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Terdiurnal oscillations in OH Meinel rotational temperatures for fall conditions at northern mid-latitude sites

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Abstract. High-precision (~0.5 K) measurements of OH Meinel (M) (6,2) rotational temperatures above the Bear Lake Observatory, UT (42°N, 112°W) during October 1996 have revealed an interesting and unexpected mean nocturnal pattern. Ten quality nights (>100 h) of data have been used to form a mean night for autumnal, near-equinoctial conditions. The mean temperature and RMS variability associated with this mean night were 203 ± 5 K and 2.4 K, respectively, and compare very favorably with expectations based on Na-lidar measurements of mean tidal temperature perturbations over Urbana, IL (40°N, 88°W) during the fall 1996. Furthermore, this comparison shows that the 8-h tide was the dominant source of the mean nocturnal temperature variability in the OH M region during this period. Additional data, obtained at Fort Collins, CO (41°N, 105°W) in November 1997, illustrate the occurrence of an 8-h component of OH temperature variability about two months after the equinox and show that daily amplitudes as high as ≅15 K are possible.

Introduction

Terdiurnal (8-h) atmospheric tidal oscillations are well established at ground level from studies of meteorological records of surface pressure and temperature [*Chapman and Lindzen*, 1970]. Initial considerations of the propagation of the 8-h tide in the atmosphere resulted in the suggestion that it should be of minor importance at ionospheric heights [*Hines*, 1968]. However, during the two decades following the initial report of 8-h oscillations in meteor-zone winds [*Revah*,1969], a number of upper-atmospheric wind studies, based on meteor and partial-reflection (MF) radar techniques [*Teitelbaum et al.*, 1989], established the terdiurnal component as a ubiquitous property of the wind field in the mesosphere and lower thermosphere (MLT) at northern mid-latitudes.

Recently, *Thayaparan* [1997] has reported the results of an investigation of the terdiurnal tide in the MLT region based on four years of MF wind measurements at (43°N, 81°W). Mean monthly 8-h amplitudes were found to be mostly in the range ≅1-6 ms^{-1}. These amplitudes are modest by near mesopause wind-field standards, but a strong short-term variability was sometimes observed, with daily amplitudes up to 20 ms^{-1} during periods of enhanced 8-h activity. Despite the long history of airglow observations, the recognition of a fairly persistent and occasionally dominant 8-h component of nocturnal variability in the mesospheric airglow emission rates and band rotational temperatures at high latitudes [*Sivjee et al.*, 1994; *Oznovich et al.*, 1995] and mid-latitudes [*Wiens et al.*, 1995; *Taylor et al.*, 1999] is rather recent. The paucity of results for this feature of airglow variability has contributed to the uncertainty in its nature and source(s).

Very recently, we have presented evidence to support a tidal interpretation of a persistent 8-h component of nocturnal variability observed in OH rotational temperatures in the spring and fall at two northern mid-latitude sites [*Taylor et al.*, 1999]. These new results were obtained using a narrow-band CCD imager capable of yielding high-precision (<1 K) OH temperatures on a time scale of 30 min. At the time of the report, only two autumnal 8-h wave events had been analyzed, both of which exhibited characteristics in good accord with expectations for the 8-h tide in the OH M region [*States and Gardner*, 2000]. However, the data set was inadequate for an unequivocal tidal interpretation.

In this letter, we present 10 nights of high-quality OH M (6,2) rotational temperatures, obtained at Bear Lake Observatory (BLO), UT, during the period October 5-17, 1996 using the same instrument described by *Taylor et al.* [1999]. The goal of this study is to define the mean near-equinoctial nocturnal temperature pattern above BLO for fall conditions and to compare it with expectations based on: (i) the seasonal Global Scale Wave Model (GSWM) and (ii) effective tidal parameters for the OH Meinel region at 40°N. We also present a 4-day set of OH temperatures, obtained at Fort Collins, CO in November 1997, to illustrate a period of strong 8-h activity with daily amplitudes up to 15 K. These new results are of special interest since they provide additional evidence for the occurrence of short-term enhancements of the 8-h tidal component at near-mesopause heights [*Thayaparan*, 1997].

OH M Temperature Measurements

The OH M (6,2) temperatures were determined using a recently-developed Mesospheric Temperature Mapper (MTM) [*Taylor et al.*, 1999]. Basically the MTM is a narrow-band ($\Delta\lambda \cong 1.2$ nm) CCD imager with a 75° field of view. In order to attain the large S/N ratios required in our study, the image data were binned on chip from the original 1024 x 1024 pixels to 128 x 128 superpixels, each with a zenithal footprint at 87 km of about 0.9 km x 0.9 km. In the present application, only the central 5 x 5 superpixels of the array were used for temperature determinations. This is the part of the chip which has been used in comparative studies with Fourier spectrometers and Na temperature lidars, both of which typically sample a limited spatial region in the zenith.

In operation, three sequential one-minute exposures were made using filters with center wavelengths of 840 nm [$P_1(2)$ λ-doublet], 846.5 nm [$P_1(4)$ λ-doublet], and 857 nm (background) for each temperature measurement, resulting in an effective sampling rate of ≅ 18 h^{-1}. Rotational temperatures were computed using the ratio method, fully described by

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Meriwether [1975] for the (8,3) band. A value 1.300 was adopted for the ratio of transition probabilities, $A[P_1(4)]$ / $A[P_1(2)]$, pertinent to our rotational temperature determinations. This value follows from the recently-updated line parameters for the Meinel system of the OH radical [*Goldman et al.*, 1998; personal communication, 1999]. In addition, the $P_1(2)$ intensities were corrected for Q(5) contamination which was estimated to be ≅2% at a temperature of 200 K. Comparisons of the MTM temperatures with those obtained by other well calibrated instruments (Na temperature lidars and FTIR spectrometers) indicate that our absolute temperatures are probably reliable to ±5 K. However, the focus of this report is temperature changes which are determined with a precision ~0.5 K in 1 h for typical OH M emission levels.

Observations and Analyses

During the period October 5-17, 1996, the MTM was operated at BLO in support of coordinated data collection events by the Midcourse Space Experiment (MSX) satellite [*Mill et al.*, 1994]. Favorable conditions prevailed during the data collection window, yielding ten high-quality data sets (average length ≅10 h). For subsequent analyses, each data set was averaged using 15, 30, and 60-min bins providing three time series of about 40, 20, and 10 temperatures, respectively.

An examination of the derived OH M temperature time series indicated that during several nights a single sinusoid, with a period less than the length of the data set, dominated the variability. This interesting feature is illustrated in Figure 1 using raw (3-min) temperatures obtained on the night of 6-7 October. Excellent viewing conditions in the zenith throughout the night resulted in 194 temperatures during the 10.2-h data window. Typical statistical error bars are given near the maximum, minimum, and the zero (mean level) crossings. The curve reflects a best-fit 4-parameter model consisting of a constant term plus a sinusoid of unknown amplitude, phase, and periodicity. The periodicity was determined to be ≅ 8.7 h.

To investigate this long-period oscillation, the data were smoothed using one-hour bins, centered on the half-hour. The resultant time series is shown in Figure 2 where the estimated statistical uncertainty associated with each sample is indicated. The curves labeled 6, 8, and 12 h follow from

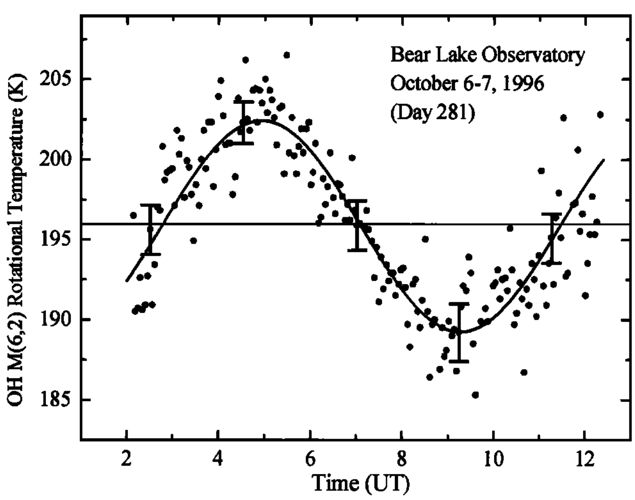

Figure 1. Time series of raw (3 min) OH M (6,2) temperatures obtained at BLO on October 6-7, 1996, illustrating a quasi-monochromatic wave event of periodicity 8.7 ± 0.7 h.

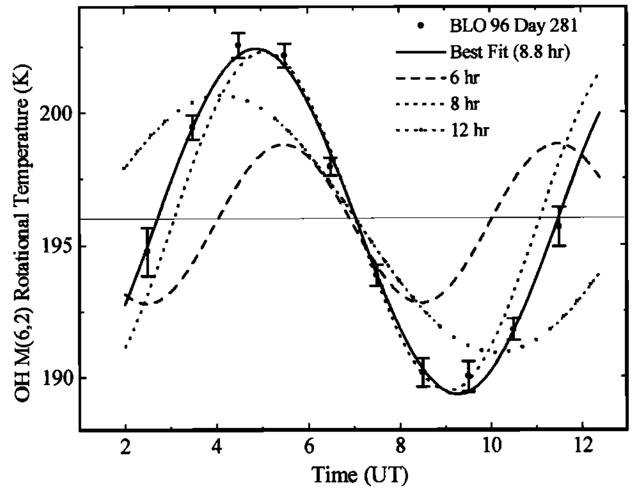

Figure 2. Time series of hourly-averaged rotational temperatures for Fig.1 with estimates of statistical uncertainty and least-squares fits based on four simple models.

least-squares fits using 3-parameter models consisting of a constant term and a sinusoid of fixed period (τ) but unknown amplitude (A_T) and phase (ϕ_T). The "best fit" curve is based on a 4-parameter model which treats the period as an additional free parameter. Final parameters are given in Table 1 together with confidence intervals, reduced chi-square (χ_r^2) values, and coefficients of determination (r^2). The clear failure of the 6-h and 12-h curves of Figure 2 to pass within two sigma of many of the data points provides qualitative evidence that these models do not adequately represent the data. This assessment is quantitatively supported by statistical parameters in the table. For example, the reduced chi-squares (χ^2 / degree of freedom) for the 6 and 12-h models are about 71 and 20, respectively. As emphasized by *Wong* [1992], reduced chi-squares ≤1 are expected for good fits. Hence, it is not surprising that both the 6 and 12-h models failed the statistical tests for significance based on critical levels associated with χ_r^2 and r^2. The 8-h model also failed the tests, but the reduced chi-square for this model was much smaller and was dominated by contributions from points near the ends of the data record (at dusk and dawn) where background corrections are more difficult. In comparison, the best-fit model, with a period of 8.8 h and a 2-sigma statistical uncertainty of about 0.4 h, is characterized by χ_r^2 = 0.82.

Figure 3a shows the nocturnal pattern of 30-min-averaged rotational temperatures for each of the ten nights of quality data. To illustrate the full geophysical variability, the data have not been normalized. It is clear that a significant fraction of the apparent variability during this period results from the spread in nightly means, which was ≅15 K. Nightly means were subsequently removed, and a "mean-night" data

Table 1. Parameters for the Models in Figure 2.

Model	A_T(K)	ϕ_T (h UT)	τ(h)	χ_r^2	r^2
3p	3.2±1.6*	5.5±1.7	6	71	0.29
3p	6.4±1.6	5.1±0.5	8	6	0.93
3p	4.9±3.2	4.2±1.6	12	20	0.73
4p	6.6±0.4	4.9±0.2	8.8±0.4	0.8	0.99

*6-h intervals are ± σ; all others are ± 2σ.

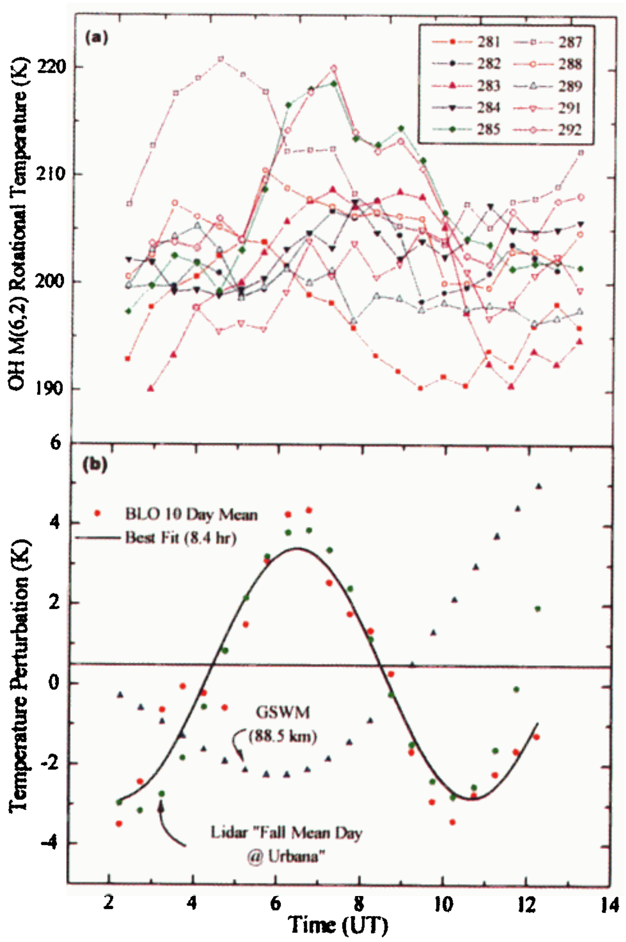

Figure 3. (a) Ensemble of OH temperature patterns (30-min averages) for ten nights of observations (Oct. 5-17) from BLO 1996. (b) Mean-night temperature perturbation obtained from the ensemble with least-squares fit. The GSWM and lidar "fall mean day" simulations are also shown.

set (Figure 3b, red circles) was formed by averaging the samples in each 30-min bin. The 3-month-seasonal temperature perturbation for fall based on GSWM is shown by the blue triangles, and the results of a tidal simulation (see discussion) based on Na wind/temperature lidar results for mean tidal perturbations over Urbana, IL during the fall of 1996 is given by the green circles.

The curve in the figure reflects a 4-parameter fit to the data. Final values for the parameters are given in Table 2 together with statistical information. The period of the sinusoid, (8.4 ± 0.5) h, strongly suggests a terdiurnal tidal interpretation and the residuals (not shown) suggest a modest contribution from a shorter-period oscillation. Attempts to fit the mean-night data with 6 and 12-h sinusoids were unsuccessful at the adopted confidence levels, as in the case of day 281 (see Figure 2). The limitation of our near-IR observations to a ~10-h nocturnal data window precludes a unique decomposition of the mean-night temperature pattern into tidal components, but the quality of the "8-h" fit in Figure 3b provides strong evidence for the dominance of this component.

Table 2. Parameters for the Models in Figures 3b and 4.

Model	A_T(K)	ϕ_T (h LST)	τ(h)	χ_r^2	r^2
3b	3.2±0.5*	7.4±0.7	8.4±0.5	0.72	0.91
4	9.3±1.3	1.3±0.4	8.1±0.5	4.5	0.90

*Intervals are ± 2σ.

To further illustrate this feature, Figure 4 shows a four-day set of 30-min-averaged rotational temperatures obtained with the MTM at Fort Collins, CO during the subsequent fall period (November 26-30, 1997). A 4-parameter harmonic fit to the mean data (filled circles) is characterized again by a periodicity of (8.1 ± 0.5) h, in close agreement with the fall 1996 BLO data. However, in this case, the maximum temperature perturbation occurs near 8.5 UT (or 1.5 LST), and the amplitude of the oscillation is (9.3 ± 1.3) K.

Discussion

The inference of 8-h tidal oscillations in the OH M region above BLO during October 1996 is supported by incoherent-scatter-radar (ISR) data obtained by *Gonocharenko and Salah* [1998] at Millstone Hill, MA (42.6°N, 71.5°W) in connection with the 14th Lower Thermosphere Coupling Study (October 8-12, 1996). Spectra, derived from the ISR-based horizontal eastward winds by the Lomb-Scargle method, exhibited a significant 8-h peak, with a spectral density comparable to that of the 12-h component for altitudes near 100 km. The ISR results, which included neutral temperatures, were limited to altitudes ≥ 95 km, and harmonic analyses were limited to the 12-h component. Nevertheless, these results establish the presence of 8-h tidal oscillations in the 95-130-km region at the time of interest and show that their amplitude was comparable to the 12-h amplitude near the top of the OH M layer, in good accord with lidar-based results at 40°N.

Our hypothesis, i.e. domination of the mean-night variability by the 8-h tide, was tested using appropriate tidal parameters for the OH M region. In particular, the altitude-resolved (0.96-km) mean tidal parameters for the 80 - 105-km region associated with the "mean day for fall at Urbana" [*States and Gardner*, 1998; private communication, 1999] were adopted since their mean day was constructed from measurements in close temporal and latitudinal proximity to those at BLO. Tidal parameters for the OH region were computed assuming a Gaussian layer of 8.0-km width (FWHM) centered at 88.5 km [*Yee et al.*, 1997]. The layer-

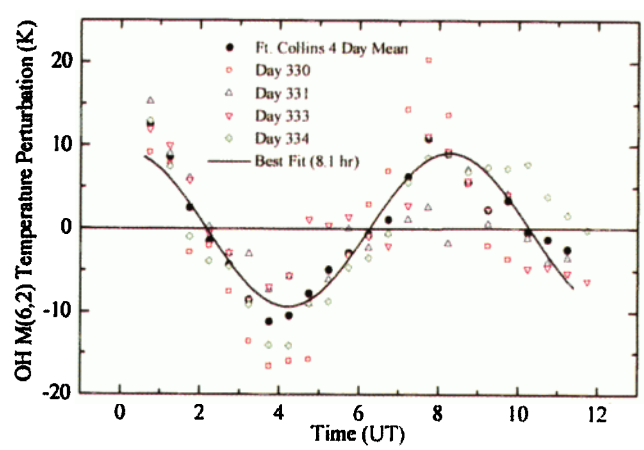

Figure 4. Time series of half-hourly-averaged OH temperature perturbations from Fort Collins, CO (Nov. 26-30, 1997). The four-day mean (black circles) and best-fit (solid curve) are shown (periodicity = 8.1 ± 0.5 h).

averaged values for the amplitude (K) and phase (h LST) of the 8, 12, and 24-h components were found to be (3.4, 7.2), (2.3, 10.5), and (6.4, 8.5), respectively. Comparison of the 8-h results with the MTM-derived terdiurnal parameters (row 1 in Table 2) indicates excellent agreement.

The simulated total tidal temperature perturbation was sampled in accord with the mean-night time series in Figure 3b. The correlation of the simulation and the data was r = 0.60, and the RMS variability of the simulation was 3.2 K, versus the mean-night value of 2.4 K. However, it was found that a two-hour increase in the effective phase of the diurnal tide optimized the agreement of the simulation with the data (Figure 3b), yielding r = 0.89 and an RMS perturbation of 2.4 K. A simulation based on the fall seasonal GSWM is also shown in the figure (blue triangles), but this time series fails to account for the salient features of the mean-night pattern. In particular, the maximum and minimum near 6.5 and 10.5 UT, respectively, features associated with the terdiunal wave component, are not present in the GSWM-based simulation.

The mean-night OH temperature pattern for fall near-equinoctial conditions at BLO was formed from ten nights (>100 h) of MTM temperatures obtained during the period October 5-17, 1996. In comparison, the mean (24-h) day for fall at Urbana was formed from 189 h of Na wind/temperature lidar measurements during a 34-day period (September 10 to October 14, 1996). Our data set did not include the nights of October 5 and 11. Thus, the overlap of the mean-night and mean-day data sets is at most eight days near the end of the mean-day window. In view of these considerations and the known changes in tidal properties during the fall, it is not surprising to find some differences in tidal properties between the mean night and mean day data sets. However, *States and Gardner* [2000] have shown that the fall (3-month) properties of the terdiurnal tide are nearly identical to those associated with their mean day for fall. Hence, the good agreement of our mean-night results and the terdiurnal properties deduced from the fall lidar measurements is understandable.

Our tidal-perturbation simulations and those of *Taylor et al.* [1999] suggest that the terdiurnal component dominated the nighttime temperature variability in the OH M region near the autumnal equinox in 1996. The latter simulations utilized tidal parameters for the 87-km level from the mean-day study at Urbana [*States and Gardner*, 1998; personal communicat-ion, 1999]. The 87-km (vector mean) phases of the 12 and 24-h components were both ≅10h LST. The superposed temperature perturbation from these components exhibited an almost-constant offset of about -5 K during the nocturnal window leaving the 8-h component, with a peak near local solar midnight, to dominate the variability during the night-time. The layer-averaged 12 and 24-h phases are 10.5 and 8.5 LST, respectively, as previously noted. Hence, the optimization of the current simulation produced by a nominal 2-h increase in phase of the diurnal tide is readily understood on the basis of results described by *Taylor et al.* [1999].

The data in Figure 4 indicate that the daily amplitude of the 8-h component of nocturnal temperature variability in the OH M region can approach 15 K (day 330) and that a 4-day mean amplitude of about 10 K is possible. Both of these short-term amplitudes greatly exceed the mean fall (3.4 K) and winter (3.0 K) 8-h amplitudes reported by *States and Gardner* [2000]. However, the mean phase of our 4-day set (Table 2) is near that expected on the basis of the fall and winter measurements at Urbana. Finally, we note that these large 8-h temperature-perturbation amplitudes provide independent evidence to support the strong, short-term enhancements of 8-h daily amplitudes in the near-mesopause wind field reported by *Thayaparan* [1997].

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