The Cloud Imaging and Particle Size Experiment on the aeronomy of ice in the Mesosphere mission: Cloud morphology for the northern 2007 season

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Abstract

The Aeronomy of Ice in the Mesosphere (AIM) mission was launched from Vandenberg Air Force Base in California at 4:26:03 EDT on April 25, 2007 becoming the first satellite mission dedicated to the study of noctilucent clouds, also known as Polar Mesospheric Clouds (PMC) when viewed from space. We present the first results from one of the three instruments on board the satellite, the Cloud Imaging and Particle Size (CIPS) instrument. CIPS has produced detailed morphology of the Northern 2007 PMC season with 5 km horizontal spatial resolution. CIPS data yield panoramic views of cloud structures at multiple scattering angles within a narrow spectral bandpass centered at 265 nm. Spatial coverage is about 50% at the lowest latitudes where data are collected (35°). Coverage increases with latitude to 100% about 70°, where camera views overlap from orbit to orbit, and terminates at about 82°. Cloud structures have for the first time been mapped out over the summertime Polar Regions completely free of slant-path distortions and limited spatial coverage characteristic of single-station ground-based imagery. These structures include 'ice rings', spatially small but bright clouds, and large regions ('ice voids') in the heart of the cloud season essentially devoid of ice particles.
The ice rings bear a close resemblance to tropospheric convective outflow events, suggesting a point source of mesospheric convection. These rings (often circular arcs) are most likely Type IV NLC ('whorls' in the standard WMO nomenclature). Modeling of ice particles in the general circulation model (WACCM) suggests that the voids are due to warm patches of descending air. Surprisingly, in contrast to ground-based views from the NLC zone (50-65° latitude zone) wave features are comparatively rare in the CIPS images and are generally confined to the edge of the ice existence region.

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Keywords: Polar Mesospheric Clouds, Mesosphere, Dynamics, Gravity waves
1. Introduction

Polar Mesospheric Clouds (PMCs) are the Earth's highest clouds, occupying the very cold atmospheric region below the summer mesopause with a latitude extent from about 55° to the geographic pole. They occur largely within the Arctic and Antarctic circles within each hemisphere. The duration of the cloud season in the north is from about mid-May to mid August and in the south from mid-November to mid-February. The polar mesopause region becomes the coldest place on earth around summer solstice, when the temperatures may fall below 130K, possibly as low as 110K at times. First identified over 120 years ago [Leslie, 1885], their nature as very small sub-micrometer water-ice crystals was not established until recently [Hervig et al., 2001]. Interest in PMCs has been generated because of they are a tracer of phenomena in this unusual part of the upper atmosphere, and are changing in ways that are not understood. They are appearing more frequently, are brighter and are being seen at lower latitudes than ever before reported [Deland et al., 2004; 2007b; Taylor et al., 2002]. The AIM mission [Russell et al., 2008 (this issue)] was designed to study the relationship of PMCs to their atmospheric environment, which could resolve the question of what causes the long-term changes in PMC brightness and frequency [DeLand et al., 2007; Shettle et al., 2007] Due to their extreme sensitivity to changes in the environment (changes in temperature as small as 3K may have profound effects on PMC growth and brightness, see Merkel et al. [2006]), PMCs are expected to be a particularly sensitive indicator of long-term global change. Indeed, PMCs may be a modern phenomenon associated with the rise of certain greenhouse gases in the industrial era [Thomas, 1996]. A significant
increase of ~5%/decade in PMC brightness has occurred over the past 27 years [DeLand et al., 2007b].

At least four factors are believed to control PMC formation: (1) temperature, (2) water vapor, (3) cosmic dust influx [Thomas, 1996], and (4) mesospheric dynamics [Hines, 1960; Turco et al, 1982]. However, there are many open questions regarding PMC formation and destruction [Rapp and Thomas, 2006], heterogeneous destruction of trace metals [e.g. Plane and Murray, 2004], the influence of gravity waves, water sequestration, solar cycle effects, and bulk transport. Despite advanced present-day modeling [e.g. Berger and Lübken, 2006, Lübken and Berger, 2007], many uncertainties relating to time dependence of cloud formation, destruction, and dynamics hamper our ability to understand the observed changes. Recent progress has been made in understanding global scale properties of PMCs and the related radar phenomenon, Polar Mesospheric Summertime Echoes (PMSEs). For a recent review of these developments, see Lübken and Berger [2007].

A relatively uncharted territory is the spatial distribution of PMC on spatial scales comparable to those of gravity waves from a few km to hundreds of km [see Chandran et al., 2008 (this issue)]. There are many thousands of ground-based photographs of NLC taken over the years, beginning with Jesse [1896]. These photographs, and naked-eye reports, reveal complicated spatial structures at sub-km resolution. A morphological classification has been established for many years [WMO, 1970], systematizing the various cloud forms into five main types, I through V. The dominant wave features appear as two types: \textit{bands} (Type II) which are periodic structures with horizontal wavelengths \(\sim 10-100\) km, and are many hundreds of km long; and \textit{billows} (Type III)
which are closely-spaced bands of 10-20 km wavelength or less, but longitudinally much shorter than bands. More detail can be found in Gadsden and Schröder [1989].

At any given moment, the bands and billows appear to be static. In time-lapse movies, they are found to move rapidly and last for many hours with wave periods of several hours. Their apparent drift speeds (the vector sum of the phase velocity and bulk wind velocity) can, at times, exceed 100 m/s [Haurwitz and Fogle, 1969]. The billows are much more transient, and may disappear over time scales of minutes to tens of minutes. The billow motions follow the bulk wind speed, since their phase velocities are small. Waves seen near the horizon can be contrast-enhanced due to strictly geometrical effects. To quote Jensen and Thomas [1994], "The geometrical effect of viewing an undulating cloud layer at a low elevation angle is maximized when the elevation angle is equal to the phase tilt of the wave.” Hence, as long as the wave trains are perpendicular to the line of sight, NLC bands should have a maximum contrast at elevation angles of 5-10°, and billows should show up best at 30-40° elevation angle. Thus a 'ripple' in the height of a uniform layer would cause a corresponding brightness ripple, which does not necessarily reflect any true variations of ice particle properties over the field of view.

However, it is known that true horizontal variations of ice properties occur, since waves are seen when the line of sight is along the wave fronts. Multi-station stereography is capable of sensing true spatial variability. Instructive stereo observations of NLC distributions were reported by Witt [1950], who showed how cloud properties vary over a 3D spatial domain. Indeed, the stereo (two-camera) technique was used 117 years ago by Jesse [1896] to demonstrate that NLC exist at what was then an extraordinary altitude of
82 km. It is remarkable that this value is still valid within the much smaller errors characteristic of lidar measurement.

The measurement of changes in PMC structure is important because it indicates upper atmospheric variability around the mean state that is critical in determining the occurrence and morphology of cloud structure, particularly in regions where temperature is marginal for ice production. For example, Gerding et al [2007] have shown that at 54°N (Kühlungsborn, Germany), deviations of temperatures down to 20 K below the climatological average are necessary for NLC to occur in this comparatively warm region, at the edge of the NLC zone of occurrence. Such large deviations occur at the troughs of atmospheric gravity waves and tides. One of the scientific objectives of the AIM mission is to determine the importance of gravity waves in influencing PMC. It is clearly important to understand this relationship quantitatively, since if long-term changes in waves were to occur, this could influence long-term variability of PMC.

Modeling the influence of waves on PMC production and loss began with Turco et al. [1982] using an early 1D version of the Community Aerosol and Radiation Model for Atmospheres (CARMA) model. Later work by Jensen and Thomas [1994] and Rapp et al [2007] has shown that, using 2D versions of the CARMA model, the effects on PMC of variable temperature and water vapor depend sensitively on the wave period. For wave periods less than about 7 hours, waves have a destructive effect on PMC brightness, since the ice particles disappear during the warm phase more rapidly than they grow during the cold phases. For longer wave periods, there is the possibility of a temporary enhancement of cloud brightness due to the fact that the cold phase lasts longer than the particle growth time of several hours. However, these time-dependent studies did not
examine the full range of possible initial conditions of pre-existing ice particles, and the
role of different background temperature.

Here we briefly review lidar measurements, which have very high spatial
resolution because of the small size of the illuminated spot. Lidar studies generally yield
ambiguous information on spatial structure because of the unknown speed of the
structures through the stationary spot. However, the one exception is the two-lidar
measurements [Baumgarten et al., 2002] that provided limited information on 2D NLC
structure. The illuminated area of backscattering at mesospheric heights may be as small
as 15 meters. The necessity to integrate the signal over several minutes to improve the
S/N ratio, and the always present motion of the NLC structure, results in a larger
effective horizontal resolution. For three-color lidar observations at the ALOMAR
observatory (69.3°N), the analysis requires longer integration times to obtain accurate
color ratios. Baumgarten et al. [2007] adopted a 14 minute integration time, and for the
spot size of the illuminated area, this implies a horizontal resolution of 34 km. The
published time series of lidar data with integration times of several minutes show back-
scattering brightness variations consistent with highly variable spatial structure, as well as
time-changing heights. For example, Figure 6 from Baumgarten et al. [2007] shows
variations of two to three over a time scale of three minutes. These very rapid
enhancements may be manifestations of the bright spots seen in CIPS images, as
discussed in Section 3.

2. The Cloud Imaging and Particle Size Experiment
The Cloud Imaging and Particle Size (CIPS) experiment on AIM is a wide angle (120° along track by 80° across track) UV imager consisting of four identical cameras arranged in a cross pattern (Figure 1). CIPS provides images of PMCs with a spatial resolution of 1 x 2 km in the nadir and about 5 km at the edges of the forward and aft cameras. The spatial resolution of CIPS provides a 100-fold increase in horizontal resolution over previous limb-viewing space experiments (see DeLand et al. [2006] for a recent review of space-based PMC observations). For a complete description of the CIPS instrument, see McClintock et al. [2008 (this issue)]. The CIPS instrument is fully operational on orbit, with all four cameras performing flawlessly. The brightness and occurrence frequencies of PMCs inferred from CIPS data is in excellent agreement with concurrent measurements from the Solar Backscatter Ultraviolet (SBUV/2) instruments [Benze et al., 2008 (this issue)]

In our standard analysis, the four CIPS camera images are merged to form a single display we call a scene with a spatial resolution of 5 x 5 km. To achieve a uniform spatial coverage, the resolution is intentionally degraded to match the geometrical smearing at the camera edges. A scene is depicted in Figure 1, showing how the native rectangular images appear as projected on a spherical earth at the normal PMC height of 83 km. The cameras are marked as Px, the fore camera; Mx, the aft camera, and the nadir cameras, My and Py. The orbital direction is to the right of the scene. The scene has dimensions 120° by 80°, as measured from the nadir direction. This results in spatial coverage of approximately 2000 km along the satellite track and 1000 km across track. As the satellite moves in orbit, the object is viewed seven times at a large range of
scattering angles. The time interval over which the multiple scenes are taken is 258 seconds.

3. Initial Imaging Results

Since the cloud scattering signature is an albedo enhancement above a comparatively bright Rayleigh scattered background, cloud detection and retrieval of cloud properties require careful removal of the background. This background varies over the viewed area due to geometrical effects of incoming and outgoing solar rays passing through mesospheric air and ozone. An important aspect with respect to the CIPS technique is the necessity to specify this Rayleigh scattering background accurately along the orbit. The air and ozone densities responsible for the value of the background radiance may vary in time and space in ways that are not known \textit{a priori}. It is necessary therefore to derive the ozone mixing ratios in the 50-65 km region (where the contribution function maximizes). The threshold at which clouds may be detected is determined in part by our ability to accurately simulate the background. For more detail on how clouds are separated from the background, see Bailey et al. [2008 (this issue)].

The cloud albedo is defined as the ratio of the scattered radiance (after removal of background) to the incoming solar irradiance, averaged over the bandpass of the instrument (see McClintock et al., [2008], this issue). The units of albedo are \text{sr}^{-1}. Here we describe the method that results in the determination of cloud albedo.
To begin, we show a cloud-free, Rayleigh scattered background in Figure 2a for a scene taken at 82°N prior to the beginning of the cloud season. The associated line plots below the figure display the albedo as a function of pixel number across the center of the scene (figure 2b) from the edge of the Mx camera (on the left) to the edge of the Px camera, and across the center of the nadir cameras from the edge of the My to the edge of the Py cameras (figure 2c). (One Gary (G) is defined as an albedo of $1 \times 10^{-6} \text{ sr}^{-1}$.) The pixel size projected to an 83-km height is 5 km. The variation in the Rayleigh scattered albedo across the scene is due to both the changing scattering and view angles. (The scattering angle is defined as the angle between the incoming solar ray and the scattered radiance vector.) The background albedo varies from about 440 to 130 G from the edge of the aft camera through the nadir and then increases to about 340 G at the edge of the forward camera. The scan across-track of the nadir cameras varies from about 180 to 150 G and then increases to about 185 G at the edge of the other camera. The small scale variations are consistent with instrument noise [McClintock et al., 2008 (this issue)] or small scale ozone variations. The background is a result of Rayleigh scattering from air molecules modified by ozone absorption in the 50-65 km height region, where optical depth unity is reached. Ozone absorption in the Hartley bands, combined with Rayleigh scattering causes a minimum in the Earth’s albedo near 260 nm [McClintock et al., 2008 (this issue)]. The spectral region chosen for the CIPS bandpass (258-274 nm) provides the maximum contrast of PMC to background scattering.

In Figure 3a we display a scene taken at similar latitude as that in Figure 2a, but for data taken in the heart of the PMC season. A comparison with Figure 2a clearly
shows the presence of PMCs with highly-variable albedo across the scene, that is obviously distinct from the relatively smooth background albedo. The line plots (Figures 3b and 3c), generated as in Figures 2b and 2c, show the PMC enhancements to the Rayleigh scattered background. The PMC albedo for this particular set of scattering angles is highly variable, with values from a few Gs to 50 or 100 Gs. This scene is typical of those taken at high latitudes during the cloud season.

Figure 4a displays the scene that results from subtracting the Rayleigh background from the albedo shown in Figure 3a. The Rayleigh background is determined by retrieving the atmospheric ozone from the non-cloud regions of the scene and forward-modeling the values of Rayleigh scattering in cloudy areas [Bailey at al., 2008 (this issue)]. In addition, to account for the increase in brightness when viewing the clouds at small scattering angles in the forward camera, the scene is approximately compensated for forward-scattering behavior of the ice particles. This procedure is not intended to be rigorous, but is a qualitative attempt to represent "normalized" cloud brightness. By trial and error, we adopted a phase function for a Gaussian distribution with a mode radius of 60 nm and a width of 12 nm. This set of parameters applies to a bright PMC seen at the ALOMAR observatory [Baumgarten et al., 2007]. We arbitrarily chose to normalize all observations to one at a 90° scattering angle. Each pixel is then ‘corrected’ by dividing its albedo value by the value of the phase function at the appropriate scattering angle. This brings out cloud features across the backward-scattering portion of the scene that would normally be suppressed. The result shows a highly variable and complicated cloud structure with bright spots, regions where clouds
are dim or even absent, and what appears to be chains of spatially small and dim regions. The line plots (Figures 4b and 4c) are the same as those in Figures 3b and 3c. They show highly variable and complicated structures over the image.

Although these complicated features no doubt are present in ground-based views, this is the first time that they have been seen from above, undistorted by the large slant paths that are characteristic of NLC views near the observer's horizon. Indeed, the slant views of NLC more clearly reveal the wave structure because of the horizontal variation of cloud height induced by gravity waves (see Jensen and Thomas [1994]). The ground-based perspective can distort the true variation of cloud properties across the wave field. CIPS viewing geometry allows a view of the 'true' spatial variability. This difference in view angles should be borne in mind when comparing NLC photographs with CIPS images. CIPS images are essentially free of effects of 'rippling' by variations in the cloud height which are the order of 1-3 km. NLC images frequently distort the brightness variation, at least whenever waves are present.

The CIPS data collected for 15 orbits each day are merged to form orbital strips that are then merged into a daily asynoptic display of cloud occurrence. An example of a picture of daily cloud occurrence is shown in Figure 5 for July 9, 2007 (Day 190), the day on which the data displayed in Figures 3 and 4 were taken. The blue background shows the orbit by orbit coverage of the CIPS instrument. The clouds are displayed white on the blue background where pure blue indicates no clouds were detected at that location. The image shows nearly continuous cloud presence at the higher latitudes, but also contains
many cloudless regions interspersed across the image. The minimum brightness displayed in these images is 5 G. The spatial variation of the clouds appears random and does not generally resemble the features seen in most ground based photographs. The relative absence of wave-like features in CIPS images will be discussed in Section 4.

Cloud structures, as viewed by CIPS, are highly variable from scene to scene and orbit to orbit and contain interesting features never before seen from space. These features include ‘ice rings’ in which regions of dim clouds are surrounded by a narrow ‘ring’ of brighter clouds. A second type of structure we have identified is spatially small, but bright clouds that have radii of approximately 10 to 20 km. These bright spots are significantly brighter than the surrounding clouds and, at times, even the Rayleigh scattered background.

An example of an ‘ice ring’ is shown in Figure 6 in the fore camera image that includes the Rayleigh scattered background. As delineated by the imposed box, it has a diameter of about 250 km. The ring is about twice as bright as the enclosed region. Ringed features, including 'broken' rings (circular arc-like structures) are a common morphological feature and occur in many sizes from ten's of km up to nearly 1000 km in diameter. An additional image contains a different presentation of this feature. Figure 7 shows a CIPS view of PMCs on day 190 (July 9, 2007). The circular features show regions of low cloud intensity surrounded by brighter clouds. The diameters of these features are about 100 km. These features must be formed by complicated upper atmospheric dynamics.
As discussed above, spatially small but very bright features also commonly occur. Examples are shown in the images and plots shown here. Figure 8a displays a forward camera image containing two bright features. These 'spots' are well defined spatially by the CIPS camera with 5 km resolution at the cloud height. Although they may have been within the field of view of other space-based instruments, the larger volumes sampled did not allow them to spatially resolve these features. However, they may have been present in lidar time series, since the typical size of the illuminated region is only a few hundred meters. They would show up as temporary enhancements lasting only a few minutes as they pass over the lidar site. For example, Figure 6 of Baumgarten et al [2007] exhibits a rapid brightening of the backscatter coefficient from a typical value of 10 units up to 40 units. The features seen in CIPS are equivalent to or brighter than the Rayleigh background at the small scattering angles seen in the forward camera. A line plot of the albedo across the two bright spots is shown in figure 8b. The plot shows that the features are bright reaching 1,100 G for one and 1,200 G for the other. Each bright feature is about 25 km wide.

The existence of these two classes of cloud features, the ice rings and the small, bright clouds, seem in conflict with the current understanding of cloud structures that rely on gravity wave temperature modulations, breaking, and momentum deposition in the mesosphere. It appears that under the cold conditions that occur in the middle of the season at the high latitudes, ice formation may be dominated by additional dynamical influence.
Thus we are finding that deep in the polar region and in the heart of the season, PMC are characterized by what appears to be convective patterns, rather than by the bands and billows usually seen at the lower latitudes, or at the extremes of the cloud season. Wave features are not rare, but more often we see rather complicated structures that perhaps overwhelm the visible effects of gravity waves. The origin of this convection is not understood, but a reasonable hypothesis is that the convection it would be favored by the steeper latitudinal temperature gradient present in the summer mesosphere. These gradients approach the adiabatic lapse rate which may drive the region close to convective instability. For example, rocket-borne measurements during summer of temperature profiles at Andöya, Norway often reveal temperature gradients close to \(-10\) K/km. The resulting instability causes a deposition of momentum and energy and has long been believed to be the driving force behind the closing of the mesospheric jet and the cold summertime temperatures. However, this process is not confined solely to the Polar Regions. Thus the change of character of the ice structures with latitude may be due to a transition to a more convective regime in the ice formation region (~80-90 km).

Alternatively, the effect of the lower temperature at these high latitudes (<130k) on the ice formation may change qualitatively as suggested by the CARMA model sensitivity calculations. At temperatures below 140K, the results of Rapp and Thomas [2006] (see their figure 20) indicate the UV brightness could be controlled more by water vapor variation than temperature. This resolution of this question poses a challenge to models which couple ice formation with the circulation [e.g. Berger and Lübken, 2007].
In addition, the CIPS data have revealed the presence of large regions that are virtually ice free. Many of these regions encompass thousands of square kilometers and are distinct from the ice rings described above in that they are not surrounded by a more dense cloud ‘ring’ and are essentially absent of clouds in the interior. They could be due to large regions of warm air, which are predicted by a recent general circulation model which contains mesospheric ice formation [Bardeen et al., 2007]. An example of an ‘ice void’ is seen in the daily view in Figure 9. The large dark area near 85N and 135W has an area of several thousand square km\(^2\). This particular region was recognized in several consecutive orbits where the orbital coverage overlaps. Its motion was calculated to be northward into the polar region, contrary to the general view that air always flows out of the pole during the summer. It is not unreasonable to suppose that this could be due to the presence of a tidal wind which can dominate the zonally-averaged general circulation. A visual scan of all daisies for the northern 2007 season reveals 19 large ‘ice voids’ spread approximately evenly throughout the season, or about 1 every 4 days.

To further illustrate the contrast seen in the cloud features as seen from the ground and from space, a daily view of the entire cloud region is shown in Figure 10. In this view, taken near the end of the cloud season on August 13, 2007 (DOY 225), two distinct types of cloud features are seen. These regions, one near longitude 135° and one near longitude of -45, are enlarged in the following figures. In the first (Figure 10a), we clearly see many bands with lengths of > 100 km and with regular separation typical of gravity wave control [see Chandran et al., 2008 (this issue)]. These are the type of gravity wave controlled bands that are seen regularly in ground based images. Figure
10b shows the more common cloud attributes seen at high latitudes in during most of the cloud season, complicated structure with embedded features distinct from those seen in Figure 10a. These types of cloud structures are more typically seen in tropospheric clouds generated by large scale convection. A detailed analysis is beyond the scope of this paper but is in progress.

4. Discussion

The CIPS instrument provides the first look from space at PMC with 5 km resolution for an entire PMC season. The images reveal details of cloud structure either never before identified (‘bright spots’) or define features in more detail than before (‘ice rings’). Perhaps the most surprising discovery is the nearly ubiquitous presence of amorphous structures extending nearly to the pole. Conspicuous by their rarity are waves, which are quite common in ground-based photographs. It must be noted that waves are not as prominent as might be thought from inspection of historical collections of NLC photographs. Photos with prominent waves are selectively chosen for distribution because of their aesthetic appeal. To our knowledge, there is no published information on the occurrence frequency of the various classes of NLC forms (including waves) in ground-based views. Also, to our best knowledge they are common in the NLC zone (50-60°), but are by no means ubiquitous. We should also note that Carbary et al. [2000] in their more limited mapping of PMC structures identified only one feature (their Figure 8 containing what they called a 'repetitive feature') that appeared wave-like, and certainly does not resemble the familiar ground-based views.
The bright spots may have been detected in lidar data, but the lidar only provides a microscopic view along an unknown cross-section, whereas CIPS reveals the 2D structure. These regions may be evidence of very localized upwelling, in which cooling occurs in a small area. Our preliminary analysis using the scattering phase function in two of these features does not show any unusual values of ice water content.

The ice rings may be the ground-based Type IV ('whorls'), which to quote Gadsden and Parvianien [1995] exhibit "partial or, on rare occasions, complete rings of cloud with dark centers". The CIPS images in the heart of the season and at high latitudes reveals cloud morphology that resembles features in the lower atmosphere convection patterns more than the striated or gravity wave like features seen from ground-based observations. For example, Figure 11 shows the image of a 'convective outflow boundary', taken by the GOES-12 geostationary weather satellite. A time-lapse movie of this event (http://www.nasa.gov/mov/204839main_GOES_CloudRings.mov) depicts a nearly-circular cloud-free region emanating from a region of intense thunderstorm activity off the coast of Cuba. The tropospheric cloud 'ring' at the boundary of this wind outflow resembles the CIPS ice rings (see figures 6 and 7). These tropospheric structures are not uncommon in the vicinity of intense convection, and suggest that the ice rings seen by CIPS are a result of a localized convective source of momentum, generating an outflow of wind. It is also possible that a localized source of gravity waves could cause such a structure. Taylor and Hapgood [1988] presented evidence for radially-outflowing gravity waves which apparently had their source near the ground. Through ray tracing they
attributed the source to be a thunderstorm. Sentman et al [1993] have described circular
features in the OH airglow (originating at ~95 km) which apparently result from a
mesospheric pressure surge caused by a sprite, which was associated with intense
thunderstorm activity.

We note that a ring of gravity waves could also cause a circular ring to occur. If
the wave caused a temperature perturbation $\pm 3K$ or greater in a region whose temperature
is high enough to be close to saturation, then as the warm crest passes through the region,
the ice particles would vanish quickly. In the cold phase, the time scale for growth is
much longer (the order of hours) so new particles would not form within a wave period.
The net result would be a circular region 'swept clear' of ice particles. The outer boundary
(the ice ring) could be a region of convergence of ice particles (a 'snow shovel' effect
perhaps). Since the ring itself is not always detectable (in which case, we have dubbed
them 'ice holes' or 'ice voids') the more fundamental property is probably the large near-
circular ice-free area.

Other possibilities for these large ice-free regions are suggested by modeling in
which the circulation is coupled to the cloud microphysics [Berger and Baumgarten,
private communication, 2007; Bardeen et al., 2007]. These models, although not having
the resolution to resolve the narrow rings, nevertheless simulate large ice-free regions,
that are warmer than their surroundings. The causes of these features in the model are
being investigated. These processes may be generated by steep temperature gradients in
the summer mesosphere that drive the region into convective instability. A further
possibility is that the ice formation process may differ between the latitudes where ice formation is marginal (in the 50-60° zone) and deep in the polar regions where temperatures can dip to as low as 110K.

Signatures of gravity wave processes in the cloud structures are observed, but for the most part they are limited to the southern edge of the cloud deck or to the early and late parts of the season [Chandran et al., 2008 (this issue)]. In the heart of the season, the signatures of gravity waves are either absent or overwhelmed by what appears to be convective processes that may be generated by steep temperature gradients in the summer mesosphere that drive the region into convective instability. A further possibility is that the ice formation processes may differ between latitudes where ice formation is marginal (in the 50-60° zone) and deep in the polar regions where temperatures can reach as low as 110K.

Work in progress that relates to cloud morphology includes the determination of systematic longitudinal variations, and correlations with concurrent measurements of temperature by the SABER instrument on the TIMED satellite. In addition, coordination of CIPS data with data from the high-precision SOFIE solar occultation instrument on AIM [Hervig et al., 2008 (this issue)] is under study. SOFIE measurements are made within in a common volume viewed by CIPS. At this time, this latter task is hindered by the comparatively weak clouds present in the CIPS images at the latitudes observed by the SOFIE instrument. We anticipate making further progress in reducing the cloud detection threshold in the CIPS images, so that we can extend the morphological studies
to lower latitudes. This will allow correlation of these newly-discovered structures with atmospheric temperature, water vapor and other constituents measured by SOFIE.

Acknowledgements:

We gratefully acknowledge the tremendous effort of the engineering and mission operation teams whose dedication and skill resulted in the success of the CIPS instrument. We thank the entire AIM science team for helpful input. The AIM mission is sponsored by NASA.
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FIGURE CAPTIONS

Figure 1. The overlapping fields of view of the four CIPS camera images projected on the PMC cloud height at 83 km. The camera names are identified. Although the focal planes are rectangular, their projection on the curved earth results in a 'bowtie' shaped coverage.

Figure 2. (a). A cloud-free scene (only Rayleigh scattering) near 82°N taken before the onset of the PMC season. The pixel size is 5km. Contour lines of latitude and longitude are shown; (b) Albedo (Garys) vs pixel number for a scan across the center of the scene; (c) Albedo vs pixel number for a scan across the nadir camera from top to bottom.

Figure 3. a. A scene with Rayleigh and PMC scattering near 82°N taken during the PMC season. The scales are identical to those in Fig. 2. b. Albedo (Garys) vs pixel number for scan across the center of the scene; c. Albedo vs pixel number for a scan across the nadir camera from top to bottom.

Figure 4. a: PMC albedo, depicted the same as Figure 2a with the Rayleigh background subtracted and phase-compensated (see text); (b): Horizontal scan of albedo across the middle of the scene. c. Vertical scan of albedo across the center of the nadir cameras.

Figure 5. Daily cloud cover of phase-compensated PMC albedo where 15 orbits of images are merged. When overlapping occurs, the most recent part of the image is
substituted. The Greenwich meridian is at 6 o'clock, and longitude is measured from this meridian positive in the counterclockwise direction, and negative in the clockwise direction. The outlines of the continents are shown as white lines. The latitude circles are shown as white circles. The circle of constant daylight is shown as the dashed circle, inside of which there is 24 hours of daylight. The dark circle surrounding the pole indicates no data.

Figure 6. a. A CIPS 'bowtie' scene with an ‘ice ring’. The scales are similar to Figure 3.

Figure 7. a. A CIPS scene showing a series of ice rings with diameters of 50 to 100 km. The scale is identical to Figure 3.

Figure 8. (a) A CIPS scene depicting raw albedo with two bright spots in the fore camera (on the right). The scales are similar to Fig. 2. (b) A scan across the bright spots within the box shown in Figure 8(a) showing the PMC albedo associated with the bright spots and the surrounding region.

Figure 9. A CIPS daily cloud occurrence plot for DOY 184 showing a large ‘ice void’ at about 85N and 135W. Scale identical to Fig. 5.

Figure 10. a: A CIPS daily cloud composite image near the end of the northern season, b: A sector of the daily image from the upper left area showing wave streak features, and c:
A sector of the daily image from the lower right area showing the complicated cloud structures similar to those seen during the majority of the season.

Figure 11. A grey-scale visible image of tropospheric convective outflow events taken by the GOES 12 geostationary weather satellite on June 8, 2007. The blue lines indicate the coastline of Cuba. A nearly-circular cloud ring is seen at the lower left, centered on the western coast of the island, where an intense thunderstorm was occurring. A time-lapse movie of this event shows clearly the evolution of the ring emanating from the region of intense convection.
Figure 1
Figure 6
Figure 8a

Figure 8b
Figure 9
Figure 10a

Figure 10b

Figure 10c