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Annual and semi-annual temperature oscillations in the upper mesosphere

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Abstract. Fourier transform spectrometer observations of the mesosphere have been performed at the University of Michigan (latitude: $42^1/_2$ N) on a long term basis. A database of near infrared Meinel hydroxyl spectra has been accumulated from which rotational temperatures have been determined. Harmonic analysis of one-day averaged temperatures for the period 1992.0 to 1994.5 has shown a distinct annual and semi-annual variation. Subsequent fitting of a five term periodic function characterizing the annual and semi-annual temperature oscillations to the daily averaged temperatures was performed. The resultant mean temperature and the amplitudes and phases of the annual and semi-annual variations are shown to coincide with an emission height slightly above 85 km which is consistent with the mean rocket derived altitude for peak nocturnal hydroxyl emission.

Introduction

There has been a marked improvement in techniques for measuring the temperature in the mesosphere during the past decades. *Groves* [1972] analyzed a series of rocket and meteor radar observations of zonal winds at various latitudes to provide an altitudinal model between 60 and 130 km as a function of seasons and latitude. Annual, semi-annual, and prevailing components of the zonal wind were extracted from which related temperature harmonics were deduced. Satellite-borne SAMS (Stratospheric and Mesospheric Sounder) measurements of zonally averaged temperature were used by *Delisi and Dunkerton* [1988] to study the seasonal variation in the semi-annual oscillation. More recently, improvements in LIDAR technology have enabled temperature profiles to be monitored on a more routine basis [*Gardner et al.*, 1989].

Advances in miniaturization and elimination of cryogenic cooling requirements has recently made possible the use of near infrared Fourier spectroscopy as a long-term solution for remote monitoring of the mesosphere. Pioneering efforts such as *Lowe* [1969] demonstrated the utility of this technique for observing nocturnal terrestrial airglow emissions. Neutral temperatures and gravity wave signatures can easily be monitored employing the near infrared measurements [*Niciejewski and Yee*, 1991; *Wiens et al.*, 1993].

The upper mesosphere and lower thermosphere are home to a number of distinct airglow layers which provide an elegant and simple method of characterizing the thermodynamics at these altitudes. Difficulties in the assignment of absolute altitudes to these emissions has tended to diminish their acceptance within the community as thermodynamic diagnostic monitors. Regardless, programs for regular observation of nocturnal airglow emissions have been ongoing for many decades [eg. *Shefov*, 1969], and their interpretation provides a method of characterizing long term behaviour such as annual variations and its harmonics. The existence of semi-annual oscillations in the middle atmosphere has been generally accepted since the 1960s, though their characterization has yet to be completed [*Delisi and Dunkerton*, 1988]. The characterization of other harmonics such as terannual and quasi-biennial are even more uncertain and require additional observations and theoretical justifications [*Fukuyama*, 1977].

This paper presents the first results of a long term study of the hydroxyl emission above a mid-latitude aeronomical observatory near Ann Arbor, Michigan. Continuous nightly measurements were initiated in early 1992 and are continuing at present. In addition, intermittent observations during the preceding three years also provide additional coverage though these data sets shall not be discussed here [one such example of an anomalously large mesospheric temperature enhancement is communicated by *Meriwether et al.*, 1994]. For the present study, temperature measurements were determined from three resolved rotational features of the Meinel OH (3-1) band. Nightly averages were constructed for the temperatures, analyzed for long term periodicities, and then fit in the best least squares sense to a function describing the periodicities - a mean temperature term, and terms describing annual and semi-annual temperature oscillations.

The annual and semi-annual variations of temperature in the stratosphere and mesosphere of the northern hemisphere originally derived by *Groves* [1972] have recently been supplemented by the satellite data described in *Clancy et al.* [1994]. In the study described presently, the temperature data tabulated by *Clancy et al.* [1994] have been subjected to the same least squares reduction applied to the ground based Fourier transform spectra in order to map the mean temperature and the annual and semi-annual temperature oscillations above south-east Michigan. The periodic characteristics extracted from the ground based data match well with the satellite temperature data for an altitude in the range 85 - 88 km at the latitude of the ground station ($42^1/_2$ N). This derived altitude for the ground based hydroxyl observations is consistent with that obtained from the series of sounding rocket-borne photometric measurements for the altitude of peak hydroxyl volume emission rate, and consequently supports the thesis that ground based nocturnal hydroxyl observations do sample the thermodynamic behaviour of the upper mesosphere.

Results

The Fourier transform spectrometer as well as the temperature determination technique have been previously described in *Niciejewski and Yee* [1991]. In the current configuration, the spectrometer was placed approximately fifteen feet beneath a transparent type-G unshrunk Plexiglass acrylic dome. A truth sample of the dome material has been saved and characterized

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for absorption in the near infrared, primarily due to water vapour, and corrections to the near infrared hydroxyl spectra are routinely applied prior to data reduction. A small, forced air, radiative space heater is used to prevent condensation from forming on the surface of the dome. Since the experiment operates continuously and is unattended, cloud cover records are required to extract spectra from clear viewing periods. These records are generated on the hour by meteorologists at Detroit Metro Airport, approximately 30 miles from the observing site. The temperature of the room enclosing the spectrometer is kept to within two degrees of its set point by an active air conditioning/heating control system. This provides a very stable ambient environment for the experiment eliminating any wandering of the ZPD (zero path difference) position of the individual interferograms. In this study, nearly 10 million interferograms were recorded from which were generated nightly mean temperature and hydroxyl intensity, though only the temperature data shall be discussed in this report.

Figure 1 displays the time series of temperature for the period 1992.0 to 1994.5. The Fourier transformed spectra were automatically corrected for Plexiglass absorption and then reduced to OH temperature and intensity pairs at the rate of one pair per ten minutes. The measurement error is dependent primarily upon signal strength, with ±5K being a representative temperature uncertainty. The cloud cover database was then used to extract pairs during clear and mainly clear sky periods. A nightly average was then constructed only if there were more than four hours of good sky conditions which corresponds to about one half of the night during the summer solstice. Unfortunately for this study, the experiment was temporarily relocated during the summer of 1992 to support a high latitude noctilucent cloud sounding rocket campaign, though the inclusion of the data gap has no detrimental effect on results reported here. The time series in Figure 1 includes the mean value as well as the standard error of the mean for each acceptable night. As expected, an annual trend in the temperature is discernable.

The temperature time series also displays higher frequency variations primarily at gravity wave and planetary wave periods when displayed on a nightly basis (not shown here). The former are being studied in the context of all sky morphological images and line of sight Doppler wind measurements and shall be the subject of a future report. In Figure 1, they are responsible for portions of each of the nightly "standard error of the mean" error bars. The semi-diurnal tide also contributes to the standard error though theoretical models such as *Forbes and Vial* [1989] suggest the effect to be ≤3K when calculated on a monthly basis.

In order to quantitatively characterize periodic geophysical signals in the temperature time series, the Lomb-Scargle solution to the "missing data" problem was employed [*Press and Teukolsky*, 1988] - standard Fourier techniques were inappropriate for the time series for obvious reasons. The frequency power spectrum indicates significant power (above the .001 significance level) at frequencies of 1 and 2 yr^{-1} corresponding to an annual and a semi-annual oscillation, the former being clearly visible in Figure 1.

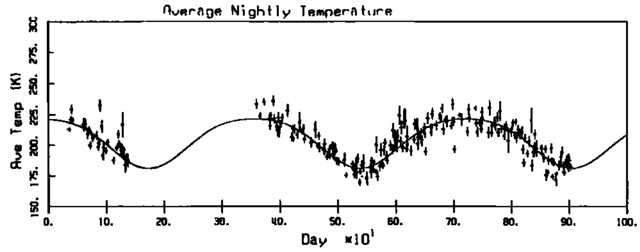

Fig. 1. Mean nightly hydroxyl rotational temperature with standard error for a two and a half year interval from 1992.0 above south-eastern Michigan. Measurements acquired during cloudy periods have been excluded. The instrument was temporarily moved to a high latitude site for the summer of 1992. The solid line corresponds to the temperature time series fit from Table 1.

TABLE 1. Least squares fit results for the temperature time series. The fit was performed both including and excluding the semi-annual frequency. The mean temperature and the amplitudes and phases for the annual and semi-annual fit are shown.

MEAN		
amplitude	204.0 ± .2 K	
ANNUAL OSCILLATION		
amplitude	20.1 ± .3 K	
phase	-.28 ± .02 month	
SEMI-ANNUAL OSCILLATION		
amplitude	3.1 ± .3 K	
phase	2.71 ± .10 month	
	FIT w/ SEMI-ANNUAL TERM	FIT w/o SEMI-ANNUAL TERM
number of degrees of freedom	250	252
reduced chi-square	4.41	4.77

The time series was then fit to the approximation

$$C(t) = a_0 + \sum_{i=1}^{2} \left(d_i \sin \frac{2\pi i}{365.25} t + e_i \cos \frac{2\pi i}{365.25} t \right)$$

where $C(t)$ is the observed nightly average temperature, a_0 is the mean temperature, the d_i and the e_i are the amplitudes of the i^{th} harmonic, i is the harmonic number, and t is the day number enumerated from January 0, 1992. The temperature values were weighted with their corresponding uncertainties. The standard technique was used to construct the amplitude and the phase for the fitted annual and the semi-annual oscillation which appear in Table 1. The phase is interpreted as the fractional month (365.25/12) for which the specific oscillation has a positive peak, ie. late December for the annual oscillation and late March (September) for the semi-annual oscillation. The resultant least squares fit is shown as the solid curve in Figure 1.

Also included in Table 1 are results from a test to determine the significance of the semi-annual term. The magnitude of the semi-annual oscillation is small but its significance may be tested as follows: formulate a null hypothesis that the semi-annual term is zero, that is the terms $d_2 = e_2 = 0$, and test this against an alternative hypothesis that the semi-annual term is non-zero [see eg. *Walpole and Myers*, 1972]. The probability of rejecting the null hypothesis when it is true, ie. committing a decision error, may be evaluated for a specific level of significance. The measured temperature data set and the evaluation of the null hypothesis requires the establishment of a critical region for the semi-annual set using the F distribution. Using

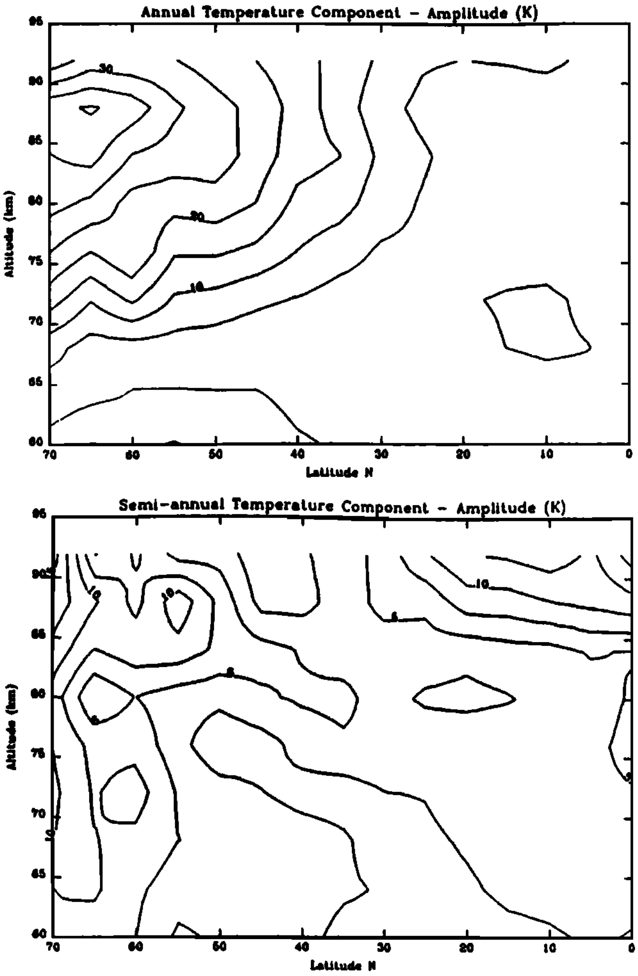

Fig. 2. a) Meridional cross-section of the amplitude of the annual component of temperature for the northern hemisphere derived from *Clancy et al.* [1994]. The contours are drawn at 5K intervals. b) Same but for the semi-annual component, with contours drawn at 2.5K intervals.

the F test at the .01 level of significance, the critical region for the temperature measurements occurs when $|F| \geq 4.61$. The evaluation using the reduced chi-square values in Table 1 gives $f = [(4.77*252 - 4.41*250)/2]/4.41 = 11.3$. Since this evaluation falls within the critical region, then the null hypothesis may be rejected and it can be concluded that the magnitude of the semi-annual term is non-zero. Consequently, even though the magnitude of the semi-annual oscillatory term is small, it is false to conclude that it is zero based on statistical tests of the model fit to the temperature data.

Discussion

Ground based hydroxyl observations always measure a columnar emission rate heavily biased towards the peak emission altitude and it is difficult to assign an altitude, let alone assume a stable altitude for the emission, a skepticism that is prevalent throughout the aeronomical community. Long term observations of the nocturnal hydroxyl airglow have been performed for many decades, though the literature does not provide many examples of presentations of long term trends in the data sets. This current study, organized primarily for the display of long term trends is capable of addressing the issue of altitude and stability of the altitude of the hydroxyl emission from examination of the annual and semi-annual temperature trends, ie. given an empirical model of altitudinal temperature profiles accumulated for all seasons, do the ground based Fourier measurements concur, and if so, for what altitude or range of altitudes?

The recent contribution by *Clancy et al.* [1994] provides a composite global climatology of temperature in the 40 to 92 km altitudinal range from SME satellite-borne limb profile observations. The climatology data is tabulated monthly for latitudes ranging from 75°S to 75°N at increments of 4 km altitude and 5 degrees latitude. The temperature data for each altitude and latitude for the northern hemisphere section have been fit to the same five term time series applied to the ground based measurements. Figure 2 displays the resultant annual and semi-annual amplitudes corresponding to the *Clancy et al.* [1994] climatology. The correspondence between *Clancy et al.* [1994] and *Groves* [1972] for the annual amplitude variations is similar for the altitudes in which they overlap. Regarding the semi-annual oscillation, the *Clancy et al.* [1994] climatology generally provide slightly lower amplitude values compared to *Groves* [1972]. The mean temperature diagram (not shown here), however, is about 10 to 15K warmer than *Groves* [1972] for upper mesospheric altitudes, and as *Clancy et al.* [1994] point out, CIRA86, though the correspondence at the lowest overlapping altitudes (≈60-70 km) is quite good.

A close-up of the annual phase variation derived from the *Clancy et al.* [1994] climatology is shown in Figure 3 (semi-annual not shown here). The full display is similar to *Groves* [1972] with a slow and steady gradient in the mesosphere at middle latitudes. The enumeration is indicated as month into the year, with January 0 equivalent to 0.0. The annual phase variation decreases monotonically as altitude increases with a range of about one month for the heights shown. The uncertainty in the least squares fit is about ±0.4K for the temperature amplitudes and ±.03 month for the annual phase.

The ground based Fourier measurements summarized in Table 1 can be directly matched against the satellite climatology for the station's latitude. The annual temperature amplitude component in Figure 2a) matches approximately in the range 85 - 88 km, while the semi-annual component matches near 86 km. Regarding the phase value, the annual term has a match near 87 km. Unfortunately, the semi-annual phase extracted from the *Clancy et al.* [1994] data at high altitudes near 40N latitude is difficult to interpret, undergoing a sign change. Referring to *Groves* [1972], a semi-annual phase of late March is

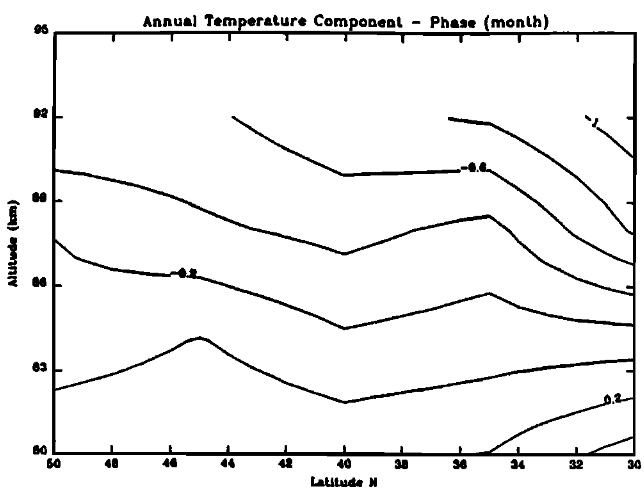

Fig. 3. Meridional cross-section of the phase of the annual component of temperature for the northern hemisphere derived from *Clancy et al.* [1994]. The contours, drawn at 0.2 month intervals, represent the month of the positive peak of the annual oscillation with January 0 equivalent to 0.0.

consistent with an altitude near 85 km for the station latitude. Considering the satellite data sets are zonal means and that the observation periods do not overlap between the satellite-borne and the ground based measurements, the close match between the four components is an encouraging sign that the ground based observations do sample the upper mesosphere above 85 km and likely not much higher than 88 km. This result is also consistent with the mean altitude for the height of the peak hydroxyl volume emission rate averaged over 34 rocket flights: 86.8 ± 2.6 km [*Baker and Stair*, 1988].

Finally, the mean temperature derived from the periodic analysis of the *Clancy et al.* [1994] climatological data set matches the present observations in Table 1 very well, assuming hydroxyl emission occurs slightly above 85 km altitude. The minimum mean temperature obtained from the least squares analysis for pertinent latitudes is 202.9K at 84 km altitude at 45°N latitude.

Conclusions

To summarize, the present set of ground-based observations provide information relating to the amplitude and phase of both the annual and the semi-annual oscillation in mesospheric temperature in addition to the mean temperature value. Judging simply by the annual phase value and the rapid variation of this phase with altitude through the mesosphere, this long term, ground based, optical data set places the hydroxyl emission near the nominal *in situ* observed altitude. Additional evidence from the amplitude of the annual oscillation as well as the weaker semi-annual oscillation strengthen this conclusion.

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