Lecture 32. Aerosol & Cloud 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 and Clouds

❑ 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.

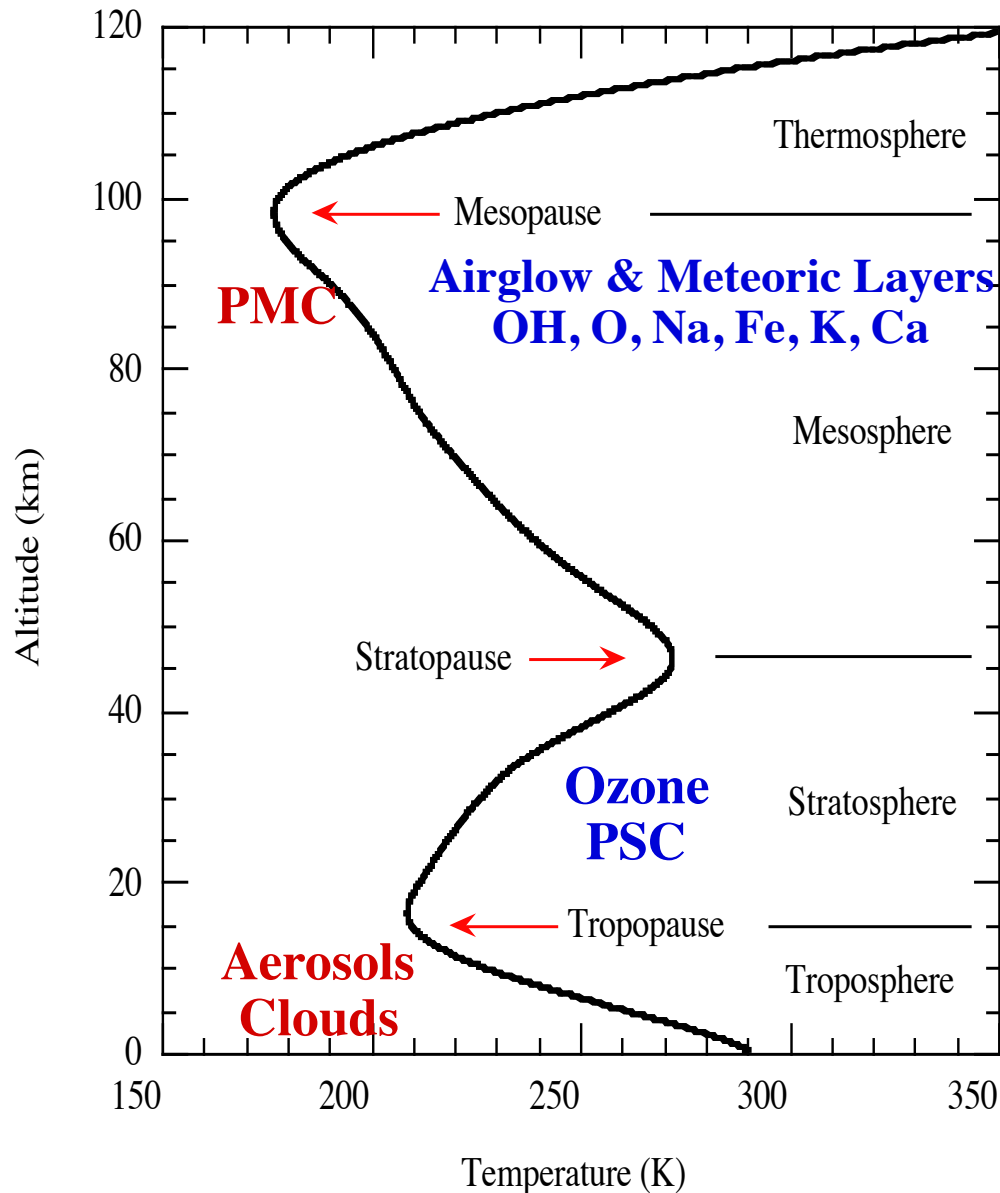❑ Routine (long-term), range-resolved observations of these parameters can only be carried out with lidar.

Earth's Radiation Budget
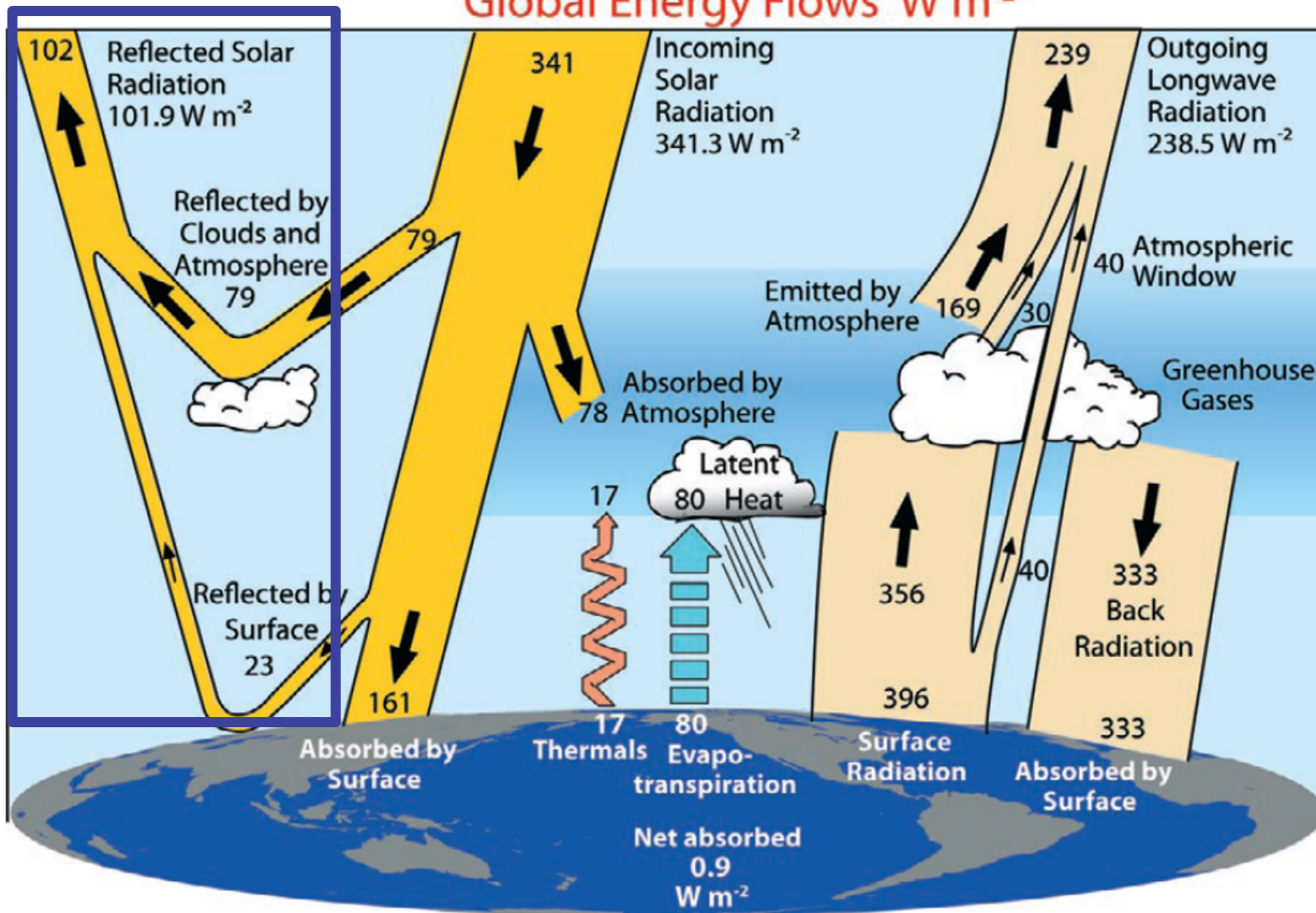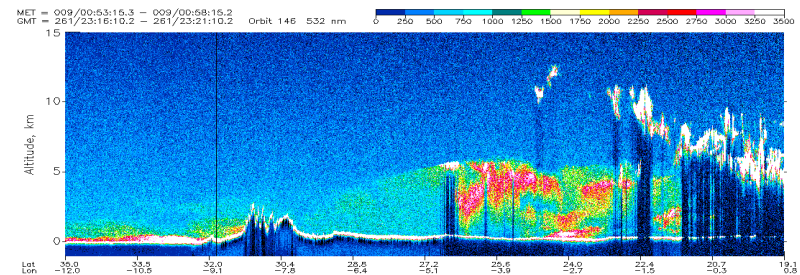

[*Trenberth et al., 2009*]

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 μm
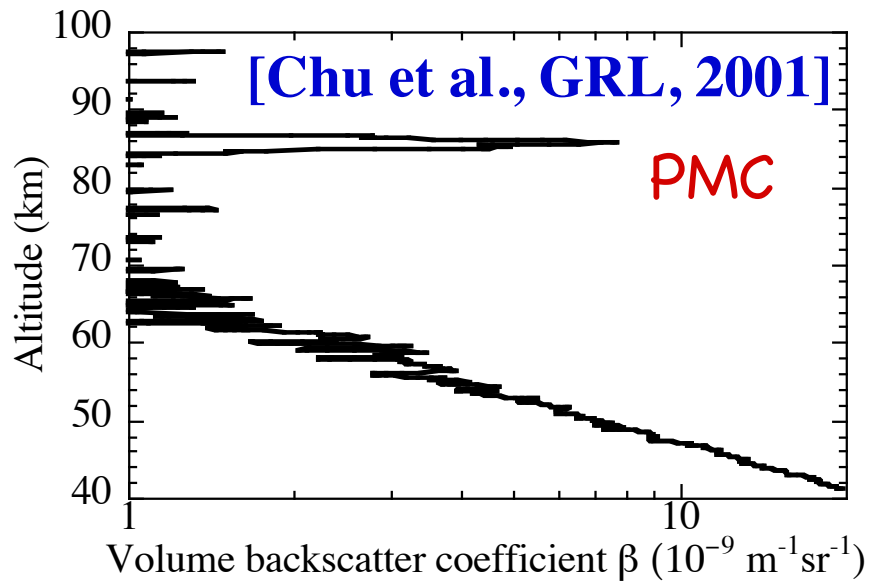accumulation mode: 0.1 < r < 1 μm,
coarse mode: r > 1 μm

4

More Motivations
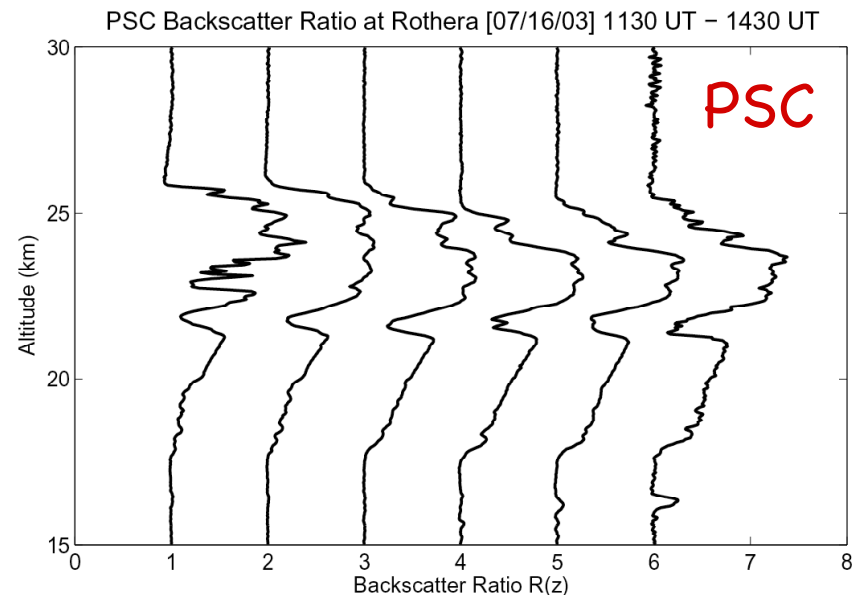
❑ Aerosol Properties – optical, microphysical, and chemical

❑ 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.

5

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.

[Chu et al., GRL, 2001]

PMC

Altitude (km)

Volume backscatter coefficient β (10^{-9} m^{-1}sr^{-1})

PSC Backscatter Ratio at Rothera [07/16/03] 1130 UT − 1430 UT

PSC

Altitude (km)

Backscatter Ratio R(z)

Polar mesospheric clouds
Noctilucent clouds

Polar stratospheric clouds

6

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

7
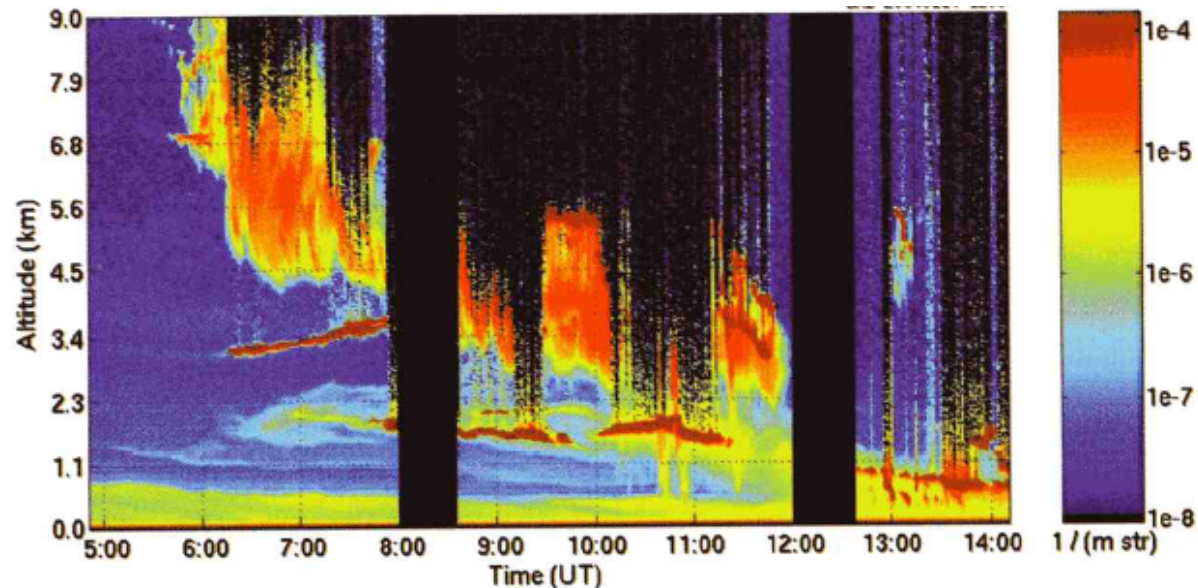
Aerosol Properties vs Lidar Detection

❑ 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

8

PMC: Early Indication of Climate Change

(a) Albedo Fits For All NH Latitudes
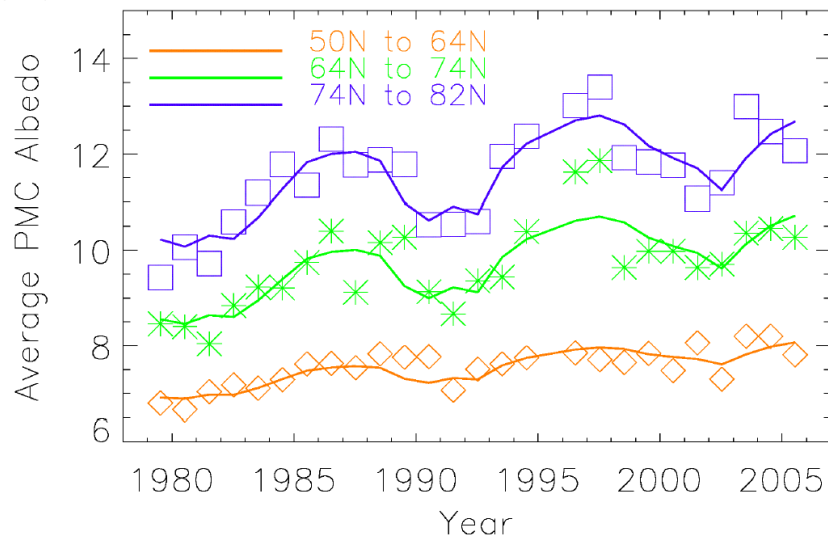
(b) Albedo Fits For All SH Latitudes
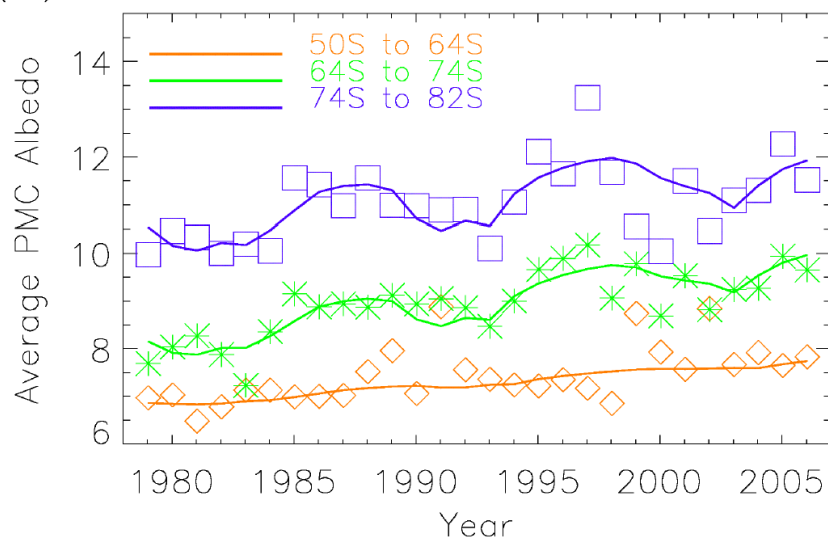
➢ **Polar mesospheric clouds (PMC), also noctilucent clouds (NLC), are thin scattering layers of nanometer-sized water ice particles, occurring ~ 80-87 km in the high-latitude summer mesopause region.**

➢ **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.**

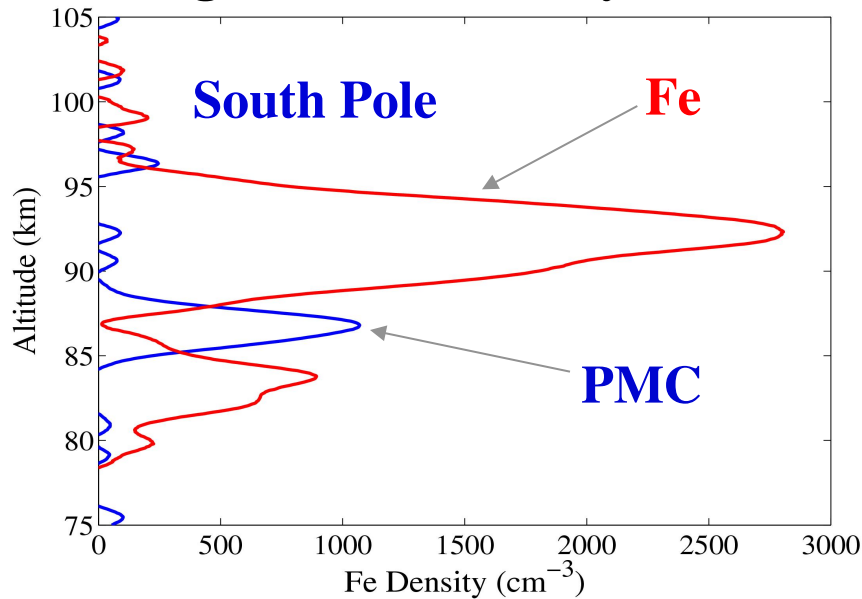**[DeLand, Shettle, Thomas, and Olivero, *submitted to JGR*, 2006]**

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.**
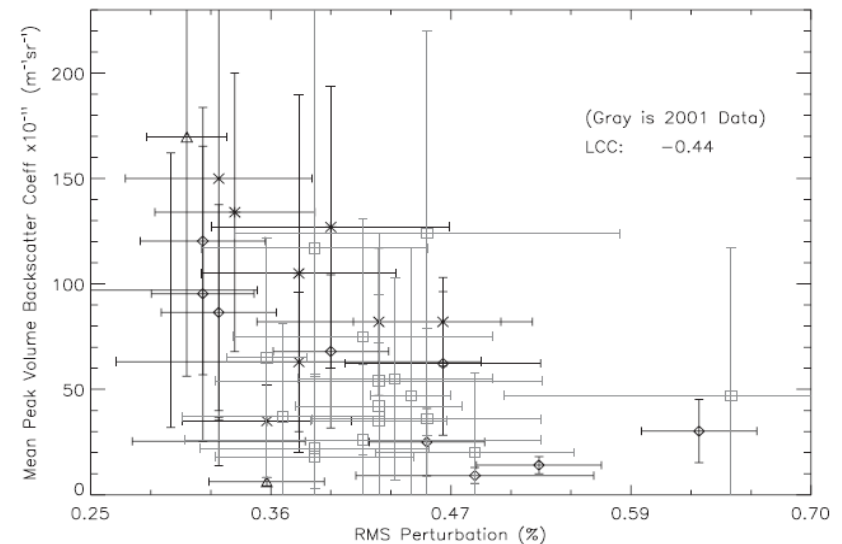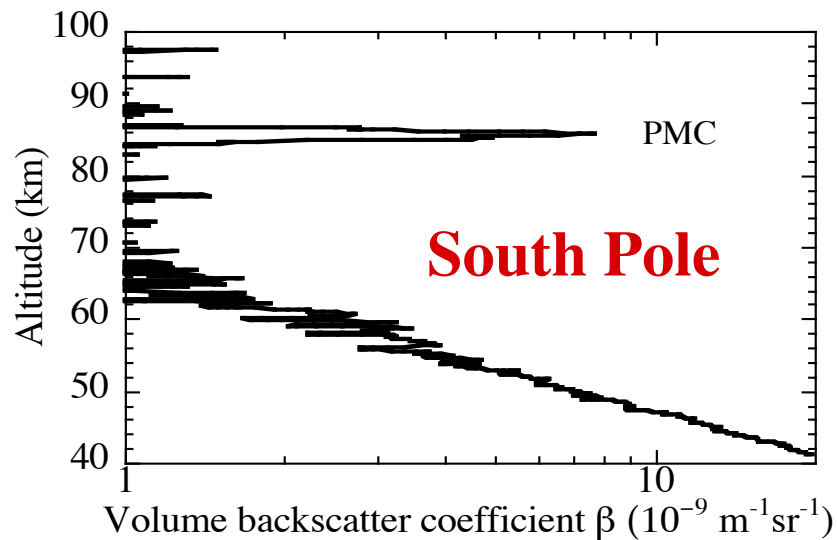

Courtesy of Pekka Parviainen

Heterogeneous Chemistry with PMC

South Pole   Fe

PMC

Altitude (km)

Fe Density (cm^{-3})

Gravity Wave Effect with PMC

(Gray is 2001 Data)
LCC: −0.44

Mean Peak Volume Backscatter Coeff x10^{-11} (m^{-1}sr^{-1})

RMS Perturbation (%)

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

[Gerrard, Kane, Thayer, *GRL*, 1998] 10

Lidar Detection of PMC

PMC

South Pole

Altitude (km)

Volume backscatter coefficient β (10^{-9} m^{-1}sr^{-1})

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

PMCs @ 90 °S
18 Jan 00

PMCs @ > 85 °N
04 Jul 99

NLCs (X5) @ 58 °N
08 Jul 99

Altitude (km)

Volume Backscatter Coefficient β (x10^{-9} m^{-1}sr^{-1})
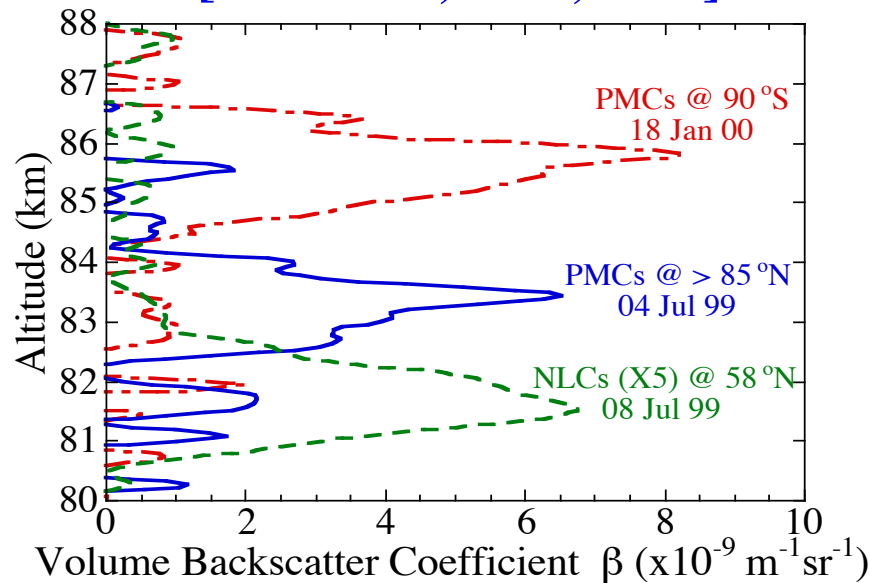
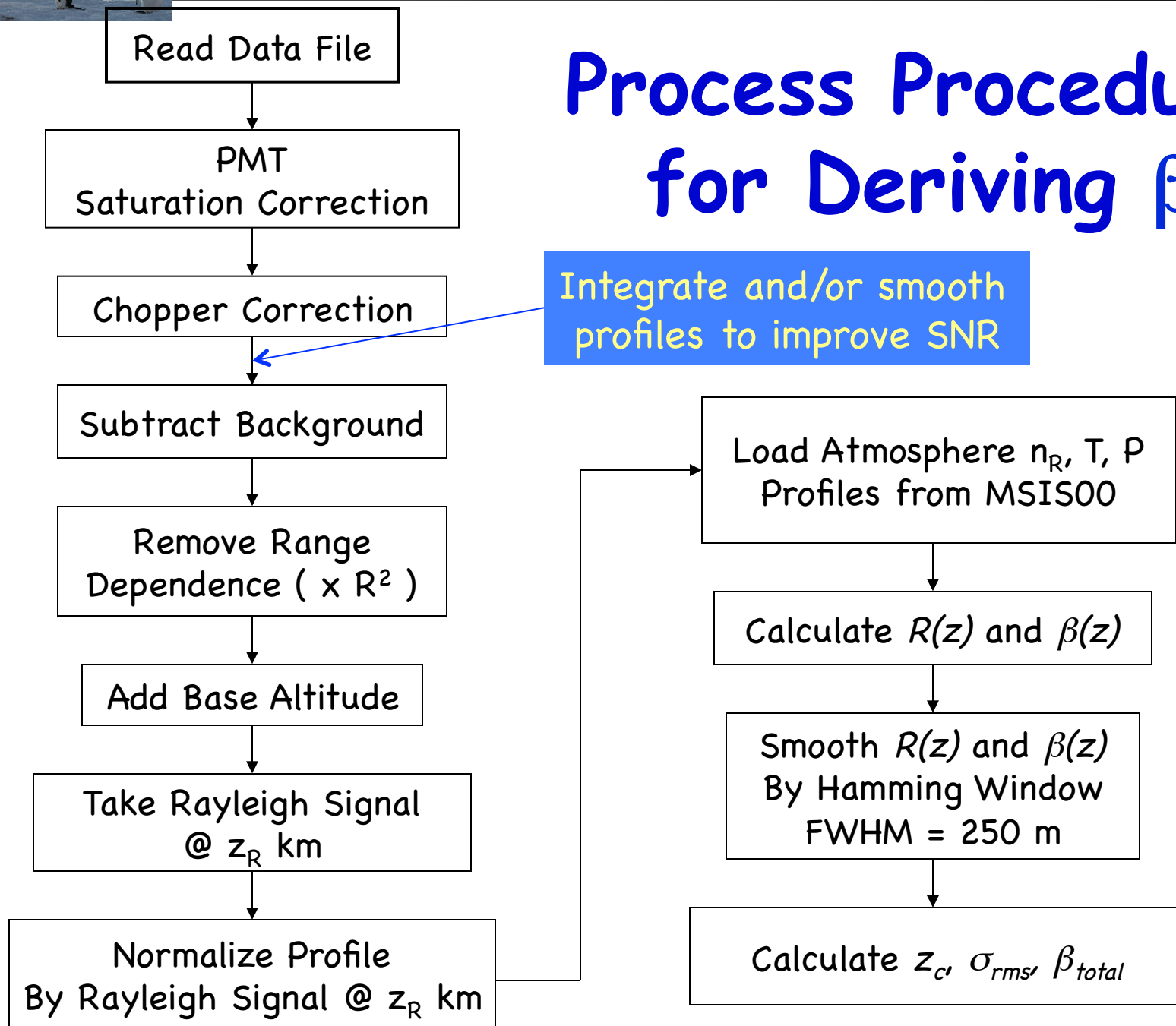$$\beta(z) = \int \frac{d\sigma}{d\Omega}(r,\pi) \frac{dn(r,z)}{dr} dr$$

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

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

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

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

11

Process Procedure for Deriving β

Read Data File

↓

PMT Saturation Correction

↓

Chopper Correction

↓

Subtract Background

↓

Remove Range Dependence (x R²)

↓

Add Base Altitude

↓

Take Rayleigh Signal @ z_R km

↓

Normalize Profile By Rayleigh Signal @ z_R km

Integrate and/or smooth profiles to improve SNR

Load Atmosphere n_R, T, P Profiles from MSIS00

↓

Calculate $R(z)$ and $\beta(z)$

↓

Smooth $R(z)$ and $\beta(z)$ By Hamming Window FWHM = 250 m

↓

Calculate z_c, σ_{rms}, β_{total}

12

Process Procedure for β of PMC

Load Atmosphere n_R, T, P Profiles from MSIS00

↓

Calculate $R(z)$ and $\beta(z)$

↓

Smooth $R(z)$ and $\beta(z)$ By Hamming Window FWHM = 250 m

↓

Calculate z_c, σ_{rms}, β_{total}

$$R = \frac{\left[N_S(z) - N_B\right] \cdot z^2}{\left[N_S(z_{RN}) - N_B\right] \cdot z_{RN}^2} \cdot \frac{n_R(z_{RN})}{n_R(z)}$$

$$\beta_{PMC}(z) = \left[\frac{\left[N_S(z) - N_B\right] \cdot z^2}{\left[N_S(z_{RN}) - N_B\right] \cdot z_{RN}^2} - \frac{n_R(z)}{n_R(z_{RN})}\right] \cdot \beta_R(z_{RN})$$

$$\beta_R(z_{RN}, \pi) = \frac{\beta}{4\pi} P(\pi) = 2.938 \times 10^{-32} \frac{P(z_{RN})}{T(z_{RN})} \cdot \frac{1}{\lambda^{4.0117}}$$

$$z_c = \frac{\sum_i \beta_{PMC}(z_i) \cdot z_i}{\sum_i \beta_{PMC}(z_i)}$$

$$\sigma_{rms} = \sqrt{\frac{\sum_i (z_i - z_c)^2 \beta_{PMC}(z_i)}{\sum_i \beta_{PMC}(z_i)}}$$

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

13

PMC Altitude: Hemispheric Difference and Latitudinal Dependence
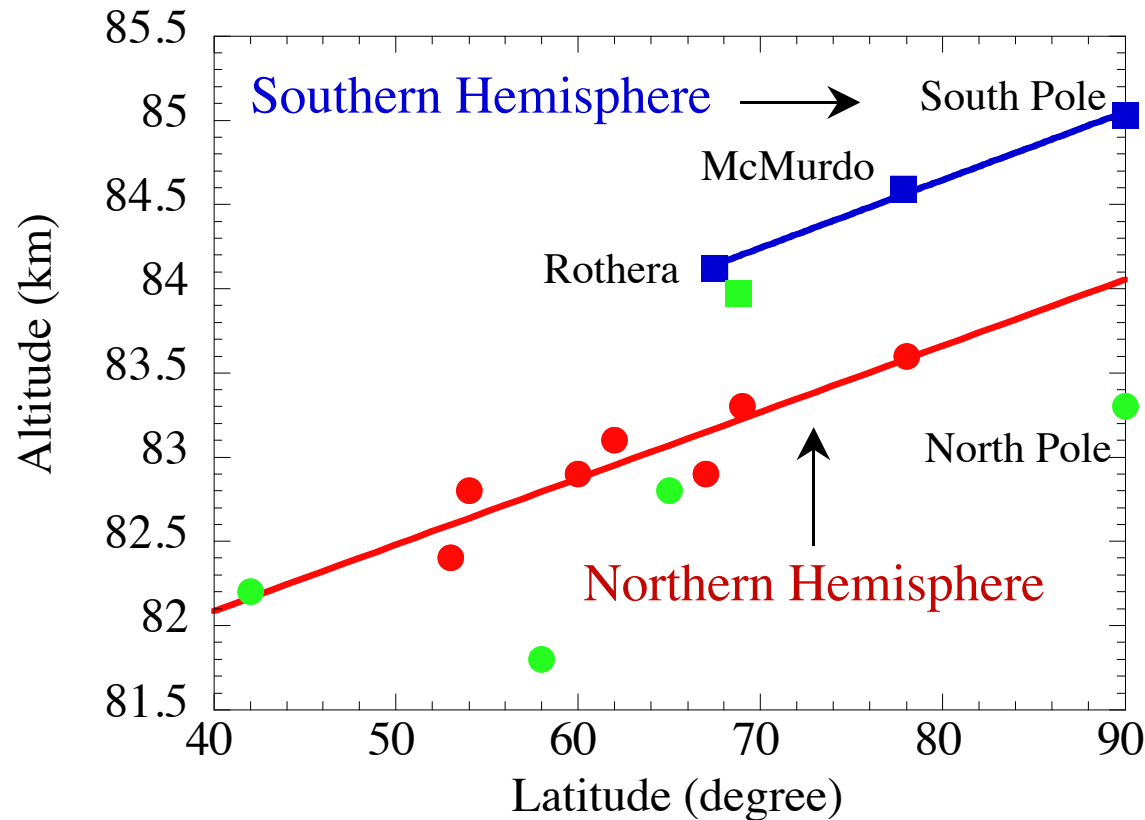
1) The primary cause is the ~6% more solar flux received during summer by the South Pole than the North Pole (Earth's orbital eccentricity) → Higher Z_{MP} & Z_{PMC}

2) Gravity wave differences & inter-hemispheric coupling → large inter-annual and seasonal variations of PMC

3) Stronger upwelling towards the pole in summer → higher Z_{PMC} at higher latitude

Inter-hemispheric Difference: Southern PMC are ~ 1 km higher than PMC in NH, confirming previous reports by Chu et al. [2001, 2003, 2004 and 2006].

Latitudinal Dependence: PMC altitude increases with latitude at a statistically significant rate of 40 ± (3−19) m/deg in SH, and 39 ± 8 m/deg in NH.

[Chu et al., GRL, 2011a]

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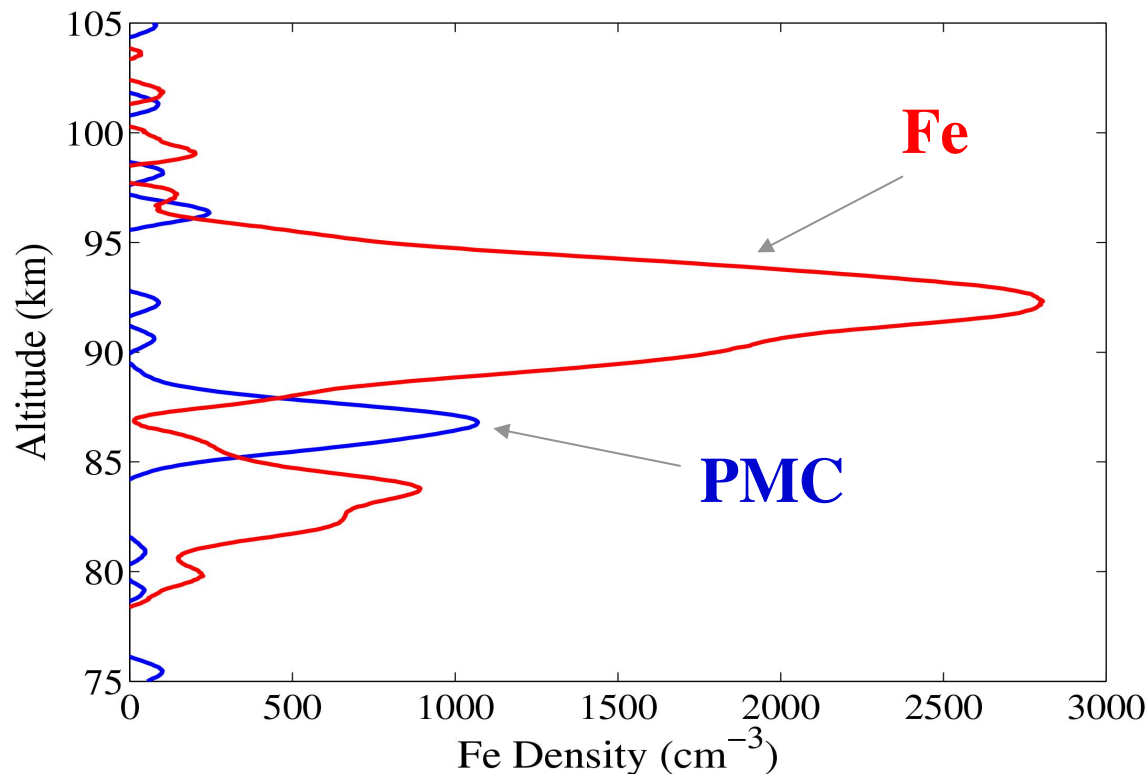
Results show that for the case with 6% more solar flux, the mesopause altitude moved upward by ~1 km and cooled by ~5 K.

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

Neutral Temperature (K)

(a)

(b)

NCAR TIME-GCM

15
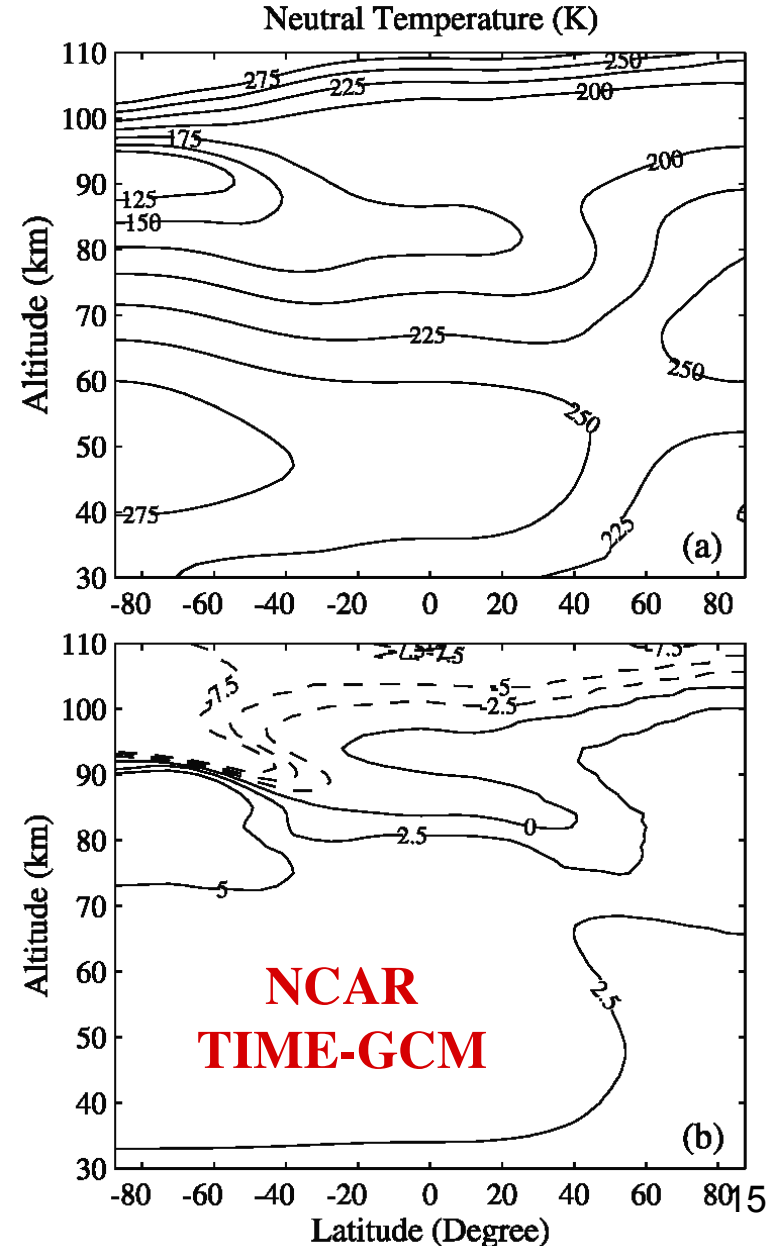
PMC Chemistry Role: Heterogeneous Removal of Metal Atoms by PMC

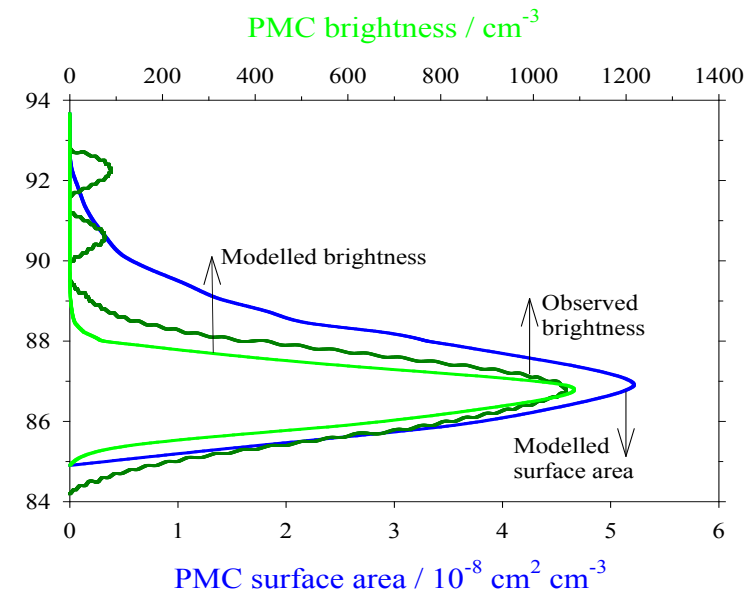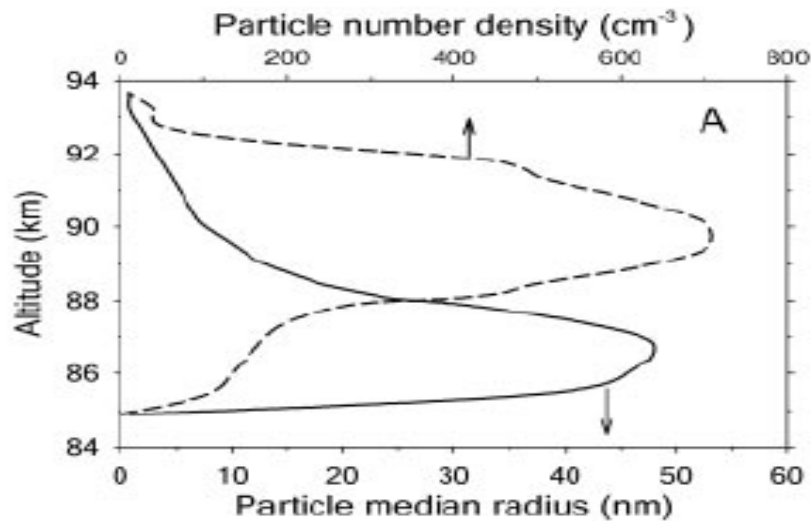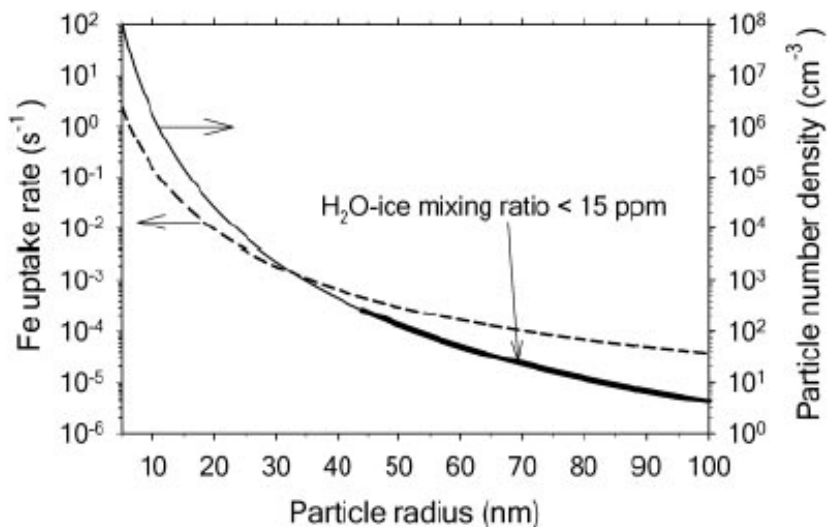**Plane, Murray, Chu, and Gardner,** *Science, 304*, **426-428, 2004**

Fe ablation flux = 1.1 x 10^4 atoms cm^{-2} s^{-1}
Uptake coefficients of Fe and Fe species on ice = 1

16

Modeling Depletion

Uptake coefficients of Fe on ice = 1

PMC brightness / cm^{-3}

Modelled brightness

Observed brightness

Modelled surface area

PMC surface area / 10^{-8} cm^2 cm^{-3}

H$_2$O-ice mixing ratio < 15 ppm

(c)

January (with PMC):
lidar
modelled

Late February:
modelled
lidar

[Fe] / cm^{-3}
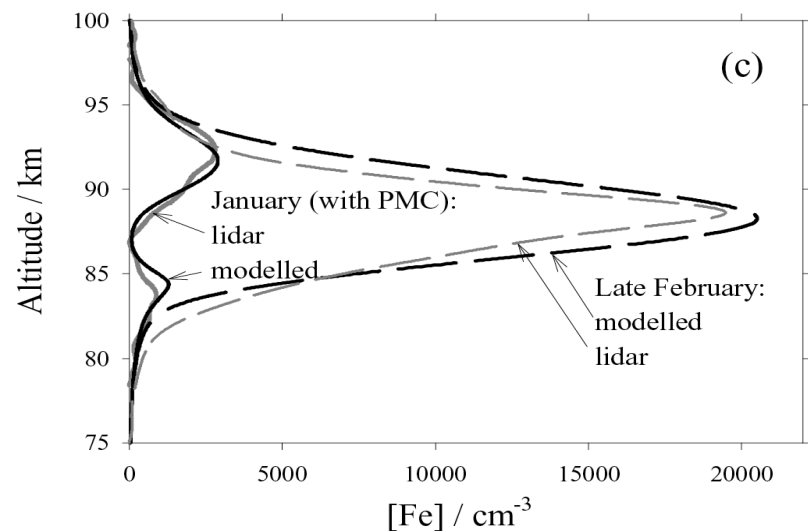
PMC Brightness is Anti-Correlated with Daily-Mean Temperature

R = −0.756

Daily-mean temperature @ 90 km

Does this result contradict Lübken et al., [1996] findings from rocket obs. of temp & lidar obs. of NLC?

"There is no apparent correlation between the conditions at the mesopause and the occurrence of NLC at lower altitudes."

The answer is NO. Two results are indeed consistent with each other. It is the difference between instantaneous measurements and daily-mean temperatures.
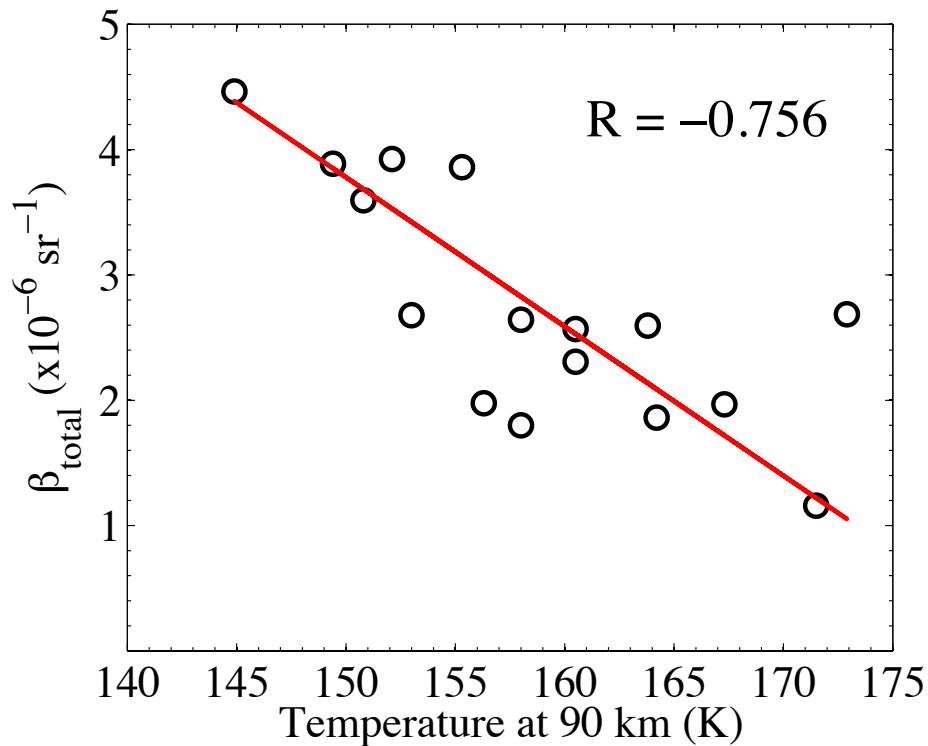
➤ The 90 km is chosen because it is above PMC occurrence height (avoiding PMC contamination) and close to the Fe peak (yielding accurate temp measurements).

➤ The daily-mean temperatures represent the background temperatures with the wave-induced oscillation smoothed out.

18

Temp Cold Phase Facilitates PMC Formation and Fe Depletion

(a) 372-nm Fe Density on 28-29 Jan 2011

(b) 374-nm Fe Density on 28-29 Jan 2011

(c) Fe Temperature on 28-29 Jan 2011
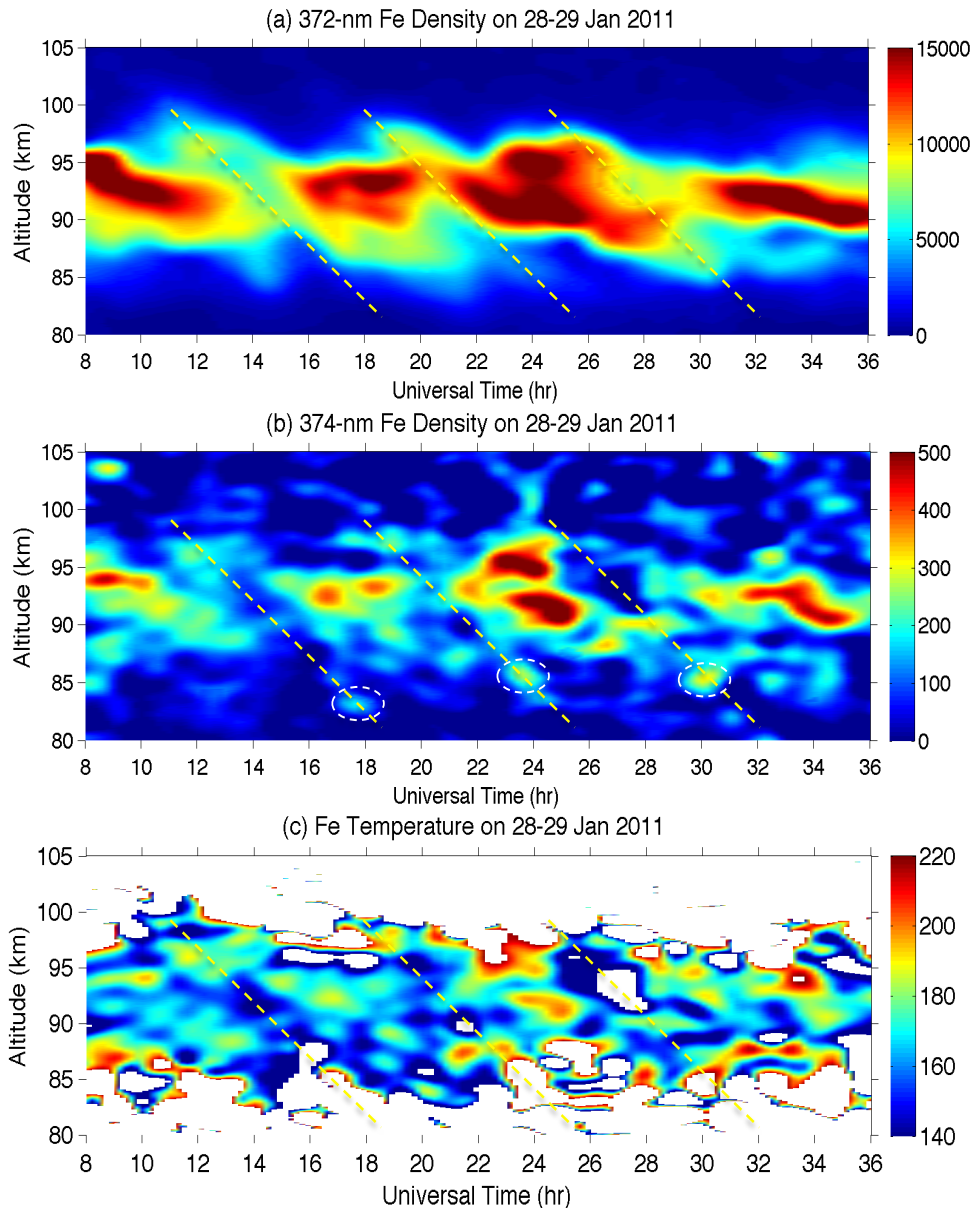
First direct evidence to support the modeling prediction by Rapp et al. [2002]: PMC formation is facilitated by the cold phase of wave-induced temp oscillation.

[Chu et al., First lidar observations of polar mesospheric clouds and Fe temperatures at McMurdo, Antarctica, *GRL,* 2011a]

19

PMC vs. Dynamics: Tidal Variations


Andoya

Rothera

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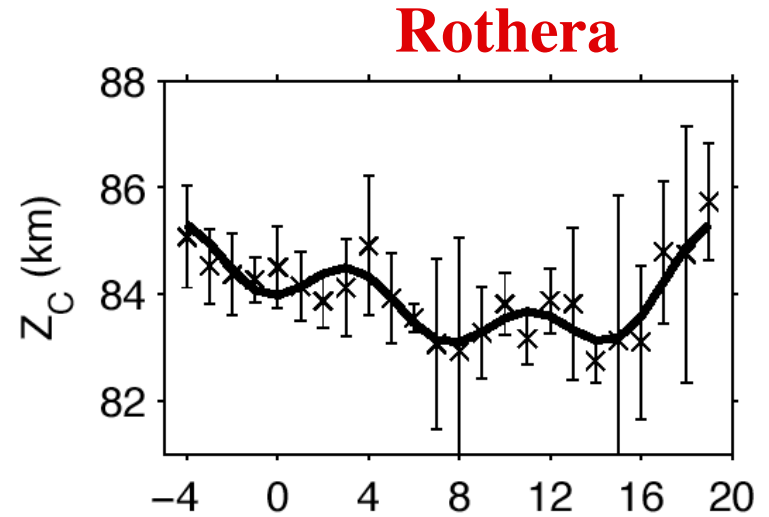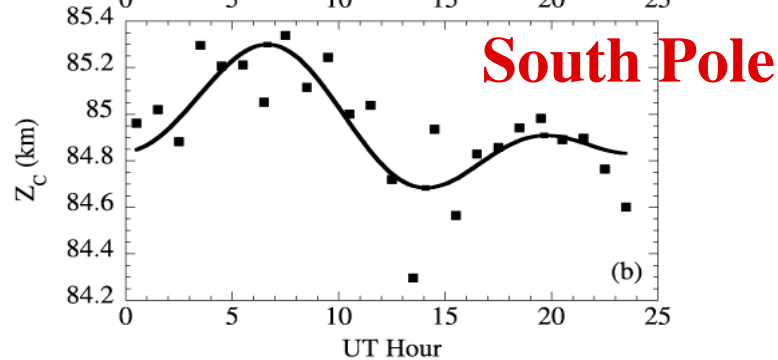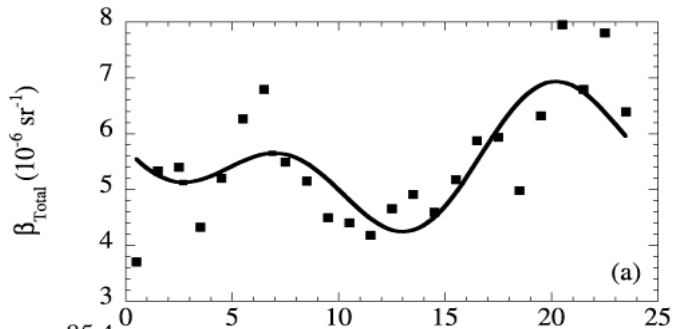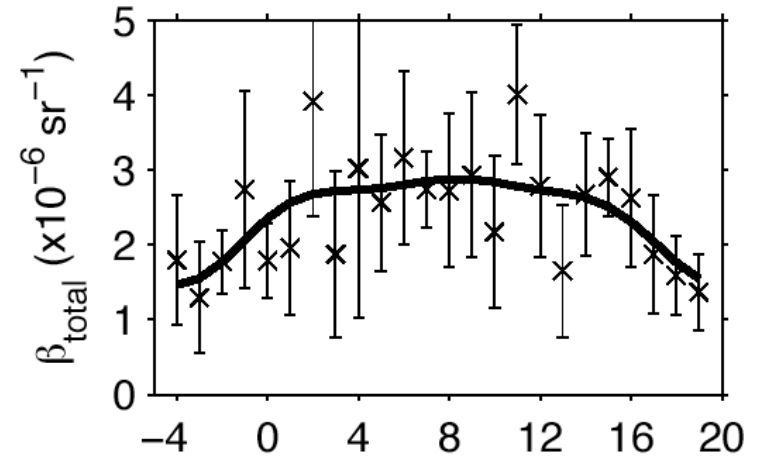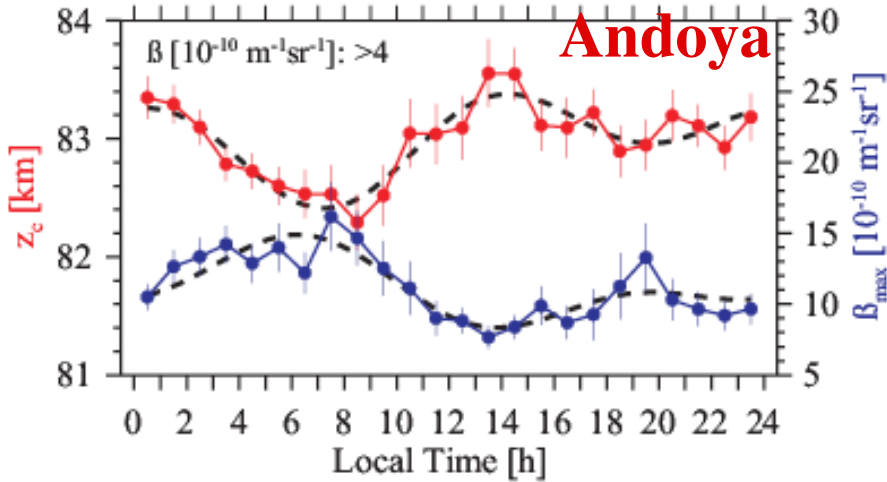
[Fiedler et al., EGU, 2005]
[Chu et al., JGR, 2003, 2006]

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.
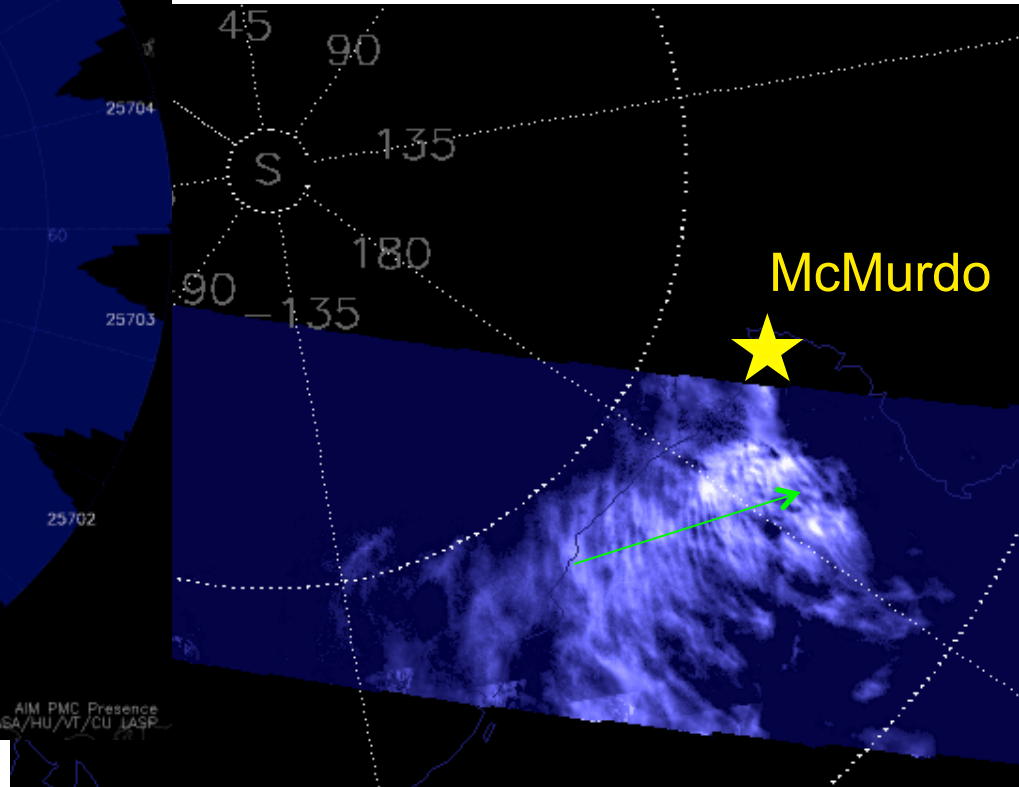

[Gerrard, Kane, Thayer, GRL, 1998]
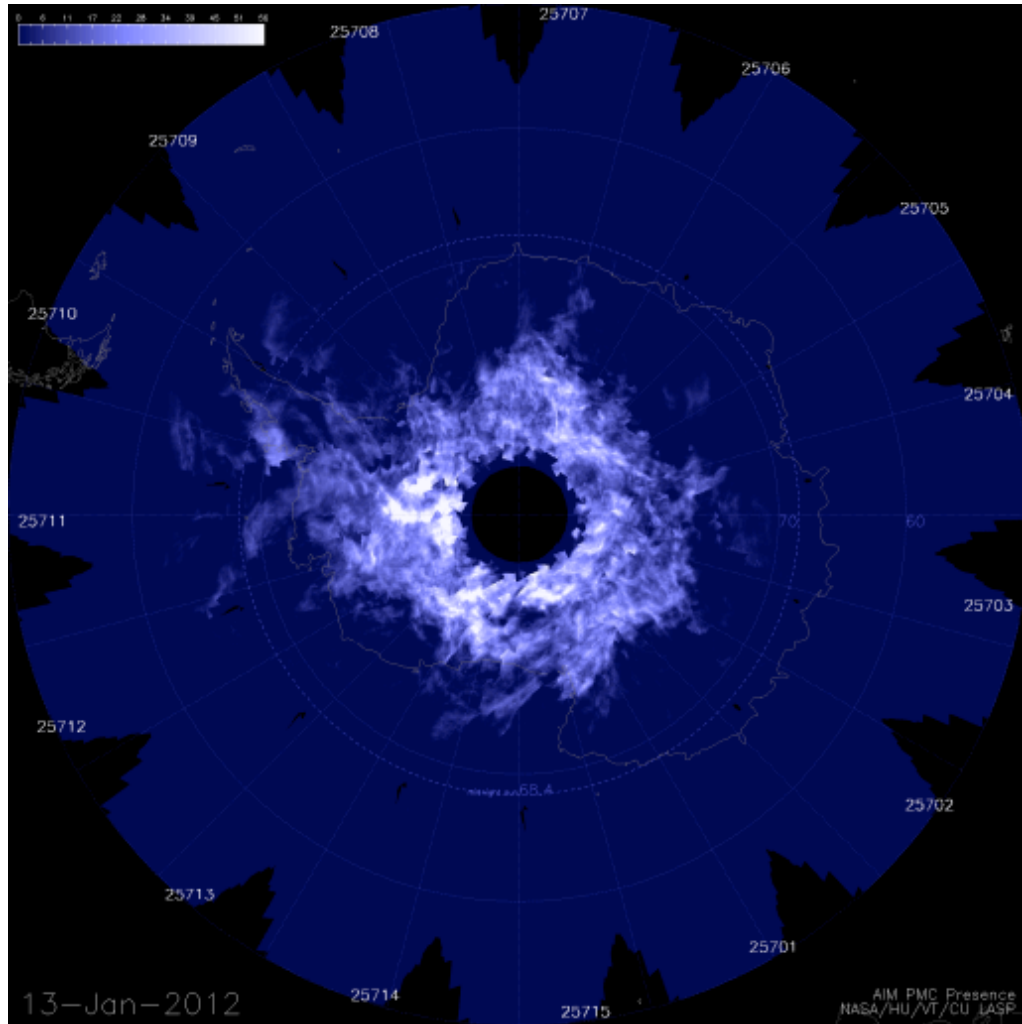
South Pole (90S)
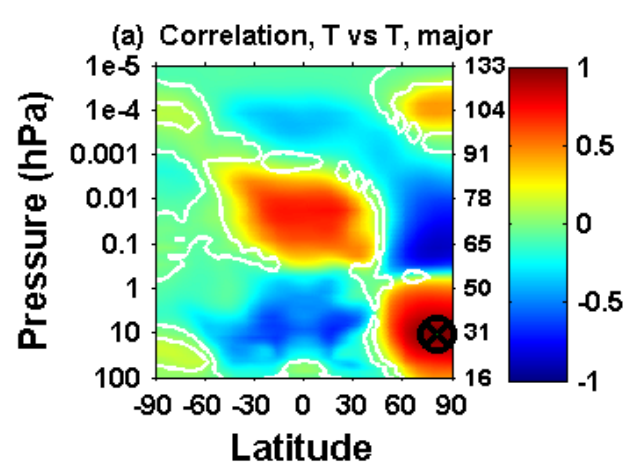

Rothera (67.5S)
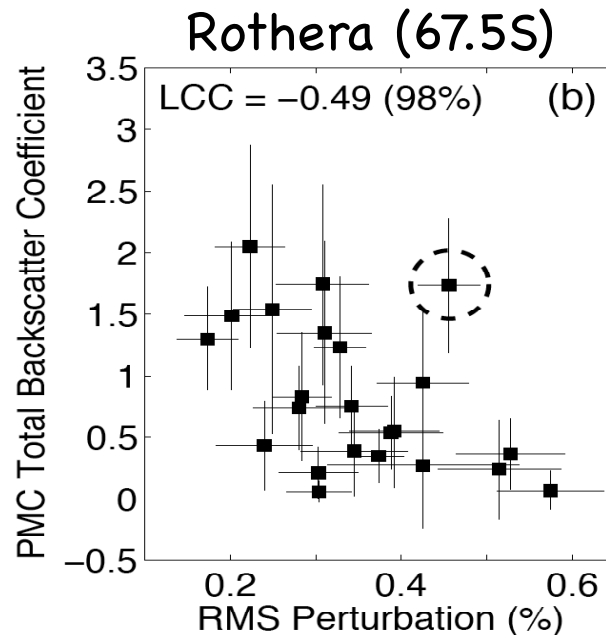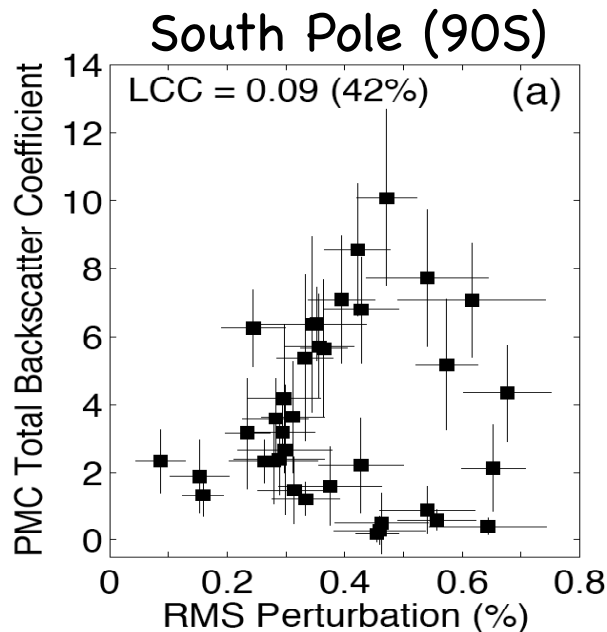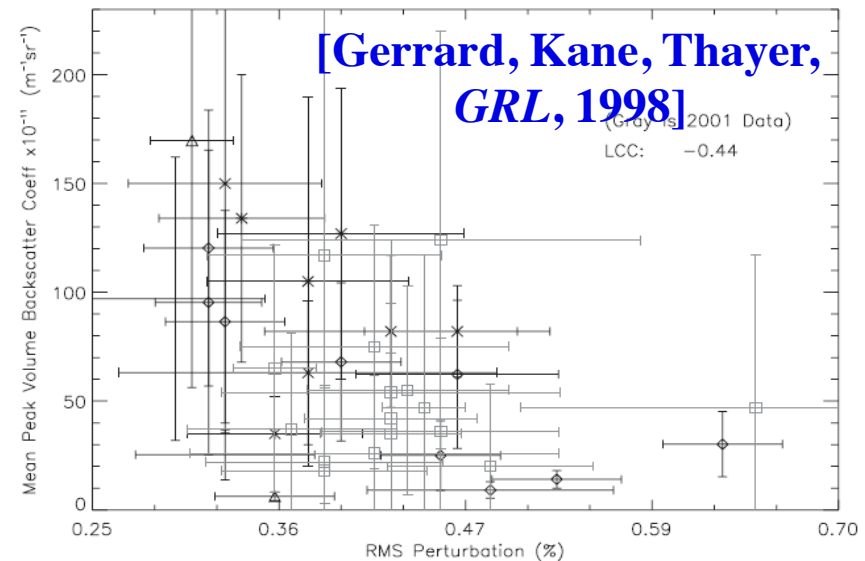
[Chu, Yamashita, et al., JASTP, 2009]

21

PMC Images by AIM-CIPS

NASA AIM Mission
Aeronomy of Ice in
the Mesosphere

McMurdo

13-Jan-2012

http://lasp.colorado.edu/aim/browse-images.php

22

Inter-hemispheric Coupling vs. PMC Inter-annual & Intra-Seasonal Variations
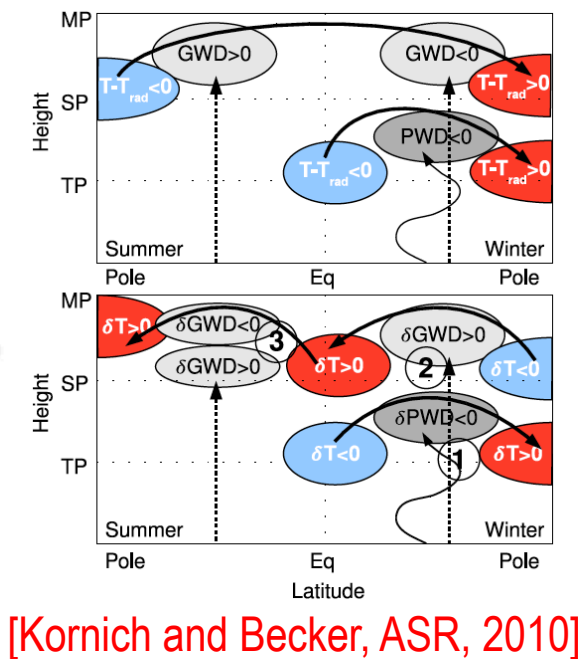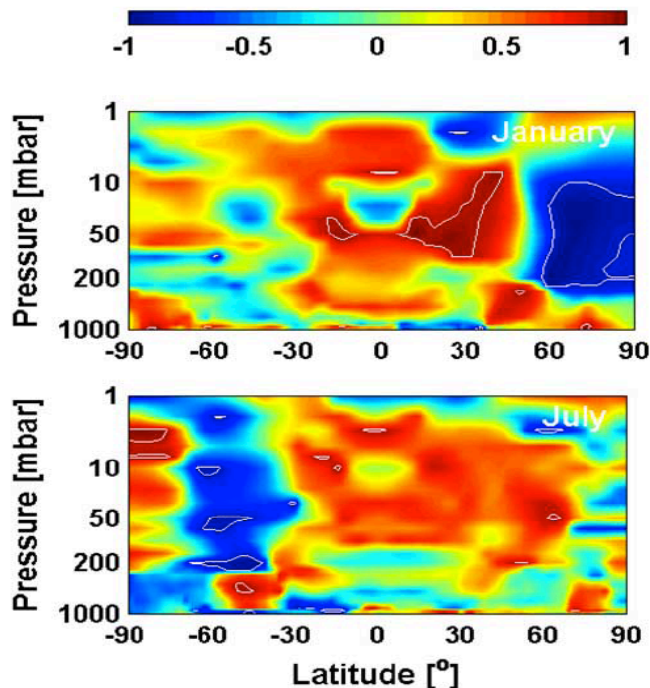
[Tan et al., 2012]

[Kornich and Becker, ASR, 2010]
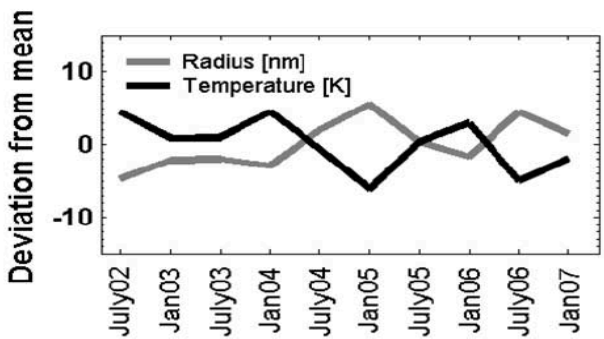
[Karlsson et al., GRL, 2007]

Inter-hemispheric stratosphere-mesosphere coupling (Tele-connection between two hemispheres by planetary and gravity waves)

Winter stratosphere temperature is anti-correlated with the summer mesospheric clouds occurrence.

Teleconnection also exists in the thermosphere.

23

Multi-Wavelength Lidar Detection

❑ 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.

24
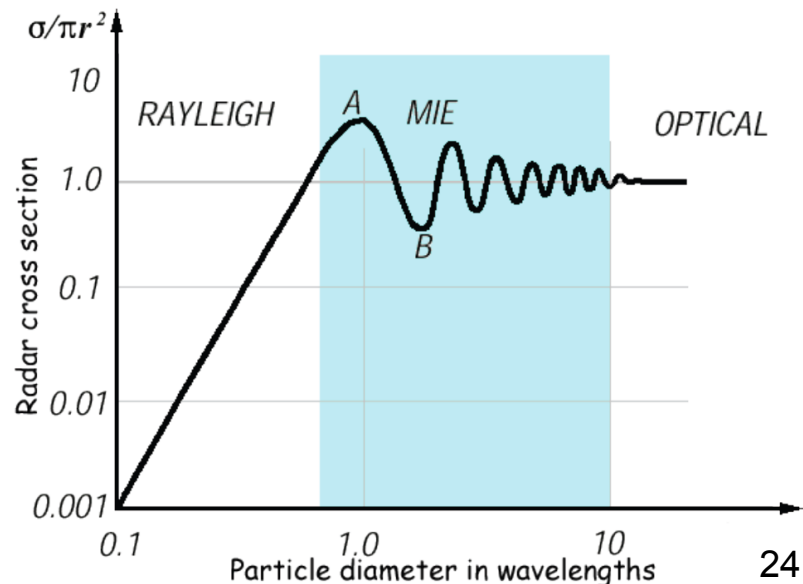
PMC Microphysics: Particle Size
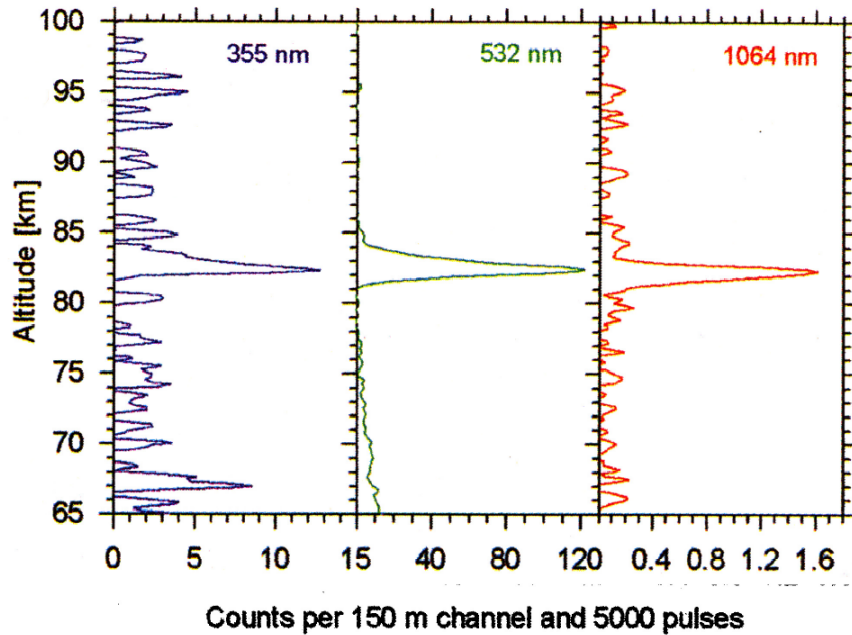
**3-Color Lidar Observations
at ALOMAR, Andoya
[von Cossart et al., GRL, 1999]**

Color Ratio is defined as

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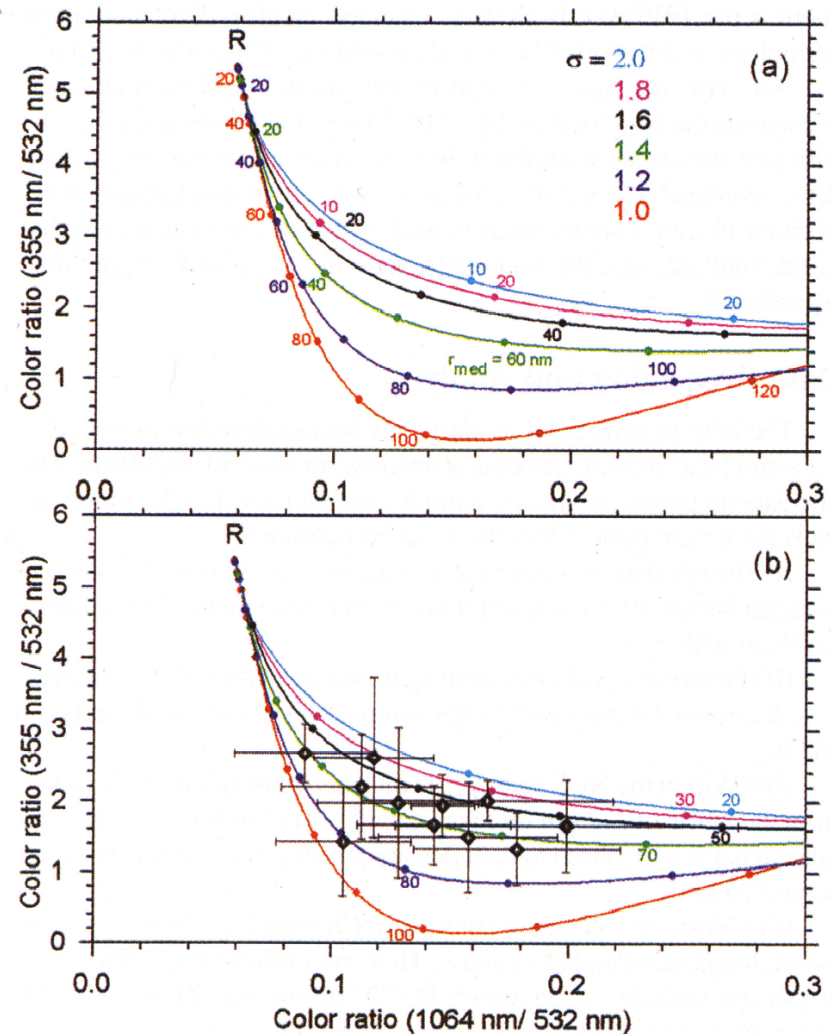

Figure 1. Panel (a) shows as a result of Mie calculations for the color ratios *CR* of used laser wavelengths a set of color coded curves for constant σ and r_{med}. In panel (b) the derived color ratios of the 11 NLC events are plotted in the field of the modelled color ratios.

25

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 Shape	**Baumgarten et al., Ice Layer Workshop, 2006**
2003	**51±6**	**18±2**	**74±19**		
2004	**46±3**	**18±1**	**94±12**	Gaussian Distribution	
2005	**46±3**	**17±1**	**113±18**		

26

Non-spherical Particle Considerations
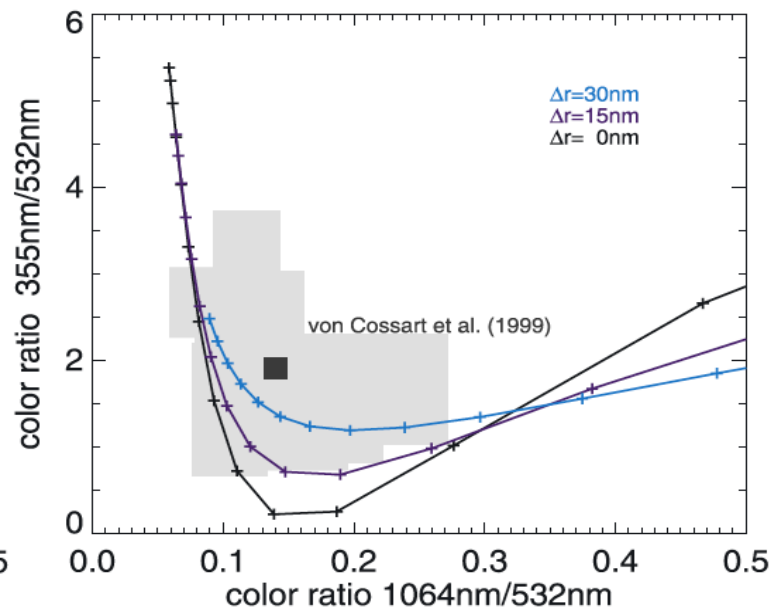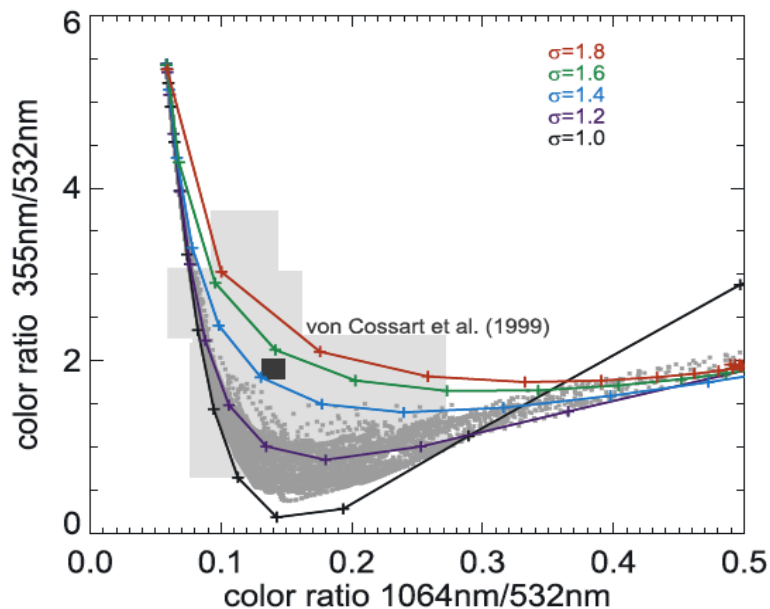
[Rapp et al., JGR, 2007]

27
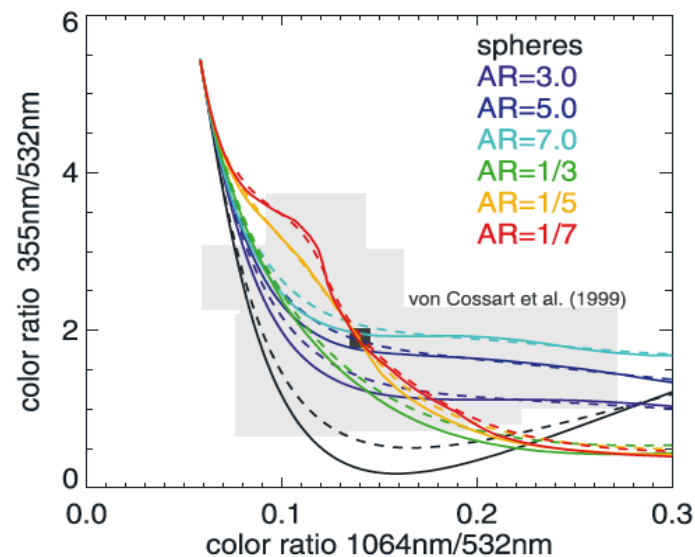
Polarization in Scattering

❑ 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

August 3, 2000 / 22:07 - 23:21
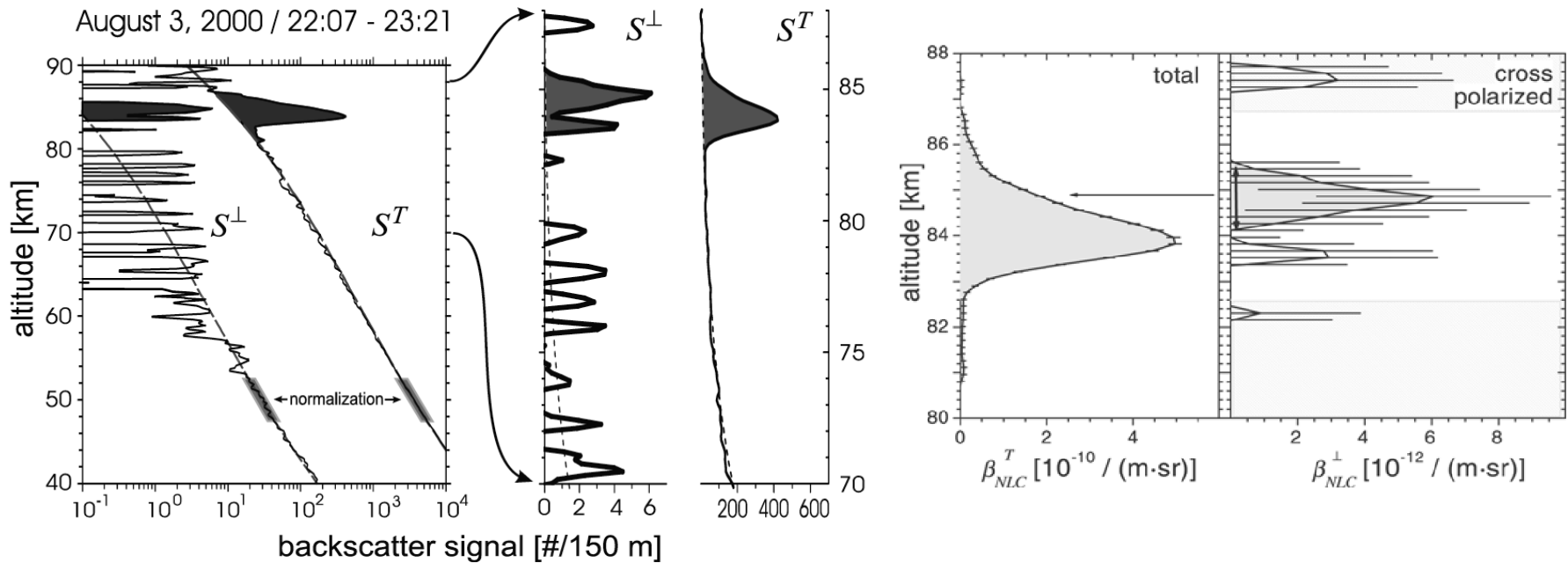
Depolarization Factor $\quad \delta_{NLC}(z) = \dfrac{\beta_{NLC}^{\perp}(z)}{\beta_{NLC}^{\parallel}(z)} = \dfrac{\beta_{NLC}^{\perp}(z)}{\beta_{NLC}^{T}(z) - \beta_{NLC}^{\perp}(z)}$

$$\delta(R) = \frac{P_{\perp}}{P_{\parallel}} = \frac{I_{\perp}}{I_{\parallel}}$$

Between 84.2-85.5km, δ_{NLC} = (1.7±1.0)%

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

[Baumgarten et al., GRL, 2002]

29

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 SH; 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**
Interhemisperhic coupling (PMC-NH stratosphere)	*Karlsson et al.*, GRL, **2007**

31

Summary

❑   Aerosol is an important topic in atmospheric science and environmental research. It can be measured/monitored by hot lidar technologies.

❑   Polar Mesospheric Clouds (PMC) 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 inter-annual variations in both hemispheres, providing a great opportunity to study the gravity, tidal, and planetary waves as well as inter-hemispheric coupling in the polar atmosphere.