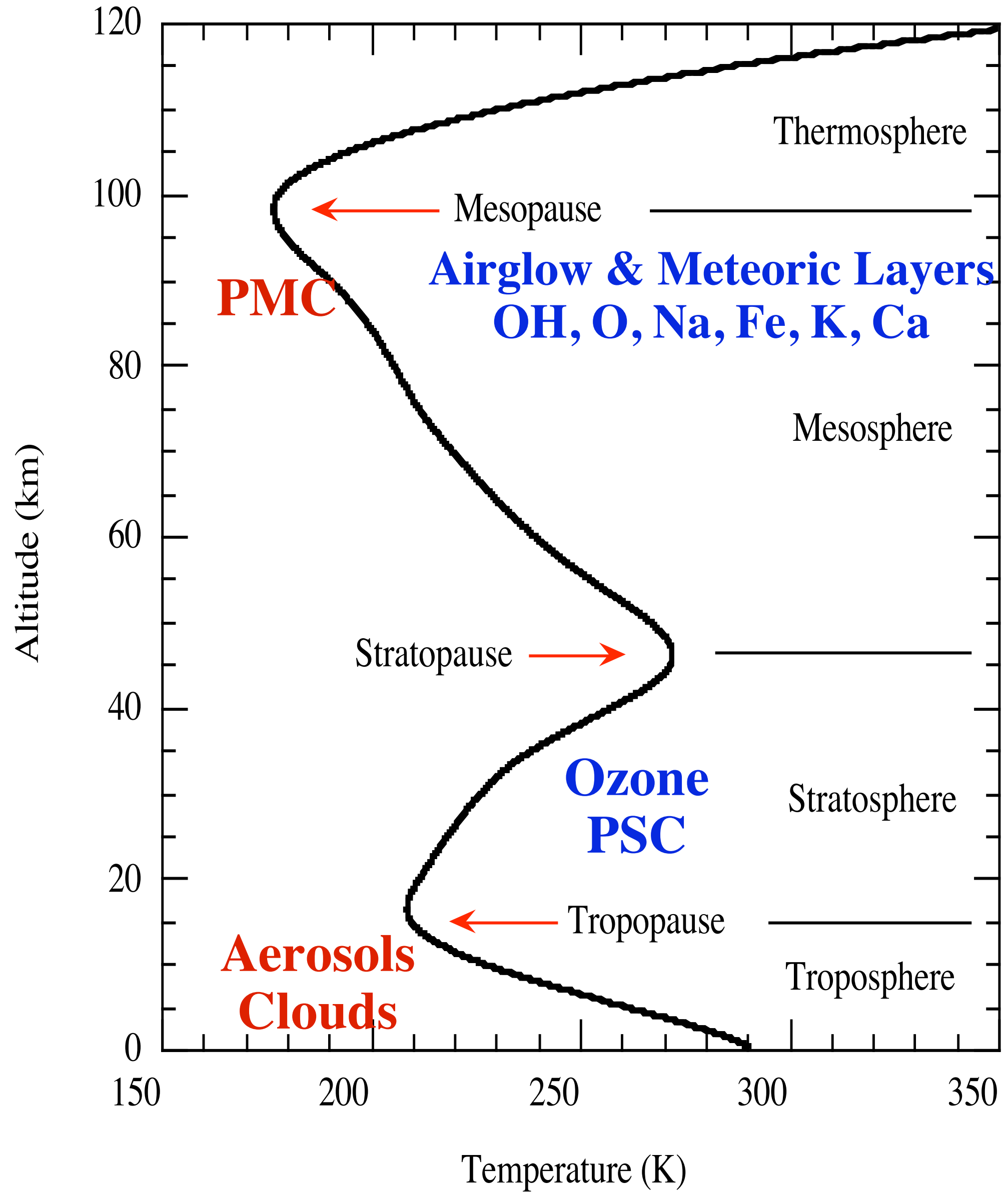
Lecture 25. Aerosol Lidar (1)
Overview & Polar Mesospheric Clouds

- ☐ Motivations to study aerosols and clouds
- ☐ Lidar detection of aerosols and clouds
- ☐ Polar mesospheric clouds (PMC) detection by lidar
- ☐ PMC physical properties
- ☐ PMC chemistry role in upper atmosphere
- ☐ PMC relation to atmospheric dynamics
- ☐ PMC microphysical properties detected by multi-wavelength and polarization lidar
- ☐ Summary

Motivations to Study Aerosols

- Atmospheric aerosols play an important role in many atmospheric processes. Although only a minor constituent of the atmosphere, they have appreciable influence on the Earth's radiation budget, air quality and visibility, clouds, precipitation, and chemical processes in the troposphere and stratosphere.
- The occurrence, residence time, physical properties, chemical composition, and corresponding complex-refractive-index characteristics of the particles , as well as the resulting climate-relevant optical properties are subject to large diversity especially in the troposphere because of widely different sources and meteorological processes.
- Therefore, vertically resolved measurements of physical and optical properties of particles such as the particle surface-area concentration, volume and mass concentrations, mean particle size, and the volume extinction coefficient are of great interest.
- Routine (long-term), range-resolved observations of these parameters can only be carried out with lidar.

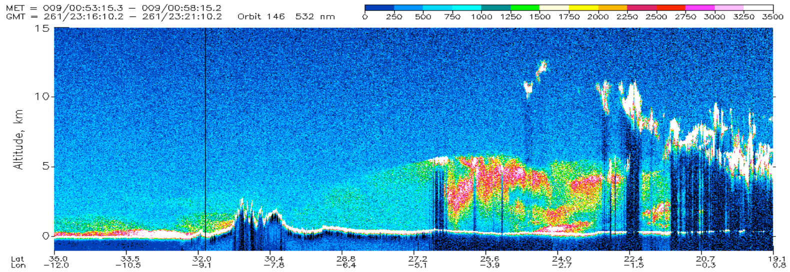
Aerosols and Clouds in Atmosphere



Polar mesospheric clouds (PMC) usually occur in polar summer

Polar stratospheric clouds (PSC) occur in polar winter and spring

Aerosols always present in troposphere with highly variable concentration and composition due to natural and anthropogenic sources



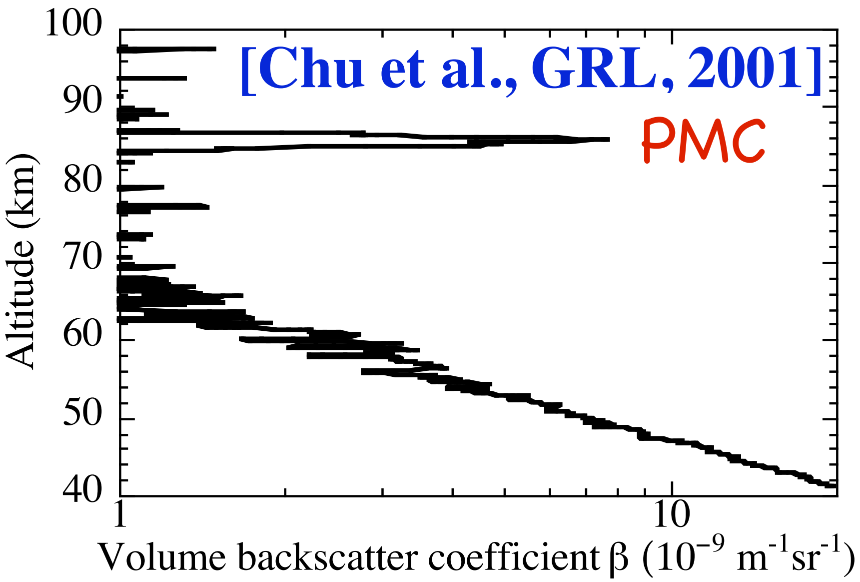
Nucleation mode: $r < 0.1\ \mu m$
accumulation mode: $0.1 < r < 1\ \mu m$,
coarse mode: $r > 1\ \mu m$

More Motivations

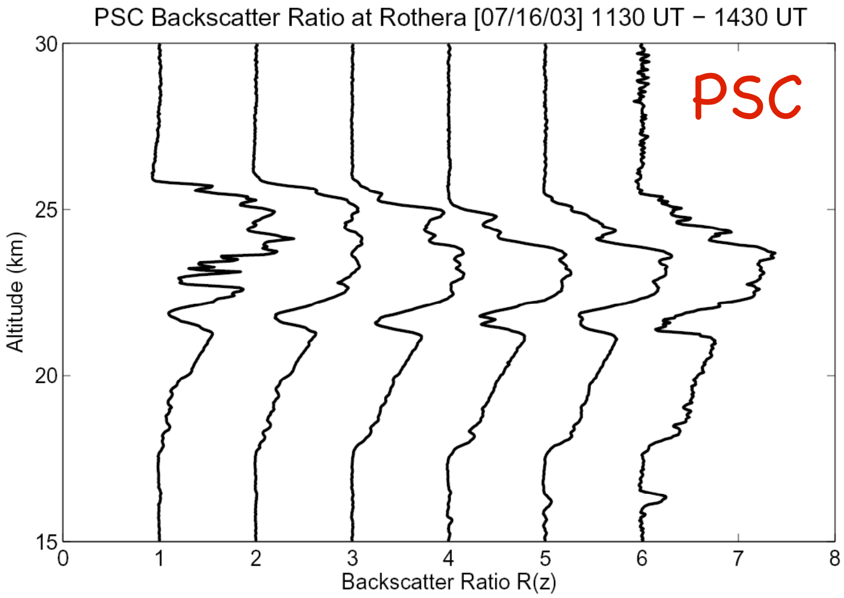
- Aerosol Properties – optical, microphysical, and chemical
- Cloud Properties – optical, microphysical, radiative for ice, water and mixed phase
- Aerosol-Cloud Interactions – aerosols act to seed clouds
- Air Quality and Pollutant Transport – Study long range transport, anthropogenic vs. natural sources, gas/aerosol interactions
- Direct and Indirect Aerosol Radiative Forcing – to improve models
- Surface and Atmospheric Radiative effects
- Clouds – Radiation Dynamical Feedback Processes
- Properties of Mixed Phase Clouds
- Polar Stratospheric Clouds – distribution, properties and lifecycle versus ozone depletion
- Polar Mesospheric Clouds - indication of global climate change
- Aerosol influence is one of the major uncertainties in atmospheric models that are used to predict global climate change.
- All aerosols and clouds are also good tracers of atmosphere environment, so excellent natural indicator or laboratory.

Lidar Detection of Aerosols/Clouds

- Aerosols and clouds are shown as distinct peaks above the Rayleigh scattering background in range-resolved lidar profiles.
- The common way to detect aerosols and clouds is to use elastic scattering lidar with Rayleigh and Mie scattering detection capability.
- Virtually this can be done by any lidars that receive scattering signals, including resonance fluorescence, DIAL, Raman, Rayleigh, & Mie.



Polar mesospheric clouds
Noctilucent clouds



Polar stratospheric clouds

Lidar Detection of Aerosols/Clouds

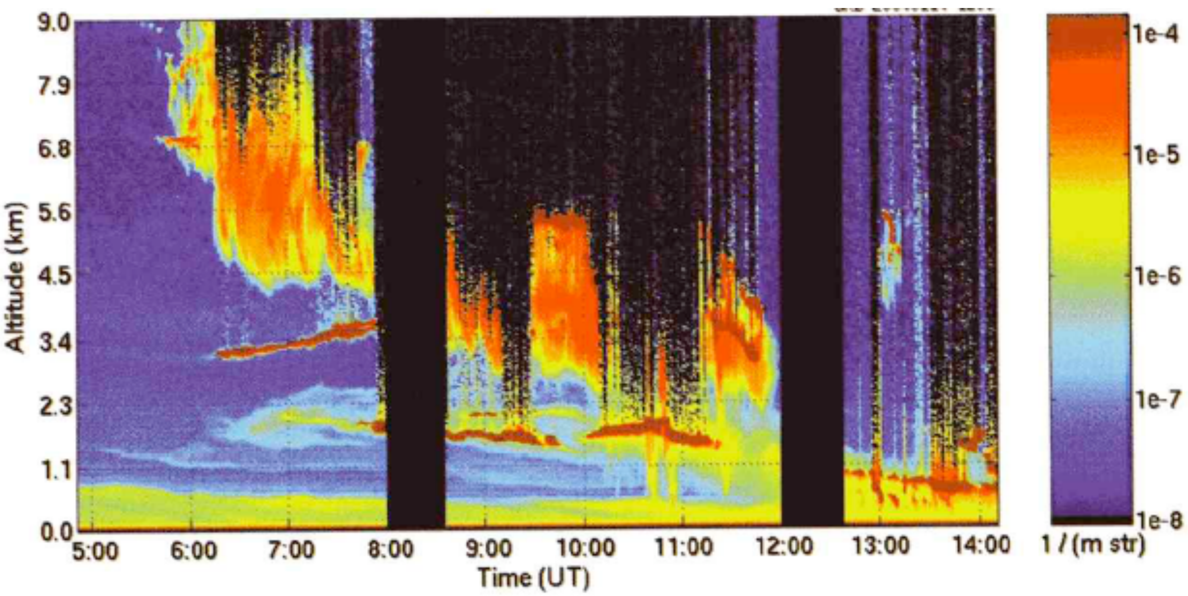
- The challenges of lidar detection of aerosols and clouds include:

(1) In lower atmosphere, the challenge is how to derive aerosol extinction when the aerosol layers are dense, i.e., to obtain extinction-corrected aerosol profiles.

(2) In middle and upper atmosphere, the challenge is how to distinguish the weak signals from Rayleigh and solar background.

(3) How to derive microphysical properties and chemical compositions for aerosols in lower, middle and upper atmosphere?

(4) …



Aerosol Backscatter Coefficient ($m^{-1}sr^{-1}$) by Univ. Wisconsin HSRL

Aerosol Properties vs Lidar Detection

❑ Physical Properties: Occurrence, Height, Residence Time, Vertical structure.

- for any scattering lidar

❑ Optical Properties: light backscatter, absorption, extinction, or albedo, complex-refraction-index

- single-channel lidar versus multi-channel lidar

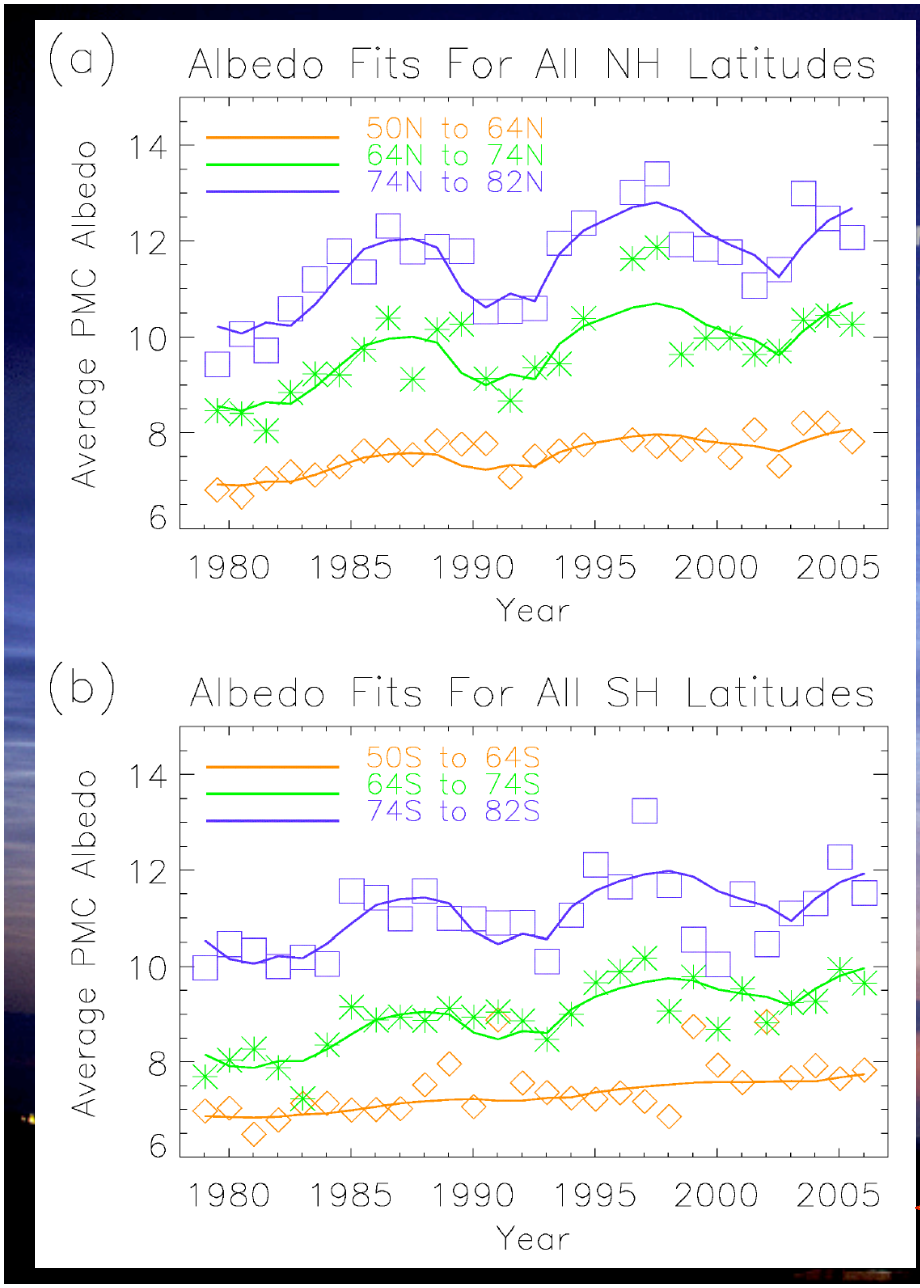
❑ Microphysical Properties: particle size, particle shape, number density, mass density, size distribution

- multi-wavelength lidar and
- polarization detection lidar

❑ Chemical Composition and Process in the Atmosphere

- laser-induced-breakdown with spectroscopic lidar

PMC: Early Indication of Climate Change



- **Polar mesospheric clouds (PMC), also noctilucent clouds (NLC), are thin scattering layers of nanometer-sized water ice particles, occurring ~ 80-87 km in the high-latitude summer mesopause region.**
- **PMC (water ice particles) are very sensitive to the change of temperature and water vapor in mesopause region.**
- **Increasing concentrations of green-house gases CO_2 and CH_4 cool the temperature but elevate water vapor in the middle atmosphere - favorable conditions for PMC formation.**
- **Increasing PMC brightness or frequency may provide an early indication of long-term climate change in the middle and upper atmosphere.**

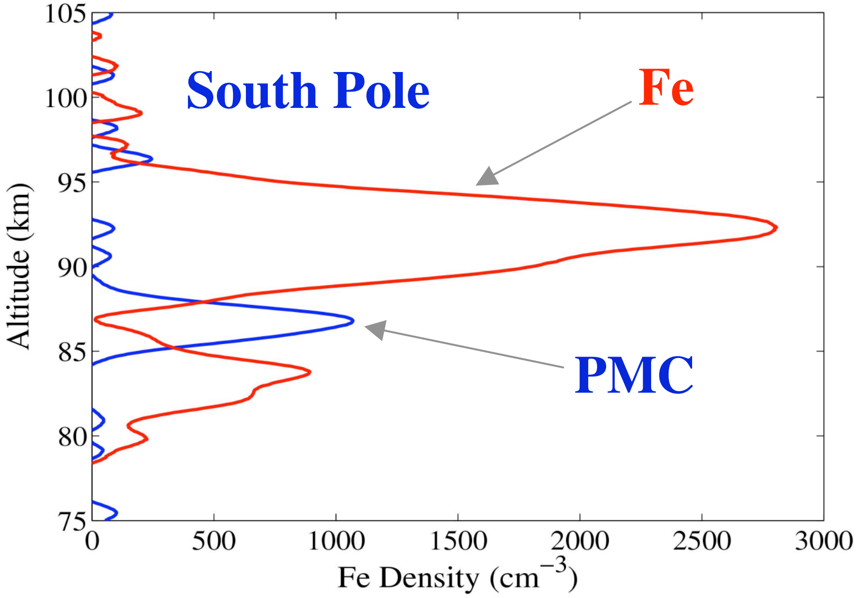
[DeLand, Shettle, Thomas, and Olivero,
***submitted to JGR*, 2006]**

PMC: Role in Chemistry & Dynamics

- PMC provide a natural laboratory for study of the polar summer mesopause region, as (1) they are very sensitive to changes of mesospheric temperature, water vapor, and vertical wind, (2) they are strongly influenced by gravity waves, tides, and planetary waves, etc.

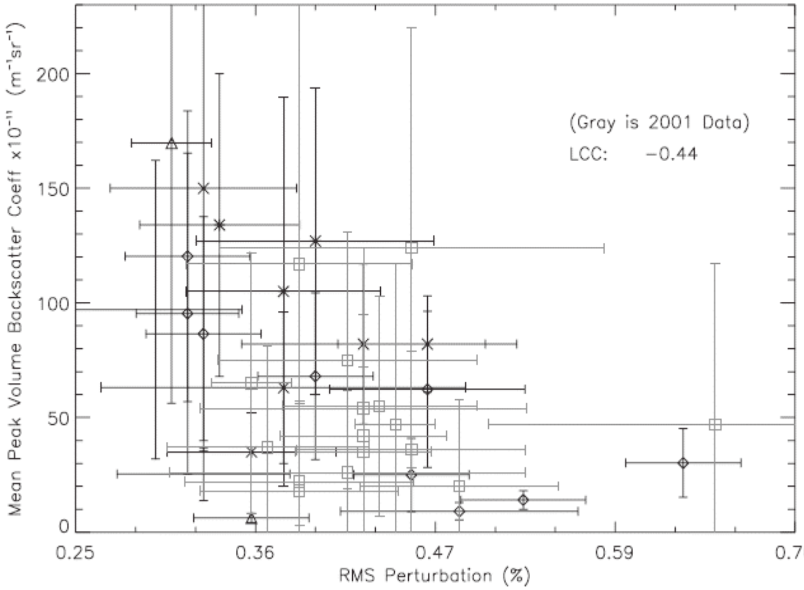
Courtesy of Pekka Parviainen

Heterogeneous Chemistry with PMC



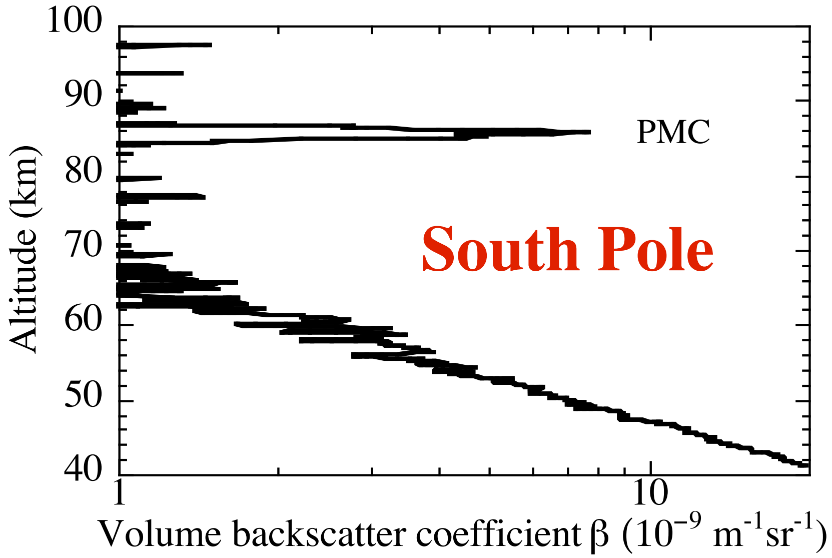
[Plane, Murray, Chu, Gardner, *Science*, 2004]

Gravity Wave Effect with PMC

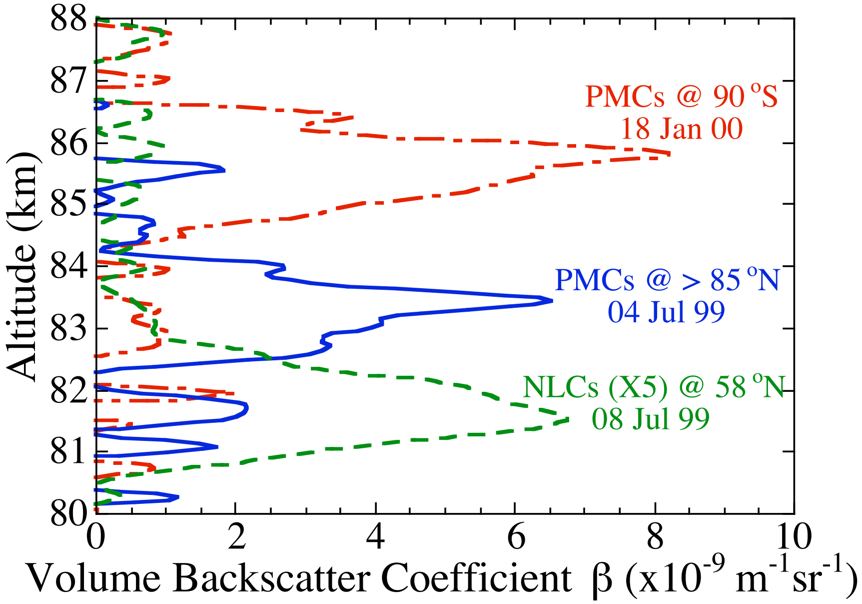


[Gerrard, Kane, Thayer, *GRL*, 1998]

Lidar Detection of PMC



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



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

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

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

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

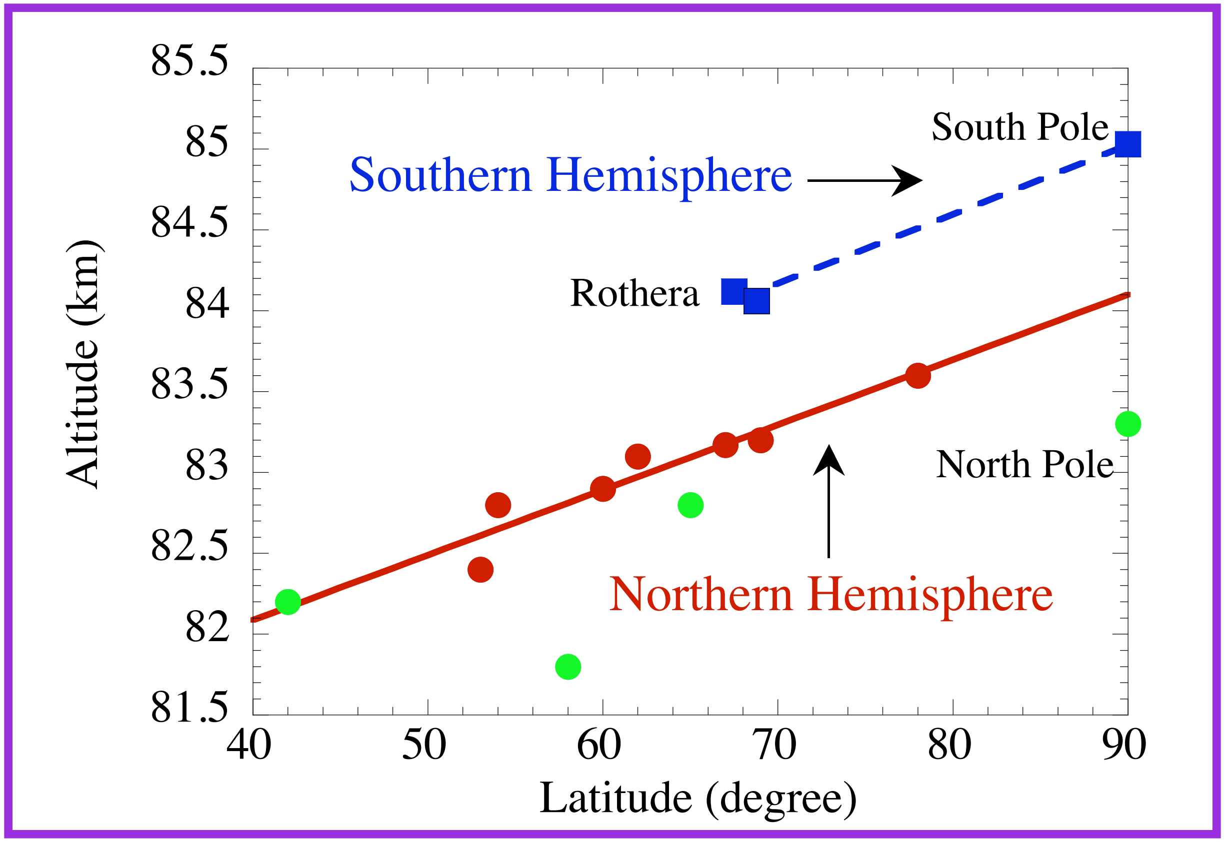
$$\sigma_{rms} = \sqrt{\frac{\sum_i \left(z_i - Z_C\right)^2 \beta(z_i)}{\sum_i \beta(z_i)}}$$

PMC Physical Properties

	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)
β_{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)
σ_{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. 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)

Southern Hemisphere PMC are Higher (Centroid Altitude), Dimmer (Brightness), and Less Frequent (Occurrence Frequency) than Corresponding Northern Hemisphere PMC

PMC Altitude: Hemispheric Difference and Latitudinal Dependence



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

[Chu et al., GRL, 2001, 2004; Chu et al., JGR, 2003, 2006]

Causes for Hemispheric Difference

Hemispheric difference (6%) in solar flux (caused by Earth's orbital eccentricity) may be responsible for the observed hemispheric differences [Chu, Gardner, Roble, *JGR*, 2003]

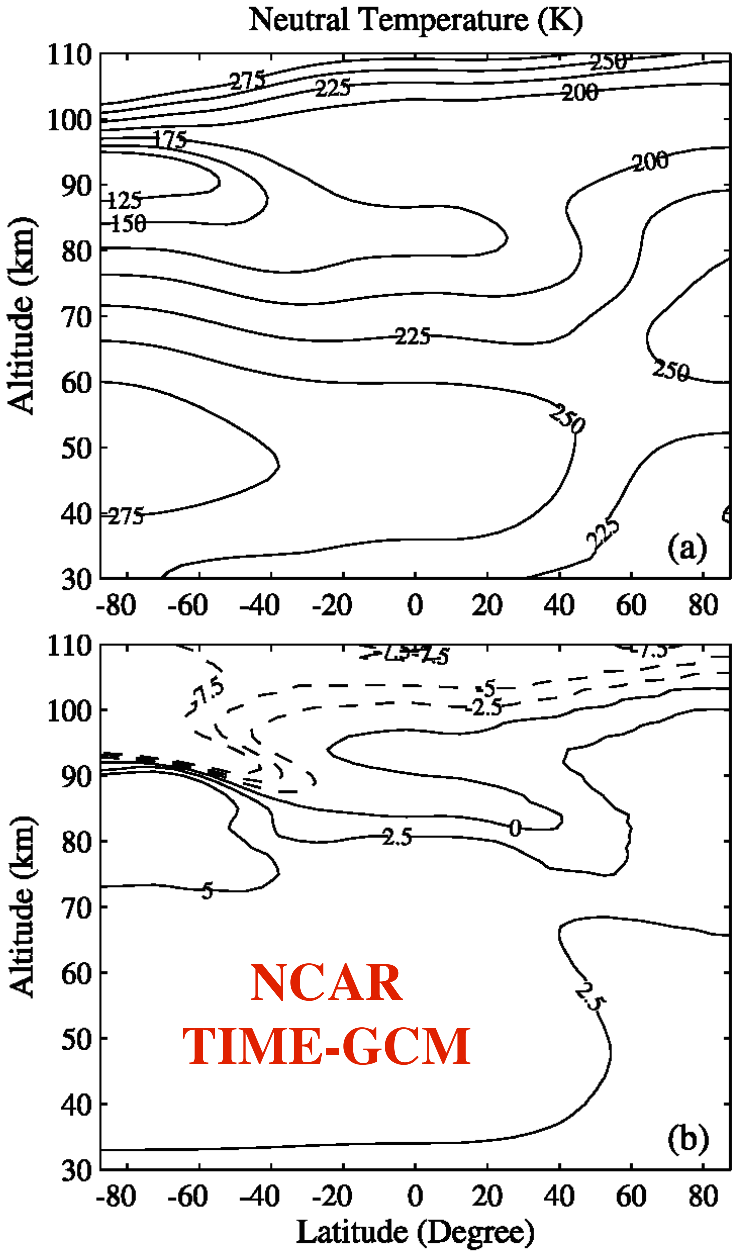
Modeling experiment with TIME-GCM: two identical runs except one run with solar flux increased by 3% and another decreased 3%

⇩

Results show that for the case with 6% more solar flux, the mesopause altitude moved upward by ~1 km and cooled by ~5 K.

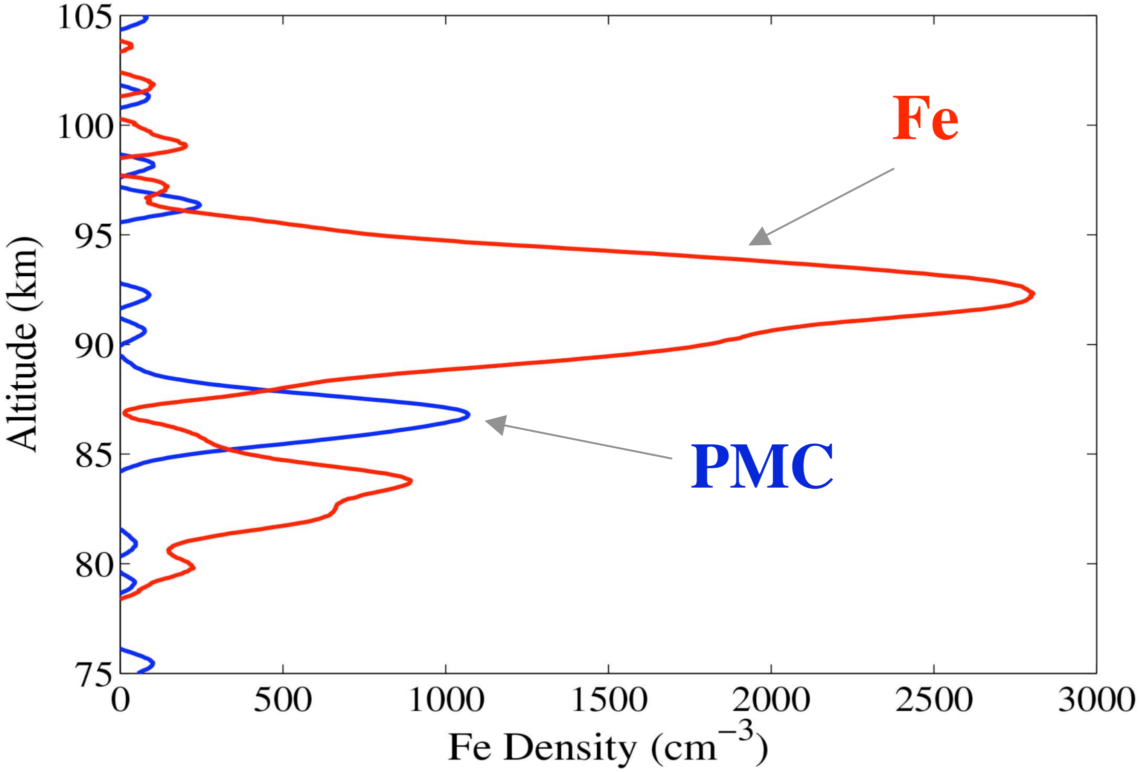
Recent LIMA + PMC models ⇨ only 3-5 K difference is needed to result in ~1 km difference in PMC altitude

Finally Data Spoke! -- John Plane



NCAR TIME-GCM

PMC Chemistry Role: Heterogeneous Removal of Metal Atoms by PMC



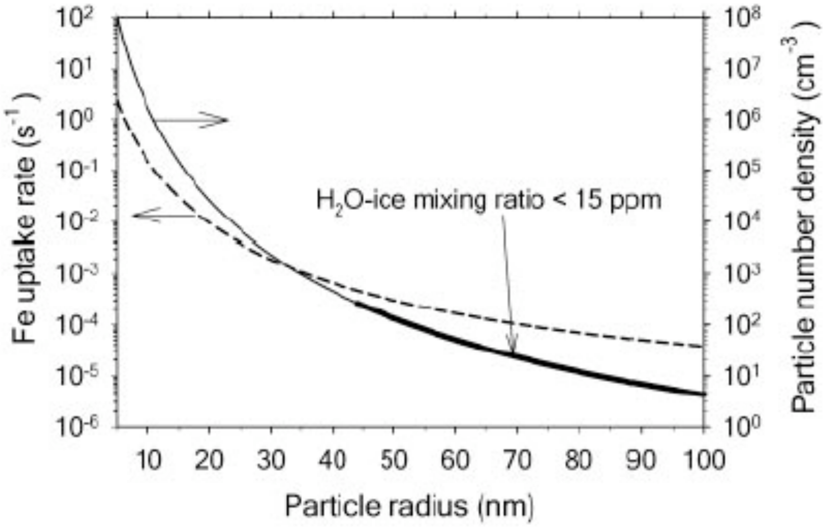
Plane, Murray, Chu, and Gardner, *Science, 304*, 426-428, 2004

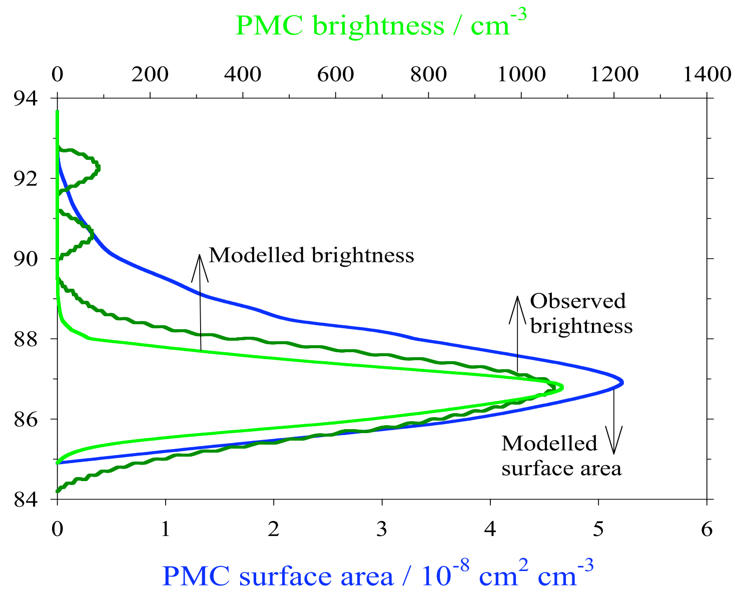
Fe ablation flux = 1.1 x 10^4 atoms cm^{-2} s^{-1}

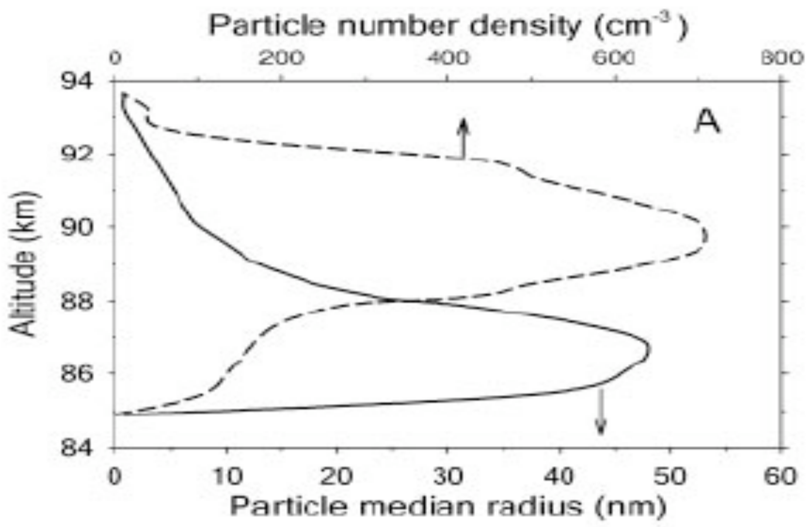
Uptake coefficients of Fe and Fe species on ice = 1

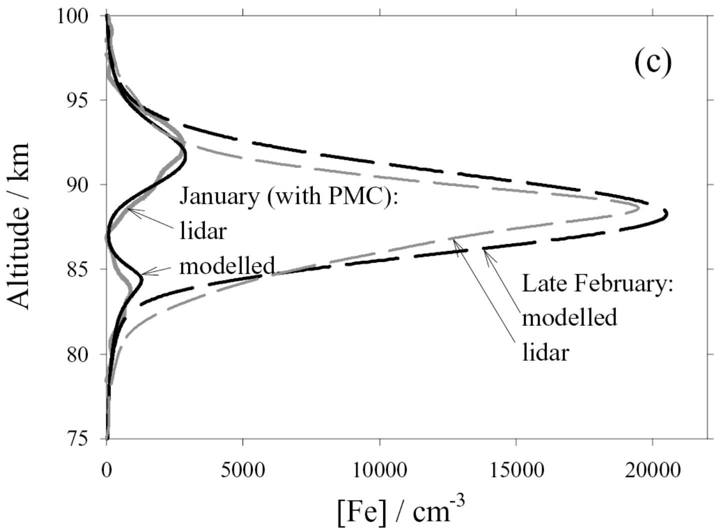
Modeling Depletion

Uptake coefficients of Fe on ice = 1



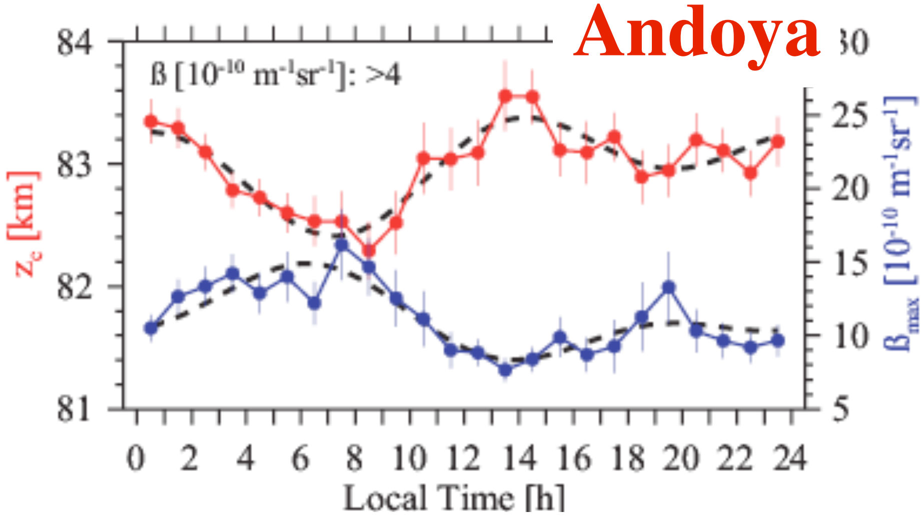


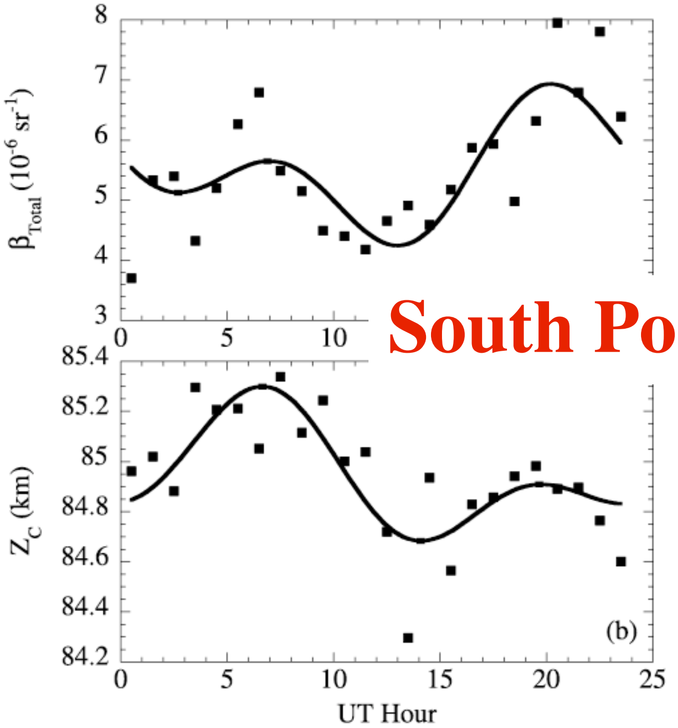


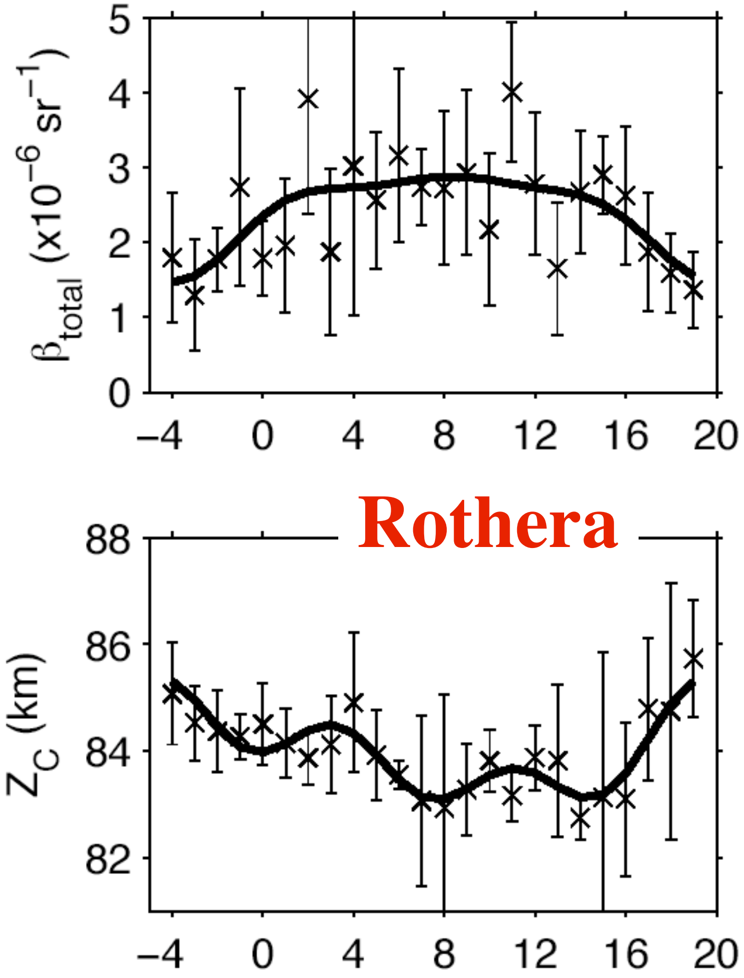


Plane, Murray, Chu, and Gardner, *Science*, *304*, 426-428, 2004

PMC vs. Dynamics: Tidal Variations


Andoya

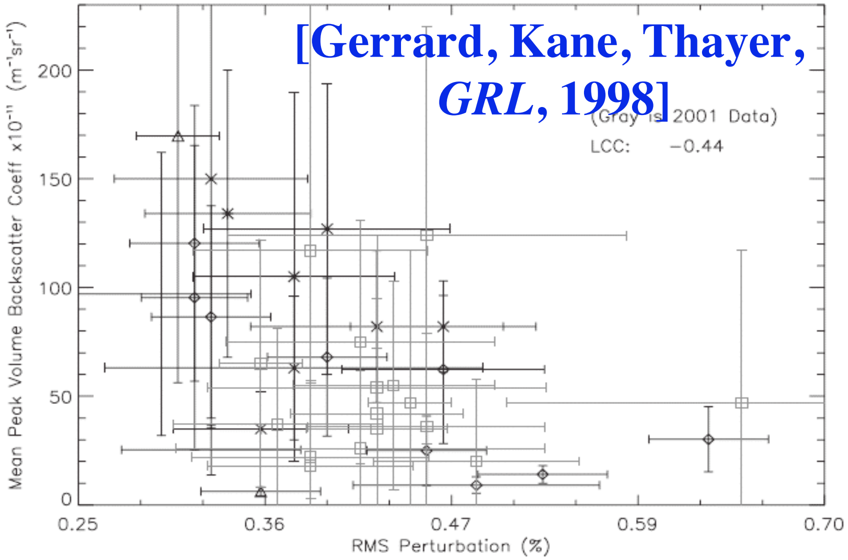

South Pole


Rothera

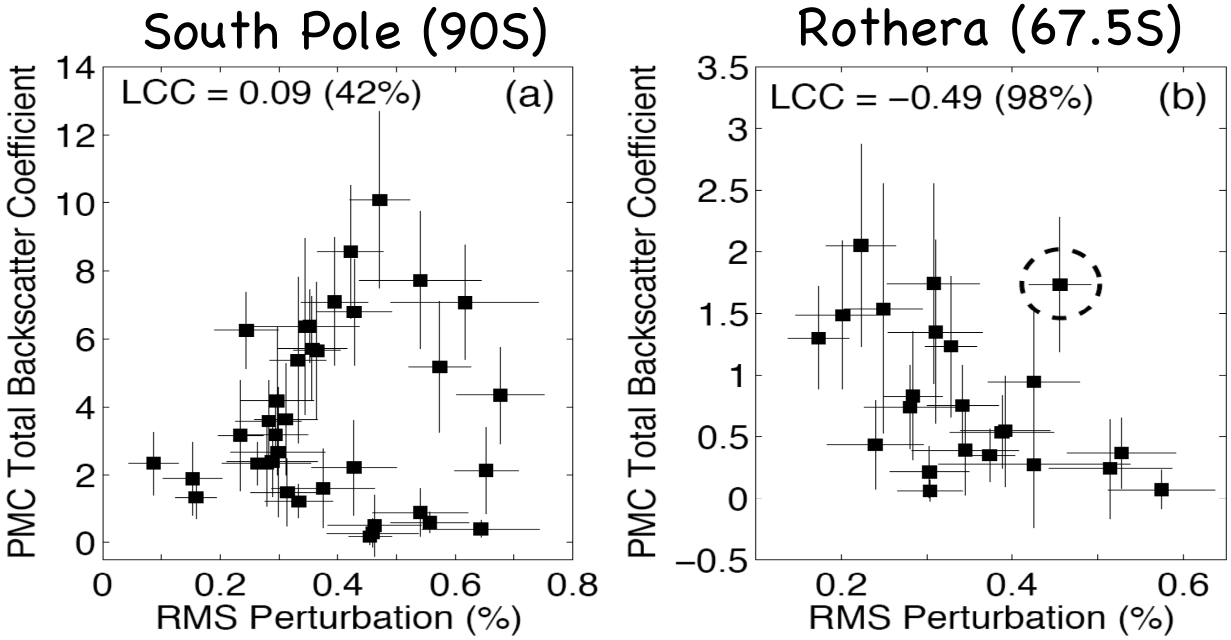
[Fiedler et al., EGU, 2005]
[Chu et al., JGR, 2003, 2006]

PMC vs Dynamics: Gravity Waves

- Gerrard et al. [1998, 2004] found the negative correlation between PMC and stratospheric gravity waves at Sondrestrom, Greenland.
- Our recent study shows the PMC brightness responses to gravity waves differently at different latitudes.

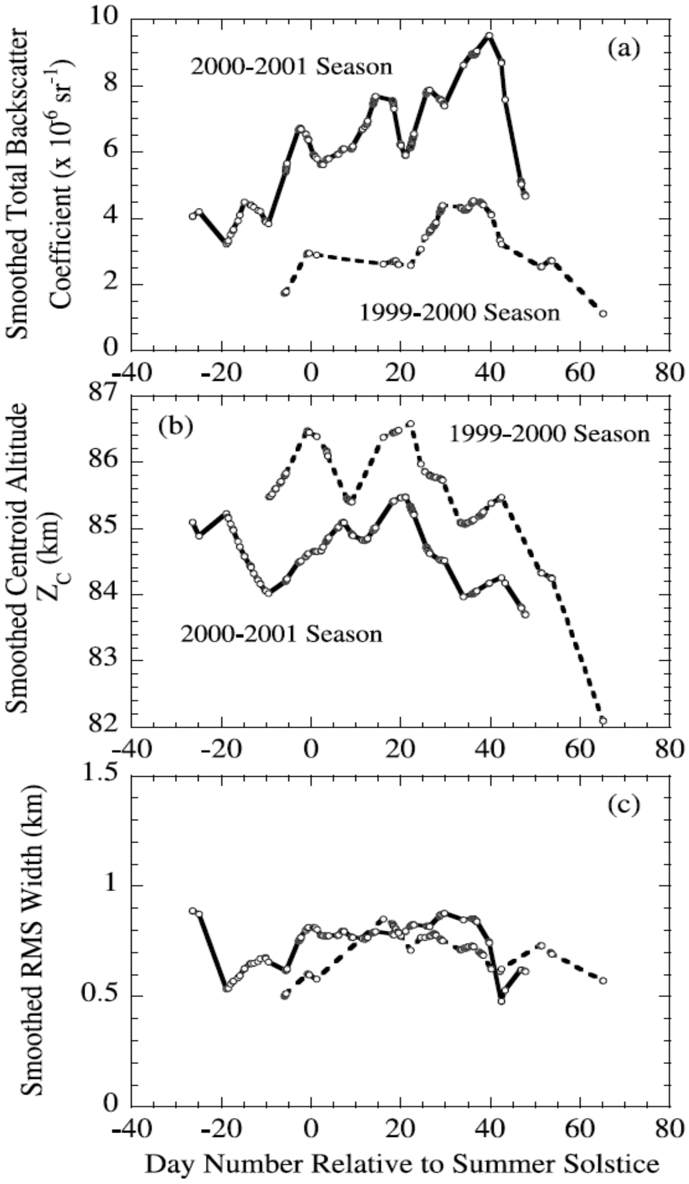


[Gerrard, Kane, Thayer, *GRL*, 1998]

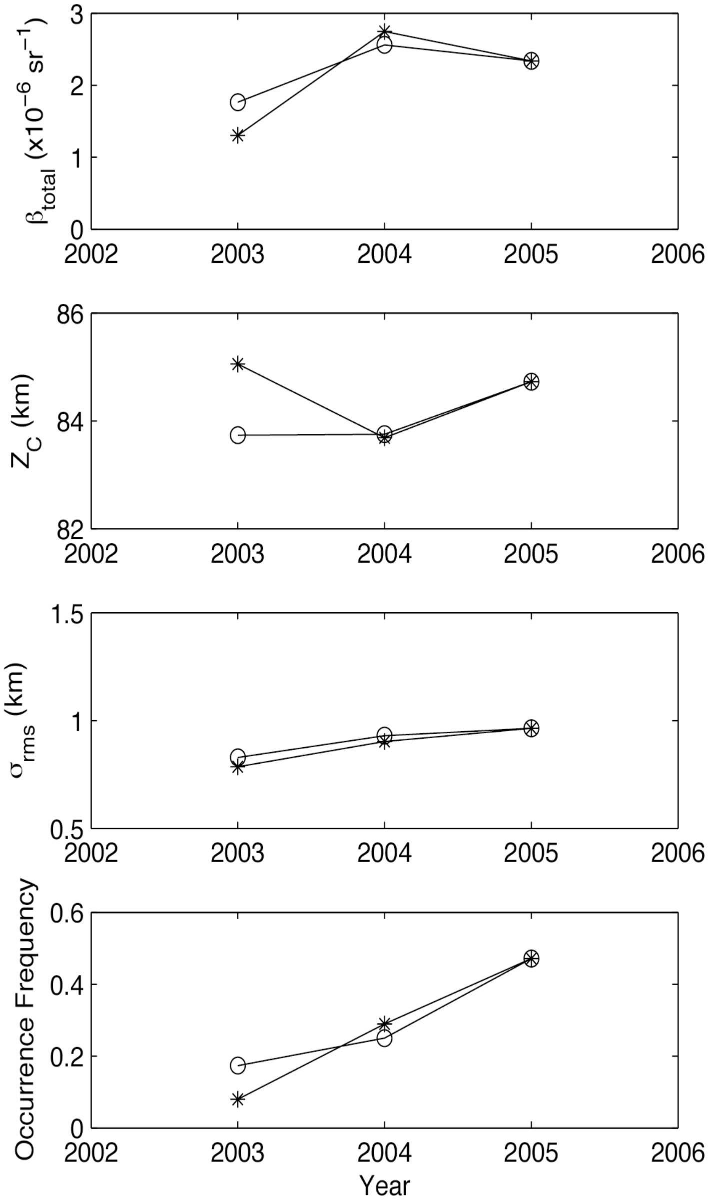


[Chu, Yamashita, et al., JASTP, 2008]

PMC Seasonal & Interannual Variations



South Pole



Rothera

Multi-Wavelength Lidar Detection

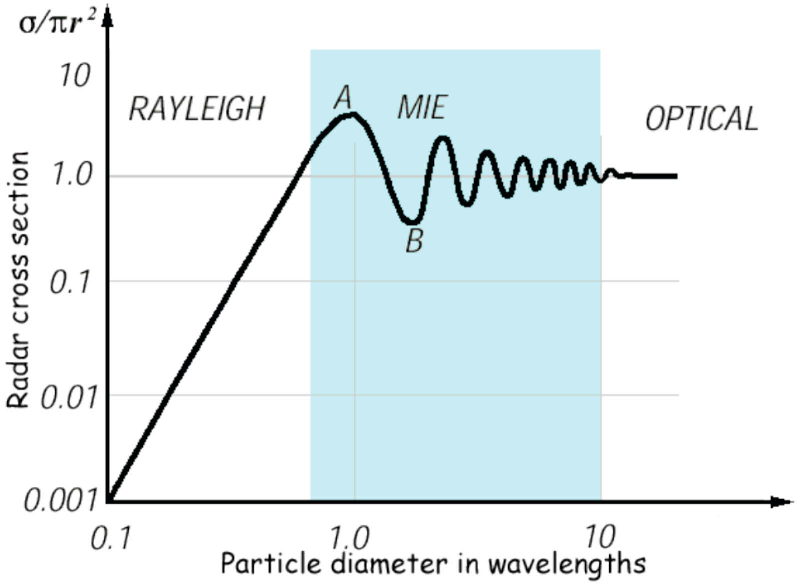
- ❑ From the name, multi-wavelength lidar is to detect the common-volume aerosols using several different wavelengths that are significant apart from each other, e.g., 1064, 532, 355 nm (fundamental, doubled, and tripled Nd:YAG laser wavelengths).
- ❑ By taking the color ratio of aerosol scattering, plus some assumptions of particle shape and size distribution, e.g., spherical particles and lognormal distribution, the multi-wavelength lidar measurements of aerosol can be used to determine the particle size (e.g., radius, width) and particle number density.
- ❑ This is based on the dependence of backscatter cross section versus the ratio of particle size/wavelength. When particle is small compared to laser wavelength, it is pure Rayleigh scattering with λ^{-4} relationship (e.g., air molecules). When particle size increases, the scattering slowly goes from Rayleigh to Mie scattering, and could experience "oscillation" with particle size/wavelength (shown in next slide).

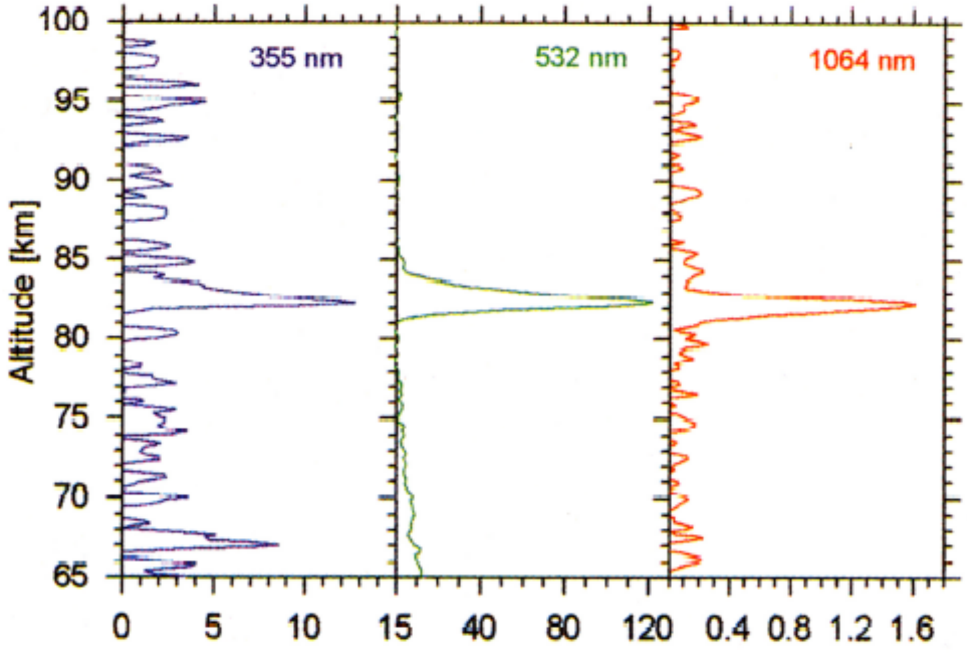
Multi-Wavelength Lidar Detection

- Lognormal Distribution of Spherical particles

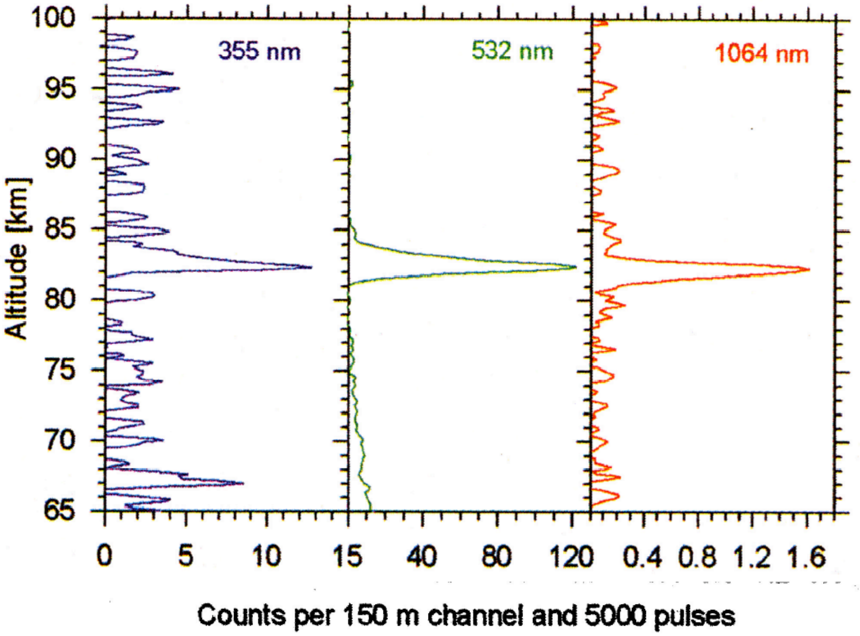
$$\frac{dn_{NLC}(r)}{dr} = \frac{N_{NLC}}{\sqrt{2\pi}\cdot r\cdot \ln\sigma}\cdot \exp\left(-\frac{\ln^2(r/r_{med})}{2\ln^2\sigma}\right) \quad (4)$$

N_{NLC}	total number density of aerosols
r_{med}, σ	median radius and width parameter of the lognormal size distribution, respectively





PMC Microphysics: Particle Size



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

Color Ratio is defined as

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

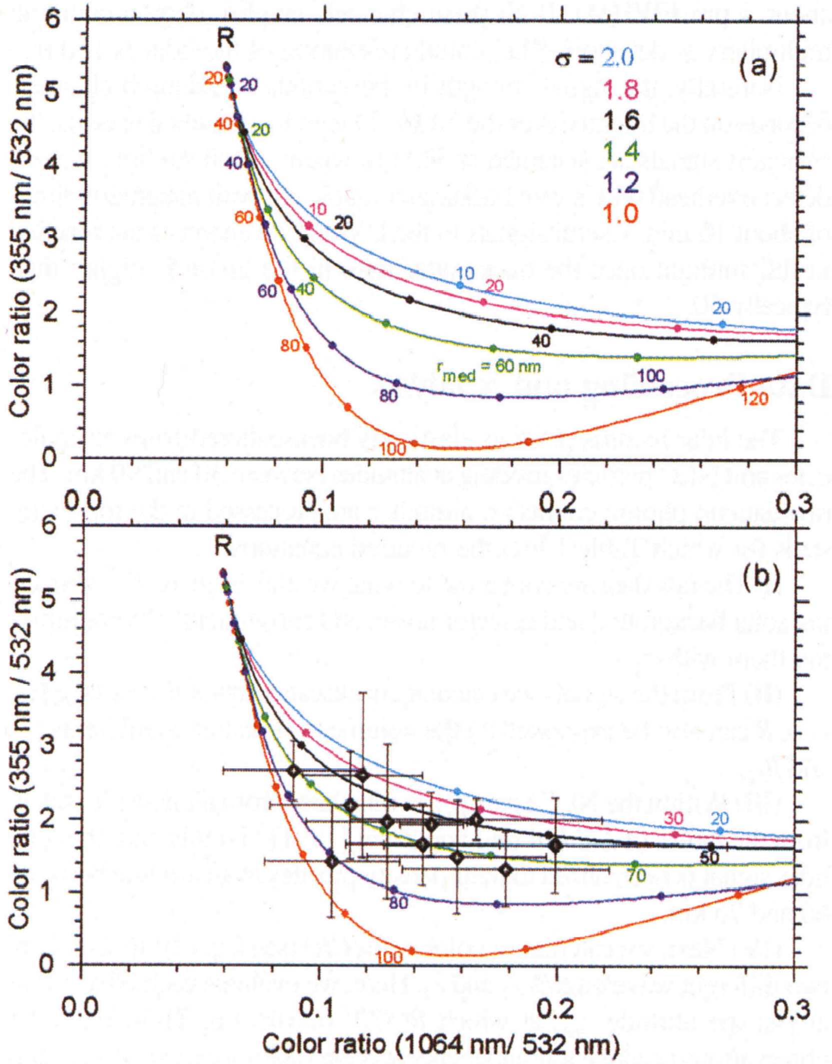


Figure 1. Panel (a) shows as a result of Mie calculations for the color ratios *CR* of used laser wavelengths a set of color coded curves for constant σ and r_{med}. In panel (b) the derived color ratios of the 11 NLC events are plotted in the field of the modelled color ratios.

Particle Size by 3-Color Lidar

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

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

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

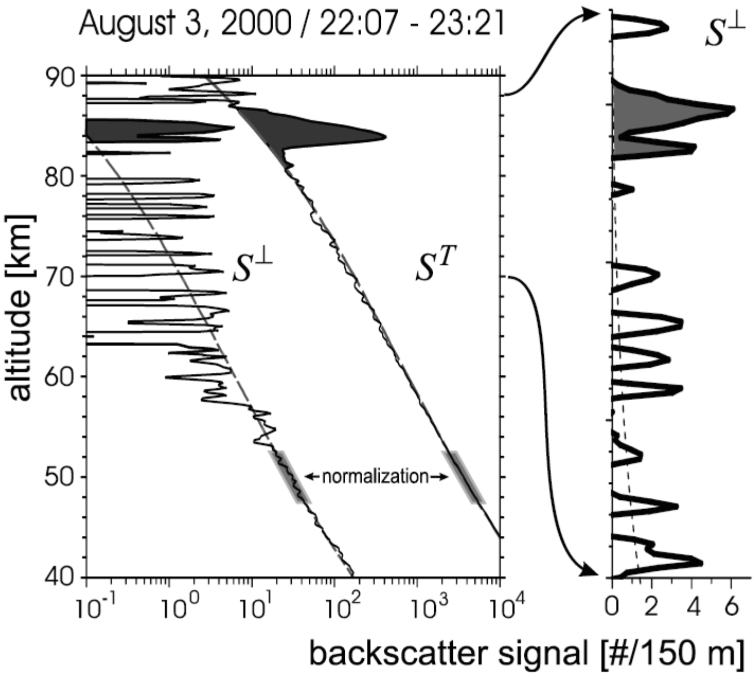
Lidar Measurement Results at ALOMAR, Andoya

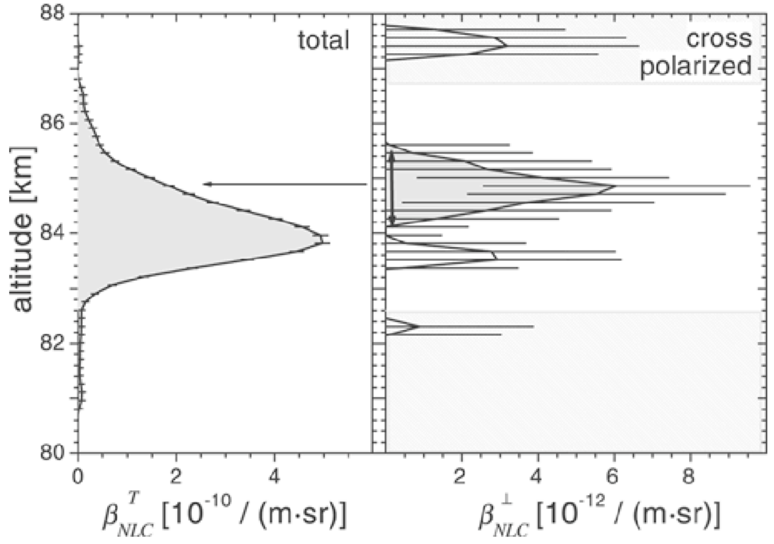
	r_{med} (nm)	σ	N (cm^{-3})	Model	Reference
1998	51	1.42	82	Spherical Lognormal	von Cossart et al., GRL, 1999
1998	61±7	16±2	61±16	Cylinder Gaussian	Baumgarten et al., Ice Layer Workshop, 2006
2003	51±6	18±2	74±19		
2004	46±3	18±1	94±12		
2005	46±3	17±1	113±18		

Polarization in Scattering

- According to Mie theory, backscattering from spherical particles does not change the polarization state of the radiation. The backscattered light has polarization parallel to that of the transmitted beam (usually linearly polarized).
- As long as the particles are small compared to the wavelength, the actual particle shape does not play a major role for the scattering properties as theories for non-spherical scatters show.
- Large non-spherical particles lead to a depolarization of backscattered radiation, i.e., partial backscattered light has polarization perpendicular to that of the transmitted beam.

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, d_{NLC} = (1.7±1.0)%

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

[Baumgarten et al., GRL, 2002]

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

Key lidar findings of PMC study in 4 categories

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 Southern Hemisphere; Discovery of 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**

Summary

- Aerosol is an important topic in atmospheric science and environmental research. It can be measured/monitored by hot lidar technologies.
- Polar Mesospheric Clouds are a potential indicator of long-term climate change. They also provide a natural laboratory and tracer for study of the polar summer mesopause region.
- Lidar observations have made crucial contributions to PMC study. A key result is the hemispheric difference and latitudinal dependence in PMC altitude, providing an insight in the asymmetry of atmospheric environment between the southern and northern hemispheres.
- PMC exhibit significant diurnal, seasonal, and interannual variations in both hemispheres, providing a great opportunity to study the gravity, tidal, and planetary waves in the polar summer mesosphere.