Spring 2005

Planetary Wave Activity Observed in Polar Mesospheric Clouds

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Planetary Wave Activity Observed in Polar Mesospheric Clouds

By

David A. Mackler

A Thesis Submitted to the
Physical Science Department
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Space Science

Embry-Riddle Aeronautical University
Daytona Beach, Florida
Spring 2005
UMI Number: EP32039

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David A. Mackler

This thesis was prepared under the direction of the candidate's thesis committee chair, Dr. John J. Olivero, Department of Physical Science, and had been approved by the members of his thesis committee. It was submitted to the Department of Physical Science and was accepted in partial fulfillment of the requirements for the Degree of Master of Science in Space Science

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ACKNOWLEDGEMENTS

I would like to thank most Dr. Olivero, who gave me the opportunity for this work and guided me through my graduate studies. I would also like to thank Dr. Olivero’s colleagues Matt DeLand, Eric Shettle, Dr. Gary Thomas, and Dr. D. W. Rusch who provided the data and gave advice. Finally I would also like to thank Dr. M. P. Hickey and Dr. Irfan Azeem for providing guidance.

Of course I also need to express my gratitude to my family for their encouragement and support.
ABSTRACT

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Title: Planetary Wave Activity Observed in Polar Mesospheric Clouds
Institution: Embry-Riddle Aeronautical University
Degree: Master of Science in Space Science
Year: 2005

In this paper, the Solar Backscatter UV spectrometer (SBUV) Polar Mesospheric Cloud (PMC) dataset was investigated for planetary wave activity following the earlier study by Merkel [2002]. To counter the sparse nature of the data, four separate methods of analysis are used in determining if planetary waves are present and how they effect PMC formation. The four methods are histograms (both in frequency of occurrence and mean albedo), periodograms using the Lomb-Scargle method, frequency-wavenumber analysis using a 2D Lomb-Scargle method from Wu et. al. [1995], and a temporal (yearly) analysis of the 5, 6.5, and 10 day wave amplitudes. The general result is a strong presence of the 5-day wave in PMC, which agrees with Merkel [2002] who used data extracted from the Student Nitric Oxide Explorer (SNOE) to observe the 5 day wave in PMC. Other period waves were also observed including the 2, 6.5, 10, and 16 day waves – although these waves were not as strong or persistent as the 5 day. Similar to past research, the 2-day wave was observed to be stronger and more frequent in the southern hemisphere. Long term trends in the amplitudes of the 5, 6.5, and 10 day waves showed a quazi two year oscillation that is possibly modulated by the 11 year solar cycle - seen as an increase in period during solar max. The results indicated that planetary wave activity influences both the frequency of occurrence and brightness of PMC through vertical and horizontal transport of water vapor into the summer polar mesopause and dynamically forced small scale temperature fluctuations. This result is concluded from coupling past research observing planetary waves in vertical and horizontal winds, water vapor, and temperature fluctuations.
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1.0 Polar Mesospheric Cloud Background

1.1 PMC Characteristics

If one were in a high latitude region of the Earth, and looked toward the heavens just past twilight one would witness an amazing display of light reflecting from irregular thin wispy clouds. These Noctilucent or “night shining” clouds (NLC) have been observed and studied for their enigmatic properties as early as 1885 (Backhouse, 1885) (see figure 1.1.1 for pictures of actual NLC), however they did not gain serious attention until the last couple of decades. When viewed from space, NLC are called Polar Mesospheric Clouds (PMC). Since the beginning of the 1970’s, instruments on satellites that were designed for other purposes have observed PMC and have been used to investigate their physical properties. Currently the importance of monitoring PMC has grown to the level that dedicated satellites are being built and ground stations watch for trends in PMC occurrence.

Figure 1.1.1 Examples of Noctilucent Clouds over Helsinki, Finland (© Timo Nousiainen http://www.meteo.helsinki.fi/~tpnousia/nlcsab/nlcsab.html)

PMC are thin ice clouds that occur only in the summer mesosphere, which means they can only be seen in a twelve week period from about mid-May to mid-August in the northern hemisphere, and from mid-November to mid-February in the southern hemisphere. Additionally PMC form normally in the polar regions, or at latitudes usually greater than 55 degrees. The unique feature of PMC is where they form in the upper
atmosphere. Most clouds that we attribute to weather patterns exist in the troposphere, extending up to about 10 km. PMC are observed near the mesopause at around 80-85 km, over 70 km above normal clouds. The summer polar mesosphere is the coldest place on the Earth, with recorded temperatures averaging at and below 150 K and lows to perhaps 100 K [Olivero, private comm.]. With water vapor concentrations at 1-10 parts per million by volume (ppmv), this makes the summer polar mesopause an ideal place for ice formation. Recent work (Hervig et al. [2001] and Carbary et al. [2001]) has indeed concluded that PMC are composed of ice particles with a broad size range (recorded sizes have radii of ~10 ~200 nm with an effective radius from 20 – 70 nm), often approximated by a log-normal size distribution [Thomas and McKay, 1985]. PMC are thought to be very sensitive to temperature and water vapor concentrations in the summer polar mesosphere. This, coupled with the fact that PMC occurrence and brightness have been increasing in many of the datasets taken since the 1960’s (Klostermeyer [2002] and DeLand et al. [2002]) points to the possibility that PMC could be indicators of changing global atmospheric conditions.

Arguably the most difficult part of PMC research is in finding a continuous dataset long enough to be able to confidently show long term changes. The Solar Backscatter Ultraviolet Spectrometer (SBUV) has been continuously observing PMC since 1978. This dataset is large enough so that two full solar cycles have been observed in PMC occurrence and brightness. This is important because there is a strong hypothesis that solar activity can affect both temperature and water vapor [Garcia, 1989] (the solar Lyman alpha radiation varies by almost a factor of two over the 11 year cycle [Woods and Rottman, 1997]). Because of the long continuous duration of the SBUV dataset, it has been chosen as the data source for the study described in this thesis.
1.2 PMC Dynamics

As mentioned in the previous section, PMC have been observed to form in the summer polar mesosphere – the coldest place on the Earth. So why is the summer polar mesosphere colder (by 70 K or more) than the winter polar mesosphere although the sun is shining continuously at the summer pole? The answer to this question is a complex combination of atmospheric phenomenon that results in dynamical forcing of the mesosphere away from radiative equilibrium.

To get a better understanding of this, first imagine the northern hemisphere summer mesosphere without the rotation of the Earth. The summer pole would heat more than the winter pole due to continuous exposure to sunlight. This in turn would cause a north-south pressure gradient and a resulting meridional flow. Now including the rotation of the Earth to the previous model adds the Coriolis effect to the meridional flow. The meridional flow would be deflected to the west in the northern hemisphere and to the east in the southern hemisphere creating zonal flows (easterlies and westerlies). Although now there are more dynamical conditions, the atmosphere might still be near radiative equilibrium. The summer mesosphere receives more solar flux, as well as more IR emitted from the surface of the Earth; therefore the summer mesosphere would still be warmer. However, as mentioned in section 1.1, recorded temperatures in the mesosphere indicate that the summer mesosphere is colder than the winter. This means that there must be some type of dynamical forcing driving the summer mesosphere out of radiative equilibrium.
The currently accepted source of the forcing is from vertically propagating internal gravity (buoyancy) waves (or just gravity waves) so called because the restoring force is gravity. Gravity waves are short period transient waves that can be created from a number of disturbance phenomena such as vertical convective motion from thunderstorms, cold fronts, and wind blowing over elevated topography. The role gravity waves play in the dynamical forcing of the mesosphere ties back into the zonal flow mentioned earlier. In the northern summer example, the winds flow to the west in the northern hemisphere and to the east in the southern hemisphere. As gravity waves propagate up through the atmosphere, they actually travel at an angle – which is they move both vertically and horizontally. Those gravity waves that have a phase speed in the same direction as the zonal flows are absorbed (or greatly reduced), while those traveling in the opposite direction are allowed through. In the northern summer example, gravity waves with phase speeds traveling toward the east are allowed through. When the gravity waves propagate into the mesosphere they become unstable and ‘break’ much like water waves break upon a shore. This gravity wave breaking dumps momentum and thus into the mesosphere, causing the easterly winds to reverse. Now the Coriolis effect takes place again. As well as affecting flows moving north and south, the Coriolis effect
also forces flows moving east and west. In this example, flows moving to the east are forced equatorward and flows moving west are forced poleward. The equatorward flow in the northern summer hemisphere induces an upwelling of air to replace the meridional flow. Therefore the mesosphere experiences compressive adiabatic heating from downward flow in the winter hemisphere and expansive adiabatic cooling from upward flow in the summer hemisphere (Figure 1.2.1), pushing the summer polar mesosphere out of radiative equilibrium.

Figure 1.2.2  Nucleation – Condensation – Sublimation Cycle
This upwelling (in summer) also provides a transport for water vapor into the mesosphere and is thought to buoy up the ice particles [Olivero, private comm.]. The currently accepted theory for PMC formation includes a cyclic relationship of condensation and sublimation. PMC begin to nucleate roughly 3 to 6 km higher than they are observed, forming around meteoric dust and trapped ions. As they condense they grow and fall in altitude, becoming more efficient at scattering light as they grow in size. When they grow too large, they fall past the mesopause and into a warmer region – where they quickly sublimate [Olivero, private comm.].

1.3 PMC and Global Change

In section 1.1 it was mentioned that changes in PMC brightness, frequency of occurrence, and lower latitude threshold could hold a clue of how the global atmospheric environment is changing. The primary accepted cause of change in the stratosphere and mesosphere are increasing carbon dioxide and methane levels – both of which arise from anthropomorphic (man made) sources [Thomas et al., 1989]. Methane in the stratosphere is dissociated by solar radiation and the free hydrogen atoms bond with ambient oxygen to form water vapor. Since the mid-eighties the National Oceanic and Atmospheric Administration (NOAA) in particular has tracked the rise in methane and carbon dioxide levels in the troposphere. Carbon dioxide is currently debated as a cause of global cooling in the stratosphere and the mesosphere (another potential cause of cooling is the loss of ozone). The resulting increase in water vapor and projected decrease in mesosphere temperature could both contribute to the changes observed in PMC activity. The only problem with this theory is that there is now no evidence of long-term temperature changes in the high latitude summer mesosphere [Lubken, 2000]. However, the lack of temperature change observed in the mesosphere does not significantly disprove that greenhouse gasses are affecting the mesosphere. In most of the mesosphere there is a stable radiative balance, incoming radiative flux from the sun is absorbed and thermal IR is emitted such that there is equilibrium. The main constituents involved are water vapor and carbon dioxide, which readily emit in the infrared, cooling the
surrounding atmosphere. The summer polar mesosphere, however, is quite a different story. The latitude bands between 55-85 degrees (negative 55-85 degrees in the southern hemisphere) are driven dynamically and are not in radiative equilibrium. Adiabatic expansion in the summer polar mesosphere causes the temperature to reduce closer in line with the adiabatic lapse rate. In this environment, any drop in temperature from greenhouse gasses could be offset by radiative absorption by carbon dioxide – thereby collectively keeping the temperature profile relatively constant. As discussed above, changes in PMC formation could hold clues to future atmospheric trends. These changes in PMC may occur from a combination of changes in temperature, water vapor ratio, as well as dynamics. Therefore it is prudent to seriously evaluate PMC occurrence.

2.0 Planetary Waves in PMC Observations

2.1 Background of Planetary Waves

Planetary waves are, as they sound, a class of atmospheric waves of planetary scales. Planetary waves were first linked to weather phenomenon by C. G. Rossby in 1939, and are a global scale example of Rossby waves (or modes). The perturbation causing planetary waves is predominantly meridional forcing of the atmosphere flowing over large-scale topography features such as mountains. As a result of the nature of the perturbation, planetary waves are more active in the northern hemisphere. A zonally moving parcel of atmosphere that is deflected equatorward moves to an area of reduced planetary vorticity, and spins up cyclonically to conserve absolute vorticity. This causes the parcel to travel poleward until it reaches an area of increased planetary vorticity, and so spins down cyclonically and returns to an equatorward trajectory. The meridional displacement will then oscillate about an undisturbed latitude until seasonal winds shift and the deflection perturbation ceases.
Planetary waves have a westward phase velocity relative to the basic state of the zonal winds for long period waves. They also propagate vertically if the mean zonal winds are westerly and do not exceed the phase speed. Large scale vertical transport can be seen in the transition time between summer and winter when planetary waves are allowed to propagate vertically into the stratosphere and cause sudden stratospheric warmings, however past research into planetary waves occurring over the span of the polar summer indicate that they may also propagate vertically when easterly winds are weak. Unlike other atmospheric waves (such as gravity or buoyancy waves) planetary waves span the longitudinal range of the globe, have low wavenumbers (number of wavelengths in $360^\circ$ longitude), and periods on the order of days. The importance of observing planetary waves and their effect on atmospheric dynamics is evident from their global scales. Aside from affecting PMC formation (section 2.2) planetary waves may also help the Earth to minimize the ozone hole that has been observed over the poles by temporarily disrupting the polar vortex (Matsuno, [1971]), allowing fresh ozone to enter and warming the polar stratosphere. The meridional transport of a rotational flow to the stratospheric poles disrupts the polar vortex, causing it to slow down (in some observations, to stop completely and reverse direction). This in turn increases the local temperature within the polar vortex. The rapid increase in temperature in the polar regions is commonly referred as a sudden stratospheric warming event, and is coupled with a mesospheric cooling event. The warming event reduces the chance of ozone destroying activity (observed primarily in the Northern Hemisphere).

Planetary waves exist in different periods, or modes. The high frequency cutoff for these waves is $2\Omega$ (or twice the rotational frequency of the Earth). This is due to the proportionality of the frequency of planetary waves to the beta-plane coefficient $\beta$. Therefore the smallest expected period is around two days. The two day wave has a wavenumber of 3 (eg. There are three wavelengths of the oscillation in $360^\circ$ longitude) and has been observed in the stratosphere and mesosphere (section 2.2). The remaining well known waves have a wavenumber of 1 and exist in periods of 5, 6.5, 10, and 16 days.
2.2 Observational Results

2.2.1 2-Day Wave

The 2-day wave has been observed in the mesosphere and lower thermosphere (MLT) in a number of different studies, spanning several time periods and spatial locations. Riggin et al. [2004] used data from the UARS High Resolution Doppler Interferometer (HRDI) and Microwave Limb Scanner (MLS) in conjunction with three medium frequency radar locations (Saskatoon, Kauai, and Christmas Island) and two meteor scatter radar sites (Obninsk, Russia and Jakarta, Indonesia) to evaluate wave properties during the summer of 1994. Wave characteristics were extracted using the Salby method [Salby, 1982a, 1982b] for the HRDI dataset and the S-transform method [Stockwell and Lowe, 2001] for the radar sites. To compare with stratopause and lower heights, a data set from the UK Met Office analysis (METO) was also used. Rather than determining the actual wavenumber and period, the study assumed W2, W3, and W4 (which mean wavenumbers 2, 3, and 4) components with periods of 1.8 to 2.4 days and examined the variability of the results. The results indicated maximum amplitudes concentrating around +/- 60 degrees latitude, but extending from +/- 40-80 degrees latitudes. The southern hemisphere displayed greater amplitudes than the northern and the amplitudes peaked vertically at 80 km. In this particular study, the period of 1-15 July had the strongest activity. A major hypothesis is that the mesospheric 2-day wave is excited in-situ as a Rossby mode and not propagated from lower altitudes.

Limpasuvan and Wu [2003] conducted a more concentrated study using the UARS MLS with time periods 15 January to 14 February 1992 and 5 January to 8 February 1993. The Salby method was used to extract wavenumber and frequency information in the southern hemisphere (28 degrees north to 68 degrees south) from 65-86 km. The results of the study indicate a definite signature of a westward propagating W3 wave with a central period of 2.1 days. Similar to the previous study discussed, the strongest amplitudes appear in mid-latitudes at around 80 km. The amplitudes were contoured as a function of
latitude and altitude and showed an equatorward tilt of the 2-day wave as the altitude decreases. Similarly the amplitudes were also plotted as a function of longitude and altitude, where the amplitudes displayed a weak westward phase tilt with increasing altitude above 65 km. Unlike the previous study, Limpasuvan and Wu [2003] suggest that the two day wave is generated by gravity waves causing instabilities in the mesospheric jet and propagates vertically from below the stratopause, however they did not rule out the possibility of the 2-day wave as a Rossby mode. The study also evaluated the phase difference in water vapor and temperature variations and found that the two differ by approximately 180 degrees across the span of the dataset; this phase difference between water vapor and temperature could strongly affect PMC formation. 

Finally S. Nozawa et al. [2003] used data from the Tromso (69.6 degrees north by 19.2 degrees east) medium frequency radar site from 1 November 1998 to 8 December 2001. The data spanned both winter and summer in the northern polar mesosphere from 70-91 km. The analysis used the Lomb-Scargle method (4 times over sampling with a sliding 8 day window). They found that the Quasi 2 Day Wave (Q2DW) has a greater activity in the winter months and from 70-82 km, the maximum amplitudes center around the winter solstice. The summer months are more constant within the dataset and increase in amplitude with altitude, up to around 91 km where the winter/summer ratio approaches 1. Above 95 km the Q2DW was attenuated, although a slight meridional component was observed as far as 108 km. Similar to the first study discussed in this section, Nozawa et al. [2003] suggest that the Q2DW is a Rossby-gravity wave mode rather than instabilities in the mesospheric jet.

2.2.2 5-Day Wave

Merkel [2002] used data obtained from the Student Nitric Oxide Explorer (SNOE) satellite to search for evidence of planetary wave activity in PMC. SNOE was launched February 1998 to study the concentration and vertical profile of nitric oxide (NO) in the thermosphere. SNOE is a limb scanner in a nearly polar orbit, spinning once every 12
seconds. It uses an ultraviolet spectrometer (UVS) to measure the altitude profiles of airglow emissions from fluorescent scattering of sunlight by NO as well as Rayleigh scattered solar radiation.

As it rotates, SNOE obtains data from the thermosphere from about 200 km down to the troposphere below 20 km. Fortunately there is a ‘gap’ in the vertical profile, between the NO signal (which drops off around 97 km) and the Rayleigh scattering signal (which doesn’t dominate until around 70 km), this gap is precisely where PMC occur, allowing SNOE to record PMC occurrence and intensity. However the NO and Rayleigh background still encroach enough that they needed to be removed from the scan. The volume density profile for NO is recorded from 140-97 km and an extrapolation of that data is used to estimate the contribution below PMC formation altitudes, which is then subtracted. Similarly the Rayleigh background is recorded and averaged for latitudes between 50-55 degrees, where PMC occurrence is rare. The scan and background are corrected for scattering angle, and then the background is subtracted. The final PMC signature is converted into a Limb Scattering Ratio (LSR), which is the ratio of the maximum PMC brightness to the average Rayleigh background in counts at the respective altitude. The results of the altitude profiles determined the range to focus on (around 82 – 84 km) for Fourier, phase, and temporal analysis.

Traveling planetary waves change as a function of time and longitude. Therefore asynopticly-sampled data from an orbiting satellite needs a unique method to resolve wave signatures. In SNOE PMC data the method used to generate periodograms was the Salby method [Salby, 1982]. The Salby method was created specifically for satellite data and employs a coordinate transform in time-longitude space. Each latitude is analyzed separately, splitting the data into a separate time series for ascending and descending observations. The time-longitude space is divided uniformly relative to the orbit of the satellite, the rotation of the Earth, and the precession rate of the satellite. One possible result of the Salby method is the calculations of amplitudes of LSR in wavenumber-frequency space. To complete the SNOE-PMC analysis, a sliding least squares fit was
applied to a whole season. This complements the wavenumber and frequency information by revealing the amplitude and phase of the wave.

The predominant result observed in all the data was a wavenumber \(-1\) (negative wavenumbers in the Salby method indicate westward movement), 5-day Rossby normal mode \((1,1)\); which was confirmed by comparing the results to possible aliasing wavenumber-frequency pairs. It appeared that the northern hemisphere 5-day wave formed bi-nodally across the season, while the southern hemisphere season was a single node. The amplitudes of the 5-day wave fluctuated greatly from season to season and there was a possible trend of the 5-day wave affecting PMC formation in the lower latitudes first, then propagating poleward as the season progresses. Finally, the strongest amplitudes of the 5-day wave occurred during the beginning and end of the PMC season. Merkel suggests that the 5-day wave may only be allowed to occur in the mesosphere when the mean zonal easterlies are weak enough in the stratosphere to allow vertical propagation to the polar mesosphere.

Wu et al. [1994] also conducted a study of the 5-day wave, using the UARS High Resolution Doppler Interferometer (HRDI). The dataset spanned from May 1992 to June 1994, specifically at 95 km and focusing around +/- 40 degrees latitude. They used a least squares method of wavenumber – frequency fitting similar to the Lomb-Scargle method. They found that the appearance of the 5-day wave was transient with a lifetime of around 10-20 days. At the altitude observed, the 5-day wave was fairly weak and had centered peaks near the equator. The summer months displayed greater amplitudes at 95 km, although it was difficult to specify if this was a trend due to the limited dataset. The zonal amplitude response was greater by a factor of 2 to 3 than the meridional response, this appears consistent with theory and as such they believed that the observed signal was the result of a \((1,1)\) Rossby normal mode.
3.2.3 6.5-Day Wave

*Talaat et al. [2001]* presented a study of properties of the 6.5-day wave as observed by the UARS HRDI from October 1993 to March 1995 in altitudes ranging from 50-155 km. The data was first converted to asynoptic coordinates [Salby, 1982], then analyzed using the Lomb-Scargle method of least squares fitting. The calculated signals were interpreted as best fitting a Rossby (1,1) mode. As seen in the *Wu et al. [1994]* study, the meridional 6.5 day wave at 95 km had significantly smaller amplitudes than the zonal component. The 6.5 day wave appeared transient (similar to previously described studies of the 5 day wave) and generally lasted for about 3 - 4 weeks. The centered period fluctuated between 5 – 7.5 days, however during strong episodes of wave activity the centered period narrowed to 6.5 – 7 days. The amplitude of the 6.5-day wave peaked around 95 km and displayed a decreased amplitude phase with height. In the altitude range observed the 6.5-day wave was largest at mid latitudes.

*Lieberman et al. [2003]* also used a dataset from the UARS HRDI in conjunction with medium frequency radar sites at Saskatoon, Canada (52° N, 107° W), Urbana, Illinois (40° N, 88° W), Kauai, Hawaii (22° N, 159° W), Christmas Island (2° N, 157° W), and Adelaide, Australia (35° S, 138° E). The specific time periods of the study were from 19 March to 17 April 1994 (at 40° S – 30° N latitude) and 15 September to 12 October 1994 (at 20° S – 40° N latitude). The data were analyzed using the Salby method and as seen in the previous study, the 6.5-day wave appeared transient. In this study the 6.5-day wave showed a greater amplitude (but highly distorted) in the southern hemisphere, however the signals in the northern hemisphere were more consistent with developing baroclinic waves. The amplitude of the 6.5-day wave increased vertically through the stratosphere and mesosphere, similarly to the results of previously described studies of planetary waves. Conversely to the *Talaat et al. [2001]* study, *Lieberman et al. [2003]* believe that the vertical propagation and wind - temperature phase relationships suggest growth due to baroclinic and barotropic instability.
2.2.4 16-Day Wave

Of the papers published on 16-day planetary waves to date, one in particular is more relevant to this thesis than others. Espy and Witt [1996] reported on observations of the 16 day wave in the temperature variations in the summer polar mesosphere. The dataset used was the rotational temperatures (3,1 band) of hydroxyl emissions (centered at 87 km) collected from a Michelson interferometer in Stockholm (59.5° N, 18.2° E) specifically from mid-June to late-August 1992 (UT days 170-235). The data was accompanied by ground-based observations of NLC in an attempt to correlate trends between temperature variations and NLC formation. The Lomb-Scargle method was used to calculate the power spectral density vs. period. The largest amplitude wave observed was centered at 15.3 days with a confidence level just over 97%. The 16-day oscillation was observed to be consistent and strong through UT day 199 (about the third week in July) where it rapidly decreased through the rest of the dataset. In this study the authors conclude that the temperature wave signature is most consistent with the 16 day (1,3) Rossby mode. The rapid decrease in amplitude described above coincided with the last NLC observed from the ground in Stockholm. Thus they conclude that the same mechanisms that end the NLC season could also affect the amplitude of the 16 day wave, however with the limited spatial and temporal range of this dataset it may not be correct to link the temperature fluctuations of the 16 day wave alone with NLC formation.

Another study of the 16-day wave was conducted by Mitchell et al. [1999] using the Sheffield Meteor Radar (53.5° N, 3.9° W) horizontal wind speeds. The specific dataset ranged from January 1990 to August 1994 with over 80% of the data in the vertical range of 87 – 97 km. The Lomb-Scargle method was used to calculate the time – amplitude spectrum in conjunction with a sliding window (48 day window, sliding 1 day with an over sampling factor of 4). Overall the 10 – 28 day wave activity appeared in bursts lasting no longer than 60 days. The strongest activity was predominantly in the local winter months between December to mid April (days 335 – 110) with an average of two to three bursts per year. A second smaller peak was observed between late July to mid
November (days 200 – 320) with only one to two bursts per year. The minimum activity occurred in late June to early July. The 10 – 28 day wave activity was mostly zonal in the summer months and meridional in the winter. The authors of the study suggest that the wave activity presented was generated in situ rather than propagating vertically.

3.0 The SBUV Dataset

3.1 SBUV History

The Solar Backscatter Ultraviolet instrument (SBUV) is a nadir pointing double Ebert-Fastie spectrometer used to determine the vertical distribution of ozone and to map the total ozone content of the atmosphere. The SBUV spectrometer was used in a number of sun-synchronous satellites from 1978 to the present (refer to A.1.1 for orbital parameters), seven of which are used in this study. Past work evaluating PMC properties used the SBUV dataset and has proven useful in evaluating long-term trends, including the effect of the solar cycle in PMC brightness [DeLand et al., 2003]. When SBUV receives reflected UV light, it is sometimes scattered not just from ozone – but also from the ice particles in PMC. Therefore to determine if a specific signal is a PMC, a set of selection rules was established (see section A.2 for selection rules).

3.2 The SBUV PMC Dataset

The final result of the inversion technique and selection rules (described in sections A.1 and A.2) is a measurement of the residual albedo as a function of longitude and latitude as well in time (see section A.3 for example plots of the data). To increase the potential of the data to resolve different period signals, all the individual datasets from each satellite was combined into one dataset for each season (northern and southern hemisphere), resulting in 24 seasons for each hemisphere ranging from 1979 – 2002. The data is limited to the specific timeframe of the PMC season, and even though the data was combined it still is small compared to similar datasets. A large season has about
9000 data points (there are three seasons with as high as 11000 – 12000 data points), while the smallest seasons have on the order of 2000 or fewer data points (there are 14 such seasons). The remaining seasons range typically around 4000 – 7000 data points. For a naming convention in this paper, a large dataset will reflect those seasons with around 4000 and above and small seasons are those with on the order of 2000 data points or less.

The majority of the seasons span about 100 days (centered around day 192 in the northern hemisphere and day 375 in the southern hemisphere). The latitude range is limited by the path of each satellite (see section A.1.1 for orbital parameters), but generally ranges from 50° – 81° (-50° to -81° in the southern hemisphere).

Of particular importance is the time spacing between successive data points, as this will determine the Nyquist limit of resolvable periodicities. Tables 3.2.1 through 3.2.4 below display the maximum and mean time spacing between datapoints for both northern and southern hemispheres, separated into small and large datasets. In the northern hemisphere the smaller datasets tend to have large time differences, ranging from 77 to almost 200 minutes. Fortunately there are significantly more larger datasets with time differences ranging from 11 to 50 minutes. In the southern hemisphere, there are slightly more smaller datasets, ranging in mean time difference from 150 to 300 minutes. However the larger datasets of the southern hemisphere seasons having a mean time difference of 12 to 50 minutes – similar to the northern hemisphere. Of course, by limiting the spatial range of the dataset to specific latitude and longitude blocks for a specific analysis method will increase the mean time difference for all evaluated seasons (as described in section 5.3). The separation of time between data points will limit the ability to resolve the two-day wave using the analysis method described in section 4.3 even for the larger datasets.

Also important to the analysis of wave activity is the signal to noise ratio, or in this case, the factor of the mean above minimum values. Tables 3.2.5 and 3.2.6 below show the
maximum, minimum, and mean albedo values (averaged over the season) for both northern and southern hemispheres. The minimum albedo values for both northern and southern hemispheres lie around $2.0 \times 10^{-6}$, with mean values at around $9.0 \times 10^{-6}$ and $8.0 \times 10^{-6}$ respectively for the northern and southern hemispheres. The largest values for the northern hemisphere are around $3.7 \times 10^{-5}$ and around $3.6 \times 10^{-5}$ for the southern hemisphere (see tables 3.2.5 and 3.2.6). Therefore the mean values are above the minimum by a factor of roughly four.

<table>
<thead>
<tr>
<th>Year</th>
<th>Max (min.)</th>
<th>Mean (min.)</th>
</tr>
</thead>
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**Table 3.2.1 Northern Hemisphere small seasons**

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<td>2000</td>
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**Table 3.2.2 Southern Hemisphere small seasons**

<table>
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**Table 3.2.3 Northern Hemisphere large seasons**

<table>
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<th>Mean (min.)</th>
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<td>1987</td>
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<tr>
<td>1994</td>
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<td>12.1</td>
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<td>1995</td>
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<td>1997</td>
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</tr>
<tr>
<td>2002</td>
<td>3587.2</td>
<td>32.7</td>
</tr>
</tbody>
</table>

**Table 3.2.4 Southern Hemisphere large seasons**
Although the use of the minimum albedo values as the noise level could be underestimating the noise, the results of this primitive evaluation of the signal to noise ratio means that careful scrutiny must be used in determining wave activity. However, due to the large timeframe of the entire SBUV dataset (from 1979 to 2002) used in this study it will be possible to look for repeating observances of waves at the focused periods.

Table 3.2.5  Northern Hemisphere Albedo (averaged over all seasons)

<table>
<thead>
<tr>
<th>Maximum x10^-6</th>
<th>Mean x10^-6</th>
<th>Minimum x10^-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.6</td>
<td>9.24</td>
<td>2.17</td>
</tr>
</tbody>
</table>

Table 3.2.6  Southern Hemisphere Albedo (averaged over all seasons)

<table>
<thead>
<tr>
<th>Maximum x10^-6</th>
<th>Mean x10^-6</th>
<th>Minimum x10^-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.2</td>
<td>8.02</td>
<td>2.18</td>
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4.0  Analysis

From the onset of this project, the objective was to conduct a planetary wave analysis on SBUV PMC data that was similar to the analysis conducted on the SNOE dataset. Therefore one aspect of the data analysis will need to reveal the wavenumber-frequency properties of waves influencing PMC formation – which in turn influences albedo, as well as to take advantage of the long time span of the SBUV data set in order to evaluate long term changes. As described in section 2.2.2, the Salby method was used to extract wavenumber – frequency trends and a sliding least squares method was used to calculate changes in amplitude and phase across the SNOE dataset. Merkel was able to use the Salby method due to the large size of a typical SNOE dataset (about 100,000 limb scans per season), as well as the continuous nature of the data. However, as described in section 3.2, the SBUV dataset is discontinuous and much more limited in size (where a
large season has around 9000 data points). The sporadic nature of SBUV PMC data is due to lower sensitivity to PMC signals, thus the specific need of selection rules, and which results in much smaller fractions of observed values (see section A.2 for a complete description of the selection rules). Therefore a different approach must be used in this case to achieve comparable results.

4.1 Spatial grouping of data

As data obtained from a satellite platform, SBUV has the potential for near global coverage of asynoptically-sampled data. However the PMC detection hits pulled from the entire SBUV dataset is much more spatially limited to regions where PMC form (around 50-90 degrees latitude). Atmospheric waves (traveling or stationary) affect a localized spatial area of the mesosphere as, for example, a water wave would affect one fixed location and depth (as both are dynamical features in a fluid medium). Therefore in order to initially discover whether the SBUV would be able to resolve planetary waves, the data is grouped into spatial blocks. A significant majority (around 80%) of the SBUV PMC data lies between the latitude range of 70 – 81 degrees (refer to section A.2.3 for orbital parameters and restrictions), with 15% lying between 60 – 70 degrees and only 5% between 50 – 60 degrees. Although planetary wave amplitudes vary significantly with latitude, the change in the 70° – 81° range is fairly small (Figure 4.1.1). Therefore to counter the sparse nature of the data, all latitudes in the dataset above 70° are grouped together and treated as one latitude band. Along with latitudinal grouping it is important in the initial analysis to group the longitude into local spatial blocks. Generally the larger the longitude block, the more data points there are in each one and the easier it would be to evaluate short term periodicities. The reduction of the mean change in time from one data point to the other reduces the Nyquist limit in period. However larger blocks would also tend to reduce the resolution of low wavenumber signals. Therefore after some experimenting, I chose to group the dataset into 30-degree longitude blocks for the initial analysis – then increase the block such that the waves still appear and the statistical confidence improves to an acceptable level.
4.2 Histograms

As a simple initial look at the structure of the SBUV PMC dataset, a histogram was generated for each season and hemisphere. To better understand what the dataset will further reveal, histograms of both the total number of PMC observations per day and the average albedo per day were created. In one mode the program simply counts and records the number of observations as a function of day, and in the other mode it records the average of the albedo values as a function of day. The two different modes are used to observe the frequency of occurrence as well as the distribution of albedo strength over each season. The expected contribution of this method is to allow a quick look into any wave structure as well as what period waves can be seen at different times over the PMC observing period. See section 5.1 for the results of this method.
4.3 Lomb-Scargle Analysis

To effectively evaluate the contribution to the dataset from different waves, it is desirable to extract the signals using some form of Fourier analysis. The SBUV PMC data are not evenly spaced nor are they continuous, therefore the Lomb-Scargle method (detailed in section B.1) was selected for both an amplitude vs. period analysis as well as a frequency vs. wavenumber analysis, as described in the next two sections.

4.3.1 Amplitude vs. Period

The 1D Lomb-Scargle method was designed specifically for discontinuous data, and therefore it is expected to work for the SBUV PMC dataset. The computation results in power spectral density (PSD) verses frequency (in the same relative units given). The method has been modified to convert the PSD to amplitude, and the amplitude is plotted versus the inverse of the frequency to examine the periodicity of the data. The average timeframe for most seasons lasts about 60 days; this allows the longer waves such as the 10-day and 16-day to be sampled about 6 times and 4 times respectively. Thus it is unlikely that the 16-day wave will be correctly identified routinely in this particular analysis. Although the data is discontinuous, the time differences in individual data points is around 0.15 days for the largest datasets and around 0.75 days for the smaller datasets. This is still small enough to allow the 2 days wave to be seen if present. The Lomb-Scargle method is applied to multiple longitude bands per season, initially creating periodagrams for blocks 0-30, 90-120, 180-210, and 300-330 degrees. This will both give four opportunities per season to observe wave activity and include some spatial resolution across the entire dataset. Once wave activity is identified near a specific longitude, the block size is modified until the statistical confidence level calculated by the Lomb-Scargle method is satisfactory. Refer to section 5.2.1 for the results of this method.
4.3.2 Frequency vs. Wavenumber

As an extension of the Lomb-Scargle method, Wu [1995] modified the original numerical recipe to include wavenumber signatures as well as frequency. In this analysis method the entire 0° – 360° longitude range is used. The result for this approach is a three dimensional array with the frequency information in the y-axis, wavenumber in the x-axis, and amplitude in the z-axis. The analysis is limited to wavenumbers between –4 and 4, where a negative wavenumber indicates a westward propagating wave. The original numerical method prescribed by Wu used a negative wavenumber to indicate eastward propagating waves, but the opposite was used for this analysis to compare with the results from the SNOE PMC analysis. Because all longitudes are used it is expected to observe the 10-day and 16-day better than with the 1D method (using the entire longitude range maximizes the number of data points and therefore weak signals will be slightly easier to detect). Refer to section 5.2.2 for the results of this method.

4.4 Temporal Change (annual) in Wave Amplitudes

Since the SBUV dataset spans over two decades (1979 – 2002) a significant find would be to determine if the amplitudes of planetary waves are effected by the solar cycle or other long term atmospheric trends, such as the quasi biannual oscillation (QBO). It is desirable to break each season into time blocks, evaluate the periodicity using the Lomb-Scargle method, then slide forward in time by a small amount (say 10% of the time block) and repeat the process. This is commonly called the Sliding Lomb-Scargle method and is useful in evaluating the temporal trends of waves. However, after testing various time blocks it was determined that the waves of interest in this work were not sufficiently resolved. Also working against this approach is the fact that the different planetary wave amplitudes are not constant across the PMC season. Different waves are observed to be significant at different times. So for this method the entire season is used to calculate the amplitude – period space. The amplitudes of the 5-day, 6.5-day, and 10-day are recorded for each season to juxtapose for temporal trends. Refer to section 6.3 for the results of this method.
5.0 Results

5.1 Histograms

A general result from all seasons evaluated was a definite periodicity in both frequency of occurrence and albedo, centered strongly around the middle of the PMS season. The periodicities were not as defined in the smaller seasons, as was expected; however the existence of periodicities in the larger datasets was definite. As a note to the results described in this section, the longitude range of the graphs was picked because they displayed the best results for the specific dataset. If the results seemed independent of longitude range then the generic range of $0^\circ$–$30^\circ$ longitude was used. Figure 5.1.1 shows the frequency of occurrence for a small season (1982 northern hemisphere). Although sparse, the 5-day wave is still easily recognizable.
Figure 5.1.1 1982 Northern Hemisphere Frequency of Occurrence Histogram

In contrast, Figure 5.1.2 shows the frequency of occurrence for a large dataset (1985 northern hemisphere). To illustrate the correlation of the strong 5-day periodicity, an overlay of a 5 day sine wave has been plotted over the central part of the season.

Figure 5.1.2 1985 Northern Hemisphere Frequency of Occurrence Histogram. The dashed curve in the right hand plot is a five-day sine wave.
In the southern hemisphere, the most dominant feature was the 2-day wave. This observation is consistent with other published works on planetary wave activity (section 2.2.1). In a few of the Southern Hemisphere seasons, the 2-day wave is not as active and it is possible to observe just the 5-day wave. Figure 5.1.3 below is an example of a Southern Hemisphere season with just the 5-day wave. The 2-day wave is also present occasionally in the Northern Hemisphere, as can be seen in Figure 5.1.4. In this figure, both the 5-day and the 2-day are easily discernable. The strong presence of the 2-day wave in the Southern Hemisphere can be seen in Figure 5.1.5, which is typical of most Southern Hemisphere datasets.

Figure 5.1.3 1988-89 Southern Hemisphere Frequency of Occurrence Histogram. The dashed curve in the right hand plot is a five-day sine wave.
Figure 5.1.4  1987 Northern Hemisphere Frequency of Occurrence Histogram

Figure 5.1.5  1996-97 Southern Hemisphere Frequency of Occurrence Histogram
The average albedo histograms displayed a similar trend to the frequency of occurrence histograms, however they did not match exactly. To compare, the following four figures are the average albedo counterpart to Figures 5.1.2, 5.1.3, 5.1.4, and 5.1.5 respectively. As can be seen, the two different sets of histograms go to zero at the same places (as should be expected) and generally follow a similar trend with small variations. The determination of whether a PMC is observed is a function of the albedo, following the selection rules – so it should be expected that the two follow similar paths. However an increase in the frequency of occurrence does not necessarily reflect a similarly proportional increase in albedo, as seen in the figures. Therefore the observed periodicities could be affecting the number density of ice particles and the size of the particles in different scales (the waves could be affecting the formation, and therefore the number density, weaker than the size).

Figure 5.1.6 1985 Northern Hemisphere Average Albedo Histogram
Figure 5.1.7  1988-89 Southern Hemisphere Average Albedo Histogram

Figure 5.1.8  1987 Northern Hemisphere Average Albedo Histogram
5.2 Lomb-Scargle Periodograms

5.2.1 Amplitude vs. Period

This section discusses the results of running the albedo - time series of the datasets through a Lomb-Scargle analysis method. It should be noted before presenting the results the strengths and weaknesses of the Lomb-Scargle method. The Lomb-Scargle method was designed to extract weak periodic signals from non-consistent or sparse data. A side effect of this method is that the resulting periodogram can include false peaks when the signal to noise ratio is low. As seen in figures 5.2.1.1 through 5.2.1.4, amplitudes of planetary waves change in time, which when observed over the entire season will appear as streaks in longitude. Therefore it would be prudent to observe individual periodograms at different longitude blocks for each season in the hopes that true peaks will be observed multiple times.
Figure 5.2.1.1  1997 Northern Hemisphere Longitude Distribution. A good string of the 5-day can be seen between 0° and 150° while the 6.5 and 10 day are more scattered.

Figure 5.2.1.2  1997 Northern Hemisphere Longitude Distribution; two-day region. Some peaks occur near the 2.4 and 1.8 level, but most of the activity for this season is around 2 days.
Figure 5.2.1.3 1987 Southern Hemisphere Longitude Distribution. The 5-day is easily seen in the middle with a strong 6.5 and 10-day peak centered around 225°.

Figure 5.2.1.4 1987 Southern Hemisphere Longitude Distribution; two-day region. There is a strong presence of the 1.8 and 2.2 day waves.
Overall the results of this method demonstrated a strong presence of the 5-day and 6.5 day wave in most seasons, with the 5-day wave slightly more consistent. Figures 5.2.1.5 and 5.2.1.6 illustrate examples of strong 5-day and 6.5-day wave activity in the northern and southern hemispheres respectively.

Figure 5.2.1.5  1987 Northern Hemisphere Periodogram (245° – 290°). The strongest signals are the 5, 6.5, and 10-day waves.
Figure 5.2.1.6 1989 Southern Hemisphere Periodogram (0° - 50°). The strongest signal is the 5-day wave.

A few of the seasons showed good presence of multiple waves, including the 2, 5, 6.5 and 10-day waves. Figure 5.2.1.7 (below) of the 1997 northern hemisphere season has peaks at 2, 5, 6.5, and 10 days. Similarly for the southern hemisphere, Figure 5.2.1.8 of the 1999 season exhibits waves at the same periods.
Figure 5.2.1.7 1997 Northern Hemisphere Periodogram ($250^\circ - 300^\circ$). Multiple waves can be seen at 2, 5, and 6.5.

Figure 5.2.1.8 1999 Southern Hemisphere Periodogram ($140^\circ - 190^\circ$). Multiple waves can be seen at 4, 5, and 10 days.
What appeared to be a two-day signature was observed in a large majority of both northern and southern seasons. As mentioned in Riggin et al. [2004] the two-day wave is not exactly two days and it is comprised of at least three recognizable signals. A 1.8-day wavenumber 4, 2.0 – 2.2-day wavenumber 3, and a 2.4-day wavenumber 2. To try and reduce the noise, each season was evaluated to determine if it had a significant ~2-day signature. Then those selected seasons were averaged (selected seasons and their longitude ranges are in Table 5.2.1.1). Figures 5.2.1.9 and 5.2.1.10 are the results of this for the northern hemisphere and 5.2.1.11 and 5.2.1.12 are for the southern. As seen in previous research, the 1.8-day and 2.4-day components were observed more frequently in the northern hemisphere and the 2.0-2.2 components were more pronounced in the southern.

Figure 5.2.1.9   Two individual examples of the quasi-two day signal in the Northern Hemisphere. The left periodogram is the 1982 season and the right is the 1997 season. For the 1982 season there are significant peaks at 1.8 and 2.2 days while the 1997 season has peaks at 1.8 and 2.4 days.
Figure 5.2.1.10  Average of selected Northern Hemisphere seasons. The strongest contribution for this average is at 1.8 and 2.2 days.

Figure 5.2.1.11  Two individual examples of the quasi-two day signal in the Southern Hemisphere. The left periodogram is the 1985 season and the right is the 1999 season. The largest contributions are 1.8 and 2.2 days.
Figure 5.2.1.12  Average of selected Southern Hemisphere seasons. The greatest contribution to this average is peaks of 2.0-2.2

Table 5.2.1.1  Selected Seasons and Their Longitude Ranges for 2-Day Averages

<table>
<thead>
<tr>
<th>North</th>
<th>Longitude Block</th>
<th>South</th>
<th>Longitude Block</th>
</tr>
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<tbody>
<tr>
<td>1982</td>
<td>70 - 130</td>
<td>1981</td>
<td>2 - 52</td>
</tr>
<tr>
<td>1983</td>
<td>180 - 220</td>
<td>1983</td>
<td>95 - 155</td>
</tr>
<tr>
<td>1985</td>
<td>270 - 320</td>
<td>1986</td>
<td>0 - 60</td>
</tr>
<tr>
<td>1986</td>
<td>240 - 270</td>
<td>1987</td>
<td>70 - 120</td>
</tr>
<tr>
<td>1988</td>
<td>310 - 360</td>
<td>1989</td>
<td>225 - 265</td>
</tr>
<tr>
<td>1994</td>
<td>210 - 240</td>
<td>1993</td>
<td>120 - 170</td>
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<tr>
<td>1995</td>
<td>210 - 270</td>
<td>1996</td>
<td>185 - 225</td>
</tr>
<tr>
<td>1996</td>
<td>340 - 370</td>
<td>2000</td>
<td>10 - 60</td>
</tr>
<tr>
<td>1997</td>
<td>265 - 305</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>150 - 180</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Aside from the well-known Rossby modes, waves in periods of 4 and 8 days were also observed repeatedly in numerous periodograms. The most probable source of this signal is not a Rossby wave but baroclinic and/or barotropic instabilities. Examples of these signatures can be seen in Figures 5.2.1.1 and 5.2.1.3 presented above and in Figures 5.2.1.13 and 5.2.1.14 below.

Figure 5.2.1.13 1984 Northern Hemisphere Periodogram (90°-130°). Strong signals can be seen at 4 and 8 days.
Figure 5.2.1.14 1980 Northern Hemisphere Periodogram (140°-170°). Again, strong signals at 4 and 8 days are present.

The largest peaks for all periodicities described in this section are on the order of $10^{-6}$, which is almost an order of magnitude higher than the mean albedo values for both hemispheres. Which indicates an overall signal to noise ratio of about 1.1. While large enough for the Lomb-Scargle method to pick out signals, it is low enough to explain false peaks seen in the periodograms. Therefore, as described in the beginning of this section, discretion must be used in positively identifying contributing waves.
5.2.2 Frequency vs. Wavenumber

The results in this section were obtained in a similar method as those of section 5.2.1, and as such are subject to the same false signatures for small signal to noise ratio datasets. However, the results have a benefit for identifying westward propagating Rossby in that the wavenumber is plotted along with the frequency. The predominant signature observed repeatedly in both hemispheres was the 5-day wave. The 6.5-day wave was also observed (usually coupled with the 5 day wave) however not as frequently as seen in the periodograms. This may indicate that the 6.5-day period signal observed in the periodograms may have contributions from other sources than just the Rossby mode. The 2 and 10-day waves were observed, although weaker and much less frequent. Unlike the one dimensional Lomb-Scargle, the two dimensional analysis was able to resolve the 16 day wave with enough accuracy to be positively identified. Figures 5.2.2.2 and 5.2.2.3 below are good examples of the 5 day wave number 1 Rossby wave, note that for this specific method the negative wavenumber indicated a westward propagating wave. The following two plots, Figures 5.2.2.4 and 5.2.2.5, show the coupling nature of the 5 and 6.5-day waves commonly observed. Figures 5.2.2.4 and 5.2.2.5 are more crowded, and although there are obvious peaks at 5 and 6.5 days (wavenumber −1), there are other false peaks obscuring the plot. Therefore the strategy is to look for repeating wave signatures. As an added note, Figure 5.2.2.1 shows the Salby sampling limits [Salby, 1982a] for the SBUV satellite. As can be seen the sampling range used in this work is within the allowed limits.
Figure 5.2.2.1 Salby Sampling Limits for SBUV Data. The red rectangle is the limits used in this section. Although the contour plots below have both positive and negative wavenumbers, only negative wavenumbers are of interest (which translates into the positive wavenumber box above due to a difference in sign convention).
Figure 5.2.2.2 1993 Northern Hemisphere Wavenumber-Frequency Contour Plot. The wavenumber 1, 5-day wave shows a strong presence.

Figure 5.2.2.3 1996 Southern Hemisphere Wavenumber-Frequency Contour Plot. Both the 5-day Rossby wave and a 4-day signal can be seen.
Figure 5.2.2.4 1994 Northern Hemisphere Wavenumber-Frequency Contour Plot. Signals at 5 and 6.5 days can be seen.

Figure 5.2.2.5 1984 Southern Hemisphere Wavenumber-Frequency Contour Plot. Although noisy, waves can be seen at 4, 5, and 6.5 days.
As described at the beginning of this section, the 10 and 16 day waves could also be observed using this method, although less frequently and smaller in amplitude. However, the frequency – wavenumber space of the results enables all wavenumber 1 waves that occur for a specific season to be seen ‘stacked’ together. This then increases the confidence that the peaks are actually Rossby waves. Figure 5.2.2.6 has wavenumber 1 periods of 5, 10, and 16 days (frequencies of 0.2, 0.1, and 0.0625) while Figure 5.2.2.7 has periods of 5, 6.5, and 10 days.

Figure 5.2.2.6  1979 Northern Hemisphere Wavenumber-Frequency Contour Plot. Stacked peaks are evident at 5, 10 and 16 days.
Figure 5.2.2.7 1999 Northern Hemisphere Wavenumber-Frequency Contour Plot.
Wavenumber 1 peaks can be seen at 5, 6.5, and 10 days.

To gain a clearer picture as to what is noise and what is signal, the frequency-wavenumber arrays for all of the seasons were averaged together. Figures 5.2.2.8 and 5.2.2.9 illustrate the strong presence of the 5-day wave in both northern and southern hemispheres. Although not nearly as strong the 6.5, 10, and 16-day waves are seen stacked below the 5 day. Notice also the influence of the 4-day periodicity in the southern hemisphere mentioned in section 5.2.1.
Figure 5.2.2.8  Average contours of frequency-wavenumber for the Northern Hemisphere. The 5-day wave stands out as the strongest signal in this average with weaker peaks at 6.5 and 10 days.

Figure 5.2.2.9  Average contours of frequency-wavenumber for the Southern Hemisphere. The strongest signal for this average is the 4-day wave with other peaks at 5, 6.5, and 10 days.
As can be seen, any evidence of a two-day signature is eliminated in this average. This is due to the fact that the two-day wave in this analysis has relatively low amplitudes for many of the seasons. To get a better view of just the two-day, only seasons in which there is a strong two-day wave were used to average. Figure 5.2.2.10 below of the 1984 Northern Hemisphere has a strong W2 2.4 day (.42 1/day) signature as well as a W3 component at around 2.13 days (.47 1/day). Figure 5.2.2.11 shows similar results with the addition of the W2 1.8 day (.56 1/day) wave. This is in agreement to other research in that the stronger components in the Northern Hemisphere are the W2 and W4. Figure 5.2.2.12 is the average over six specific seasons displaying peaks at the W2, W3, and W4 frequencies. It is quite clear that the W2 and W4 are the strongest peaks. In the Southern Hemisphere, the W3 component at frequencies of .45 - .48 is expected to be more prominent than the others – as was discussed in section 6.2.1. Figure 5.2.2.13 shows this, with no apparent contribution from the W2 or W4. However there were a few (three) seasons showing the W2 and W4 in the Southern Hemisphere more prominent than the W3, such as in Figure 5.2.2.14. Figure 5.2.2.15 is the average for the Southern Hemisphere. The W3 component is easily distinguishable, at both .45 and .47 1/day.
**Figure 5.2.11** 1989 Northern Hemisphere. The W2.4 (42), W3.2 (45), and the W4.18 (56) day (1/day) waves are present.

**Figure 5.2.10** 1994 Northern Hemisphere. The W2.4 (42) and the W3.2 (47) day (1/day) waves are present.
Figure 5.2.2.12  Average for the Northern Hemisphere (selected seasons). The strongest contributors are the W2 2.4 (.42) and W4 1.8 (.56) day (1/day) waves.

Figure 5.2.2.13  1982 Southern Hemisphere. The W3 2.2 (.455) and 2.1 (.47) waves are present.
Figure 5.2.2.14  1993 Southern Hemisphere. Waves at W2 2.4 (.42) and W4 1.8 (.56) days (1/days) can be seen.

Figure 5.2.2.15  Average of the Southern Hemisphere (selected seasons). The strongest contributors are the W3 2.2 (.455) and 2.1 (.47) day (1/day) waves.
5.3 Temporal Change (annual) in Wave Amplitudes

*DeLand et al.* [2002] used SBUV albedo data to show that PMC observation exhibits an anti correlation trend with the solar cycle. Therefore it was desirable to determine whether the solar cycle could also affect amplitudes of the planetary waves. Unfortunately this connection could not be proved or disproved with any certainty. The amplitudes of the 5, 6.5 and 10-day waves calculated in this method represent an average across an entire season, as the datasets are too limited to use smaller time blocks (remember that the SBUV PMC season only lasts about 100 days centered around the summer solstice). Any correlation could be the result of distortion caused by the differing dataset sizes (smaller datasets could exhibit more merging of peaks, causing a higher amplitude). Figures 5.3.1 and 5.3.2 below show examples of the yearly wave amplitudes of the 5, 6.5, and 10 day waves over a specific longitude block (selected for optimal clarity). The graphs are overlaid with the Lyman alpha, to evaluate if the amplitudes do change as a function of solar cycle. It is possible, however, that the amplitudes do not change much – but the increase in photodissociation rates reduce the number density of the clouds such that it appears to influence the amplitude of waves. Also seen in the two graphs is a quasi two-year oscillation. However, if this oscillation actually exists, the data is only able to resolve at the Nyquist limit.
Figure 5.3.1  Southern Hemisphere Yearly Wave Amplitudes (120° - 160°)

Figure 5.3.2  Northern Hemisphere Yearly Wave Amplitudes (30° - 90°)
6.0 Conclusion

Despite the sparse nature of the SBUV PMC dataset, the results of this work show over four separate analysis methods a definite and strong presence of multiple period Rossby waves. Although the intent of this work was to compare and contrast the work of Merkle, the limited number of data points for each season prevented the inter-seasonal temporal analysis that Merkle conducted. Conversely the research done by Merkle was limited in the annual variability from years 1998 to 2002, while the number of seasons available for this work was from 1979 to 2002 – allowing long term trends to be evaluated. Major points of interest are as follows:

- The 5-day Rossby wave was observed to be the strongest of the periodicities. It was observed slightly more frequently and stronger in the Northern Hemisphere.

- The 6.5-day Rossby wave was observed less frequently than the 5 day in the 1D periodograms but at about the same average amplitude. It was observed considerably less in the 2D periodograms, indicating that the amplitude in the 1D periodograms may be being augmented from other sources than a free Rossby mode.

- The remaining wave periods of focus (2, 10, and 16 day) were observed less frequently with smaller amplitudes than the 5 and 6.5-day waves. It is unclear at this time whether this is due to vertical or horizontal damping due to mean winds or if it is a result of this specific dataset. Since the time scale of a PMC season is less than 100 days there is less sampling of the 10 and 16 day wave, and on the other side the 2 day wave gets close to the Nyquist period for some seasons where only a specific longitude block is selected.
• Theoretically Rossby waves cannot propagate into the mesosphere vertically when the zonal winds are easterly, however planetary waves in PMC were observed. This means that the waves occurred in the lifetime of the PMC season, centered around the solstice and not near the equinox. It has been suggested that this vertical transport can occur when the easterlies are weak. Therefore observations of planetary waves are either excited in-situ or propagate vertically when the mesospheric jet is weak.

• Both types of histograms used (frequency of occurrence and average daily albedo) showed an obvious periodicity at around 5 days. Both Northern and Southern hemispheres had the prominent 5-day variability similarly frequent but the Southern hemisphere showed a more frequent presence of a periodicity at around 2 days, this is consistent with previous research. The frequency of occurrence histograms showed a pattern that began low in the early part of the season and gently increased to a peak and then waned back low at the end. The average albedo histograms, on the other hand, showed more of a sharp increase at the beginning of the season and generally remained constant until the end, where it dropped off rapidly. Although this may have something to do with the formation rates of the PMC particles, it is most likely a product of the selection rules for SBUV PMC data. The selection rules only allow the brightest PMC to be included in the data, so the weaker PMC at the beginning and end of the season are not included and as such any gradual increase or decrease of the albedo is not seen.

• Periodograms of the entire season, slided over the longitude range, showed a significant variability of planetary wave activity across the entire summer polar mesosphere. For the most part, the planetary waves showed activity in small longitude blocks, being seen as just a small peak. However in some seasons the wave activity appeared as more of a line spanning over a larger longitude block (see section 6.2.1). This could be taken as a coincidence as the analysis method
calculated the periodogram for the entire season at a specific longitude, and therefore has no temporal information about movement. Or it could be taken as a longitudinal movement of a peak, due to the fact the periodogram had a signal at the specific period at a number of coaligned longitudes. The longitudinal distribution also had peaks coaligned that would shift to a higher or lower period across the longitude range.

- Annual peak values of the 5, 6.5, and 10-day waves seem to follow a semi two-year oscillation. This could be directly tied to an observed two-year modulation of mesospheric cooling events, which are caused by planetary waves disrupting the polar vortex. The peak values also appear to follow the same anti-correlation with the solar cycle as PMC brightness. However it is unsure whether this is an actual change in planetary wave amplitude or just a reduction in number density of particles in PMC.

- A relatively strong and frequent periodicity was observed at both 4 and 8 days, both of which are theoretically dispersive for a Rossby free mode. Past observations of the 4-day wave have revealed as occurring only in the winter polar stratosphere and describe it as a “warm pool” of air propagating eastward with wavenumbers 1 through 4. Theoretical work has shown that barotropic instability can produce quasi-nondispersive modes with a period similar to the observed 4 days. PMC form only in the summer polar mesosphere, therefore unless there is some form of hemispherical transport of wave energy from the winter to the summer stratosphere/mesosphere the most probable cause of the 4 and 8 day signals is an instability in the polar jet either combining/shifting another existing wave or oscillating on its own.

- Although there is currently no evidence of a long-term change in mesospheric temperature, small changes can still exist with the introduction of dynamical features such as planetary waves. The meridional flow is a relatively constant
(over the PMC season) source of water vapor, however this is easily influenced by wave activity. Therefore the coupling mechanism between planetary waves and PMC formation is the forced introduction of water vapor and small-scale temperature changes just below the mesopause.

7.0 Future Studies.

A main weakness of the SBUV dataset was the non-continuous and sparse nature of the data as a result of having to select out only the brightest albedo values. Therefore there was not enough data points available close together in time to reduce the Nyquist period for smaller blocks of time. In this work, the entire season had to be used to resolve the periods observed. An optimal analysis would be to observe the change in occurrence and amplitude of the 2 and 5-day Rossby waves as well as the 4-day wave observed in this work. Observing when the 4-day wave occurs could couple it to past work or illuminate a new feature. Further studies coupling wave activity and PMC activity could bring a better understanding of PMC formation theory.
REFERENCES


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Olivero, J. J., Private Communication, 2004


APPENDIX

A.1 Solar Backscatter Ultraviolet Spectrometer

A.1.1 Orbital Observational Limits

In 1978 SBUV began service aboard Nimbus-07. The next generation of SBUV instruments, called SBUV/2, were to be flown on the NOAA series satellites and began collecting data in 1984 on NOAA-09. Since then SBUV/2 instruments have been launched on NOAA-11, NOAA-14, NOAA-16, and NOAA-17 – which was launched in June 2002 (refer to table A.1.1 for active times of individual satellites). Both the Nimbus and NOAA satellites flew in a polar sun-synchronous orbit, although each had slightly different orbital parameters.

Table A.1.1.1 SBUV Satellite Orbital Parameters

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Period (min)</th>
<th>Altitude (km)</th>
<th>Velocity (km/s)</th>
<th>Active Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nimbus 07</td>
<td>104.15</td>
<td>955</td>
<td>7.375</td>
<td>1978 – 1989</td>
</tr>
<tr>
<td>NOAA 09</td>
<td>101.76</td>
<td>842</td>
<td>7.433</td>
<td>1985 – 1996</td>
</tr>
<tr>
<td>NOAA 14</td>
<td>101.89</td>
<td>848</td>
<td>7.429</td>
<td>1996 – 2000</td>
</tr>
<tr>
<td>NOAA 17</td>
<td>101.20</td>
<td>850</td>
<td>7.446</td>
<td>2002 - 2003</td>
</tr>
</tbody>
</table>

The Nimbus 07 satellite orbited at an altitude of 955 km with a period of ~104 minutes. This results in a longitude separation of 26 degrees per orbit. The NOAA satellites had a slightly different orbit at an altitude of ~850 km and a period of ~101.7 minutes. Although the orbit changed, the spatial separation is very similar to the Nimbus 07 satellite – with a longitude separation of 25.3 degrees per orbit. This similarity in spatial separation allows the different satellites to be combined where the data overlaps. Depending on the mean difference in time between datapoints for each season, the longitude separation between points ranges from 2.75° – 15° with a center separation of 7.25° (calculated using the large seasons for both northern and southern hemispheres).
A.1.2 Data Retrieval

Recorded data is first corrected for time dependant and wavelength dependant changes in instrument properties such as gain, PMT temperature dependence, and response. Raw measurements are then processed by NOAA/NESDIS using the NASA V6 algorithm. After processing the radiance values are stored for analysis in Q-values, defined as follows:

\[ Q_\lambda = \frac{I_\lambda}{F_\lambda \beta_\lambda P(\theta)} \]

Where \( I_\lambda \) is the radiance of wavelengths less than 297.5 nm, \( F_\lambda \) is the solar irradiance, \( \beta_\lambda \) is the Rayleigh scattering coefficient, and \( P(\Theta) \) is the Rayleigh scattering phase function. For PMC research using the SBUV data, the Rayleigh scattering coefficient and phase function are multiplied out to leave the albedo:

\[ A_\lambda = \beta_\lambda P(\theta) Q_\lambda = \frac{I_\lambda}{F_\lambda} \]

A.2 SBUV PMC Detection

A.2.1 SBUV PMC Detection Algorithm

One of the possible signals present in SBUV nadir observations is the scattered sunlight from PMC below. The following procedure for determining if a signal is the result of a PMC was developed in DeLand et al. [2002]. It ensures that albedo values used for PMC research from the SBUV data set are observed PMC and not background or ozone albedo. The down side to this procedure is that for a nadir pointing instrument such a SBUV, only the brightest PMC make it through the filtering process.
The central idea of developing a process to view PMC is that it must stand out significantly from the background terrestrial albedo. Therefore this particular algorithm takes advantage of the very low terrestrial albedo in the mid-UV, with a minimum due to ozone absorption at approximately 250 nm [Thomas et al., 1991]. The first step is to separate out 'polar' measurements (defined as all data poleward of 50 degrees latitude) and applying a 4th order polynomial fit (see Figure A.2.1.1) as a function of the solar zenith angle (complimentary to the scattering angle) for each of the five shortest wavelengths. The background fit is then subtracted out and the following selection rules determine if the residual albedo ($r_\lambda$) is a PMC;

![Figure A.2.1.1](image)

Figure A.2.1.1  PMC Albedo vs. Solar Zenith Angle. The data points represented by squares are those accepted as PMC.

1. The residuals for the three shortest wavelengths must all be positive.
   \[ r_{252}, r_{273}, r_{283} > 0 \]

2. The slope of the linear regression of the five residuals (five shortest wavelengths) must be negative.
   \[ m_\lambda < 0 \]
3. For one days’ worth of data, the 252nm albedo is separated into 10 bins over the solar zenith angle with an equal number of samples in each bin. For each of the bins the average albedo and standard deviation are calculated. The 252 nm residual must then exceed the product of the standard deviation and the ratio of the average albedo divided by a reference average albedo (the reference albedo is the average of the values at 81 degrees latitude for a day).

\[ r_{252} > (\sigma_{252} \cdot \{A_{252}\}_{\text{bin}} / A_{252}(81^\circ)) \]

4. The 252nm residual albedo must exceed the 273nm residual albedo.

\[ r_{252} > r_{273} \]

The above algorithm is applied to each day’s data for five iterations, excluding samples identified as PMC from the background fit for each iteration.

A.2.2 False Positive Filtering

Although selective, the algorithm described in section A.2.1 can still allow a false detection of a PMC due to fluctuations in upper stratospheric ozone or random measurement errors. Evaluation of data from time periods outside of the normal PMC season results in detection rates less than 1% using the selection algorithm. This detection rate increases to 1-2% in the northern hemisphere spring due to an increase in gravity wave activity. Therefore the 252 nm residual albedo values that passed the selection algorithm must also be greater than \( 7 \times 10^{-6} \). At solar zenith angles of 70° or greater the albedo drops off dramatically, therefore the threshold limit is changed to 5% for residual albedo data with a solar zenith angle greater than 70°.
A.3 Final SBUV Dataset Format

SBUV PMC albedos that pass the selection rules and false positive filtering (again, refer to section A.2) are stored in arrays, separated into individual satellites, seasons, and hemisphere. The general format of the SBUV PMC data is described in table A3.1.

Table A.3.1 SBUV PMC Data Format

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<thead>
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<th>Data Type</th>
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<th>Data Type</th>
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<tr>
<td>1</td>
<td>Satellite Number</td>
<td>9</td>
<td>Solar Zenith Angle [degrees]</td>
</tr>
<tr>
<td>2</td>
<td>Year</td>
<td>10</td>
<td>Orbit Flag: 0 = ascending, 1 = descending</td>
</tr>
<tr>
<td>3</td>
<td>Day of Year</td>
<td>11</td>
<td>Absolute albedo at 252 nm</td>
</tr>
<tr>
<td>4</td>
<td>Day from Solstice</td>
<td>12</td>
<td>Residual Albedo at 252 nm (4th order fit)</td>
</tr>
<tr>
<td>5</td>
<td>Measurement Time [seconds UT]</td>
<td>13</td>
<td>Residual Albedo at 252 nm [percent]</td>
</tr>
<tr>
<td>6</td>
<td>Mean Local Solar Time (longitude corrected) [hours]</td>
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<td>Slope vs. Wavelength of albedo residuals [1/nm]</td>
</tr>
<tr>
<td>7</td>
<td>Latitude [degrees]: negative = S, positive = N</td>
<td>15</td>
<td>Error of Slope for Residual Regression Fit</td>
</tr>
<tr>
<td>8</td>
<td>Longitude [degrees]: positive = East, negative = West</td>
<td></td>
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</tr>
</tbody>
</table>

Figure A.3.1 below is an albedo vs. local time plot for just one satellite (taken mid season). The gaps in the data are artificially generated artifacts from orbital sampling over a limited spatial area. This is also seen in Figure A.3.2 of latitude vs. local time. Although a sun synchronous orbiter, the local time coverage of the satellites is enough to resolve long wave signals in a specific spatial location.
Figure A.3.1  Albedo vs. Local Time for the 1984 Northern Hemisphere Season

Figure A.3.2  Latitude vs. Local Time for the 1984 Northern Hemisphere Season
B.1 Lomb-Scargle Method

Data having continuous, evenly spaced data points in time can easily have all contributing signals extracted to the Nyquist limit by using some form of a Fast Fourier Transform (FFT). However many realistic remote sensing platforms cannot or do not collect data evenly and regularly. Even systems intending for continuous data retrieval may need to calibrate or experience technical problems. The most common method for this type of data to extract frequency information is the Lomb-Scargle method. First developed in 1975 by Lomb and further modified by Scargle in 1982 this method takes advantage of constructive/destructive interference between the data and a sampling frequency. For a time series $X(t_i)$ where $i = 1, 2, 3 \ldots, N_0$, the power spectral density of a frequency $\omega$ is:

$$P_x(\omega) = \frac{1}{2} \left\{ \frac{\sum_{i=1}^{N_n} X(t_i) \cos \omega(t_i - \tau)}{\sum_{i=1}^{N_n} \cos^2 \omega(t_i - \tau)} \right\}^2 + \left\{ \frac{\sum_{i=1}^{N_n} X(t_i) \sin \omega(t_i - \tau)}{\sum_{i=1}^{N_n} \sin^2 \omega(t_i - \tau)} \right\}^2$$

where $\tau$ is defined by the relation:

$$\tan(2\omega\tau) = \frac{\sum_{i=1}^{N_n} \sin 2\omega t_i}{\sum_{i=1}^{N_n} \cos 2\omega t_i}$$

When defined in this manner this method becomes equivalent to a least squares fitting of sine curves to the data. The resulting power spectral density is then normalized by the variance of the data. When normalized, the power spectrum follows an $e^{-z}$ (where $z$ is the power of a specific frequency) probability distribution. The negative side of this method is it is slow. It requires $10^2 N^2$ operations to analyze $N$ data points. The Lomb-Scargle method also produces confidence levels (99.9%, 99.0%, 95%, 90%, and 50%), which
represent how significant a particular frequency is in relation to the exponential fit of the power spectrum. The confidence levels are calculated as follows:

\[ P = \ln \left( \frac{N}{[0.001, 0.005, 0.01, 0.05, 0.1, 0.5]} \right) \]

Where \( P \) is the power of the confidence level at each of the six probabilities and \( N \) is the number of datapoints. Then if a amplitude vs. frequency periodogram is desired, the value for the power is converted by:

\[ P_{\text{amp}} = 2 \sqrt{\frac{P \sigma}{N}} \]

Where \( \sigma \) is the variance of the data. Therefore if the variance is small, the confidence level will also be small.

*Wu et al.* [1995] modified the method further to include spatial information as well as frequency specifically for data collected by satellites. The modified model for the 2D method is:

\[ X_i = A \cos(2\pi(\omega t_i + s\lambda_i)) + B \sin(2\pi(\omega t_i + s\lambda_i)) \]

Where \( s \) is the wavenumber (number of wavelengths in 360°) and \( \lambda \) is the longitude of a data point. The resulting power for a frequency is obtained from:

\[
P_X = \left[ \frac{1}{\sum_{i=1}^{N} \varepsilon_i^2} \sum_{i=1}^{N} \frac{X_i \cos(2\pi[\omega t_i + s\lambda_i] - \tau)}{\varepsilon_i^2} \right]^2 + \left[ \frac{1}{\sum_{i=1}^{N} \varepsilon_i^2} \sum_{i=1}^{N} \frac{X_i \sin(2\pi[\omega t_i + s\lambda_i] - \tau)}{\varepsilon_i^2} \right]^2 \]
Where $\tau$ is:

$$\tau = \frac{1}{2} \tan^{-1} \left[ \left( \sum_{i=1}^{N} \frac{1}{\xi_i} \sin[4\pi(\omega x_i + s\lambda_i)] \right)^2 \right]$$

$$\left/ \left( \sum_{i=1}^{N} \frac{1}{\xi_i} \cos[4\pi(\omega x_i + s\lambda_i)] \right)^2 \right.\right]$$

Similar to the 1D method, this is a slow analysis. The $10^2N^2$ number of operations required are looped through a wavenumber range. Therefore the wavenumber range and resolution can be modified specifically for the phenomenon of interest.