Lidar observations of polar mesospheric clouds at Rothera, Antarctica (67.5°S, 68.0°W)

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[1] Polar mesospheric clouds (PMC) were observed by an Fe Boltzmann temperature lidar at Rothera (67.5°S, 68.0°W), Antarctica in the austral summer of 2002–2003. The Rothera PMC are much weaker, less frequent, and not as high as the PMC observed at the South Pole. The mean PMC altitude is 83.74 ± 0.25 km, which is approximately 1.3 km lower than the South Pole clouds. A comparison of numerous cloud observations indicates that southern hemisphere PMC are about 1 km higher than northern clouds at similar latitudes. Lidar measurements also show that the mesopause region temperatures at Rothera in late January are warmer than at the South Pole, while the Fe layer at Rothera has higher density and a lower peak altitude compared to the summertime Fe layer at the South Pole. These Fe density and temperature observations are qualitatively consistent with the PMC observations. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 0394 Atmospheric Composition and Structure: Instruments and techniques. **Citation:** Chu, X., G. J. Nott, P. J. Espy, C. S. Gardner, J. C. Diettrich, M. A. Clilverd, and M. J. Jarvis (2004), Lidar observations of polar mesospheric clouds at Rothera, Antarctica (67.5°S, 68.0°W), *Geophys. Res. Lett.*, *31*, L02114, doi:10.1029/2003GL018638.

1. Introduction

[2] Recent lidar observations at the South Pole have revealed an inter-hemispheric difference in the altitudes of polar mesospheric clouds (PMC) [*Gardner et al.*, 2001; *Chu et al.*, 2001, 2003]. The mean PMC altitude derived from more than 430 hours of PMC data during two summer seasons at the South Pole is approximately 2 km higher than PMC observed in the northern hemisphere. Radar observations have also shown that the strength of polar mesosphere summer echoes (PMSE) is much weaker in the southern hemisphere compared to the northern hemisphere [*Woodman et al.*, 1999]. This difference in PMSE strength has been attributed to hemispherical differences in the mesopause temperatures, water vapor concentrations, and winds. Satellite observations show some evidence of an inter-hemispheric difference in the thermal structure in the mesopause region, but not exactly at the mesopause altitude and only near solstice [*Huaman and Balsley*, 1999]. Although *in-situ* rocket measurements did not see this temperature difference [*Lübken et al.*, 1999], the rocket measurements were made after solstice when no significant inter-hemispheric differences were observed by the satellite. Due to the lack of precise long-term measurements of the mesopause region, especially at very high latitudes in the southern hemisphere, quantitative explanations for the PMSE differences remain elusive.

[3] Lidar measurements of PMC at the South Pole and at numerous sites in the northern hemisphere have provided accurate information on PMC characteristics in both hemispheres. Nevertheless, most northern hemisphere lidar measurements were made at much lower latitudes than the North Pole. To better characterize the geographic differences in PMC parameters, it is essential to make additional lidar observations at lower latitudes in Antarctica. Through a collaboration between the University of Illinois and the British Antarctic Survey, the University of Illinois Fe Boltzmann temperature lidar that made the South Pole PMC observations was relocated to Rothera, Antarctica (67.5°S, 68.0°W) in December 2002. PMC were successfully detected at Rothera in the austral summer of 2002–2003. In this paper, we characterize the Rothera PMC and compare the cloud statistics with lidar data taken from the South Pole and from the northern hemisphere to study regional and hemispheric differences.

2. Observations

[4] Data collection at Rothera Research Station began on 20 December 2002 and will continue for three years. This lidar operates at 374 and 372 nm, and is capable of both daytime and nighttime measurements of atmosphere temperatures in the upper stratosphere, mesosphere and lower thermosphere, as well as Fe densities, aerosols, and cloud layers. Information about the lidar design and measurement principles can be found in *Chu et al.* [2002]. For Rothera PMC data analysis, the photon count profiles were integrated for one hour and were vertically smoothed by a Hamming window with FWHM of 960 m. More details about the data analysis can be found in *Chu et al.* [2003].

[5] The first PMC at Rothera was recorded on 29 December 2002, and the last one on 26 January 2003. PMC were observed on 8 different days with roughly even distribution throughout this nearly one-month period. This initial PMC season was surprisingly short as compared with the South Pole PMC season of 75 days [*Chu et al.*, 2003]. However, no data were collected before 20 December 2002 and only sporadically in early February 2003, so the actual

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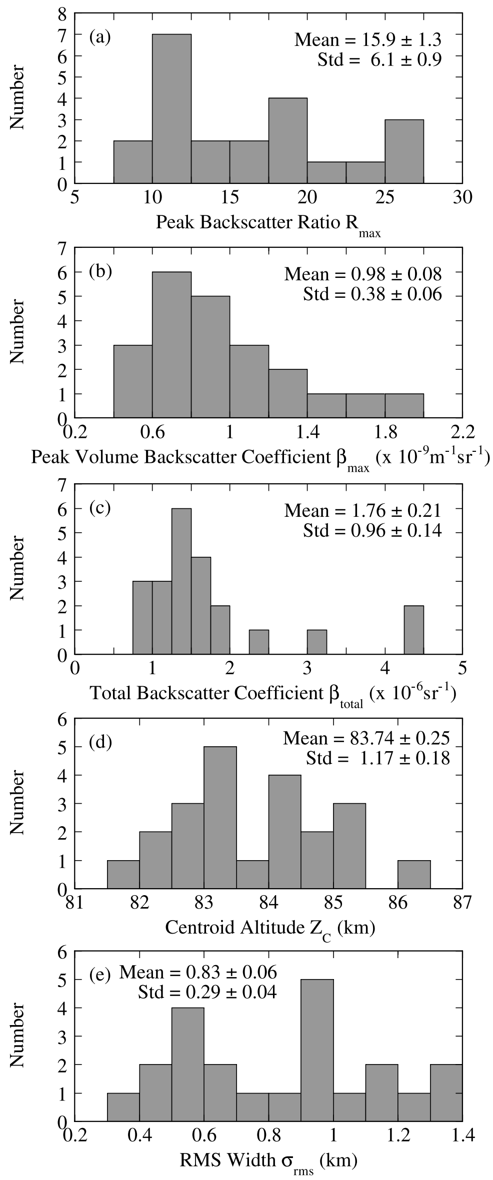

Figure 1. Histograms of PMC characteristics at Rothera in the 2002–2003 summer season. Also plotted are their mean values with standard errors, and standard deviations with errors.

PMC season could be longer than observed. Histograms of hourly mean PMC peak backscatter ratio R_{max}, peak volume backscatter coefficient β_{max}, total backscatter coefficient β_{total}, centroid altitude Z_C and layer rms width σ_{rms} are plotted in Figure 1 for Rothera. Table 1 is a comparison of the PMC mean characteristics and the standard deviations of PMC distributions observed at Rothera and the South Pole. The most significant differences are that the Rothera PMC are much weaker, less frequent, and not as high as the PMC observed at the South Pole. The Rothera PMC brightness (expressed as R_{max}, β_{max} and β_{total}) and occurrence frequency are only about 25–33% of the South Pole values. This was expected, given the findings from the SME and SNOE satellites that PMC brightness and frequency increase towards the pole [*Thomas and Olivero*, 1989; *Merkel*, 2002]. The PMC layer width at Rothera is a little larger than at the South Pole. The mean centroid altitude is 83.74 ± 0.25 km, which is approximately 1.3 km lower than the South Pole mean (85.03 ± 0.05 km), but 0.8 km higher than the mean at Sondrestrom (82.9 km) and 0.4 km higher than the mean at Andoya (83.3 km), both in the northern hemisphere at similar latitudes.

[6] In this first PMC season, PMC were observed during 22 hours out of a total 127 hours of lidar measurements, giving a PMC occurrence frequency at Rothera of 17.3%. This is much lower than the occurrence frequency of 67.4% measured at the South Pole (90°S) [*Chu et al.*, 2003] and 43% measured at Andoya (69°N) [*Fiedler et al.*, 2003]. It is also a little lower than the 24% occurrence frequency measured at Sondrestrom (67°N) [*Thayer et al.*, 2003]. The lidar observations were limited by the frequently overcast sky at Rothera so the low occurrence frequency during this first summer may not be representative. The actual occurrence frequency of Rothera PMC could be higher than observed. The seasonally averaged PMC frequency obtained by the SME satellite from 1981–1986 was about 10% at 67.5°S [*Thomas and Olivero*, 1989]. Hence, the low PMC occurrence frequency measured by the Fe lidar at Rothera is generally consistent with SME satellite observations made two decades ago.

3. Influence of Temperature

[7] PMC are water ice particles that form in the supersaturation region near the cold summer mesopause. The weaker PMC at Rothera may be related to the differences in temperature and water vapor in the mesopause region at Rothera compared to the South Pole. Available water vapor (the amount by which the actual water vapor pressure exceeds the saturation water vapor pressure) is strongly influenced by the local temperature [*Thomas*, 1991]. Plotted in Figure 2 is the temperature profile measured by the Fe/Rayleigh lidar during a continuous 40 h observation period on 19–21 January 2003 at Rothera. Also plotted for comparison is the mean temperature for this week at the South Pole derived from the UISP-02 observations described by *Pan and Gardner* [2003]. The mesopause temperature at the South Pole is 142 ± 3 K while the mesopause temperature at Rothera is 153 ± 5 K. In fact, the region between 80 and 100 km is much warmer at Rothera compared to the South Pole during this period.

[8] *Lübken et al.* [1999] conducted rocket-borne falling sphere measurements of the mesopause region temperatures at Rothera in January and February 1998. Their temperature at 82 km (~150 K) in late January is about 12 K colder than

Table 1. Comparisons of the PMC Mean Characteristics and the Standard Deviations of PMC Distributions (i.e., Geophysical Variability in Parentheses) Between Rothera and the South Pole

Mean (Std)\Parameters	South Pole (1999–2001)	Rothera (2002–2003)
R_{max}	58.4 (29.0)	15.9 (6.1)
β_{max} (10^{-9} m^{-1} sr^{-1})	3.75 (2.06)	0.98 (0.38)
β_{total} (10^{-6} sr^{-1})	5.45 (3.73)	1.76 (0.96)
Z_C (km)	85.03 (1.02)	83.74 (1.17)
σ_{rms} (km)	0.75 (0.30)	0.83 (0.29)
Occurrence Frequency	67.4%	17.3%
PMC Hours	437	22

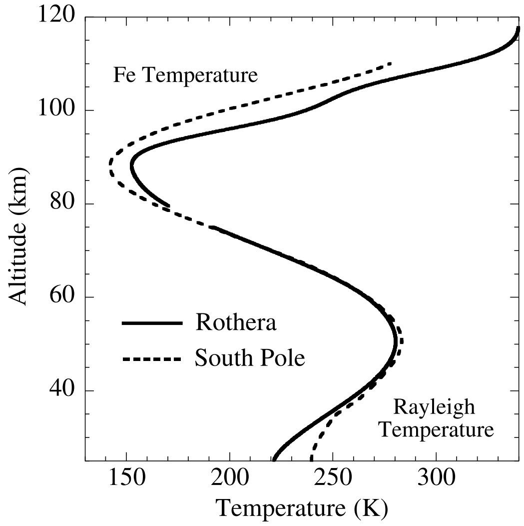

Figure 2. The measured temperature profile above Rothera during a continuous 40 h observation on 19–21 January 2003 is compared with the mean temperature for this week at the South Pole derived from the UISP-02 observations of *Pan and Gardner* [2003].

the lidar observations reported here. However, the rocket measurements showed considerable day-to-day variability and were limited to a single local time. Since the lidar observations exhibited only 6 h of PMC during the 40 h measurement period, it is not surprising that the mean temperatures are warmer than the mean reported by *Lübken et al.* [1999]. Usually, 150 K is the upper temperature limit for PMC formation in the mesopause region [*Thomas*, 1991]. The Rothera mesopause temperature is near this upper limit. The existence of relatively warm summer temperatures between 80 and 90 km is probably the main reason why the PMC at Rothera were much weaker and less frequent than at the South Pole.

[9] The Fe density at Rothera is much higher than at the South Pole, especially in the range of 80–90 km, as shown in Figure 3. The peak altitude of Rothera Fe layer is 90 km, which is about 2 km lower than the South Pole peak at about 92 km. It is well known that the Fe chemistry is temperature dependent. The primary sink reaction $FeO + O_2 \rightarrow FeO_3$ on the Fe layer bottom side proceeds more rapidly at lower temperature [*Rollason and Plane*, 2000], which results in much lower Fe densities in summer. Thus, the higher Fe density observed at Rothera compared to the South Pole is consistent with the warmer mesopause region temperatures.

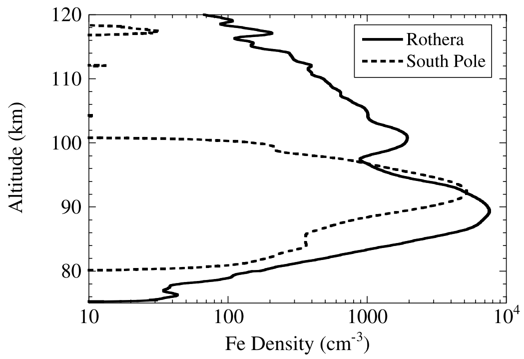

Figure 3. Comparison of the Fe layer density at Rothera and the South Pole in late January.

4. Geographic Differences in PMC Altitudes

[10] To explore geographic differences in PMC altitudes, we plot in Figure 4 the mean PMC altitudes measured by lidars and ground-based triangulation versus latitude for both the southern and northern hemispheres. The lidar data were from the South Pole (90°S) [*Chu et al.*, 2003], Davis (68.6°S) [*Klekociuk et al.*, 2003], Rothera (67.5°S), North Pole (90°N) and Gulf of Alaska (58°N) [*Gardner et al.*, 2001], Svalbard (78°N) [*Höffner et al.*, 2003], Andoya (69°N) [*Fiedler et al.*, 2003], Sondrestrom (67°N) [*Thayer et al.*, 2003], Poker Flat (65°N) [*Collins et al.*, 2003], Juliusruh and Kühlungsborn (55/54°N) [*Alpers et al.*, 2000; *von Cossart et al.*, 1996], and Logan (42°N) [*Wickwar et al.*, 2002]. Three other northern data points were adapted from *von Zahn and Berger* [2003], in which they summarized the triangulation measurements of NLC altitudes from several sources for 62°N, 60°N, and 53°N. The lidar data at 90°S, 67.5°S, 78°N, 69°N, 67°N, and 55/54°N were averaged over many hours for one or more seasons. There were only a few hours of observations at 90°N, 65°N, 58°N, and 42°N. These four points (open circles) were excluded in the linear fit (solid line) to the northern PMC altitudes but are plotted for reference. The data at 90°N, 65°N, and 58°N fall below this trend line while the data from 42°N lies on the line. The two southern points (filled squares) were obtained from many days of measurements by the same Fe lidar at the South Pole and Rothera. The single Davis (68.6°S) observation (open square), obtained on 09 January 2002, is slightly above the dashed line linking the Rothera and South Pole means. Both the southern and northern hemisphere trend lines indicate that PMC alti-

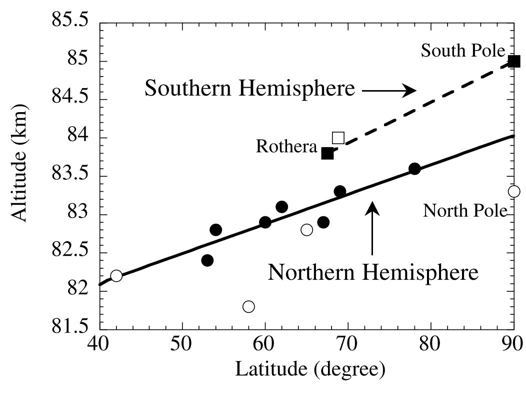

Figure 4. PMC altitude versus latitude in both hemispheres. Circles are for the northern hemisphere, and squares are for the southern hemisphere. Filled circles indicate large data sets and are used to obtain the linear fit (solid line). Open circles indicate limited data sets and are excluded in the fit. The open square is for the Davis data. See text for references.

tudes are generally higher at higher latitudes. What is more interesting in Figure 4 is that the southern line is significantly higher than the northern line. The altitude difference between the two hemispheres is about 1 km for similar latitudes.

[11] Recent SNOE satellite observations from 1998 to 2001 show that the mean altitude of PMC in the northern hemisphere is 82.7 km with a standard deviation (geophysical variability) of 1.2 km while the mean altitude in the south is 84.4 km with a standard deviation of 2.0 km [*Merkel*, 2002]. Despite the geophysical variations, *Merkel* [2002] concludes that on average southern hemisphere clouds are 1.7 km higher than northern clouds. Similarly, a recent re-analysis of SME satellite data from 1981 to 1986 indicates that the southern PMC mean height of 83.2 km is about 1 km higher than the mean northern cloud height of 82.2 km [*Merkel*, 2002]. The altitude differences observed by these satellites are generally consistent with the differences found by lidar and triangulation measurements shown in Figure 4. We conclude from all these measurements that there is a significant inter-hemispheric difference in PMC altitudes. The southern hemisphere PMC are higher than their northern counterparts.

[12] *Gardner et al.* [2001] and *Chu et al.* [2003] attributed the inter-hemispheric difference in PMC altitudes to differences in the vertical upwelling, which affect the buoyancy acting on the PMC particles, the height and temperature of the mesopause, and the height of the saturation region. These differences appear to be associated with hemispherical differences in solar heating and gravity wave forcing. The upwelling is greater and the saturation region is generally higher in the southern hemisphere because the earth is closest to the sun in early January and so summertime solar heating is 6% stronger than in the northern hemisphere. Differences in gravity wave activity, which modulate the meridional circulation system, also contribute to hemispherical differences in PMC altitudes and their inter-annual variations. Additional observations and detailed modeling are needed to clarify these issues.

5. Conclusions

[13] PMC were successfully detected at Rothera during the 2002–2003 summer with much lower occurrence frequency and weaker brightness than at the South Pole. Our lidar measurements show that in late January the mesopause region temperatures are warmer at Rothera compared to the South Pole. Also in late January, the Fe layer at Rothera has a much higher density and lower peak altitude than the South Pole. These Fe density and temperature observations are qualitatively consistent with the PMC observations since warmer temperatures contribute to higher Fe densities and weaker PMC.

[14] The PMC mean altitude at Rothera is 83.74 ± 0.25 km, which is approximately 1.3 km lower than the South Pole clouds. An overall comparison between the southern and northern hemisphere PMC using available data obtained by lidar and ground-based triangulation measurements shows an inter-hemispheric difference in PMC altitudes. The southern hemisphere PMC are about 1 km higher than the northern hemisphere clouds observed at similar latitudes. The SNOE and SME satellite observations appear to support this finding. These initial observations help clarify inter-hemispheric and regional differences in PMC characteristics.

[15] We are aware that we only have limited PMC data set in the first summer season, so the significance of the Rothera PMC statistics is also limited. More observations will be taken over the next few years at Rothera to reinforce the above findings of the geographic differences, to fully characterize the seasonal variations of the thermal structure above Rothera, and to provide detailed statistics on the characteristics of PMC at this high latitude Antarctic site.

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