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Lidar Observations of Polar Mesospheric Clouds at South Pole: Diurnal Variations

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Abstract. Polar mesospheric clouds (PMCs) were observed by a ground-based Fe Boltzmann temperature lidar for 65 h on 17-19 and 24-26 January 2000 above the geographic South Pole. The mean PMC backscatter ratio, volume backscatter coefficient, total backscatter coefficient, layer centroid altitude, and layer rms width are 53.5, 2.9×10^{-9} $m^{-1}sr^{-1}$, 4.3×10^{-6} sr^{-1}, 85.37 km, and 0.78 km, respectively. Strong semidiurnal and diurnal oscillations were observed in the PMC backscatter ratio, volume backscatter coefficient, total backscatter coefficient, and centroid altitude. The oscillations are all maximum around 0630 and 1900 UT. The variations appear to be linked to vertical advection of the PMC scattering layers by a persistent oscillation in the vertical wind velocity. Scattering is strongest when the PMCs are highest which suggests that the colder temperatures at higher altitudes near the mesopause facilitate the formation of larger PMC particles.

Introduction

Polar mesospheric clouds (PMCs) and their visual counterparts, noctilucent clouds (NLCs), form near 85 km at high latitudes during the three months around summer solstice when mesopause temperatures fall below 150 K [*Thomas*, 1991]. Numerous visual, photographic, rocket, satellite, radar, and lidar observations obtained in the Northern Hemisphere have been used to characterize the altitude distribution, occurrence frequency, geographic extent, scattering properties, and seasonal variations of PMC/NLC. Several papers provide excellent overviews of PMC/NLC characteristics and our current understanding of the formation mechanism [e.g., *Gadsden and Schröder,* 1989; *Thomas,* 1991, 1994]. During the past decade lidar observations have contributed significantly to the study of PMC/NLC [e.g., *Hansen et al.,* 1989; *Thayer et al.,* 1995; *von Cossart et al.,* 1997; *von Zahn et al.,* 1998; *von Cossart et al.,* 1999; *Alpers et al.,* 2000]. Lidar observations have provided precise information about the altitude, thickness, and volume backscatter coefficient of the PMC scattering layers. Twenty-four hour lidar measurements at Andoya (69°N) have revealed strong semidiurnal oscillations in the altitude and backscatter ratio [*von Zahn et al.*, 1998] which are believed to be associated with atmospheric tides.

Most of the observations of PMC/NLC in the Southern Hemisphere have been made by satellite instruments [e.g., *Thomas and Olivero,* 1989; *Debrestian et al.,* 1997; *Carbary et al.,* 1999]. This is due to the scarcity of observers in the critical latitude range and the considerable challenges of deploying instruments in Antarctica. Our group installed an Fe Boltzmann temperature lidar at the Amundsen-Scott South Pole Station in Nov 99 and made the first lidar observations of PMCs on 11 Dec 99 [*Gardner et al.*, 2001]. In this paper we describe the diurnal variations in the PMC structure using data collected on 17-19 and 24-26 Jan 00. The data reveal strong diurnal and semidiurnal oscillations in the PMC altitude and backscatter parameters. These results are compared with similar observations in the Northern Hemisphere and with previous diurnal observations of winds, temperature, and Na densities above the South Pole.

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Observations

The University of Illinois Fe Boltzmann temperature lidar is deployed 488 m north of geographic South Pole in the Atmospheric Research Observatory. It includes two lasers (and two receiving telescopes) that operate at the 374 nm and 372 nm Fe resonance wavelengths [*Chu et al.,* 2001]. Since the summertime at South Pole is continuously sunlit, the lidar is designed to make measurements during both day and night. Several hundred hours data were collected at South Pole during the 1999-2000 austral summer season. For this paper we concentrate on the 69 h of data collected on 17-19 and 24-26 Jan 00 since each data set is longer than 12 h and corresponds to the period of maximum PMC activity. For typical mesospheric temperatures the Fe scattering is approximately 20-30 times weaker at 374 nm compared to 372 nm. Because small concentrations of Fe can exist between 82 and 86 km where PMCs are typically observed, the PMC characteristics reported here were derived from the 374 nm lidar channel data to minimize contamination by Fe scattering. Typically, the 374 nm Fe signal is less than 1% of the PMC signal. Even so, both lasers were detuned periodically during the observation periods to confirm the existence of the PMCs.

After subtracting the background photon counts and compensating for the range dependence of the signal levels, the lidar data were averaged for one hour, normalized to the Rayleigh signal at 50 km, and then scaled to produce a backscatter ratio profile. The peak backscatter ratio R_{max}, peak volume backscatter coefficient β_{max}, total backscatter coefficient β_{Total}, centroid altitude Z_C, and rms width of the PMC layers were then computed from the hourly mean profiles using standard techniques [e.g., *von Zahn et al.,* 1998] and the pressure, number density, and temperature profiles from MSIS90 model. The centroid altitude and rms width were computed from the volume backscatter coefficient profiles. An example of the calculated backscatter ratio and volume backscatter coefficient profiles for a PMC layer observed at 0713-0758 UT on 19 Jan 00 is shown in

Figure 1. The PMC layer has a peak backscatter ratio of 145 and a peak volume backscatter coefficient of 9.35×10^{-9} $m^{-1}sr^{-1}$. Its centroid altitude is 85.36 km. PMCs were observed during 65 of the 69 h so that the PMC detection rate was 94.2%. The mean PMC peak backscatter ratio, peak volume backscatter coefficient, total backscatter coefficient, layer centroid altitude, and layer rms width are 53.5, 2.9×10^{-9} $m^{-1}sr^{-1}$, 4.3×10^{-6} sr^{-1}, 85.37 km, and 0.78 km, respectively.

To investigate the diurnal variations of the PMC layers, each PMC parameter was averaged in universal time to obtain 23 one-hour means (no PMCs were detected during 13-14 UT). Each one-hour mean was evaluated using at least two hours of observational data. The resulting hourly mean values are plotted versus UT in Figure 2 along with the 12 and 24 h harmonic fits. All PMC parameters (except the scattering layer width) exhibit strong diurnal and semidiurnal oscillations. The oscillations are all maximum around 0630 and 1900 UT. The parameters of the harmonic fits plotted in Figure 2,

$$y = A_0 + A_{12}\cos[\frac{2\pi}{12}(t - UT_{12})] + A_{24}\cos[\frac{2\pi}{24}(t - UT_{24})], \quad (1)$$

are summarized in Table 1. The fits are all statistically significant as the high correlation coefficients and small relative errors demonstrate. The phases of the 12 and 24 h components are similar for all four PMC parameters. The amplitudes of the 12 and 24 h are comparable for the backscatter ratio, volume backscatter coefficient, and total backscatter coefficient. The 12 h amplitude of the centroid altitude oscillation is about twice the 24 h amplitude.

Discussion

Strong 12 and 24 h oscillations in the altitude and backscatter ratio of PMC/NLC were reported by *von Zahn et al.* [1998] at Andoya (69°N, 16°E) in June and July 1997. The mean PMC/NLC centroid altitude at Andoya is 82.7 km compared to 85.3 km at South Pole. Like the South Pole measurements, the 12 and 24 h backscatter ratio amplitudes are comparable at Andoya while the 12 h centroid altitude amplitude (0.79 km) is approximately double the 24 h amplitude (0.44 km). In contrast to the South Pole measurements, at Andoya the backscatter ratio is maximum whenever the PMC centroid altitude is minimum. *Von Zahn et al.* [1998] attributed the PMC/NLC oscillations to tidal perturbations in temperature and vertical winds. They suggested that the anti-phase relationship between backscatter ratio and altitude was caused by changes in the size of the PMC/NLC particles as they form at higher altitudes and then slowly fall to lower altitudes as their size and weight increases. The PMC backscatter cross section is approximately proportional to the 6^{th} power of the particle radius. According to *von Zahn et al.* [1998], the lower altitude PMCs contain the heavy larger particles and therefore, would exhibit larger backscatter ratios compared to the smaller higher altitude PMC particles.

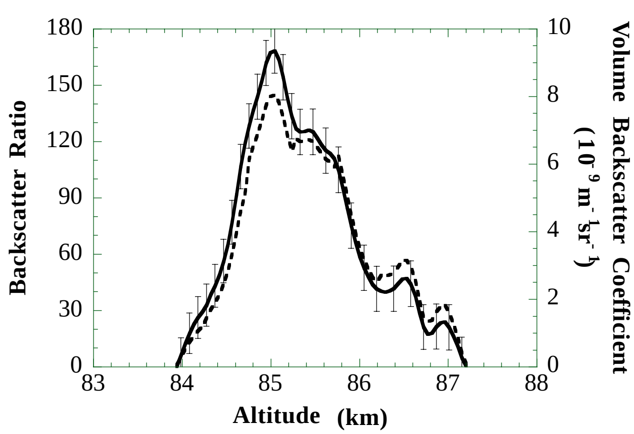

Figure 1. Backscatter ratio (dashed line) and volume backscatter coefficient (solid line with error bar) of a PMC layer observed above South Pole at 0713-0758 UT on 19 January 2000.

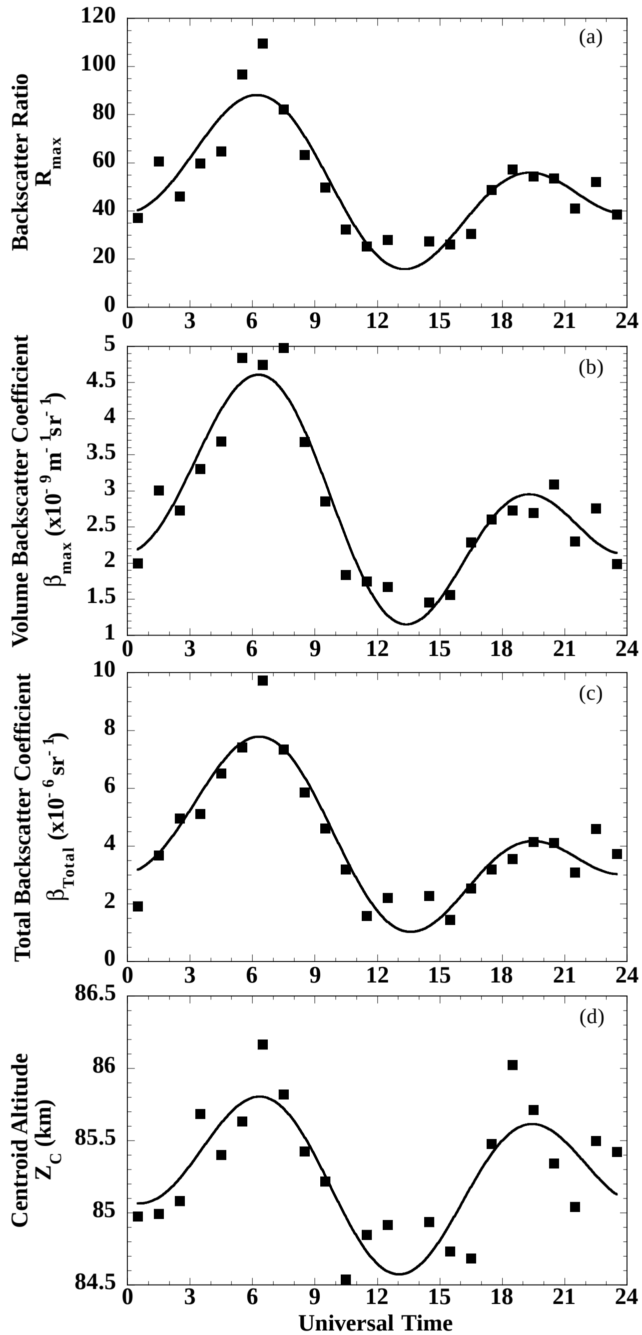

Figure 2. Diurnal variations of the South Pole PMCs a) peak backscatter ratio, b) peak volume backscatter coefficient, c) total backscatter coefficient, and d) layer centroid altitude plotted versus UT. The solid curves are the 12 and 24 h harmonic fits.

Table 1. Parameters for harmonic fits to PMC diurnal variations at South Pole

	R_{max}	β_{max} (10^{-9} m^{-1}sr^{-1})	β_{Total} (10^{-6} sr^{-1})	Z_c (km)
A_0	50.07 ± 2.04	2.74 ± 0.07	4.07 ± 0.17	85.255 ± 0.061
A_{12}	21.06 ± 2.94	1.01 ± 0.11	1.82 ± 0.25	0.435 ± 0.088
A_{24}	20.13 ± 2.90	0.97 ± 0.10	2.10 ± 0.24	0.265 ± 0.088
UT_{12}	6.67 ± 0.26 UT	6.70 ± 0.19 UT	6.77 ± 0.25 UT	6.87 ± 0.37 UT
UT_{24}	4.27 ± 0.55 UT	4.63 ± 0.41 UT	4.81 ± 0.44 UT	2.29 ± 1.22 UT
Correlation	91.6%	95.2%	93.4%	79.6%
RMS Residual	8.63	0.31	0.72	0.257

Classical tidal theory shows that the amplitudes of the traveling diurnal and semidiurnal oscillations approach zero near the geographic poles. However, zonally symmetric tides (zonal wavenumber s = 0) can have nonzero vertical and horizontal wind oscillations and nonzero temperature oscillations at the Poles [*Forbes,* 1982a,b]. Numerous groups have observed strong 12 h oscillations in Na density and horizontal winds at mesopause altitudes above South Pole [e.g., *Collins et al.,* 1992; *Hernandez et al.,* 1993; *Forbes et al.,* 1995]. These oscillations have been attributed to an inertio-gravity wave [*Hernandez et al.,* 1993] and to the nonlinear interaction between the migrating semidiurnal tide and a stationary wave with a zonal wavenumber of 1 [*Forbes et al.,* 1995]. The observations that are most relevant to the PMC data are the Na lidar measurements made by our group at South Pole on 25 June 1990 [*Collins et al.,* 1992]. Strong vertical displacements of the Na layer were observed between 74 and 84 km. The oscillation period was approximately 12 h and the displacement amplitude decreased from 1.9 km at 79 km to approximately 0.32 km at 85 km. These mid-winter Na lidar data show clearly the impact of vertical advection on the bottom side of the Na layer profile.

The data plotted in Figure 2 suggest that the PMC particles are also advected vertically in response to oscillations in the vertical wind. PMC particles are small and the clouds are tenuous. Multi-color lidar observations at Andoya have shown that the mean PMC/NLC particle radius is 51 nm and the mean density is 82 cm^{-3} [*von Cossart et al.,* 1999; *Alpers et al.,* 2000]. The vertical structure and dynamics of the clouds are believed to be greatly influenced by the temperature structure of the mesopause region and by the vertical winds. Current theories and models suggest that the PMC particles begin forming near the cold mesopause and then fall as they grow in size and weight until the combined effects of increasing atmospheric density at lower altitudes and upward vertical winds are sufficient to support the particles in a stable layer [e.g., *Thomas,* 1991, 1994]. Upwelling associated with the diabatic circulation system is strongest directly over the poles in mid-summer [*Garcia and Solomon,* 1985] and is expected to influence the vertical structure of the tenuous PMCs. The seasonal variation in PMC altitude observed by *Chu et al.* [2001] at South Pole suggests that the upwelling does affect the PMC altitude. The observed diurnal PMC vertical displacement velocity (maximum ∼5 cm/s) is comparable to the predicted mid-summer upwelling velocity of a few cm/s [*Garcia and Solomon*, 1985]. Thus, it is not surprising that the PMCs observed at the South Pole are higher (2.6 km) than those observed at Andoya (69°N) since the summertime upwelling is expected to be stronger at the South Pole compared to 69°N.

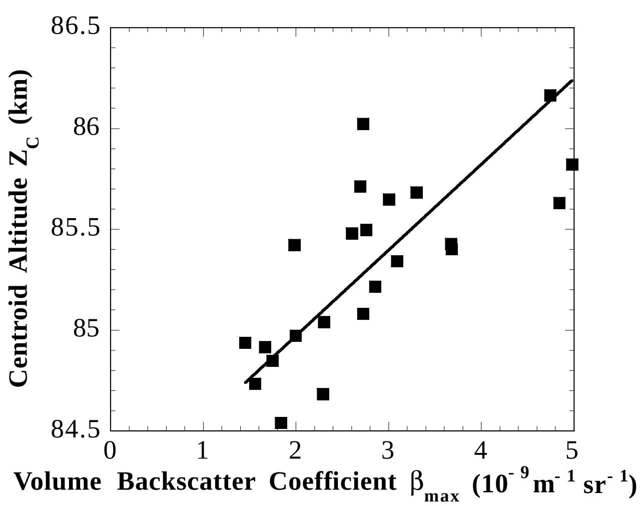

Figure 3. Hourly mean PMC layer altitude plotted versus volume backscatter coefficient. The solid line is the maximum likelihood regression fit Z_C(km) = 84.12 + 0.4253 β_{max}(10^{-9} m^{-1}sr^{-1}). The correlation coefficient for the fit to the 23 data points is 69.1%.

The observed phase relationship between the PMC altitudes and the backscattering properties at the South Pole may be related to the colder temperatures at higher altitudes. Because the mesopause altitude is approximately 88 km at high latitudes in mid-summer, an upward vertical displacement associated with tidal oscillations in the vertical winds would result in adiabatic cooling and would transport the PMC particles closer to the mesopause. The upwardly displaced PMC particles would then grow in size in response to the colder temperatures which results in stronger scattering. Figure 3 is a plot of the volume backscatter coefficient as a function of altitude. The linear trend suggests that a 1.5 km upward displacement from about 84.5 km to 86 km increases the volume backscatter coefficient by almost a factor of 4. For a constant particle density, this corresponds to a 25% increase in particle radius.

Conclusions

The South Pole PMC scattering layers exhibit strong diurnal and semidiurnal variations in backscatter ratio, volume backscatter coefficient, total backscatter coefficient, and centroid altitude. The variations appear to be linked to vertical advection of the PMC scattering layers by a persistent oscillation in the vertical wind velocity. The semidiurnal oscillation in the PMC altitude is twice the amplitude of the diurnal oscillation. Semidiurnal s = 0 Hough functions peak near the Poles and so this zonally symmetric tide is the most likely source of the vertical oscillations of PMC altitudes. Scattering is strongest when the PMCs are highest which suggests that the colder temperatures at higher altitudes near the mesopause facilitate the formation of larger PMC particles. Similar observations at Andoya (69°N) show a clear anti-phase relationship between altitude and scattering, i.e., scattering is strongest when the PMC layers are at the lowest altitudes. These two contradictory observations suggest that the relationship between PMC altitude, particle size, and backscatter coefficients is more complex than the simple qualitative explanations given here and by *von Zahn et al.* [1998].

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