Aerosol Retrievals using Airborne Lidar and MODIS Measurements

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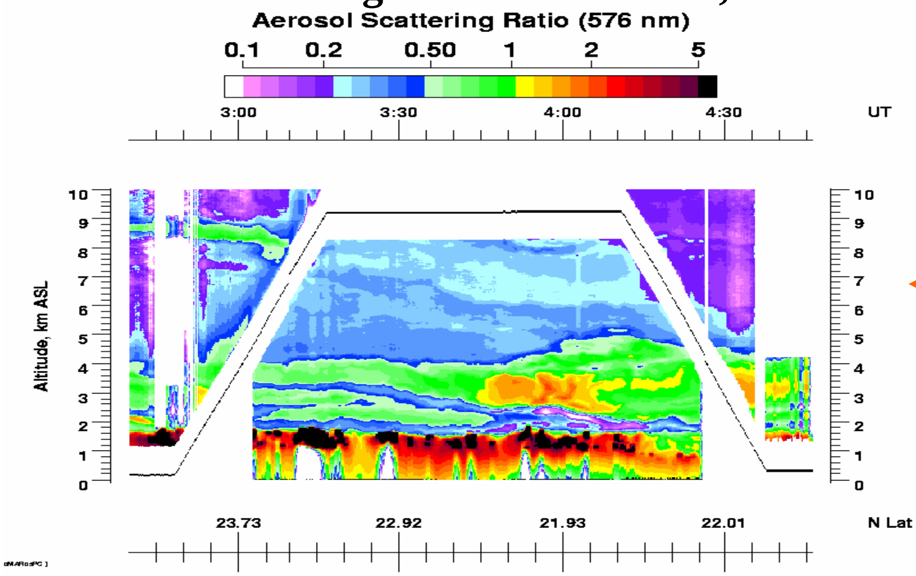
MODIS Atmospheres Meeting, October 31, 2006

Objectives

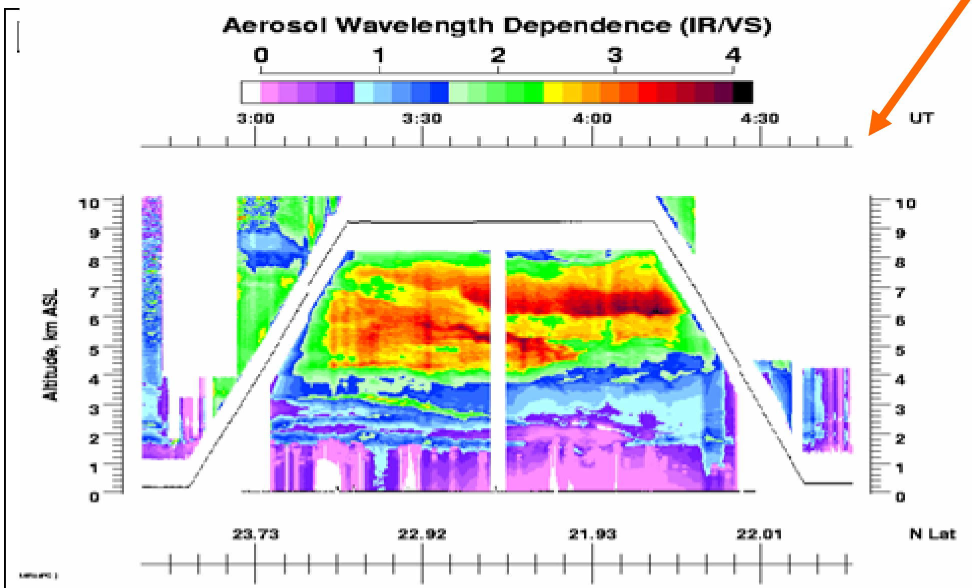
- Retrieve aerosol extinction and optical thickness profiles from lidar data
- Identify aerosol types vs. altitude
- Evaluate ability of GOCART model to simulate aerosol extinction profiles and aerosol type
- Use combination of airborne lidar and MODIS to provide information regarding the vertical distribution of aerosol properties (size, fine mode fraction)

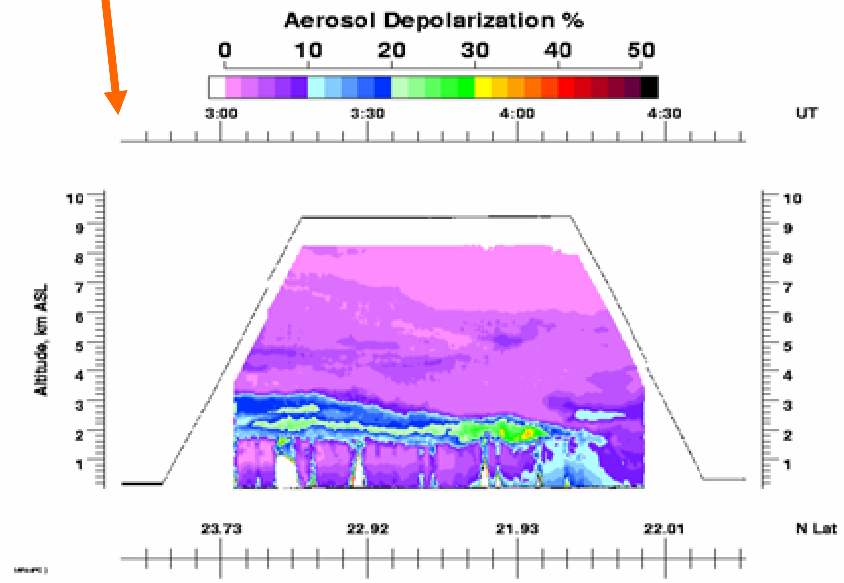
NASA Langley Airborne UV DIAL Measurements

TRACE-P Flight 14 March 23-24, 2001



- Simultaneous Nadir and Zenith Ozone & Aerosol Profiling
- Deployed on NASA DC-8 for TRACE-P (2001), INTEX NA (2004)
- Aerosol extensive parameters (300, 576, 1064 nm)
  - aerosol scattering ratio
  - backscatter
  - extinction
- Aerosol intensive parameters
  - backscatter wavelength dependence
  - depolarization





Aerosol Profile Retrievals

• **Problem - backscatter lidar equation (1 equation with 2 unknowns - backscatter and extinction)**

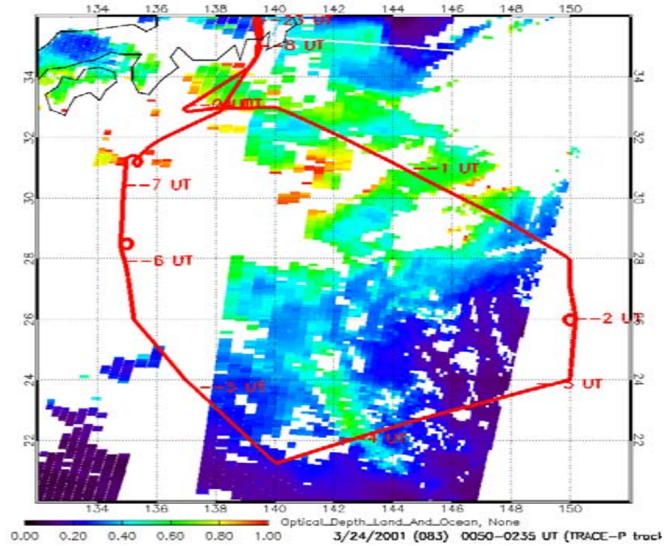
➢ **Solution - use aerosol optical thickness (e.g. total aerosol transmission) derived from MODIS and/or model (e.g. GOCART, MATCH) to constrain solution and derive average lidar ratio**

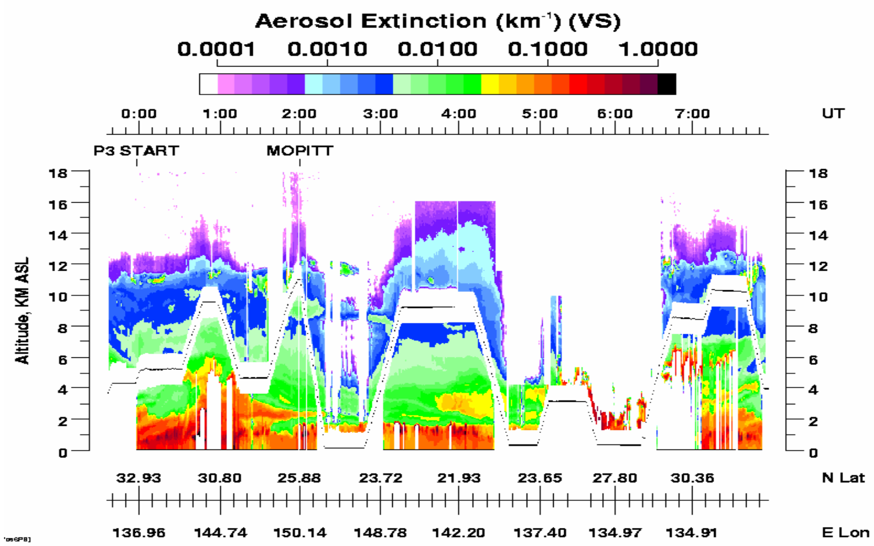
➢**Since DC-8 flights occurred over areas not measured by MODIS, we require other ways to estimate AOT over flight tracks**

• **For TRACE-P (Spring 2001), GOCART was used due to good match between GOCART and MODIS AOT**

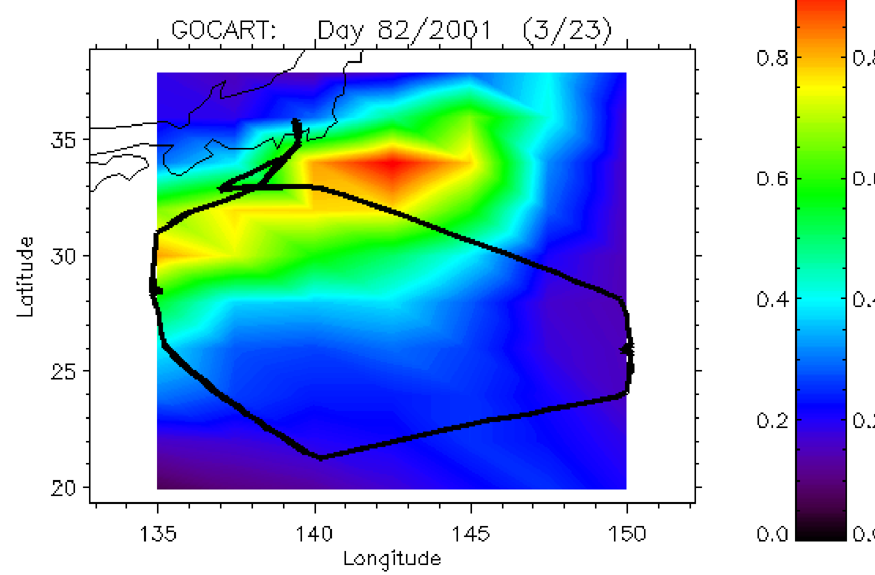
• **For INTEX-NA (Summer 2004), we used MATCH simulations of AOT - MATCH assimilates MODIS AOT**

TRACE-P Flt 14 – 03/23-24/2001





AOT (550 nm)

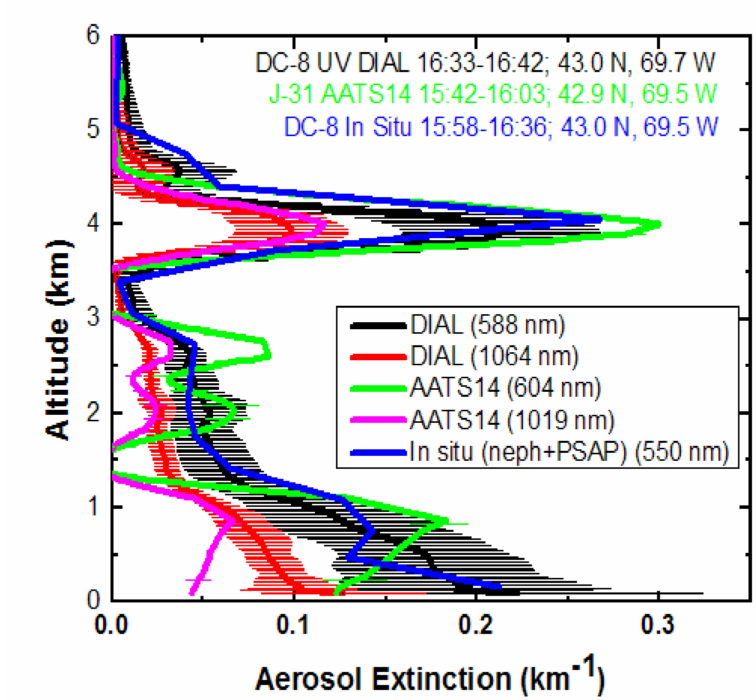


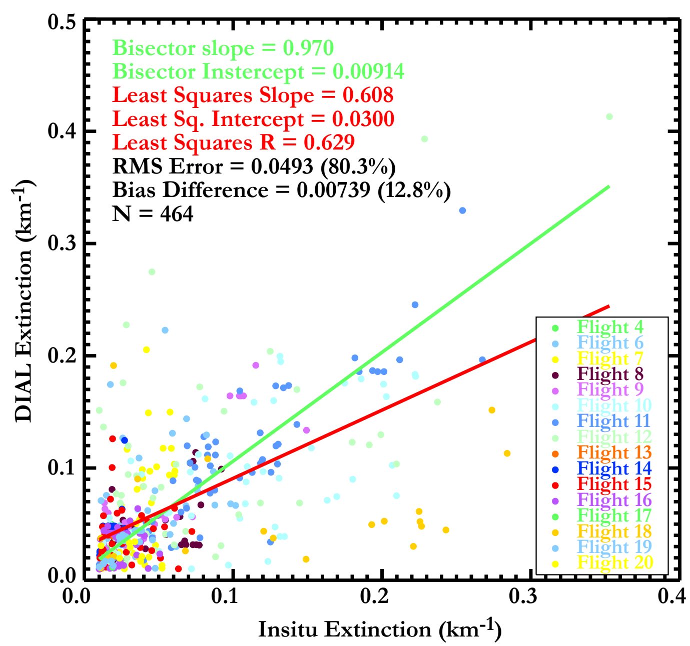
Aerosol Profile Retrievals

- Aerosol extinction and backscatter profiles were computed for TRACE-P and INTEX
- Retrieved aerosol extinction profiles were evaluated using remote sensing and in situ data
- TRACE-P
    - extinction from in situ scattering (neph) + absorption (PSAP) on DC-8 (all flights)
- INTEX NA
    - extinction from in situ scattering (neph) + absorption (PSAP) on DC-8 (all flights)
    - extinction from airborne Sun photometer AOT measurements on J-31 (one flight)

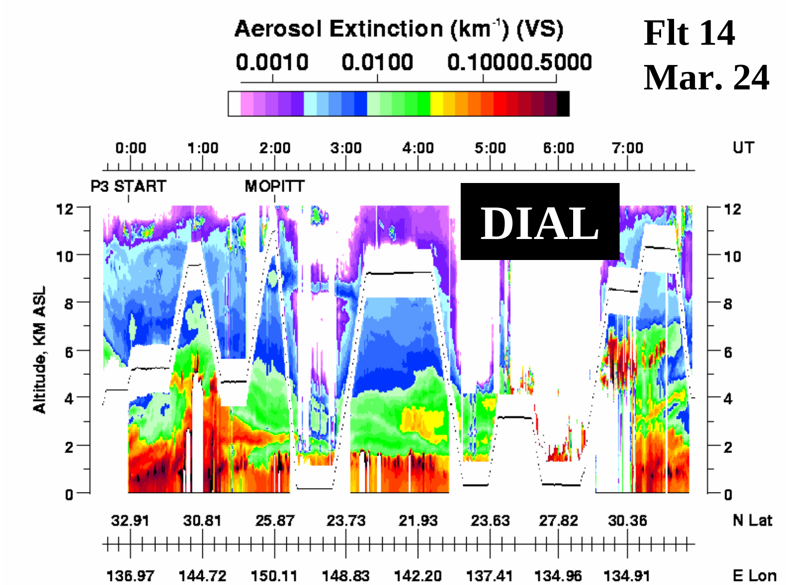
➢ **Results - Bias differences were relatively small (0.007 km-1 or about 13%, DIAL larger), rms differences were considerably larger (0.05 km-1, 80%)**

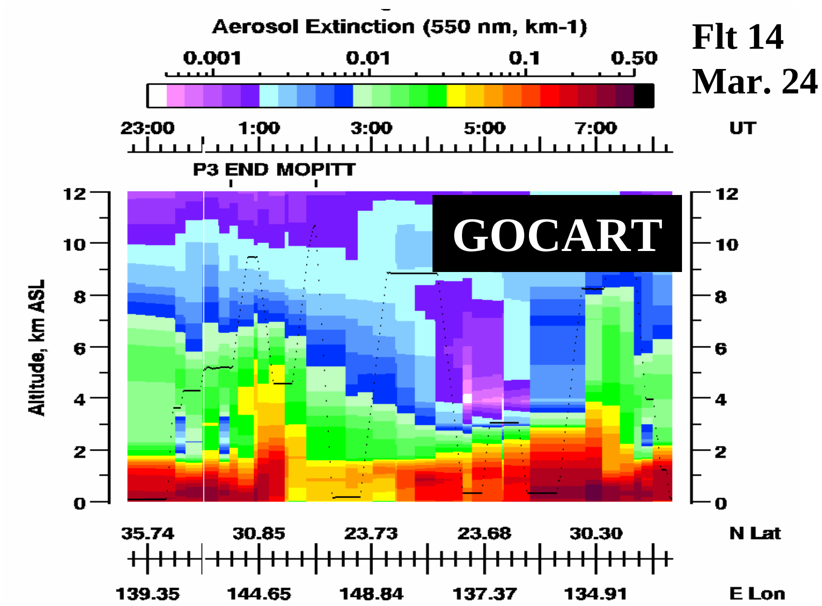
- Relatively large temporal (10-20 minutes) and spatial (30-200 km) differences between the lidar and in situ profiles contributed to the rms differences



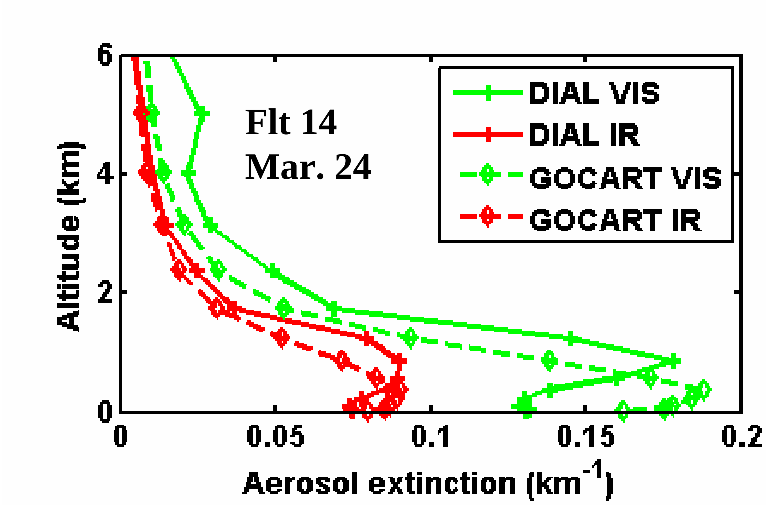


Comparison of Vertical Profiles – DIAL and GOCART (TRACE-P)



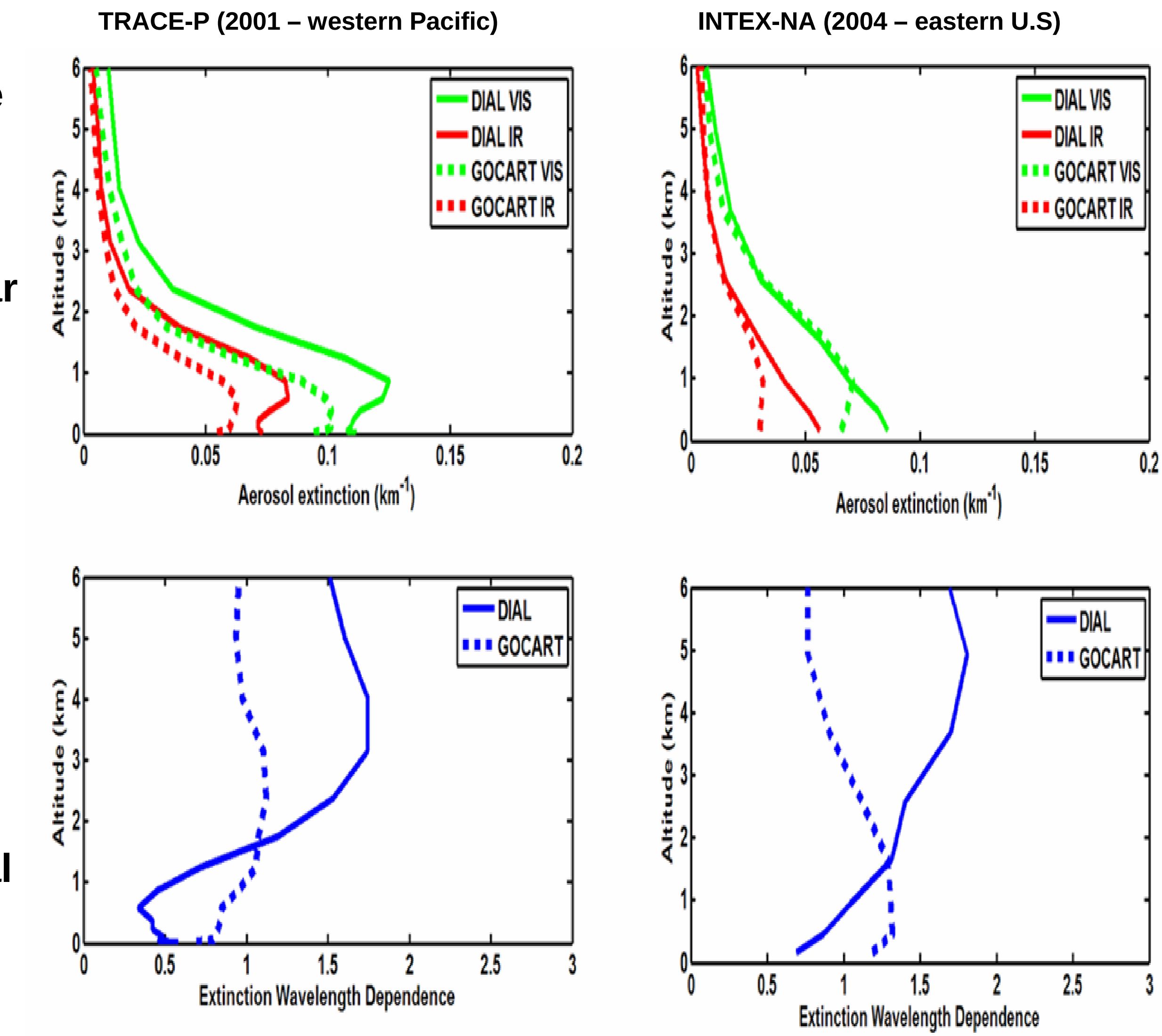


- **Lidar aerosol extinction profiles are used to evaluate GOCART aerosol simulations**



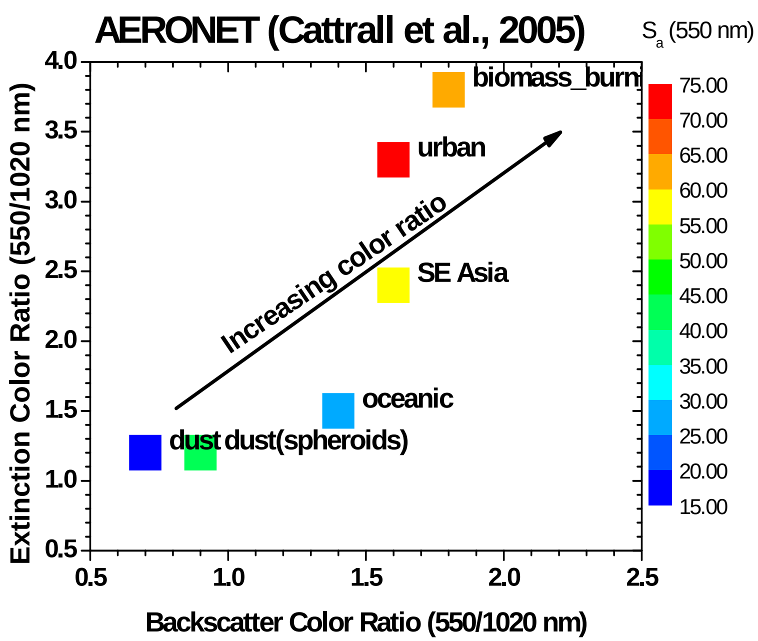
Comparison of Vertical Profiles – DIAL and GOCART (TRACE-P)

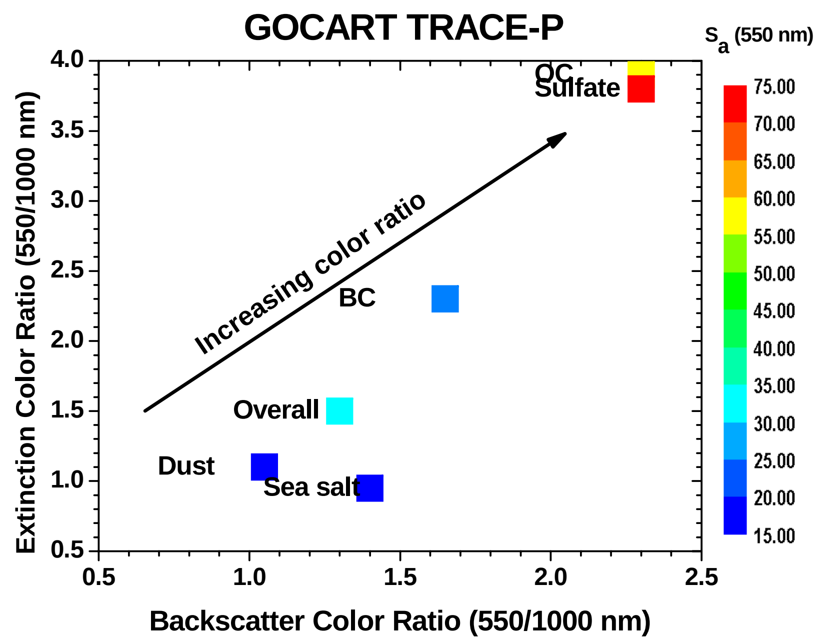
- **Lidar aerosol extinction profiles are used to evaluate GOCART aerosol simulations**
- **During TRACE-P, GOCART profiles were lower than lidar throughout troposphere, with smallest differences near the surface**
- **During INTEX-NA, GOCART and lidar profiles agreed above 1 km, largest differences near the surface**
- **Different behavior may be related to more frequent occurrence of elevated layers during TRACE-P**
- **GOCART shows less vertical variability in wavelength dependence (particle size) than lidar**



Aerosol Classification Using Lidar Measurements

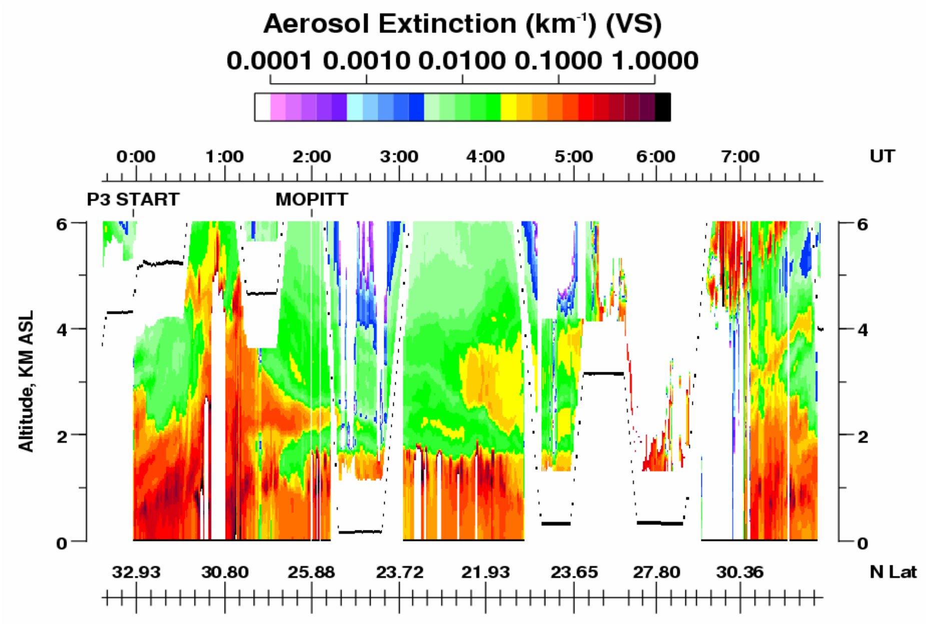
Can we use DIAL measurements of aerosol intensive parameters (backscatter and extinction color ratios, depolarization) to help identify aerosol type?

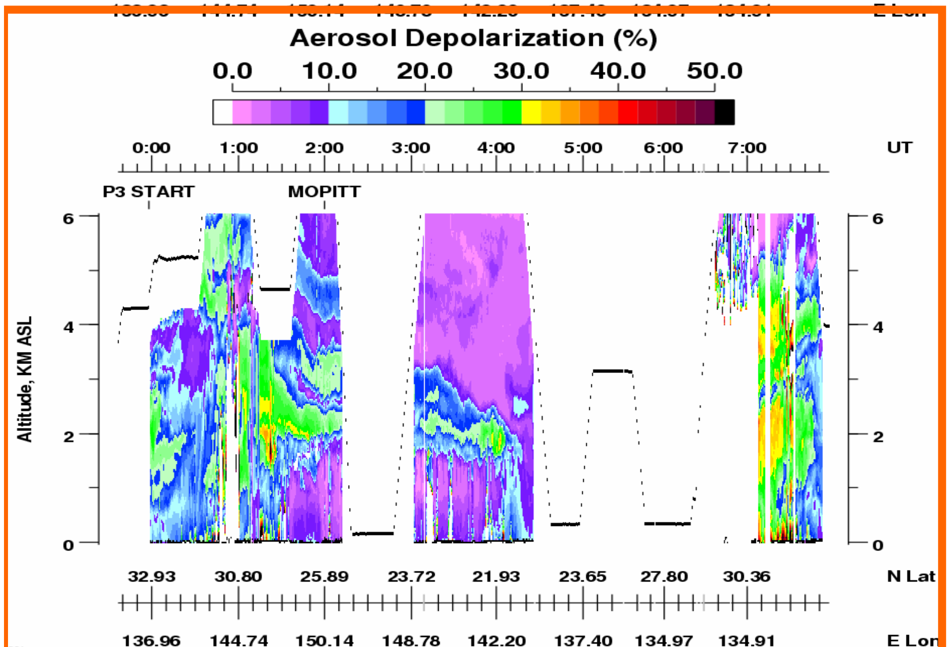


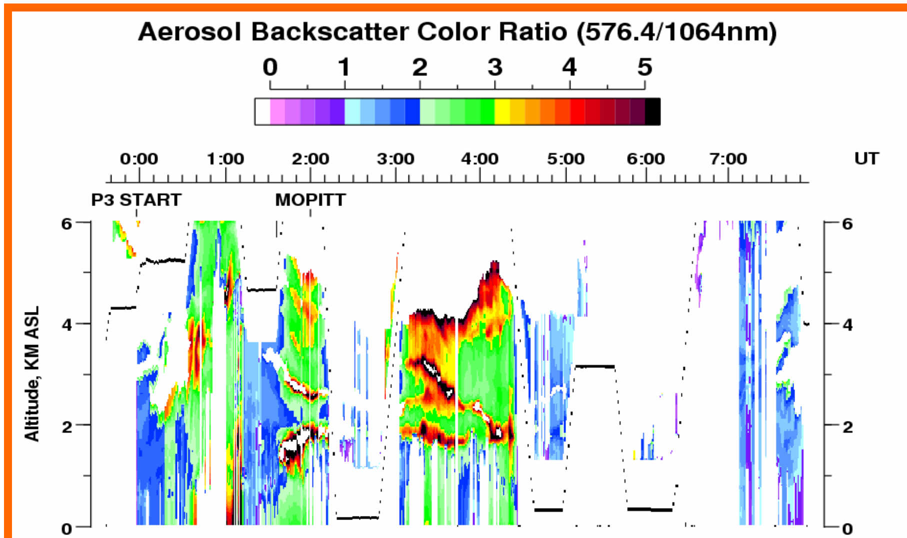


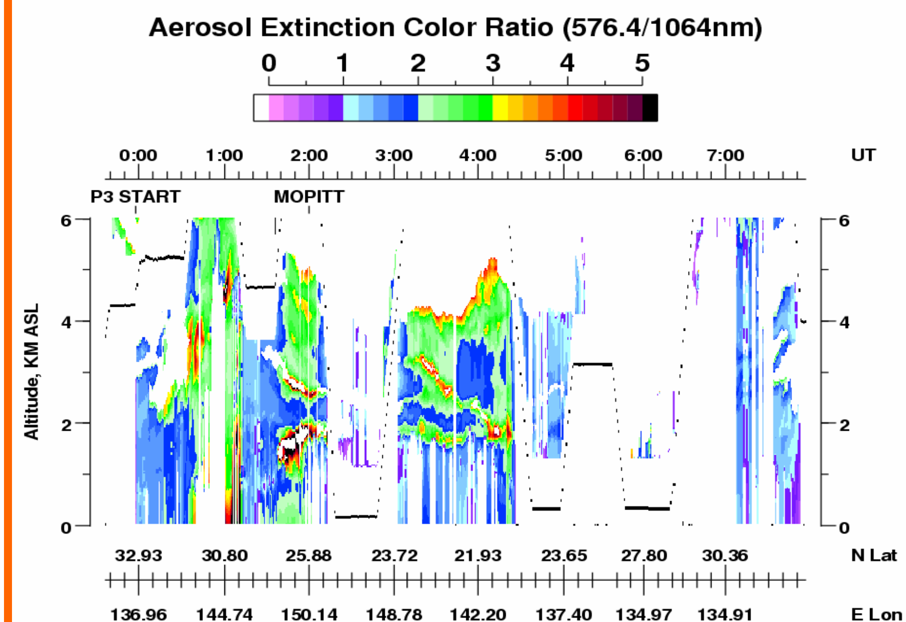
- **Aerosol types were grouped using intensive parameters derived from DIAL**
  - **Extinction color ratio**
  - **Backscatter color ratio**
  - **Depolarization**

Aerosol Classification Using Lidar Measurements

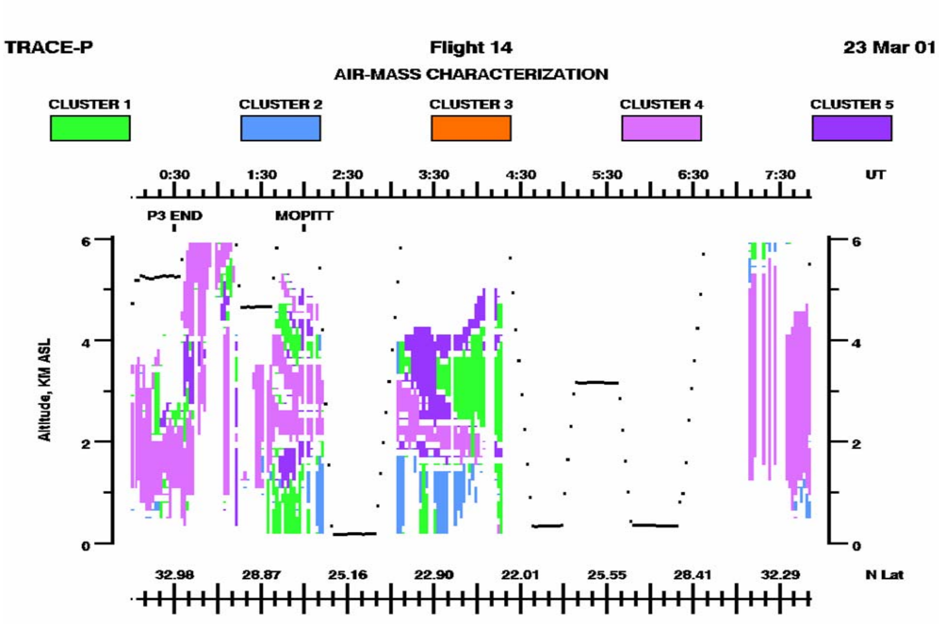


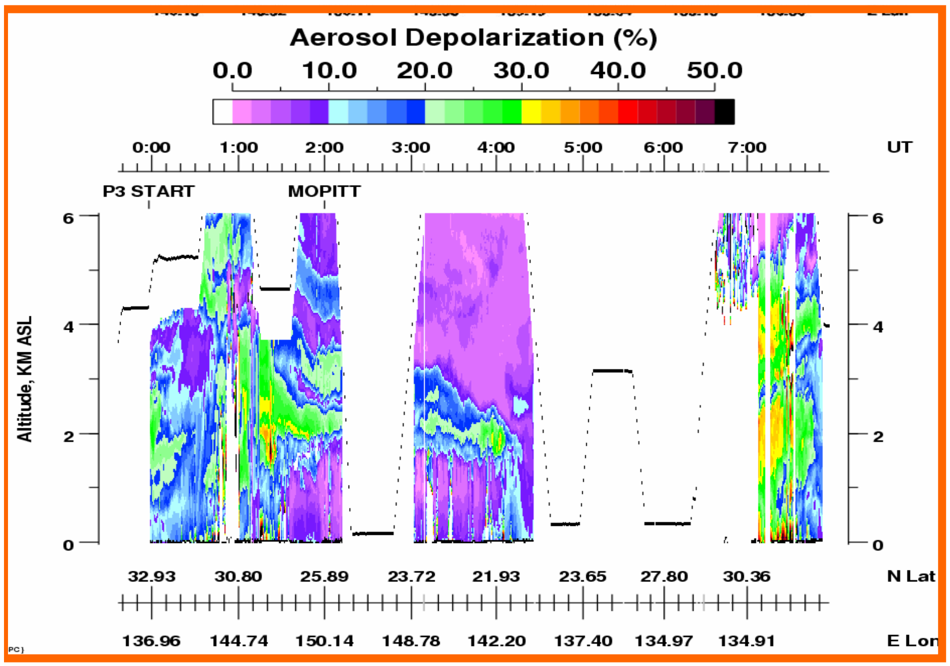


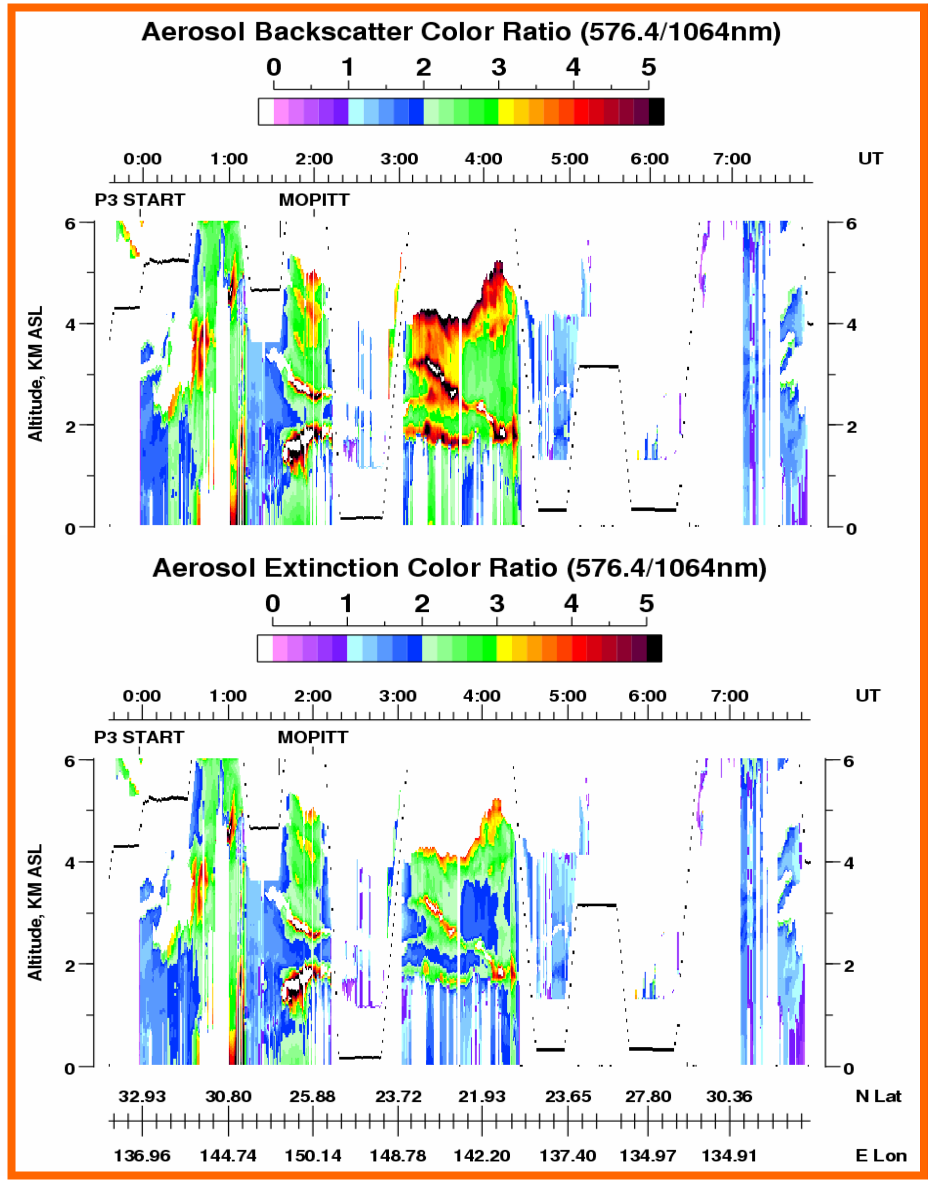




Aerosol Classification Using Lidar Measurements

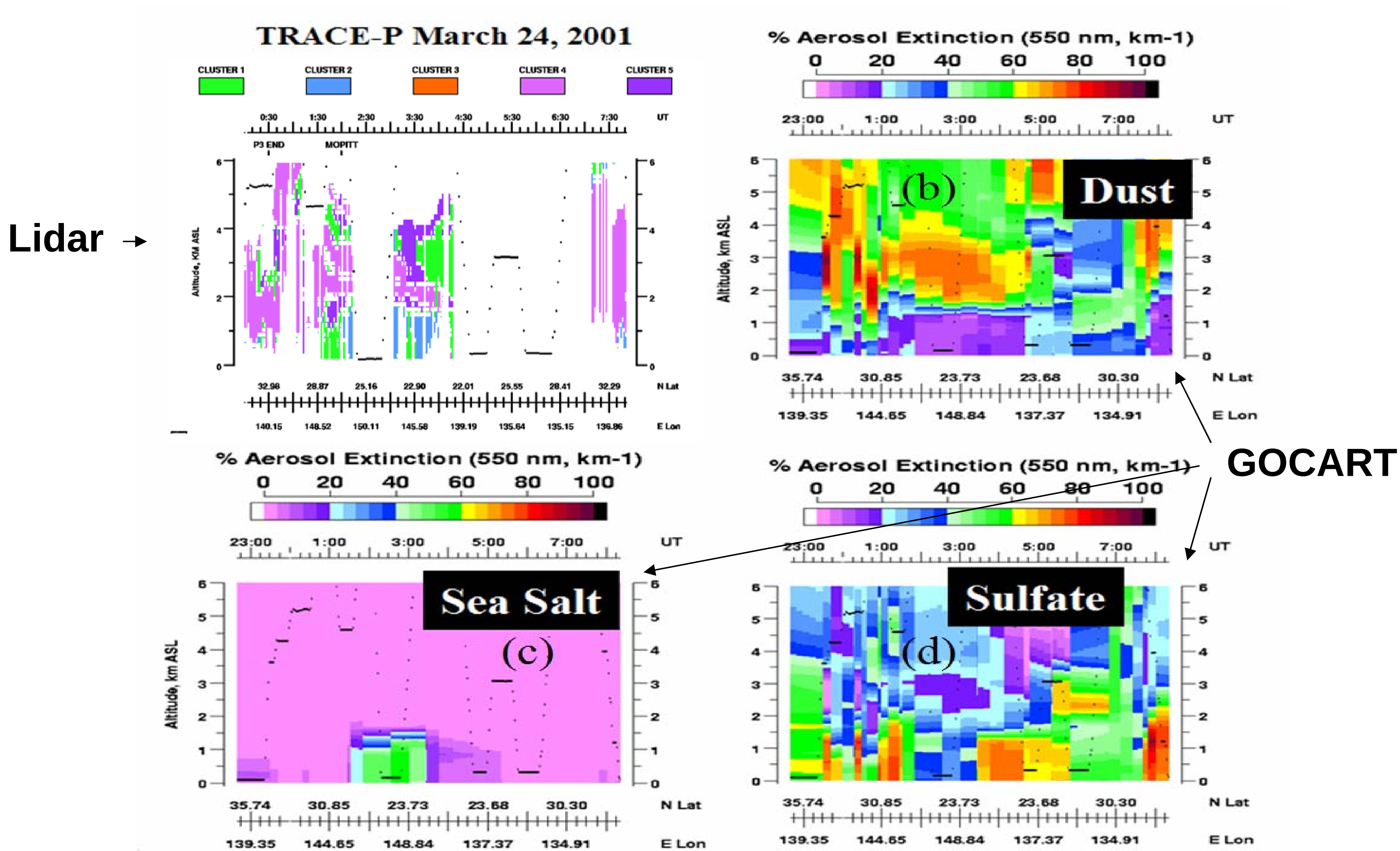






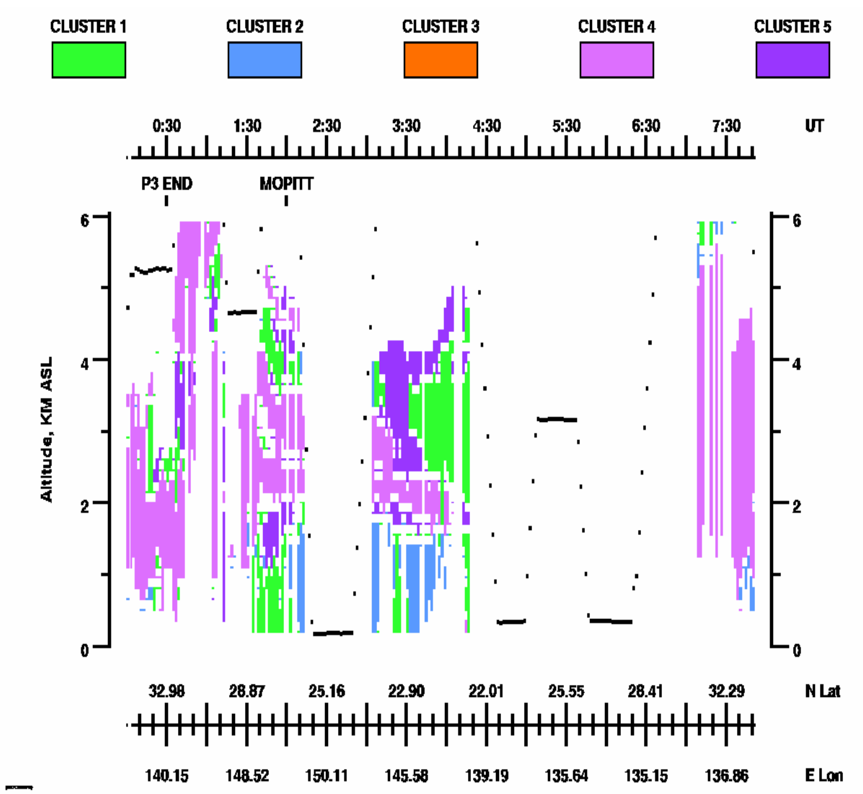
Evaluate GOCART model simulations of aerosol type

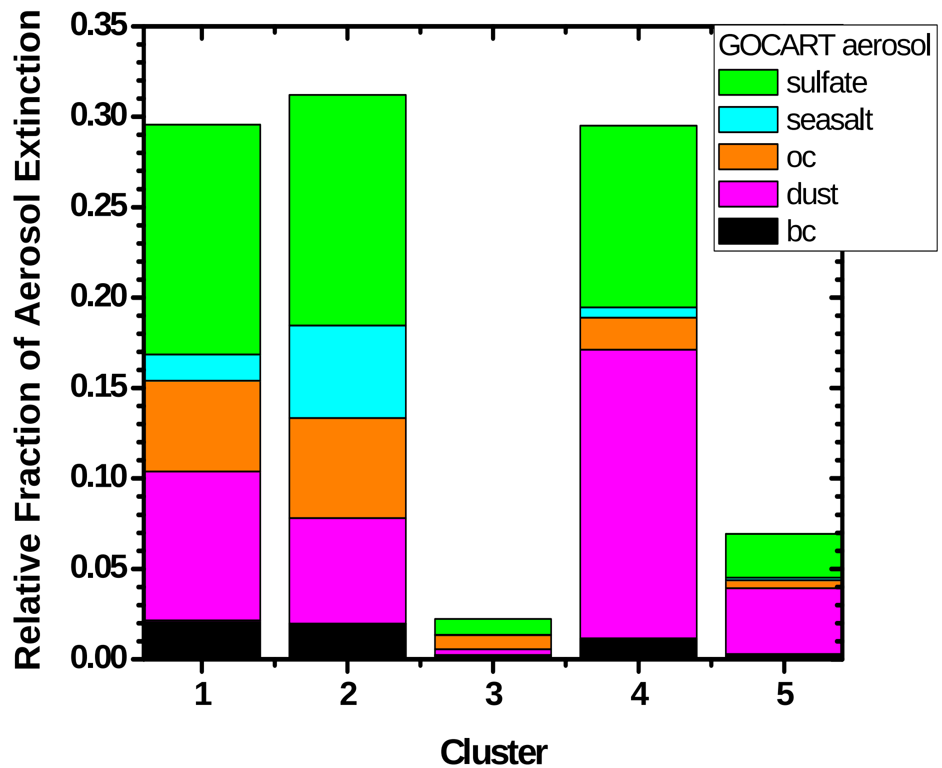
Use lidar profile measurements to evaluate GOCART model simulations of aerosol type



Evaluate GOCART model simulations of aerosol type

- No one-to-one correspondence between GOCART aerosol types and aerosol clusters but some correlation among the clusters and types
  - Cluster 1 – highest fraction of sulfate
  - Cluster 2 – highest fraction of sea salt
  - Cluster 3 – highest fraction of carbon
  - Clusters 4, 5 – highest fractions of dust





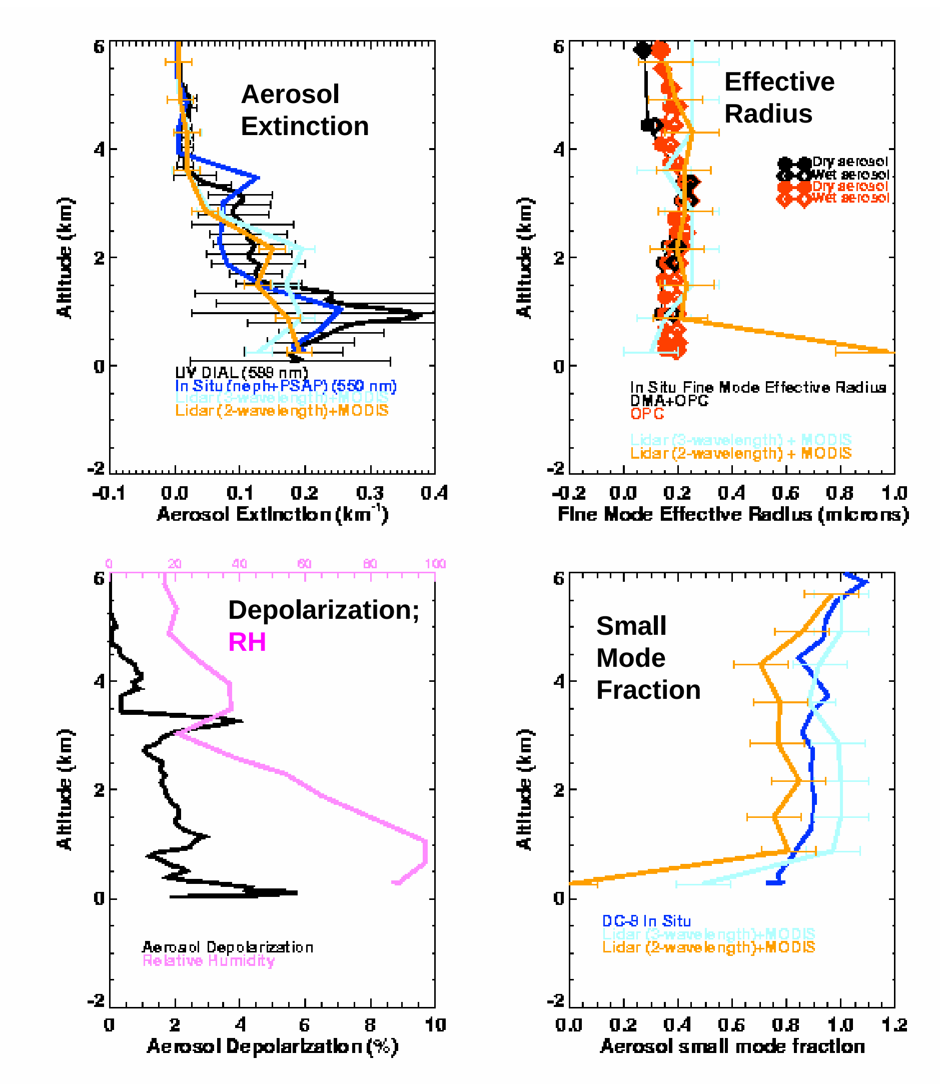
MODIS+lidar Aerosol Retrieval

- Retrieval algorithms – (2 Wavelength)
  - (Kaufman et al., IEEE, 2003; GRL, 2003; Léon et al., JGR, 2003)
  - Aerosol size distribution – bimodal lognormal
  - MODIS aerosol models – 20 combinations of 4 fine, 5 coarse particles
  - Size of each mode is assumed to be altitude independent
  - Relative weight of each mode is determined as a function of altitude from lidar backscatter color ratio
  - Retrievals are constrained to fit MODIS measurements
    - Spectral reflectance
    - Column AOT and r_{eff}
- Modifications – (3 Wavelength)
  - UV wavelength (300 nm) – more information on fine particle size
  - Constrain to MODIS AOT to account for lidar calibration uncertainties
  - Depolarization – adjust the backscatter phase function for nonsphericity
- Evaluation
  - Retrievals were evaluated using DC-8 in situ measurements

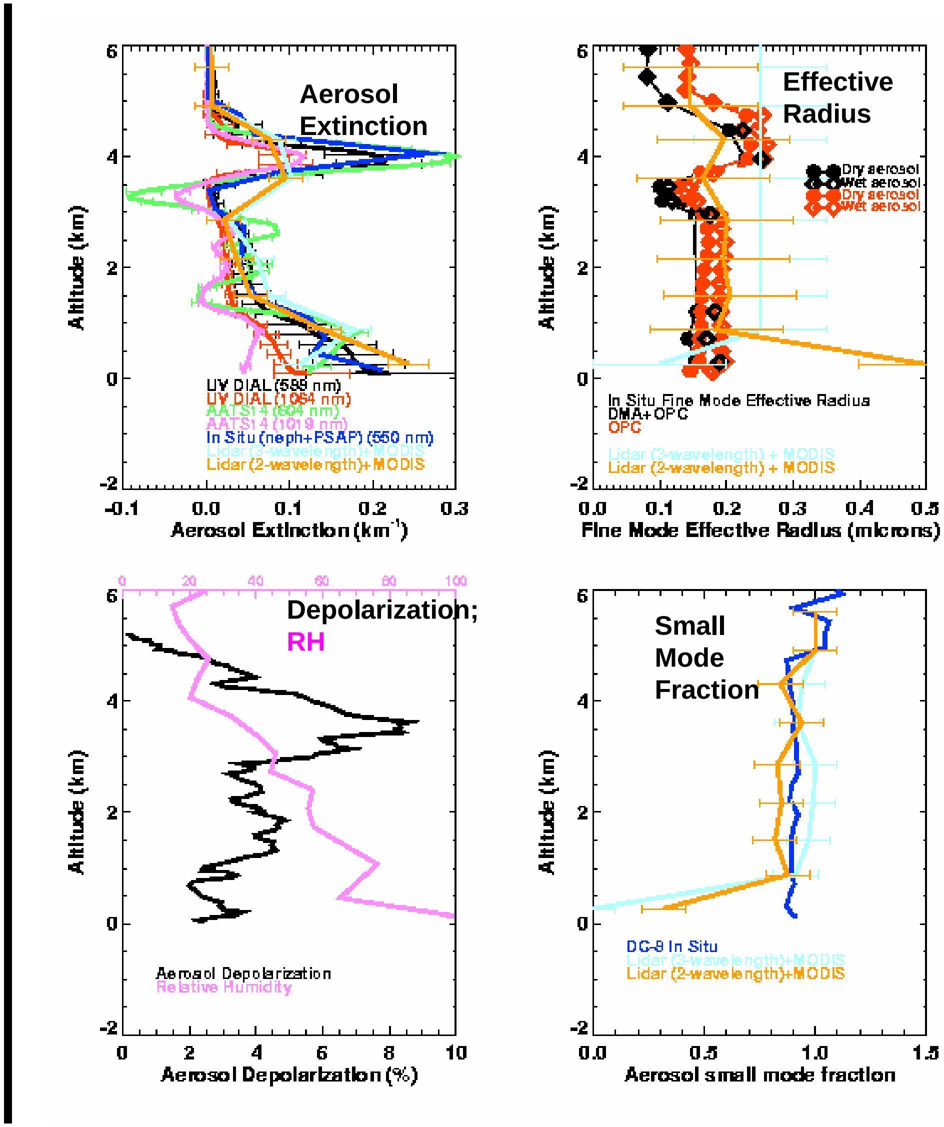
MODIS+lidar Aerosol Retrievals

July 22, 2004

13:08-13:30 UT



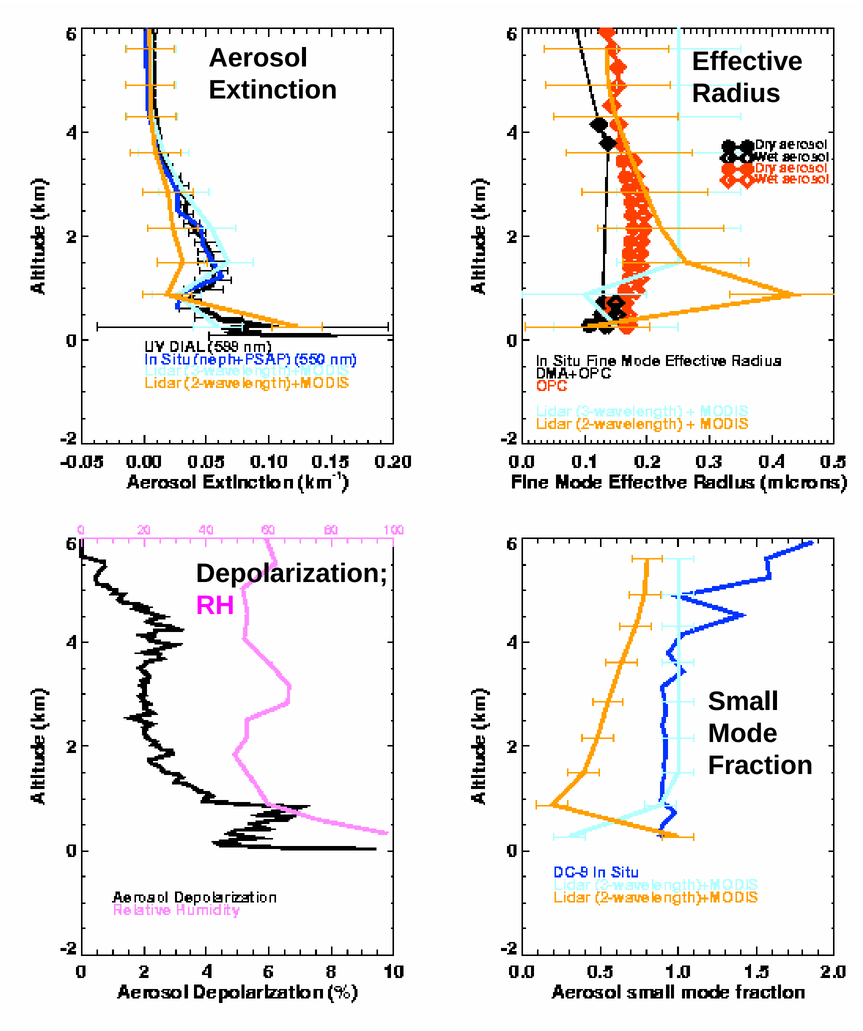
16:33-16:42 UT



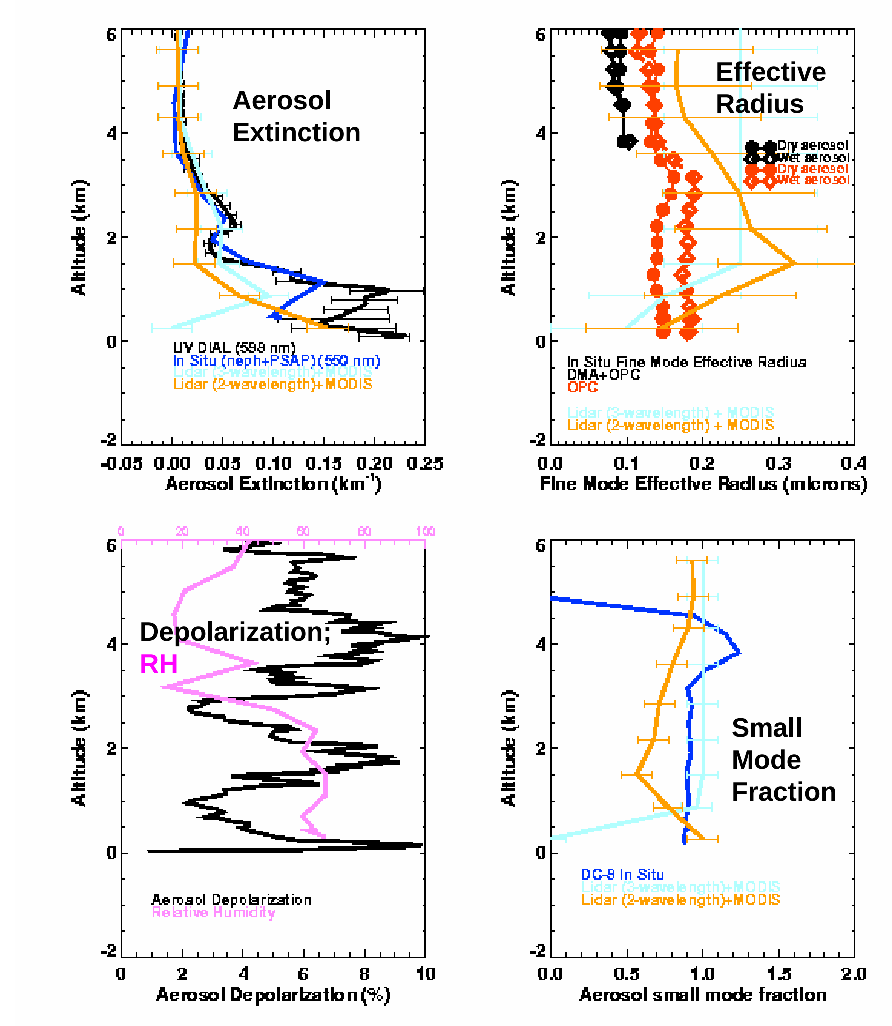
MODIS+lidar Aerosol Retrievals

July 18, 2004

14:45-15:22 UT

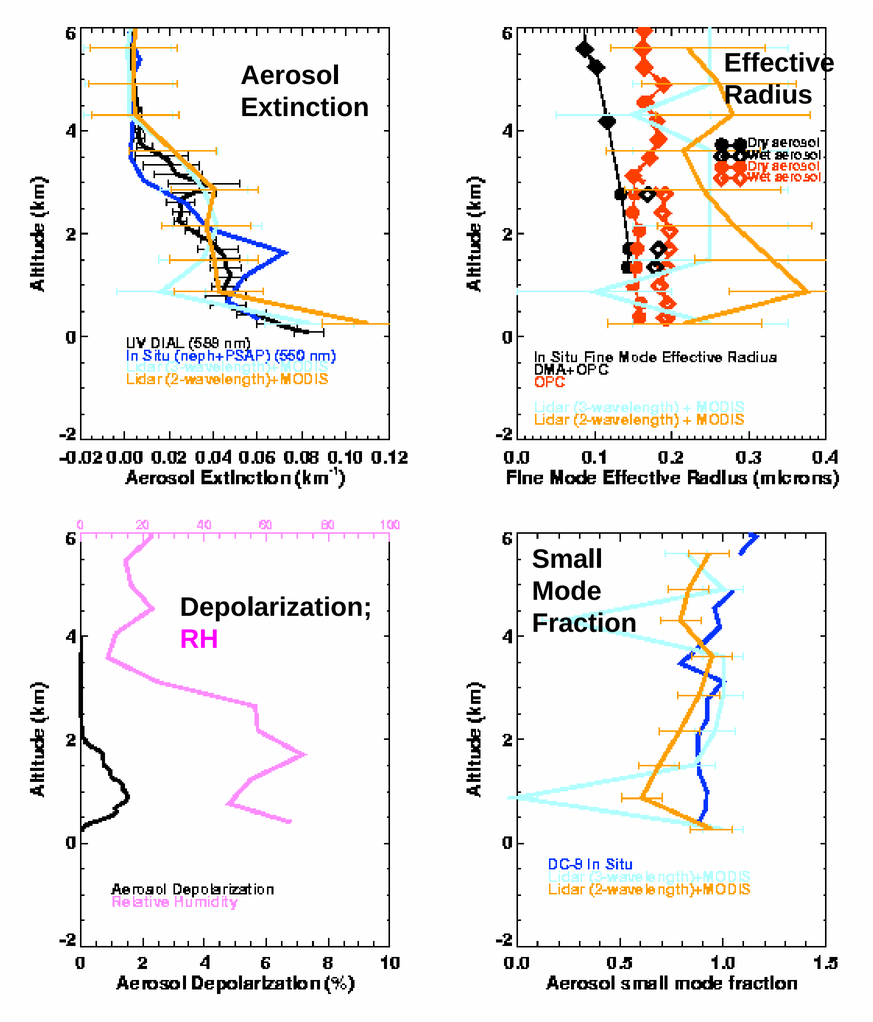


21:07-21:40 UT



MODIS+lidar Aerosol Retrievals

August 2, 2004 18:13-18:34 UT

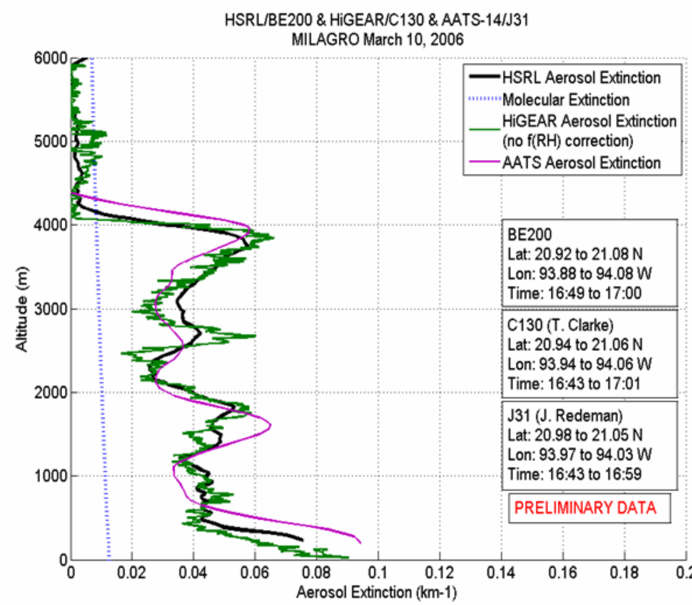


- Generally promising results
- Works best for AOT > 0.15
- Need more cases with coincident and colocated in situ data to evaluate results with various aerosol types

NASA Langley Airborne High Spectral Resolution Lidar (HSRL)

- **HSRL independently measures aerosol and molecular backscatter**
  – Can be internally calibrated
  – No correction for extinction required to derive backscatter profiles
- **HSRL enables independent estimates of aerosol backscatter and extinction**
  – Extinction and backscatter estimates require no S_a assumptions
  – Provide *intensive* optical data from which to infer aerosol type

Comparison of Aerosol Extinction Measurement
(Preliminary Data)



- AATS14 data courtesy of Phil Russell, Jens Redemann, John Livingston (NASA)
- HIGEAR data courtesy of Tony Clarke (Univ. of Hawaii)

Products

Extensive – depend on type and amount

Aerosol Backscatter 532 nm
Aerosol Backscatter 1064 nm (standard retrieval)
Aerosol Extinction and Aerosol Optical Thickness

Intensive – depend on type

Extinction-to-Backscatter Ratio (S_a) (532nm)
Aerosol Depolarization (532 & 1064 nm)
Aerosol Depolarization Ratio (1064/532 nm)
Aerosol Wavelength Dependence (1064/532 nm)

Additional information over that provided by DIAL will aid:

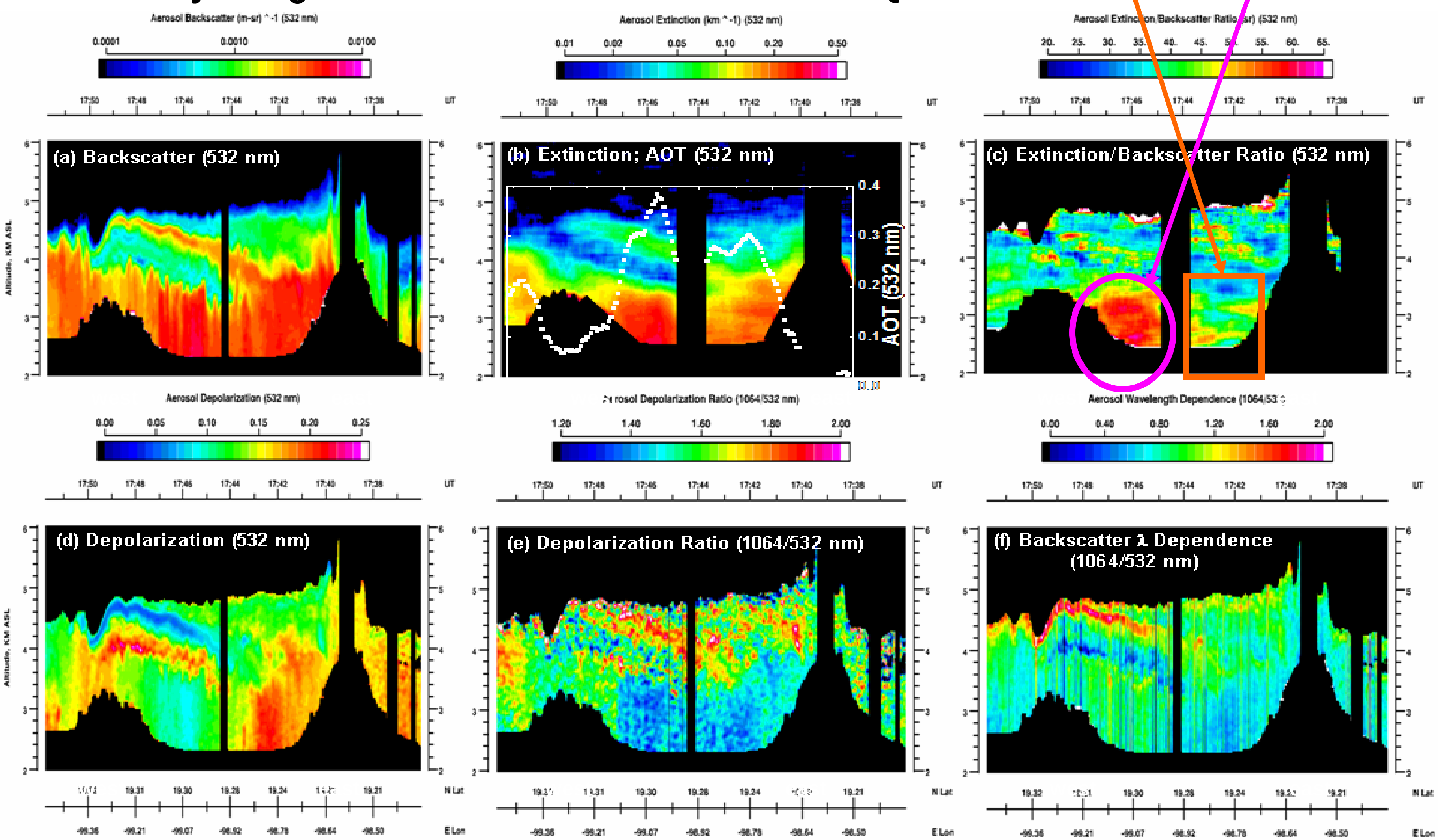
- combined lidar+MODIS retrievals
- determination of aerosol type

Characterize the horizontal distribution of aerosol types

LaRC Airborne HSRL Measurements over Mexico City, March 13, 2006

- western part of city- high S_a, high WVD, low depolarization – urban aerosol
- eastern part of city - low Sa, low WVD, high depolarization – dust

➢ Currently using HSRL measurements to assess RAQMS and STEM models



Summary

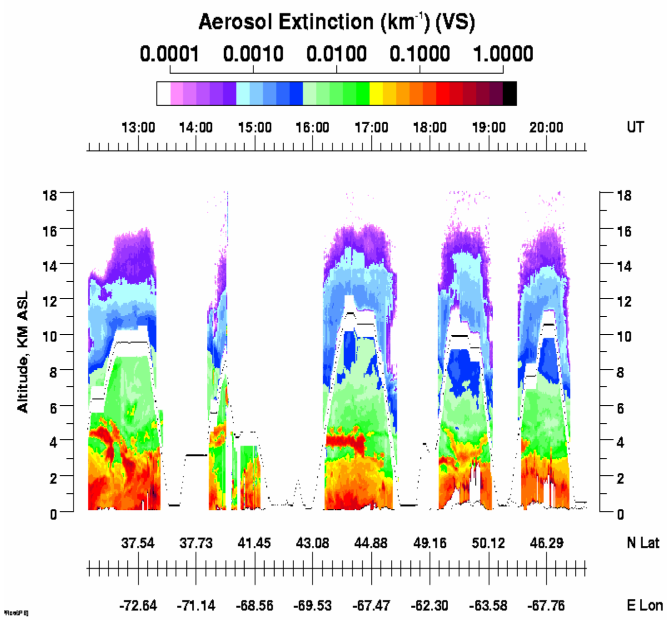
- MODIS data helped constrain airborne lidar retrievals of aerosol extinction profiles, and backscatter and extinction color ratios - TRACE-P (2001) and INTEX NA (2004)
- Combination of lidar+MODIS measurements over ocean used to retrieve profiles of fine mode fraction and effective radius
  - Evaluated algorithms that use both 2 and 3 wavelength lidar measurements
  - Good agreement with extinction, fine mode fraction for AOT (550 nm) > 0.15
- Evaluating GOCART simulations (TRACE-P and INTEX NA)
  - Aerosol extinction – in general agreement with lidar profiles, but details differ depending on campaign
- Work in progress – using lidar measurements to identify & group aerosol types
  - Use cluster analysis techniques to identify and group aerosols
  - Some correspondence between TRACE-P clusters and GOCART aerosol types
- Future
  - Use aerosol extinction, backscatter, depolarization measurements from LaRC airborne High Spectral Resolution Lidar (HSRL) – INTEX-B/MILAGRO (Mexico City), TEXAQS/GoMACCS (Houston) for combined lidar+MODIS+PARASOL retrievals and identification of aeosol type

Backup Slides

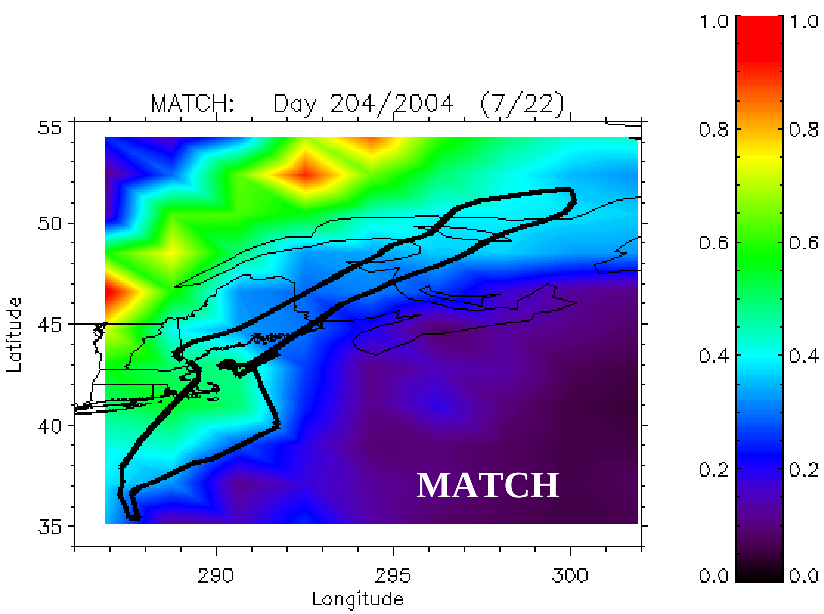
Aerosol Profile Retrievals

- Since DC-8 flights occurred over areas not measured by MODIS, we require other ways to estimate AOT over flight tracks
- For INTEX-NA (Summer 2004), initial GOCART simulations had lower AOT than MODIS due to underestimate of smoke emissions, so we have initially used MATCH simulations of AOT provided by NCAR for CERES
- MATCH assimilates MODIS AOT

INTEX-NA Flt 11 – 07/22/2004



AOT (550 nm)



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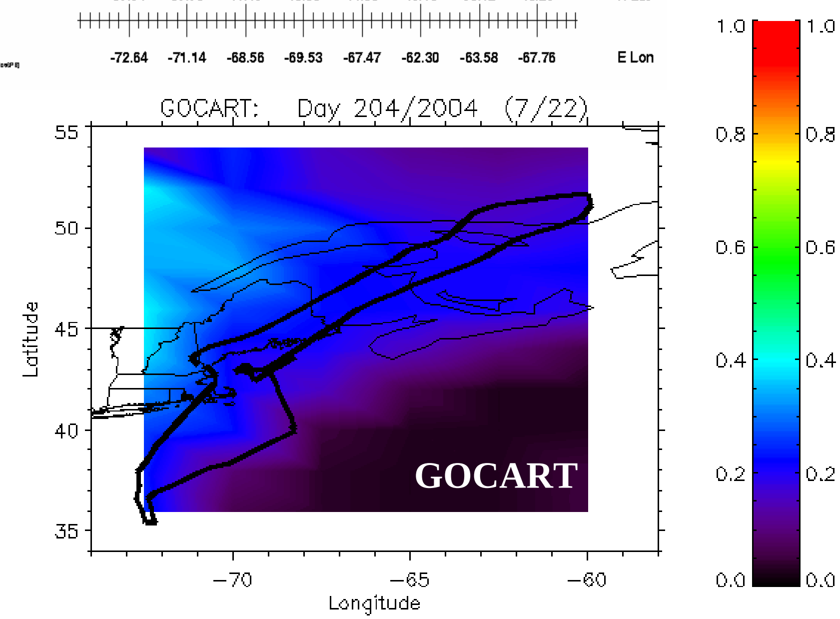
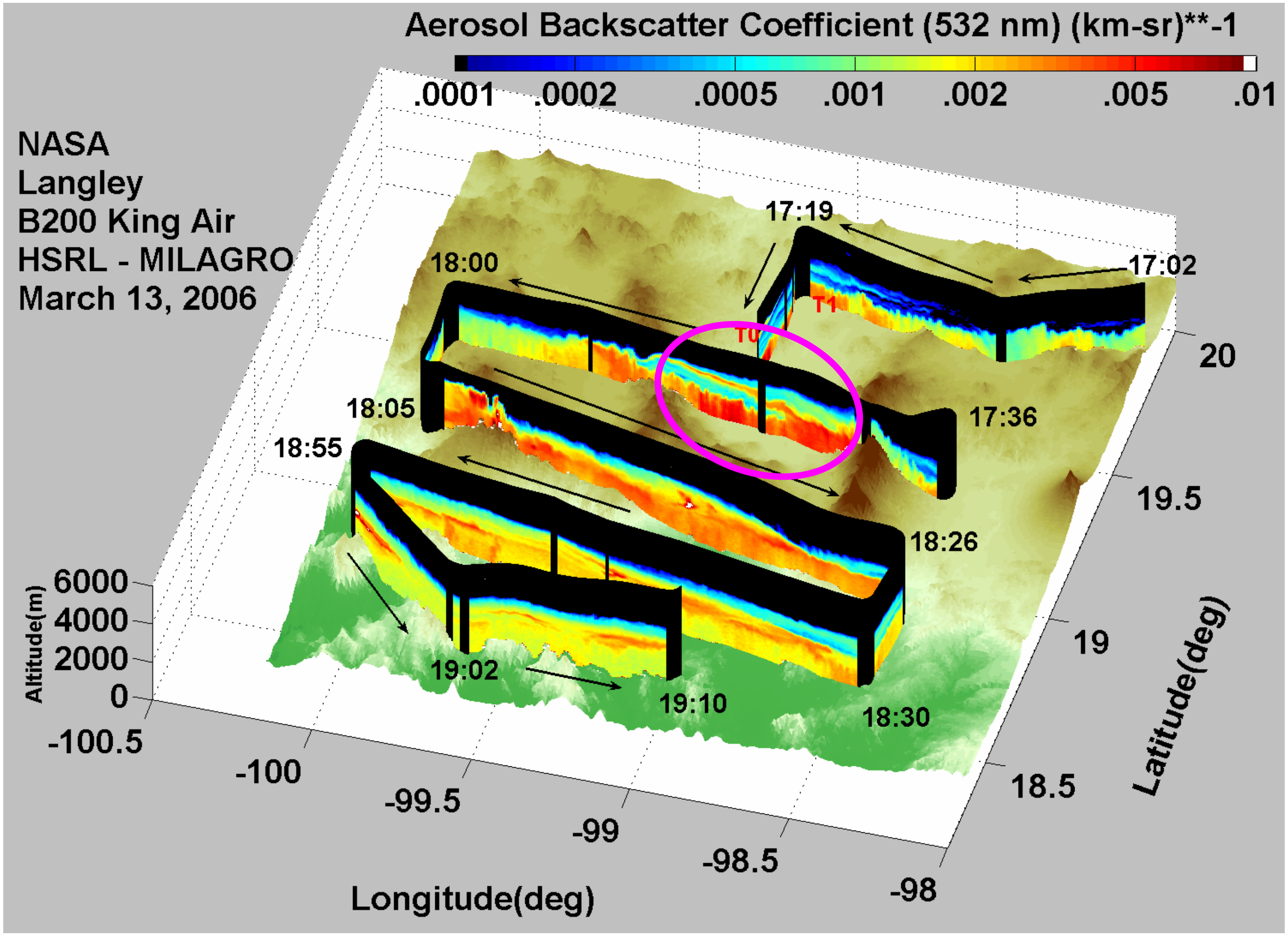


Outline

- Objectives
- Airborne Lidar Aerosol Measurements
- GOCART model evaluation
- Aerosol classification using lidar data
- Lidar + MODIS retrievals
- Summary and Future

HSRL Measurements over Mexico City region



NASA Langley Airborne High Spectral Resolution Lidar (HSRL)

- **HSRL independently measures aerosol and molecular backscatter**
  - Can be internally calibrated
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  - More accurate aerosol layer top/base heights

- **HSRL enables independent estimates of aerosol backscatter and extinction**
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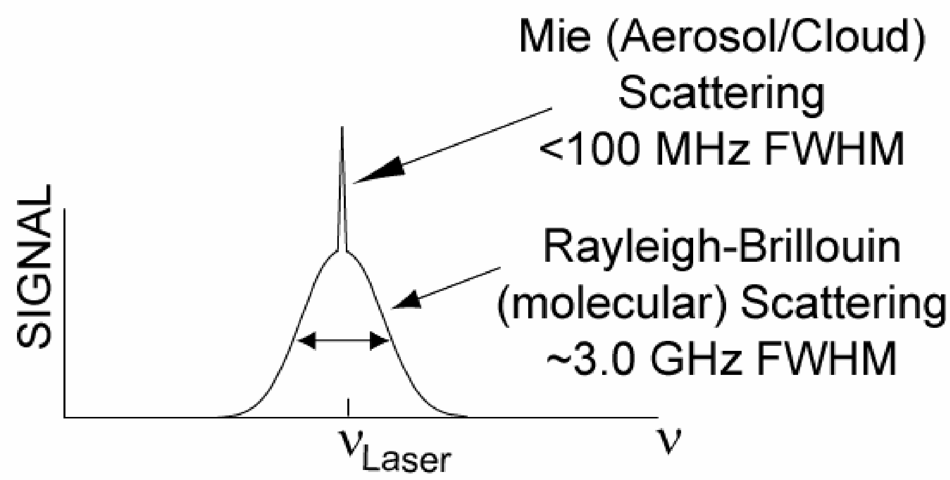
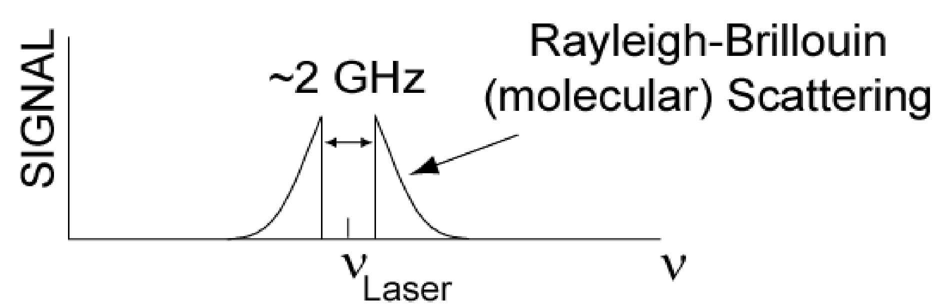
Intensive – depend on type

Extinction-to-Backscatter Ratio (S_a) (532nm)
Aerosol Depolarization (532 & 1064 nm)
Aerosol Depolarization Ratio (1064/532 nm)
Aerosol Wavelength Dependence (1064/532 nm)

Atmospheric Scattering



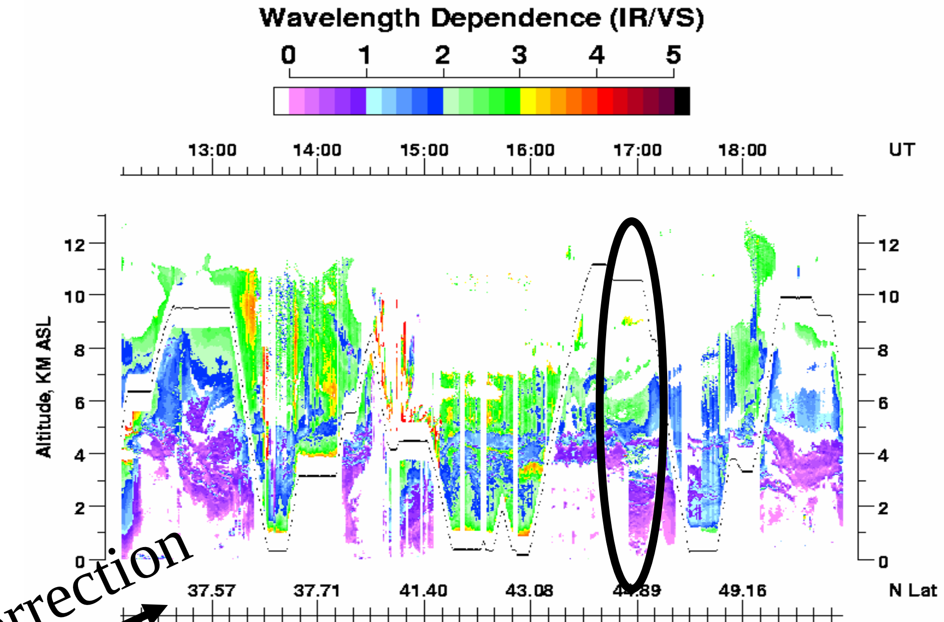
Effect of Iodine Vapor Notch Filter



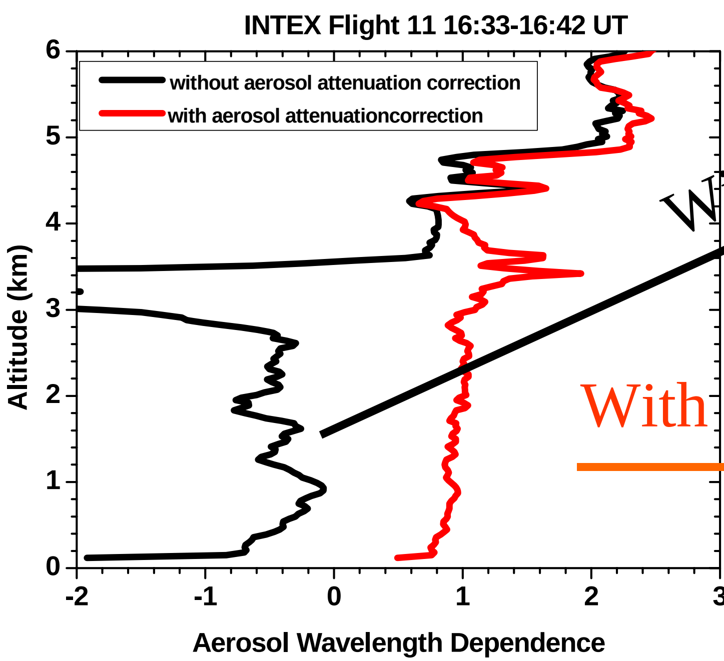
Aerosol Wavelength Dependence – July 22, 2004

• Attenuation correction applied using MODIS AOT constraint

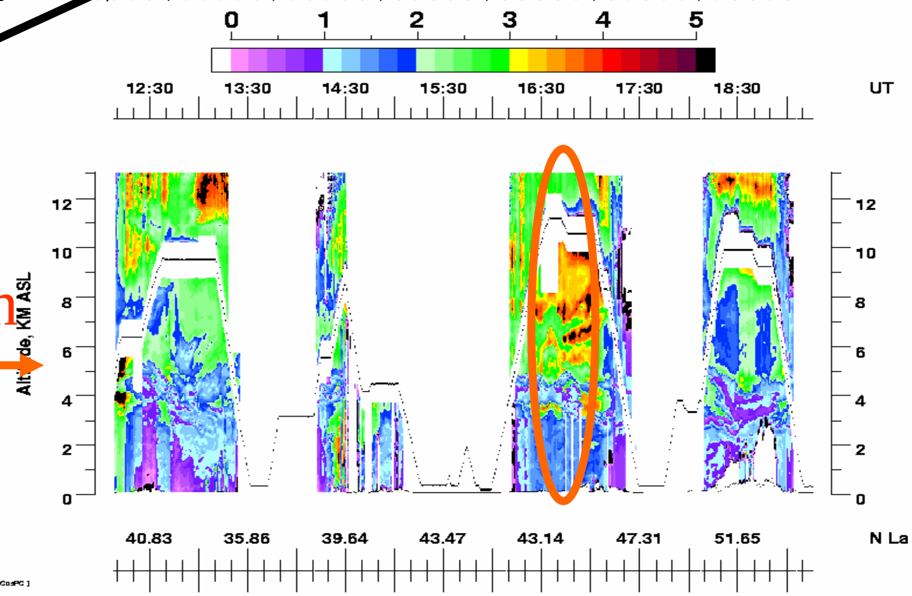
• Correction retrieves profiles under layers of large aerosol attenuation



Without correction

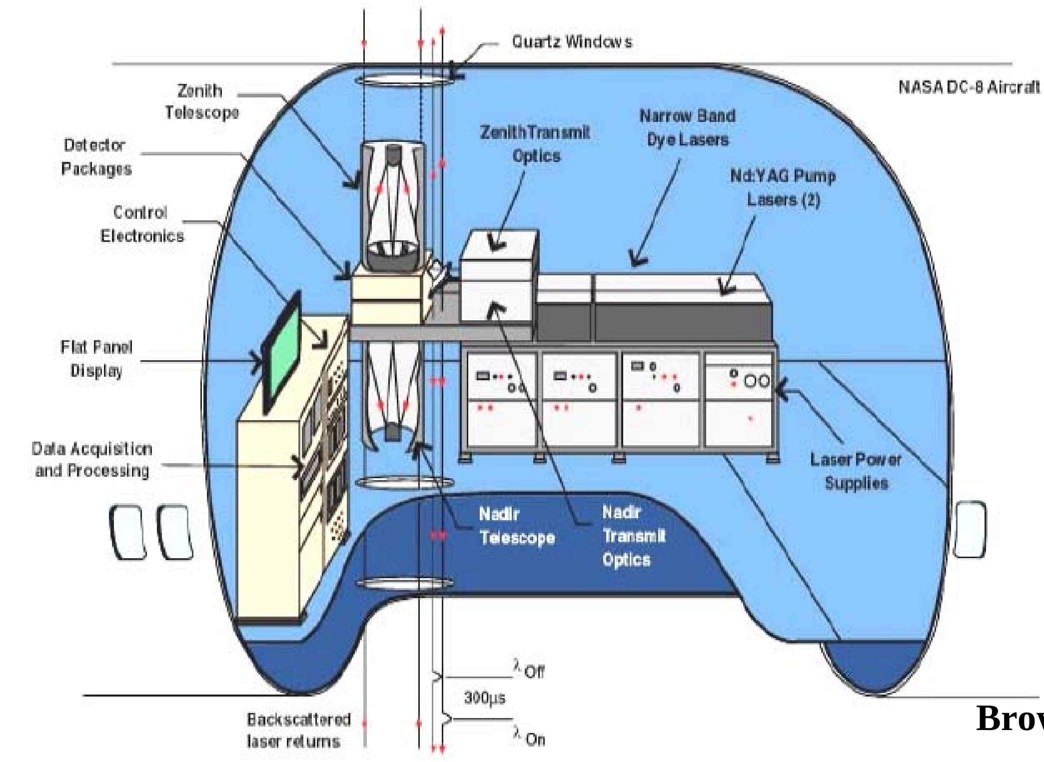


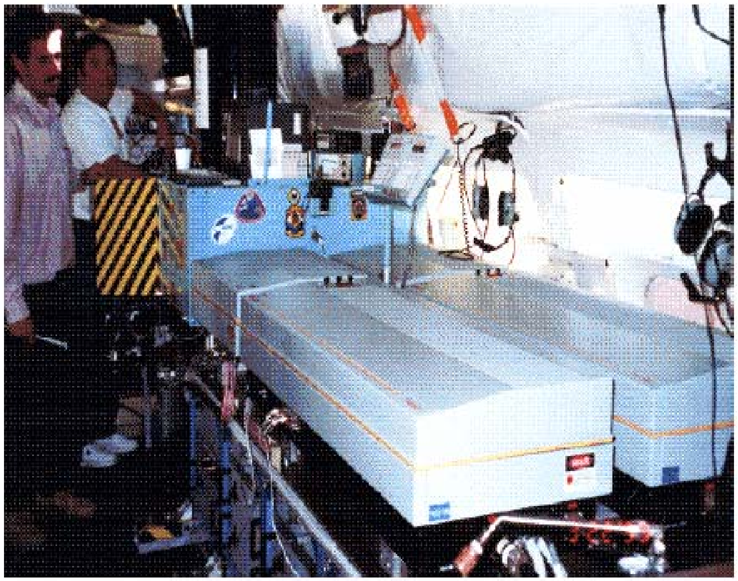
With correction



NASA Langley Airborne UV DIAL Measurements

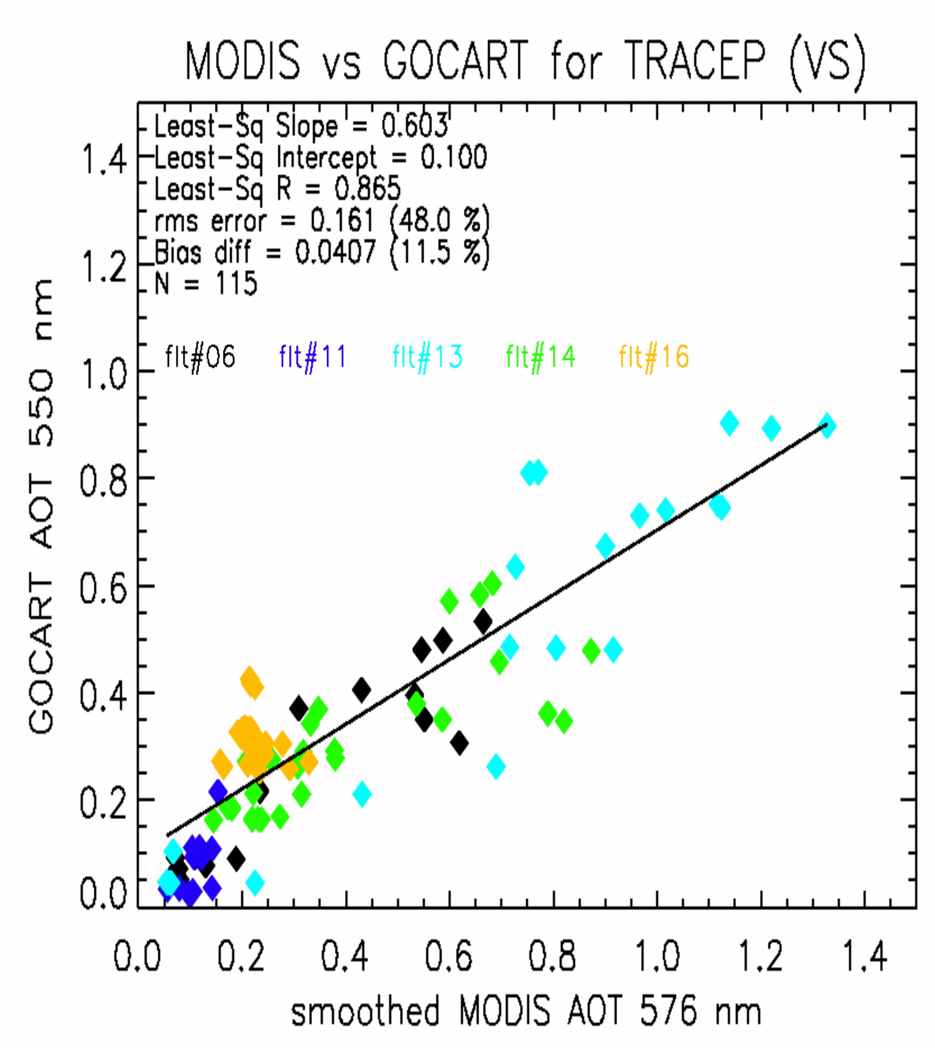
- **Ozone Differential Absorption Lidar (DIAL) Profiles (λ_{on}=289 nm & λ_{off} =300 nm)**
- **Aerosol & Cloud Scattering Ratio Profiles (300, 576, & 1064 nm)**
- **Simultaneous Nadir and Zenith Ozone & Aerosol Profiling**
- **Nadir Aerosol Depolarization Profiles (576 nm)**
- **Deployed on NASA DC-8 for TRACE-P (2001), INTEX NA (2004)**

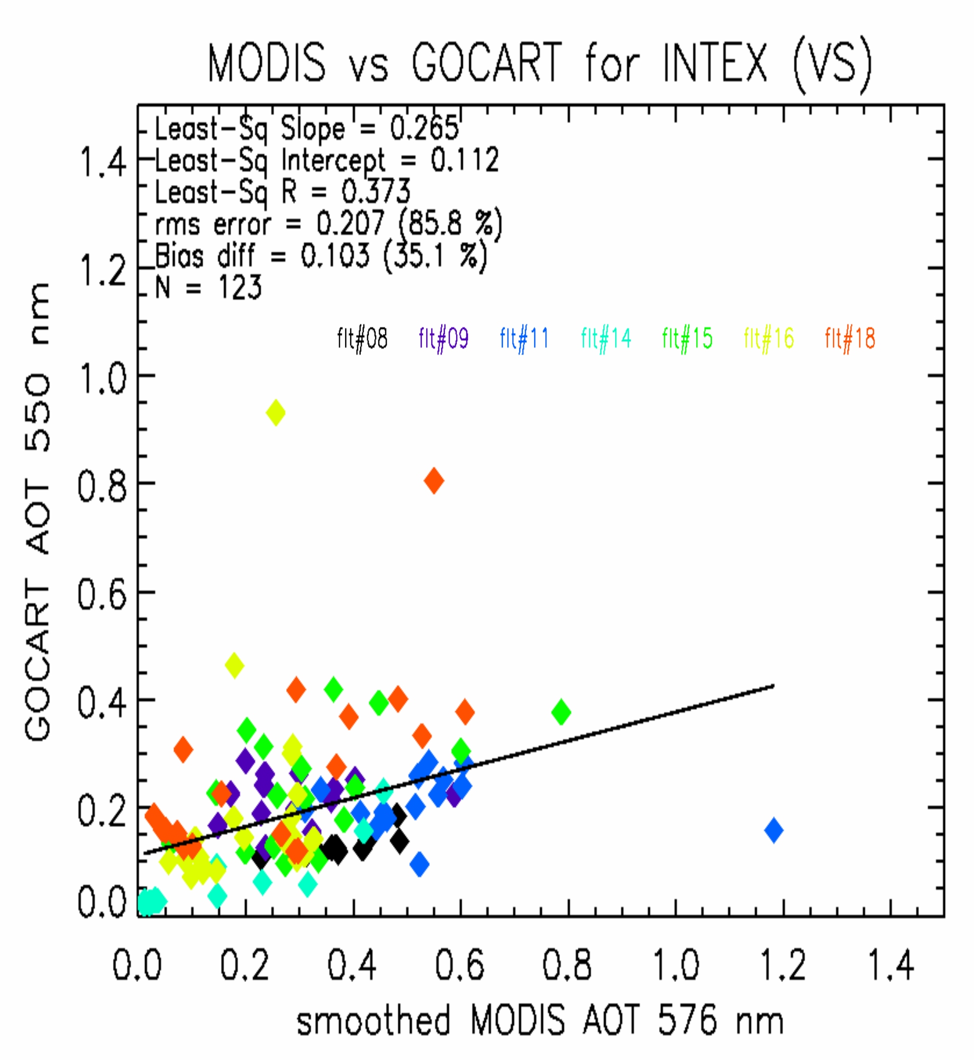




Browell et al., J. Geophys. Res, 108(D20), 8805, 2003.

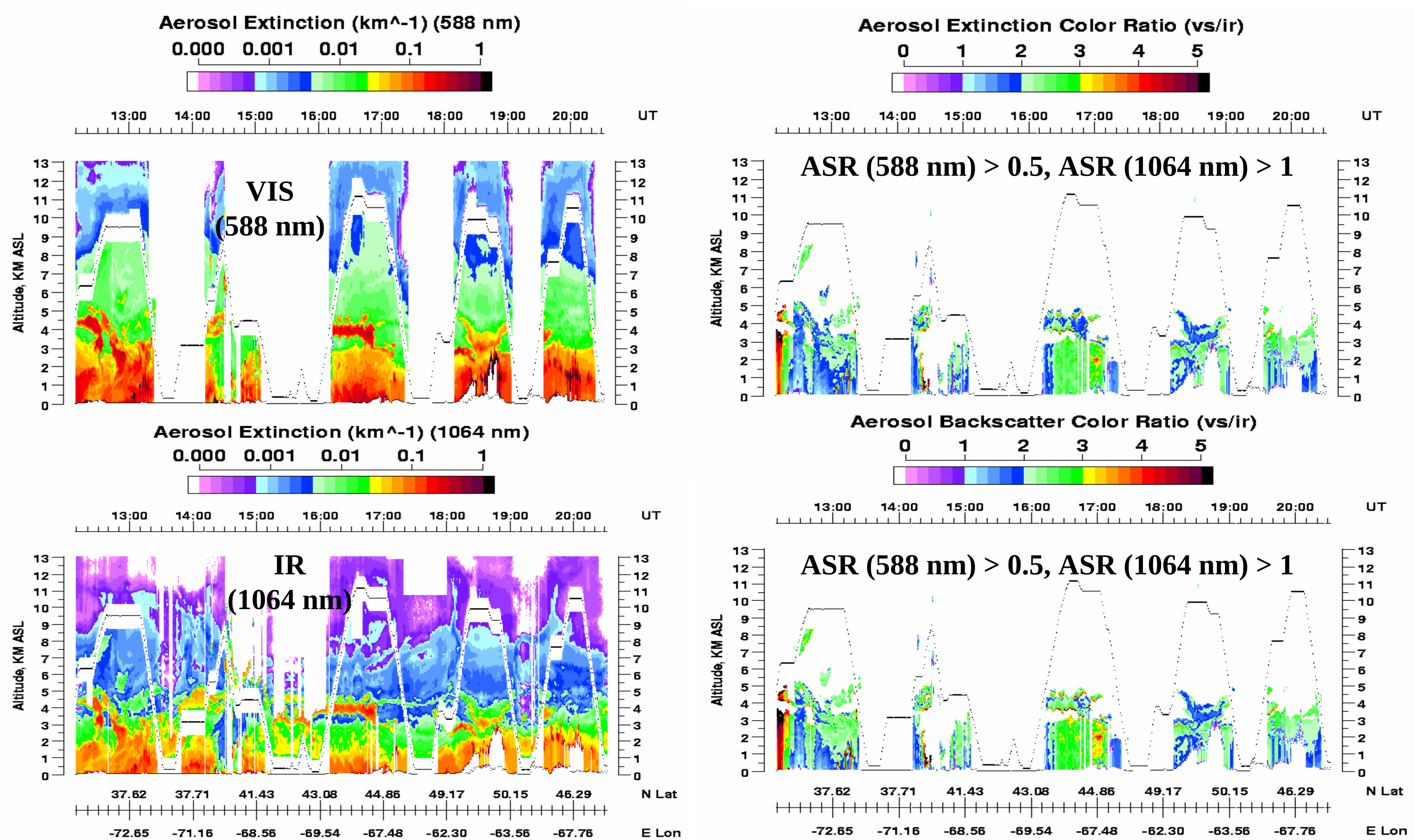
GOCART and MODIS AOT Comparisons





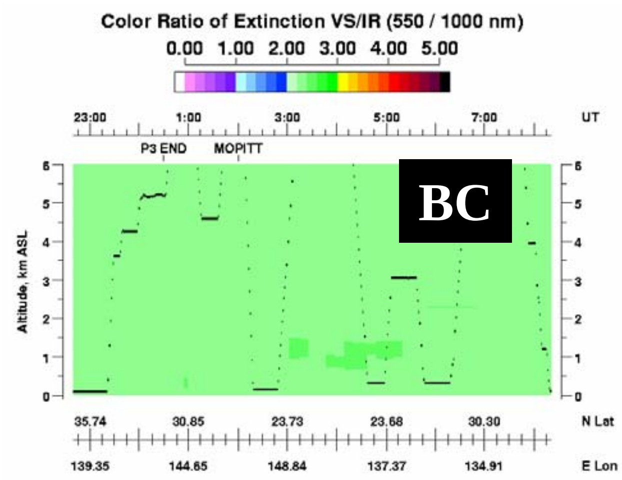
Aerosol Extinction and Color Ratio Profiles – July 22, 2004

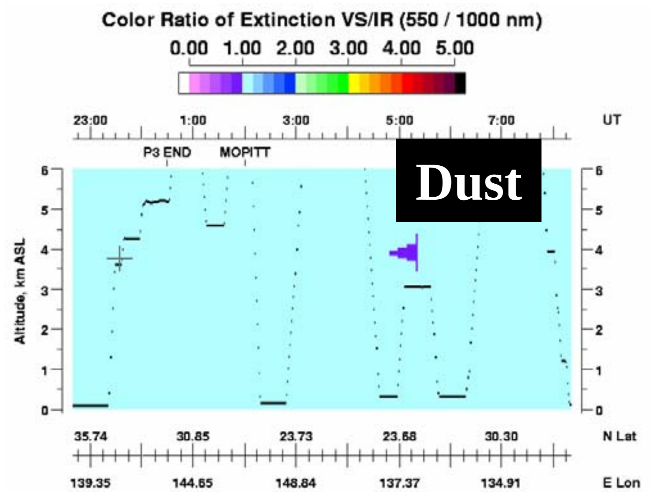
- Example retrievals constrained with MATCH AOT



Vertical Profile of Aerosol Extinction Color Ratio – GOCART

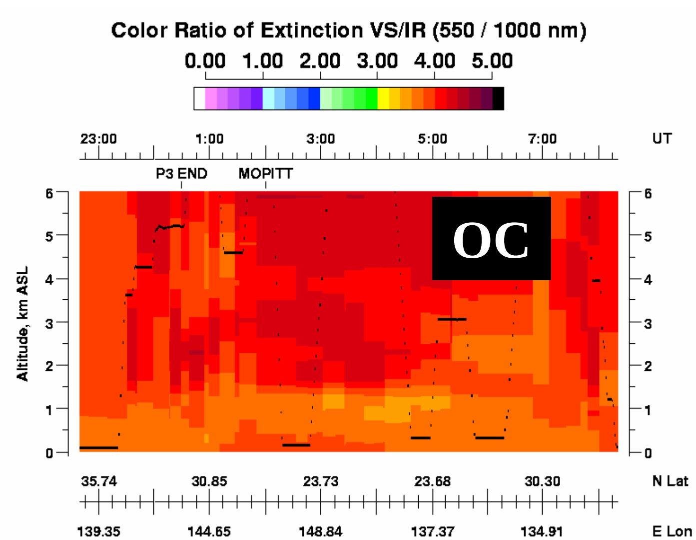
TRACE-P March 24, 2001

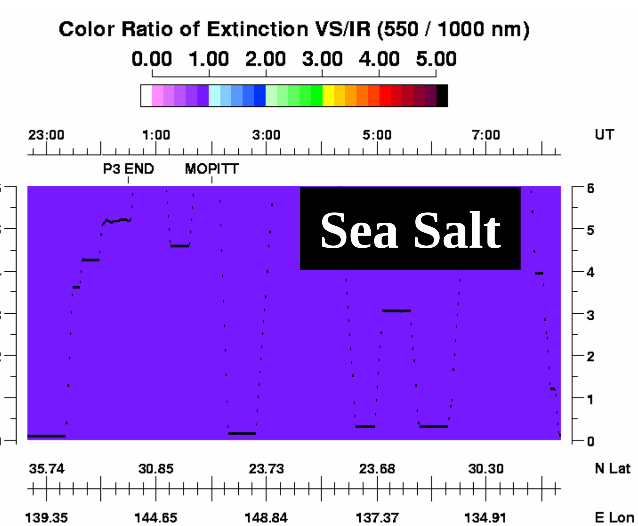


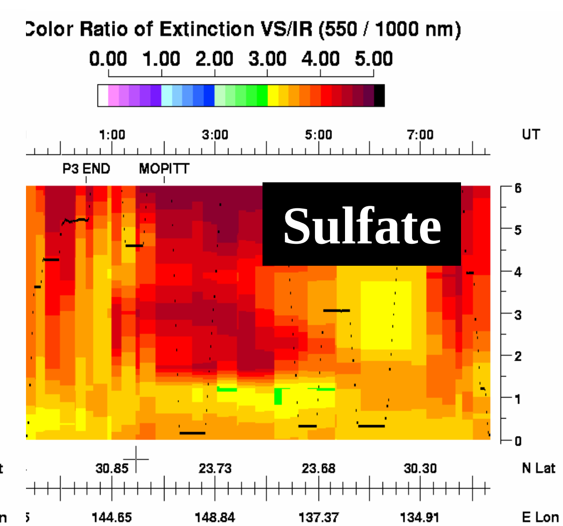


Extinction Color ratios

- BC – 2.2-2.4
- Dust – 1.1
- OC – 3.5-4.2
- Sea salt – 0.9-1.0
- Sulfate- 3.0-4.6

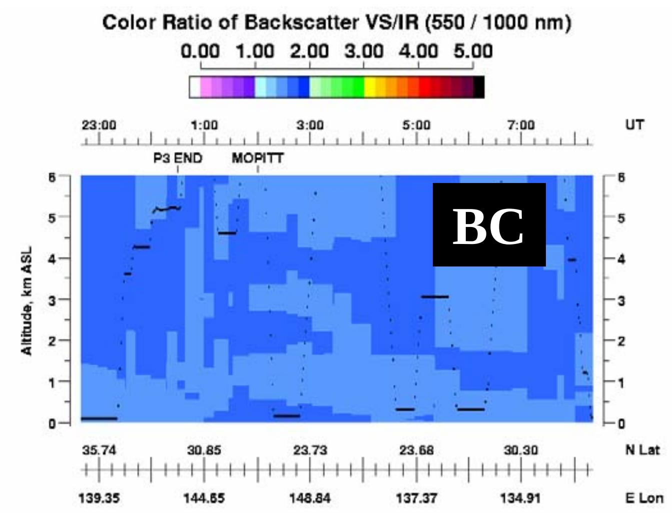


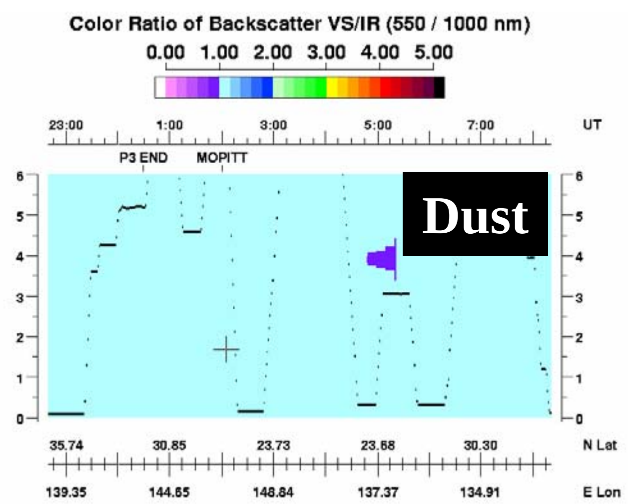




Vertical Profile of Aerosol Backscatter Color Ratio – GOCART

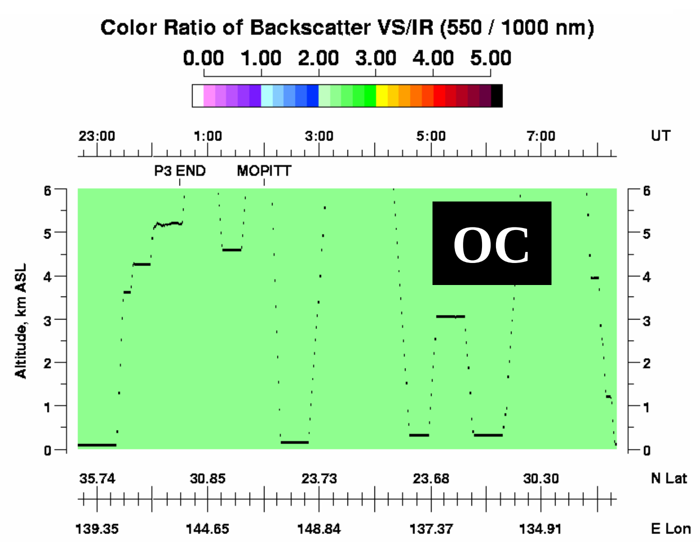
TRACE-P March 24, 2001

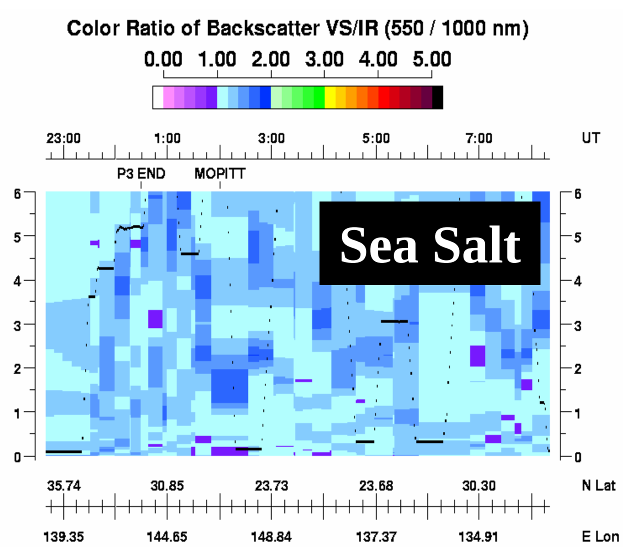


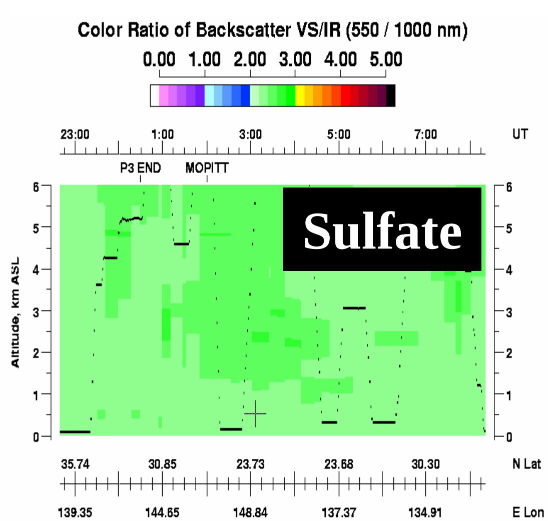


Backscatter Color ratios

- BC – 1.6-1.7
- Dust – 1.0-1.1
- OC – 2.3
- Sea salt – 1.1-1.7
- Sulfate- 2.2-2.4

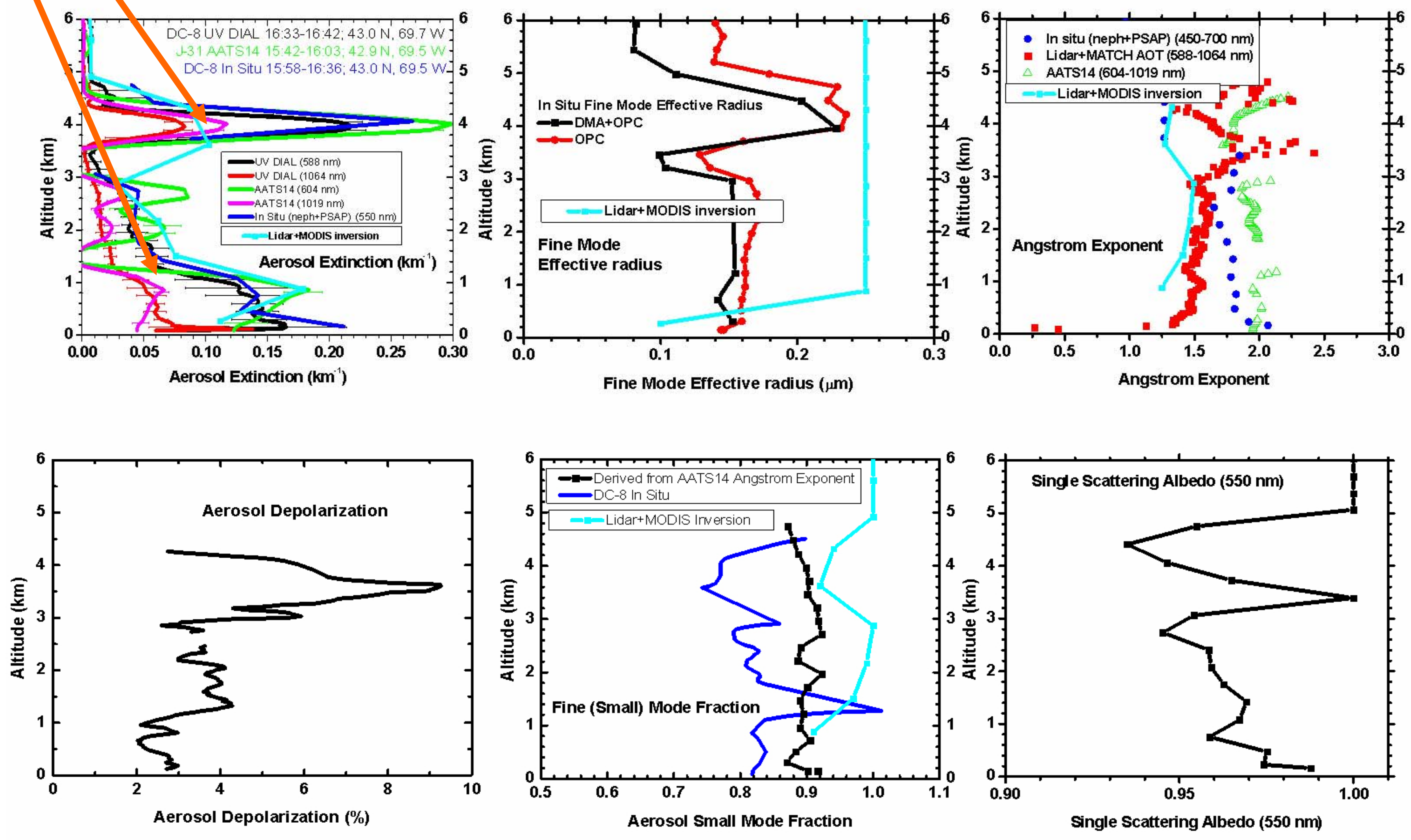


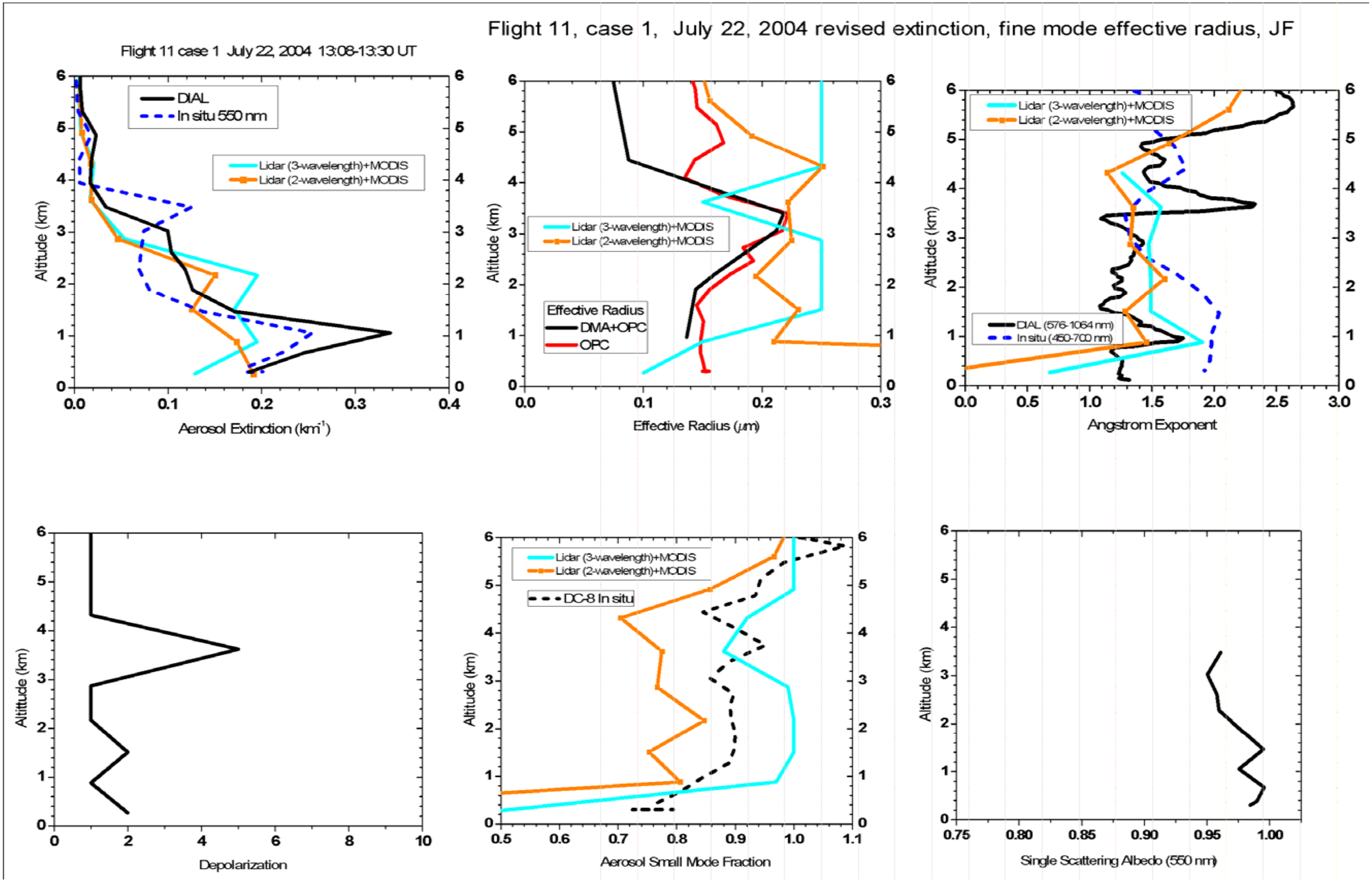




Preliminary Aerosol Profile Properties – Retrieval Results - July 22, 2004

- (biomass) High HCN, ethyne, CO, O3, H2O, airmass from Canada, mixed with pollution (NO2 spike)
- (pollution) High SO2, CO, O3, low H2O, fresh urban and industrial. trajectories from great lakes, and East Coast (near end) but very simimal chemical signature

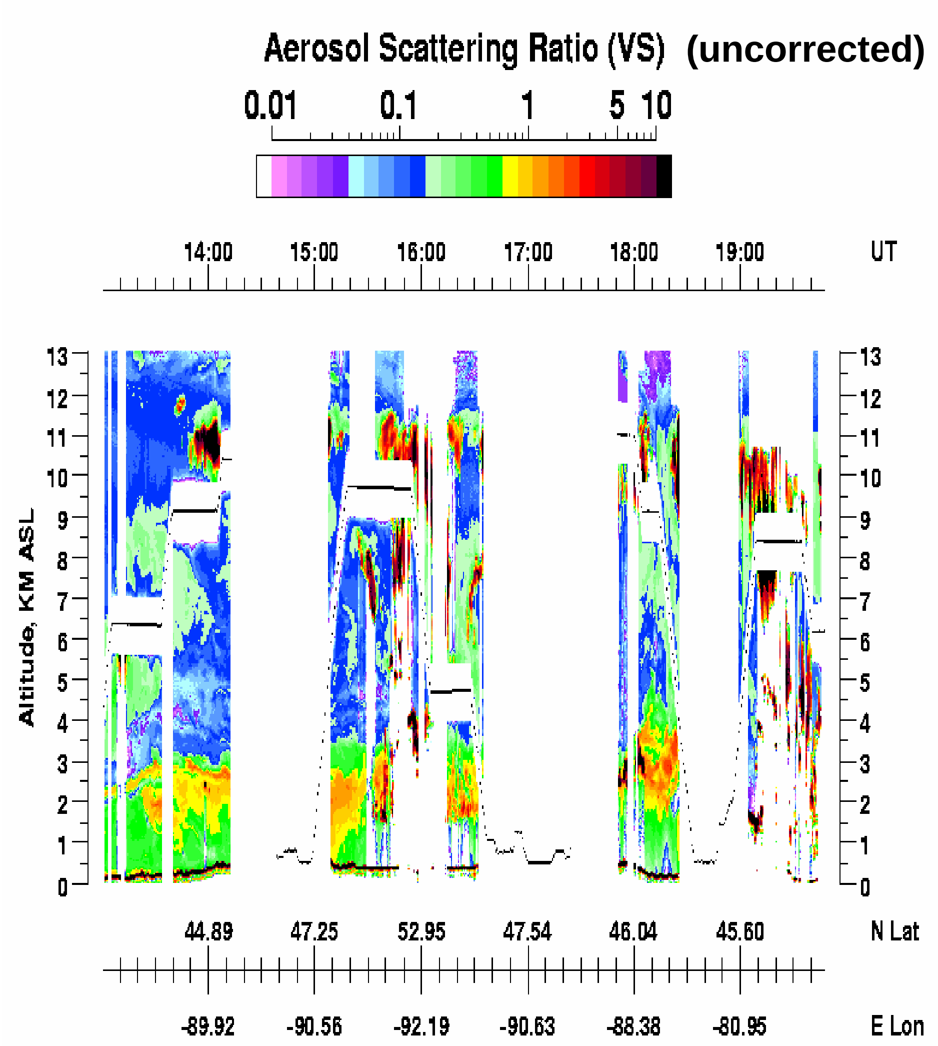




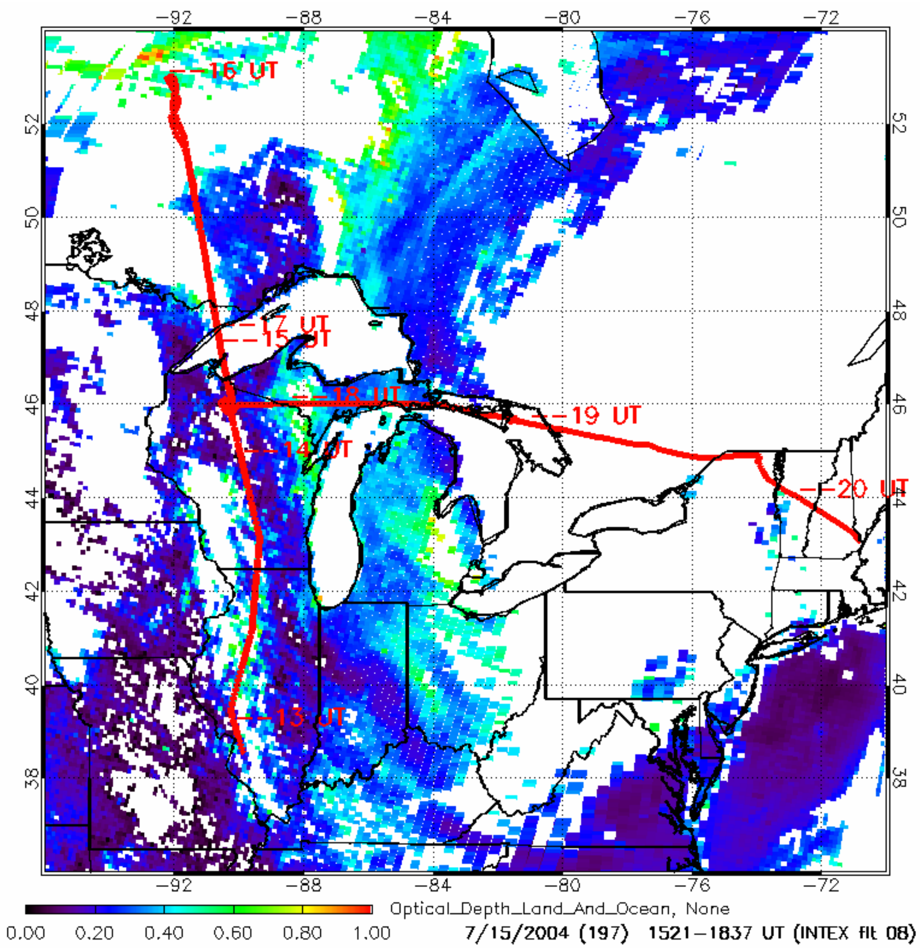
Flight 11, case 1, July 22, 2004 revised extinction, fine mode effective radius, JF
Flight 11 case 1 July 22, 2004 13:08-13:30 UT
DIAL
In situ 550 nm
Lidar (3-wavelength)+MODIS
Lidar (2-wavelength)+MODIS
Altitude (km)
Aerosol Extinction (km-1)
Effective Radius
DMA+OPC
OPC
Effective Radius (µm)
DIAL (576-1064 nm)
In situ (450-700 nm)
Angstrom Exponent
Depolarization
DC-8 In situ
Aerosol Small Mode Fraction
Single Scattering Albedo (550 nm)

Aerosol Measurements – July 15, 2004

DC-8 Flight 8

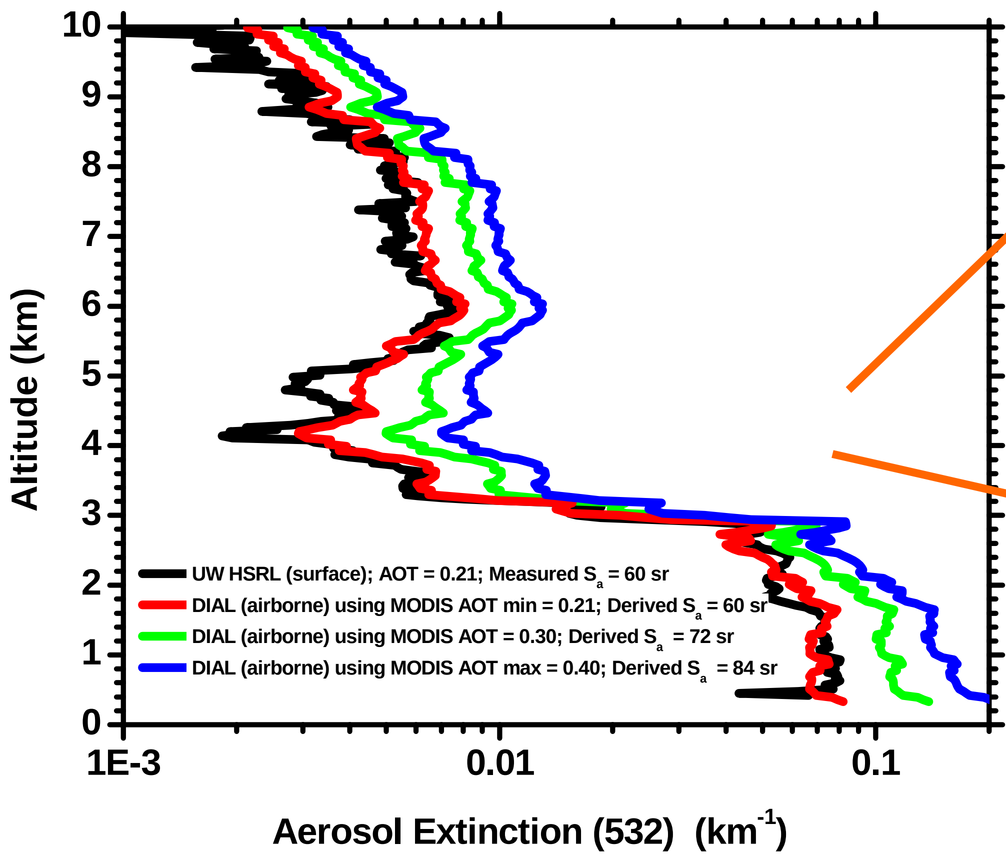


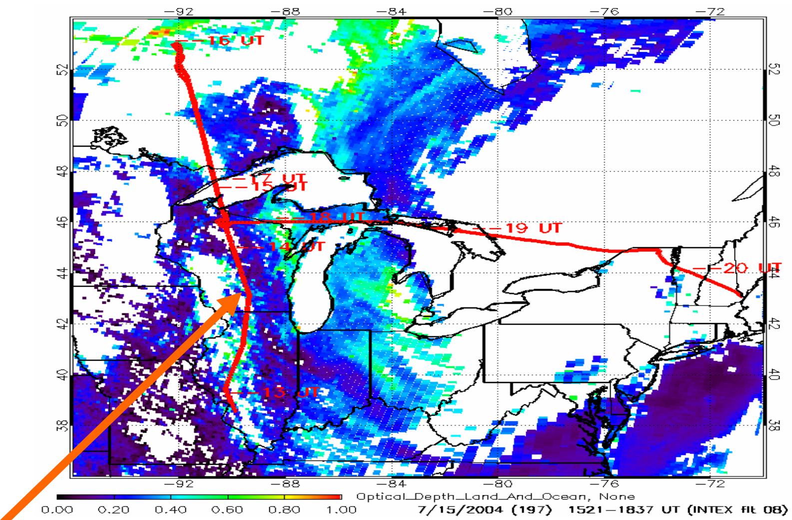
MODIS AOT (550 nm)

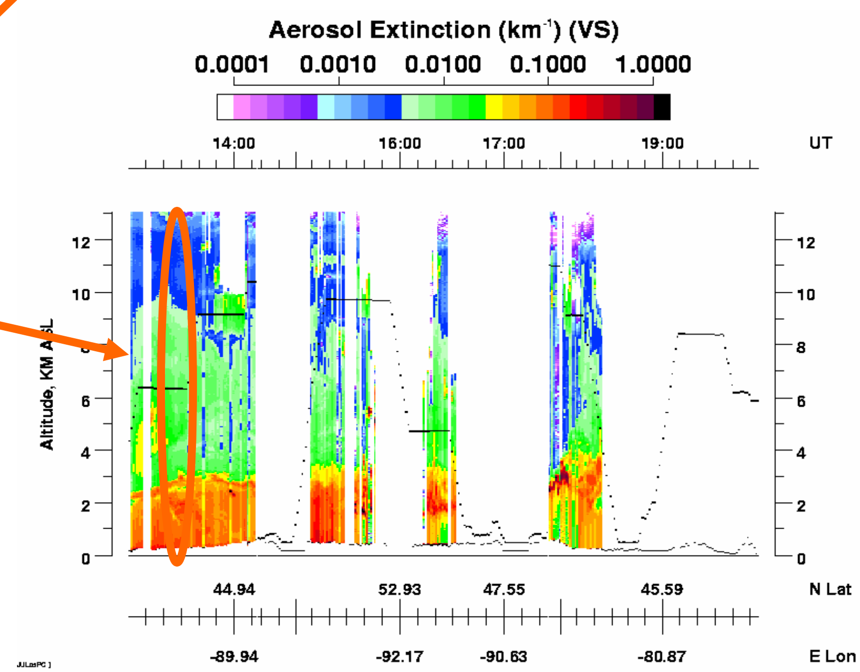


Aerosol Extinction Comparison – July 15, 2004

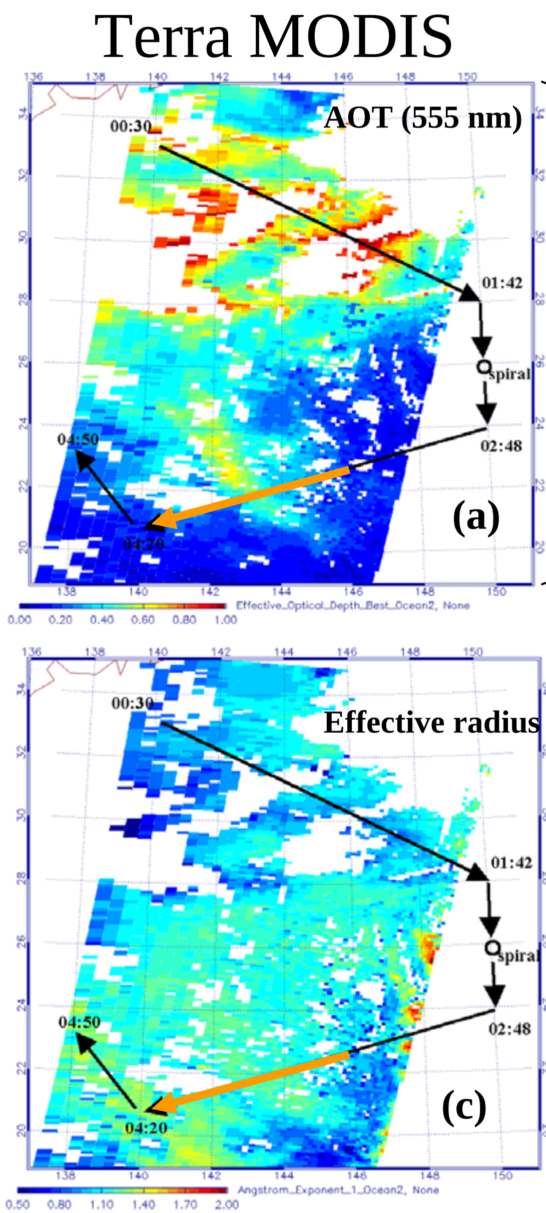
• Comparison with ground-based Univ. of Wisconsin HSRL lidar that measures backscattering and extinction directly
• UV DIAL retrieval constrained using MODIS AOT (land)
• Better agreement when using lower error bound of MODIS AOT which supports investigations that indicate MODIS AOT over land is biased slightly high

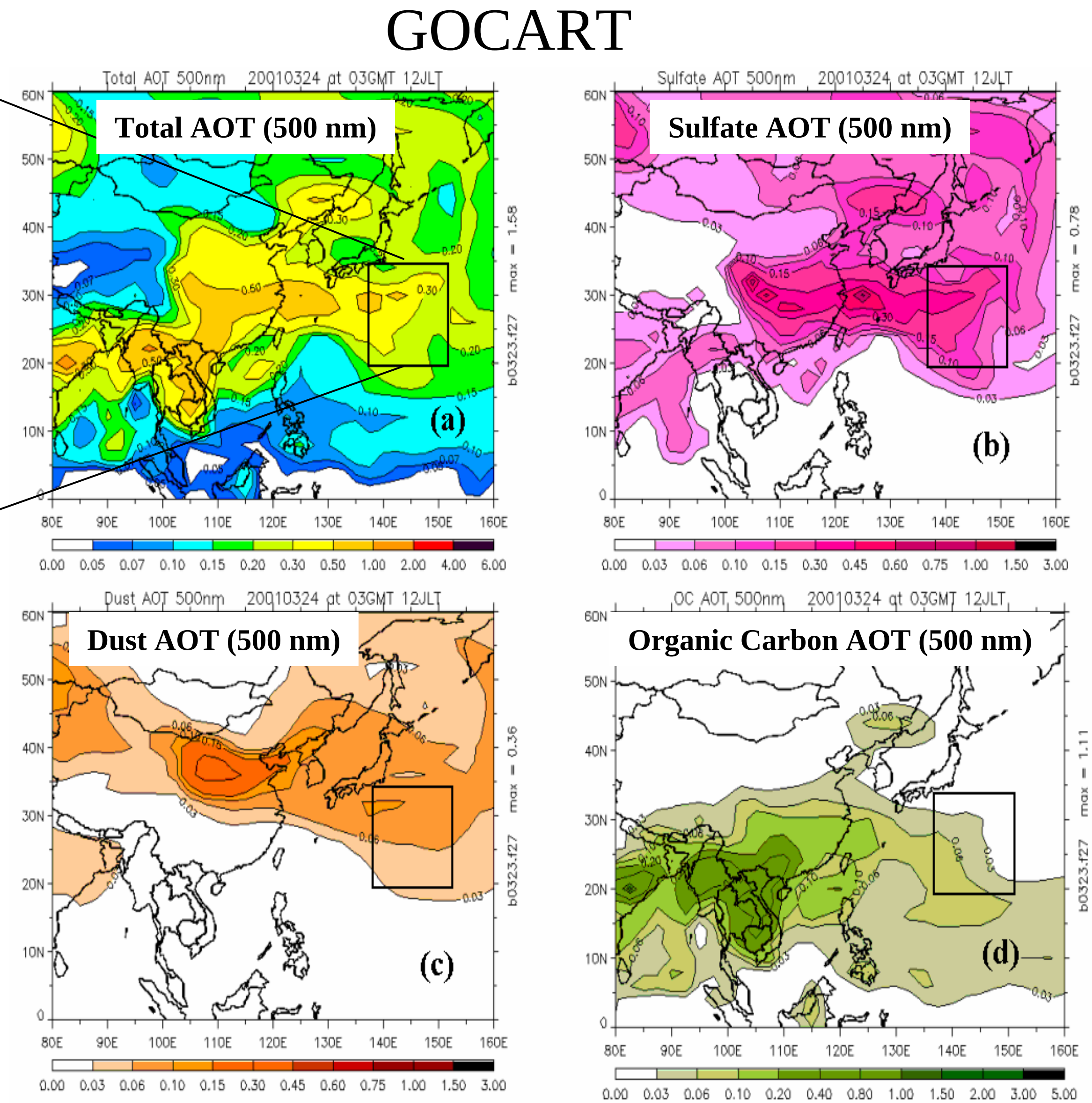






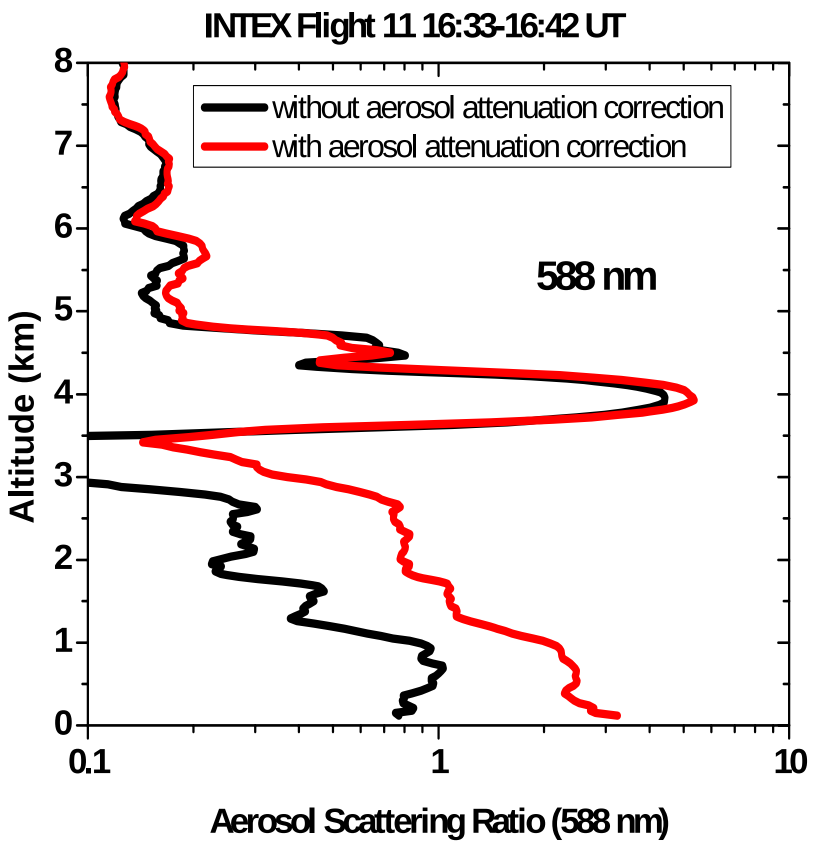
March 24, 2001 MODIS+GOCART

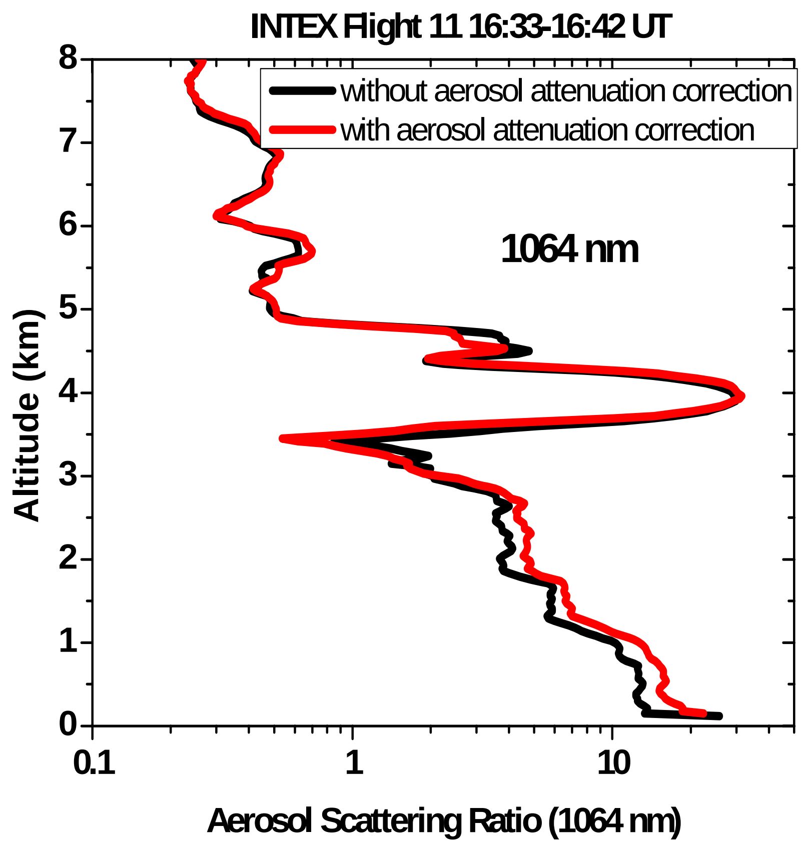




Aerosol Profile Retrieval – July 22, 2004

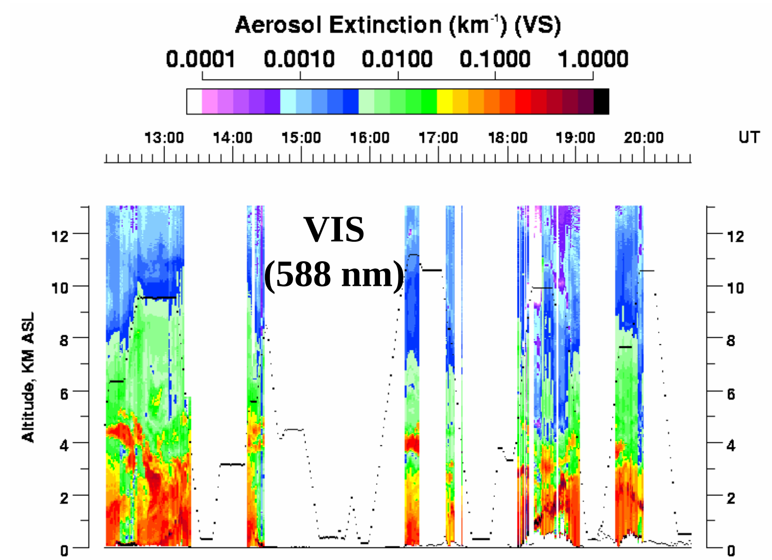
- Attenuation corrected applied using MODIS AOT constraint
- Correction at low altitudes ~ 200-300% at 588 nm, 20-40% at 1064 nm

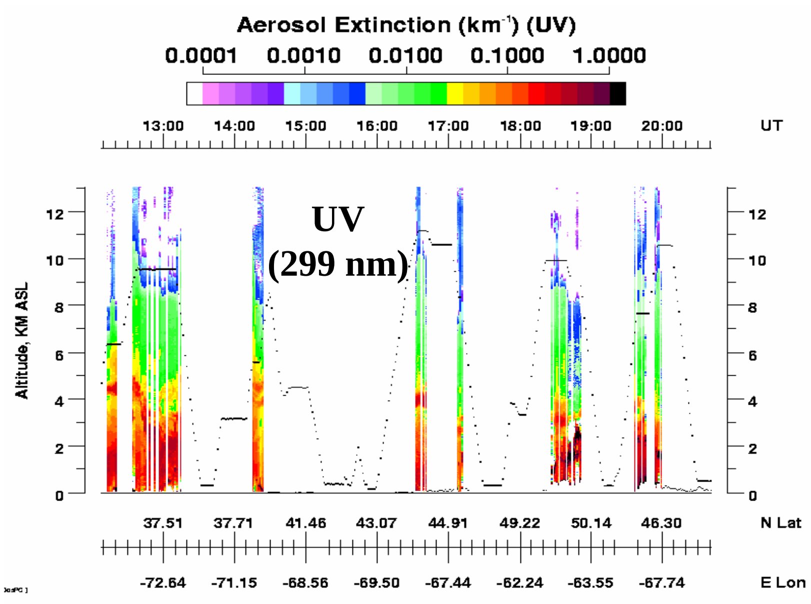


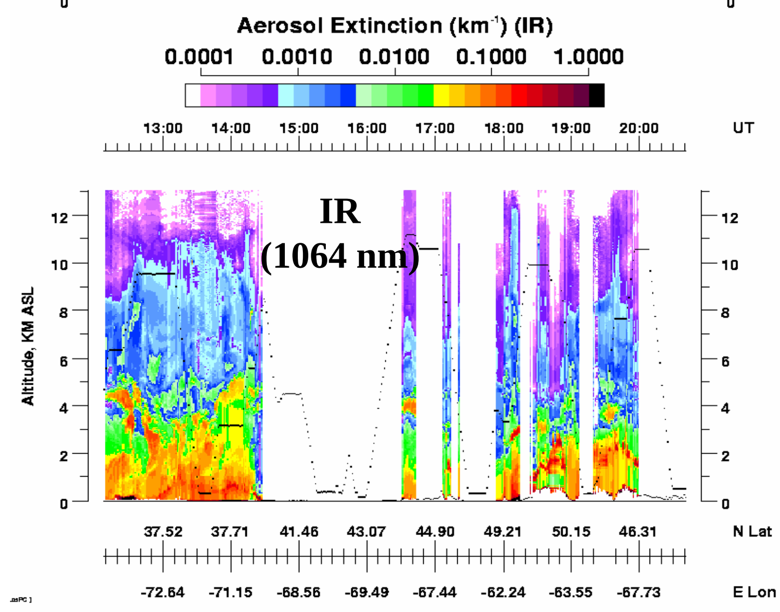


Aerosol Extinction Profiles – July 22

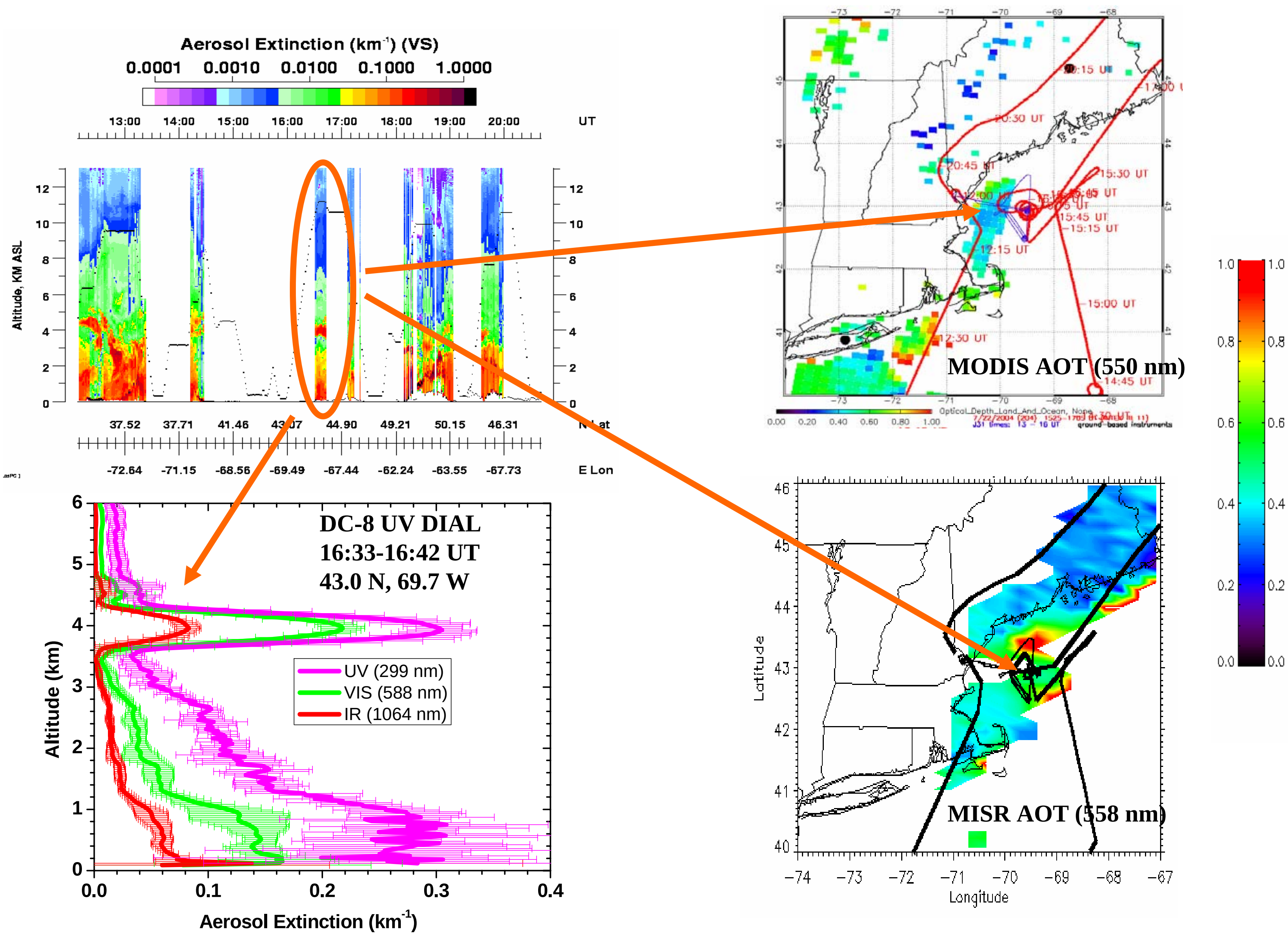
- Retrievals used constrained with MODIS AOT
- Currently limited to locations where satellite retrievals of AOT are present







AOT and Aerosol Extinction Profiles – July 22



Aerosol Profile Retrievals

• Problem - Backscatter lidar equation (1 equation with 2 unknowns)

Measured Signal

Range from Instrument

Calibration Constant

Molecular Backscatter Coefficient

Molecular Extinction Coefficient

← **Known**

Determined from measured signals and meteorological data

$$P(r) = \frac{C}{r^2}\left[\beta_m(r) + \beta_p(r)\right]\exp\left\{-2\int_0^r\left[\sigma_m(r') + \sigma_p(r')\right]dr'\right\}$$

Particulate Backscatter Coefficient

Particulate Extinction Coefficient

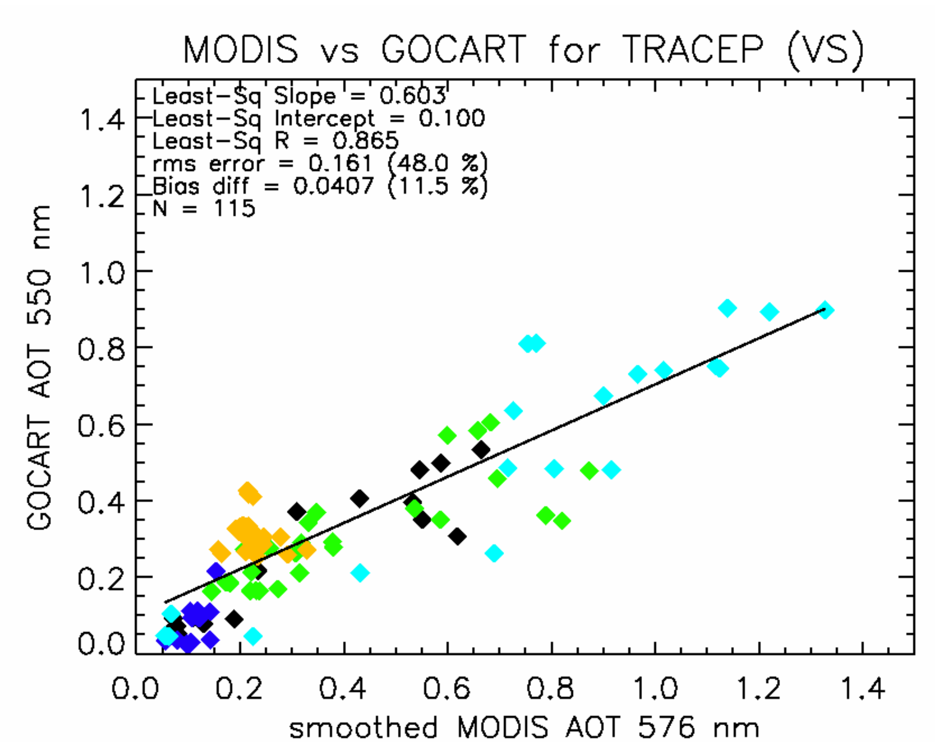
← **Retrieved Parameters**

"Lidar Ratio" = $\frac{\sigma_p(r)}{\beta_p(r)} = S_p$ ⟵ Assumption of value for extinction-to-backscatter (S_p) ratio required for backscatter lidar retrieval

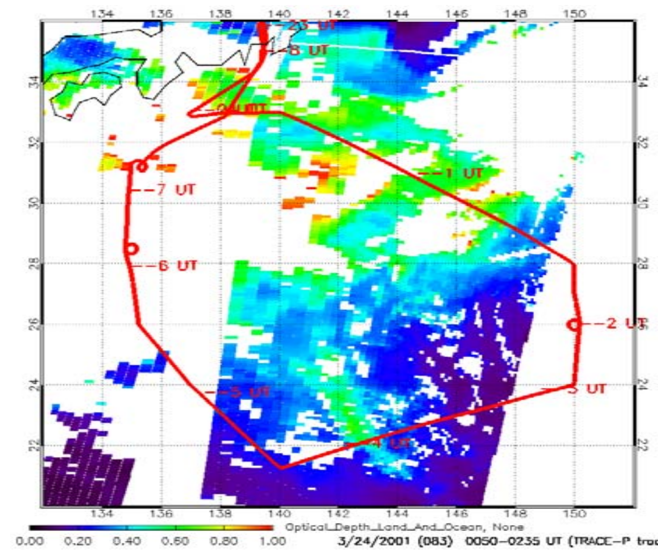
• Solution – we use aerosol optical thickness (e.g. total aerosol transmission) derived from MODIS and/or model (e.g. GOCART) to constrain solution and derive average lidar ratio

MODIS and GOCART AOT – TRACE-P

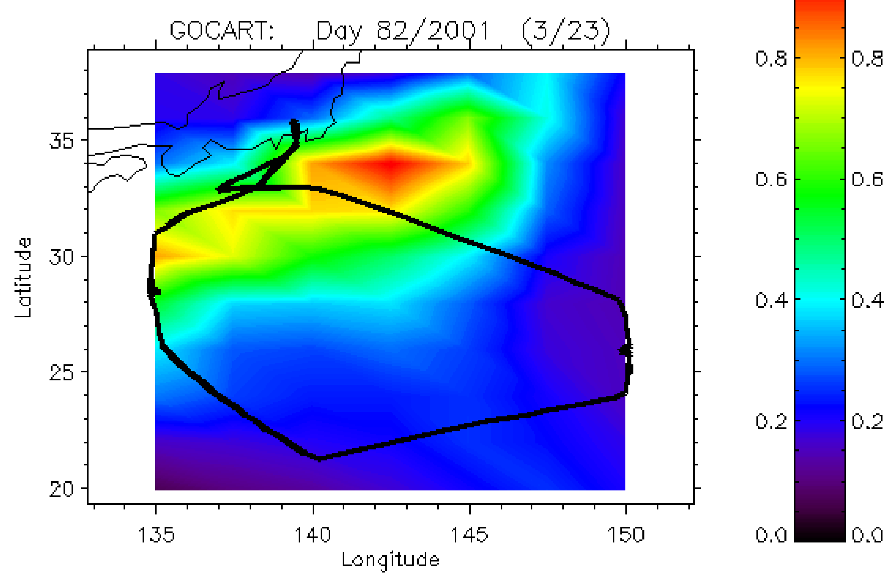
• Since DC-8 flights occurred over areas not measured by MODIS, we require other ways to estimate AOT over flight tracks
• For TRACE-P, we used GOCART simulations of AOT that have been adjusted according to least-squares fit between GOCART and MODIS AOT



TRACE-P Flt 14 – 03/23-24/2001

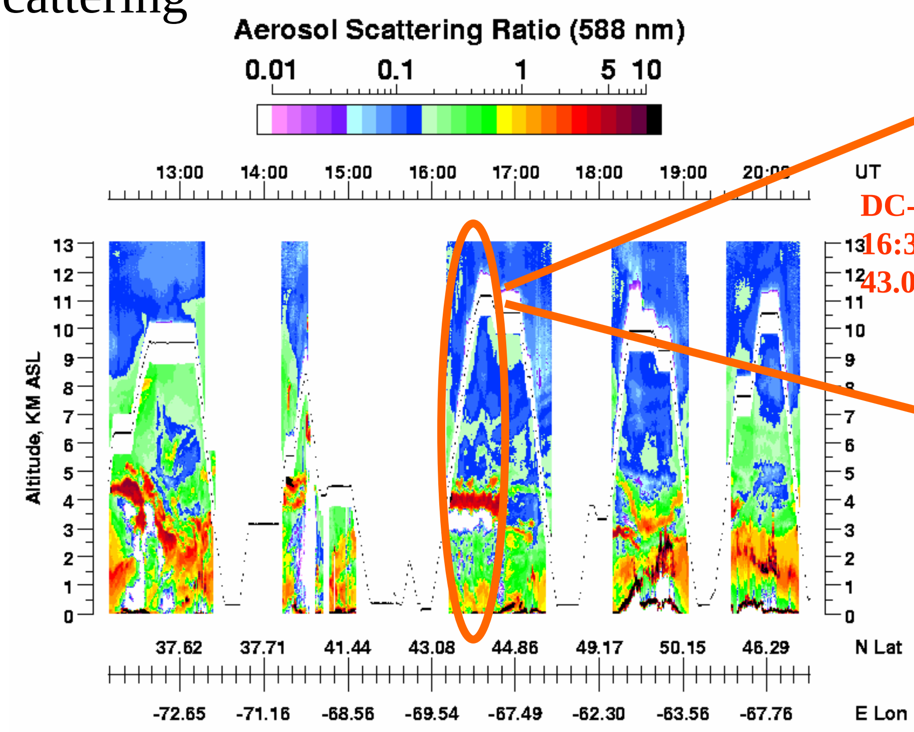


AOT (550 nm)



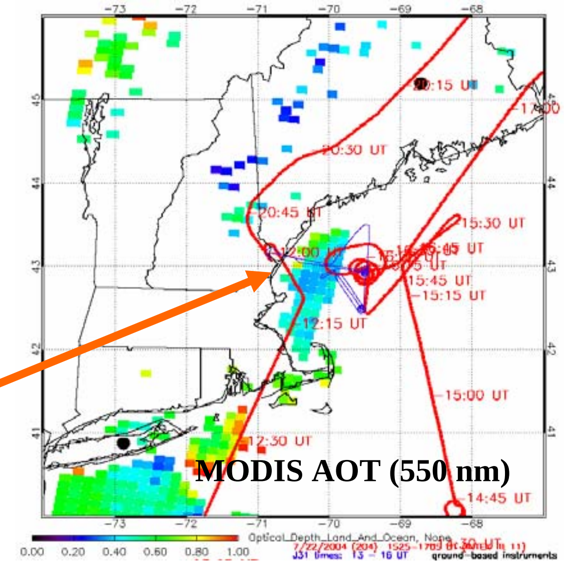
Aerosol Profile Retrieval – July 22, 2004

- MODIS and MISR Aerosol Optical Thickness (AOT)
- Terra Overpass at 15:30 UT on July 22, 2004 – DC-8 Flight 11
- Aerosol scattering ratio - (aerosol/molecular) scattering

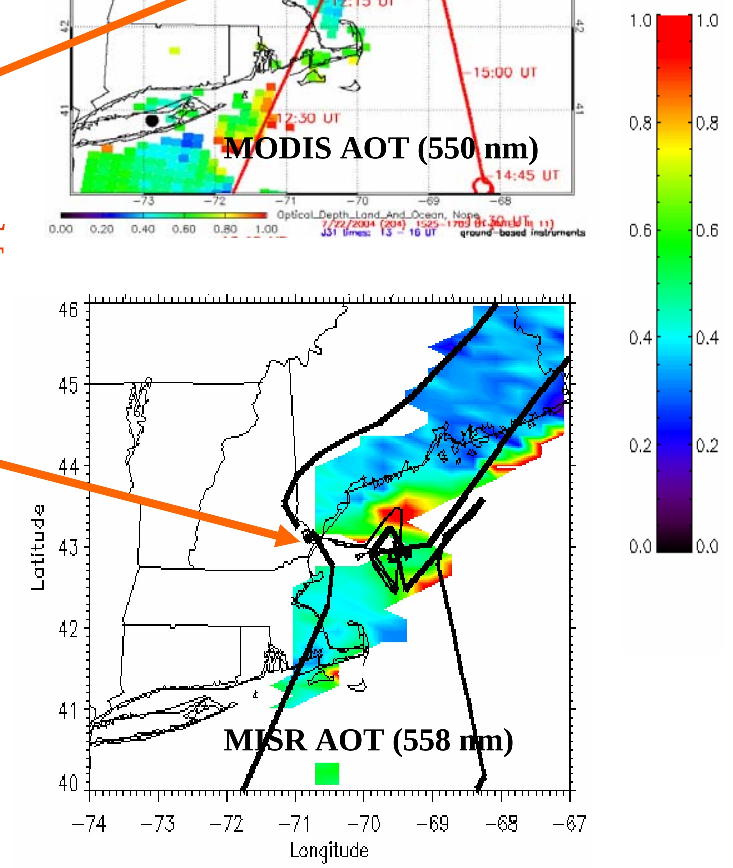


UV DIAL ASR (uncorrected)

DC-8 UV DIAL
16:33-16:42 UT
43.0 N, 69.7 W



AOT



Aerosol Scattering Ratio – July 22, 2004

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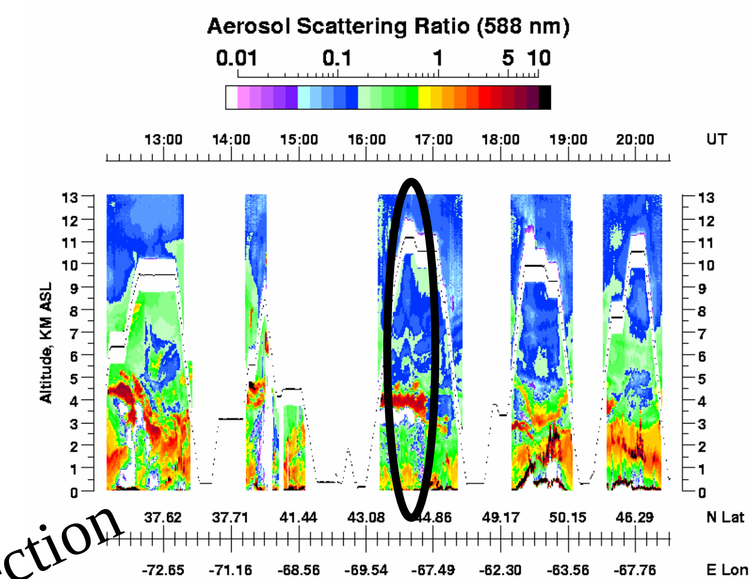
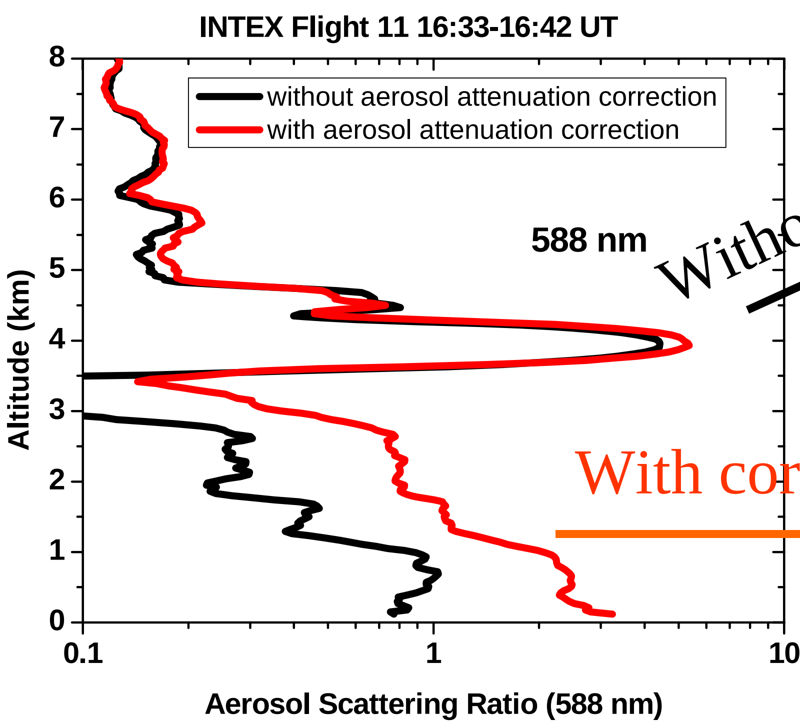
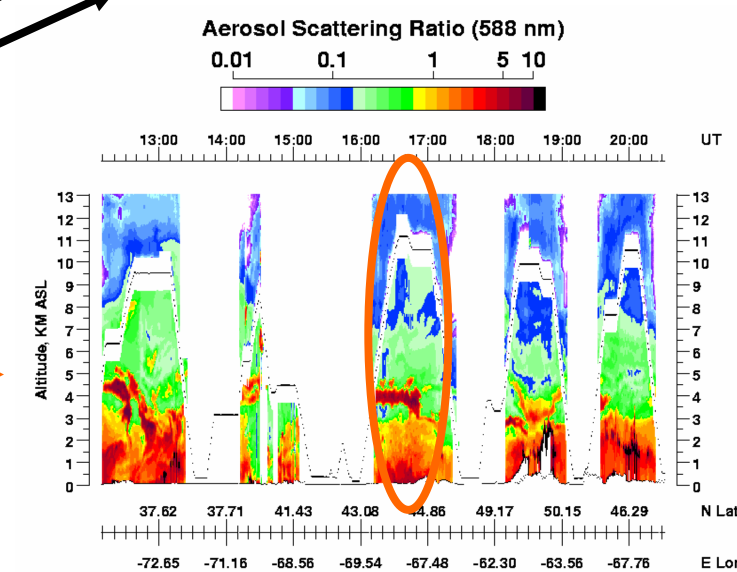
- Correction at low altitudes ~ 200-300% at 588 nm, 20-40% at 1064 nm





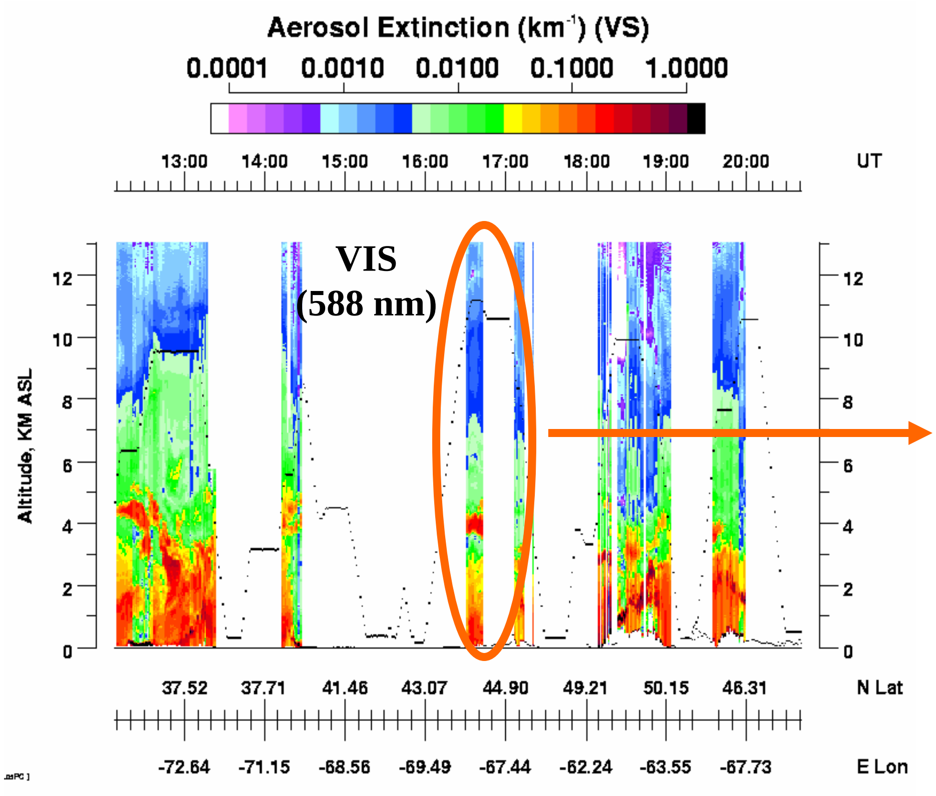
Without correction

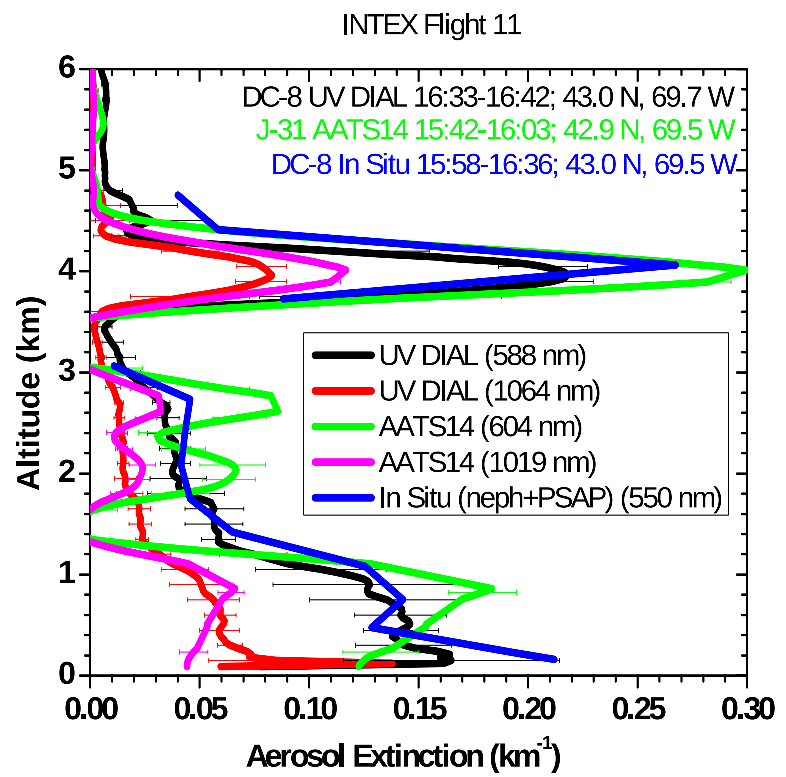
With correction



Preliminary Aerosol Extinction Comparison – July 22, 2004

- UV DIAL
- NASA Ames Airborne Sun Photometer (AATS14) on J-31 aircraft
- Scattering (nephelometer) + Absorption (PSAP) in situ on DC-8





Preliminary AOT Comparison – July 22, 2004

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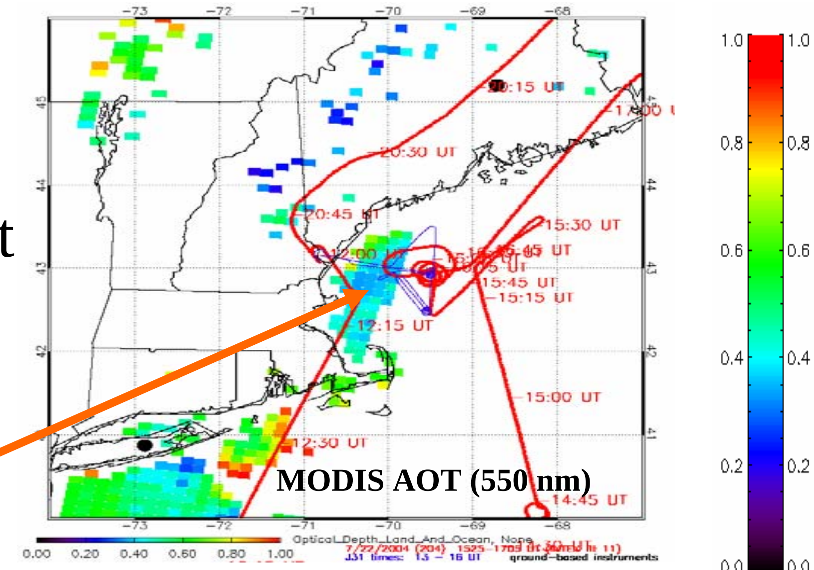

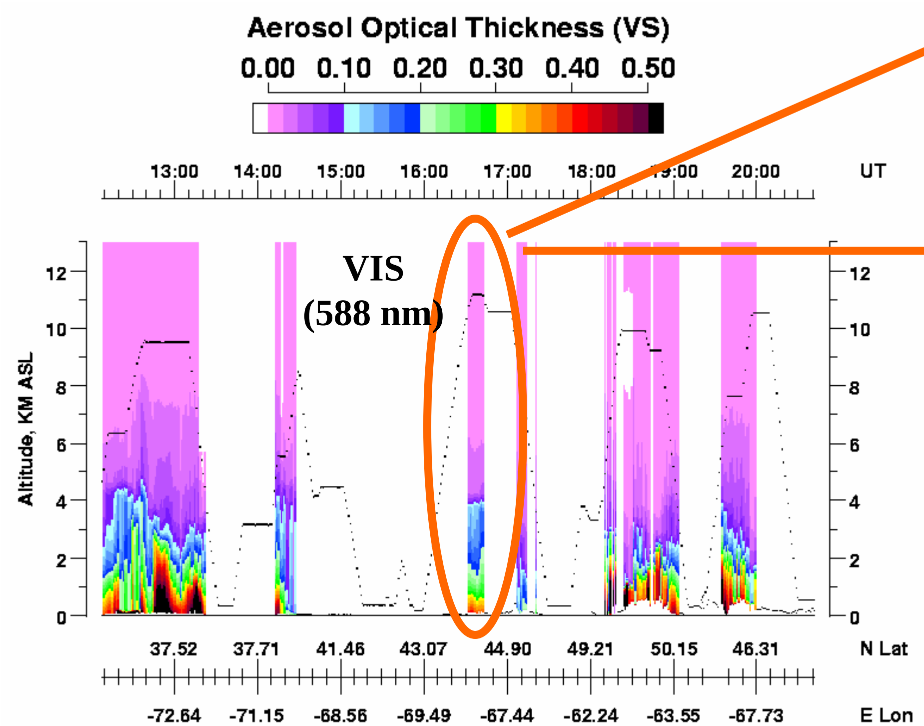

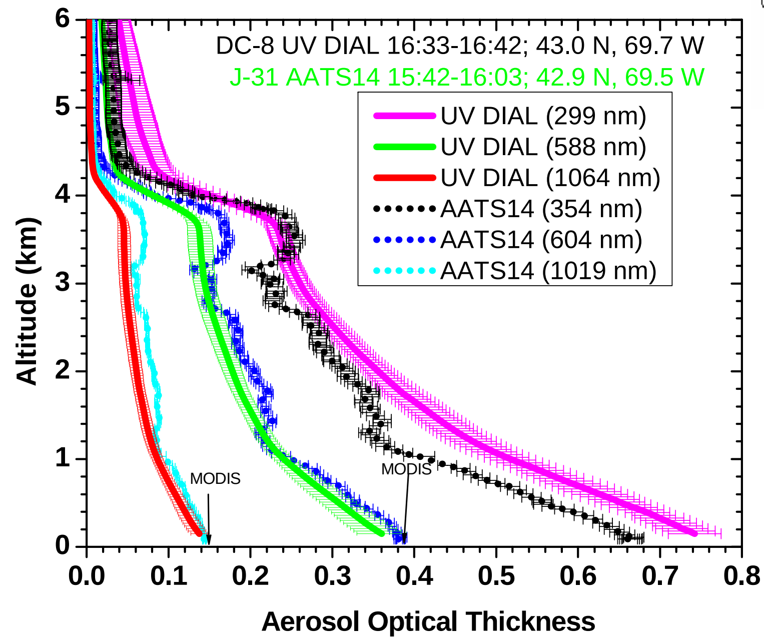

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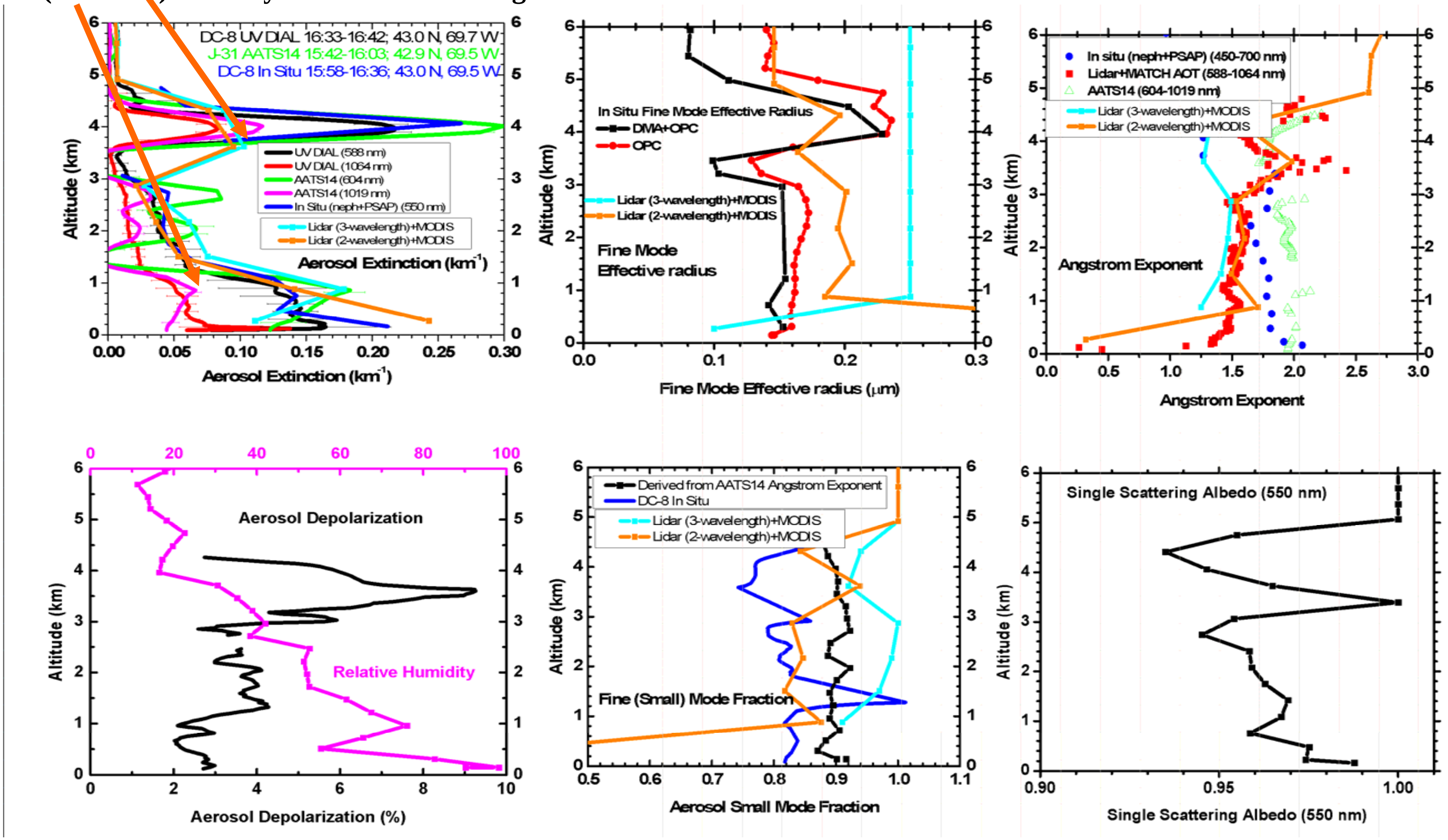
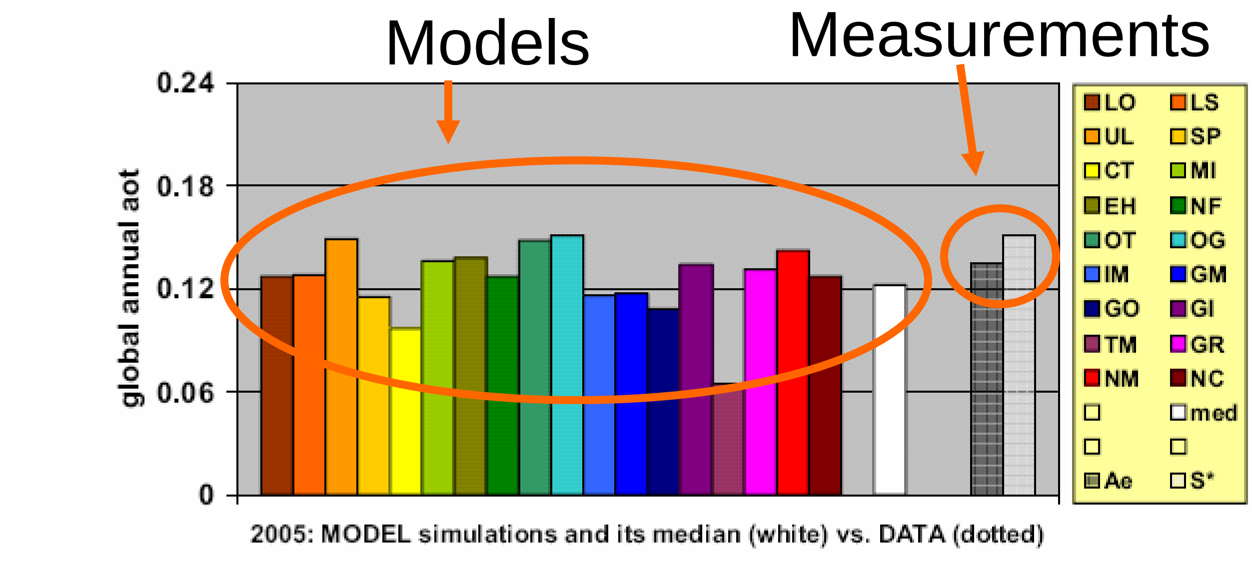


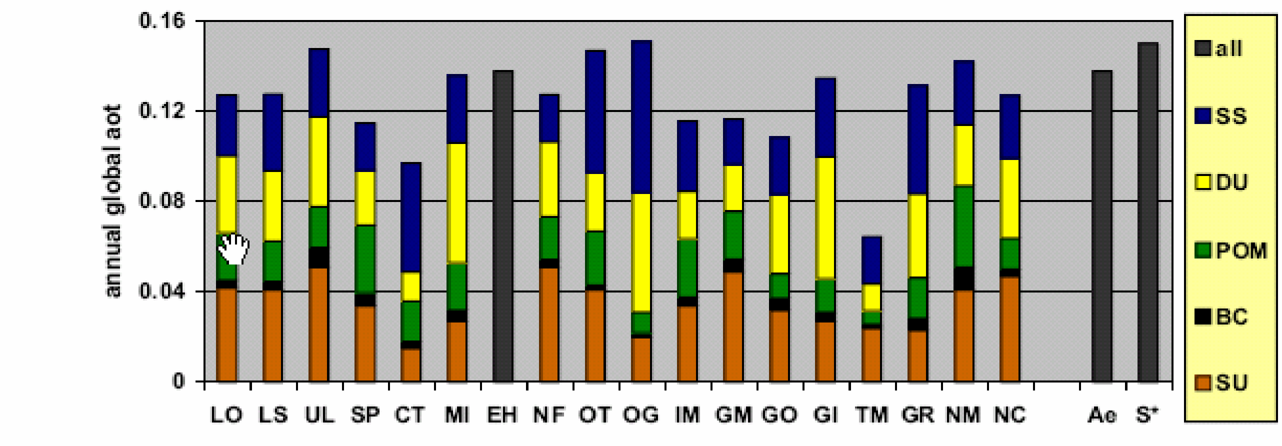
Aerosol Model Comparisons

Global



Model representations of global annual AOT have become closer to observations

But…

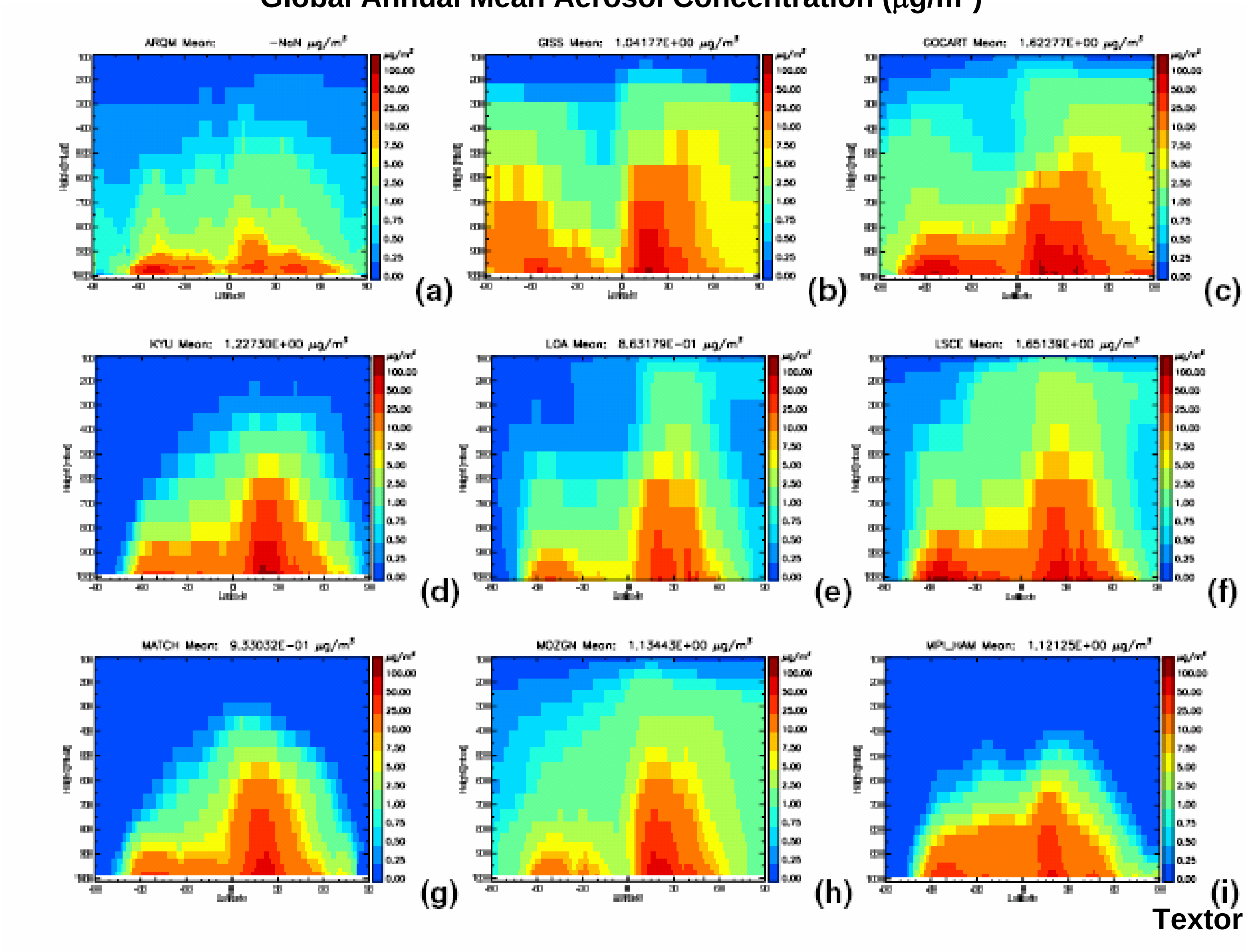


Large model differences compositional mixture

Kinne et al., 2005

Large Variation in How Models Represent Aerosol Profiles

Global Annual Mean Aerosol Concentration (μg/m³)



Textor et al., 2005