# Review of Key Findings From Lidar Observations of Polar Mesospheric Clouds

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# Acknowledgements To

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Chester Gardner (UIUC) for South Pole Collaboration

Patrick Espy (BAS) for Rothera Collaboration

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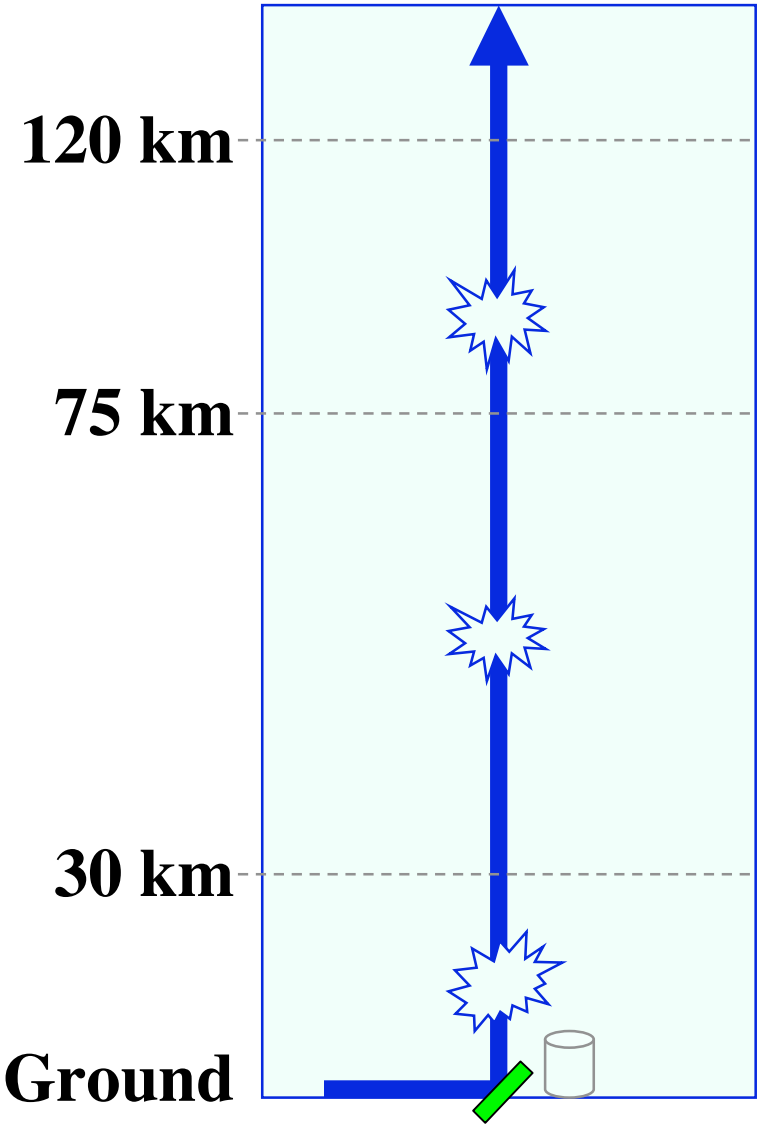
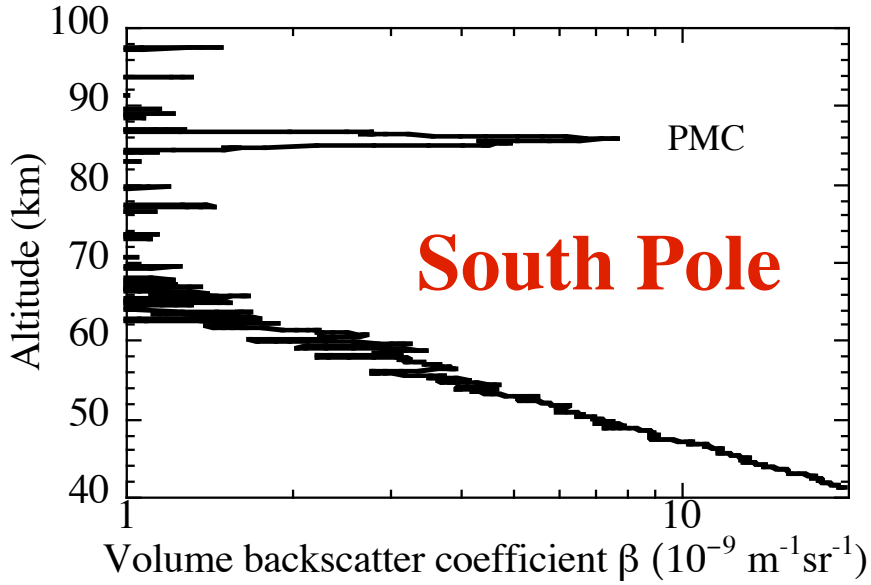
# Lidar Detection of PMC



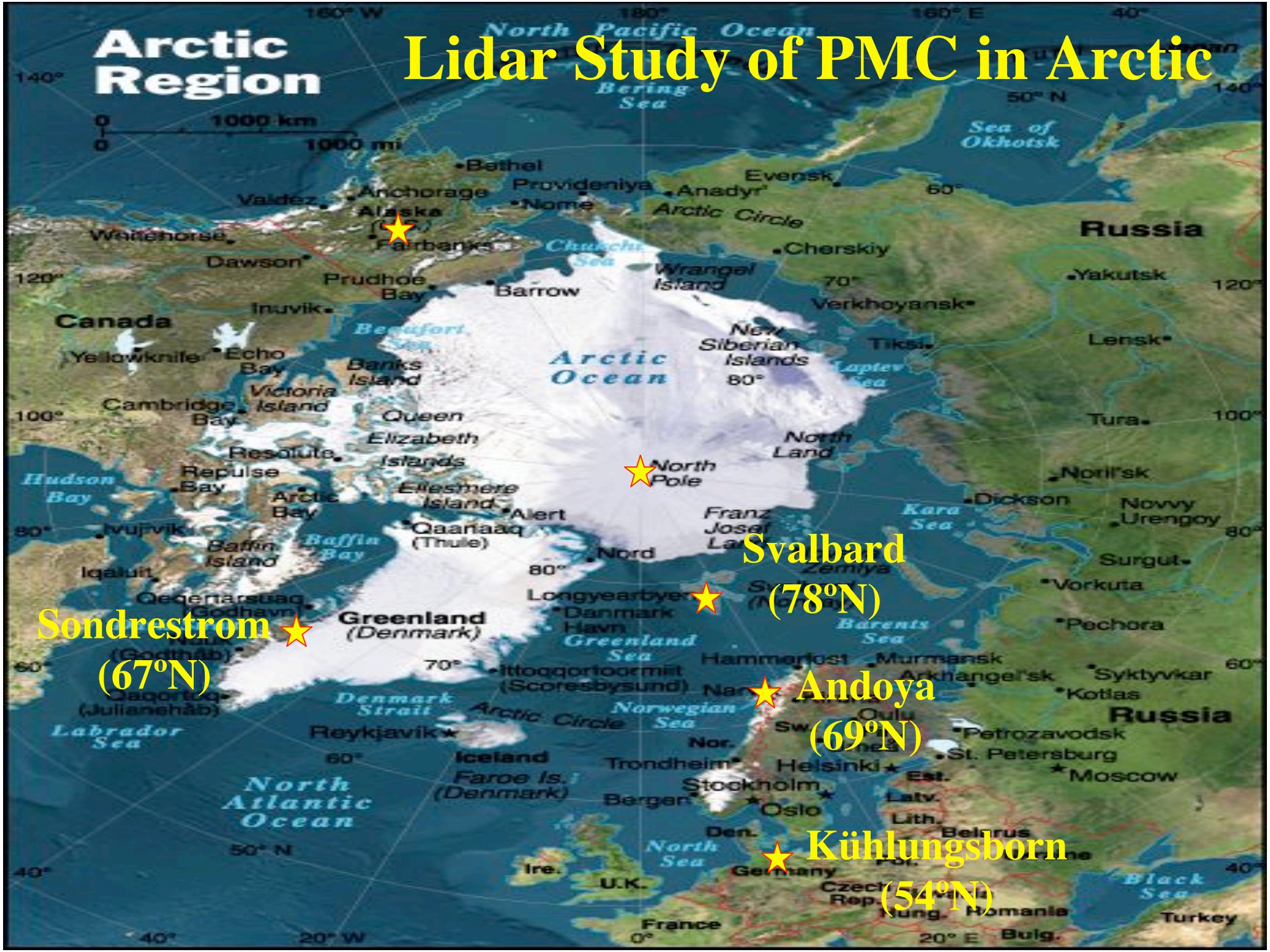

**Time of Flight ⇨ Range / Altitude, Full-Diurnal Detection**

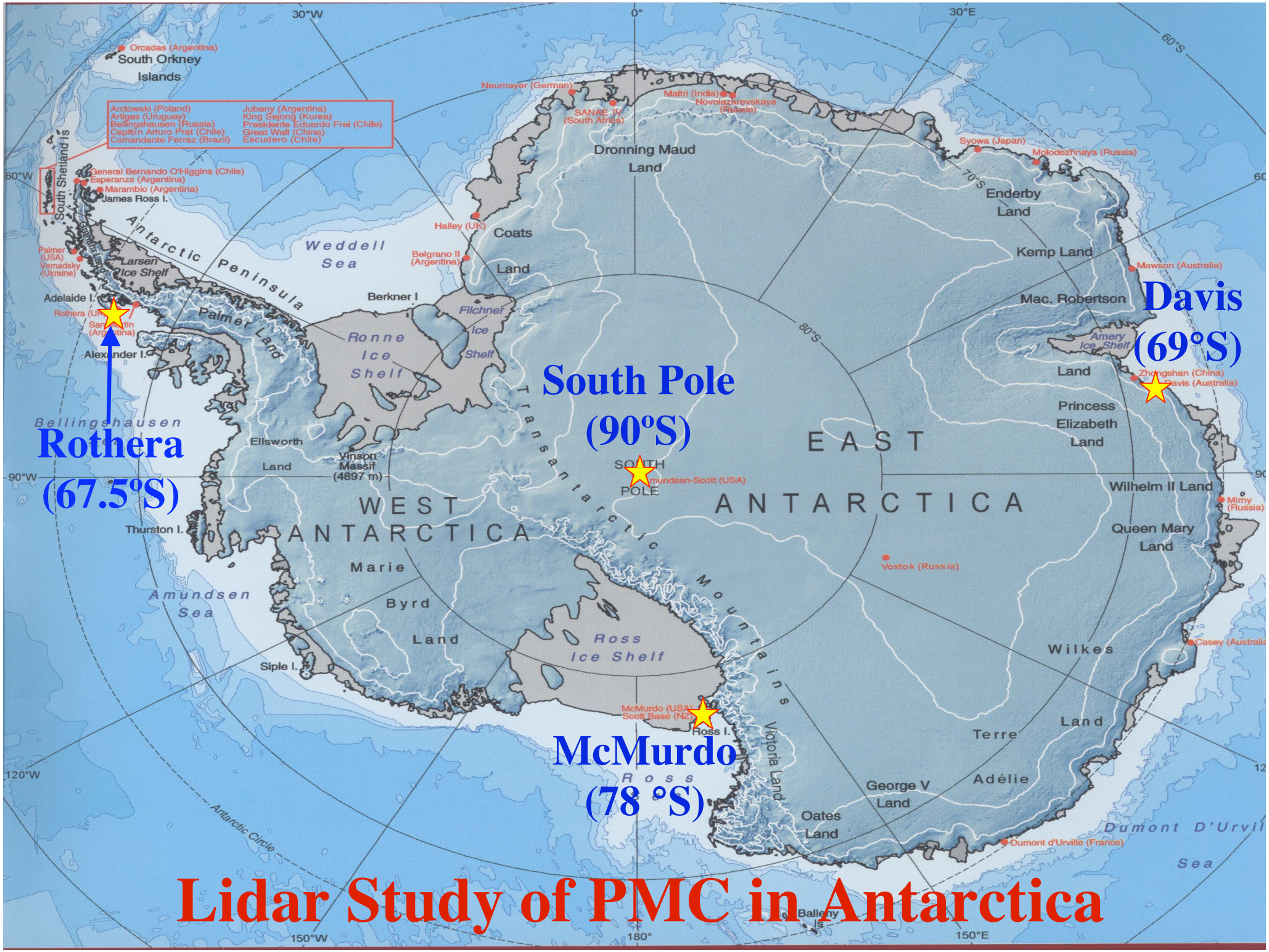
# PMC Properties Studied by Lidar

- Physical Characteristics and Optical Properties
  - Altitude, Width, Vertical Structure, Occurrence, etc
  - Volume/Total Backscatter Coefficient and Backscatter Ratio
  - Interhemispheric Difference, Latitudinal Dependence
  - Relationship of PMC Altitude and Brightness
  - Common Volume Observations of PMC and PMSE
- Microphysical Properties
  - Particle Size, Shape, and Number Density
- Chemistry Role in Upper Atmosphere
  - Heterogeneous Chemistry with Metal Atoms
- Relation to Atmospheric Structure and Dynamics
  - Diurnal, Seasonal, Interannual Variations,
  - Relations to Temperature, Water vapor, Vertical Wind,
  - Influence by Gravity Waves, Tides, Planetary Waves, Solar Flux

**Review key lidar findings of PMC study in 4 categories**

# Lidar Study of PMC in Arctic






# Lidar Study of PMC in Antarctica

# Definitions of PMC Parameters

$$\beta(z) = \int \frac{d\sigma}{d\Omega}(r,\pi)\frac{dn(r,z)}{dr}dr$$

$$\beta_{\max} = \max\left[\beta(z)\right]$$

$$\beta_{total} = \int \beta(z)dz$$

$$Z_C = \frac{\sum_i z_i \beta(z_i)}{\sum_i \beta(z_i)}$$

$$\sigma_{rms} = \sqrt{\frac{\sum_i \left(z_i - Z_C\right)^2 \beta(z_i)}{\sum_i \beta(z_i)}}$$

All backscatter coefficients were converted to 374 nm using the following color ratios:

$$\frac{\beta(374nm)}{\beta(532nm)} = 2.28; \qquad \frac{\beta(374nm)}{\beta(770nm)} = 7.3$$

under assumption of lognormal distribution of spherical particles with a median radius of 40 nm & a width of 1.4 [Höffner et al., 2003].

$$\sigma_{rms} = FWHM / \sqrt{8\ln 2}$$

$$\beta_{total} = \sqrt{2\pi} \cdot \beta_{\max} \cdot \sigma_{rms}$$

Above equations were used to convert data, assuming Gaussian distribution of PMC layer, when lack of parameters.

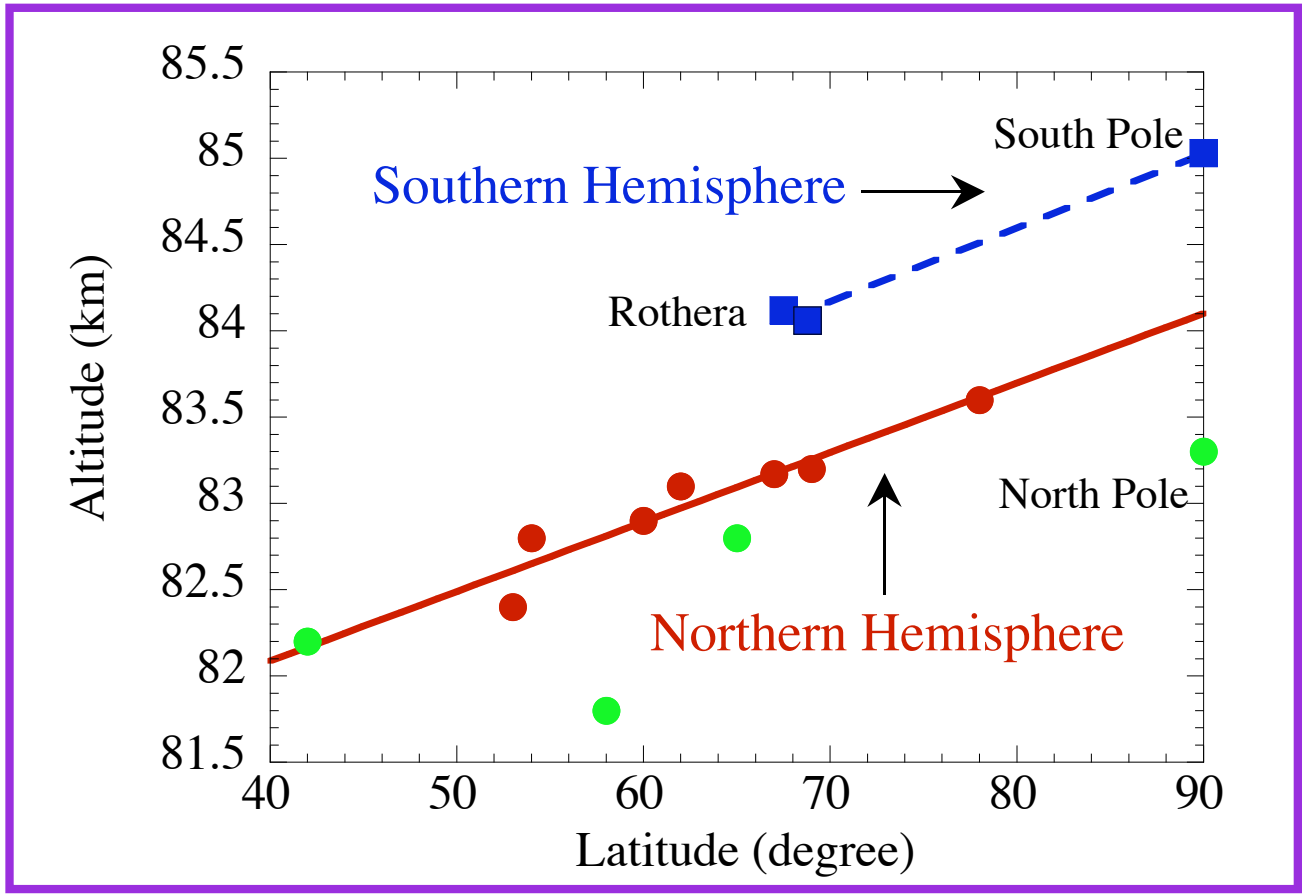
# Mean Physical Characteristics

| | South Pole (90°S) | Davis (69°S) | Rothera (67.5°S) | Svalbard (78°N) | Andoya (69°N) | Sondre (67°N) |
|---|---|---|---|---|---|---|
| $Z_C$ (km) (std) | 85.03±0.05 (1.02) | 84.06±0.16 (3.70) | 84.12±0.12 (1.35) | 83.6 (1.0) | 83.2±0.05 (1.2) | 83.17±0.03 (1.11) |
| $\beta_{total}$ ($10^{-6}$ $sr^{-1}$) | 5.45 ± 0.19 (3.73) | 0.83 (1.09) | 2.34 ± 0.11 (1.28) | 5.1 (convert) | 2.60 (convert) | 2.48 (2.33) |
| $\beta_{max}$ ($10^{-9} m^{-1} sr^{-1}$) | 3.75 ± 0.10 (2.06) | 1.61 (1.68) | 1.12 ± 0.05 (0.55) | 3.0 (2.77) | 2.03 (2.07) | 2.20 (2.12) |
| $\sigma_{rms}$ (km) | 0.75 ± 0.02 (0.30) | 0.92 (1.42) | 0.93 ± 0.03 (0.32) | 0.68 (convert) | 0.51 (0.26) | 0.49 (0.25) |
| Occur Freq. | 67.4% | 19.3% | 27.9% | 74% | 36.4% | 11.8% |
| PMC Hour | 437 | 136.5 | 128 | 226 | 825 | 215 |
| Obs. Hour | 648 | 706.2 | 459 | 306 | 2265 | 1816.7 |
| Obs. Year | 1999-2001 | 2001-2006 | 2002-2005 | 2001 + 2003 | 1997-2004 | 1994-2003 |
| PMC Period (to solstice) | 11/24-2/24 (-27 – 65) | 11/20-2/28 (-30 – 69) | 11/19-2/2 (-31 – 43) | 6/11-8/21 (-10 – 61) | 6/1-8/15 (-20 – 55) | 6/11-8/22 (-10 – 62) |

# References for Above Statistics


1. South Pole: Chu et al., JGR, 2003
2. Davis: Klekociuk et al., JGR, in preparation, 2006
3. Rothera: Chu et al., JGR, in review, 2006
4. Svalbard: Höffner et al., Ice Layer Workshop, 2006
5. Andoya: Fiedler et al., EGU conference, 2005
6. Sondrestrom: Thayer and Pan, JASTP, 2006

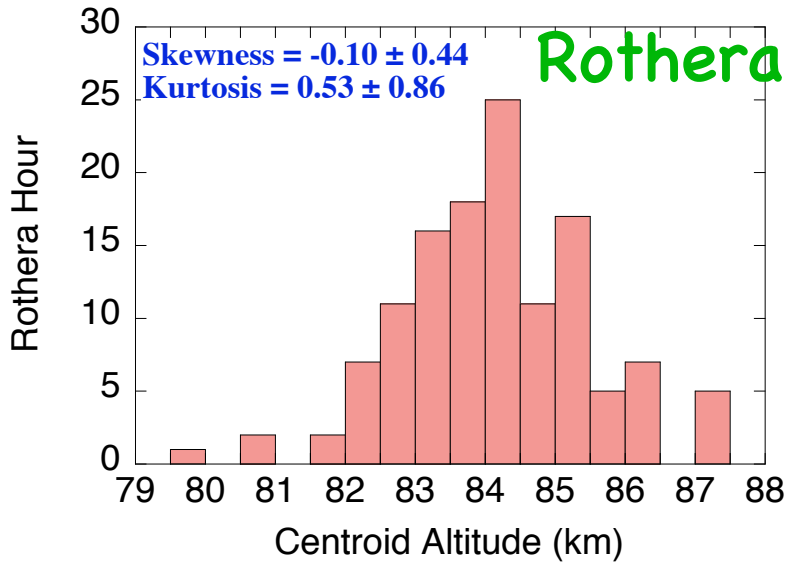
# PMC Altitude: Hemispheric Difference & Latitudinal Dependence

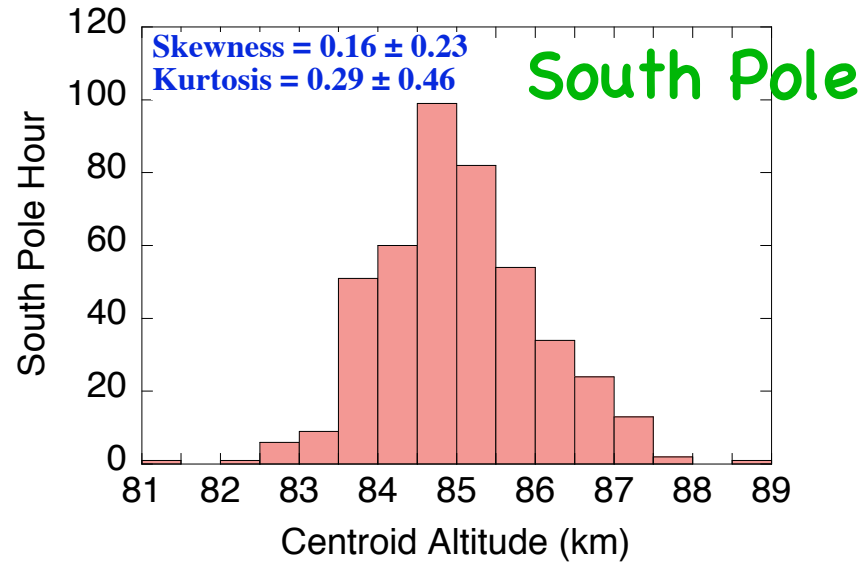


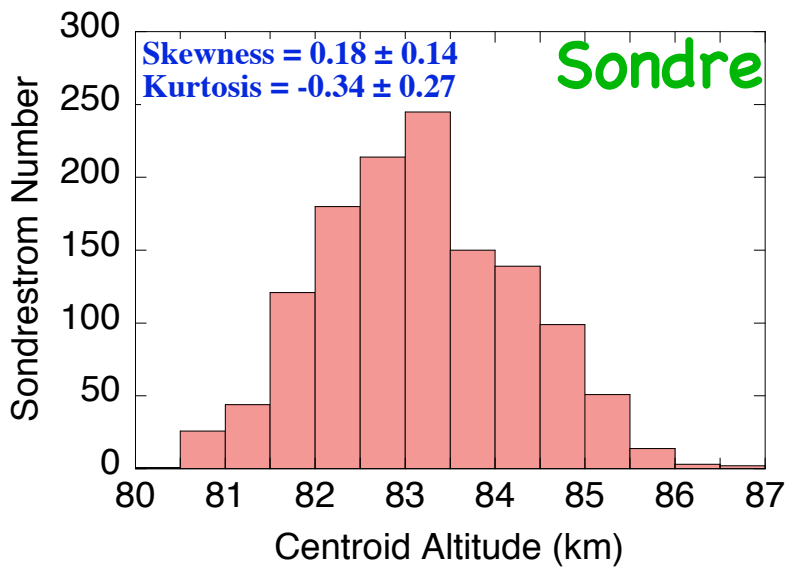

**Southern PMC are ~ 1 km Higher than Corresponding Northern PMC**
**PMC Altitudes are Higher at Higher Latitudes**

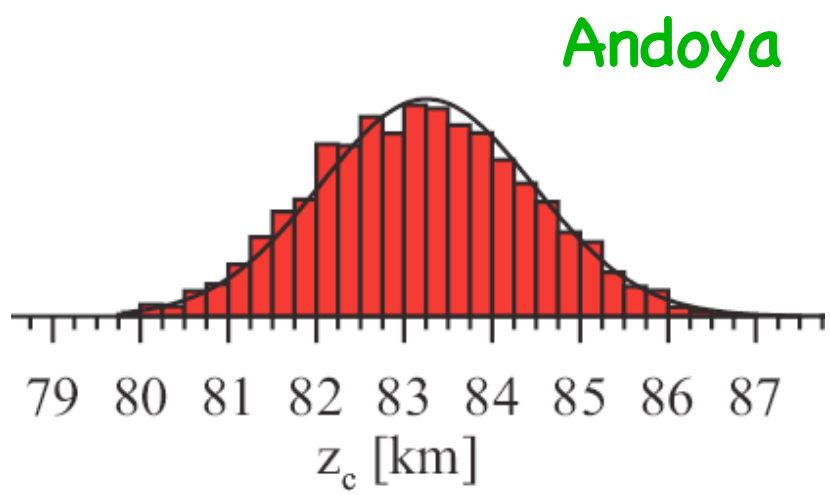
**[Chu et al., GRL, 2001; Chu et al., GRL, 2004]**

# Symmetric (Gaussian) Distribution of $Z_C$



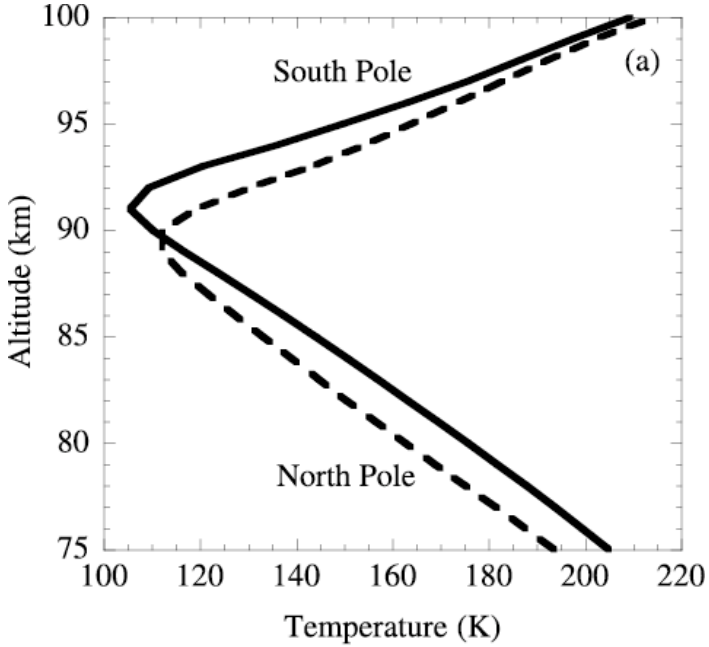



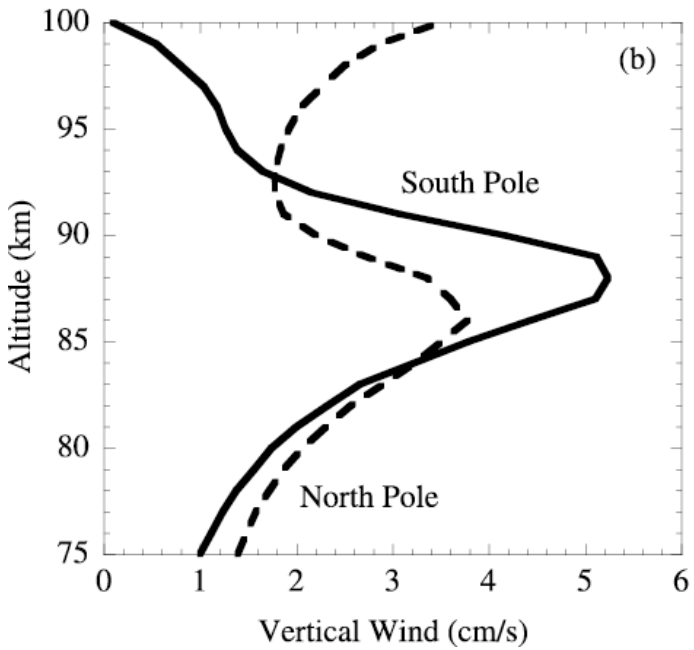



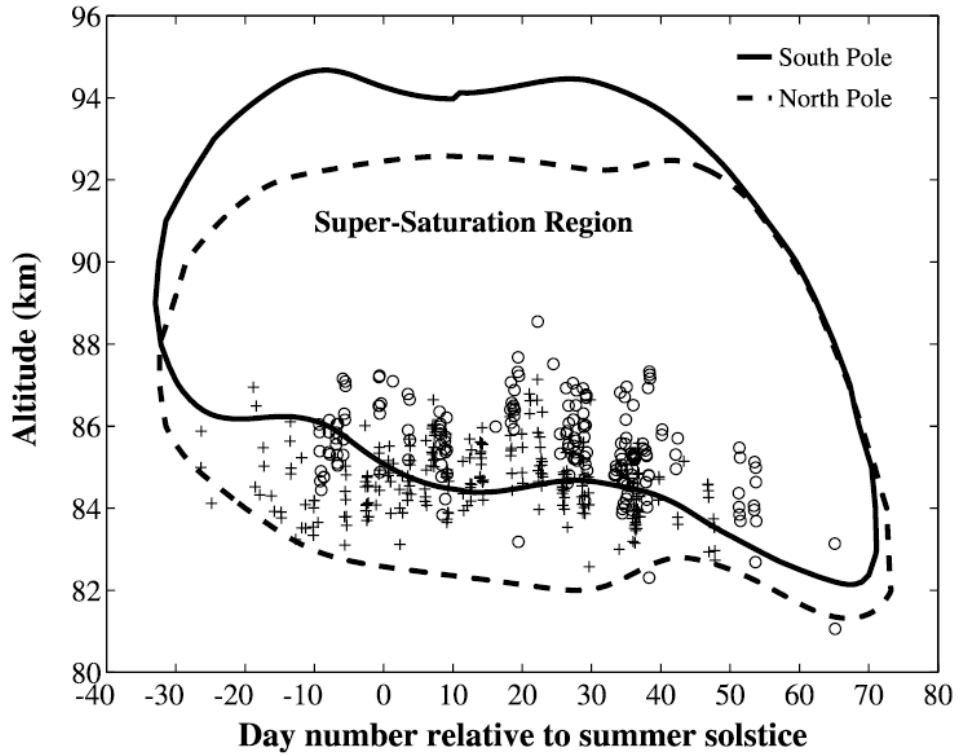

$$Skewness(x_1,\ldots,x_N) = \frac{1}{N}\sum_{j=1}^{N}\left[\frac{x_j - \bar{x}}{\sigma}\right]^3$$

$$Kurtosis(x_1,\ldots,x_N) = \left\{\frac{1}{N}\sum_{j=1}^{N}\left[\frac{x_j - \bar{x}}{\sigma}\right]^4\right\} - 3$$

# Model Study of Hemispheric Difference



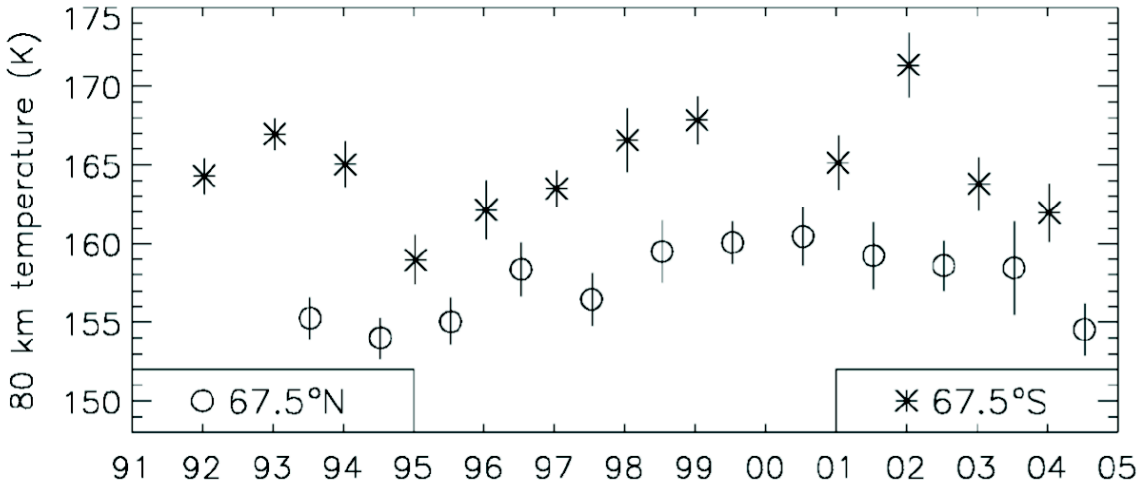




**TIME-GCM Predictions by Raymond Roble of NCAR [Chu et al., JGR, 2003]**

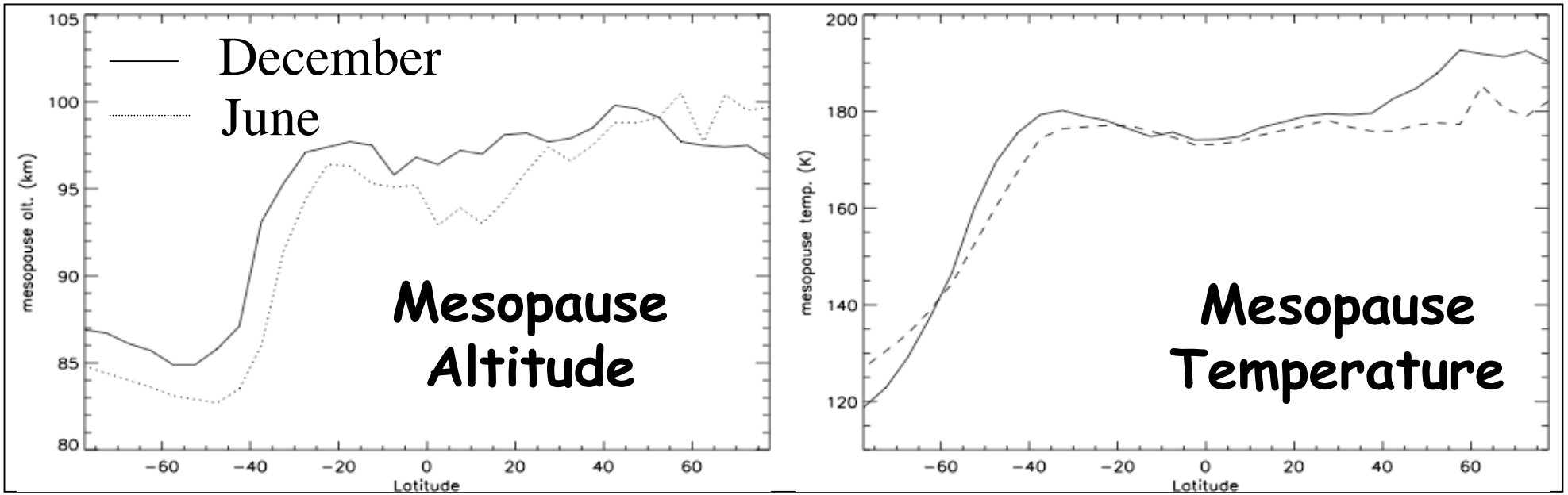
**Gravity waves may also count for the hemispheric difference [Siskind et al., JGR, 2003]**

# Recent Results from Satellite



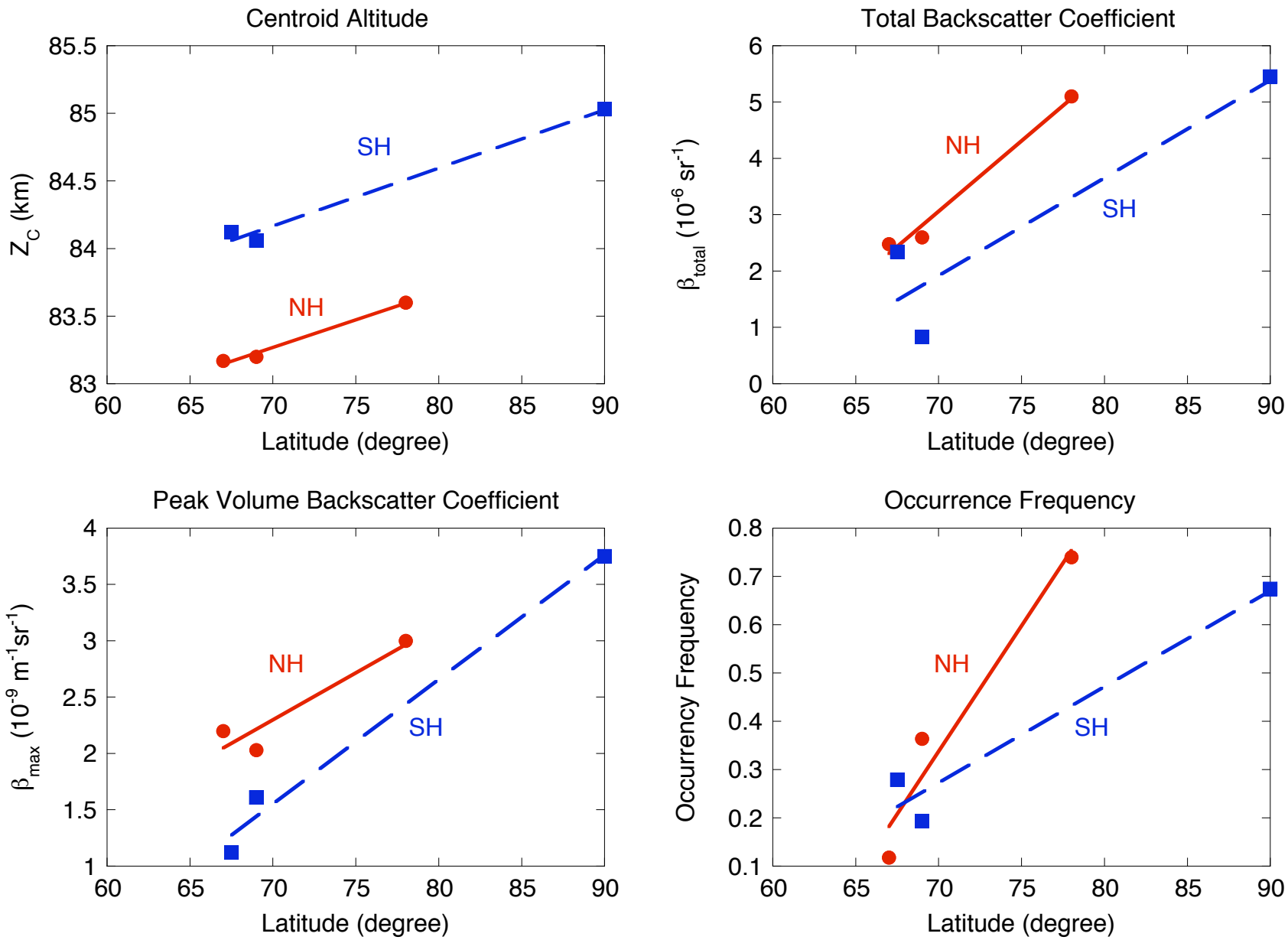

**UARS/HALOE data show that SH summer temperature at 80km is warmer than NH**

**[Hervig and Siskind, JASTP, 2006]**




**TIMED/SABER data show that SH summer mesopause locates at higher altitude and has colder temp than NH [Xu et al., submitted to JGR, 2006]**

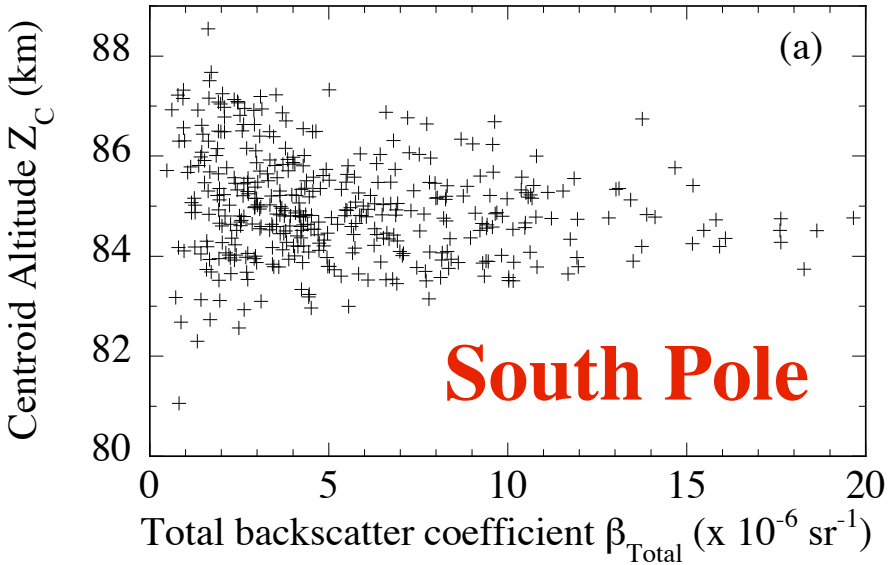
# Hemispheric Difference & Latitudinal Dependence



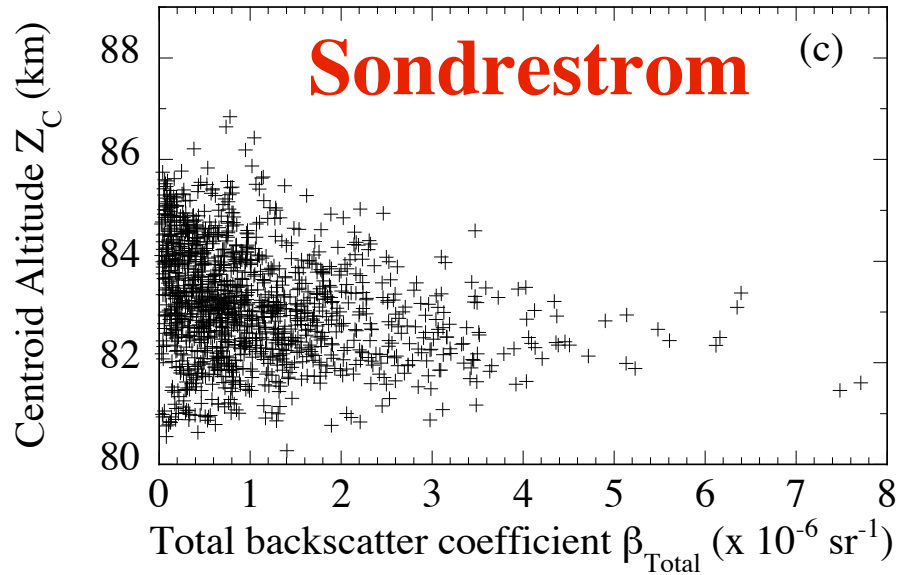

**SH PMC are higher Z, dimmer, and less frequent than NH**

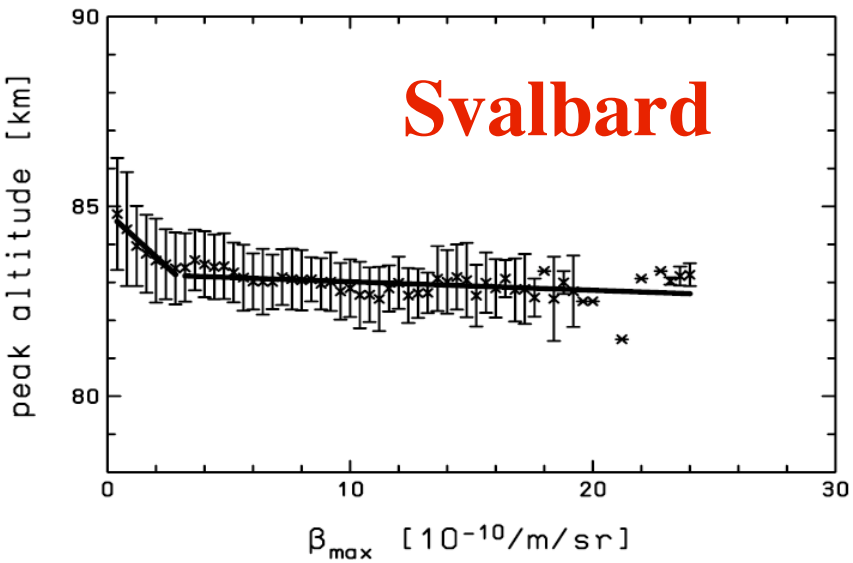
# Relationship of Altitude and Brightness

**[Chu et al., 2003]**

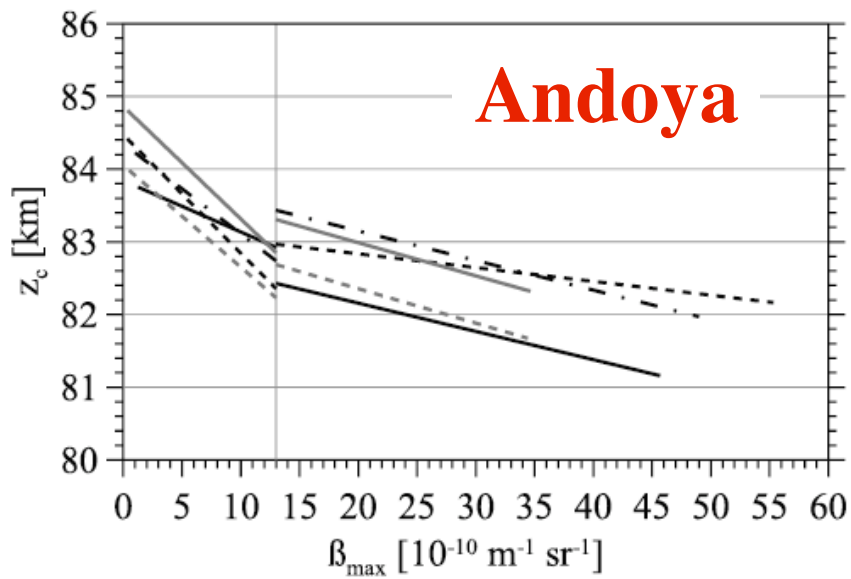



**[Thayer and Pan, 2006]**



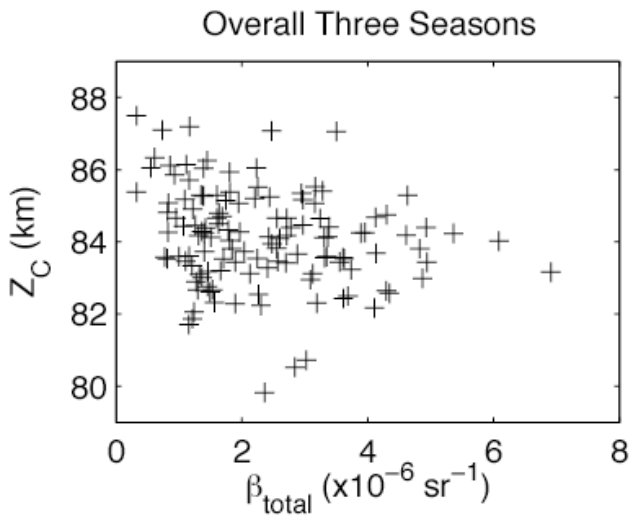



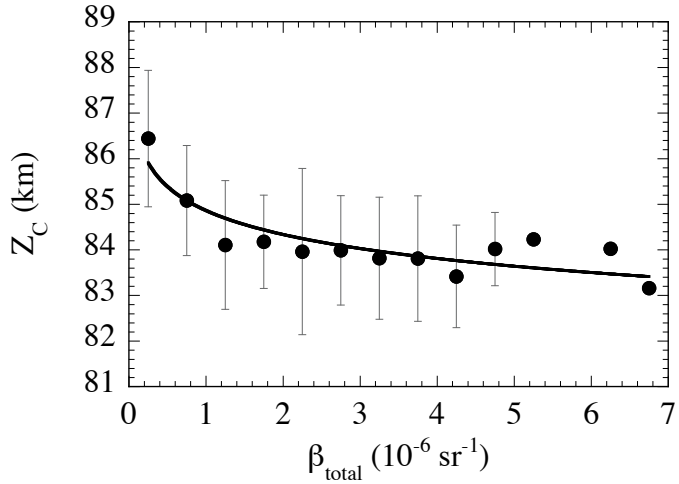

**[Höffner et al., 2003]**

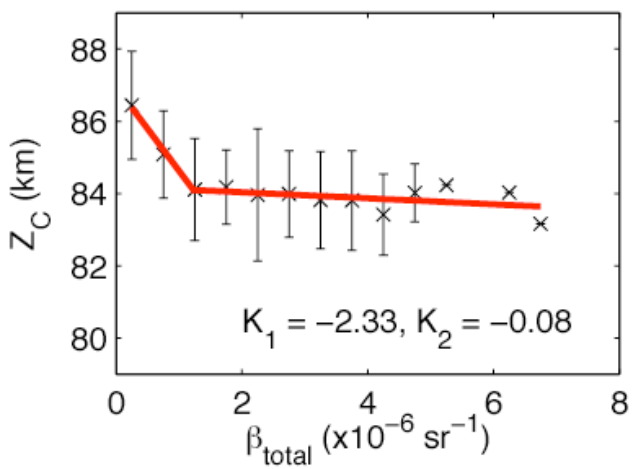


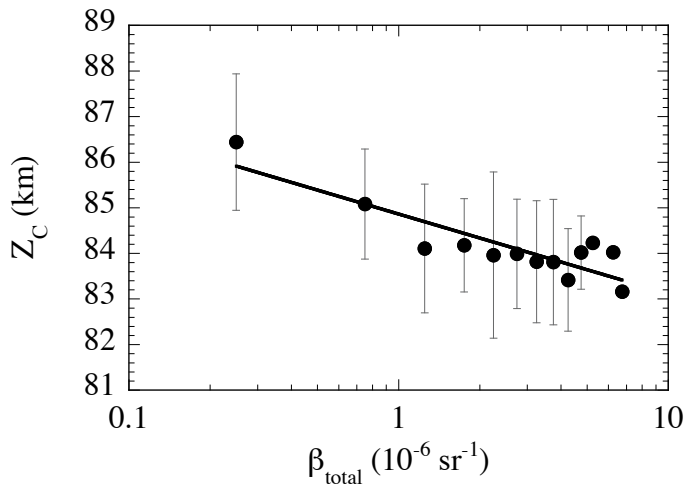

**[Fielder et al., 2003]**

# PMC @ Rothera



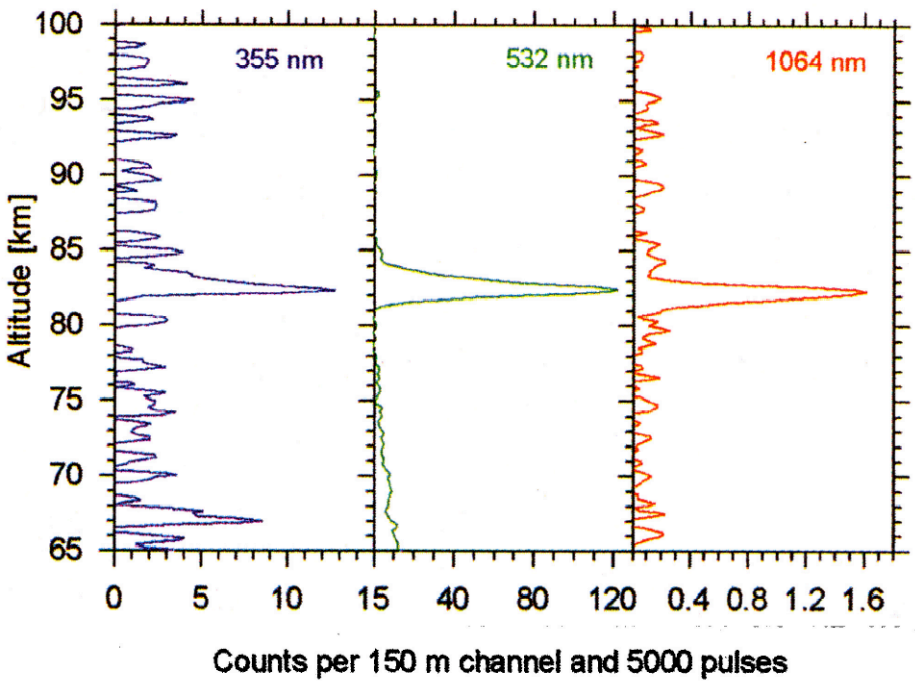

$$z = 74.4 - 0.76 \cdot \ln(\beta_{total})$$
$$R = 87.9\%$$

Logarithm may be a better fit?

[Chu et al., JGR, in review, 2006]

| | Rothera | Andoya | Svalbard |
|---|---|---|---|
| $K_1$ ($\times 10^6$ km·sr) | -2.3 ± 0.2 | -0.46 | -0.45 ± 0.6 |
| $K_2$ ($\times 10^6$ km·sr) | -0.08 ± 0.06 | -0.10 | -0.018 ± 0.006 |
| Divider ($\times 10^{-6}$ sr$^{-1}$) | 1.6 | 3.8 | 3.9 |

# PMC Microphysics: Particle Size




## 3-Color Lidar Observations at ALOMAR, Andoya [von Cossart et al., GRL, 1999]

Color Ratio is defined as

$$CR(\lambda_1,\lambda_2,z) = \frac{\beta_{PMC}(\lambda_1,z)}{\beta_{PMC}(\lambda_2,z)}$$

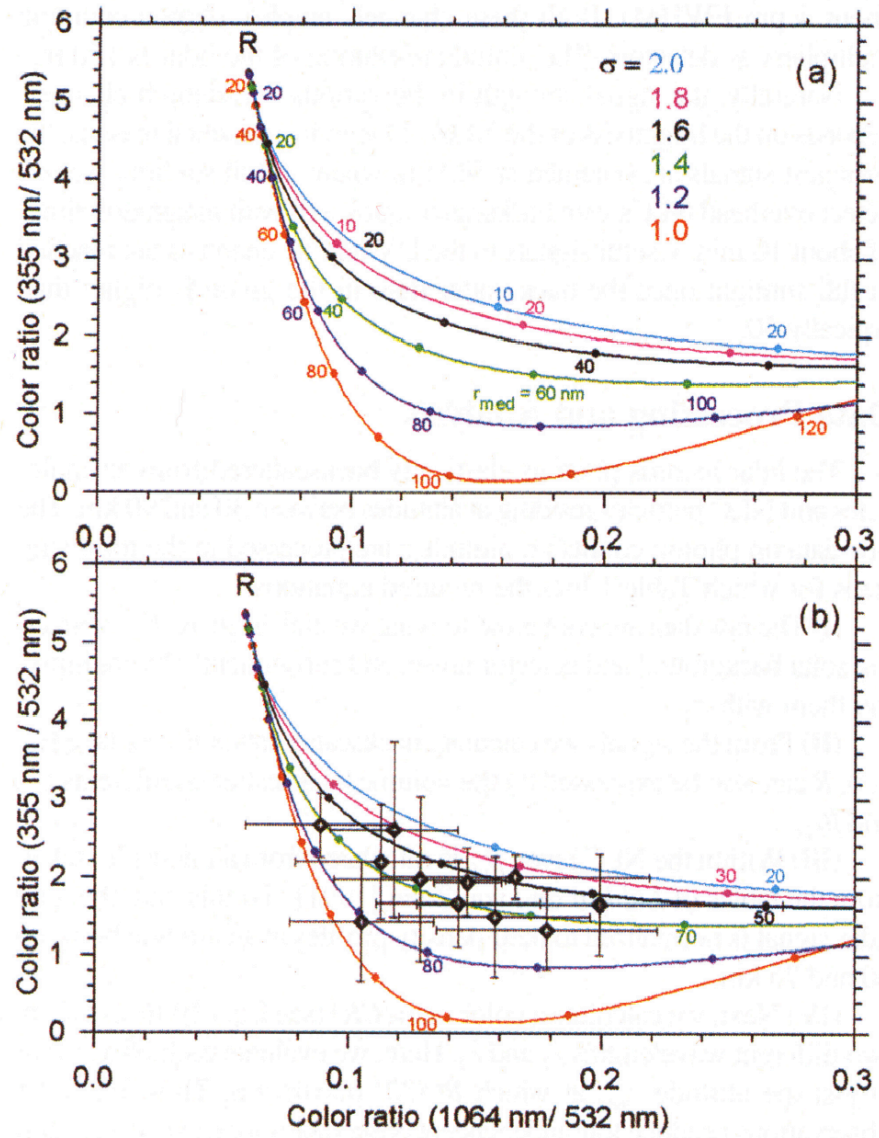



**Figure 1.** Panel (a) shows as a result of Mie calculations for the color ratios *CR* of used laser wavelengths a set of color coded curves for constant $\sigma$ and $r_{med}$. In panel (b) the derived color ratios of the 11 NLC events are plotted in the field of the modelled color ratios.

# Particle Size by 3-Color Lidar

1. Spherical particles ⇨ Mie Scattering Theory
2. Mono-mode log-normal size distribution

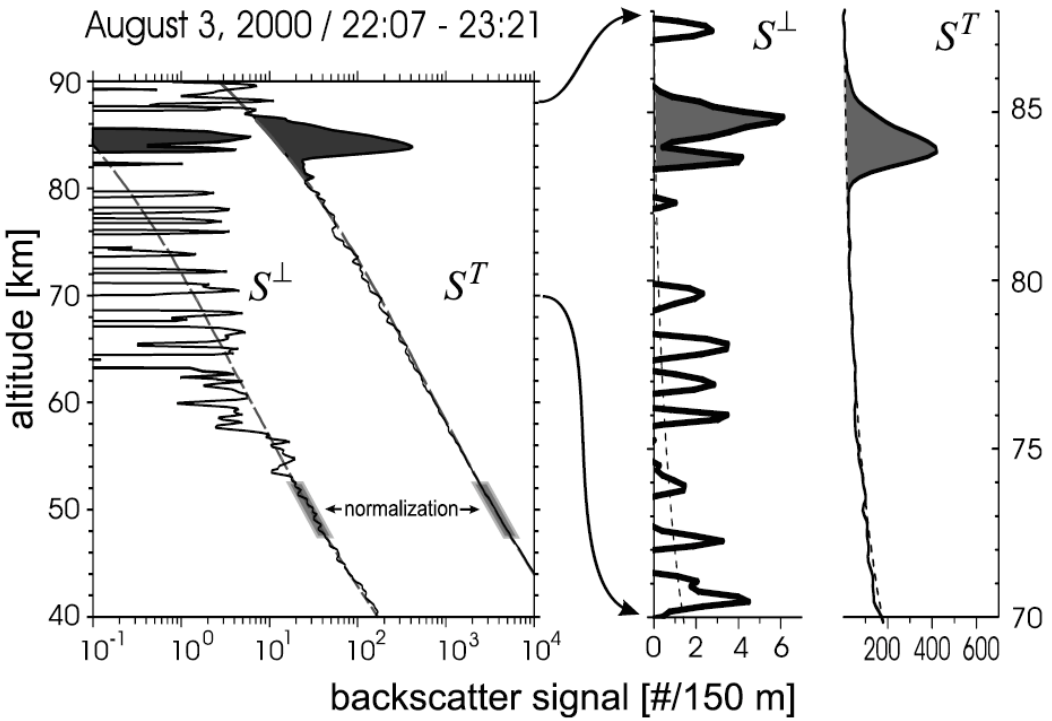
$$\frac{dn(r)}{dr} = \frac{N}{\sqrt{2\pi} r \ln\sigma} \exp\left( -\frac{\ln^2\left(r / r_{med}\right)}{2\ln^2\sigma} \right)$$

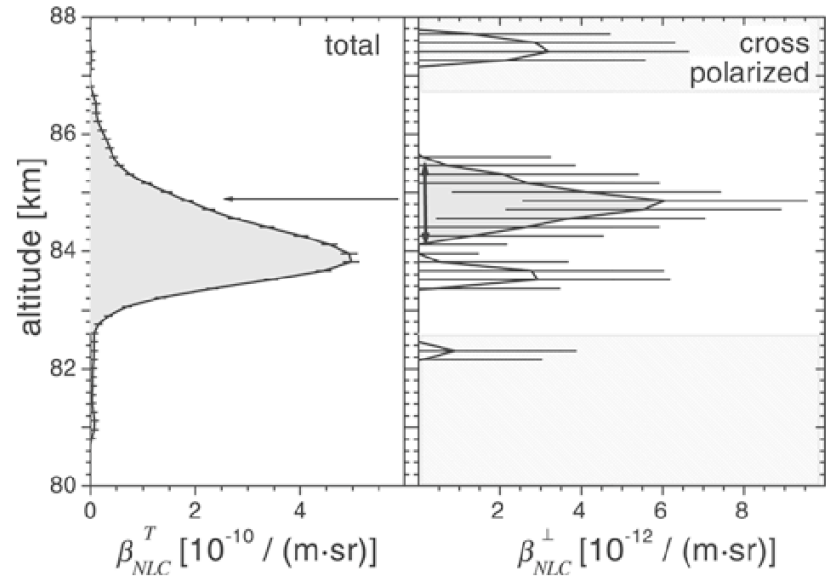
3. Refractive index of ice from [Warren, 1984]

## Lidar Measurement Results at ALOMAR, Andoya

| | $r_{med}$ (nm) | σ | N ($cm^{-3}$) | Model | Reference |
|---|---|---|---|---|---|
| 1998 | 51 | 1.42 | 82 | Spherical Lognormal | von Cossart et al., GRL, 1999 |
| 1998 | 61±7 | 16±2 | 61±16 | Cylinder Gaussian | Baumgarten et al., Ice Layer Workshop, 2006 |
| 2003 | 51±6 | 18±2 | 74±19 | | |
| 2004 | 46±3 | 18±1 | 94±12 | | |
| 2005 | 46±3 | 17±1 | 113±18 | | |

# Particle Shape by Polarization Lidar




Depolarization Factor

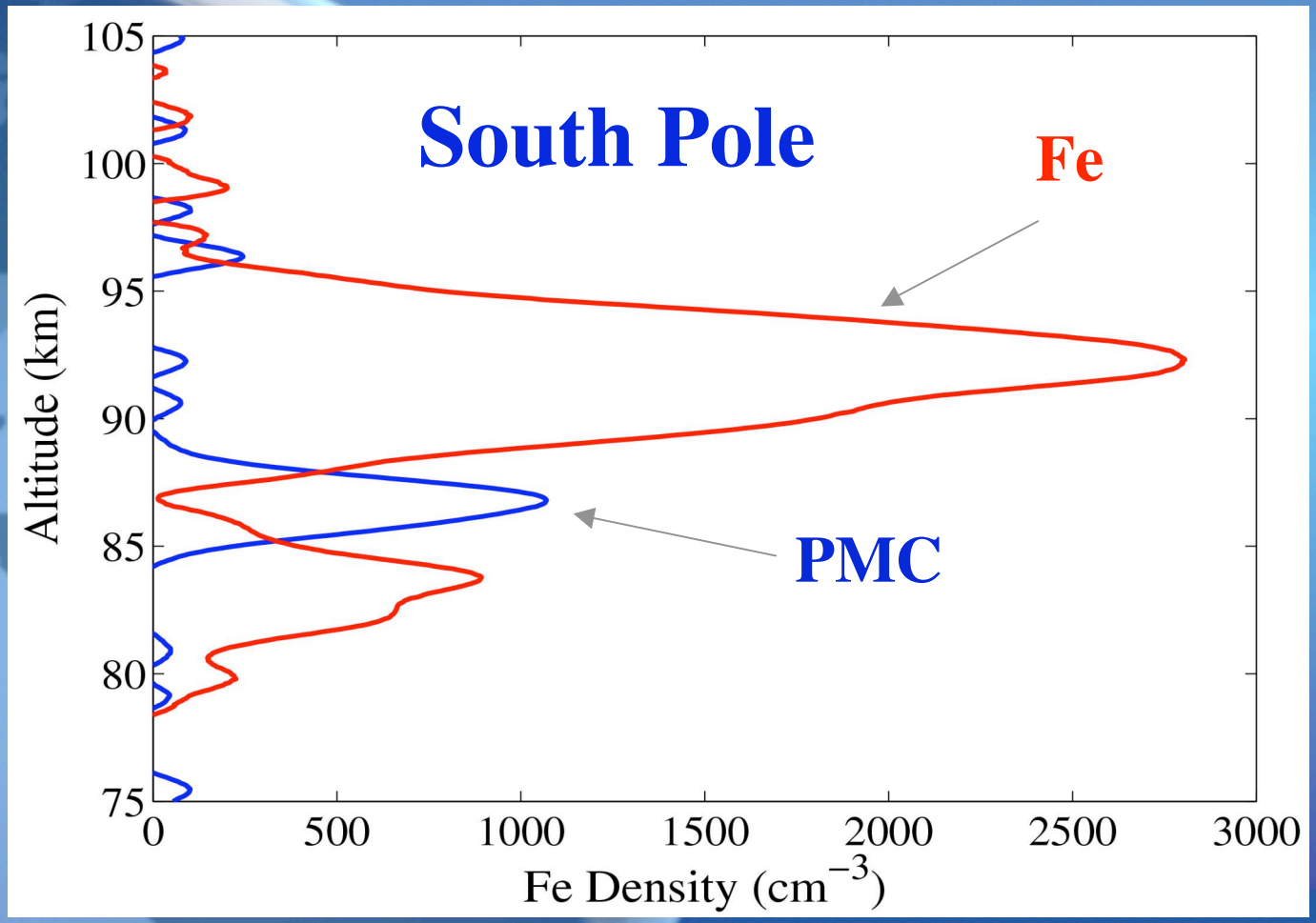
$$\delta_{NLC}(z) = \frac{\beta^{\perp}_{NLC}(z)}{\beta^{\parallel}_{NLC}(z)} = \frac{\beta^{\perp}_{NLC}(z)}{\beta^{T}_{NLC}(z) - \beta^{\perp}_{NLC}(z)}$$

Between 84.2–85.5km, $\delta_{NLC}$ = (1.7±1.0)%

⇨ **Elongated particle with length-over-width ratio > 2.5**

**[Baumgarten et al., GRL, 2002]**

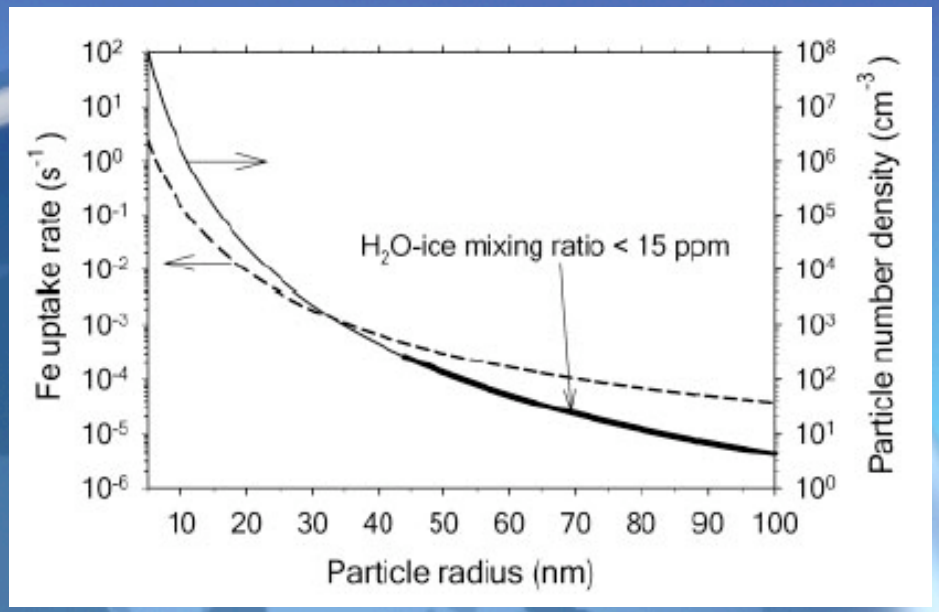
# PMC Chemistry Role: Heterogeneous Removal of Metal Atoms by PMC

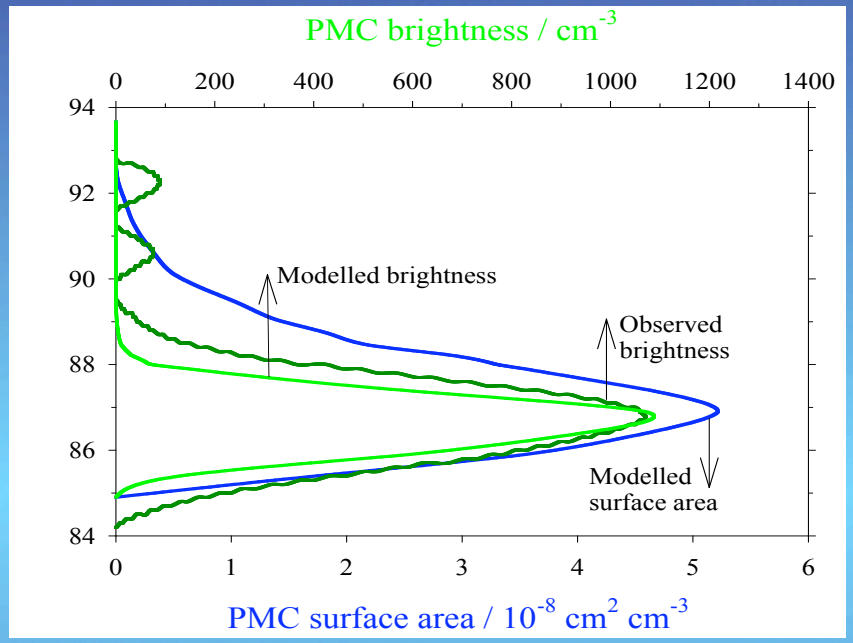


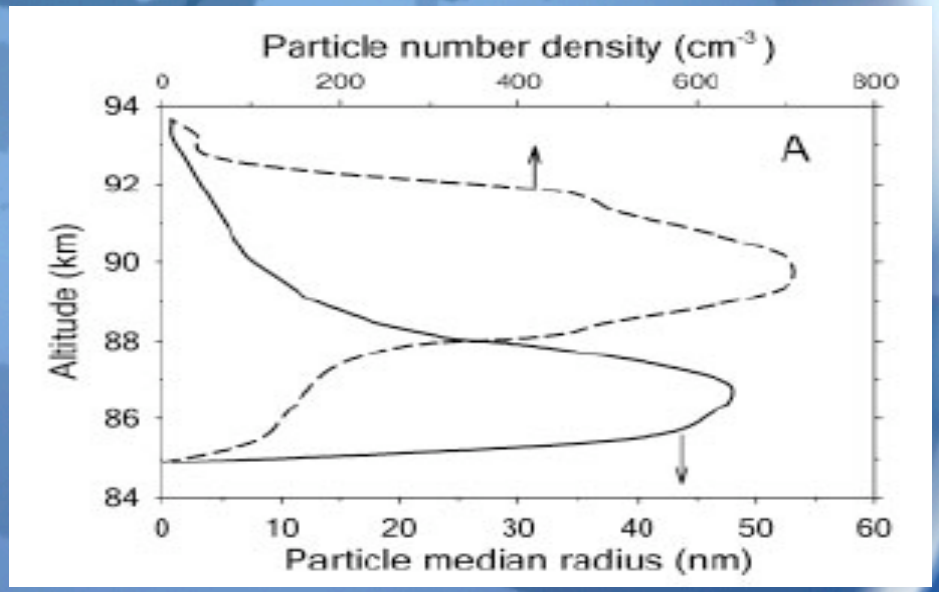

**Complete Fe bite-out occurs in the presence of strong PMC events**
**Competition between uptake of Fe on ice surface and input Fe flux (meteor ablation & vertical transport by eddy diffusion)**

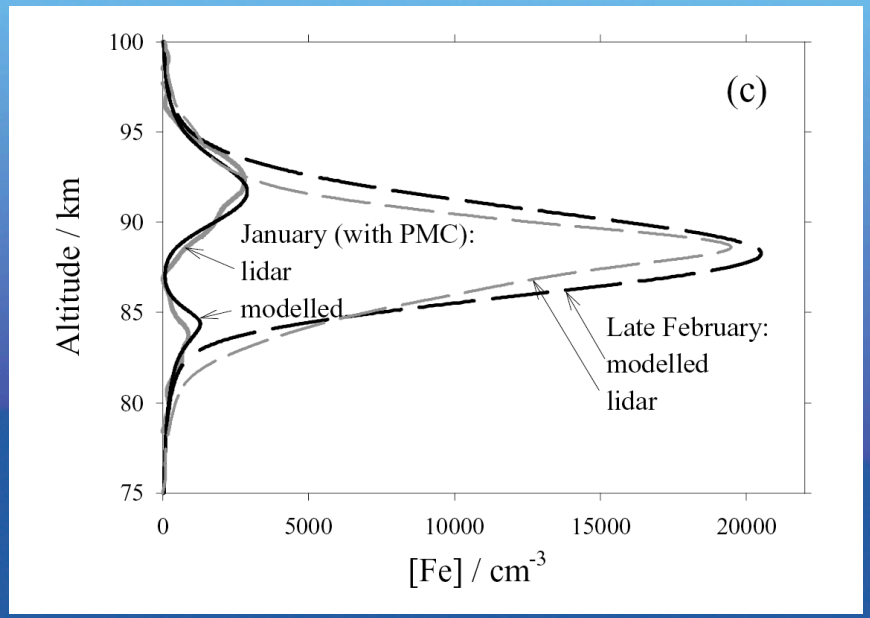
# Modeling Depletion

## Uptake coefficients of Fe on ice = 1



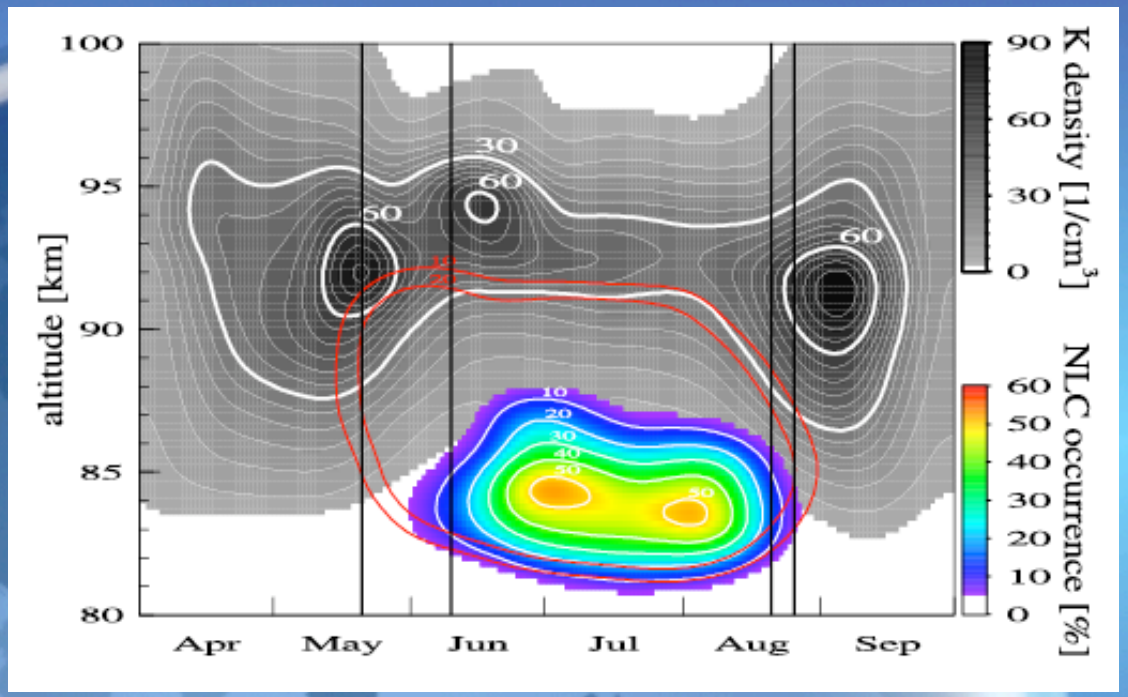



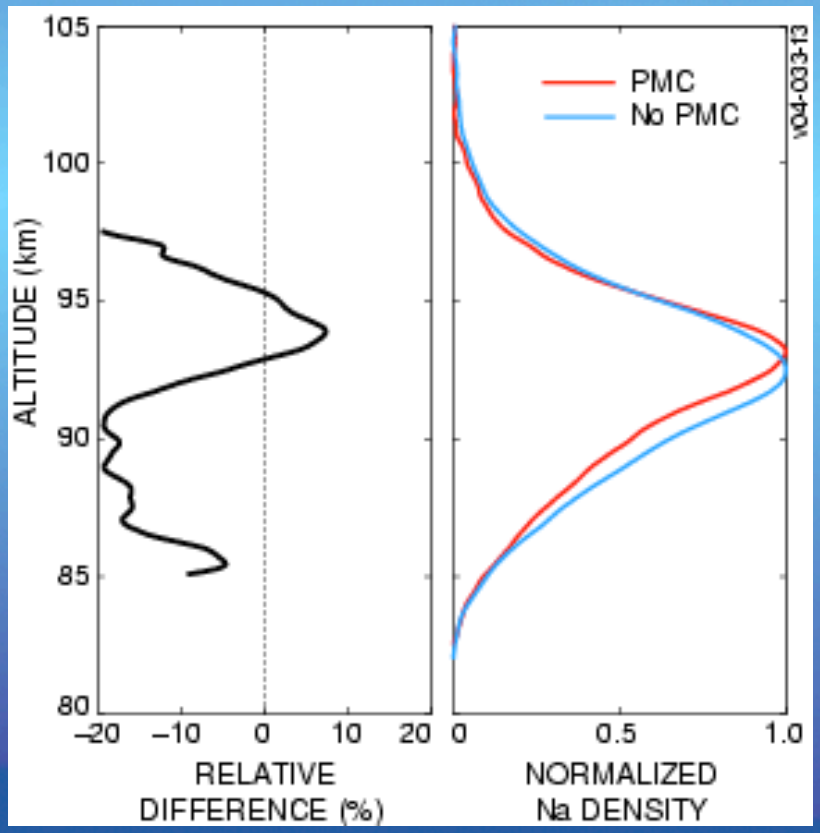




**Plane, Murray, Chu, and Gardner, *Science*, *304*, 426-428, 2004**

# More on Heterogeneous Chemistry

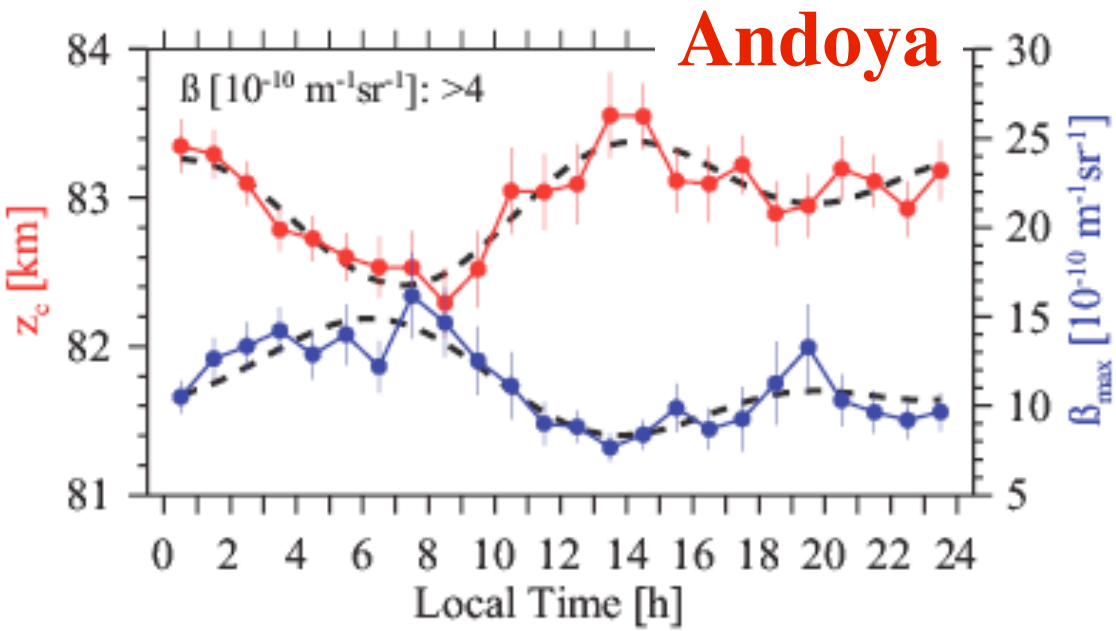


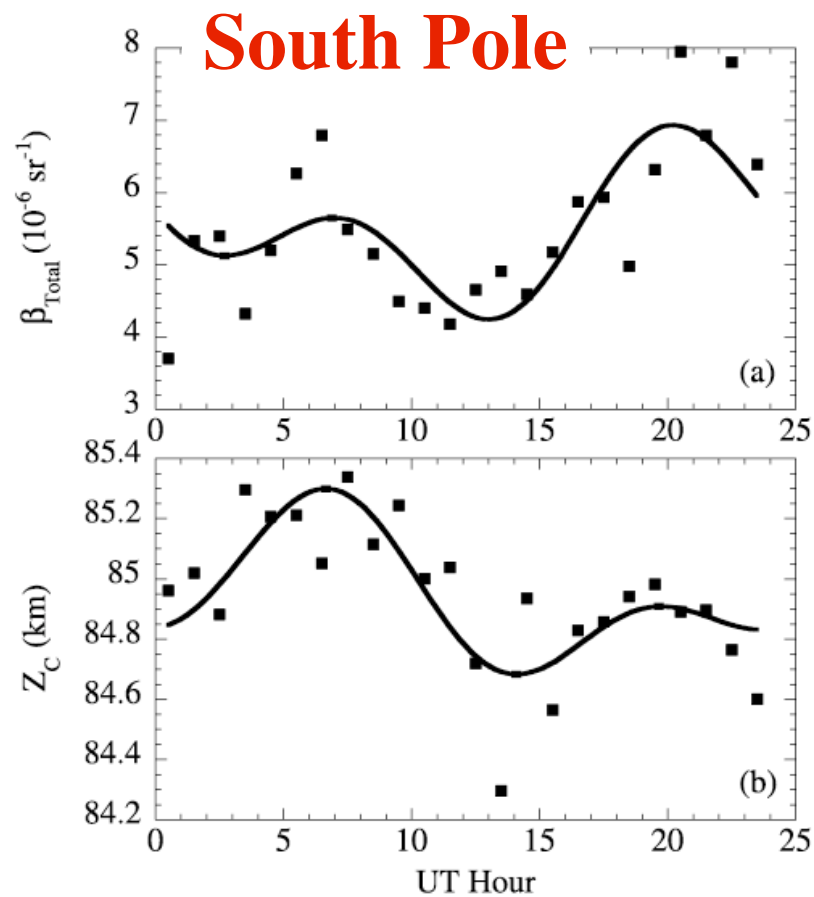

**K Density vs. PMC at Svalbard [Lübken & Höffner, GRL, 2004]**




**Na Density vs. PMC at Greenland [Thayer & Pan, JASTP, 2006]**

# Diurnal Variations at Andoya and SP

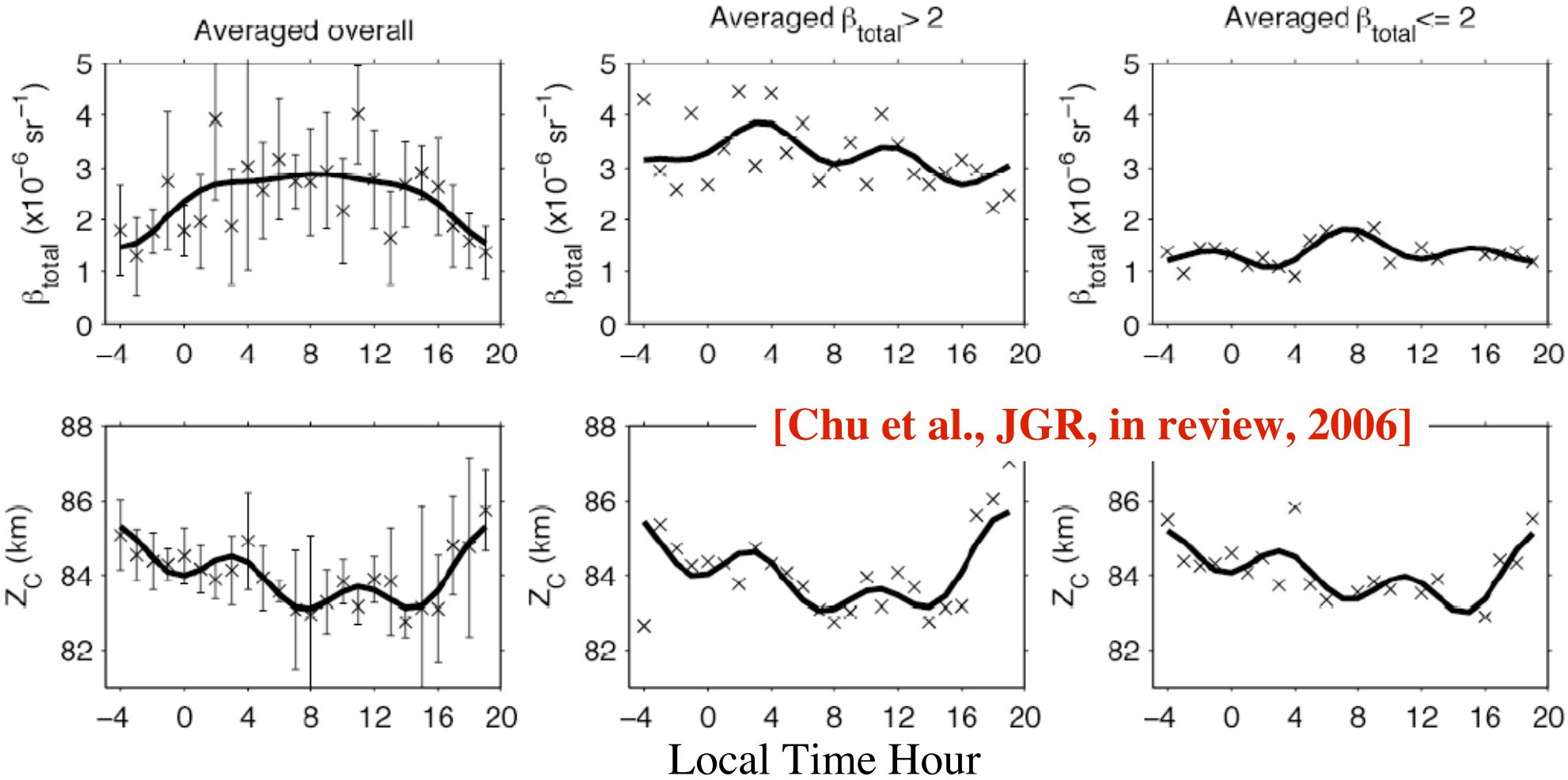



[Fiedler et al., EGU, 2005]
[Chu et al., JGR, 2003]

| | | $A_0$ | $A_{12}$ | $\varphi_{12}$ | $\Delta\varphi_{12}$ | $A_{24}$ | $\varphi_{24}$ | $\Delta\varphi_{24}$ |
|---|---|---|---|---|---|---|---|---|
| ALOMAR | $\beta_{max}$ | 11.2 | 1.5 | 6.71 | 5.32 | 2.3 | 4.92 | 9.96 |
| | $z_c$ | 83.0 | 0.30 | 1.39 | | 0.28 | -5.04 | |
| South Pole | $\beta_{max}$ | 21.4 | 2.2 | -4.41 | 0.57 | 1.9 | -2.71 | 8.28 |
| | $z_c$ | 84.9 | 0.15 | -4.98 | | 0.21 | 5.57 | |

# Diurnal Variations at Rothera




[Chu et al., JGR, in review, 2006]

| Overall | $A_0$ | $A_{24}$ | $A_{12}$ | $A_8$ | $\Phi_{24}$ | $\Phi_{12}$ | $\Phi_8$ | R |
|---|---|---|---|---|---|---|---|---|
| $\beta_{Total}$ | 2.41 | 0.61 | 0.24 | **0.10** | 7.93 | 1.90 | 0.16 | 64.8% |
| $Z_C$ | 83.98 | 0.75 | 0.24 | **0.52** | -2.25 | 7.19 | 3.24 | 88.7% |

# PMC versus Gravity Waves

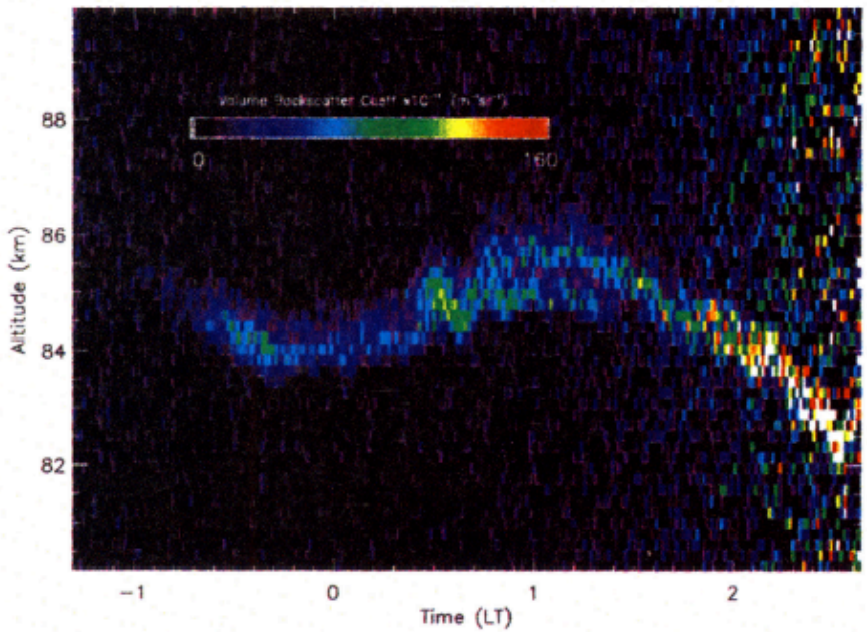



**Figure 1.** Noctilucent Cloud observed by the ARCLITE Rayleigh Lidar in Sondrestrom, Greenland on the night of 8/8/96-8/9/96. At later times, the increasing background noise due to sunrise is demonstrated. Note the apparent wave structure of the cloud, with a period of ~2-3 hours.

**[Gerrard et al., GRL, 1998]**

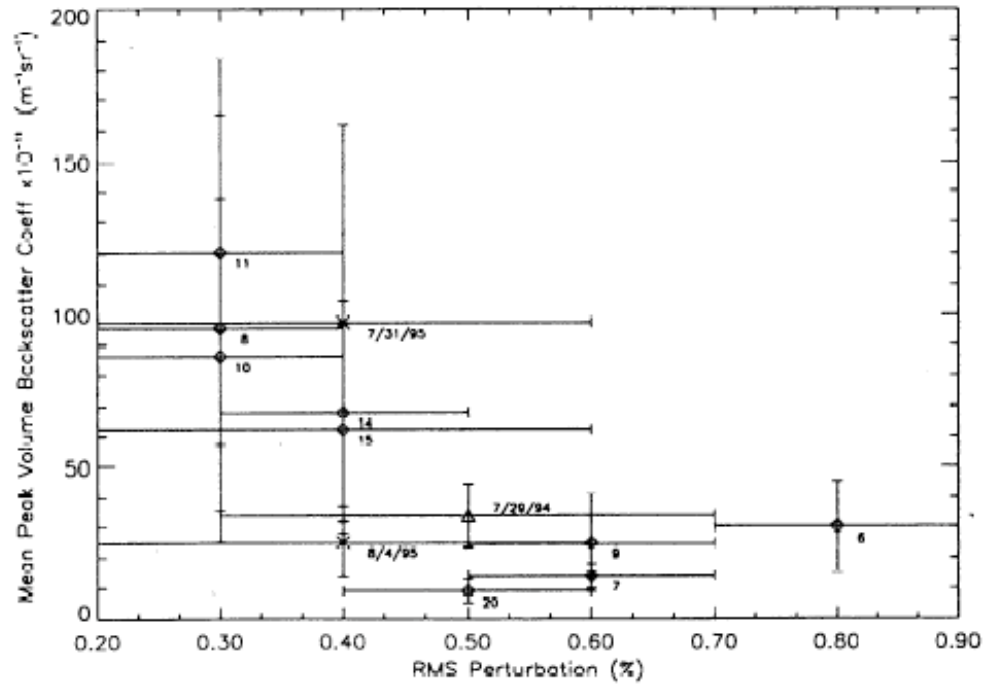
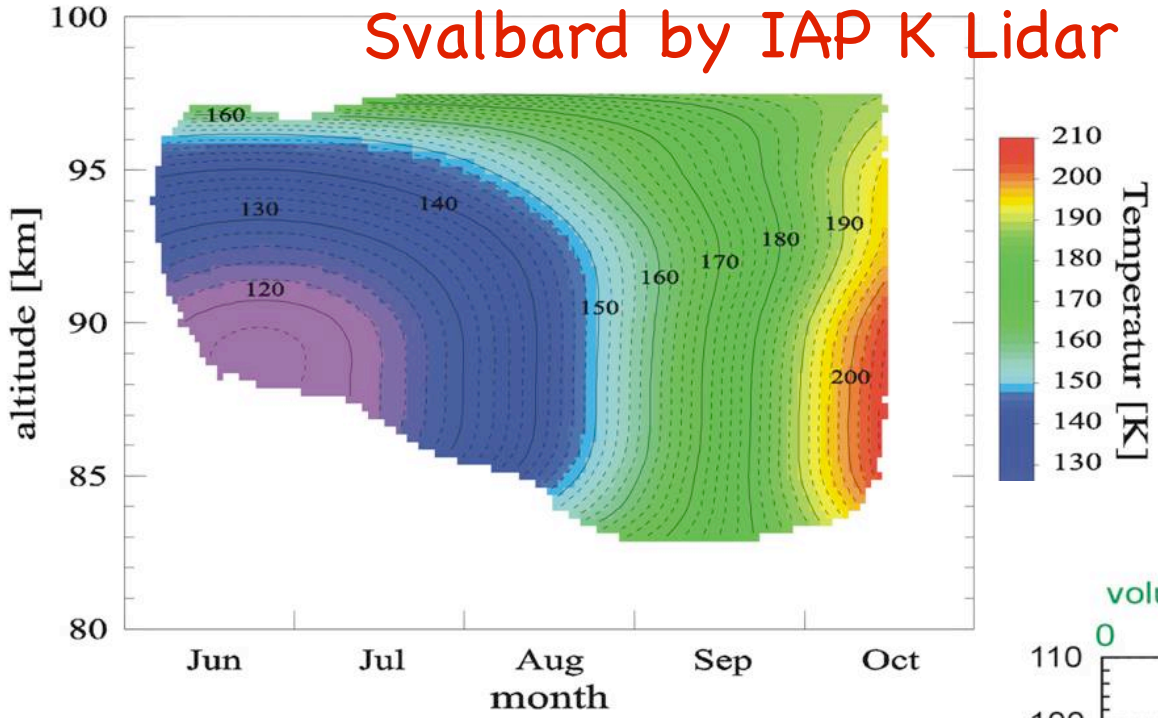


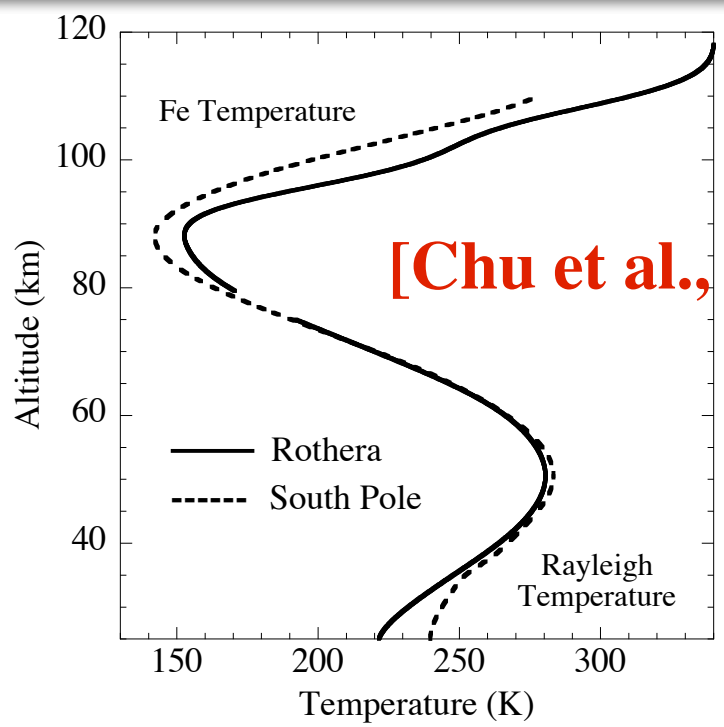

**Figure 3.** Noctilucent Cloud (NLC) backscatter strength vs. RMS stratospheric density perturbation. Backscatter ranges are geophysical variances ($\pm 1\sigma$ from the mean measured throughout the night). The error on the average RMS value includes shot noise error and geophysical variability. Numbers next to points represent the day in August 1996, unless otherwise denoted.

**Strength of Stratospheric Gravity Waves and Brightness of PMC are Negatively Correlated**

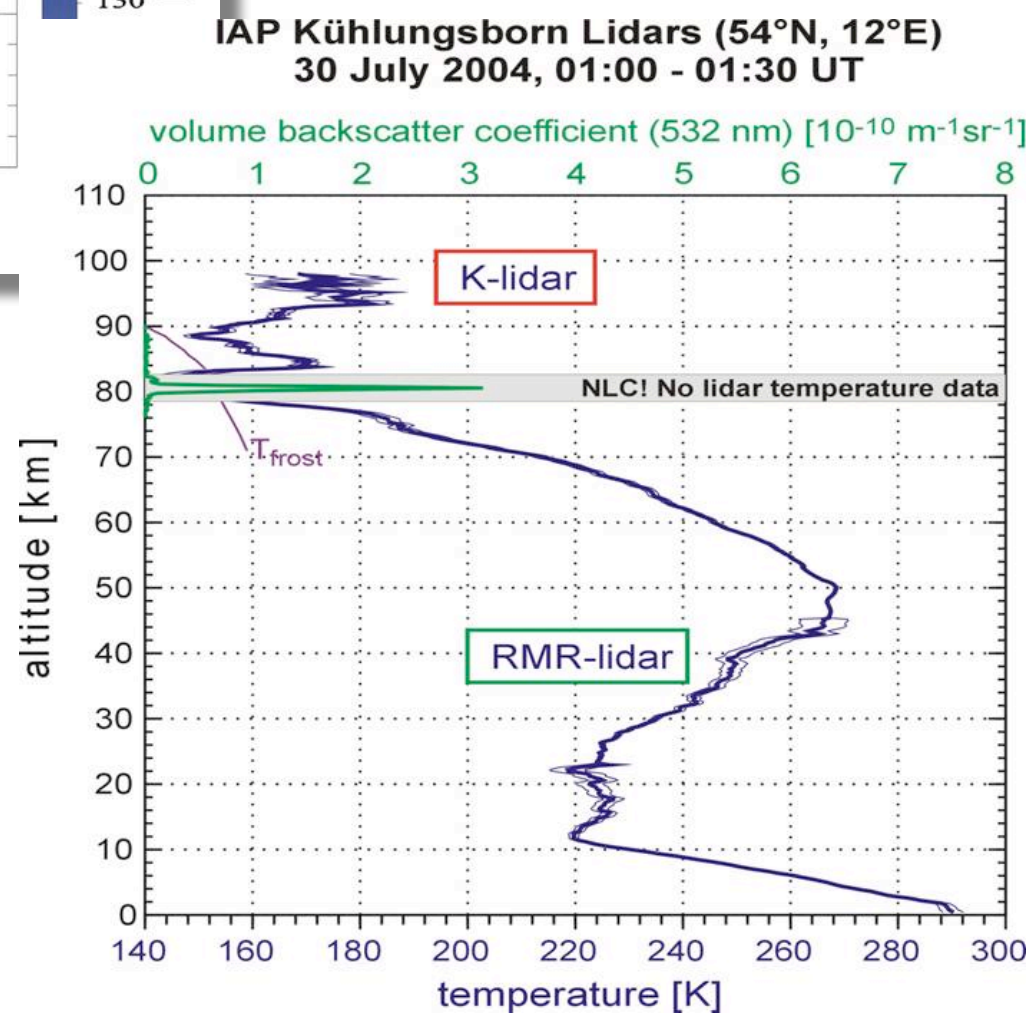
# PMC versus Temperature

[Höffner et al., ILRC, 2006]



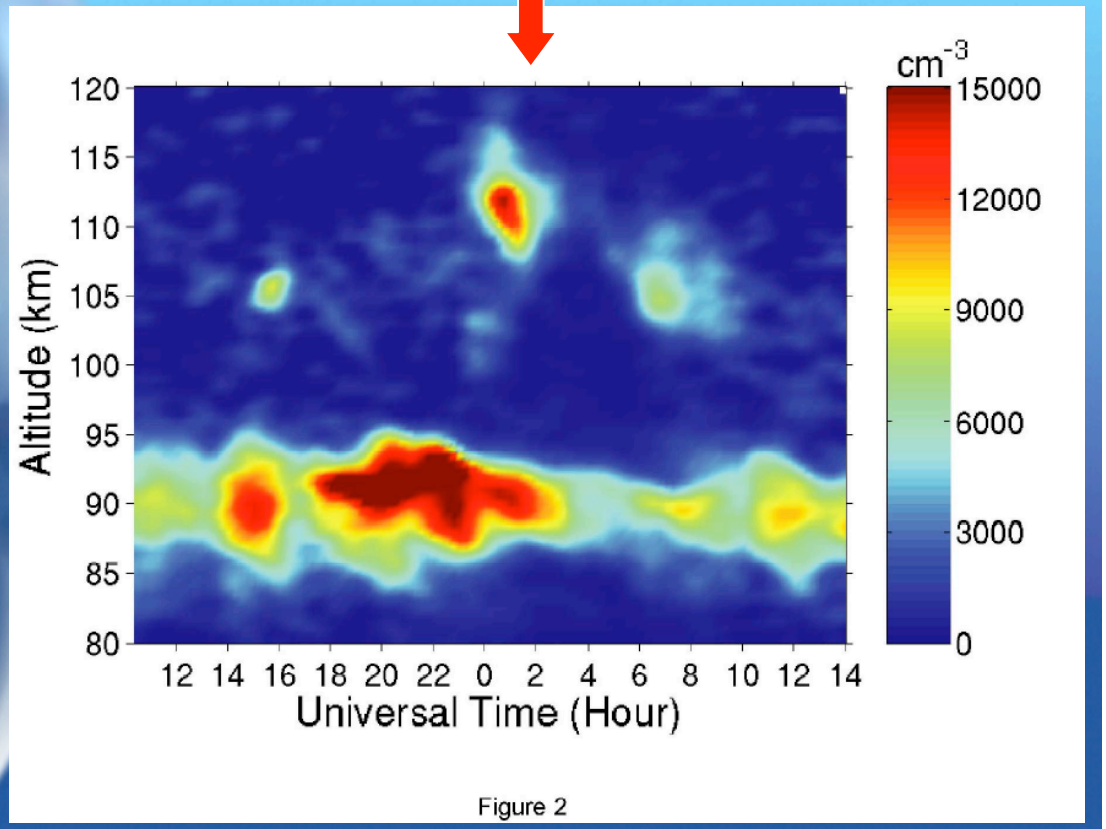

[Chu et al., 2004]

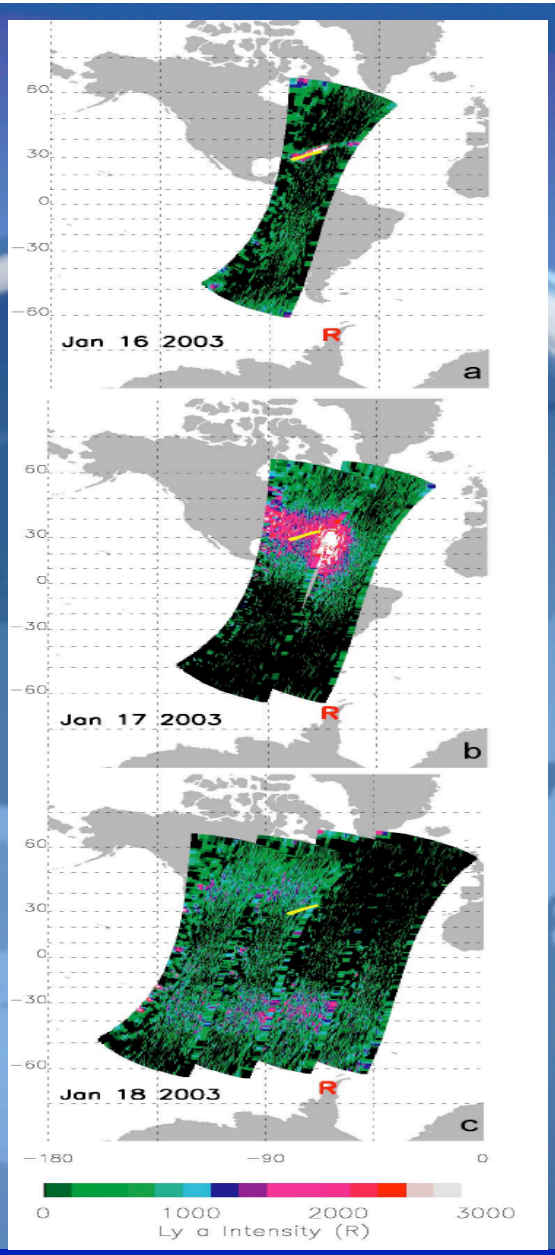


# Shuttle Formed PMC in Antarctica

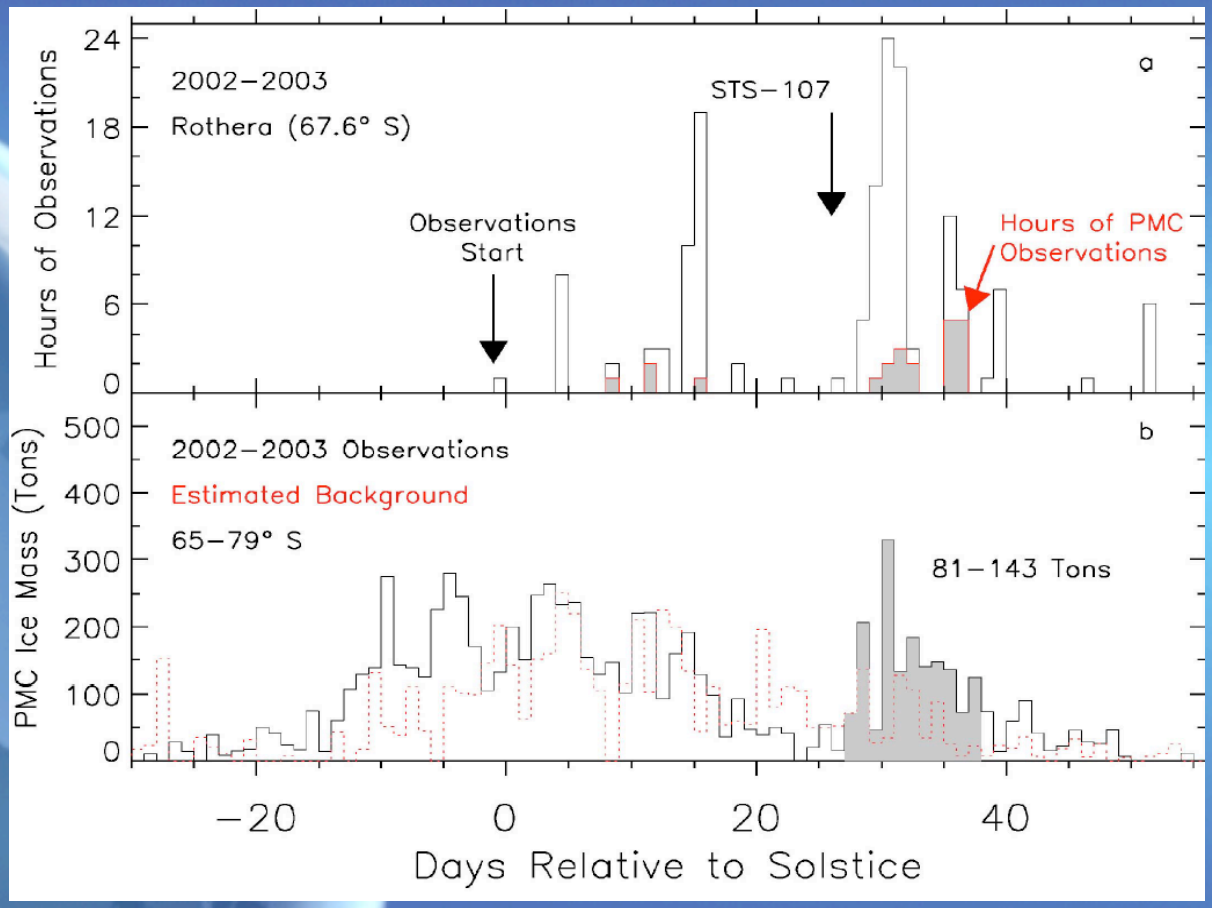
Columbia Space Shuttle Was Launched on January 16, 2003 from Kennedy Center.

3 Days Later (Jan. 19-20, 2003) High-Altitude Sporadic Fe Layers were Observed at Rothera by Fe Lidar






## Lyman α Images from GUVI / TIMED




**[Stevens et al., GRL, 2005]**

**The evidence for an important contribution of PMC by shuttle traffic calls into question of any interpretation of late 20th century PMC trends solely in terms of global climate change.**

# Milestones in Lidar Study of PMC

| Milestones | Authors, Journal, Year |
|---|---|
| First PMC observations by lidar in NH | ***Hansen et al.,*** GRL, 16, 1445-1448, **1989** |
| Ice crystal and temperature associated with PMC | ***Thomas et al.,*** GRL, 21, 385-388, **1994** |
| First common volume observation of PMC/PMSE | ***Nussbaumer et al.,*** JGR, 101, 19161-19167, **1996** |
| Diurnal variations of PMC altitude and brightness | ***von Zahn et al.,*** GRL, 25, 1289-1292, **1998** |
| Gravity wave influence on PMC | **Gerrard et al.,** GRL, 25, 2817-2820, **1998** |
| Particle size and number density measurement using multicolor lidar | ***von Cossart et al.,*** GRL, 26, 1513-1516, **1999** |
| First PMC observations by lidar in SH, Hemispheric difference in PMC altitude | ***Chu et al.,*** GRL, 28, 1203-1206, **2001** |
| Diurnal variations of PMC at the South Pole | ***Chu et al.,*** GRL, 28, 1937-1940, **2001** |
| Particle shape study using polarization lidar tech | ***Baumgarten et al.,*** GRL, 29, 1630, **2002** |
| Hemispheric difference study with model | ***Chu et al.,*** JGR, 108, 8447, **2003** |
| Latitudinal dependence of PMC altitude | ***Chu et al.,*** GRL, 31, L02114, **2004** |
| Heterogeneous removal of metal atoms by PMC ice particles in the mesopause region | ***Plane et al.,*** Science, 304, 426-428, **2004** |
| Space shuttle formed PMC in Antarctica | ***Stevens et al.,*** GRL, 32, L13810, **2005** |

Of course, biased point of view!

# Conclusions

- Lidar observations have made significant contributions to PMC study in four main categories: physical characteristics, microphysical properties, PMC in heterogeneous chemistry, and PMC relations to atmospheric conditions and dynamics.

- Key results include, e.g., hemispheric difference in PMC altitude, heterogeneous removal of metal atoms by PMC ice particles, particle size distribution, non-spherical particle shape, PMC diurnal, seasonal and interannual variations, etc.

- More lidar observations of PMC are needed in areas of PMC microphysics, heterogeneous chemistry, more latitudinal coverage, & PMC response to atmosphere conditions/dynamics.

- Coordinating ground-based or airborne lidars with AIM satellite mission will benefit the PMC study. McMurdo station in Antarctica and several Arctic stations are good choices.