Aerosol Retrievals using Airborne Lidar and MODIS Measurements

Richard Ferrare (1), Edward Browell (1), Syed Ismail (1), Yoram Kaufman (2),
Lorraine Remer (2), Vanderlei Martins (3), Mian Chin (2),
John Hair (1), Chris Hostetler (1), Carolyn Butler (1,3),
Sharon Burton (1,3), Vince Brackett (1,3), Marta Fenn (1,3),
Anthony Notari (1,3), Susan Kooi (1,3), Marian Clayton (1,3)
Phil Russell (4), Jens Redemann (4,5), John Livingston (4,6), Beat Schmid (4,5),
Gao Chen (1), Antony Clarke (7), Jean Francois Léon (8)

(1) Science Directorate, NASA Langley Research Center,
MS 401A, Hampton, Virginia, 23681, USA
(2) NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771, USA
(3) University of Maryland Baltimore County, Baltimore, MD
(3) Science Application International Corporation, Hampton,
NASA Langley Research Center, MS 927, VA 23666 USA
(4) NASA Ames Research Center, Moffett Field, CA
(5) Bay Area Environmental Research Institute, Sonoma, CA
(6) SRI International, Menlo Park, CA
(7) University of Hawaii, Honolulu, HI
(8) Laboratoire d’Optique Atmospherique, Lille, France

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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

- Simultaneous Nadir and Zenith Ozone & Aerosol Profiling
- Aerosol extensive parameters (300, 576, 1064 nm)
  - aerosol scattering ratio
  - backscatter
  - extinction
- Aerosol intensive parameters
  - backscatter wavelength dependence
  - depolarization

TRACE-P Flight 14 March 23-24, 2001

Aerosol Wavelength Dependence (IR/VS)

Aerosol 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
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
Lidar aerosol extinction profiles are used to evaluate GOCART aerosol simulations. During TRACE-P, GOCART profiles were lower than lidar throughout the 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.
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

Flight 14
AIR-MASS CHARACTERIZATION
23 Mar 01

Aerosol Backscatter Color Ratio (576.4/1064nm)

Aerosol Extinction Color Ratio (576.4/1064nm)

Aerosol Depolarization (%)
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 $r_{\text{eff}}$
- 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

Aerosol Extinction  Effective Radius  Aerosol Extinction
Depolarization; RH  Small Mode Fraction  Depolarization; RH

Small Mode Fraction
MODIS+lidar Aerosol Retrievals

July 18, 2004

14:45-15:22 UT

21:07-21:40 UT

Aerosol Extinction

Effective Radius

Depolarization;

Small Mode Fraction

Aerosol Extinction

Effective Radius

Depolarization;

Small Mode Fraction
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
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

**Product**

**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 ($S_a$) (532 nm)
- 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

**Comparison of Aerosol Extinction Measurement**

<table>
<thead>
<tr>
<th>Product</th>
<th>NASA LaRC King Air B200</th>
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*New*

- AATS14 data courtesy of Phil Russell, Jens Redemann, John Livingston (NASA)
- HiGEAR data courtesy of Tony Clarke (Univ. of Hawai'i)
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 $S_a$, low WVD, high depolarization – dust

Currently using HSRL measurements to assess RAQMS and STEM models.
Summary

- 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 aerosol type
Backup Slides
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.
• Objectives
• Airborne Lidar Aerosol Measurements
• GOCART model evaluation
• Aerosol classification using lidar data
• Lidar + MODIS retrievals
• Summary and Future
HSRL independently measures aerosol and molecular backscatter
- Can be internally calibrated
- No correction for extinction required to derive backscatter profiles
- More accurate aerosol layer top/base heights

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

**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)

**Atmospheric Scattering**
- Mie (Aerosol/Cloud) Scattering
  - <100 MHz FWHM
- Rayleigh-Brillouin (molecular) Scattering
  - ~3.0 GHz FWHM

**Effect of Iodine Vapor Notch Filter**
- Rayleigh-Brillouin (molecular) Scattering
  - ~2 GHz
• Attenuation correction applied using MODIS AOT constraint
• Correction retrieves profiles under layers of large aerosol attenuation
• Ozone Differential Absorption Lidar (DIAL) Profiles ($\lambda_{on}=289$ nm & $\lambda_{off}=300$ nm)
• Aerosol & Cloud Scattering Ratio Profiles (300, 576, & 1064 nm)
• Simultaneous Nadir and Zenith Ozone & Aerosol Profiling
• Nadir Aerosol Depolarization Profiles (576 nm)

GOCART and MODIS AOT Comparisons

MODIS vs GOCART for TRACEP (VS)

- Least-Sq Slope = 0.603
- Least-Sq Intercept = 0.100
- Least-Sq R = 0.865
- rms error = 0.161 (48.0 %)
- Bias diff = 0.0407 (11.5 %)
- N = 115

MODIS vs GOCART for INTEX (VS)

- Least-Sq Slope = 0.265
- Least-Sq Intercept = 0.112
- Least-Sq R = 0.573
- rms error = 0.207 (85.8 %)
- Bias diff = 0.103 (35.1 %)
- N = 123
Aerosol Extinction and Color Ratio Profiles – July 22, 2004

- Example retrievals constrained with MATCH AOT

\[
\begin{align*}
\text{ASR (588 nm)} & > 0.5, \quad \text{ASR (1064 nm)} > 1 \\
\end{align*}
\]
Extreme 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
(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 similar chemical signature
Aerosol Measurements – July 15, 2004

DC-8 Flight 8

MODIS AOT (550 nm)
• 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

Terra MODIS

- AOT (555 nm)
- Effective radius

GOCART

- Total AOT (500 nm)
- Sulfate AOT (500 nm)
- Dust AOT (500 nm)
- Organic Carbon AOT (500 nm)
• 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 Extinction (km\(^{-1}\)) (VS)

0.0001 0.0010 0.0100 0.1000 1.0000

INTEX Flight 11 16:33-16:42 UT

Aerosol Extinction (km\(^{-1}\))

Altitude (km)

MODIS AOT (550 nm)

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

UV (299 nm)
VIS (588 nm)
IR (1064 nm)

MISR AOT (558 nm)
Aerosol Profile Retrievals

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

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

“Lidar Ratio” = \[ \frac{\sigma_p(r)}{\beta_p(r)} = S_p \]

\[ \text{Assumption of value for extinction-to-backscatter (} S_p \text{) ratio required for backscatter lidar retrieval} \]

- 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
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.
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)
• Attenuation correction applied using MODIS AOT constraint
• Correction at low altitudes ~ 200-300% at 588 nm, 20-40% at 1064 nm
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
• UV DIAL
• NASA Ames Airborne Sun Photometer (AATS14) on J-31 aircraft

Aerosol Optical Thickness (VS)

0.00 0.10 0.20 0.30 0.40 0.50

MODIS

MODIS AOT (550 nm)

VIS (588 nm)

DC-8 UV DIAL 16:33-16:42; 43.0 N, 69.7 W
J-31 AATS14 15:42-16:03; 42.9 N, 69.5 W

UV DIAL (299 nm)
UV DIAL (588 nm)
UV DIAL (1064 nm)
AATS14 (354 nm)
AATS14 (604 nm)
AATS14 (1019 nm)
- (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 similar chemical signature
Model representations of global annual AOT have become closer to observations.

But...

Large model differences in compositional mixture.

Kinne et al., 2005
Large Variation in How Models Represent Aerosol Profiles

Global Annual Mean Aerosol Concentration ($\mu g/m^3$)

Textor et al., 2005