Characterizing the Vertical Distribution of Aerosols over the ARM SGP Site

Richard Ferrare[a], David Turner [b], Marian Clayton[c], Mian Chin[d], Sarah Guibert[e], Michael Schulz[e]

[a] *NASA Langley Research Center, Hampton, Virginia*
[b] *Pacific Northwest National Laboratory, Richland, Washington*
[c] *Science Applications International Corporation, Hampton, Virginia*
[d] *NASA Goddard Space Flight Center, Greenbelt, Maryland*
[e] *Laboratorie des Sciences du Climat et de l'Environment, CEA/CNRS-LSCE, France*

AEROCOM Meeting, December 3, 2004

Outline

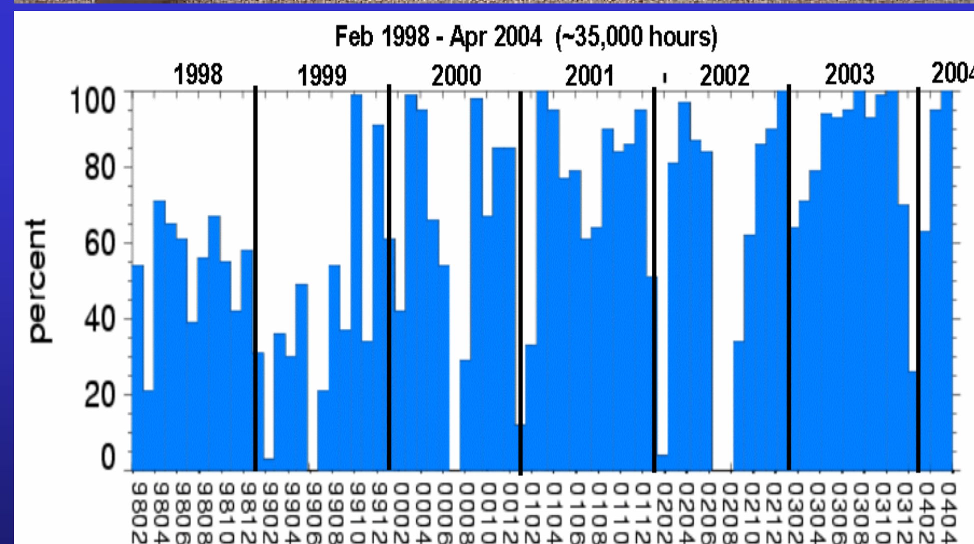
- DOE ARM SGP CRF Raman Lidar System
- Aerosol and Water Vapor Measurements
- AEROCOM comparisons
- Additional aerosol measurements at ARM SGP

Acronyms

DOE = Department of Energy
ARM = Atmospheric Radiation Measurement
SGP = Southern Great Plains
CRF = Climate Research Facility
CARL = CRF Raman Lidar

CART Raman Lidar (CARL)

- DOE ARM SGP CF site (Lamont , Oklahoma) (36^{o} 37 ' N, 97^{o} 30 ' W)
- Nd:YAG (355 nm) (day/night)
- Wavelengths
  - Rayleigh/Mie (355 nm)
  - Depolarization (355 nm)
  - Raman water vapor (408 nm)
  - Raman nitrogen (387 nm)
- 39 meter range resolution
- water vapor and aerosol profiles
- precipitable water vapor and aerosol optical thickness
- aerosol and cloud depolarization
- designed for continuous, autonomous operation



Additional information: http://www.arm.gov/docs/instruments/static/rl.html

(Turner et al., JAOT, 2002)

CART Raman Lidar/AERI+Model Clear-Sky Product

Data: available via ftp from ARM Experiment Center (http://www.arm.gov)

Color images at: http://playground.arm.gov/~turner/raman_lidar_quicklooks.html

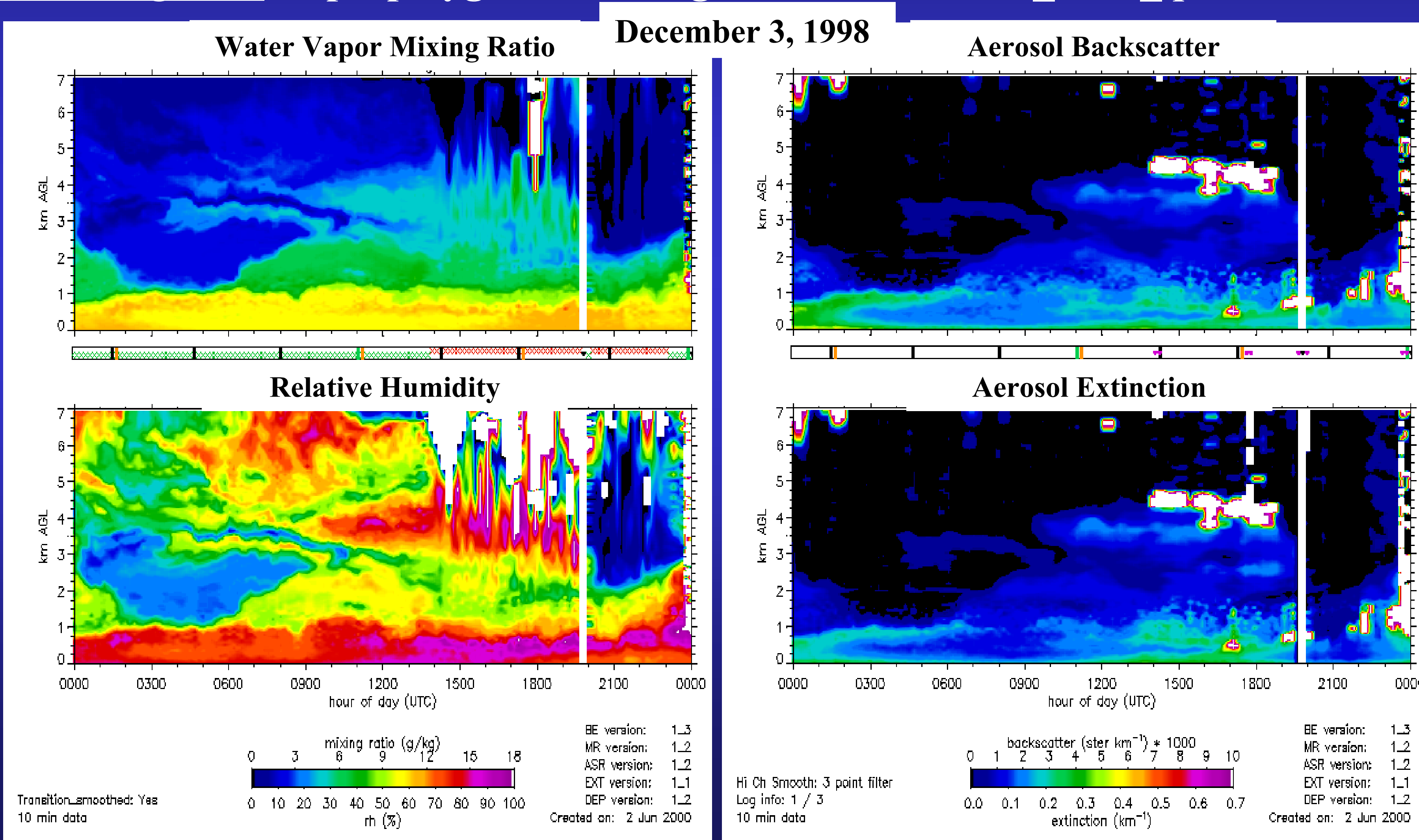
Measurement	Altitude Range	Vertical Resolution	Nominal Temporal Resolution	Error	Precision	Detection Limit
Aerosol Backscattering (355 nm)	0.060-8 km	78 m	10 min	0.0005 $(km\text{-}sr)^{-1}$ 5-10%	2%	0.0002-0.0004 $km\text{-}sr^{-1}$
Aerosol Extinction (355 nm)	0.1-8 km	150-500 m	10 min	0.03 km^{-1} 5-10%	5%	0.02-0.03 km^{-1}
Aerosol Optical Thickness (355 nm)	-	-	10 min	5% or 0.03	5%	0.03
Water Vapor Mixing Ratio	0.060-8 km (night) 0.060-4 km (day)	78 m	2-10 min	5%	2%	0.002 g/kg
Relative Humidity	0.060-8 km (night) 0.060-4 km (day)	78 m	2-10 min	5%	5%	1%
Precipitable Water Vapor	-	-	10 min	5%	5%	2 mm
Linear Depolarization	1-14 km	39 m	1-10 min	10%	2%	
Temperature (AERI+Model)	0-3 km (AERI) 3-15 (Model)	100 m - 1 km	8 min	1 K	1 K	
Cloud Base Height	0.060-14 km	78 m	1-10 min	78 m	39 m	0.060 km

CARL Aerosol and Water Vapor Profiles

Automated algorithms for routine retrievals of water vapor and aerosol profiles (Turner et al., *J. Atmos. Oceanic Tech.*, 19, 2002)

Data: available via ftp from ARM Experiment Center (http://www.arm.gov)

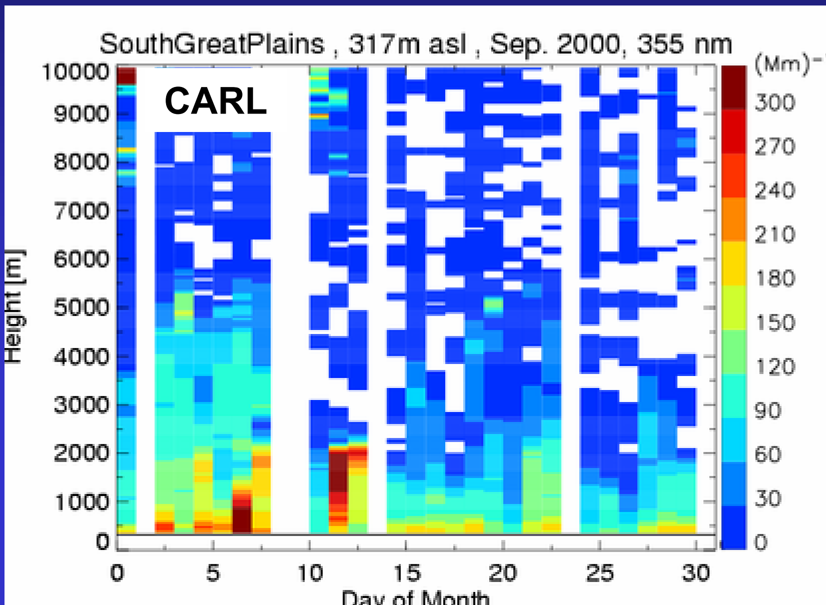
Color images at: http://playground.arm.gov/~turner/raman_lidar_quicklooks.html

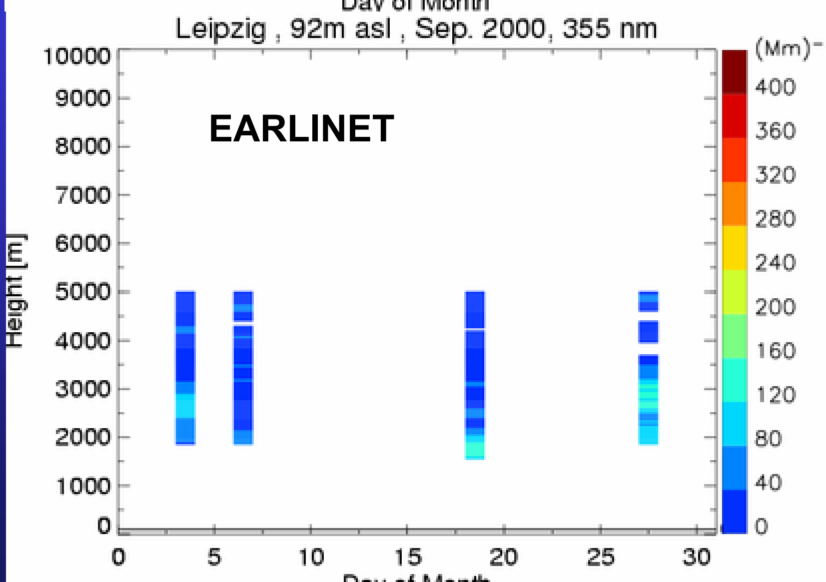


Continuous vs. Periodic Measurements

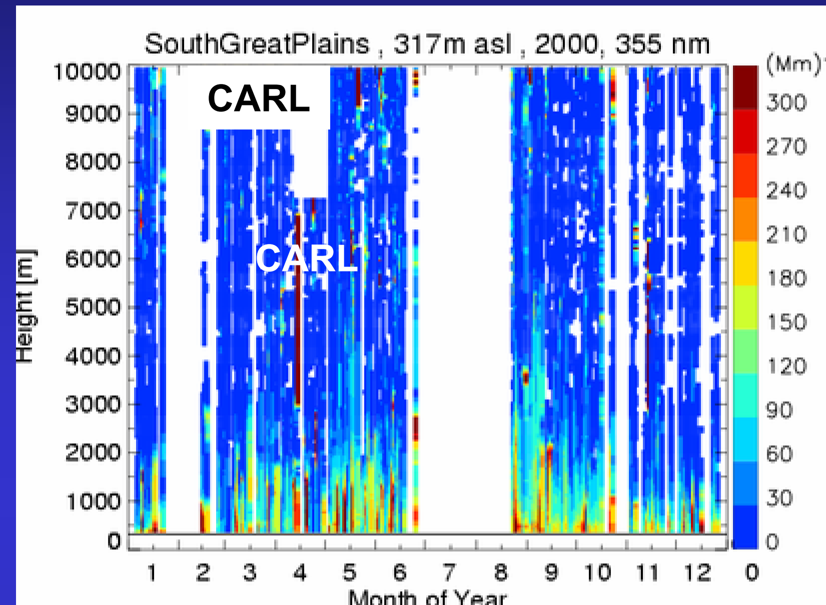
CARL – continuous
EARLINET – periodic

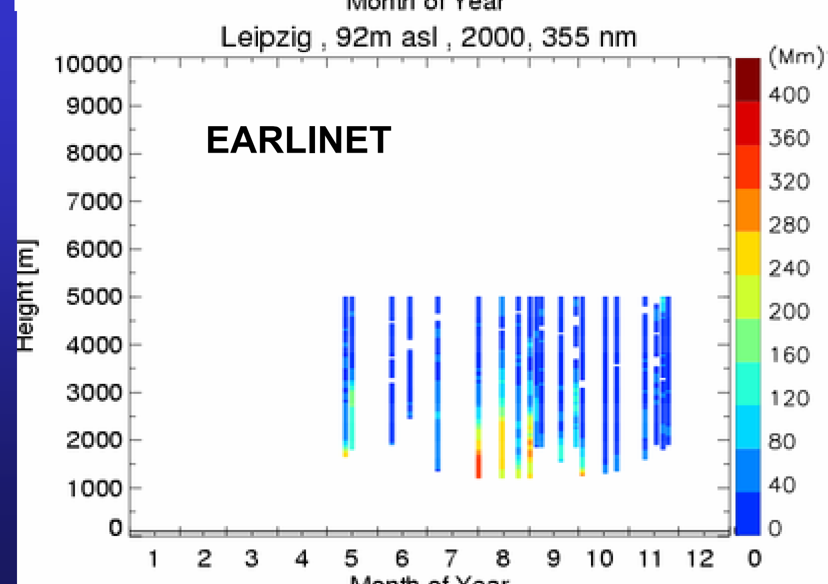
Monthly



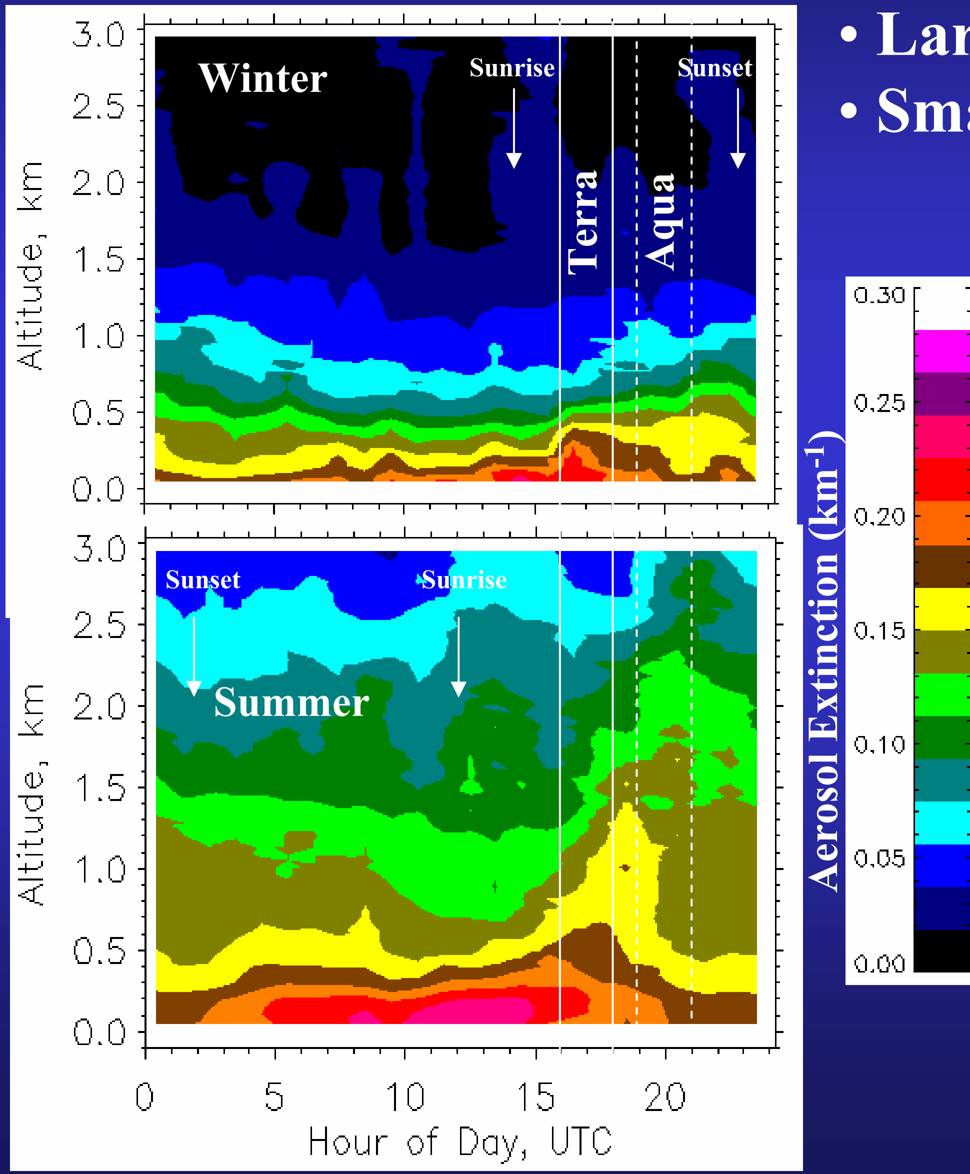


Yearly



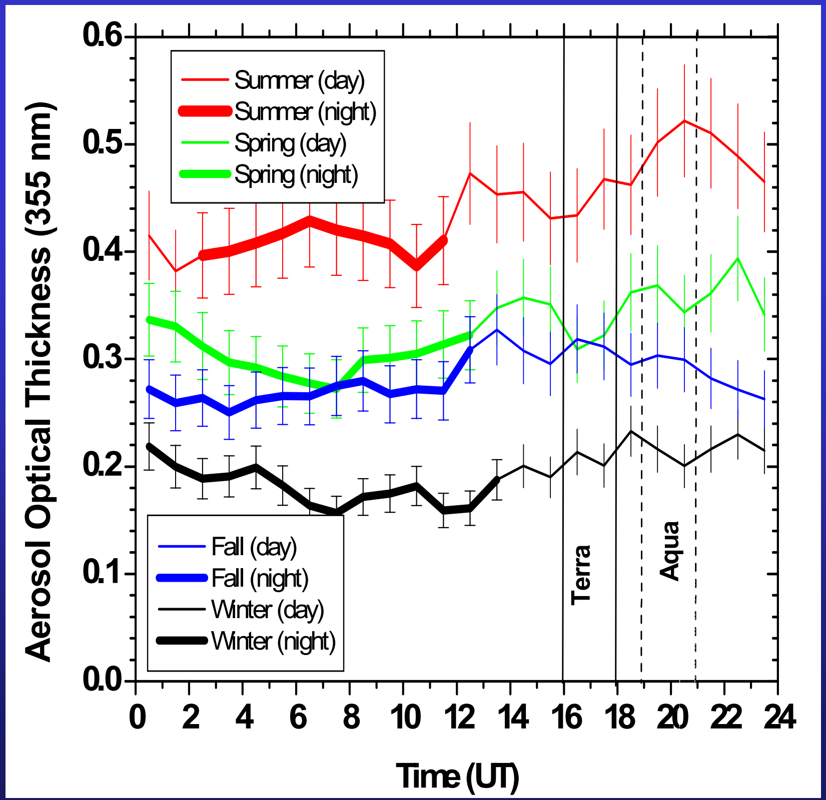


Average Diurnal Variation of Aerosol Extinction Profiles and AOT



- Large changes in vertical profile
- Smaller changes in AOT (st. dev ~ 10%)

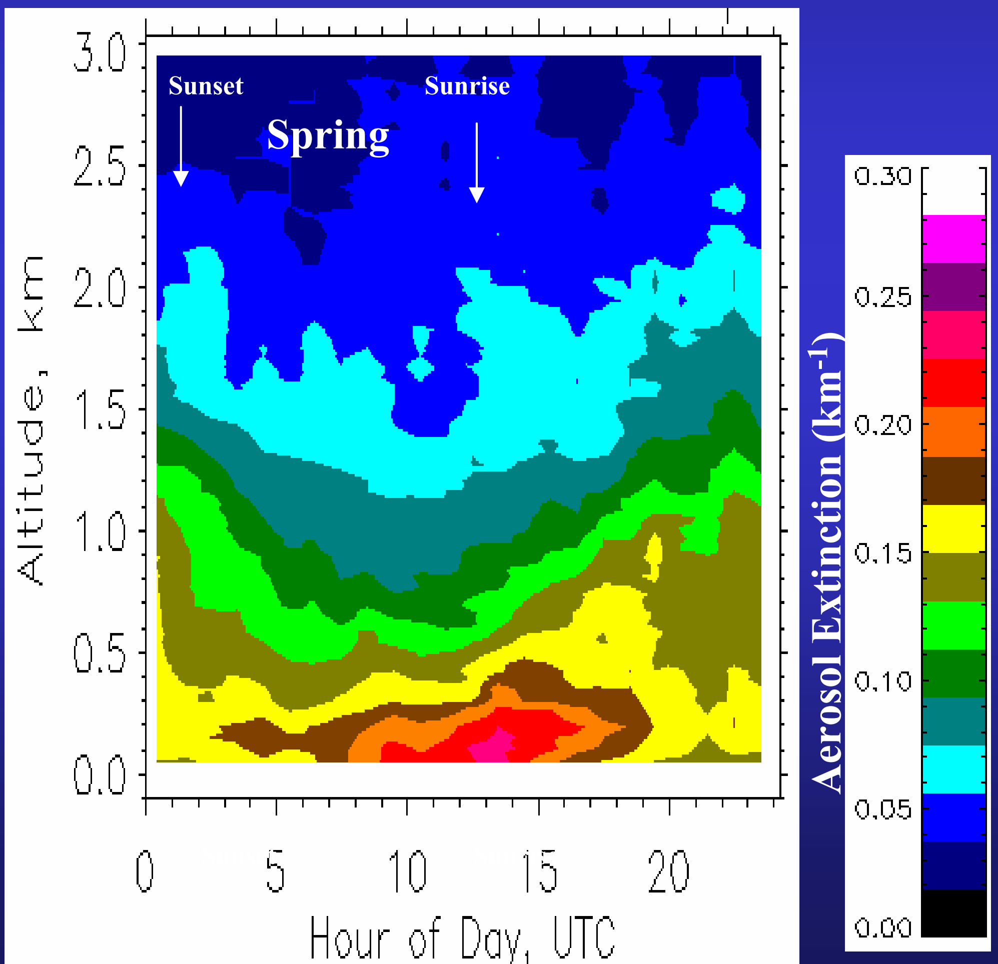
AOT



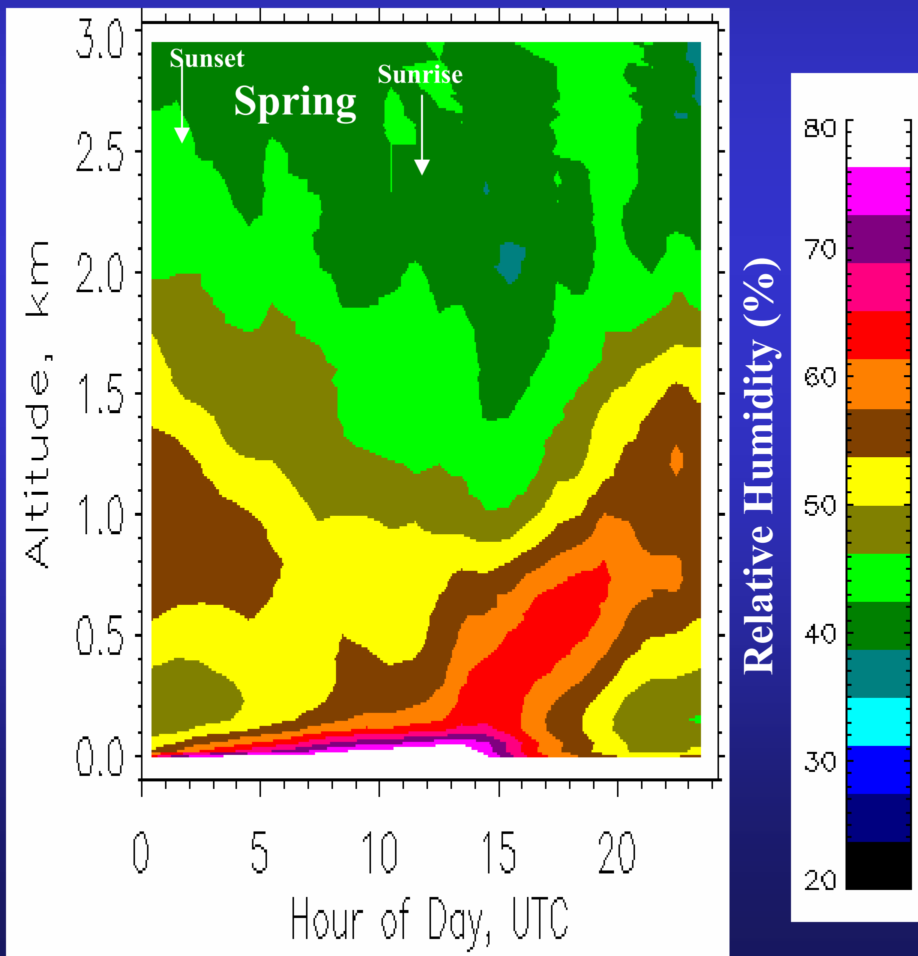
Correlation between Aerosol Extinction and Relative Humidity

- CARL aerosol extinction profiles averaged over 946 days (Mar. 1, 1998 – Dec. 31, 2001)
- Higher extinction concentrated over smaller vertical extent at night
- Highest aerosol extinction and RH found near surface at night

Aerosol Extinction

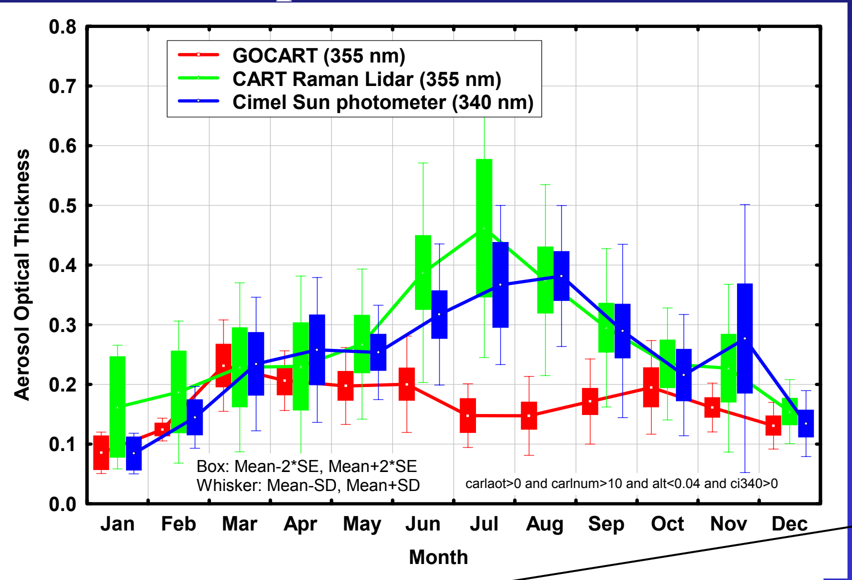


Relative Humidity



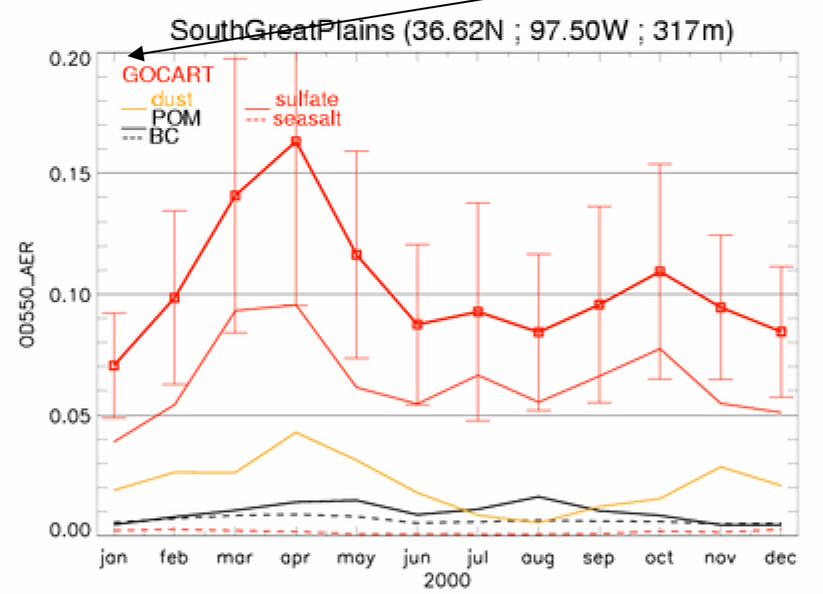
Observed versus Modeled Aerosol Optical Thickness

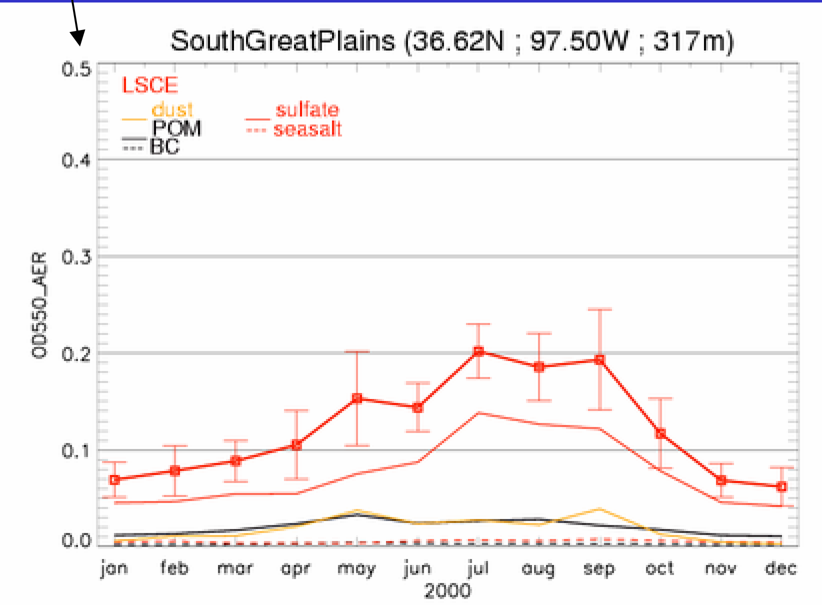
Initial Comparisons with GOCART and INCA (LSCE) models



- SGP data from 2000-2001
- GOCART reproduces AOT during Fall-Spring but misses Summer peak
- INCA shows Summer peak

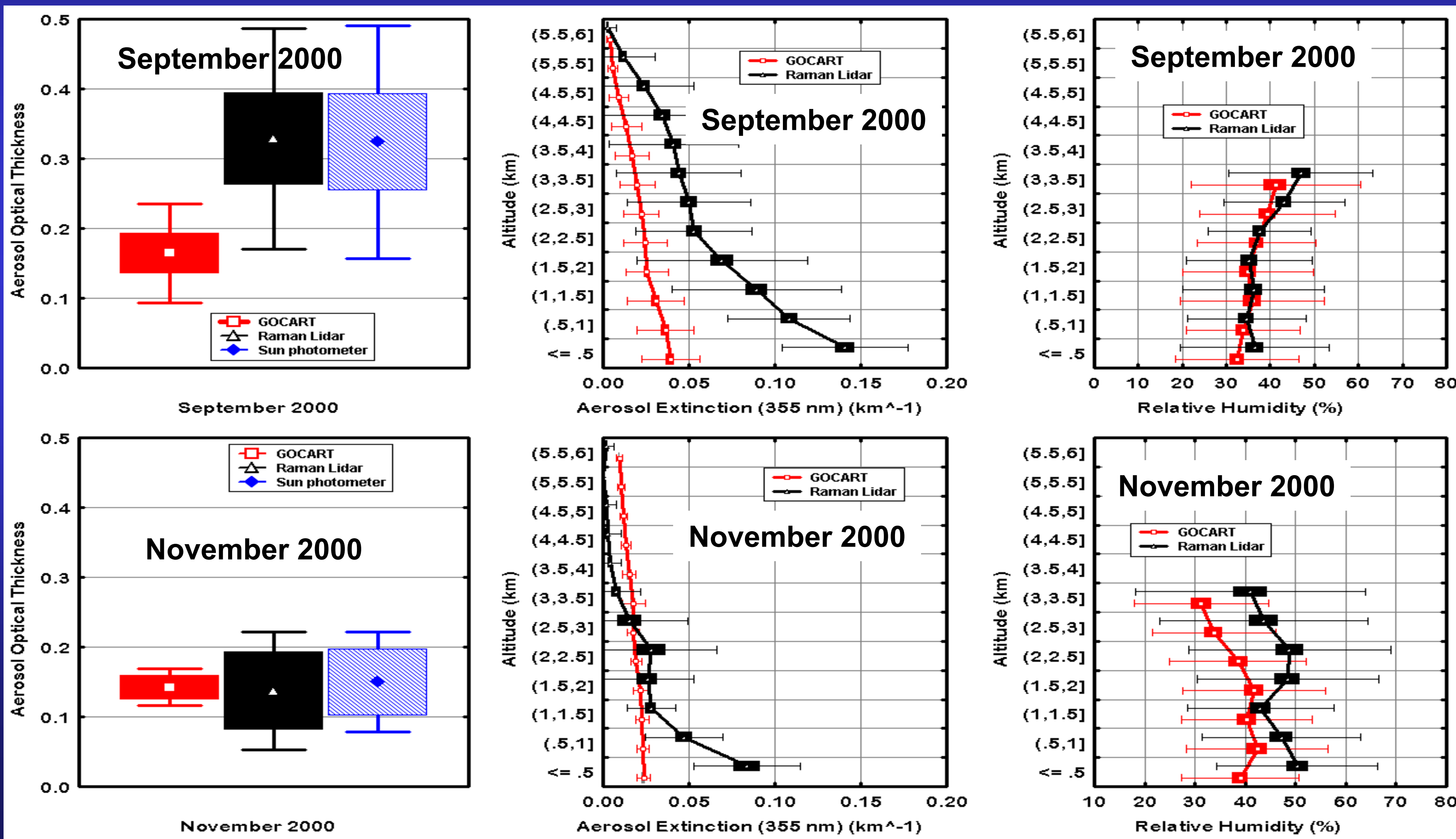
Note change in scales



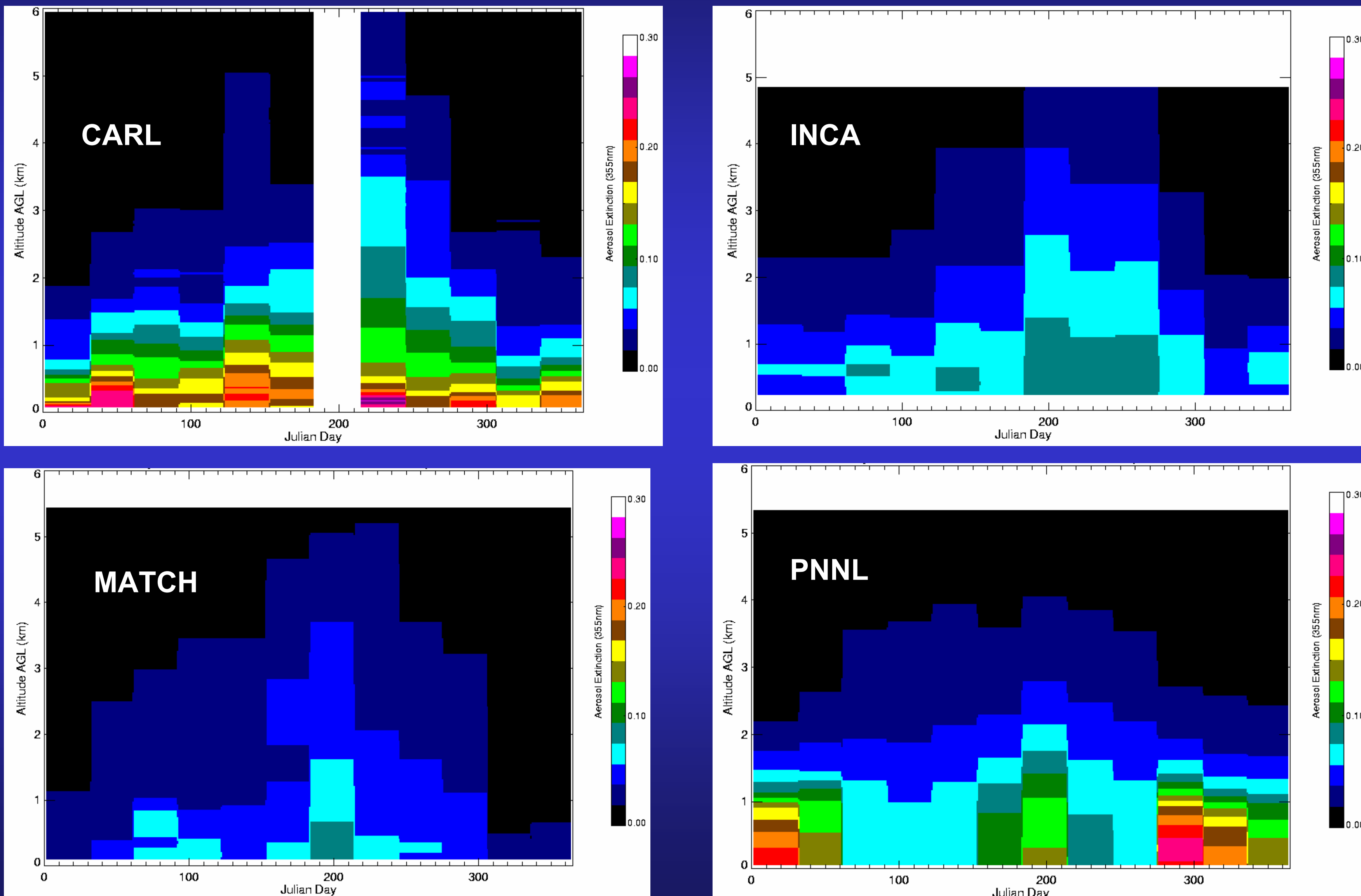


Observed versus Modeled Aerosol Profiles

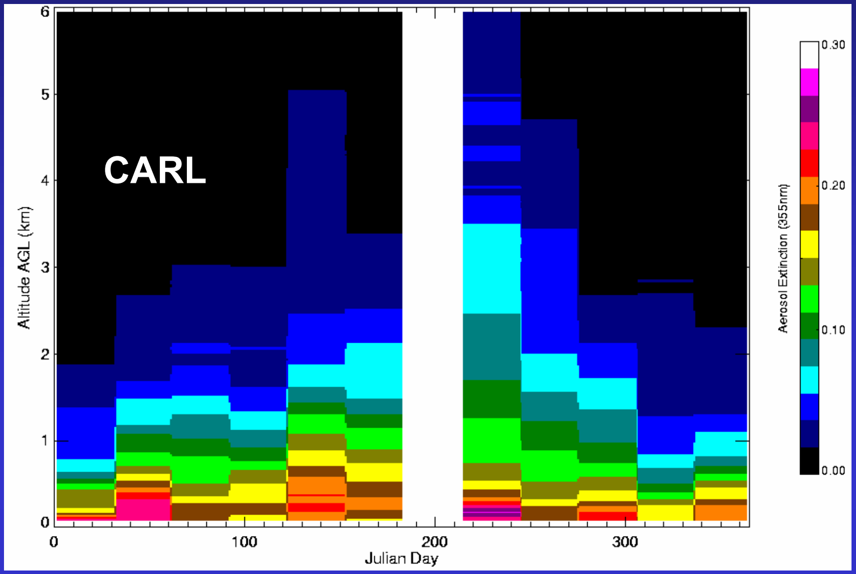
- **GOCART mean aerosol profiles show smaller vertical variability than the mean CARL observation**

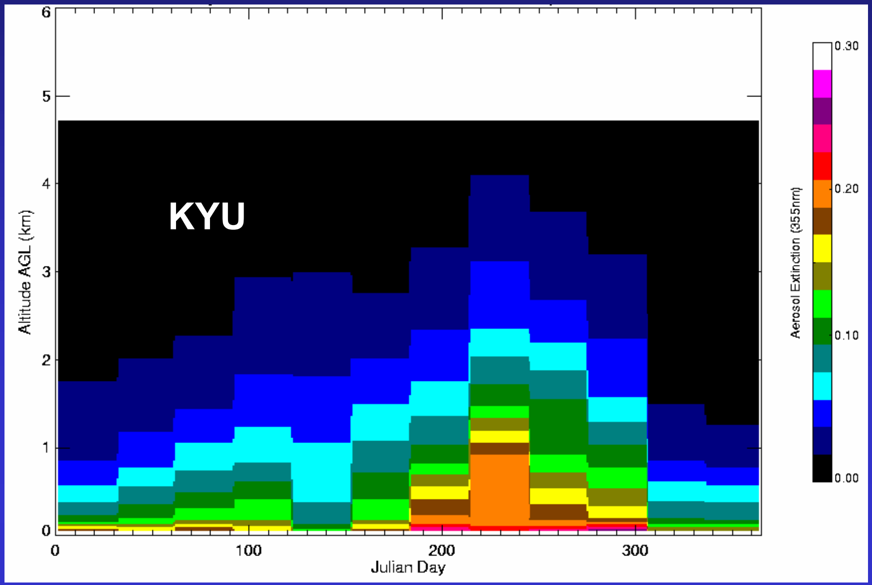


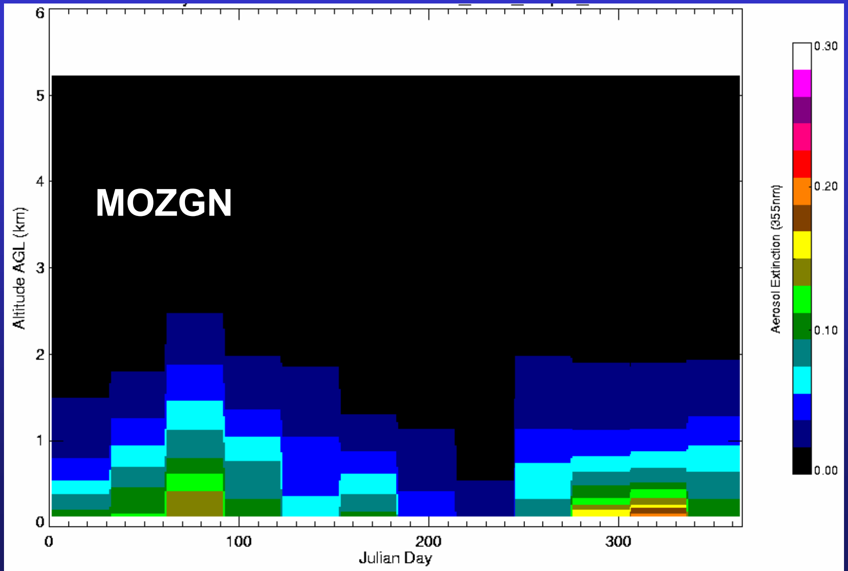
Measured versus Modeled Monthly Average Aerosol Profiles

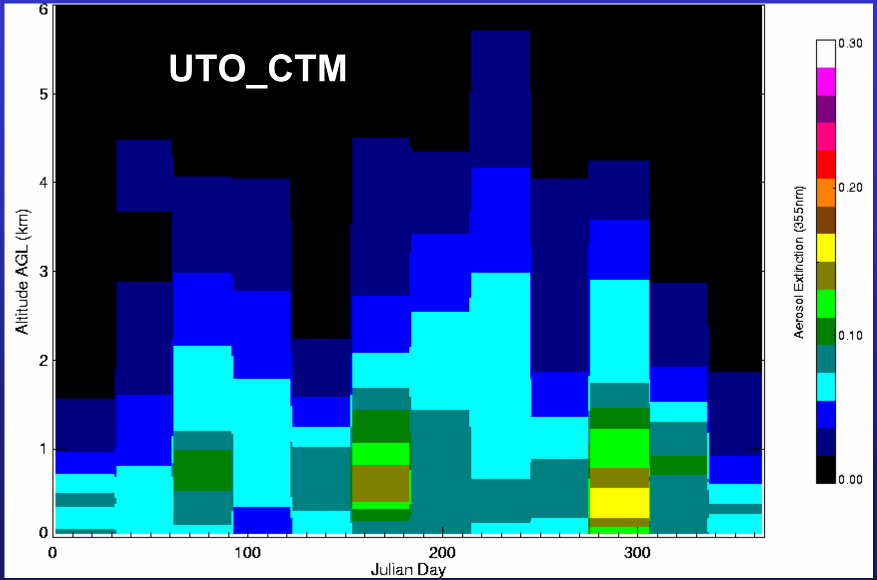


Measured versus Modeled Monthly Average Aerosol Profiles



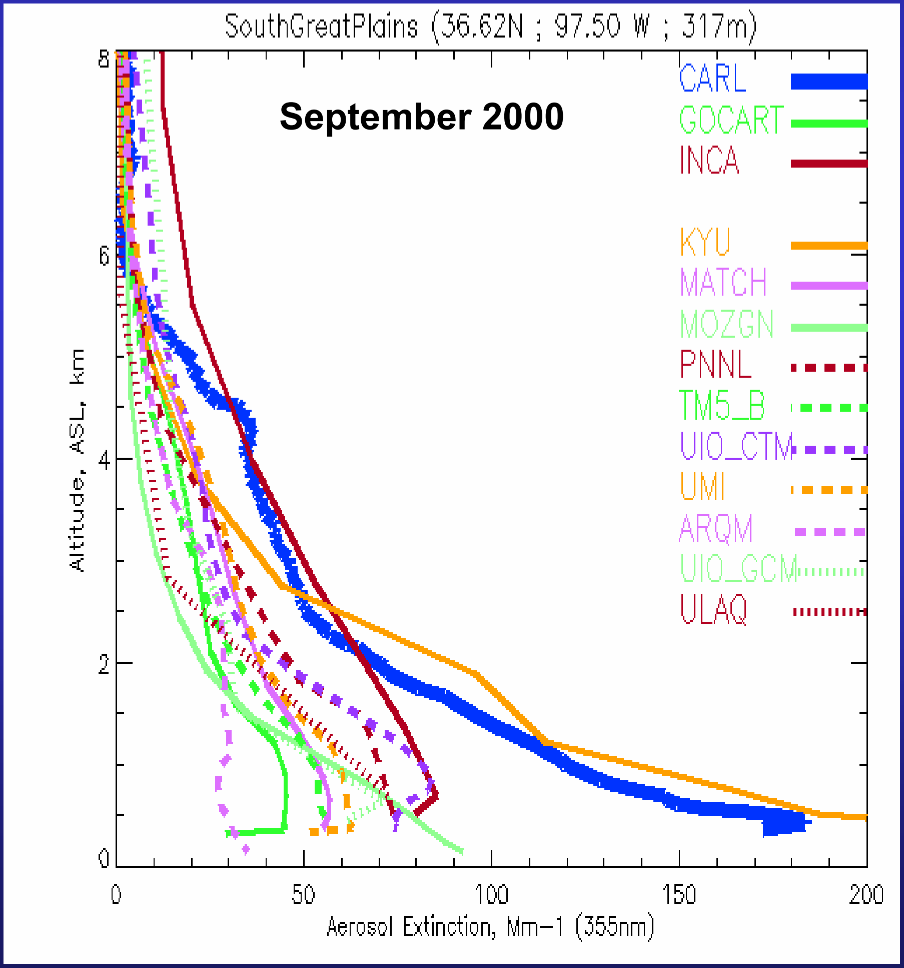


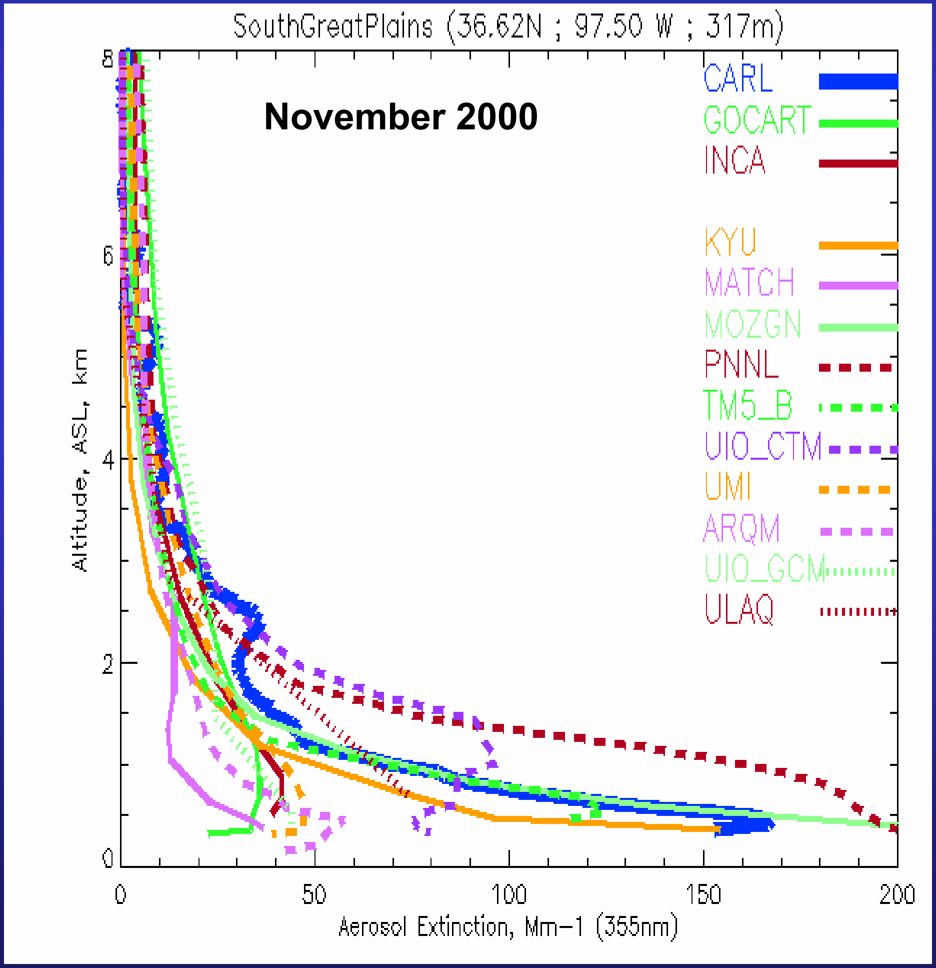




Observed versus Modeled Aerosol Profiles

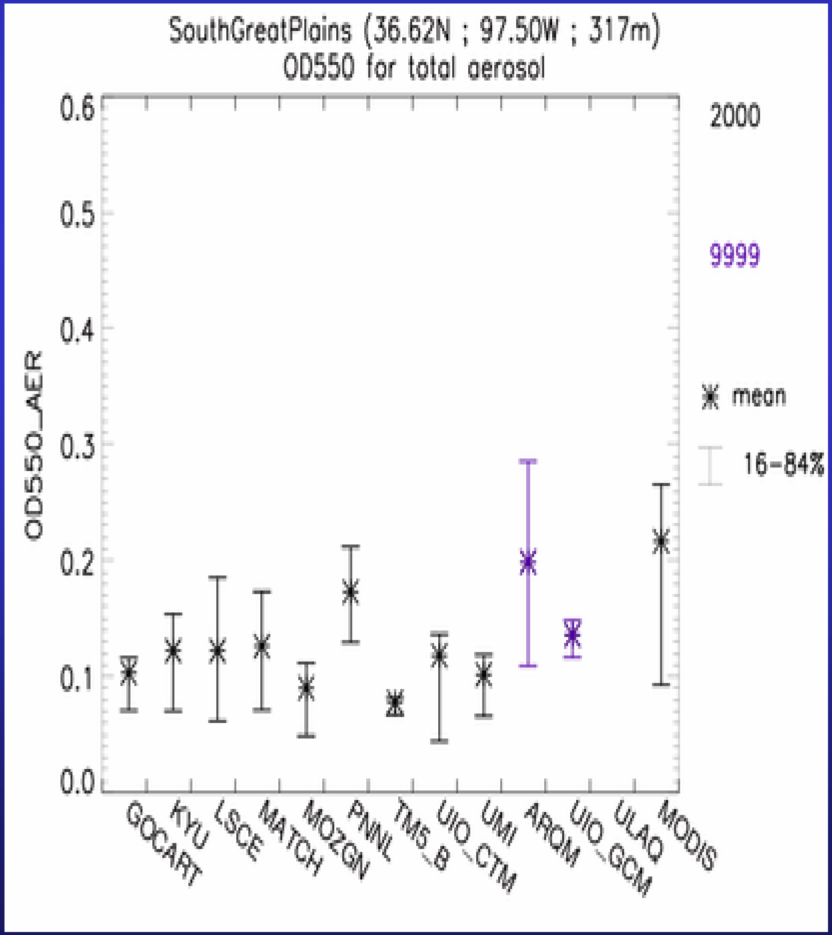
- Considerable variation in model profiles near the surface

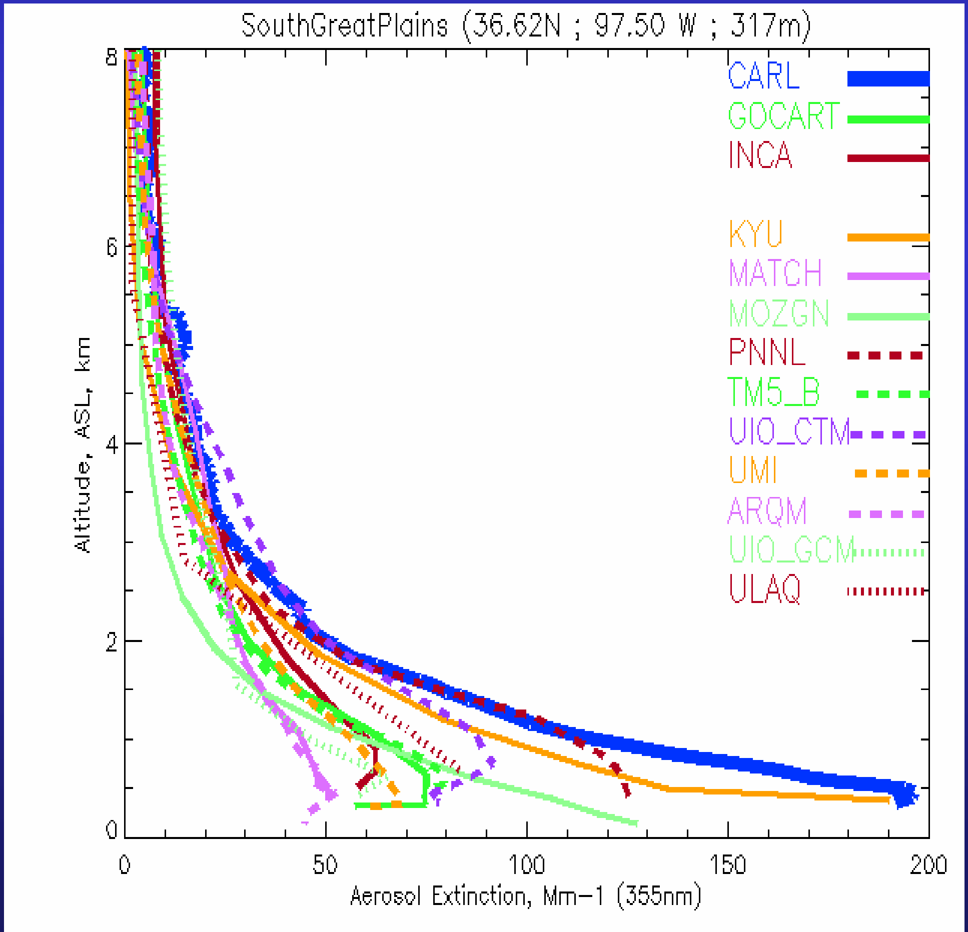




Measured versus Modeled Aerosol Profiles

- Large differences in vertical distributions of aerosols from models
- Model AOT is slightly lower than AOT measured by CARL and Cimel Sun photometer
- Model aerosol extinction is considerably lower than CARL near surface

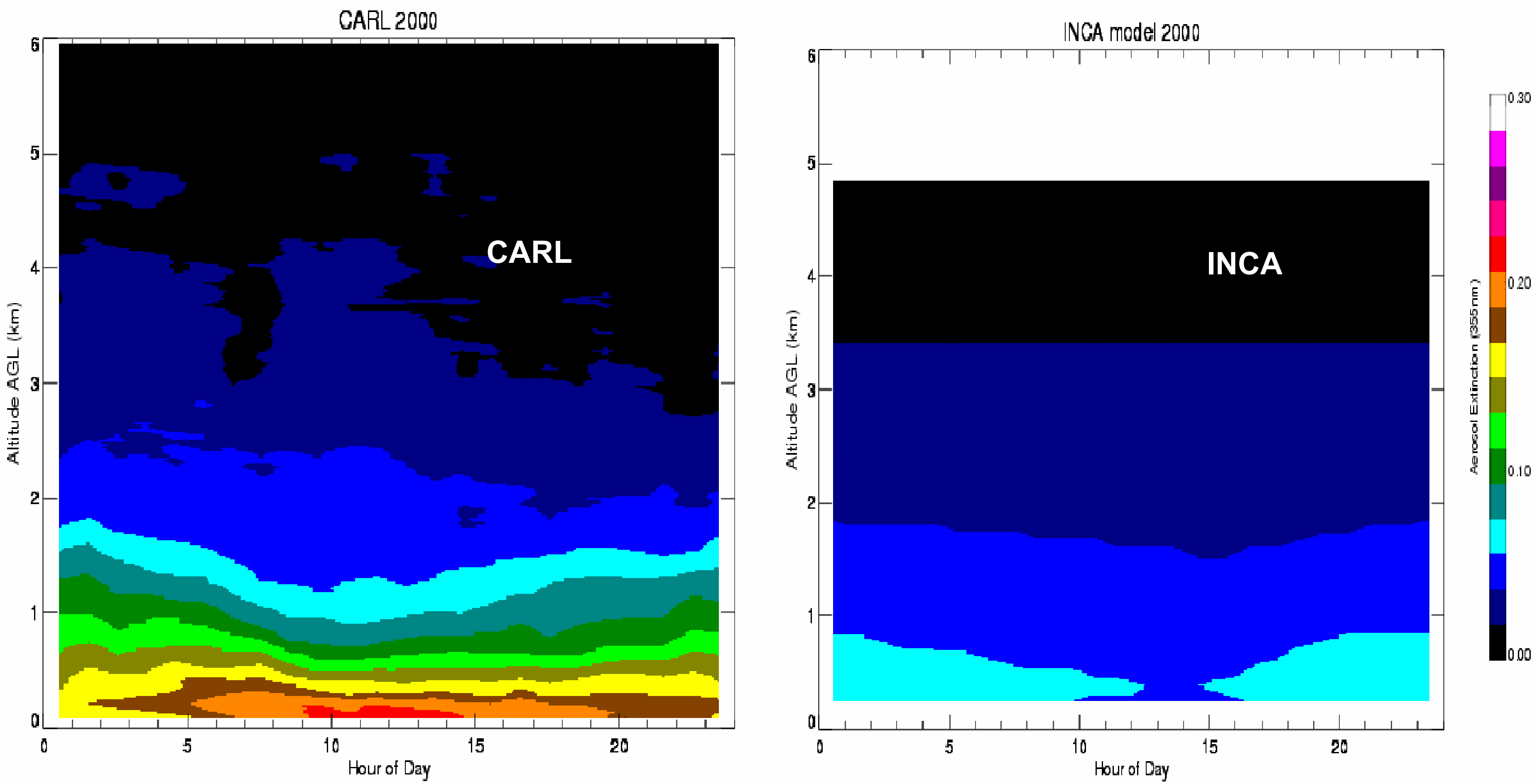




Diurnal Variation in Aerosol Profiles

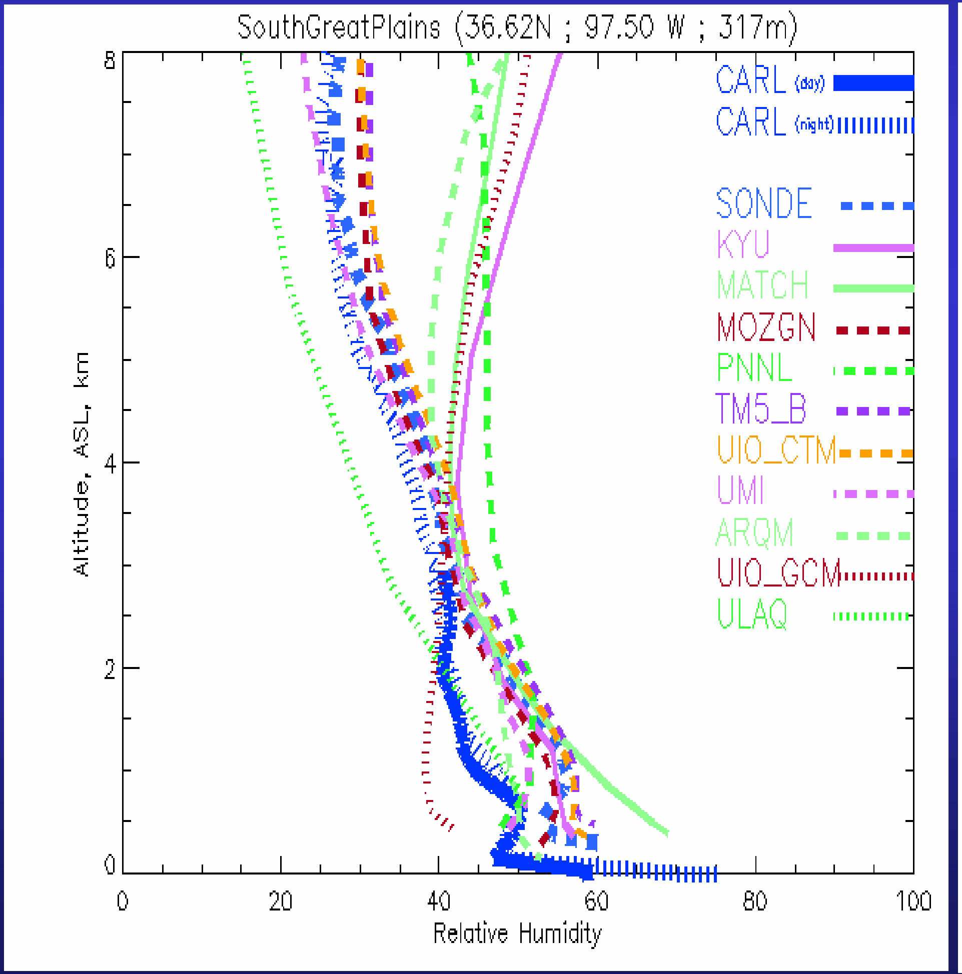
Diurnal variation in aerosol extinction profiles

- Measured profiles show larger variation near surface
- Measured variation is highly correlated with relative humidity
- Modeled variation near surface is smaller

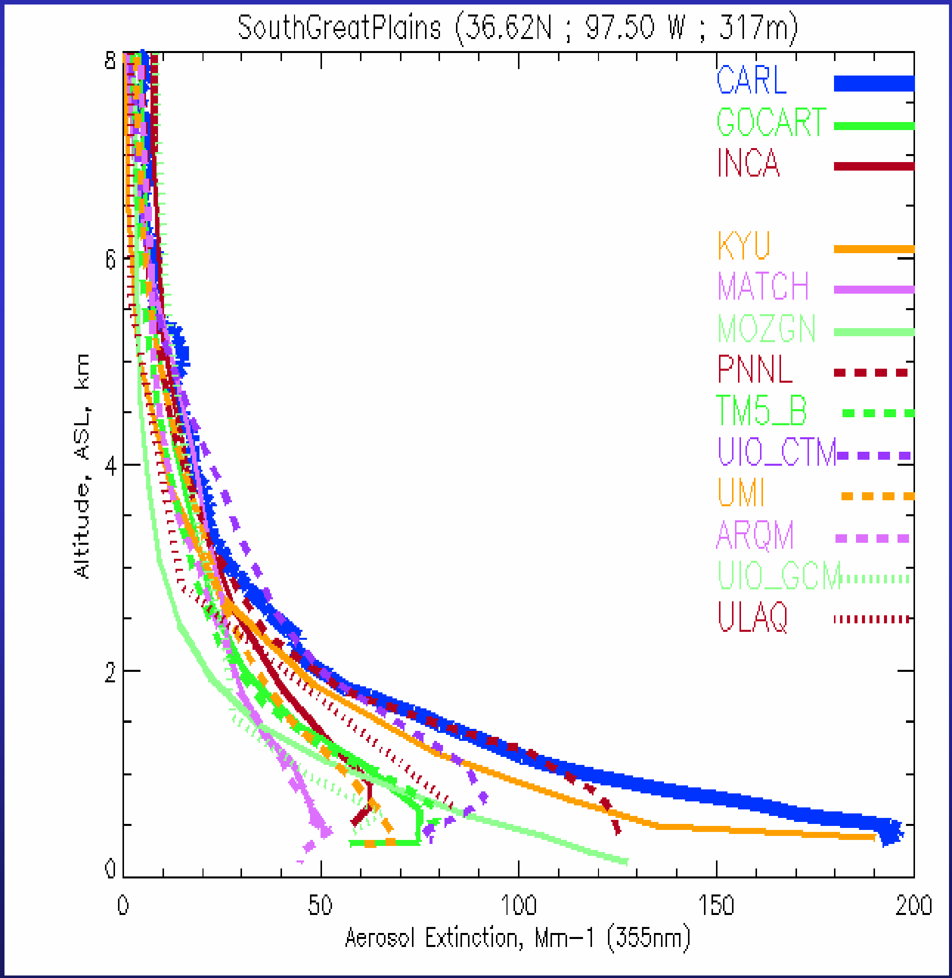


Measured versus Modeled RH and Aerosol Profiles

Relative Humidity

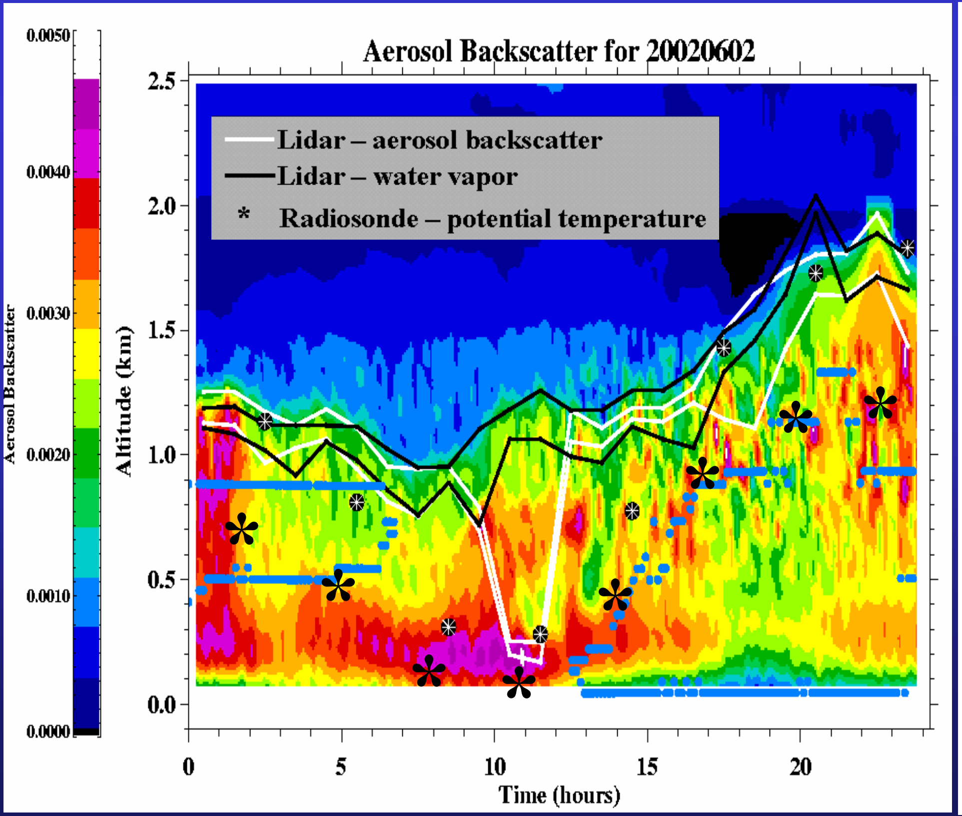


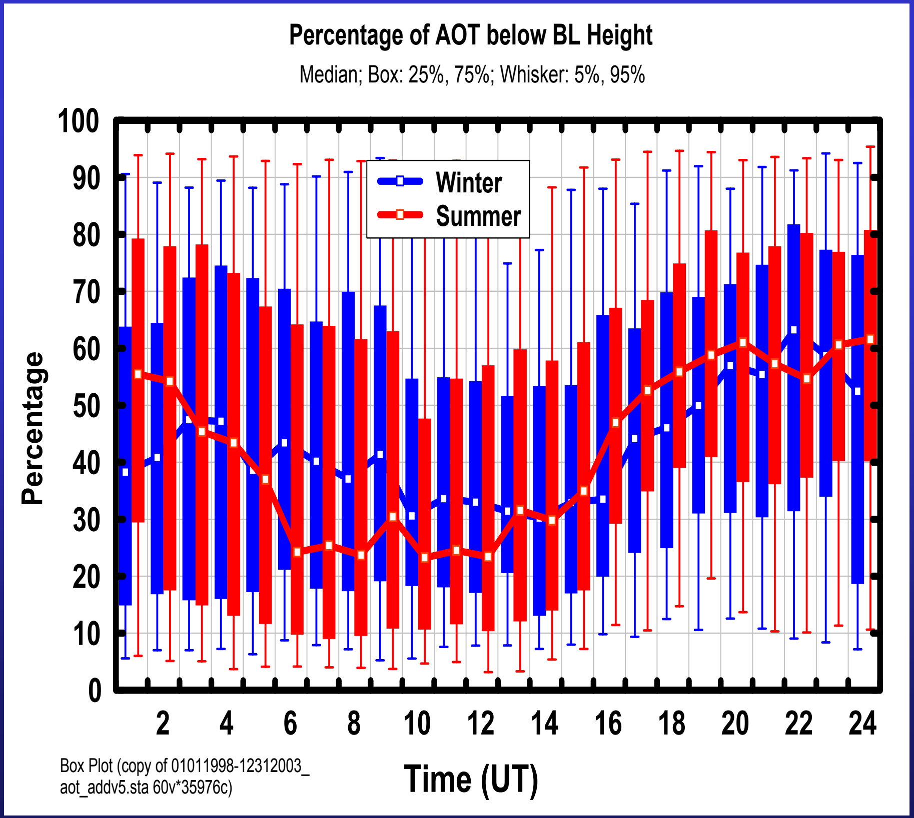
Aerosol Extinction



Retrievals of Boundary Layer Height

- Amount of AOT within PBL
  - varies with time of day
  - does not vary significantly with season or AOT
- Significant fraction of AOT (>25%) is above PBL

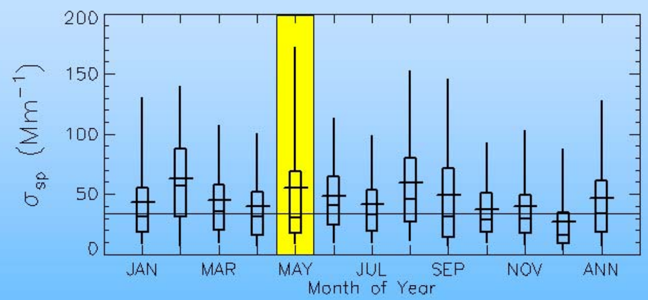




Aerosol Observing System (AOS)

Four-Year Climatology (1996-2000) of Aerosol Optical Properties at Surface

Aerosol Climatology at SGP - σ_{sp}

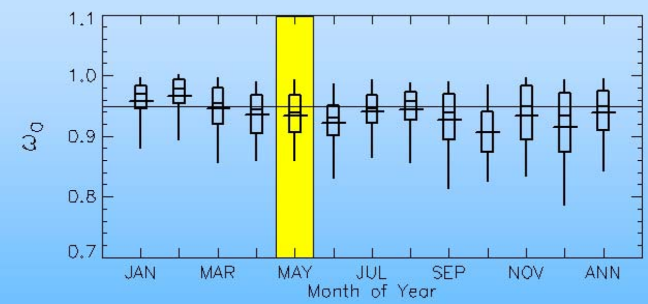


Aerosol Scattering

Source: Sheridan et al., JGR, 2001.

J. Ogren 03-05-12

Aerosol Climatology at SGP – ϖ_0

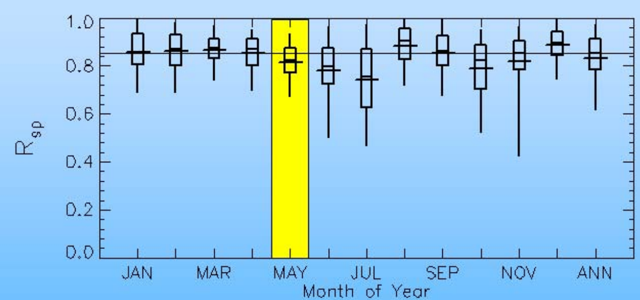


Single Scattering Albedo

Source: Sheridan et al., JGR, 2001.

J. Ogren 03-05-12

Aerosol Climatology at SGP - R_{sp}

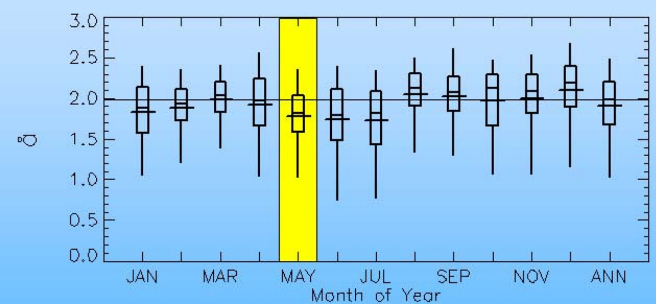


Fine mode fraction

Source: Sheridan et al., JGR, 2001.

J. Ogren 03-05-12

Aerosol Climatology at SGP - $\mathring{a}_{GR}$

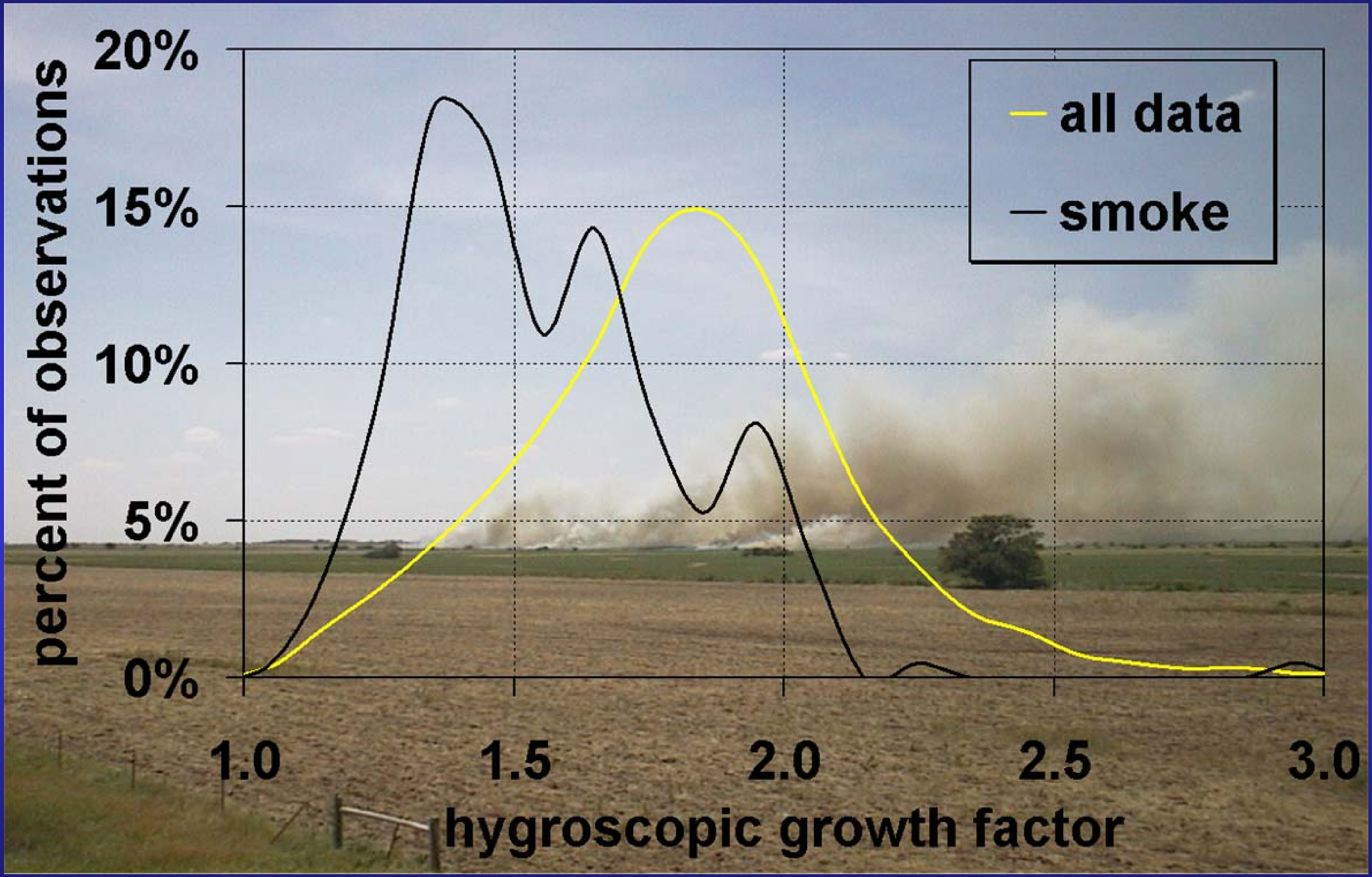


Angstrom exponent

Source: Sheridan et al., JGR, 2001.

J. Ogren 03-05-12

Aerosol Hygroscopic Growth at SGP



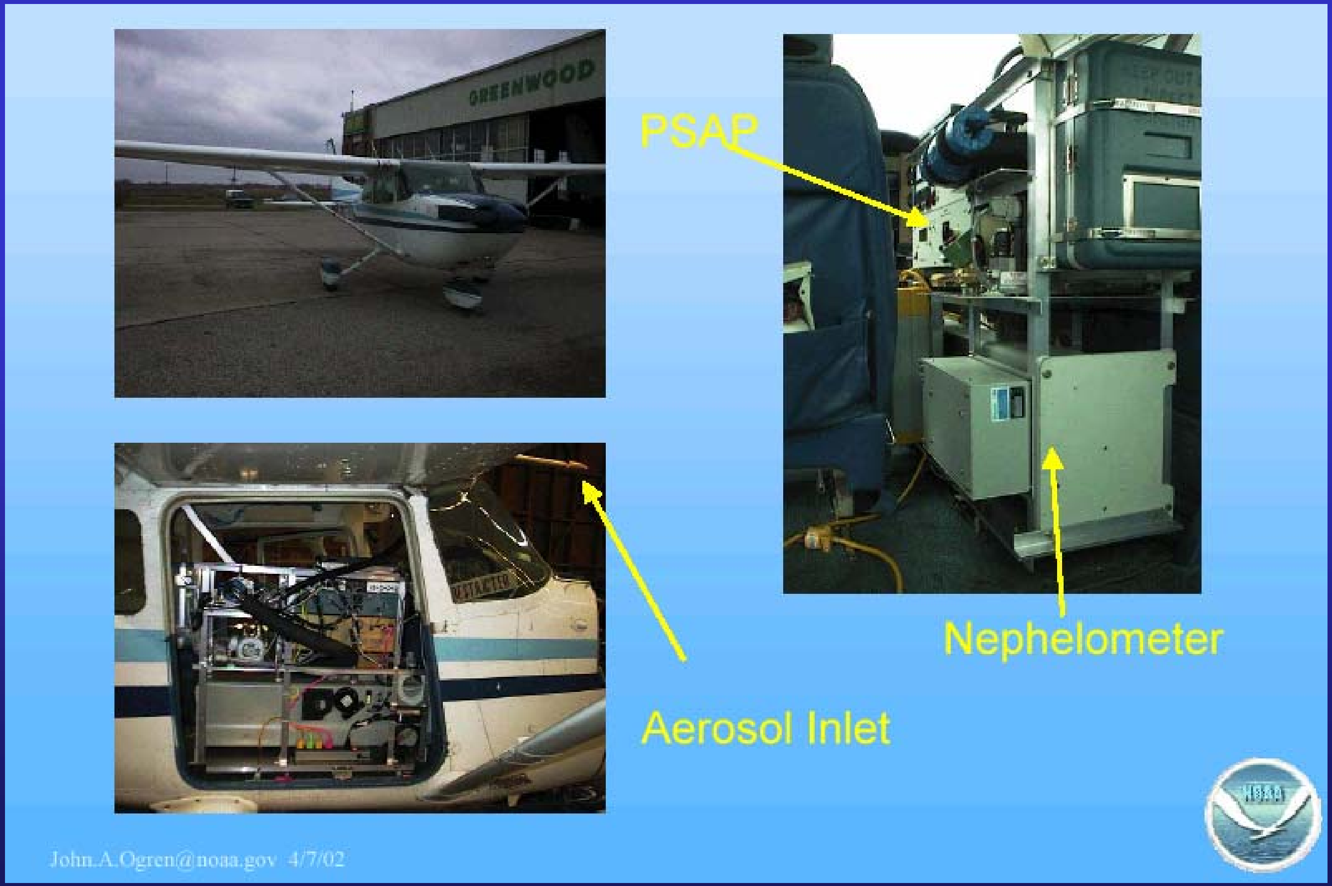
Sheridan et al., 2001 JGR

Aerosol Profiling

In Situ Aerosol Profile (IAP) – Cessna 172

- **Primary Measurements**
  - Aerosol scattering (3 λ) (dry)
  - Aerosol absorption (1 λ) (dry)
  - Hemispheric backscatter fraction (dry)
  - Aerosol scattering (1 λ) (high RH)
- **Derived Parameters**
  - Aerosol single scatter albedo
  - Aerosol optical thickness
  - Angstrom exponents

2-3 profiles/week



IAP Aerosol Profiling

Two-Year Climatology (2000-2002) of Aerosol Optical Properties over SGP

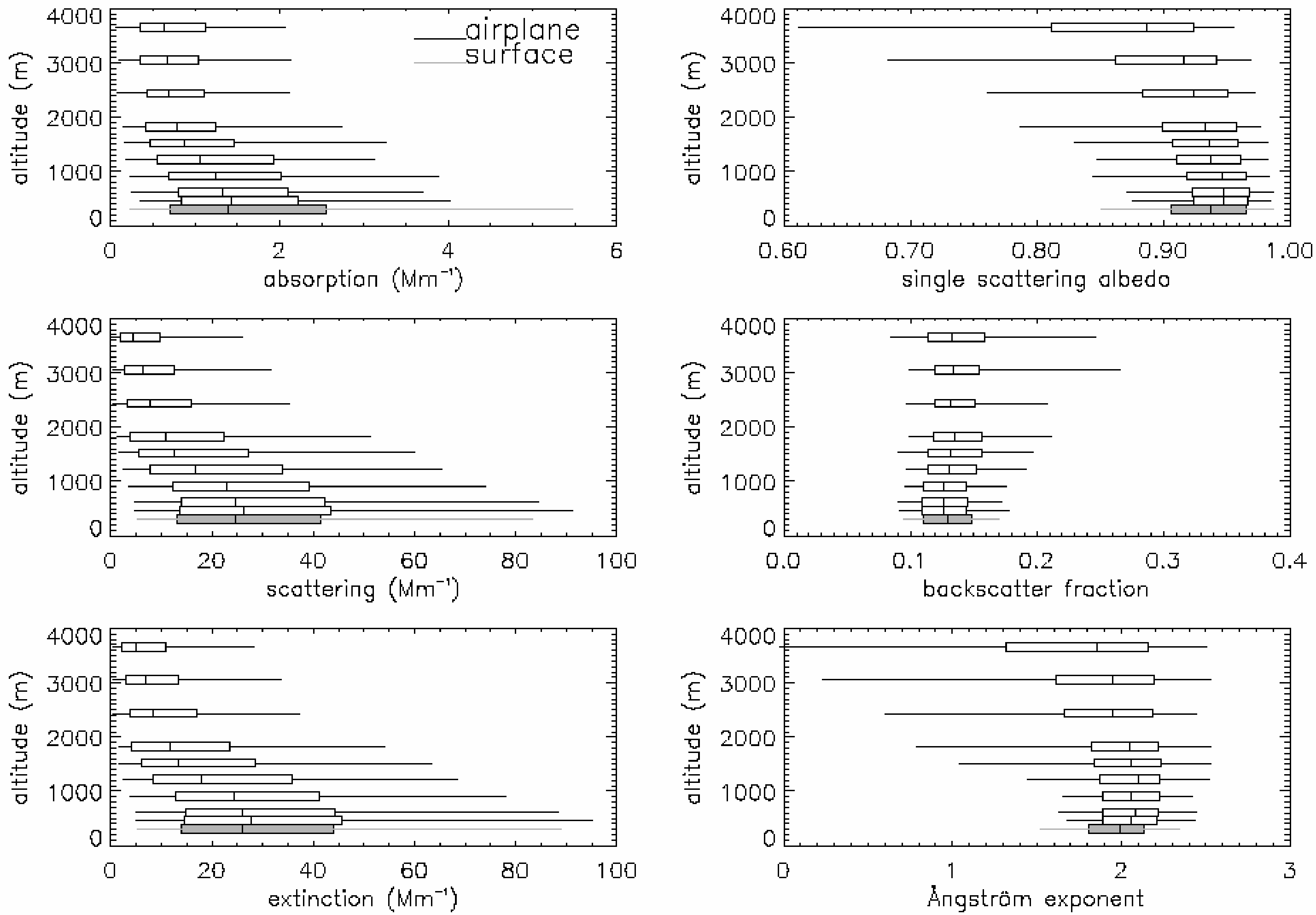


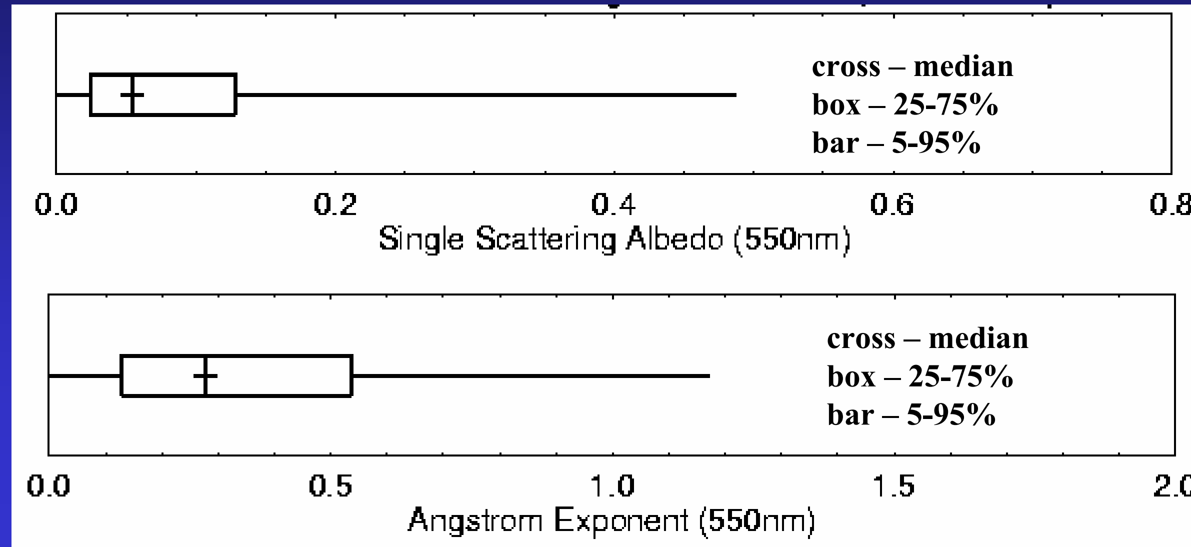
Figure 4. Profile statistics (5, 25, 50, 75, and 95 percentiles) at STP conditions. Intensive properties based on segment averages of σ_{ap} and $\sigma_{sp} > 0.5$ Mm^{-1}. Filled box represents surface data.

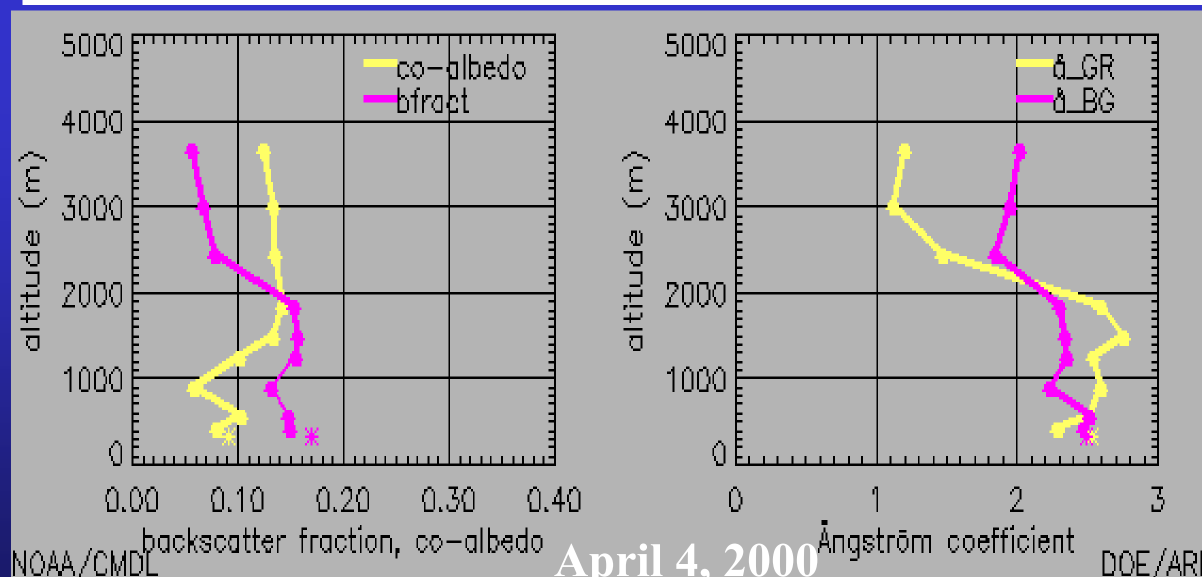
(dry, submicron)

(Andrews et al., JGR, 2004)

Vertical Variability of Aerosols – IAP Measurements

- Examined vertical variability of aerosol parameters using more than 300 IAP profiles from Mar. 2000-June 2003
- Computed range of values for each profile and weighted by aerosol scattering
- SSA varied by 0.12 or more in ~25% of cases
- Angstrom exponent varied by 0.5 or more in ~25% of cases

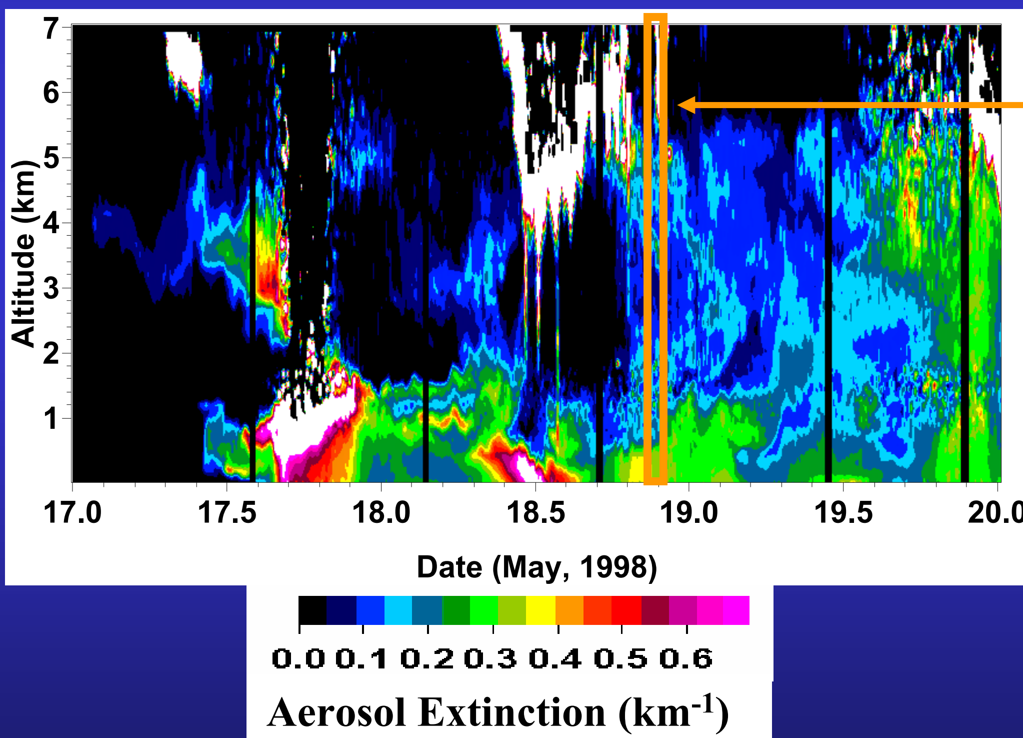


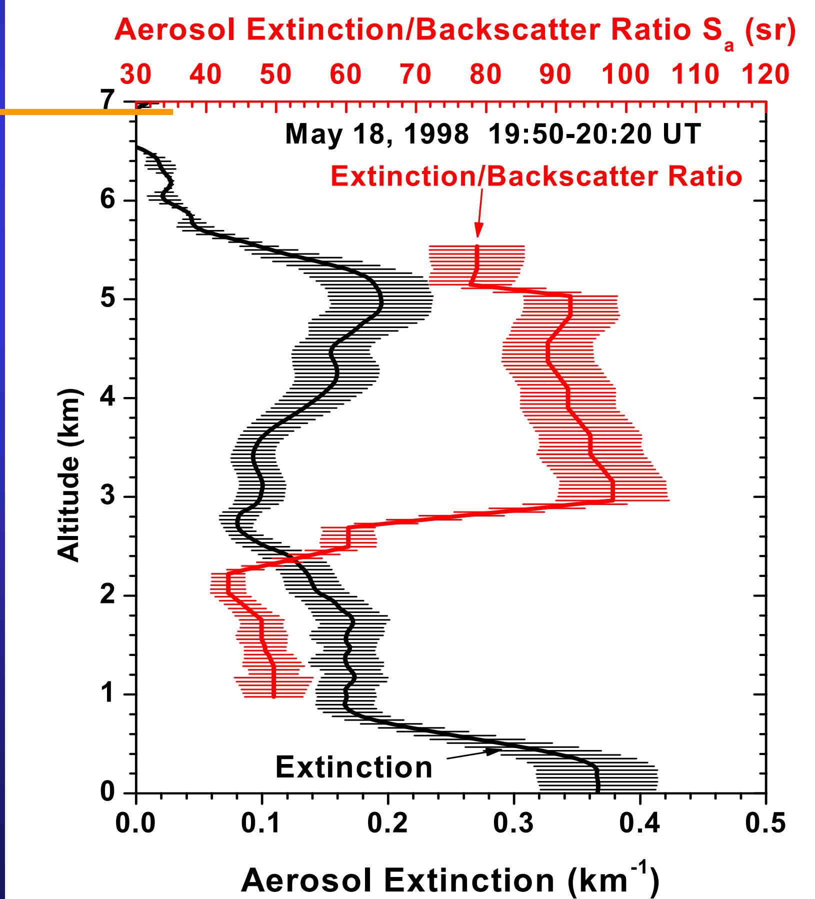


CARL observations of the aerosol vertical variability

- Aerosol extinction/backscatter ratio ("lidar ratio") varies with altitude due to changes in aerosol size, composition, and shape
- Raman lidar measurements of lidar ratio indicate that large variations in these aerosol properties with altitude occur ~30% of the time

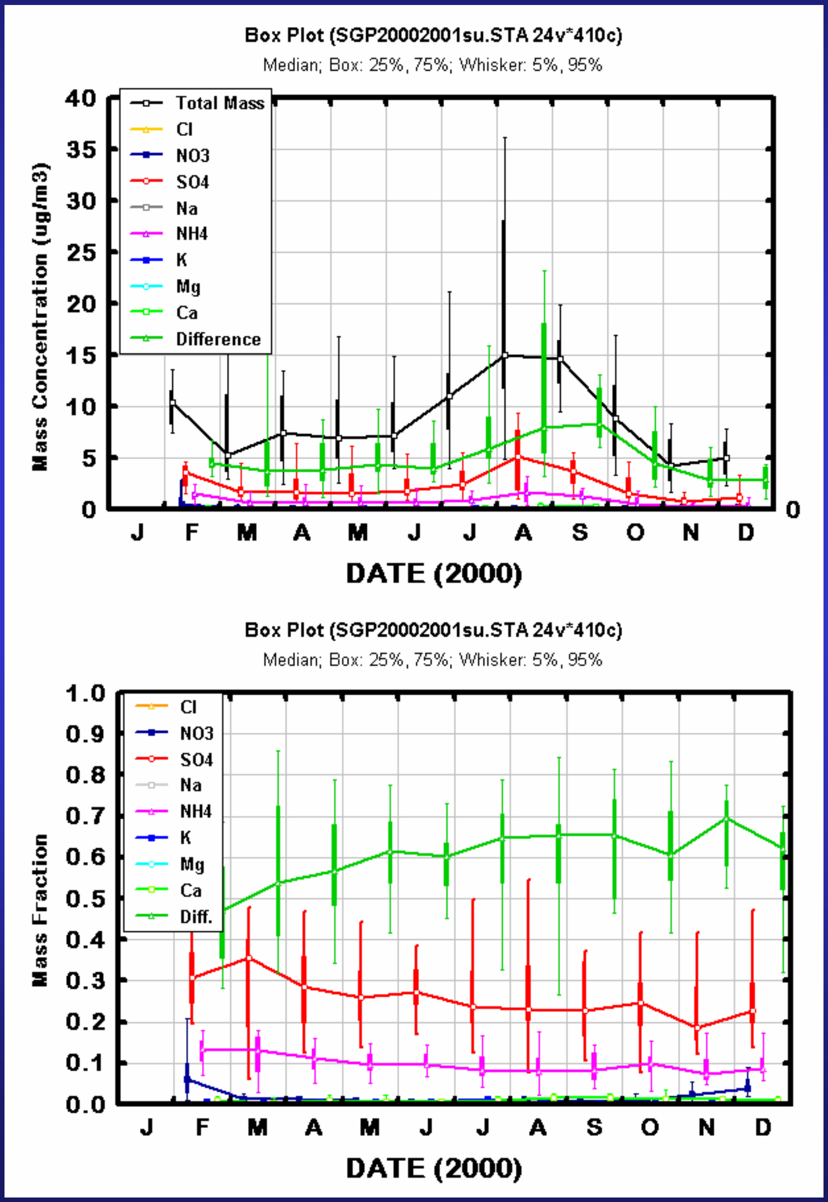
Elevated layer of smoke from fires in Central America (May, 1998)





(Peppler et al., *Bull. AMS*, 81, 2000)
(Ferrare et al., *J. Geophys. Res.*, 106, 2001)

Aerosol Chemistry Measurements



- **What?** ARM Sponsors aerosol chemistry measurements
- **Who?** Dr. Patricia Quinn - NOAA/PMEL
- **Why?**
  - Determine mass scattering efficiencies of major aerosol components (Cl-, NO3-, SO4-2, Na+, NH4+, K+, Mg2+, Ca+2)
  - Validate the output from chemical transport models
  - Link aerosol sources to aerosol radiative properties.
- **When?** Period: 2000 – present
  - Daily submicron samples
  - Weekly supermicron sample
- **How?**
  - Measure concentrations of aerosol mass and inorganic ions
  - Differencing aerosol mass and ion data, derive “residual” mass composed of dust and/or carbonaceous aerosol
- **Future funding in question** – requires endorsements (AEROCOM?)

Summary

- CARL routinely provides continuous profiles of aerosol backscattering and extinction, depolarization, RH
- Seasonal average profiles
  - Aerosol vertical distributions and scale heights vary with AOT and season
- Diurnal variability
  - Large changes in vertical profile, smaller changes in integrated values
  - Correlations in aerosol extinction, relative humidity
- PBL variability
  - Amount of AOT within PBL varies with time of day
  - Amount of AOT within PBL does not vary significantly with season
  - Significant fraction of AOT (>25%) is above PBL
- Model mean aerosol profiles typically show smaller vertical variability than the mean CARL observations
- In situ aerosol measurements on periodic small aircraft flights provide additional profiles of aerosol intensive properties
- Additional surface measurements of aerosol size, chemistry can be used to evaluate model performance

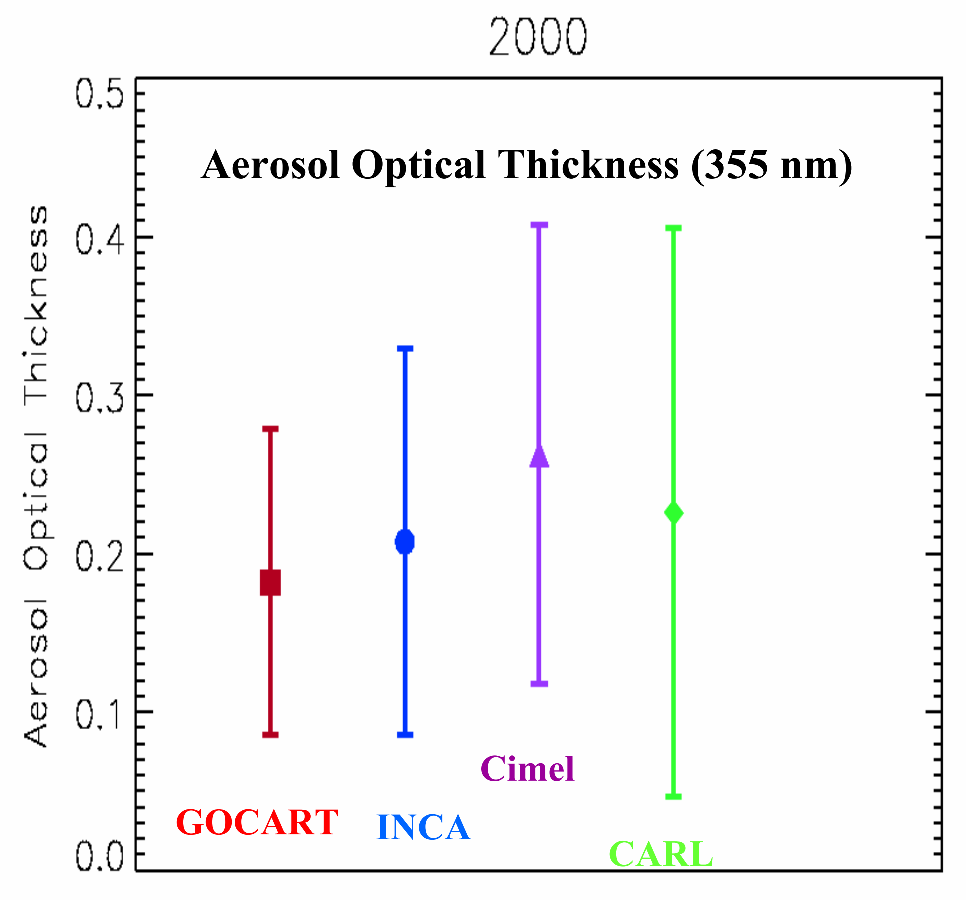
Backup slides

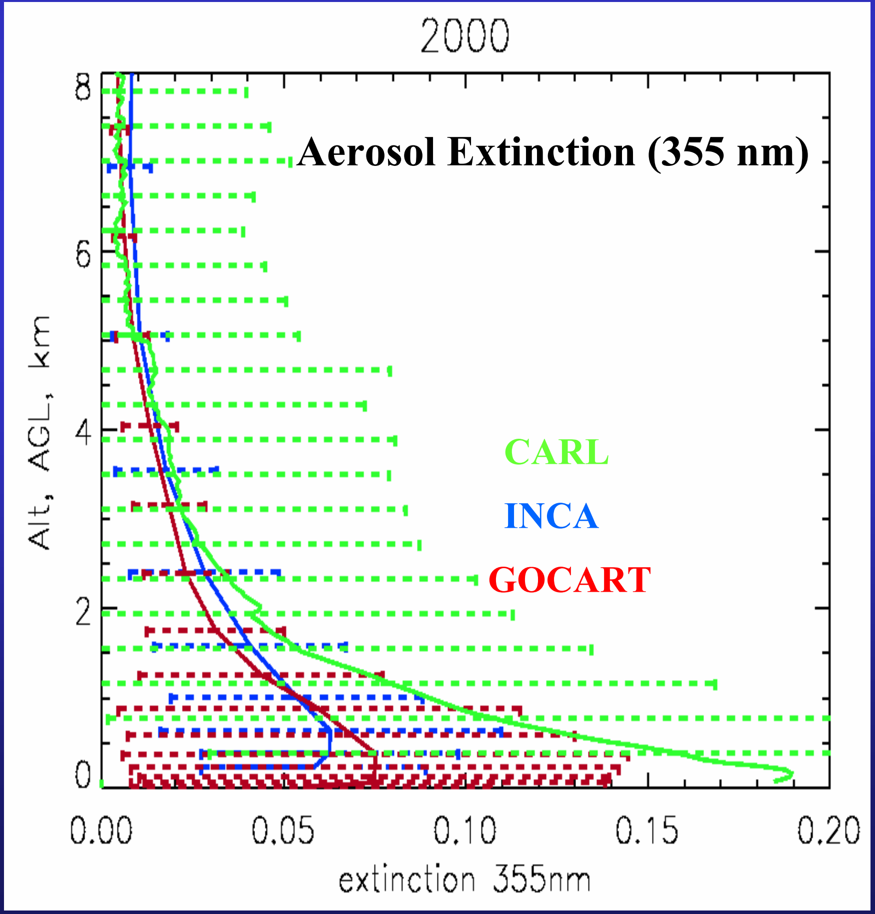
Routine Aerosol-Related Measurements at SGP

Instrument	Primary Measurement	Derived quantities
AOS (Surface)	Aerosol light scattering at 3 λ Aerosol absorption coefficient (RH $\leq$ 40%), (< 1, 10 μm) Light scattering (green) as f(RH) Aerosol number distribution (0.1 to 10 μm) Total condensation particle concentration Ozone	Aerosol extinction coefficient Aerosol single scattering albedo Angstrom exponent Hemispheric backscatter fraction
CSPOT (Cimel) Sun and sky photometer	AOT (6 λ) Sky radiance in principal plane and almucantar	Angstrom exponents Aerosol size distribution Refractive index Single scatter albedo
MFRSR	AOT (5 λ)	Angstrom exponent Direct/diffuse ratio
RSS	Direct spectral irradiance Diffuse spectral irradiance	AOT $f(\lambda)$
CART Raman Lidar	Aerosol backscatter profiles Aerosol extinction profiles Aerosol optical thickness profiles Water vapor mixing ratio profiles	Relative humidity (z)
MPL	Relative aerosol backscatter	Aerosol backscatter profiles Aerosol extinction profiles
In-situ Aerosol Profiling (IAP)	Aerosol scattering (3 λ) (dry) Aerosol absorption (1 λ) (dry) Hemispheric backscatter fraction (dry) Aerosol scattering (1 λ) (high RH) (future)	Single scatter albedo AOT Angstrom exponents
Aerosol Sample	Aerosol mass concentration Aerosol ionic composition	

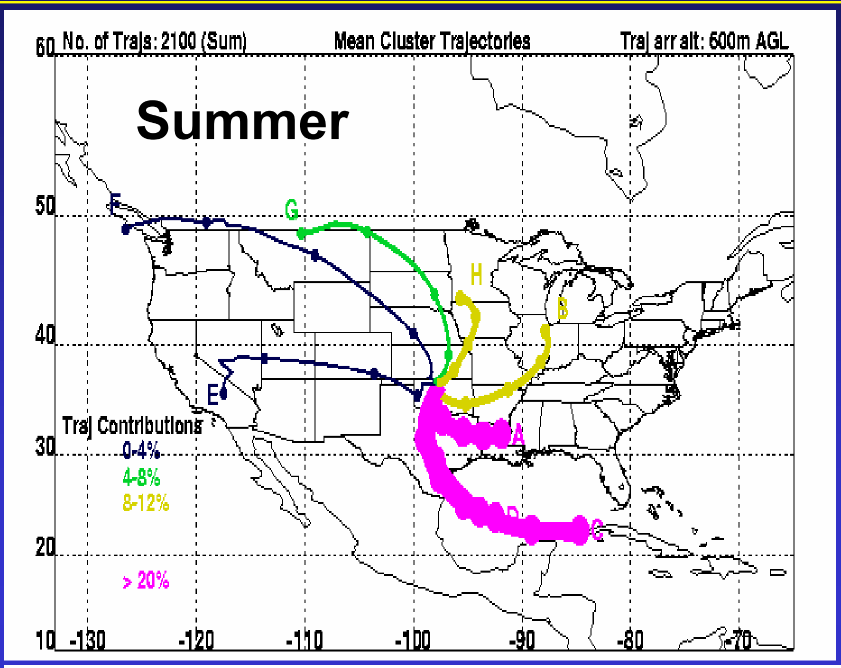
Measured versus Modeled Aerosol Profiles

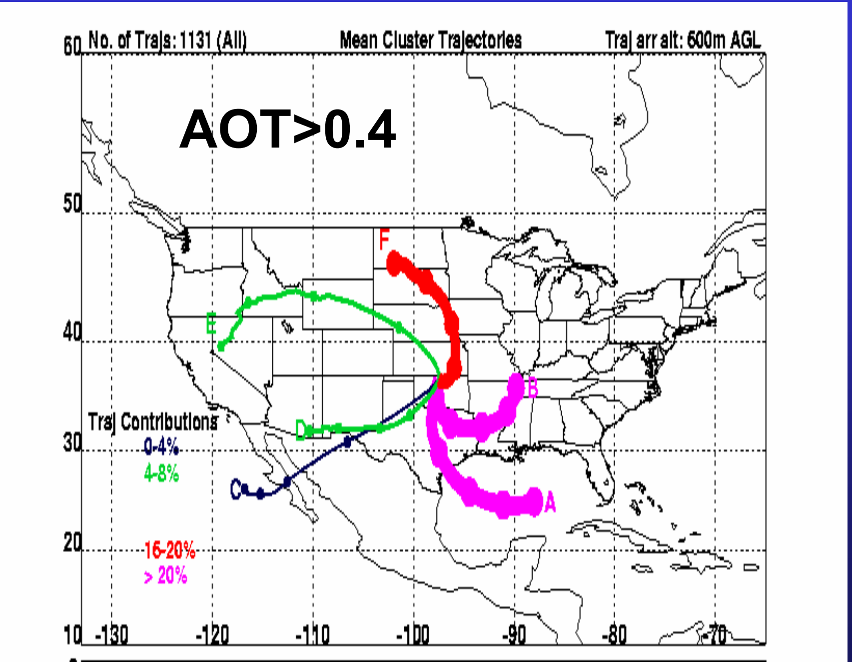
- Large differences in vertical distributions of aerosols from models
- Model AOT is slightly lower than AOT measured by CARL and Cimel Sun photometer
- Model aerosol extinction is considerably lower than CARL near surface



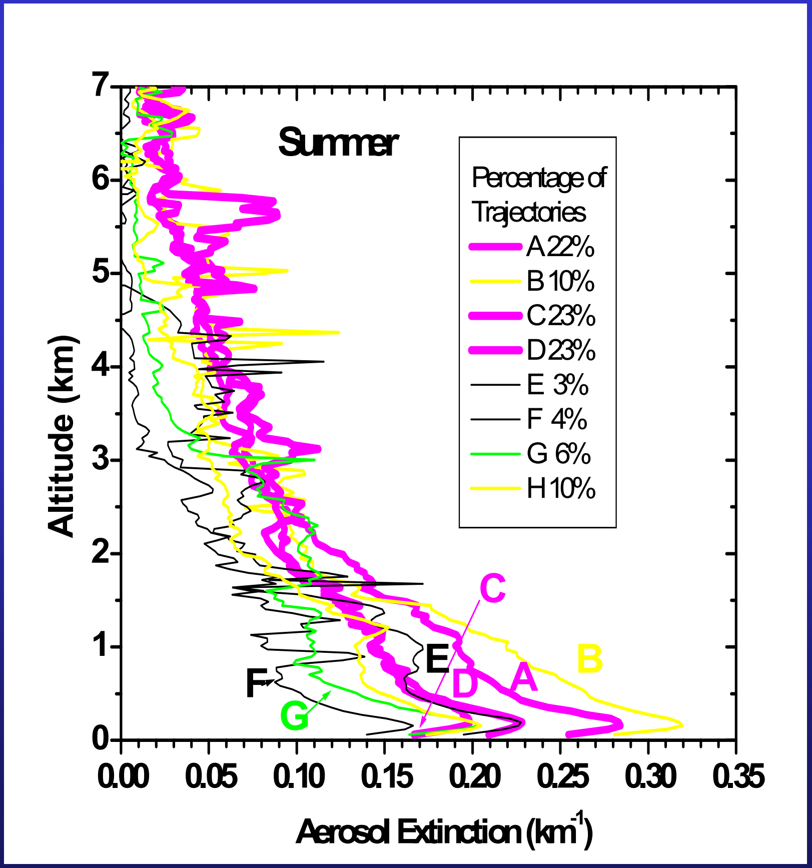


Backtrajectories - Summer

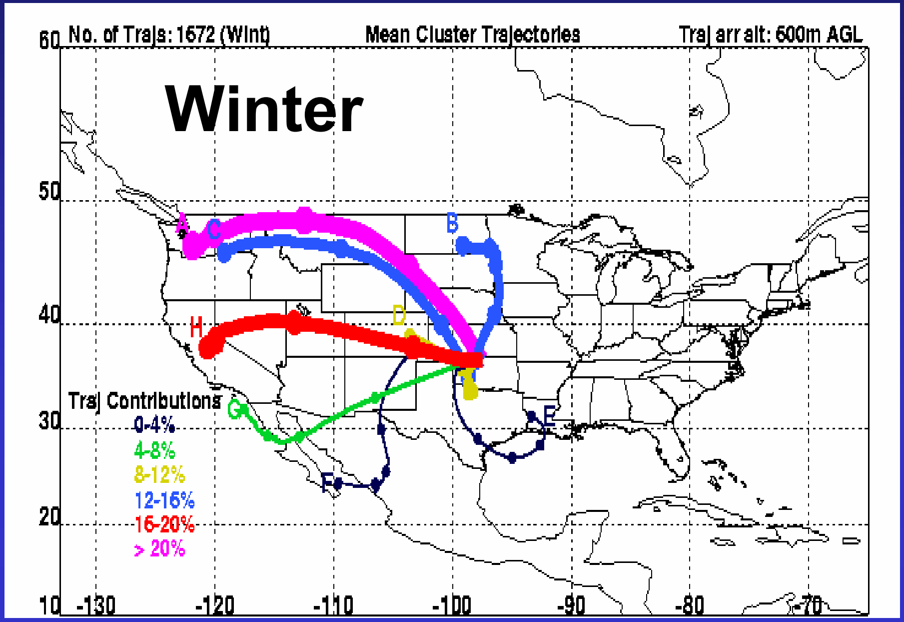


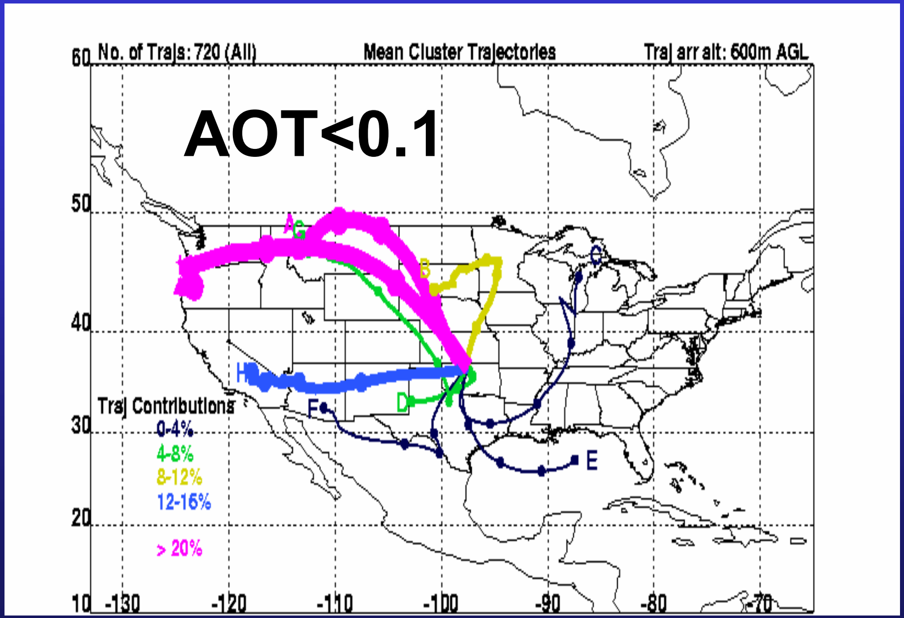


- Four-day backtrajectories were computed using NOAA/ARL HYSPLIT4* model
- These trajectories were divided into distinct clusters corresponding to large scale transport patterns using the methods described by Dorling et al. (1992)†
- CARL profiles show enhanced water vapor and aerosols from southerly and southeasterly flow

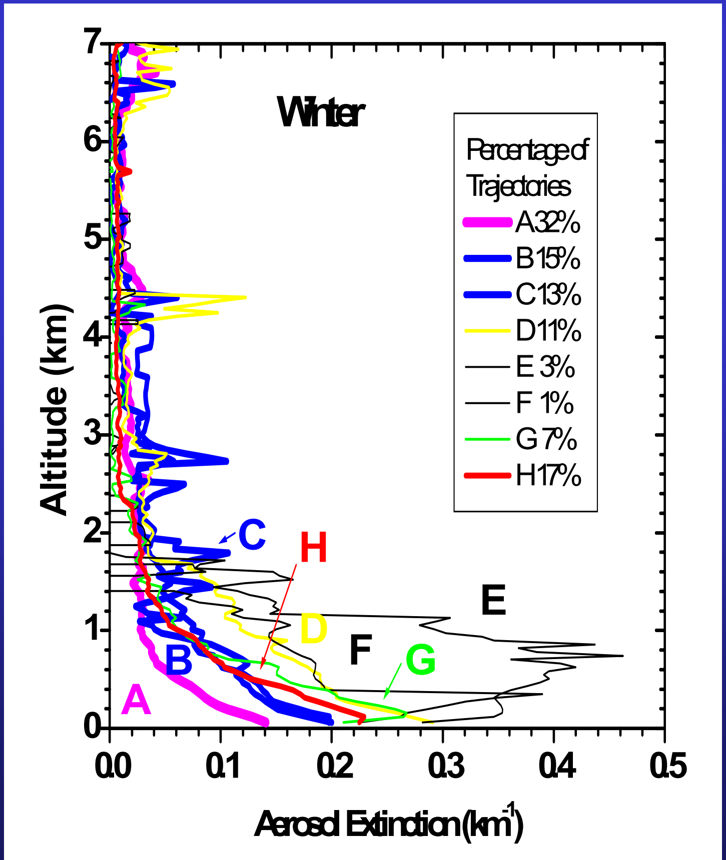


Backtrajectories - Winter

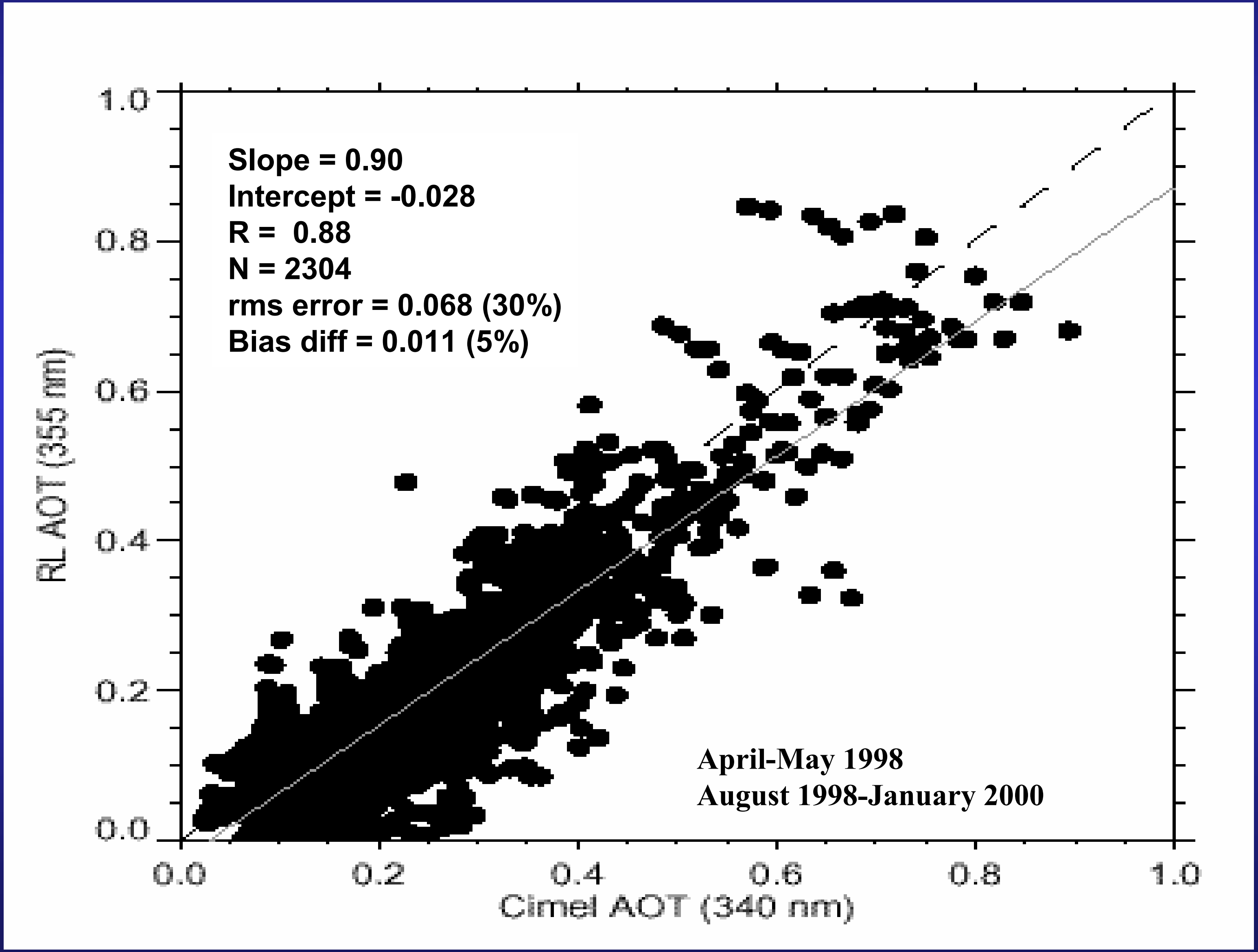




- Majority of trajectories from west and northwest
- CARL profiles show low water vapor and aerosols from westerly and northwesterly flow



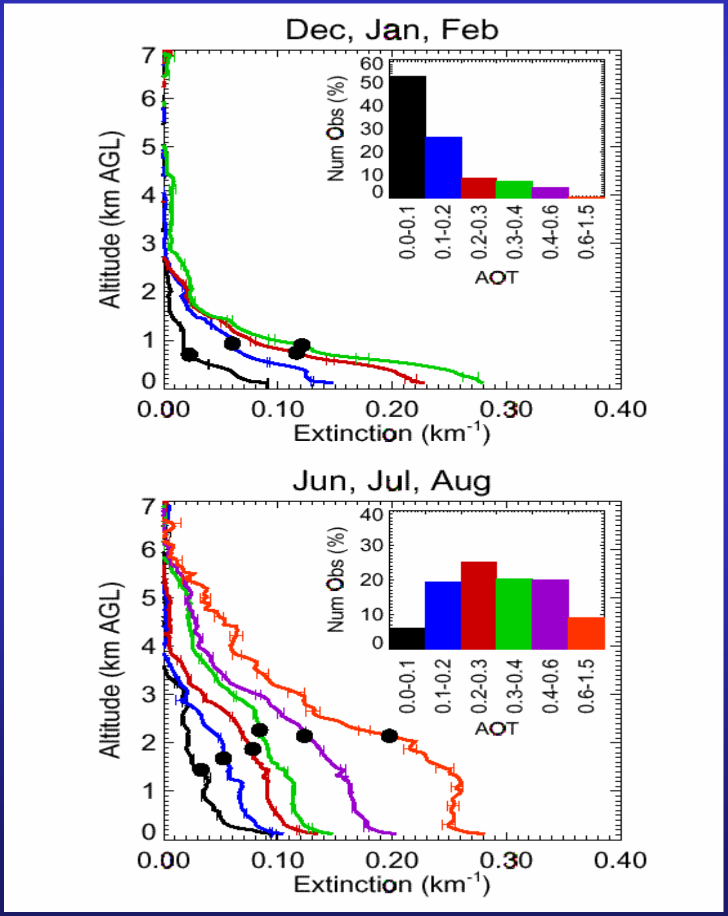
Raman lidar/Cimel AOT comparison



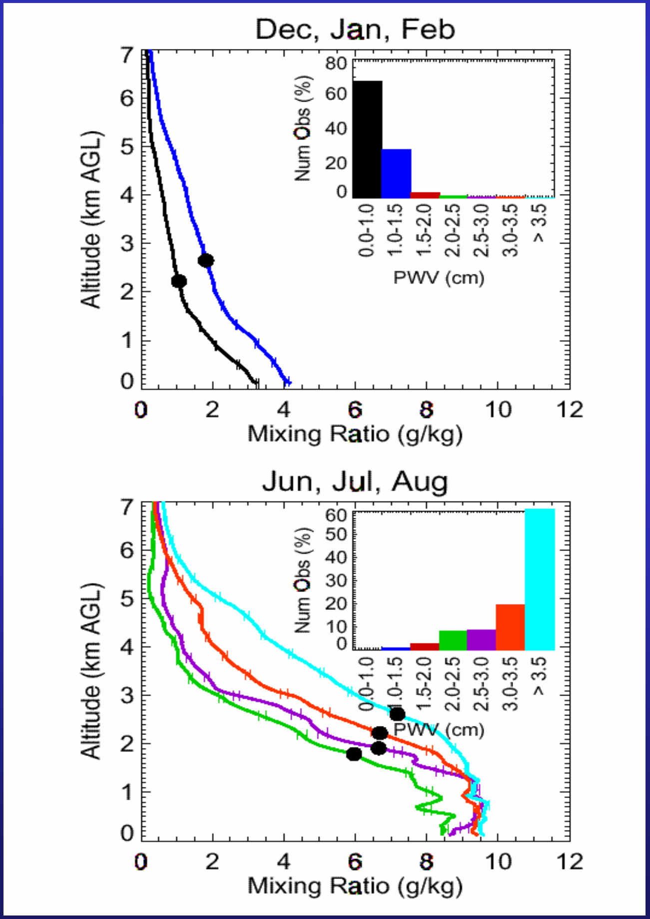
Average aerosol extinction and water vapor profiles

- Aerosol vertical distributions and scale heights vary with AOT and season
- Water vapor vertical distributions and scale heights are relatively constant

Average aerosol extinction profiles and histograms of aerosol optical thickness



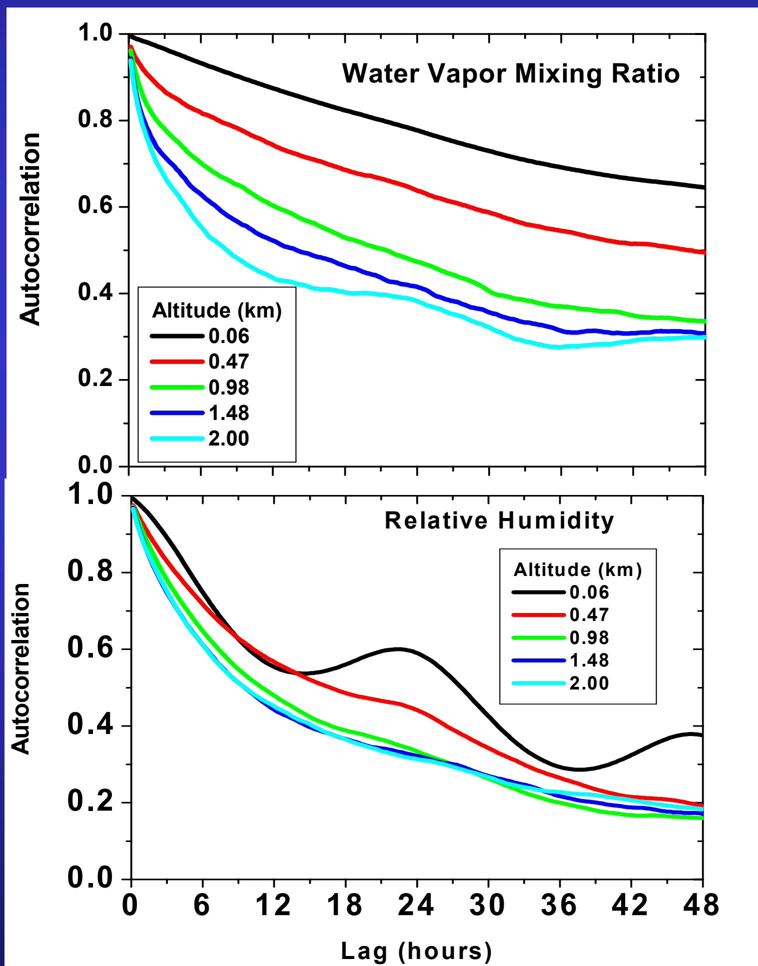
Average water vapor profiles and histograms of precipitable water vapor

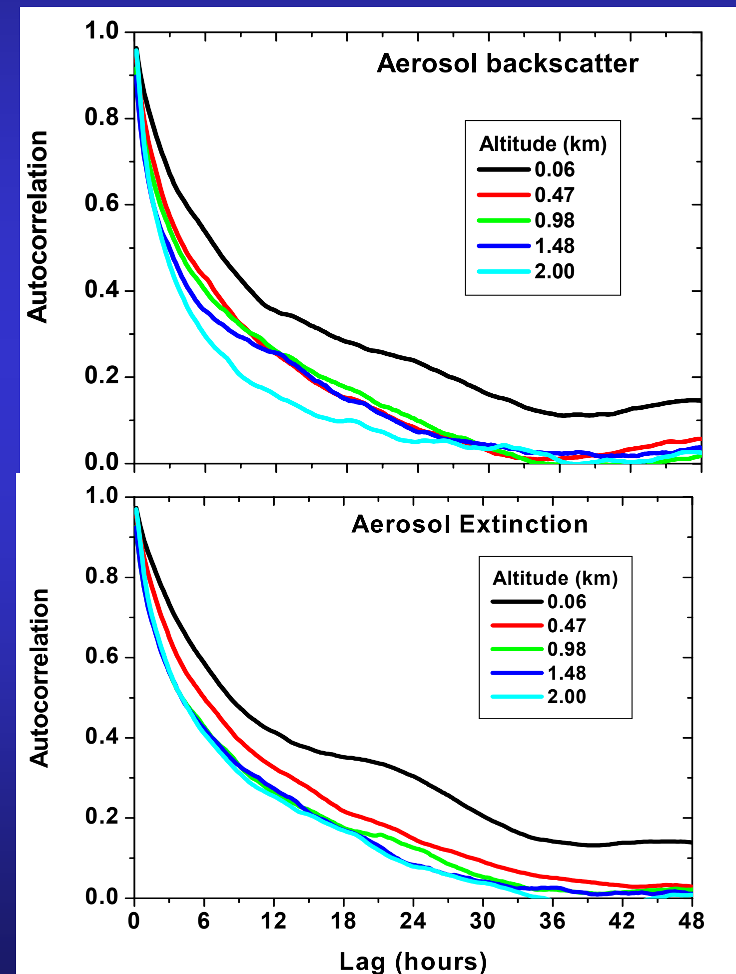


(Turner et al., Geophys. Res. Letters, 28, 2001)

Autocorrelation Functions

- CART Raman Lidar data from 2000-2001
- Water vapor shows less variability than aerosol, particularly near surface

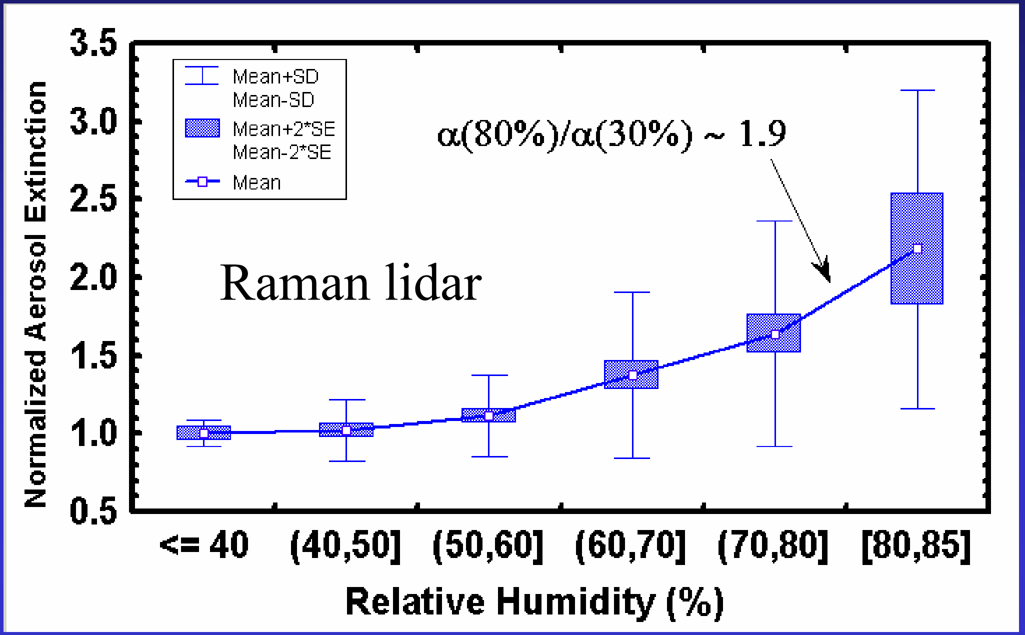


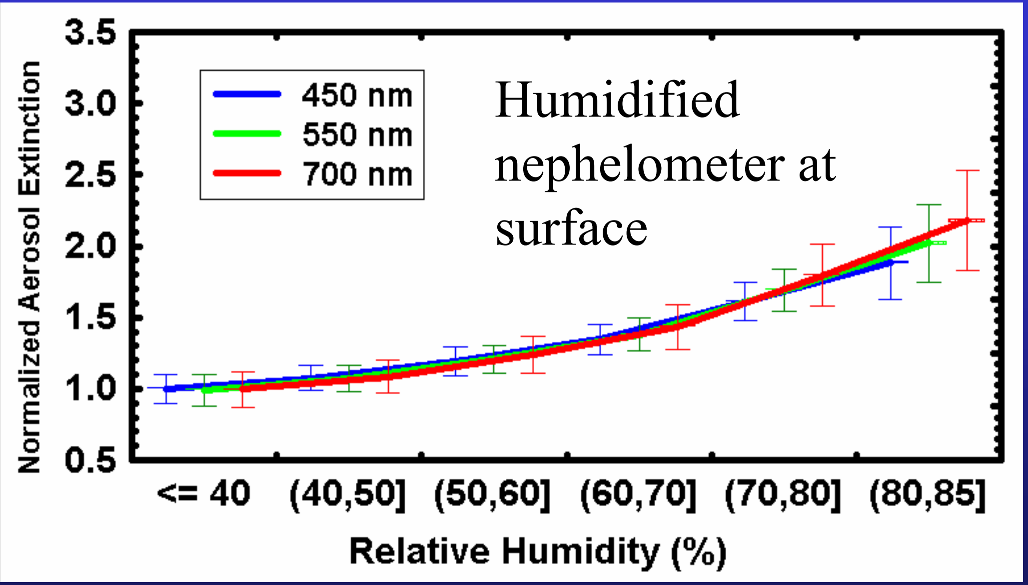


*Anderson, T., et al., Mesoscale Variations of Tropospheric Aerosols, J. Atmos. Sci., 60, 119-137, 2003.

Hygroscopic Aerosol Growth

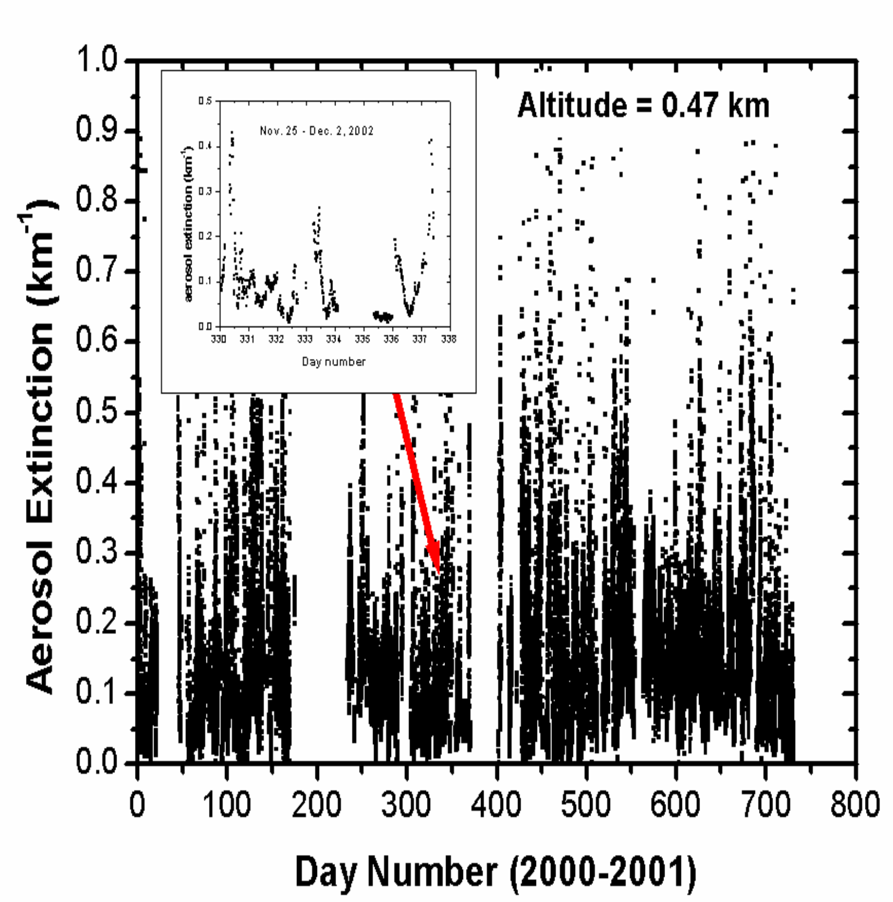
- Preliminary study
- Used 20 cases (1998) near top of daytime BL
- $\alpha_a(RH=80\%)/\ \alpha_a(RH=30\%) \sim 1.9$
- Measurements are consistent with results from humidified nephelometer at surface

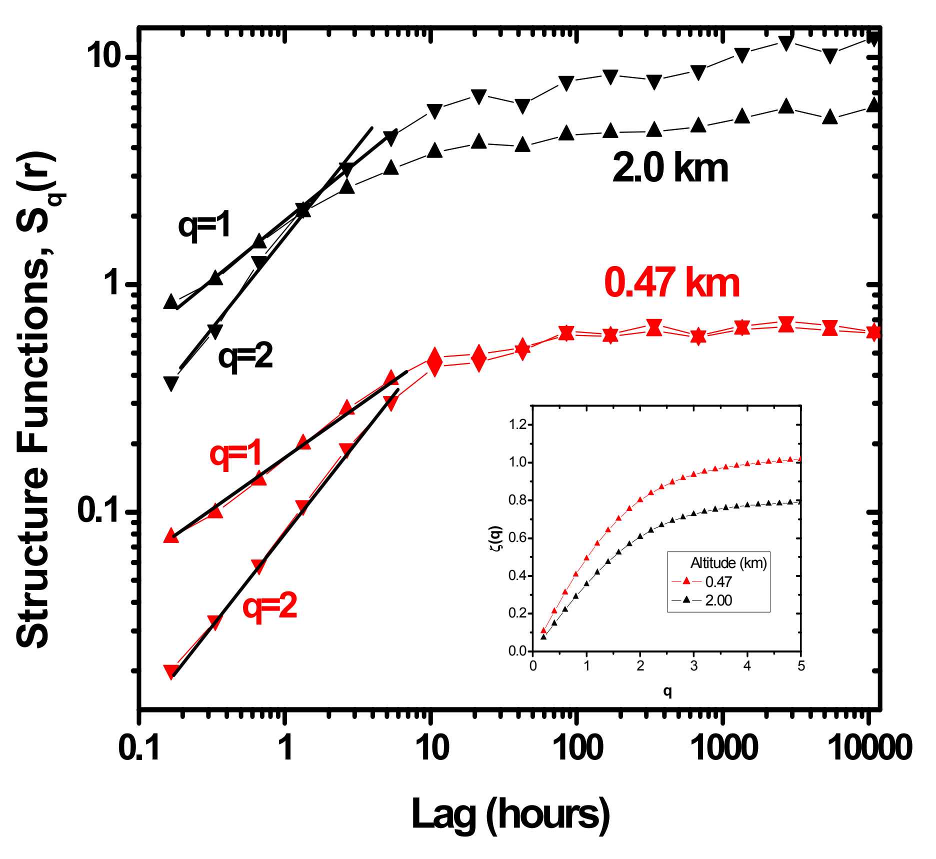




Aerosol Extinction Structure Functions

- Changes in structure function slopes at 6-8 hours (~200-280 km) indicate scale break associated with transition to stationary regime
- Power law spectral slope $\beta = \zeta(2)+1$ varies between 1.6-1.8
- Spectral exponent decreases with altitude





Aerosol Optical Thickness and Radiative Influences

Cimel Sun Photometer (CSPOT)

- **Primary Measurements**
  - **Aerosol optical thickness (multiwavelength)**
  - **Sky radiance in principal plane and almucantar**
- **Derived Parameters**
  - **Angstrom exponents**
  - **Aerosol size distribution**
  - **Aerosol single scattering albedo**
  - **Aerosol refractive index**

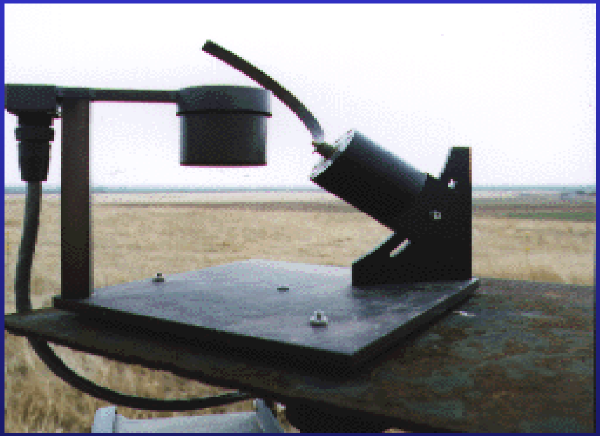
Rotating Shadowband Radiometer (RSS)

- **Primary Measurements**
  - **Direct spectral irradiance**
  - **Diffuse spectral irradiance**
- **Derived Parameters**
  - **Aerosol optical thickness (λ)**

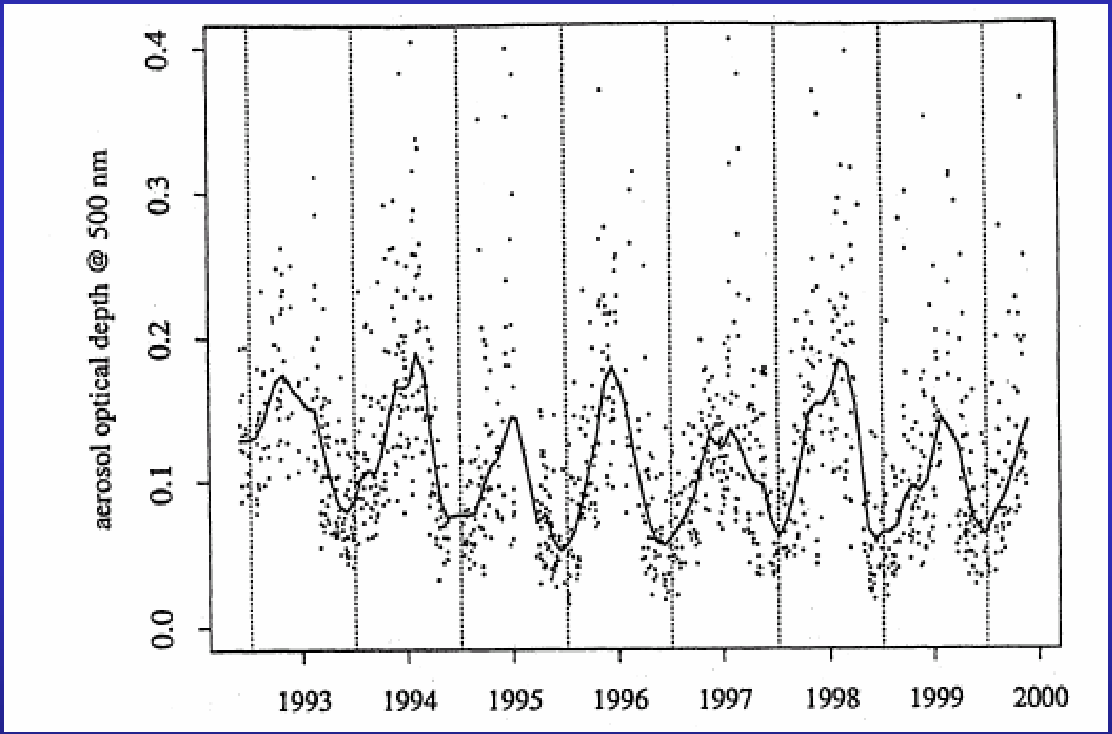
Aerosol Optical Thickness and Radiative Influences

MultiFilter Rotating Shadowband Radiometer (MFRSR)

- **Primary Measurements**
  - **Aerosol optical thickness (multiwavelength)**
- **Derived Parameters**
  - **Angstrom exponents**
  - **Direct/diffuse ratio**



Aerosol Optical Thickness (550 nm)



Multiple-year record of aerosol optical depth at ARM SGP site in north-central Oklahoma (Michalsky et al., 2001)

Aerosol Profiling

Micropulse Lidar (MPL)

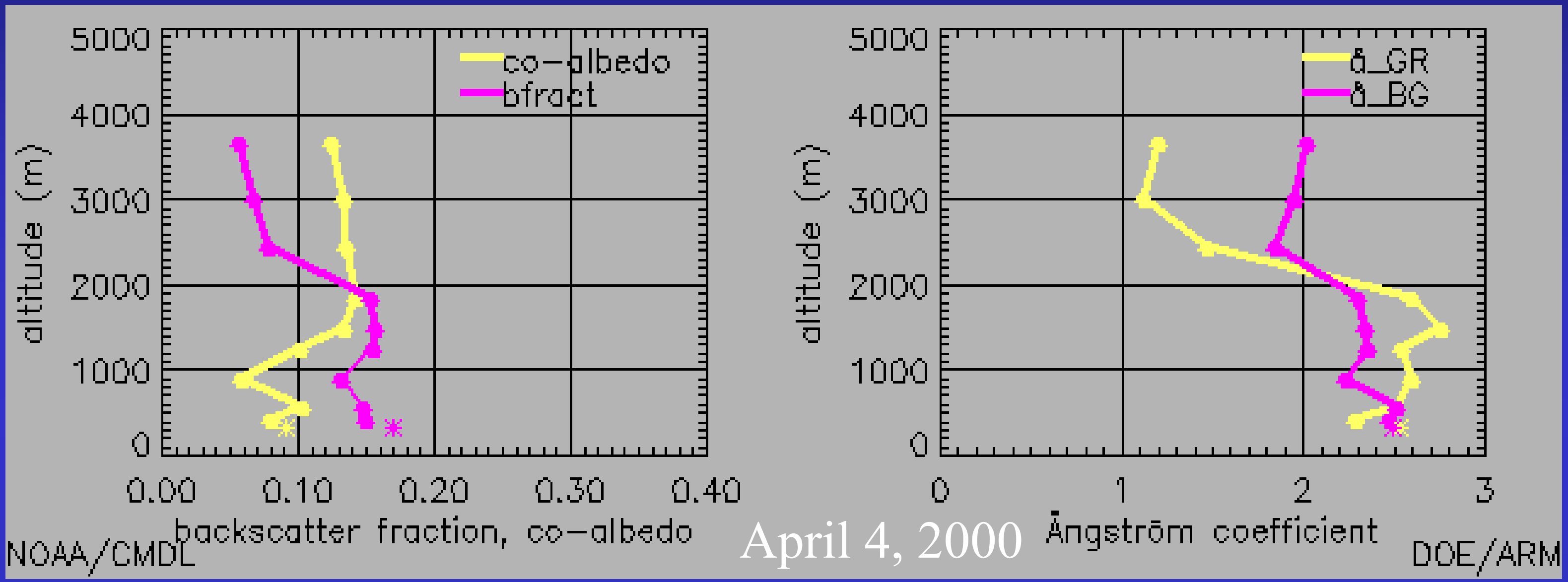
- **Primary Measurements**
  - **Relative aerosol backscatter**
- **Derived Parameters**
  - **Aerosol backscatter profiles**
  - **Aerosol extinction profiles**

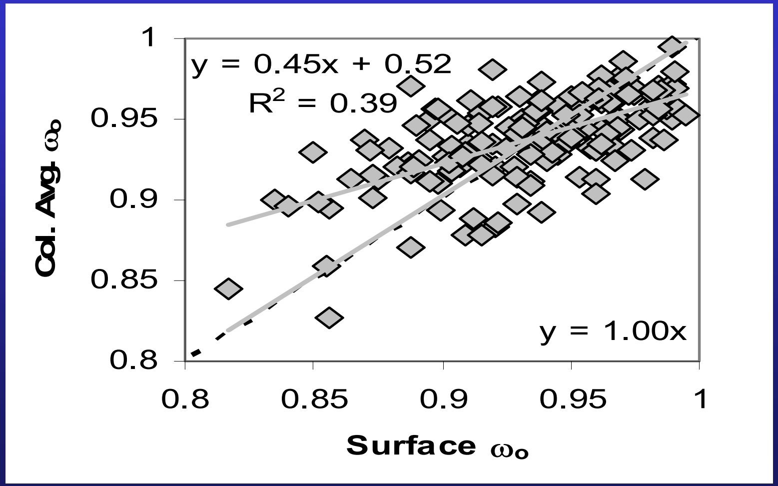
CART Raman Lidar (CARL)

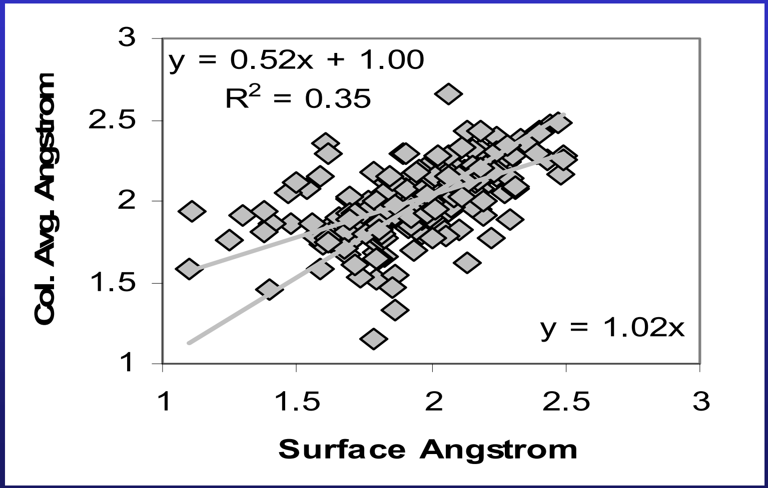
- **Primary Measurements**
  - **Aerosol backscatter profiles**
  - **Aerosol extinction profiles**
  - **Aerosol optical thickness**
  - **Water vapor mixing ratio**
  - **Precipitable water vapor**
  - **Depolarization ratio profiles**
- **Derived Parameters**
  - **Relative humidity**
  - **Cirrus optical thickness**

Vertical Variability of Aerosols – IAP Measurements

- IAP flights often show large vertical variability in intensive parameters
- Surface measurements often differ from column averages







John Ogren, Elisabeth Andrews NOAA/CMDL

Raman Lidar Retrieval of Boundary Layer Height and AOT

- PBL Height Methods:
  - Radiosonde - Potential temperature - (Heffter, 1980)
  - Raman Lidar - Aerosol backscatter, water vapor via Haar wavelet – (Brooks, 2003)
- Best agreement during afternoon, early evening

- Amount of AOT within PBL
  - varies with time of day
  - does not vary significantly with season or AOT
- Significant fraction of AOT (>25%) is above PBL