5-15-1996

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Observation of a quasi 16-day oscillation in the polar summer mesospheric temperature

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Abstract. Night-time measurements of the hydroxyl Meinel (3,1) rotational band were used to infer the mesospheric temperature over Scandinavia from June through August, 1992. The resulting temperature time series showed spectrally-distinct, statistically-significant fluctuations with periods between 2 and 16 days, although only the 16-day oscillation will be discussed here. The period, amplitude and temporal history of this wave agree with model predictions and radar wind measurements of the (1,3) Rossby normal mode, and are therefore consistent with its identification as the temperature signature of this mode. The relationship of these summer temperature oscillations and the occurrence of noctilucent clouds is discussed.

Introduction

The summer polar mesosphere is partially shielded from westward-propagating waves by the filtering effect of the underlying easterly stratospheric flows [Lindzen, 1981]. In addition, the breaking of eastward-propagating gravity waves in the lower mesosphere retards the mean flow creating the strong up-welling that cools the mesopause [Lindzen, 1981]. As a result, water vapor near the mesopause can condense into clouds, which, when they remain sualit and visible against the dark twilight sky, are known as "night-shining" or Noctilucent Clouds (NLC).

Thomas [1991] has provided a review of the theoretical mechanisms thought to be responsible for mesospheric cloud formation. For typical summer mesospheric conditions, nucleation and particle growth will occur when the temperature is below the saturation point of 140-145 K [Thomas, 1991]. The growth- sedimentation models of Turco et al. [1982] and Jensen and Thomas [1988] show that under these conditions, it takes several hours to a day for the particles to grow to an optically visible cloud. However, the particles will sublimate in as little as a few minutes as temperatures exceed 150 K.

In an effort to reconcile measurements showing a warm mesopause (>150 K) in the presence of NLC [Taylor et al., 1995] it has been speculated that the cloud formation process requires the presence of short-vertical-wavelength gravity waves in the mesosphere to structure the temperature profile [Philbrick et al., 1984]. Thus, clouds could form in the cold minima while keeping the average temperature high. However, Turco et al. [1982] found that such gravity waves eroded an NLC due to the hysteresis associated with the disparate growth and sublimation rates. In contrast, Jensen et al. [1989] found that long-period waves (τ~1 Day) with temperature amplitudes ~7 K enhanced nucleation without significantly eroding the NLC. Similarly, Thomas [1991] suggested that planetary waves could play a role in NLC formation.

Planetary waves signatures in the high-latitude summer mesopause winds and temperatures have been predicted to occur [Dickinson, 1968; Wu and Miyahara, 1988; Forbes et al., 1995]. Williams and Avery [1992] have observed oscillations with nominal periods of 5, 16, 1.8 and 2 days in measurements of the neutral winds during the polar Summer, and have identified these as consistent with the dominant (1,1), (1,3), (2,0) and (3,0) Rossby normal modes, respectively. However, to date there have been no corresponding measurements of the temperature amplitude of these waves in Summer. In this report we present observational evidence of a quasi 16-day oscillation in the ground-based measurements of the mesospheric temperature made from Scandinavia during the NLC seasons (June through August). The temperatures were derived from spectral measurements of the hydroxyl (OH) Meinel band, and were accompanied by ground-based observations of NLC. The temporal behaviour of the period and amplitude of the oscillation will be presented and compared with the wind results of Williams and Avery [1992].

Measurements and Analysis

Observations and Instrumentation

Hydroxyl nightglow spectra were used to derive rotational temperatures, which were taken to be the average neutral temperature over the 8 km thick OH layer centred near 87 km [Baker and Stair, 1988]. During 1992, measurements were made from mid-June through late-August (UT Days 170-235) at Stockholm (59.5°N, 18.2°E) in order to observe the temporal behaviour of OH temperatures during the polar Summer. A compact Michelson interferometer was used to scan the spectral region between 1000 and 1700 nm at ~0.5 nm resolution. Interferograms were rapidly scanned and coherently summed to provide an integration time of ~5 minutes per spectrum. After processing the interferograms using the techniques detailed by Espy et al. [1995], the spectral and wavelength calibrations were applied, and the rotational temperature of the OH Meinel (3,1) band near 1530 nm was fit.

Rotational Temperature Analysis

The technique used to fit rotational temperatures to the measured spectra is described in detail by Espy et al. [1995]. In brief, the spectral region containing the P and Q branches of the (3,1) Meinel vibration-rotation band was synthesized by con-
vollving the instrumental line-shape function with the line strengths of Mies [1974], a Boltzmann model of the rotational-level population, and a model scattered solar spectrum [Berk, 1989]. The rotational temperature, integrated band strength and a scaling for the solar scatter were then adjusted to give a best, least-squares fit to the data. In order to remove the contribution of continuum radiation, both the data and the model were high-pass filtered before fitting. The statistical uncertainty in the individual fits of integrated band radiance and rotational temperature was typically 2-3%.

**Time-Series Analysis**

After sunset, the hydroxyl band radiance can vary by up to a factor of two as O3 comes into photo-chemical equilibrium. However, the OH rotational temperature generally displays little (<1%) dependence on solar zenith angle throughout the night. In addition, thin tropospheric clouds can rapidly diminish the hydroxyl intensity without appreciably changing the measured rotational temperature. Thus, due to the rapidly changing range of zenith angles encountered during the night in the polar Summer, and in order to avoid the effects of tropospheric clouds, only the OH rotational temperature was used in this analysis of long-period (>2 day) waves.

In order to perform the time-series analysis, the data were integrated throughout the night to provide an average OH temperature. Each nightly average contained between 20 and 80 individual temperature determinations, each with a statistical uncertainty of 2-3%, so that the statistical uncertainties of the resulting nightly averages were <1%. Temperature variations due to the non-uniform sampling of the diurnal and semi-diurnal tides throughout each night were calculated using the model results of Hagan et al. [1995]. Although these variations were approximately 0.28 K (0.2%), the shortest data set (day 222) was biased by as much as 1.8 K (1%). As shown in Figure 1, only 6 (of 66) days were missing from the data, and long-period oscillations are evident, particularly at the start of the data set. Specifically, there is a strong, albeit damped, quasi-16-day fluctuation evident with minima near days 175, 190, and 205.

Due to the gaps in the data, a Lomb-Scargle (LS) periodogram analysis was used to model the spectral content of the data [Press and Rybicki, 1989]. A linear fit, shown by the dashed line in Figure 1, was subtracted from the data to remove DC offsets and trends whose periods were commensurate with the data set length [Kennedy, 1980]. This was necessary to minimize spectral leakage and to preserve the probability distribution of the periodogram [Scargle, 1982; Horne and Baliunas, 1986], although the time-domain variance was calculated using one less degrees of freedom to account for the subtraction of a linear trend rather than a simple mean. The resulting LS spectral estimates, normalized by the time-domain variance, are shown in Figure 2 and exhibit a peak at 15.3-days. Additionally, probability levels are shown in Figure 2 which indicate the confidence with which one may reject the null hypothesis that a spectral amplitude occurred as a result of random-noise fluctuations in the time-domain data. Thus, the peak at 15.3-days has less than a 3% probability of being caused by random noise.

It should be noted that the spectral estimates of the periodogram are normalized by the total variance of the time-domain data, which includes the variability of the large-amplitude, statistically-significant periodic component [Horne and Baliunas, 1986]. In addition, the amplitude of the smaller peaks, already diminished from this over-estimate of the variance, can be further affected by spectral leakage and side-lobe beating from the large amplitude peak [Scargle, 1982]. Thus, the significance levels shown in Figure 2 are rather conservative, and apply only to the largest amplitude peak in the periodogram [Horne and Baliunas, 1986; Bütter et al., 1994].

Due to the short length of the data set, just over four cycles of the significant periodogram peak, an independent model of the spectral content of the data based on the Maximum Entropy (ME) technique was also used [Berg, 1975; Reid, 1979; Barrodale and Erickson, 1980; Fougere, 1985]. This model has the advantage that it does not suffer from side-lobes or spectral leakage, and its spectral estimates have inherently higher signal to noise than those of the LS periodogram [Fougere, 1985]. In addition, it was designed for short sample harmonic processes [Berg, 1975], and has been shown to be effective in detecting periodic components in data which contain as little as 0.25 cycles [Barrodale and Erickson, 1980]. However, as this analysis requires evenly spaced data, the missing data were linearly interpolated. Eight autoregressive (AR) coefficients minimized the log-likelihood error estimate [Makhoul, 1975], and were found to be significant using the test suggested by Reid [1979]. The ME spectral estimates, normalized by the modified time-domain variance, and the significance level at which one may reject the null hypothesis that a spectral estimate represents a cyclic trend in the data [Reid, 1979], were calculated. In agreement with the LS estimate, the ME analysis shows that the peak at 15 days cannot be rejected at the 95% confidence level.

![Figure 1. Nightly average hydroxyl rotational temperatures (solid symbols). Linear trend is shown as dashed line, and band pass filtered 16-day wave by solid line. Symbols marked with a large X indicate nights when NLC were observed.](image-url)

![Figure 2. Lomb-Scargle periodogram of the temperature data less linear trend shown in Figure 1. Significance levels shown apply only to the peak at 15.3 days.](image-url)
Results and Discussion

As may be seen from the spectrogram in Figure 3, the period of the nominal 16-day oscillation in temperature is nearly constant at ~14 days until late in the third week of July (UT day 199). This is similar to the behaviour seen in the wind field by Williams and Avery [1992], who in 1984 observed a nearly stable 14 day period that abruptly shifted to longer periods near the end of July. In a similar fashion, the peak amplitude of the temperature wave seen here occurs at the start of the second week of July (UT day 188), rapidly decreasing thereafter. Once again, this behaviour is mirrored of the wind data of Williams and Avery [1992], who observed the maximum amplitude occurring between the second and third week of July, followed by a rapid decrease in amplitude. Finally, the interpolated data of Figure 1 were band passed filtered to isolate the 16 day component, using the spectrogram results to ensure the entire frequency range of the wave was passed. These results, with the linear trend restored, are indicated by the solid curve in Figure 1, and show a maximum temperature amplitude of 5 K, in agreement with the modeling predictions of Forbes et al. [1995]. Thus, given this
correspondence with theoretical predictions and wind measurements of the magnitude and temporal behaviour of the period and amplitude, these results would appear to be consistent with the temperature signature of the of the least damped 16 day mode, the (1,3) Rossby normal mode [Salby, 1981].

The sharp decrease in the temperature amplitude observed near UT day 214 corresponds to the last NLC observed from the ground at Stockholm. In addition, the WINDII instrument aboard the UARS satellite observed a rapid disappearance of mesospheric aerosols during this same period [G. Shepherd, personal communication, 1993]. Thus, the same mechanisms that warm the mesopause to end the NLC season would also seem to affect the amplitude of the 16 day wave. Surprisingly, the NLC observations shown in Figure 1 tend to occur during the warm phases of the 16 day wave. This de-coupling of the OH temperatures from the NLC could result from the altitude of the OH layer changing out of phase with the temperature at the mesopause, or it could indicate that the nucleation and growth of the aerosols takes place poleward of the observations where the phase and amplitude of the 16-day wave is not known. Hence, given the present observations, it is not possible to quantify the effect that the temperature fluctuations associated with the 16-day wave have upon the NLC nucleation and growth.

Acknowledgments. This work was supported by the International Meteorological Institute, Stockholm University, and by grants from the National Science Foundation (ATM-8801175 & ATM-9302481) and the National Aeronautics and Space Administration (NAG-1-1334). The authors are indebted to the staff of the Department of Meteorology at Stockholm University, particularly Drs. J. Stegman and D. Murtagh, for their logistical support and helpful discussions.

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