and June. The zonal wind diurnal phases between these two stations also follow a similar seasonal trend, especially at 85 km. Overall, the zonal wind diurnal tidal behavior measured by these two stations is in good agreement, but lidar has a more dramatic variation due possibly to its smaller area and duration of observation. We have also compared the lidar mean zonal wind field with Platteville radar data (not shown in this paper), and they are in good agreement as well. The summer mesospheric jet occurs at almost the same month and same altitude, but the zonal wind peak in July above 95 km was measured by the lidar to be over 40 m/s, which is about 10 m/s faster than the radar measurement.

5. On November–December Anomaly in the Observed Temperature Tide

[21] To the end of 2003, the CSU sodium lidar has about 20 months with full diurnal cycle observations. To build a tidal climatology, the consistency and variability of the observed tidal behavior need to be tested and studied. Since our data set is probably not long enough to determine climatology, we chose in this section to compare selected bimonthly tidal results between years 2002 and 2003, mainly focusing on the November-December period because of the “anomalous” temperature diurnal tidal feature we mentioned earlier. We call it an anomalous event here, because the models predict downward phase progression in this region, but we find almost no phase progression at all in the diurnal temperature component.

[22] Before studying the anomalous temperature tidal behavior in this period, we first check the goodness of the harmonic fit for both temperature and winds by comparing the contours of data to those reconstructed from best harmonic fit to data taken from all four campaigns in November-December 2002. Time series of the hourly mean temperatures to the best bimonthly fit. This is done in Figure 9 with nine panels. In Figures 9a–9c, there are three temperature contours. Figures 9a and 9c are contours of data taken in the two longer campaigns, between days 309 and 311, and between days 347 and 349, respectively. Figure 9b is the reconstructed contour based on the best harmonic fit to data from all four campaigns. The arrangements of Figures 9d–9f and of Figures 9g–9i are the same, except that they are for zonal and meridional winds. The mean temperatures for these two campaigns agree reasonably well with our 8-year nocturnal mean temperatures. For example, at 90 km, the 8-year nocturnal means are 214 K and 212 K for November and December [She et al., 2000], which may be compared to diurnal means, 212.4 K and 211.2 K, for 309–311 and 347–349, respectively, for these campaigns. We could further investigate the temperature gradient and wind shear by calculating the buoyancy frequency and Richardson number, within this region to discuss the atmospheric stability [Li et al., 2005], but that is outside the scope of this paper.

[23] While as shown in Figure 9, the reconstruction from the best fit of the sum of mean and tidal perturbations with period of 24, 12, 8 and 6 hours, captures the features in the data contours generally, the details for each case differ. We discuss these details in temperatures (top row) here. The evanescence-like phase structure in the temperature reconstruction (below 90 km) reflects the dominance of diurnal tide (over perturbations with period of 12, 8 and 6 hours) when data of all four campaigns were included; Figure 10a indeed showed the Lomb power of diurnal tide to be greater than that of the semidiurnal tide below 87 km. The evanescence-like phase structure is also evident in the data contours of one campaign (days 309 to 311), but not evident in the other data set (347–349), which showed more phase tilt (~3.6 km/h for the temperature max in the middle of day 348). On the contrary, the evanescence-like phase structure shown in Figure 6b refers to the diurnal component only. The raw data sets (309–311 versus 347–349) are difference, suggesting tidal variability as expected. The semidiurnal tide during the 347–349 campaign happens to be stronger than the diurnal tide, leading to a more tilted phase (temp max) up to 94 km in the data contour for this campaign, Figure 9c, in consistent with semidiurnal tide dominance.

[24] We have performed tidal analysis for each of the four campaigns (see Table 1) separately, and the diurnal and semidiurnal temperature amplitude and phase for each campaign were plotted and compared (not shown). The difference between diurnal and semidiurnal phase profiles is very clear in each case, in that the semidiurnal tides show downward phase progression, while the diurnal phases are either evanescent or varied back and forth from a vertical line near midnight. The causes for tidal variability may be different from one campaign to the next; our results show that the tidal phases are reasonably robust, while the tidal amplitudes showed considerable day-to-day variability. We also note that below 90 km, diurnal and semidiurnal tidal amplitudes are comparable in three campaigns, except for the 347–349 campaign, in which the best fit semidiurnal amplitude is more than twice as large as the diurnal amplitude with a downward semidiurnal phase progression of ~3.3 km/h. The diurnal amplitude below 90 km is strongest for the 309–311 campaign, and its phase structure resembles that of the composite (Figure 6b) the most. The scenario shown in Figures 9a–9c is in agreement with this investigation.

[25] We then assess significance of the signal by calculating its Lomb power and associated 95% and 50% confidence levels as discussed in section 2. In Figure 10, we plot the Lomb power profiles for the 12-hour and 24-hour periods in the temperature and wind fields during this period for both 2002 and 2003. As expected, the semidiurnal period was the most significant in November-December, especially at higher altitudes, during both years. The Lomb power for all three components in 2003 data were higher than those in 2002 data. Also, the temperature diurnal component is more significant than the wind components for both years. The Lomb powers in temperature diurnal tides below 98 km were above the 95% confidence level.
Figure 9. Data and harmonic fit comparison. (a–c) Three temperature contours. Figures 9a and 9c are contours of data taken in the two longer campaigns between days 309 and 311 and between days 347 and 349, respectively. Figure 9b is the reconstructed contour based on the best harmonic fit to data from all four campaigns. (d–i) Same arrangement except that they are for zonal and meridional winds.
However, the zonal and meridional diurnal tide are relatively weak, especially the meridional wind. In 2002, the diurnal component in meridional wind at almost all altitudes were below the 50% confidence level, which means this signal cannot be distinguished from noise. The Lomb powers are higher in 2003, but the meridional wind between 92 and 100 km is still less than the 50% confidence level. If data of both years are combined, the 12-hour Lomb power for each tidal component increased considerably compared to the 2003 powers alone, as much as 50%, but the increase in the 24-hour powers is barely noticeable (not shown), except that the Lomb power in temperature below 90 km increased up to nearly 20 because of the significant Lomb power between 80 and 90 km in the 2002 data, suggesting a robust presence of diurnal period perturbations in early winter temperatures over Fort Collins, Colorado.

[26] To further demonstrate the consistency of the diurnal tides between 2002 and 2003, we plot the amplitude and phase of diurnal temperature, zonal, and meridional winds in Figure 11. Also plotted are GSWM00 predictions for comparison. We notice that in 2003, the temperature diurnal phase showed slightly more of a propagating behavior, but the vertical wavelength was over 150 km, which indicates a possible multimode mixture, with an evanescent mode dominating in this region, especially true
above 85 km. The diurnal temperature amplitudes in 2002 and 2003, also showed a similar vertical structure and quantitative agreement with each other. The zonal wind diurnal phase shows a typical downward phase progression in 2003, with the vertical wavelength about 30 km. It is interesting to notice that at 86 km, both meridional wind and zonal wind show some signs of a phase transition. Although the diurnal phases in both zonal and meridional winds, Figures 11d and 11f, showed very good agreement with GSWM00 predictions in both years, only the 2003 results below 95 km had a confidence level above 95%. On the other hand, the temperature diurnal phases below 98 km, though in disagreement with GSWM00, are consistent between two years with confidence levels much higher than 95% in both years. Since the wind diurnal tides, especially the meridional component, are relatively weak, the anomalous diurnal perturbations appear to affect mainly temperatures with a maximum increase at midnight.

[27] The winter “anomalous” diurnal tidal behavior observed by the lidar, and its consistency is interesting and revealing. Our earlier diurnal cycle study conducted in 1998–1999, also showed a similar evanescent mode in December 1998, see days 348 and 350 in Figure 4f of...
She et al. [2002], which further confirms this robust phenomena. The cause of a dominant evanescent mode in the temperature diurnal signal in the mesopause region is not fully understood at this point. As we discussed earlier, mode coupling could make the evanescent mode more important than the propagating mode in some altitude regions. However, there seems to be no significant in situ heating source in the mesopause region, except for mesospheric ozone which might be too low in density to generate such a considerable effect. Chemical heating is a possibility, as it was known to be a nighttime heating source [Mlynczak and Solomon, 1993], but its effect in diurnal perturbation is not clear. Quasi-stationary planetary-scale waves are the dominant feature of the winter middle atmosphere [Smith, 2003; Wang et al., 2000], and it is also well known that planetary wave and tidal interactions can generate considerable nonmigrating tides, but whether this will cause midnight heating is still an open question that deserves investigation. Unfortunately, during the 2002 and 2003 early winter months (November and December), our lidar campaigns were not long enough to reveal the planetary wave scale modulation in the mesopause region.

6. Conclusions

[26] Since May 2002, the CSU lidar group has performed full diurnal cycle observations semiregularly. The first year results allow study of the seasonal variation of the solar thermal tidal behavior over Fort Collins, Colorado. The bimonthly binned temperature, zonal and meridional wind diurnal amplitudes and phases were calculated. Though not the main objective of the paper, these observed results were compared with GSWM (both 00 and 02 versions) predictions. To study the consistency of our lidar tidal results, we analyzed the newer data acquired in November and December 2003, where large discrepancies exist between model and observation, as well as an early diurnal data set from December 1998.

[29] In addition to nearly constant phase in November-December temperature, there exist cases of phase transition from one slope to the other. Though we have referred to literature discussion on similar trapped/propagating mode transition, a definite mechanism for the observed cases is still lacking. The wavy pattern observed in many diurnal amplitudes and some nearly constant amplitudes all revealed the complexity in tidal behavior in the MLT. Though we suspect many of these features are repeatable from one year to the next, verification will come from future campaigns. Convincing explanations of these interesting observations are lacking and we hope that our results will stimulate interests in this direction. On the other hand, we feel that a number of conclusions can already be derived from our analysis.

[30] First, except for the November-December temperatures and meridional winds in July-August which both show evanescent mode domination, most of the lidar results show a dominant propagating mode, in general agreement with GSWM predictions.

[31] Second, there are several cases of mode transitions in our lidar results, showing a mixture of evanescent modes and propagating modes in this region.

[32] Third, by comparing the results of winter temperature data from 2003 and from 1998, we find that the dominance of the evanescent mode in the November-December temperature diurnal tidal phase persists from one year to the next. We suggest that this nearly trapped diurnal temperature phase structure, which is not accompanied in the corresponding horizontal wind phase structure, may be caused by a local (longitude-dependent) source of diurnal period heating which maximizes at midnight.

[33] Fourth, other than January-February, the observed diurnal amplitudes are closer to GSWM00 predictions, which are typically smaller by a factor of 2 than GSWM02. Thus it raises a question about the contribution of the modeled latent heat as nonmigrating source for diurnal tide at midlatitudes.

[34] Fifth, there exist persistent wavy patterns in the diurnal amplitude profiles with a wavelength of ~10 km, particularly in the equinox months. This may be the result of beating between two modes with the same tidal period. This interpretation awaits further correlative studies.

[35] In summary, the result of our bimonthly mean decomposition of diurnal period oscillations in mesopause region temperature, zonal and meridional winds over Fort Collins, Colorado (41°N, 105°W), using lidar data between May 2002 and April 2003 was presented. This work represents the first comprehensive study of this type based on observational data which measures both temperature and horizontal wind with good height resolution. However, because of the still somewhat limited duration of the data set and the day-to-day variability of the diurnal tide, it is still too early to consider this a true climatology. We plan to continue the same data acquisition mode for about two additional years. At that time, we should have enough data to credibly assess the tidal variability, and to bin the data every month to match the resolution of tidal models.

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