Lecture 27. Aerosol Lidar (3)

- Measurement of aerosol extinction from multi-channel lidar (Raman lidar and HSRL)
- Lidar study of polar mesospheric clouds
- Summary

Raman Lidar and HSRL

- Raman lidar measures

(1) elastic scattering from aerosols & molecules,

(2) inelastic (Raman) scattering by N_2 or O_2 molecules.

For example, if 532 nm laser is Raman shifted by N_2, the V-R Raman signal is at 607 nm.

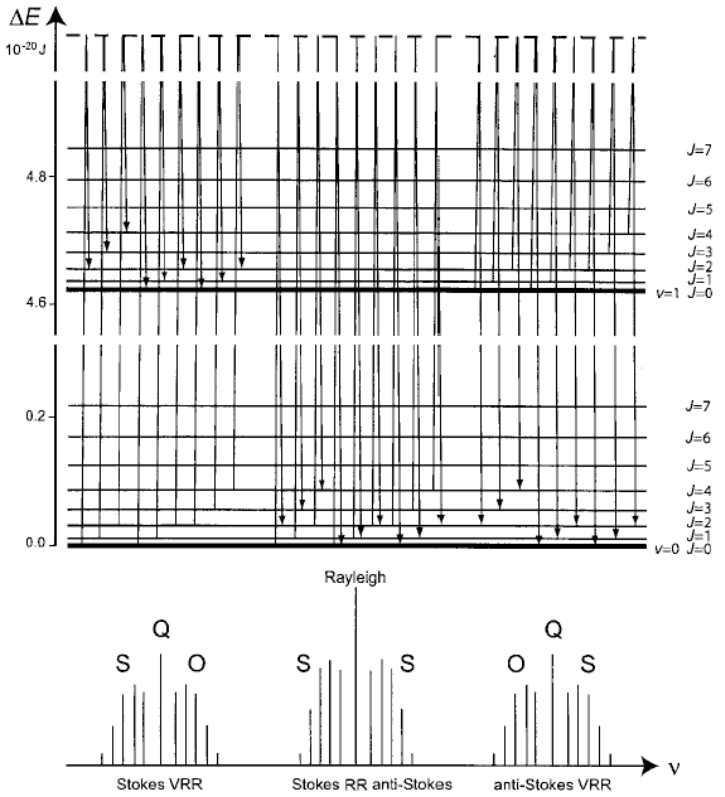


Fig. 9.1. Vibration–rotation energy levels of the N_2 molecule, Raman transitions, and resulting spectrum.

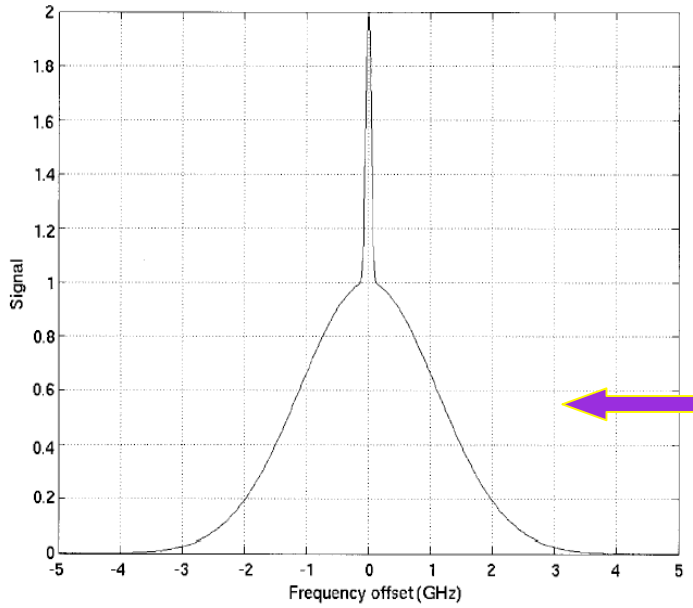


Fig. 5.1. Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.

- High-Spectral-Resolution-Lidar (HSRL) is to measure the molecule scattering separately from the aerosol scattering, utilizing the different spectral distribution of the Rayleigh and Mie scattering.

Derive Extinction from Raman/HSRL

- For the pure Rayleigh channel in HSRL or the Raman channel

$$P(R,\lambda_{Ra}) = \frac{E_o \eta_{\lambda_{Ra}}}{R^2} O(R,\lambda_{Ra}) \beta_{Ra}(R,\lambda_0) \exp\left\{-\int_0^R \left[\alpha(r,\lambda_0) + \alpha(r,\lambda_{Ra})\right] dr\right\}$$

On the way up On the way down

where P is the power of return signal from Rayleigh or Raman scattering,

R is range and λ_0 is the outgoing laser wavelength,

λ_{Ra} is the wavelength of Rayleigh or Raman scattering,

E_0 is the transmitted laser pulse energy,

$\eta_{\lambda Ra}$ is the lidar optical and detection efficiency at wavelength λ_{Ra},

O is the overlapping function between laser and receiver FOV,

β_{Ra} is the backscatter coefficient of Rayleigh or Raman scattering,

$\alpha(\lambda_0)$ is the extinction on the way up to the backscatter region,

$\alpha(\lambda_{Ra})$ is the extinction on the way back to the lidar.

For HSRL, $\lambda_0 = \lambda_{Ra}$ (elastic); For Raman, $\lambda_0 \neq \lambda_{Ra}$ (inelastic)

Derive Extinction from Raman/HSRL

- The backscatter coefficient of Rayleigh or Raman scattering from air molecules can be calculated as

$$\beta_{Ra}(R,\lambda_0) = N_{Ra}(R)\frac{d\sigma_{Ra}}{d\Omega}(\pi,\lambda_0)$$

where N_{Ra} is the number density of air molecules for Rayleigh scattering or the number density of N_2 or O_2 for Raman scattering.

$d\sigma_{Ra}/d\Omega(\pi,\lambda_0)$ is the molecular differential cross section for the Rayleigh or Raman scattering process at the laser wavelength

- From above two equations, we have

$$\alpha(R,\lambda_0)+\alpha(R,\lambda_{Ra}) = \frac{d}{dR}\ln\frac{N_{Ra}(R)}{S(R,\lambda_{Ra})}+\frac{d}{dR}\ln O(R,\lambda_{Ra})$$

where $S(R,\lambda_{Ra})$ is the range-corrected molecular signal: $S(R,\lambda_{Ra}) = P(R,\lambda_{Ra})R^2$

- In the optimum case O(R) ≡ 1, i.e., good overlap

$$\alpha_{aer}(R,\lambda_0)+\alpha_{aer}(R,\lambda_{Ra}) = \frac{d}{dR}\ln\frac{N_{Ra}(R)}{S(R,\lambda_{Ra})}-\alpha_{mol}(R,\lambda_0)-\alpha_{mol}(R,\lambda_{Ra})$$

Derive Extinction from Raman/HSRL

- To obtain the extinction coefficient at the transmitted wavelength λ_0, we have to introduce the Angstrom exponent å(R), which describes the wavelength dependence of the particle extinction coefficient.

$$\frac{\alpha_{aer}(\lambda_0)}{\alpha_{aer}(\lambda_{Ra})} = \left(\frac{\lambda_{Ra}}{\lambda_0}\right)^{a(R)}$$

- Thus, the final solution of aerosol extinction is given by

$$\alpha_{aer}(R,\lambda_0) = \frac{\frac{d}{dR}\ln\frac{N_{Ra}(R)}{S(R,\lambda_{Ra})} - \alpha_{mol}(R,\lambda_0) - \alpha_{mol}(R,\lambda_{Ra})}{1+\left(\frac{\lambda_0}{\lambda_{Ra}}\right)^{a(R)}}$$

- For HSRL, the denominator of the above equation is 2, because $\lambda_0 = \lambda_{Ra}$

- Angstrom exponent å(R) ranges from 0-1.45 for 350-800 nm. Overestimation and underestimation of the å value by 0.5 leads to relative errors on the order of 5%.

Derive Backscatter from Raman/HSRL

- Aerosol backscatter coefficient can be calculated from the ratio of the total backscatter signal (aerosol + molecule) to the molecular backscatter signal as below.

$$\beta_{aer}(R,\lambda_0)+\beta_{mol}(R,\lambda_0)=\left[\beta_{aer}(R_0,\lambda_0)+\beta_{mol}(R_0,\lambda_0)\right]\frac{P(R_0,\lambda_{Ra})P(R,\lambda_0)}{P(R_0,\lambda_0)P(R,\lambda_{Ra})}\frac{N_{Ra}(R)}{N_{Ra}(R_0)}$$
$$\times\frac{\exp\left\{-\int_{R_0}^{R}\left[\alpha_{aer}(r,\lambda_{Ra})+\alpha_{mol}(r,\lambda_{Ra})\right]dr\right\}}{\exp\left\{-\int_{R_0}^{R}\left[\alpha_{aer}(r,\lambda_0)+\alpha_{mol}(r,\lambda_0)\right]dr\right\}}$$

Here, R_0 is a reference point, which is usually chosen in upper troposphere or lower stratosphere so that it is free of aerosols and the molecular backscatter coefficient can be reliably estimated from atmos conditions.

- The aerosol lidar ratio is then given by

$$L_{aer}(R,\lambda_0)=\frac{\alpha_{aer}(R,\lambda_0)}{\beta_{aer}(R,\lambda_0)}$$

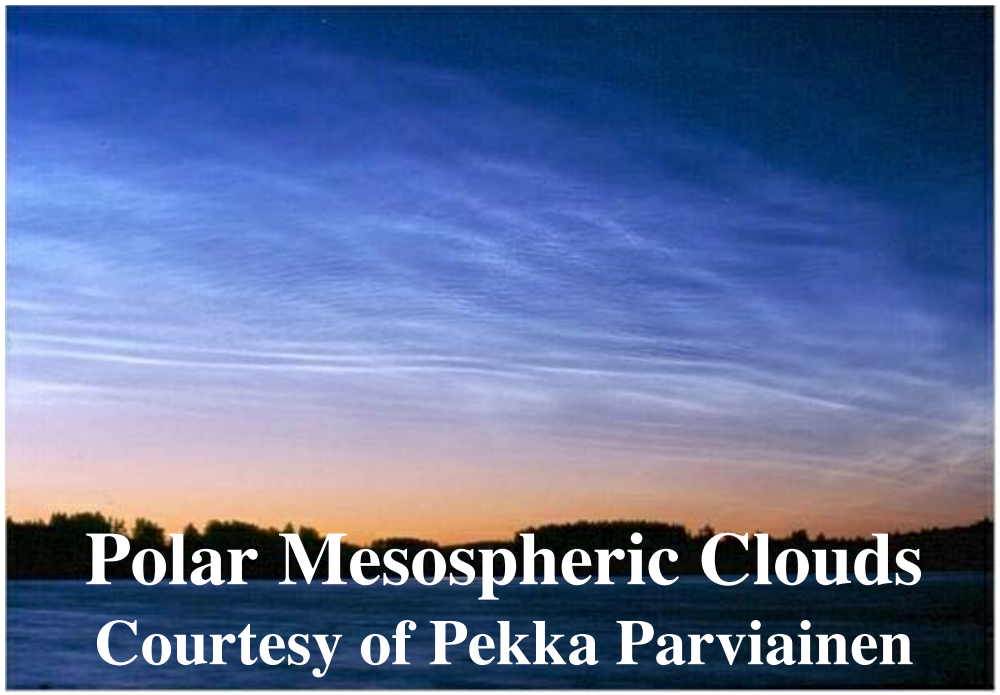
Properties of Aerosols in Atmosphere

Table 4.1. Properties of aerosol types [1][a]

Aerosol type	N (cm^{-3})	r_{eff} (μm)	*ssa* (0.55 μm)	g (0.55 μm)	*å* (0.35–0.55 μm)	*å* (0.55–0.8 μm)
Cont. clean	2600	0.247	0.972	0.709	1.10	1.42
Cont. average	15,300	0.204	0.925	0.703	1.11	1.42
Cont. polluted	50,000	0.150	0.892	0.698	1.13	1.45
Urban	158,000	0.139	0.817	0.689	1.14	0.43
Desert	2300	1.488	0.888	0.729	0.20	0.17
Marit. clean	1520	0.445	0.997	0.772	0.12	0.08
Marit. polluted	9000	0.252	0.975	0.756	0.41	0.35
Marit. tropical	600	0.479	0.998	0.774	0.07	0.04
Arctic	6600	0.120	0.887	0.721	0.85	0.89
Antarctic	43	0.260	1.000	0.784	0.34	0.73
Stratosphere (12–35 km)	3	0.243	1.000	0.784	0.74	1.14

[a] Number concentration is denoted by N. The effective radius r_{eff} describes the mean size of the particle ensemble. The single-scattering albedo *ssa* is defined as the ratio of total scattering to extinction of the investigated particle ensemble. The asymmetry parameter g is a measure of light scattered toward the forward direction compared with the light scattered toward the back direction. The Ångström exponent *å* [2] describes the spectral slope of the optical coefficients. All numbers hold for a relative humidity of 80%. Effective radius is calculated for 50% relative humidity. A further discussion of some of the parameters is given in Section 4.3.

PMC Detection in Polar Region

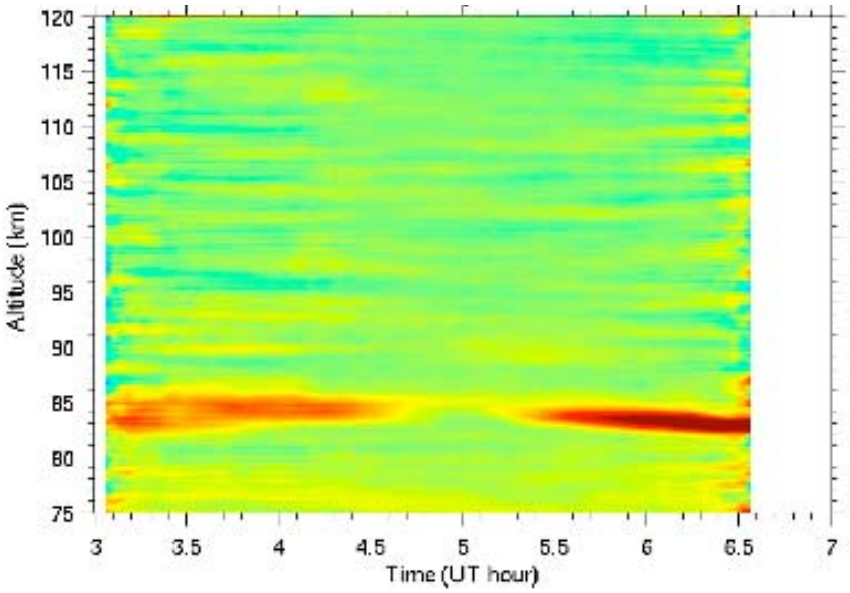


Polar Mesospheric Clouds
Courtesy of Pekka Parviainen

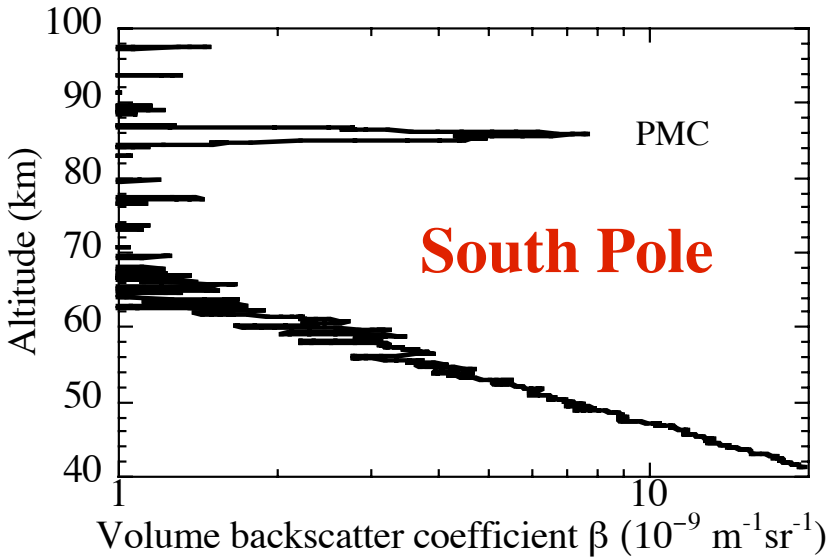
PMC are the thin scattering layers (consisting of water ice particles) ~ 85 km, >50° latitudes, in summer

PMC are regarded as a possible indicator of global climate change Natural laboratory for testing atmosphere models and dynamics

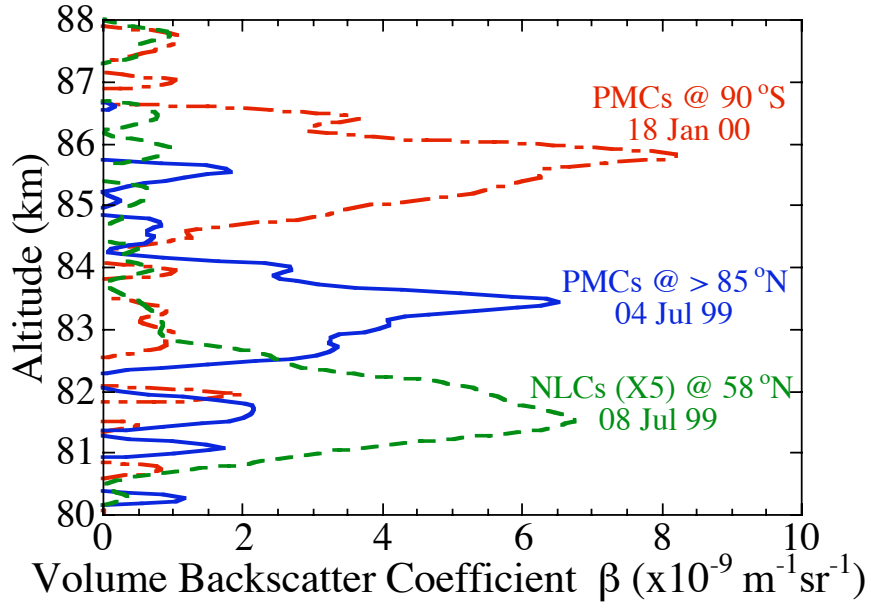
Fe Boltzmann lidar is highly capable of PMC detection
1) Short wavelength (374, 372 nm)
2) High laser power
3) Daytime capability



Lidar Detection of PMC



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



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

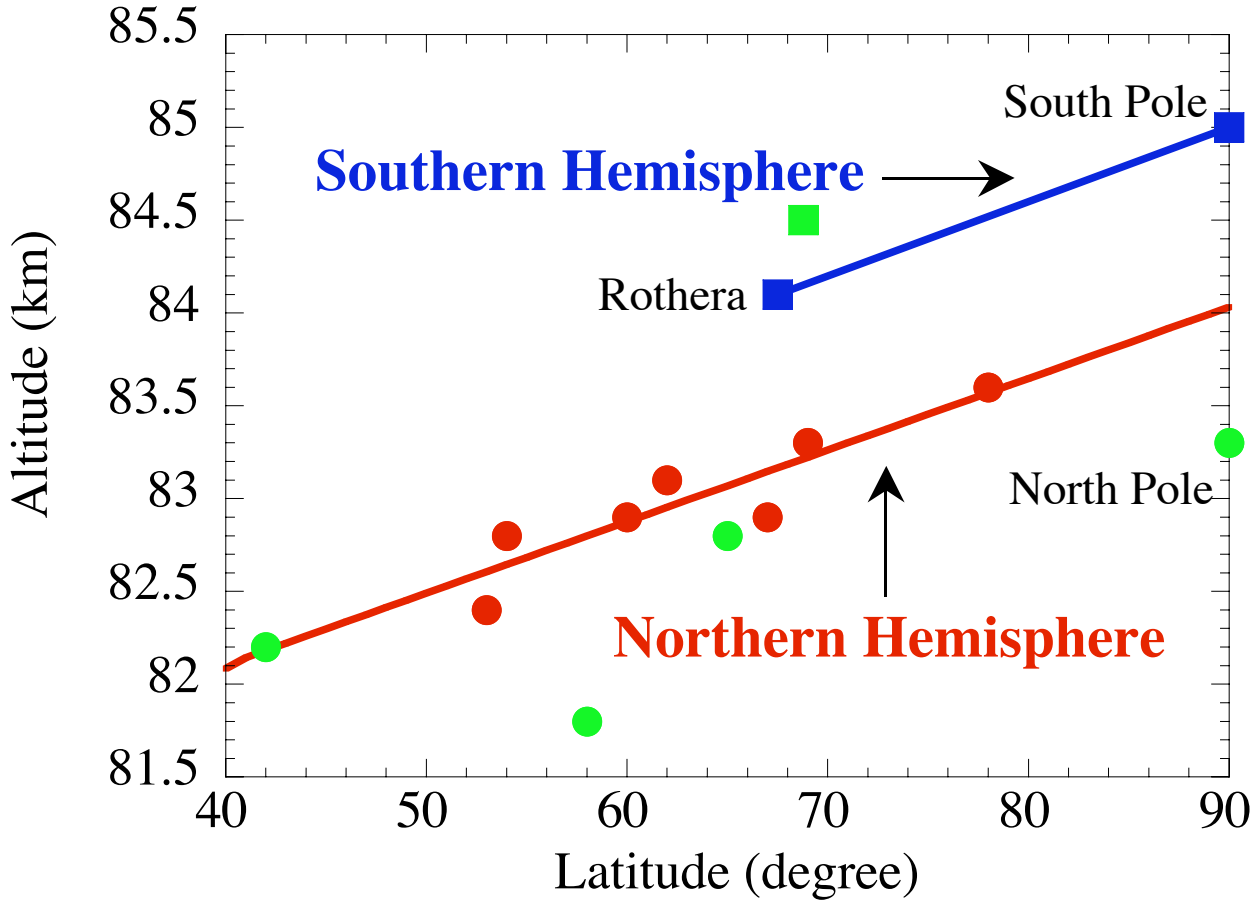
$$\beta_{\max} = \max\left[\beta(z)\right]$$

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

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

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

Hemispheric Difference in PMC Altitude



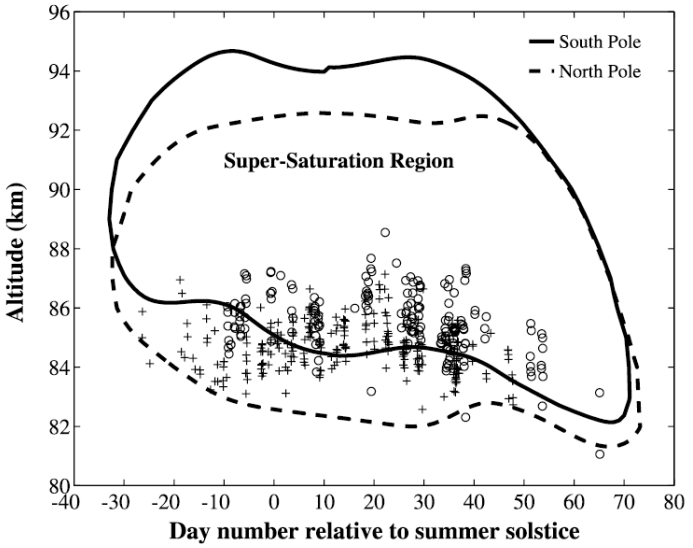
Southern PMC are ~ 1 km higher than Northern PMC

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

Model Study of Hemispheric Difference

PMC evolution is described by the growth-sedimentation-sublimation model

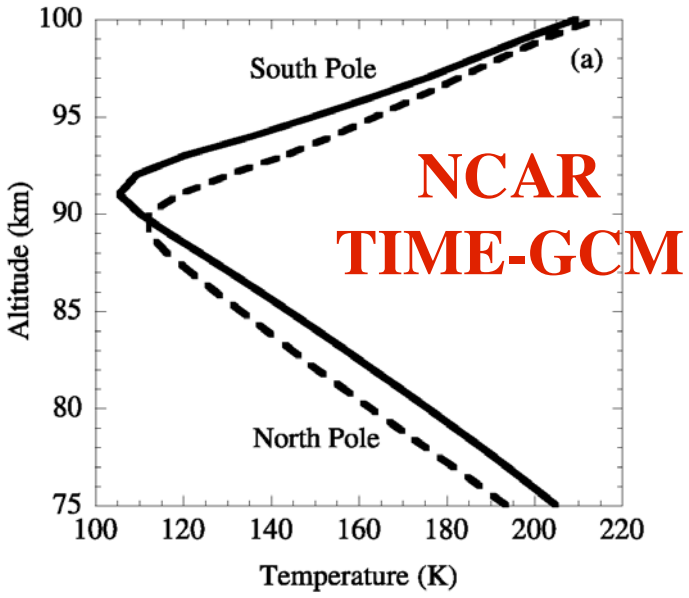
Observed difference in PMC altitude requires the southern hemisphere saturation region locating at higher altitude than the northern hemisphere



Force Balance Equation of PMC Particle

$$m_{ice} g = C \rho_{air} w$$

Since the atmosphere density decreases exponentially with height, the observed PMC altitude difference requires the upwelling vertical wind being larger in SH than in NH



[Chu, Gardner, Roble, *JGR*, 2003]

Causes for Hemispheric Difference

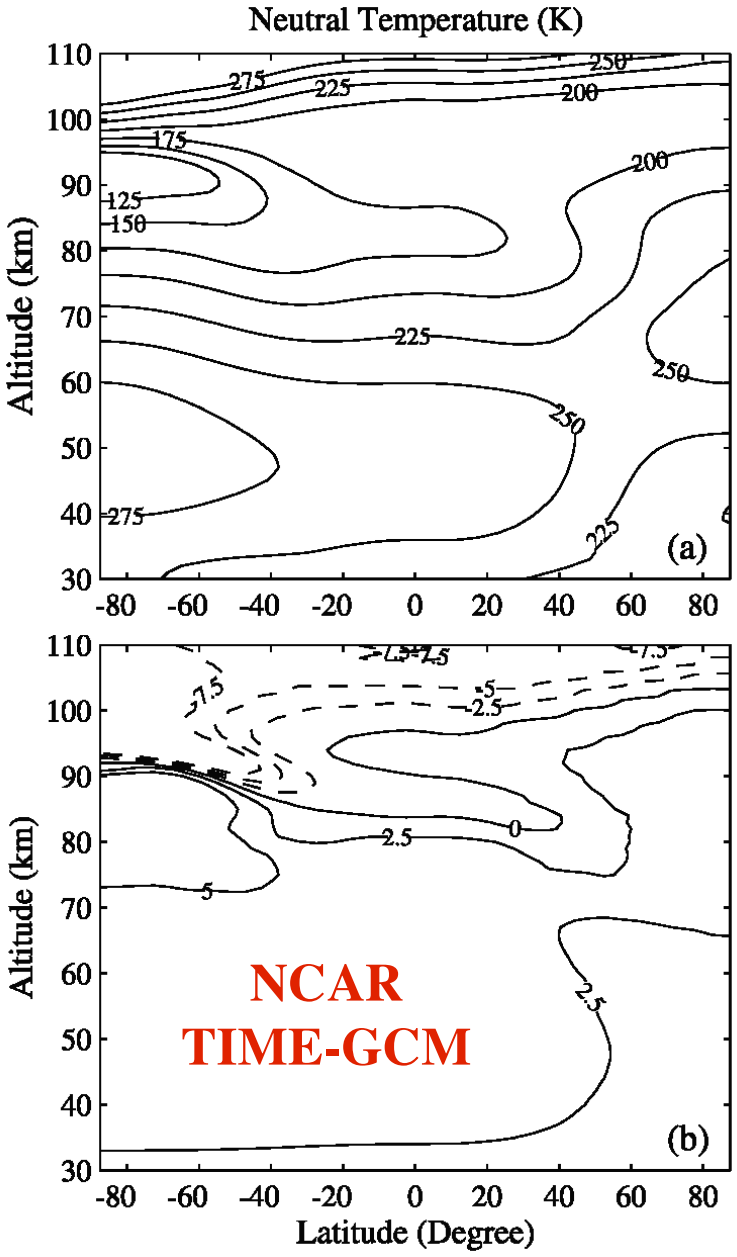
Hemispheric difference (6%) in solar flux (caused by Earth's orbital eccentricity) may be responsible for the observed hemispheric differences [Chu, Gardner, Roble, *JGR*, 2003]

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

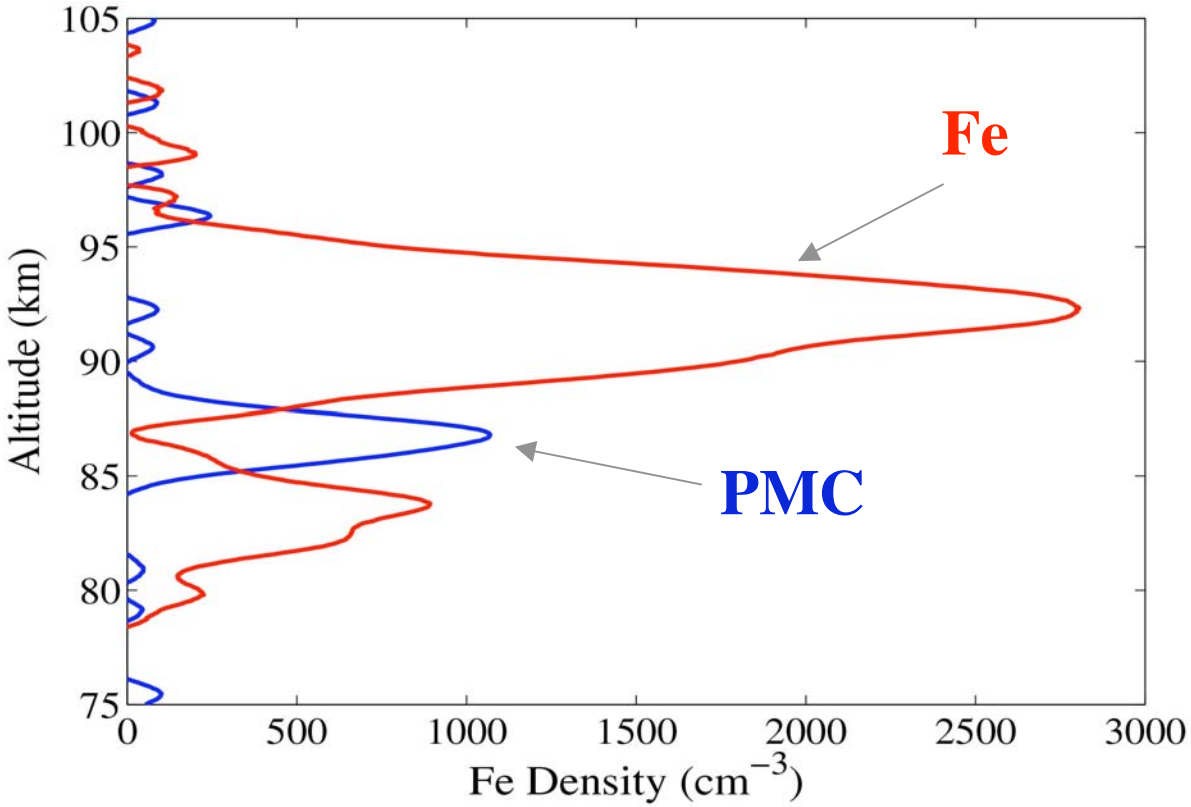
Results show that for the case with 6% more solar flux, the mesopause altitude moved upward by ~1 km and cooled by ~5 K.

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



Heterogeneous Removal of Fe by PMC



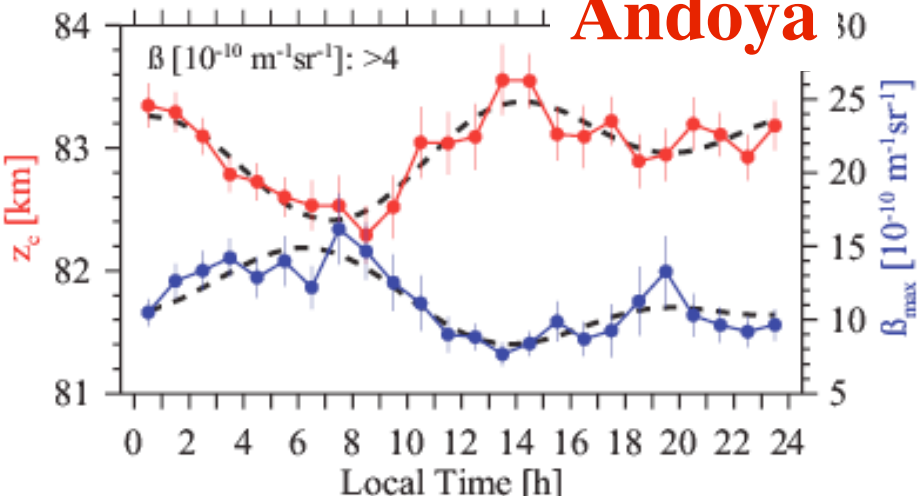
Plane, Murray, Chu, and Gardner, *Science, 304*, 426-428, 2004

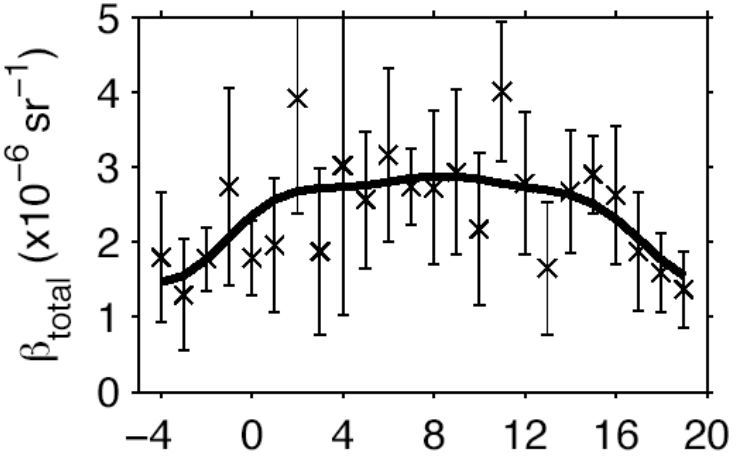
Fe ablation flux = 1.1 x 10^4 atoms cm^{-2} s^{-1}

Uptake coefficients of Fe and Fe species on ice = 1

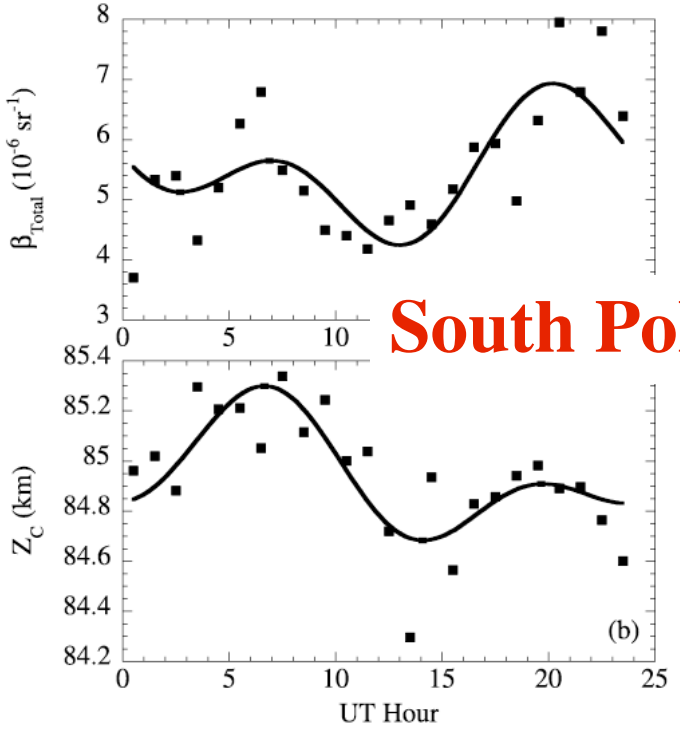
PMC Diurnal Variations

Andoya

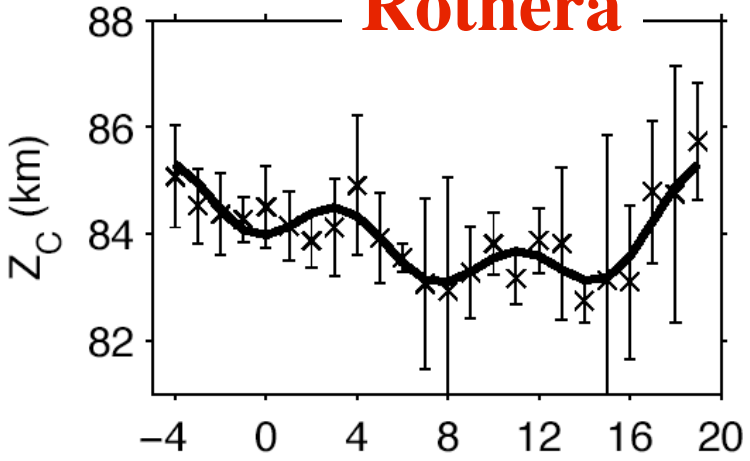




South Pole

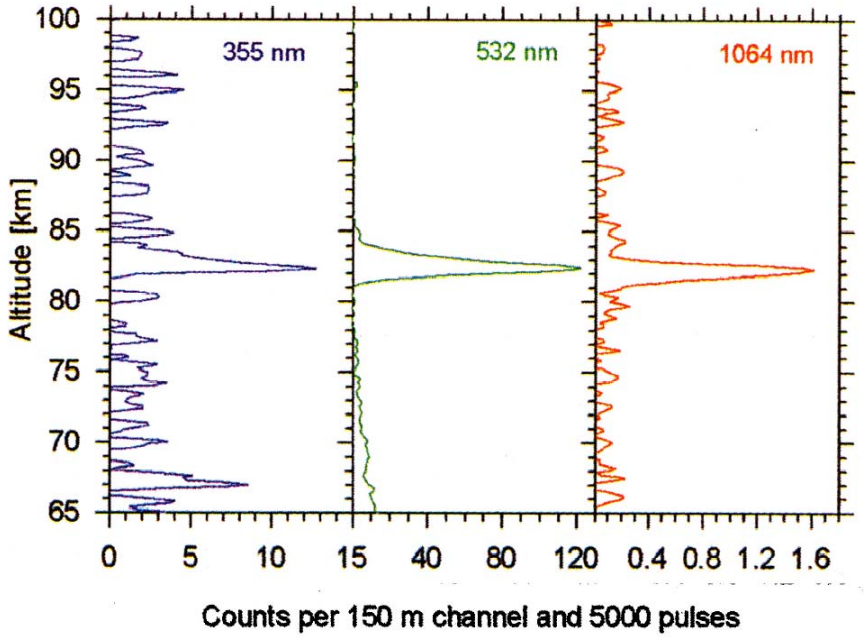


Rothera



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

PMC Microphysics: Particle Size



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

Color Ratio is defined as

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

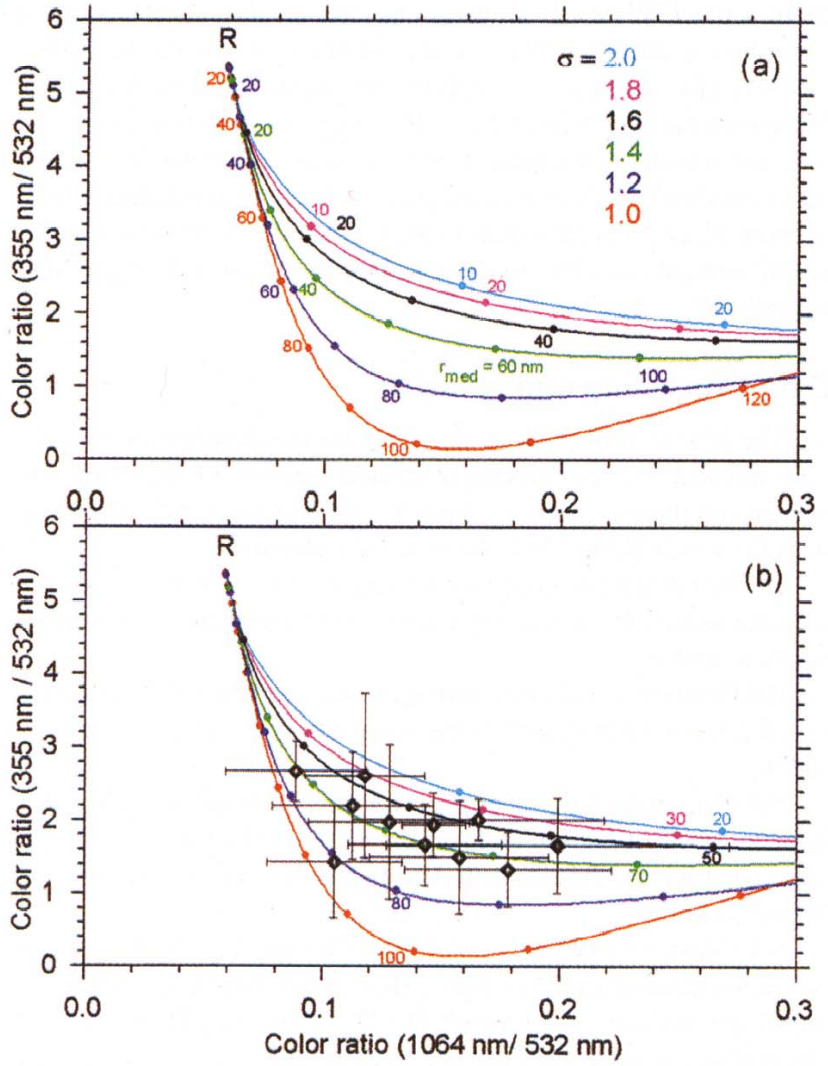


Figure 1. Panel (a) shows as a result of Mie calculations for the color ratios *CR* of used laser wavelengths a set of color coded curves for constant σ and r_{med}. In panel (b) the derived color ratios of the 11 NLC events are plotted in the field of the modelled color ratios.

Particle Size by 3-Color Lidar

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

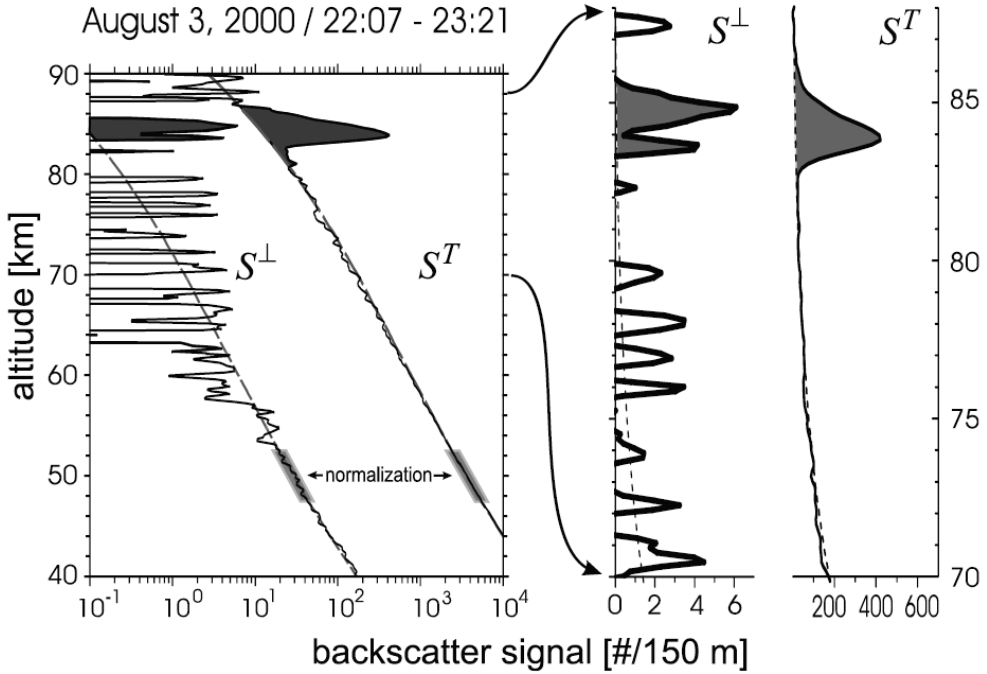
$$\frac{dn(r)}{dr} = \frac{N}{\sqrt{2\pi}\, r \ln\sigma} \exp\left(-\frac{\ln^2\left(r / r_{med}\right)}{2\ln^2\sigma} \right)$$

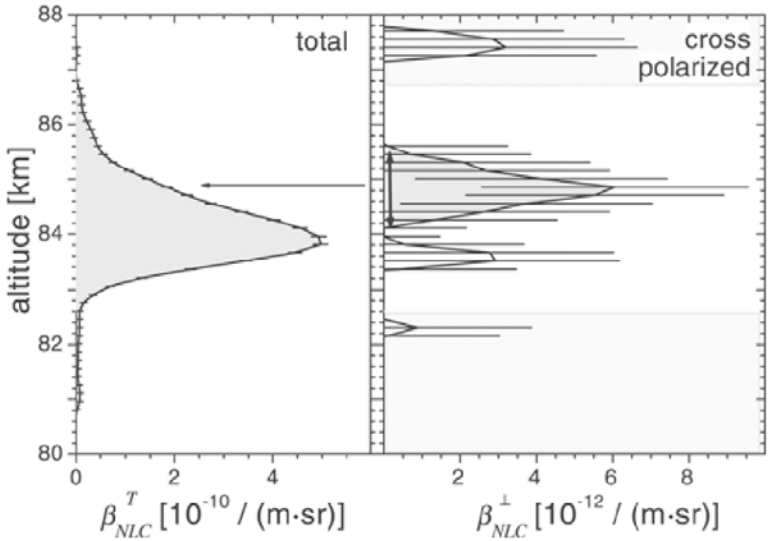
3. **Refractive index of ice from [Warren, 1984]**

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, 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

Summary

- Multi-channel lidars like Raman lidar and HSRL provide addition information by adding Raman channel or separate molecular scattering from aerosol scattering. Both can measure aerosol backscatter and extinction nicely. However, HSRL is more desirable as Rayleigh scattering is much stronger than Raman scattering.
- 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.