Gravity wave observation from the Cloud Imaging and Particle Size (CIPS) Experiment on the Aeronomy of Ice in the Mesosphere (AIM) Spacecraft

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Abstract

In this paper we present first results of gravity wave observations on polar mesospheric clouds during the summer of 2007, in the northern hemisphere. The Cloud Imaging and Particle Size (CIPS) experiment is one of the three instruments on board the Aeronomy of Ice in the Mesosphere (AIM) spacecraft that was launched into a sun-synchronous orbit on April 25, 2007. CIPS is a 4 camera wide-field (120° x 80°) imager designed to measure PMC morphology and particle properties and has a spatial resolution of 1 x 2 km in the nadir. One of the objectives of AIM is to investigate gravity wave effects on PMC formation and evolution. CIPS images show distinct wave patterns and structures in PMC’s. These structures range from a few kilometers to a few hundred kilometers, similar to ground based photographs of Noctilucent Clouds (NLC’s). The horizontal wavelengths of the observed waves range between 15 and 300 km, with smaller wavelength structures of less than 50 km being most common. We present examples of individual wave events observed by CIPS and statistics on wave structures observed in the northern hemisphere during the summer months of 2007. We also
present a global map of gravity wave events observed from CIPS. The spectrum of the PMC structures for the three summer months show a clear peak at wavelengths less than 50 km.

Keywords: polar mesospheric clouds, gravity waves, mesosphere

1. Introduction

Photographs of Noctilucent Clouds (NLC’s) and Polar Mesospheric Clouds (PMCs) often exhibit a distinct wave structure with spacing of ~10 to 100 km or more. These structures are described as “bands” while the smaller scale features, with a spacing of ~3 to 10 km have been termed “billows” or “whirls” depending on their form [Witt, 1962; Haurwitz and Fogle, 1969; Fritts and Rastogi, 1985; Gadsden and Parvianien, 1995; Thomas, 1991].

The structures seen in the clouds can potentially yield information about the dynamics of wave motion in the upper mesosphere where they are believed to control the mesospheric circulation [Lindzen, 1982; Holton, 1983]. Indeed they are known to be directly responsible for altering the circulation which leads to the very low polar temperatures responsible for the conditions necessary for ice formation. Remote sensing of the mesopause region using airglow imaging techniques have shown evidence of gravity waves with length scales similar to those seen in NLC near the mesopause [Swenson and Espy, 1995; Taylor and Garcia, 1995; Hines, 1968; Fritts, 1984]. Henceforth in this paper, we will refer to PMC linear structures having three or more spatially-coherent peaks and troughs in the scattered radiance as 'gravity waves (GW)'. In actuality they are proxy indicators of waves, through the combined effects of the periodic changes in temperature, water vapor and vertical motion.

GWS propagate upward from lower altitudes where they grow in amplitude and become unstable ('break') in the upper mesosphere and lower thermosphere. They deposit substantial momentum and energy in this region could play an important, if not a crucial, role in PMC formation and destruction [Turco et al., 1981; Jensen and Thomas, 1993; Rapp et al., 2002]. Ground-based views of NLC are possible during summer in a limited latitude zone (~50-60°) where the lighting conditions allow scattering of sunlight to be visible against a relatively dark sky. These views reveal the nearly ubiquitous presence of waves, at least at these latitudes during
the NLC season (approximately two months from mid-May to mid-August in the NH [Gadsden, 1998]). The smaller-scale NLC 'billows' which often accompany larger band structures may be manifestations of the wave-breaking process itself, wherein waves become convectively unstable and create secondary waves normal to the original wave front [Fritts et al., 1993]. The scales of internal atmospheric gravity waves typically encompass horizontal wavelengths of a few tens of km to several thousand km, and ~1 to several tens of km in the vertical [Manson, 1990, Fritts, 1984]. Typical horizontal phase speeds of 10-60 m/s have been reported by Haurwitz and Fogle [1969], but values exceeding 100 m/s are known to occur, often opposite the direction of the bulk flow. The bands seen in ground based NLC photography typically exhibit periods of less than an hour and horizontal scales of up to a few hundred km and represent only a fraction of the total wave spectrum [Fritts, 2003]. The longer period (with larger horizontal scales) gravity waves are expected to play an important role for PMC formation than the short period waves as their time scales are similar to the expected PMC growth/decay time. Microphysical modeling predicts that the dividing period is about seven hours, below which ice particles are destroyed by the wave, and above which the ice particles can be at least temporarily enhanced in size, and thus brightness [Rapp et al., 2002]. Experimental evidence that short-period gravity wave activity is inversely proportional to PMC backscattering was provided by Gerrard et al. [1998; see also Thayer et al., 2003]. Lidar backscattering of PMC at Söndrestrom, Norway indicate persistent gravity wave influences with periods of 2 to 3 hours [Thayer et al., 2003]. There is an abundance of temperature measurements in rocket flights that show that high-latitude, summertime GW cause significant fluctuations in temperature, exceeding 5K. For example, Rapp et al., [2002] showed that NLC occurred in the immediate vicinity of negative fluctuations in temperature in three of seven rocket-borne high-resolution (200 m) ionization gauge measurements. Their detailed model simulation showed that this correlation resulted from a complex interplay between growth, sedimentation and vertical velocity fluctuations.

Ground based observations being local and almost all of them being south of 70° latitude (predominantly in the northern hemisphere) are limited in their use to study the large-scale distribution of gravity waves. PMC mapping from space can yield this type of information over the entire summertime polar
Carbary et al. [2003], using data from the ultraviolet and visible imaging and spectrographic imaging instrument (UVVISI) on the Midcourse Space Experiment (MSX) satellite, observed horizontal structures in PMC’s of typical size 100 km with some structures >100 km. Nadir angles of 84° limited the spatial resolution along the line of sight, but structures of a few km were resolved normal to the viewing direction. Hundreds of images were processed, from a total of ~25,000 separate images taken over 22 separate orbits in the southern hemisphere (SH) of 1997/98 and in the northern hemisphere (NH) 1999. However, the reported images covered only narrow strips, about 100 km wide, and were not sufficiently numerous to define latitudinal or seasonal characteristics. The Cloud Imaging and Particle Size Experiment (CIPS) represents a significant advance over MSX for several reasons: (1) The viewing geometry is more favorable, ranging from nadir viewing to a maximum of 60° off-nadir; (2) the field of view is an order of magnitude greater (~1000 km x 2000 km) permitting overlapping coverage of the polar region up to 82°; and (3) the CIPS coverage of the polar region has 100% duty cycle with 15 orbits per day over the full northern2007 PMC season. The CIPS experiment was carried on board the Aeronomy of Ice in the Mesosphere (AIM) satellite, which was launched on April 23, 2007 into a near-polar sun-synchronous orbit of ~ 600 km height with an inclination of 97.8°. Mounted on the earthward side of the spacecraft, the CIPS cameras possess an unparalleled view of the PMCs over the polar region at a uniform (~ 5 km) spatial resolution. It should be noted that the noon-midnight sun-synchronous geometry of the AIM orbit means that only two bands of local solar time are sampled, centered around 2200 hrs (the orbital upleg for the NH at 64-74°N) and 1400 hrs (the downleg). It is possible that GW characteristics may depend upon local time, for example, if they are affected by tidal winds (for example, see Liu and Hagan, 1998 for numerical simulations of tidal interactions with gravity waves). This limitation should be kept in mind in comparison with other data.

2. The CIPS Instrument

The CIPS experiment is a panoramic UV nadir imager with a spectral triangular bandpass, centered at 265 nm extending from 258 nm to 274 nm (half-power points). This region in the UV is chosen to maximize cloud contrast, due to the relative weakness of the Rayleigh-scattered sky background from absorption of solar
radiation in the ozone Hartley bands. CIPS consist of four cameras with each camera taking 34 images per orbit. Each camera uses a 2048 x 2048 pixel detector binned to provide a 1x 2 km resolution in the nadir at 83 km, the nominal PMC altitude. On-board binning results in a 360 (along track) x 180 (cross track) array of science pixels [McClintock et al., 2008 (this issue)]. The combined camera array has a 120° x 80° field of view. Projected to cloud altitude, the total field of view of ~ 2000 x 1000 km centered at nadir. CIPS takes multiple exposures of the polar atmosphere, permitting a variety of scattering angles to be measured of the same volume of space. Since PMC scatter light more efficiently in the forward-scattering direction, the seven-image combination helps determine cloud presence and thus allows a background separation and mapping of the much weaker PMC. The details of this separation procedure is described in more detail in Bailey et al. [2008, this issue] and Rusch et al. [2008, this issue]. The 5-km spatial resolution enables the mapping of PMC structures at scales which allows full resolution of the NLC bands. The images are marginal for viewing the small-scale (wavelengths <10 km) billow structures, and will not be discussed in this paper.

3. Analysis

The first step in the analysis of waves is to manually identify clear wave events in the data. A wave event is defined as a regular set of three or more spatially-coherent linear features in the CIPS albedo maps. Shown in Figure 2a is a four camera CIPS ‘bowtie’ image. There is an overall increase of PMC albedo, from left to right, as the scattering angle increases. The fore and aft cameras have an integration time of 0.73 seconds and the nadir cameras have an integration time of 0.75 seconds. (The UV albedo (sr^{-1}) is defined as the ratio of the scattered irradiance divided by the incoming solar irradiance, averaged over the spectral band pass.) Distinct wave patterns can be seen near the top left of the image. The next step is to trace a series of pixel-wide sections normal to the wave fronts (as indicated by the line across the CIPS images in Figure 2a). A low-order polynomial is fitted to each trace essentially performing a high-pass filter. This polynomial fit is designed to remove most of the underlying smoothly-varying PMC signature. The difference of the albedo values from the fit is calculated and the variations are assumed to be albedo perturbations purely due to the wave dynamics. Next, a wavelet analysis is performed on these difference values of albedo, a method which is well suited to a
finite 'wave packet'. The wavelet transform technique is used to analyze time series that contain many different
frequencies, or in this case of a spatial scan, with many composite wavelengths. This technique has been found
suitable for analysis of CIPS images which often show multiple wave structures. Since here we are primarily
interested in the wavelet power criteria, the choice of wavelet function is not really critical, however the Morlet
wavelet was chosen since it can give information about both amplitude and phase and is better suited for data
with oscillatory behavior [Torrence et al., 1998]. The Morlet wavelet consists of a plane wave modified by a
Gaussian. The Morlet wavelet function is given by the equation:

\[ \psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2 / 2} \]  

(1)

where \( \omega_0 \) is the non dimensional “wavenumber” and \( \eta \) is a non dimensional “distance” parameter. The
wavelet used has zero mean and is localized in distance [Farge, 1992]. Figure 1 shows the shape of the Morlet
wavelet used for the analysis. In the wavelet analysis, the mean power spectrum for each series analyzed is
computed first, and if a peak in the wavelet power spectrum is significantly above this background power, then
it is be assumed to be a true feature. We have used a significance level of 99% for our analysis which implies
that the peaks have 1% probability of being caused by noise in the data. An alternative method is to use a fast
Fourier transform (FFT) analysis. The wavelet results were compared with an FFT analysis on the same
difference values. The FFT analysis and wavelet analysis both clearly identify the dominant wavelength in the
series. However, the secondary waves with lesser power are more easily brought out in wavelet analysis as
compared to FFT analysis.

4. Results.

We present wave structures seen in PMC’s in the northern hemisphere during the summer months of
June, July and August. A visual analysis was first performed on the data and from this we were able to identify
a large number of wave events. All these wave events were analyzed and here we present statistics on these
preliminary results. The spectra of PMC wavelengths range from 13 km to approximately 400 km. In this
section we present two specific examples of gravity waves in PMC’s. Figure 2 is an example of a short wavelength gravity wave and figure 3 is an example of a long wavelength gravity wave. Figure 2 a. is a CIPS 'bowtie' image clouds taken at the peak of the PMC season in July. This image is a composite of the four fields of view, all taken simultaneously which shows distinct wave patterns in PMC’s. In Figure 2 a., a wave field can be seen extending ~ 1000 km between 110° W and 120° W and 65-67° N. A wavelet analysis for two sections shown in figure 2 a., indicates a dominant wavelength of 45 km as shown in figure 2 b. Figure 2 c. shows the geographical region over which the coherent wave pattern is seen. The dashed box in fig 2a. corresponds to the boxed region in figure 2c. over which the coherent wave pattern is seen.

Figure 3 a. is a CIPS image taken at the start of the PMC season on June 5 over Northern Greenland in orbit 611. It indicates the presence of a long wavelength gravity wave. This wave field can be seen in multiple orbits, separated by about 90 minutes. Another interesting feature of this wavefield is that it seems to aligned along latitudinal lines. Figure 3 b. shows how the wave fields line up in consecutive orbits in images taken 96 minutes apart. The wave structure analyzed at three sections indicated by 1, 2 and 3 in figure 5 a shown in the wavelet plot in figure 6, indicate the presence of a wave with a horizontal wavelength close to 250 km and a secondary wave with a horizontal wavelength of 100 km. At section (1.) the 250 km wave is stronger and dominates the wavelet plot. At section (3.) the 100 km wave dominates and at section (2.) the wavelet plot shows a mixture of the two waves as an equal distribution of power between the two waves at 100 km and 200 km. This change in the dominant wave structure seen in the clouds occurs over a distance of approximately 600 km in the along-track direction. The top most plot in figure 6 is a wavelet analysis of the same section as section i. in orbit 611, from an overlapping image from orbit 610 taken 96 minutes earlier. This plot also shows the presence of the same kind of wave structures as that seen in the analysis of the three sections in orbit 611 with a secondary peak at 100 km and a strong peak between 210 – 250 km. An analysis of the geo-location of the wave structure indicates that the wave has moved in the northwest by 85 km in 96 minutes yielding a speed of ~ 55 km/hr or ~ 15 m/s. This speed is of course the component sum of the bulk speed of the wind and the phase
Since Period is given by $P = \lambda / V$, where $\lambda$ is the wavelength and $V$ is the wave velocity, a horizontal wave speed of 55 km/hr for a 250 km horizontal wavelength wave indicates a period of 4.5 Hours.

Taking the horizontal wavelength and the period of the gravity wave, the vertical wavenumber can be estimated from the dispersion relation for internal gravity waves [e.g., Gill, 1982], which is given by:

$$\omega^2 = \frac{N^2 k_x^2 + F^2 k_z^2}{k_x^2 + k_z^2}, \quad (2)$$

Here $k_x = 2\pi / \lambda_x$ is the horizontal, and $k_z = 2\pi / \lambda_z$ is the vertical wave number of the wave; $N$ is the Brunt Vailala frequency; and $\omega = 2\pi / T$ is the frequency. $F$ is the coriolis parameter and for the timescales of the waves considered here, it can be neglected. The vertical wavelength calculated from the dispersion relation for the wave structure in figure 3 is 8.5 km.

### 4.1. Statistical distribution of wave structures.

Table 1 summarizes the preliminary wave structures detected throughout the northern hemisphere summer season. In June 41.18% of all observed waves have horizontal wavelengths greater than 100 km. In July it drops to 32.35% and in August it again rises to 42.86%. In July during the peak of the cloud season we observe a greater number of smaller wavelength structures. Figure 5 shows the same data as in Table 1 in a histogram plot. The wavelengths have been put in 15 km bins. Although the spectrum looks rather ragged because of the small number of events, there is a definite peak near 35-40 km in horizontal wavelength during all three months during the summer. The histogram plot for the whole season in figure 5 clearly illustrates this. During the months of June and August the distribution is more evenly distributed between wavelengths even though there is a small number of events at wavelengths <50 km. In the month of July there is a bigger peak at about 35 km. Figure 6 plots the geographical location of the observed wave events color coded for different months. There is a concentration of wave events over NW Greenland, Eastern Canada and over the Arctic Ocean just north of central Siberia.
Large scale structures with wavelengths more than 200 km as well as small scale structures of very few km’s in wavelength can be seen in PMCs. The clouds generally seem to favor structures between less than 50 km. However the extent of observed wave structures in clouds lies between 15 km and 400 km in wavelength. The structures seen in CIPS images are in accordance with previous investigations which have noted wavelengths of 20 -100 km in both PMCs as well as their presumed drivers, gravity waves [e.g., Witt, 1962, Fritts, 1984; Espy et al., 1995]. 62 % of all wave events observed during the season are < 100 kms in wavelength as opposed to only 12.5 % with wavelength > 200 kms. This is quite different from results of Carbary et al. who had noted that PMC’s tend to favor structures at scales of 500 – 1000 km and saw very few structures less than 100 km. During our preliminary investigations, we detected gravity waves in all four CIPS cameras, though a wave event was rarely observed extending across cameras and therefore the images were generally not analyzed across cameras. This limited our analysis to structures less than 500 km. Analysis of the CIPS images for wavelengths greater than 500 km is part of our immediate future research. Based on our initial results, an interesting observation is that, in July we see 67 % of smaller wavelength waves, while in June and August we see 58 and 57 % respectively, There is a significant rise in the number of smaller scale gravity waves observed during the peak of the cloud season. While we generally do not see a preferential east west alignment of gravity waves along latitudinal lines, there are a lot of wave events which are aligned east west along latitudinal lines similar to observations by Carbary et al. We were limited to a lower latitude of 65 degrees below which the clouds were not bright enough for our preliminary visual analysis to detect gravity waves. Most of the wave events observed have very small timescales and are rarely seen in consecutive orbits making it difficult to get relative phase speeds and parameterization of the wave. Simultaneous AIM measurements along with ground based measurements using lidar and photography of wave events will yield information about the vertical profiles of the waves and help in gravity wave parameterization and help in better understanding gravity wave effects on clouds. Simultaneous ground based observations along with AIM has been planned and is part of our future work.
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Figure Captions

Figure 1. The Morlet wavelet used for analysis with the real (solid) and imaginary (dashed) parts.

Figure 2. Figure 2 a. is a CIPS bowtie image clouds taken on July 22nd, which shows very distinct wave patterns in PMC’s. In Figure 2 a., a wave field can be seen extending close to 1000 km between 110 degrees west and 120 degrees west and 65 - 67 degrees north. A wavelet analysis of the albedo variation from a
smoothed background fit for two sections shown in figure 2 a., indicates a very strong wavelength of 45 km as shown in figure 2 b. Figure 2 c shows the geographical extent of the observed coherent wave pattern.

**Figure 3.** Figure 3 a. is a CIPS image taken at the start of the PMC season on June 5 over Northern Greenland in orbit 611. It indicates the presence of a long wavelength gravity wave. This wave field can be seen in multiple orbits. Figure 3 b. shows how the wave fields line up in consecutive orbits (denoted by the numbers on top of the images) in images taken 96 minutes apart. The outline is the coast of Northern Greenland.

**Figure 4.** An analysis of the wave structures at three sections indicated by 1, 2 and 3 in figure 3 a.

**Figure 5.** Histogram plots of the occurrence of wave events observed in Northern hemisphere in the months of June, July and August of 2007.

**Figure 6.** The geographical locations of the wave events observed during summer 2007 in the Northern hemisphere.

**Table Caption**

**Table 1.** Summary of wave structures seen throughout the northern hemisphere summer season
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Figure 4 shows an analysis of the wave structures at three sections indicated by i, ii and iii in figure 3 a.
Figure 5 shows histogram plots of the occurrence of wave events observed in Northern hemisphere in the months of June, July and August of 2007.
Figure 6 showing the geographical locations of the wave events observed during summer 2007 in the Northern hemisphere.
Table 1 summary of wave structures seen throughout the northern hemisphere summer season

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<th>Month</th>
<th>$\lambda &lt; 100$ km</th>
<th>$100 &lt; \lambda &lt; 200$ km</th>
<th>$\lambda &gt; 200$ km</th>
<th># of Events</th>
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<td>19</td>
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<td>61(25.42 %)</td>
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