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Observations of the 5-day planetary wave in PMC measurements from the Student Nitric Oxide Explorer Satellite

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[1] The Student Nitric Oxide Explorer (SNOE) satellite has been observing Polar Mesospheric Clouds (PMCs) since 1998 and has successfully measured seven PMC seasons. In the summer seasons, the Ultraviolet Spectrometer (UVS) limb measurements include detections of PMCs between 80 – 90 km. SNOE observations of PMCs have a significant advantage over other PMC measurements in that it can observe them globally each day. Because SNOE orbits the earth 15 times a day, daily global images of PMC brightness may be produced. Variations in the PMC brightness with a 5-day period are observed from the measurements. The 5-day wave is observed in both the northern and southern hemisphere polar summers at high latitudes. This is the first direct global scale wave analysis performed on PMC measurements and indicates the effects of dynamics on PMC formation. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3384 Meteorology and Atmospheric Dynamics: Waves and tides. **Citation:** Merkel, A. W., G. E. Thomas, S. E. Palo, and S. M. Bailey, Observations of the 5-day planetary wave in PMC measurements from the Student Nitric Oxide Explorer Satellite, *Geophys. Res. Lett.*, *30*(4), 1196, doi:10.1029/2002GL016524, 2003.

1. Introduction

[2] Polar Mesospheric Clouds (PMCs) are layers of ice particles which form in the cold summer mesosphere at high latitudes between 80 and 90 km [*Hervig et al.*, 2001]. PMCs are detected in the cold summer mesosphere in the three-month period around summer solstice in each hemisphere. The formation of PMCs is directly dependent on the available humidity, temperature and nucleation sites and therefore should serve as a visible sign of change in any of these parameters. PMC occurrence and brightness are extremely variable and are thought to be a direct effect of dynamical changes in the summer mesosphere.

[3] The formation of PMCs appears to be influenced by transient atmospheric motions. Planetary wave signatures in the mesosphere region, specifically 5-day oscillations, have been observed in radar wind observations [*Williams and Avery*, 1992; *Jacobi et al.*, 1998], SME satellite measurements of ozone [*Rosenlof and Thomas*, 1990], satellite measurements of winds and temperature [*Wu et al.*, 1994; *Talaat et al.*, 2001]; and ground-based observations of noctilucent clouds (NLCs) and radar observations of polar mesospheric summer echoes (PMSE) [*Gadsden*, 1985; *Sugiyama et al.*, 1996; *Kirkwood and Réchou*, 1998; *Kirkwood et al.*, 2002].

[4] Unfortunately, a direct Fourier analysis cannot provide coupled frquency and wavenumber information from ground-based measurements. Therefore the source and global characteristics of the observed oscillation are difficult to characterize. Satellite measurements of PMCs offer additional information on planetary wave influences on mesospheric cloud characteristics. Although other satellite missions with measurements of PMCs (WINDII, MSX, SME, and SBUV) have combined node (ascending and descending) data, the databases are limited, making a Fourier analysis difficult.

[5] SNOE's extensive PMC database and global coverage offers a unique opportunity to search for global scale variations in PMC brightness measurements and resolve the coupled wavenumber and frequency characteristics of the determined wave features. This has not been previously accomplished on direct PMC measurements.

2. Data and Analysis

[6] The SNOE spacecraft was launched in February of 1998 to make global observations of nitric oxide (NO) and the sources of energy that produce it. The SNOE spacecraft is in a circular, Sun-synchronous orbit with a near-polar data footprint that covers 82.5°S to 82.5°N latitude, and a local time at its ascending node of 1030 AM/PM. The spacecraft is oriented with its spin-axis perpendicular to the orbital plane spinning with a period of 12 seconds. The spinning motion of the spacecraft allows altitude profiles (200 km–0 km) of NO emissions and Rayleigh-scattered solar photons at 215 nm and 236.5 nm to be obtained from the Ultraviolet Spectrometer (UVS) during the downward part of the spin in the plane of the orbit. The data footprint covers 360° in longitude in 24 hours (15 orbits per day). The UVS profiles are registered in altitude to 1.5 km accuracy as described in *Merkel et al.* [2001].

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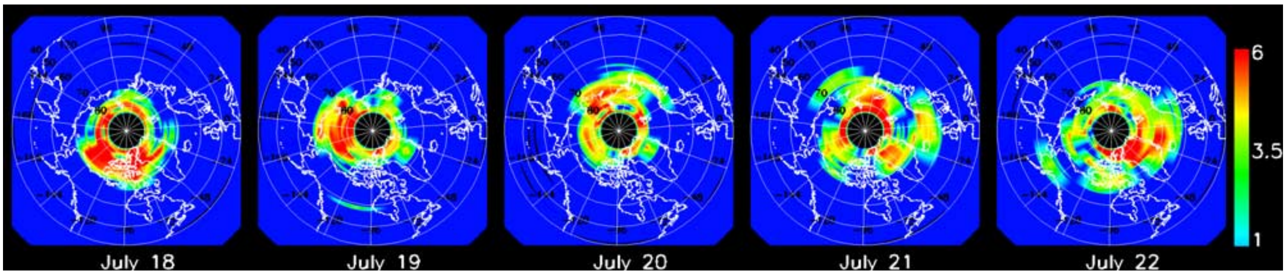

Figure 1. Five day sequence of global measurements of PMCs in the northern hemisphere in 2001. The color bar represents PMC brightness in limb scattering ratio (LSR).

[7] The UVS observes scattered sunlight and therefore detects PMCs in the limb profiles three months out of the year, in the region of summer solstice in each hemisphere. A detection algorithm, previously employed for the analysis of SME PMC data, is used to determine if a limb profile contains a PMC [*Thomas and Olivero*, 1989]. If a deviation between a measured limb profile and an average Rayleigh background profile in the altitude range of 80 km–90 km is more than 4 standard deviations in both spectral channels, then a PMC is detected. Small contributions from high altitude NO emissions are subtracted from the limb profiles [*Merkel*, 2002]. When a cloud is detected, it is represented by brightness with the term limb scattering ratio (LSR). LSR is the ratio of the maximum limb brightness (minus the background) to the average Rayleigh background in counts at the respective detection altitude. LSR is zero for a no-cloud situation. Because SNOE orbits the earth 15 times a day, it obtains a global, constant local time snapshot of the mesosphere. By combining the 15 orbits, daily global images of PMC LSR can be produced. With 15 data points per latitude band (each band is $3/4$ of a degree) an image is produced by linearly interpolating between data points and displaying on a global map. It is noted that all detected clouds used in this analysis are not filtered for detection altitude. All LSR data shown in this paper apply to the 215 nm channel.

[8] Figure 1 displays five consecutive days of PMC LSR data mapped on a polar projection of the northern hemisphere. The maps illustrate the dynamically driven formation of PMCs by tracking the movement of a bright (high LSR identified by red) mass of particles as it circles the North Pole with a 5-day period. For example, the first frame in Figure 1 (July 18) shows a bright (red) mass of particles around $-120°$ longitude. The second frame (July 19) also shows a bright mass of particles around $168°$ longitude. This strongly suggests that a bright concentration of cloud particles moved westward $\sim 72°$ in longitude in a time period of one day. In the successive frames, the feature appears to be propagating westward with a dominant wave 1 structure. Since PMC formation and brightness are dependent on supersaturated conditions, a longitude variation is essentially a modulation of a supersaturated region.

[9] With the apparent wave modulation observed in the raw data, a Fourier analysis is performed to extract wavenumber and frequency pairs. Because SNOE only makes one longitude measurement per orbit, the data is not sampled synoptically (concurrent longitude samples at a single time sample) nor uniformly, therefore a two-dimensional Fourier analysis cannot be directly applied. To overcome this obstacle, *Salby*'s [1982a] method for Fourier analyzing asynoptic data is used to estimate the joint frequency-wavenumber spectra for the SNOE PMC brightness data.

[10] With an estimate of the wavenumber and frequency, the amplitude and phase of the wave is obtained with a sliding least squares fit over the whole PMC season. This analysis determines the latitudinal and temporal structure of the 5-day wave for each season.

3. Results

[11] Salby's Fourier analysis method was applied to the SNOE PMC brightness data for four northern hemisphere (NH) PMC seasons and three southern hemisphere (SH) PMC seasons from 1998 to 2001. Figure 2a illustrates the result of the analysis for the northern 2001 season at 73°N, using PMC brightness data from day of year 150 to 224. The dominant feature is the westward propagating 5-day wave, with wavenumber 1 similar to the Rossby normal mode (1, 1). Figure 2b represents a horizontal slice through Figure 2a at wavenumber -1. It is evident that the 5-day period is dominant in this wavenumber region. The dotted line in Figure 2b represents the 99% significance level. Although only one latitude band is presented, this wave feature is present during all the observed PMC seasons.

[12] With an estimate of the most prominent wavenumber and frequency in the SNOE PMC brightness data, the amplitude and phase of the wave are obtained with a sliding linear least square fit over the whole PMC season. This analysis determines the temporal and latitudinal structure of the 5-day wave for each season. A sliding window of 15-days with a 14-day overlap was used for this analysis. The fit is performed by sliding the 15-day window through the whole PMC season (124 days), one latitude band at a time. The 15-day window was chosen so that the analysis was performed over three wave cycles. The amplitude in LSR and the phase represented as the longitude of maximum amplitude are tabulated for each 15-day window analysis. Because each latitude band ($3/4°$) is analyzed separately with a fit performed every 15-days with a 14-day overlap, the resolution of the resulting amplitude and phase is considerable. With so many separate calculations, the consistency between points adds to the credibility of the result.

[13] The contour plots in Figure 3 exhibit the compiled amplitude results in units of LSR for the analyzed northern and southern seasons. The characteristic determined amplitude oscillates about a mean amplitude value, which both vary in time. The average 5-day wave maximum amplitude is 0.63 LSR in the NH and 5.0 LSR in the SH (the peak-to-peak amplitude is twice this amount), with the maximum

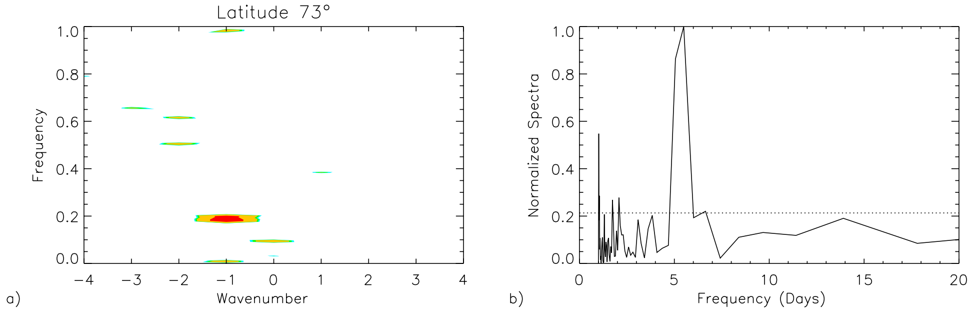

Figure 2. The result of the Fourier analysis for the northern hemisphere in 2001 at 73°N. Figure (a) shows a contour plot of the spectra with a dominant feature at a frequency of 0.2 (5-day period) and wavenumber −1. Figure (b) is a cross section from Figure (a) taken at wavenumber −1. The dotted line indicates the 99% significance level.

amplitude varying yearly. Because of the orientation of the orbit, the UVS detects forward scattered light in the southern hemisphere, thus making the mean LSR larger than in the North (backscatter detection). The smallest contour level in Figure 3 corresponds to the background amplitude for the 5-day wave, estimated to be 0.3 LSR (NH) and 1.5 LSR (SH). The characteristic background noise level is the defining level between noise and a real response. Using 2× the average maximum amplitude divided by the estimated hemispheric mean brightness of 2.3 LSR (NH) and 6.0 LSR (SH), the 5-day wave represents a 55% (NH) and 166% (SH) hemispheric perturbation about the mean brightness. Therefore the 5-day wave represents a significant perturbation on PMC brightness.

[14] It can be seen from Figure 3 that the temporal and latitudinal structure of the 5-day wave is variable from year-to-year. In the northern 1998 and 1999 seasons there appears to be a bi-nodal characteristic in the seasonal variation, with maximum amplitude separated by a time period with no wave structure. In both these seasons, the modulation is largest at the beginning and end of the PMC seasons (June and August). The structure in the 2000 season also illustrates bi-nodal characteristics, however, the nodes seem to be situated in the middle of the season. In 2001, the wave structure only appears strongest in the middle of the PMC season. The latitudinal structure appears to extend through all the calculated latitudes in the North.

[15] In the South, the 5-day wave occurs at the end of the of the 1998–1999 and 1999–2000 seasons. There appears to be only one node (compared to the NH) which occurs at the end of the season however, year 2000–2001 illustrates a 5-day perturbation throughout the whole season. The southern latitudinal structure appears to be isolated at the higher latitudes.

[16] Figure 4 is a bisection of the northern 2000 amplitude contour in Figure 3 taken 42 days after solstice. In this profile the LSR amplitude structure (represented in red) maximizes near 78°N latitude. The phase of the wave (longitude of maximum) at each amplitude measurement is represented in blue. The error bars represent the estimated 1σ confidence interval for the fitted 5-day wave amplitude and phase. Because this figure represents a bi-section through all calculated latitude bands on a specific day, each data point corresponds to analyses on independent observations. The consistency of the data between latitude points adds to the credibility of the analyzed wave structure. The red dash-dot line illustrates the significance level estimated by the background amplitude previously defined.

4. Discussion and Conclusion

[17] Until there are simultaneous measurements of temperature, water vapor and PMCs, we will not know if temperature or water vapor is driving PMC formation.

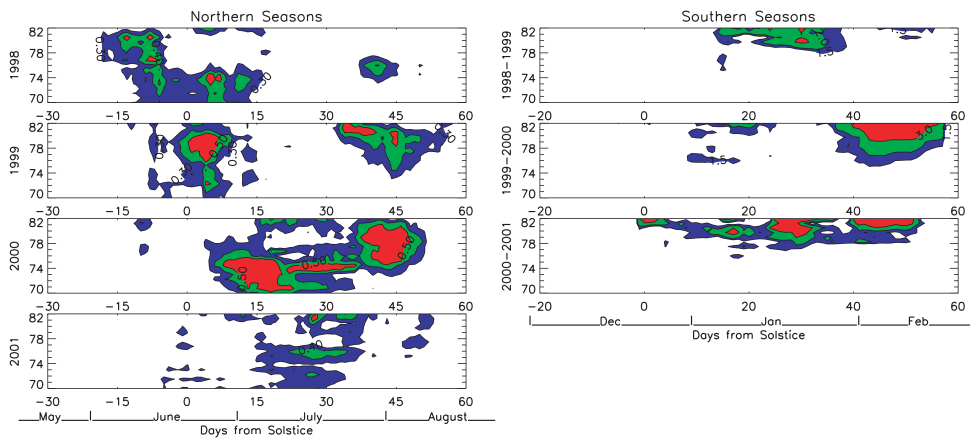

Figure 3. The compiled amplitude results in LSR from the sliding linear least squares fit for all the PMC seasons. The contours have axes of latitude and days relative to solstice. The contour levels for the NH are red ~0.5, green ~0.4, and blue ~0.3. The contour levels for the SH are red ~3.0, green ~2.0, and blue ~1.5.

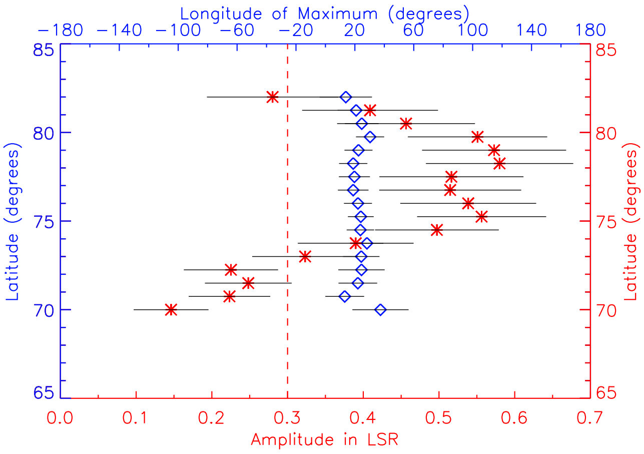

Figure 4. Amplitude (red asterisks) and phase (blue diamonds) for August 2000, 41 days after solstice, day number 215. Phase is defined as the longitude of maximum amplitude. The dashed red line represents the significance level estimated by the background noise level in LSR.

Along these lines, the question remains as to which of these parameters is more important in modulating PMCs by the 5-day wave. Recent results presented by *Kirkwood et al.* [2002], illustrate a strong correlation between a 5-day wave oscillation observed in PMSE observations and temperature measurements. Kirkwood's analysis presents strong evidence that the 5-day wave oscillations are driven by temperature variations on the order of 7 K. Assuming that the summer polar mesosphere has a constant water vapor layer of 4 ppmv, the frost point temperature at 88 km is 144 K. A perturbation of 7 K on this base temperature would be sufficient to generate supersaturated conditions (ratio of partial pressure of water vapor to the saturation pressure equals 10) and produce a cloud base that can be tracked and analyzed like the features illustrated in the SNOE data. Water vapor advected from below on a 5-day cycle (caused by gravity wave filtering on a 5-day cycle) can not be ruled out as a possible cause of the observed PMC variability in brightness. However, currently there are only observations of planetary waves in temperature and wind (not water vapor).

[18] Although a 7 K amplitude change is enough to generate supersaturated conditions with constant water vapor, without a microphysical model it is not possible to estimate the corresponding variation in LSR amplitude in the SNOE measurements. Nevertheless, the presented analysis has successfully demonstrated that the 5-day wave is present in the summer mesosphere and is a contributing factor to the global variation of PMC development. In addition, the presented analysis supports the notion that PMCs act as a tracer of even modest changes in saturation conditions on a global scale. Because the SNOE observations illustrate a global oscillation of PMC brightness indicative of a planetary wave this analysis presents an opposing view to the 1-D microphysical model presented by *Sugiyama et al.* [1996].

[19] In this paper, we have presented PMC results from SNOE that indicate the presence of a 5-day modulation in PMC brightness. This analysis represents the first time a wave analysis has been performed on PMC measurements. The SNOE analysis strongly suggests that the wave feature is the westward propagating Rossby normal mode (1, 1). The 5-day wave is variable in its latitudinal and temporal structure, and its seasonal characteristics change yearly. The wave structure is also present in the southern hemisphere as would be expected from this global phenomenon. At its strongest, the 5-day wave modulates the PMC brightness by 55% and 166% of its mean limb scattering ratio, North and South respectively. Future analysis is needed to establish a relationship between the SNOE PMC brightness and temperature change.

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