ABSTRACT
A study of air quality was performed using a compact, aircraft aerosol lidar designed in the Science Directorate at NASA Langley Research Center and MODIS AOD retrievals. Five flights of lidar measurements conducted in the Hampton-Norfolk-Virginia Beach region showed complex regional aerosol distributions. Comparisons with MODIS AOD at 10x10-km and 5x5-km resolutions show good agreement with correlation R-squared values of 0.82 and 0.88, respectively. Linear regressions of PM2.5 and AOD within the range of 5-40 $\mu$g m$^{-3}$ and 0.05-0.7 result in R-squared values ~0.71 and ~0.82 for MODIS and CAL respectively. The linear regressions reflect approximately 54 $\mu$g m$^{-3}$ to 1 AOD. These relationships are in agreement with previous findings for air pollution aerosols in the eastern US and in northern Italy. However, large vertical variation is seen case by case with planetary boundary heights ranging between 0.7 and 2 km and uncertainties between 0.1 and 0.4 km. The results of the case studies suggest that AOD can be used as an indicator of surface measurements of PM2.5 but with larger uncertainties associated with small aerosol loading (AOD < 0.3).

INTRODUCTION
Aerosols are stable suspensions of solid or liquid particles in air ranging in size from 1 nanometer to 10 microns. It is important to study the size, origin, and height of aerosols in the atmosphere because they can affect weather, climate, and the health of humans that breathe in the small particles. A particular hazard to human health is aerosols or particulate matter (PM) of diameter less than 2.5-micrometers, designated as PM2.5 or fine particles. Studies have shown exposure to PM2.5 has a significant association to premature death, respiratory and cardiovascular disease, lung disease, decreased lung function, asthma attacks, and irregular heartbeat.

Agencies are seeing the need to deal with air pollution not just on a national basis, but also on a regional basis because air from one city is easily transported to another city. In fact, one Environmental Protection Agency (EPA) report found that in 2002 about 59 million people in the United States live in counties where the PM2.5 concentration regularly exceeds the EPA safe limits. The EPA has made specific efforts to monitor and model PM2.5 mass concentration in urban areas. Ground station monitors throughout the United States make in-situ measurements of PM2.5 mass concentration. The MODIS (MOderate resolution Imaging Spectroradiometer) instrument, aboard the Aqua and Terra satellites, gives daily measurements of the aerosol optical depth (AOD). Efforts have been made to correlate the satellite measurements of AOD with the PM2.5 mass concentration measured on the ground. IDEA (Infusing satellite Data into Environmental Air quality applications) is a project that combines the work of NASA, NOAA, and the EPA in order to better predict air quality forecasts. However, the problem is complicated because MODIS gives the integrated extinction for an atmospheric column without resolving the vertical distribution of the aerosols. Therefore, the MODIS AOD often will not correlate with measurements taken at or near the surface where the ground stations are located. Aerosol layers and contamination from thin cirrus clouds can lead to poor correlation between MODIS and ground PM2.5 measurements.

Lidar is a powerful tool for atmospheric aerosol profiling because it resolves the vertical distribution of an atmospheric column. Any correlation between MODIS AOD and ground station PM2.5 monitors will be difficult without the use of lidar or a similar instrument capable of measuring aerosols as a function of altitude.

This paper will describe results from aerosol lidar flights conducted in the Hampton-Norfolk-Virginia Beach region (Figure 1). All flights last approximately one hour, originate from the Newport-News International Airport (PHF), and overpass the Chesapeake Light House where an AERONET sunphotometer is located as part of the CERES Ocean Validation Experiment (COVE). Atmospheric soundings of temperature and relative humidity were
obtained from the NASA Wallops Flight Facility (WFF) 120-km northeast of the region.

Figure 1. Hampton- Norfolk-Virginia Beach region. The flight track is indicated by the solid white line (Image obtained from Google Earth).

This region is unique in that it is an urban region with a population of approximately 1.6 million and covers roughly 10,100 square-kilometers$^4$. The Chesapeake Bay and Atlantic Ocean are along the region’s eastern border. This creates a demarcation between a region with aerosol sources and the Atlantic region with no urban sources. Ground stations to monitor PM2.5 are located in Hampton, VA at the Virginia School for the Deaf and the Blind, Norfolk, VA at the NOAA Headquarters, and in Virginia Beach at the Virginia Department of Environmental Quality Regional Office.

The issues of concern in this urban study are: what is the typical urban boundary layer height, how does the aerosol concentration change when going from land to ocean, are aerosol plumes common in the troposphere, how does the integrated lidar aerosol extinction compare to the MODIS AOD, using back trajectories are aerosols being transported into the urban area, and how do aerosol profiles correlate with ground aerosol monitoring stations?

**LIDAR SYSTEM DESCRIPTION**

The lidar system is mounted on an aluminum frame as shown in Figure 2. The frame sits on seat-track mounts designed to adapt the system into a Lear Jet aircraft and pointed in the nadir direction. The laser is a frequency doubled Nd:YAG, 20-Hz, with 1.5-mrad divergence output. The 532-nm (80-mJ) and residual 1064-nm (60-mJ) pulses are transmitted into the atmosphere using a steerable 45$^\circ$ turning mirror.

The aerosol lidar receiver uses a 30.5-cm diameter (f/2) parabolic telescope with a 1.6-mrad field of view. A 1-mm diameter optical fiber is mounted at the focal point of the telescope which passes the light into the receiver box. The received light is collimated and split into 532-nm and 1064-nm channels, with a further split of the 532-nm channel into photon counting (10%) and analog (90%) signal channels. The 1064-nm signal passes through a 1-nm FWHM filter and then is focused onto an avalanche photodiode diode (APD) detector. The 532-nm signal passes through a 0.5-nm FWHM filter before being split into separate analog and photon counting channels$^5$.

Figure 2. Diagram of CAL aircraft lidar system

Signals from the 1064-nm and 532-nm analog channels are filtered by a 1.5 MHz filter and then digitized with a 14-bit, 5-MHz waveform digitizer. The waveforms are averaged for 2 seconds before being stored on the computer hard drive. This results in a 30-m vertical aerosol profile resolution, and at the typical aircraft speed of 200 m/s, a horizontal resolution of 400-m. The 532-nm photon counting channel is sent to a multichannel scaler where typically a 10-sec integration (200 ns dwell time) is used prior to storing the file on the computer hard drive.

**METHODOLOGY**

The power returned to the lidar receiver, $P(z)$, is given by the lidar equation as:

$$P(z) = C \frac{1}{z^2} (\beta_m(z) + \beta_a(z)) T^2(z).$$  \hspace{1cm} (1)

$C$ is the calibration constant, $\beta_m(z)$ is the molecular backscattering coefficient, $\beta_a(z)$ is the aerosol backscattering coefficient, and $T(z)$ is the one-way transmittance from the lidar to the height $z$. The lidar data is inverted using the Fernald method$^6,7$ to
determine the aerosol backscatter coefficient, $\beta_a$. The lidar AOD, $\tau$, is calculated as:

$$\tau = S_a \int_0^{z_*} \beta_a(z) dz$$

(2)

where $S_a$ is the lidar ratio and $z_*$ is an altitude where it is assumed only molecular scattering occurs.

On three of the lidar flights, the 532-nm channel was not available, so an additional calculation was performed to convert the 1064-nm lidar AOD to a 532-nm AOD using the Angstrom exponent retrieved from AERONET. For two different wavelengths $\lambda_{1064}$ and $\lambda_{532}$ the Angstrom exponent, $\gamma$, relates the optical thicknesses $\tau_{1064}$ and $\tau_{532}$ such that:

$$\tau_{532} = \tau_{1064} \left( \frac{\lambda_{1064}}{\lambda_{532}} \right)^\gamma$$

(3)

In this calculation, it was assumed that the Angstrom exponent for the 500-nm and 1020-nm AERONET wavelengths could be used for the 532-nm and 1064-nm lidar wavelengths with negligible error. Optical depths calculated using Equation 3 are referred to as the converted 532-nm AOD in the sections that follow.

To determine the appropriate lidar ratio, the lidar AOD is matched to the MODIS AOD over small segments of the lidar flight track, and the Angstrom exponent from AERONET is used for the entire flight track. While previous studies have shown that the lidar ratio and Angstrom exponent vary with altitude, it is assumed that within the boundary layer, these values will not vary greatly. In the case of the converted 532-nm lidar-derived AOD, only the 1064-nm lidar ratio is used to invert the lidar signal, then the Angstrom exponent is used to determine the 532-nm AOD.

RESULTS

Lidar flights were conducted on the dates of August 1, 2005, August 3, 2006, September 22, 2006, February 14, 2008, and June 19, 2008. This section will present an example of the data collected from the February 14, 2008 aircraft lidar flight, as well as a summary of data from the entire campaign. Comparisons of the lidar derived AOD to MODIS AOD and correlations between lidar and MODIS AOD to PM2.5 mass concentrations will be shown. For consistency, only the converted 532-nm data is presented in this study.

February 14, 2008 Flight

February 14, 2008 (Figure 3) represents an example of a low aerosol loading day. The lidar ratio for the 1064-nm signal was 40-sr and an Angstrom exponent of 0.9539 was used for comparison with MODIS. The low value for the Angstrom exponent indicates larger aerosol particles than those observed from previous flights. The heavy rainfall on the previous day resulted in a low aerosol loading and PM mass concentration. The Aqua overpass occurred at 18:10 UTC. The aircraft lidar flight started at 18:00 UTC and ended at 18:54 UTC with an altitude of 6.1-km.

In contrast to most days, the AOD from MODIS and CAL both indicate a higher aerosol loading over the ocean than over land. The back trajectories show the ground-level winds coming from Northern Virginia/Maryland, while the fast moving, upper-level winds come from the direction of West Virginia/Ohio Valley. Thus, the ocean profile is influenced by pollution from Washington D.C., while the land profile is influenced from cleaner areas farther west, which may explain why the aerosol loading over the ocean was higher than over land.

The aerosol extinction profiles show a maximum at less than 1-km above the surface, consistent with the temperature inversion from a Wallops Island sounding performed that day. Another peak in extinction is near 4-km which is possibly due to transport from West Virginia/Ohio Valley power plants. The COVE sunphotometer was unavailable this day; however, a Microtops II Sunphotometer was used to make 500-nm AOD measurements before (0.054) and after (0.0435) the lidar aircraft flight, which is consistent with MODIS values in the vicinity. The PM2.5 mass concentration retrieved from the Hampton TEOM was 7.0-$\mu$g m$^{-3}$ and the Virginia Beach FRM measurement was 9.4-$\mu$g m$^{-3}$, indicating low PM concentration.

MODIS and Lidar AOD Comparisons

The nearest MODIS pixel for each point in the lidar flight tracks (August 1, 2005 – June 19, 2008) was determined in order to compare the optical depths from MODIS to the lidar-derived AOD from CAL. Figure 4 shows the results of the averaged 532-nm AOD converted from 1064-nm AOD for all of the flights using the 10x10-km MODIS retrieval (550-nm). MODIS pixels determined to contain smoke contamination were removed. Because of a significant time difference between the lidar flight and MODIS overpass on August 3, 2008, the ocean data was also removed. The horizontal distance between the CAL and MODIS AOD measurements was typically within 9-km. The R-squared correlation between MODIS AOD and CAL AOD is slightly higher over the ocean (0.8569) than over land (0.8569). The total r-squared correlation (including land and ocean) was 0.8196.
Figure 3. (a) Comparison of MODIS (550 nm) 10x10-km and CAL (converted 532-nm) AOD on 14 February 2008; (b) Comparison of MODIS (550-nm) 5x5-km and CAL (converted 532-nm) AOD, (c) AOD of CAL flight track with back trajectories at different altitudes (shown in different colors) and PM2.5 mass concentrations; the back trajectory markers represent 1-hour time intervals, (d) Aerosol extinction lidar profile over land, (e) Aerosol extinction lidar profile over ocean at COVE site, and (f) Temperature (solid line) and relative humidity (dotted line) from Wallops Island sounding.
There is a better agreement between MODIS and CAL AOD at lower optical depths (< 0.3).

Figure 4. Comparison of averaged CAL AOD (converted 532-nm) and MODIS AOD (550-nm) using 10x10-km MODIS pixels. Includes all flights from August 1, 2005 – June 19, 2008. The R-Squared values for land and ocean are 0.8019 and 0.8569, respectively. The total R-Squared value is 0.8196.

Figure 5 shows the comparison of MODIS (550-nm) and averaged CAL (converted 532-nm) AOD using the 5x5-km MODIS retrieval. The horizontal distance between CAL and MODIS measurements at this resolution was typically within 3-km. The R-squared correlation (0.8845) is slightly higher than the correlation using the 10x10-km retrieval. The larger error bar for the June 19, 2008 data point is due to the large variability in CAL AOD, likely caused by hydrated aerosols in a cloudy area. There were no coincident AOD values at 5x5-km resolution for the August 1, 2005 flight.

Figure 5. Comparison of averaged CAL AOD (converted 532-nm) and MODIS AOD (550-nm) using 5x5-km MODIS pixels including lidar flights from August 3, 2006 – June 19, 2008. The R-Squared value for CAL-MODIS AOD is 0.8845. Note that there were no coincident MODIS AOD values for the August 1, 2005 lidar flight.

PM2.5 and AOD Correlation
AOD represents the column-integrated extinction from the surface to the tropopause (or boundary layer height if there are no aloft aerosols in the free atmosphere), while PM2.5 is only measured at the surface level. Thus, good correlation would require vertically well mixed and less spatially variant conditions. In the correlation between PM2.5 mass concentration and MODIS AOD, the closest 5x5-km MODIS pixel was chosen to match with the ground PM2.5 value; except for three cases where no 5x5-km AOD was in the vicinity of the ground stations, and 10x10-km AOD values were then used. The PM2.5 mass concentrations from the Virginia Beach monitor represent 24-hr averaged FRM measurements, while the Hampton PM2.5 mass concentrations are hourly TEOM measurements. The comparisons between PM2.5 mass concentrations and CAL AOD uses the AOD values of the closest point to the PM2.5 monitor from the flight tracks.

Due to the unavailable hourly TEOM data from the Hampton PM2.5 monitor at the time of the lidar flights on August 1, 2005 and August 3, 2006, these two dates are removed from PM2.5 analysis. Note that the use of TEOM as opposed to FRM is due to mismatches of FRM measurements (taken by a 3-day cycle) with lidar flights over the Hampton area, which is not the case in Virginia Beach (FRM measurements are taken daily).

Table 1 shows a comparison of lidar and PM2.5 data at the Hampton and Virginia Beach monitoring stations for each lidar flight. Even for the short distance between Hampton and Virginia Beach, there are large variations when correlating MODIS AOD with PM2.5, partly due to spatial variability and partly due to vertical distributions, making the correlation difficult. The large standard deviation shown on June 19, 2008 was attributed to smoke plumes from the Great Dismal Swamp fires. Figure 6 shows the correlation between PM2.5 and MODIS AOD (solid line) and the correlation between PM2.5 and CAL AOD (dashed line).

The R-squared correlations for MODIS and CAL are 0.71 and 0.82, respectively. MODIS tends to have a higher AOD than CAL with respect to same PM2.5 mass concentration. The difference could be partially due to the difference in the footprint of the two instruments. CAL has a footprint on the order of a meter-squared while MODIS averages the AOD within a footprint on the order of 25 or 100 kilometers-squared, so it may include aerosol loading unseen by CAL. On the other hand, despite the spatial variability of aerosols, the higher MODIS
**Table 1. Comparison of Hampton and Virginia Beach PM2.5 monitors**

<table>
<thead>
<tr>
<th>Date</th>
<th>PBL height (km)</th>
<th>Lidar AOD</th>
<th>PM2.5 (µg m(^{-3}))</th>
<th>∆x* (km)</th>
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</thead>
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<tr>
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<td>Hampton VA Beach</td>
<td>Hampton VA Beach</td>
<td>Hampton VA Beach</td>
</tr>
<tr>
<td>1 Aug 05</td>
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<td>0.1242</td>
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</tbody>
</table>

* ∆x is the horizontal distance between the PM2.5 monitor and the aircraft.
** 1 Aug 05 and 3 Aug 06 were removed from analysis because of missing hourly PM2.5 data

AOD values are consistent with previous studies in the coastal zones because of underestimated surface reflectance due to surface inhomogeneity or sub-pixel water contamination. 10,11

![Figure 6. Correlation of PM2.5 to MODIS and CAL AOD using the Hampton and Virginia Beach PM2.5 monitors. The solid line represents the linear fit for the MODIS correlation and the dashed line represents the CAL correlation.](image)

The mean horizontal distances between the Hampton and Virginia Beach PM2.5 monitors and the nearest aircraft measurements were 9-km and 24-km, respectively. The typical horizontal distance between both PM2.5 monitors and the nearest MODIS pixel was 9-km. A linear regression produced a slope of 57.3 µg m\(^{-3}\) and intercept of -4.3 µg m\(^{-3}\) for the MODIS correlation (or 46.2 µg m\(^{-3}\) by forcing the intercept to zero), and a slope of 49.4 µg m\(^{-3}\) and intercept of 4.7 µg m\(^{-3}\) for the CAL correlation (or 61.4 µg m\(^{-3}\) by forcing the intercept to zero). Using an AOD of 1 for the linear regressions gives PM2.5 mass concentrations of 53 µg m\(^{-3}\) and 54.1 µg m\(^{-3}\) for MODIS and CAL, respectively. These relationships with PM2.5 mass concentrations are in agreement with previous studies in the eastern US and in the Po Valley of northern Italy for pollution aerosols. The largest differences between these two linear fits occur at the lowest AOD values (<0.3) while PM2.5 mass concentrations are less varying. More measurements, particularly on days with variant PM2.5 with respect to AOD, are needed in order to obtain a stronger correlation.

**CONCLUSIONS**

A regional aerosol study has been conducted in the Hampton-Norfolk-Virginia Beach region using a compact aerosol lidar. This aerosol lidar is small, low mass, and compact; thus aircraft lidar measurements can be made quickly and at relatively low cost. Five flights were conducted from August 2005 through June 2008 showing diverse and complex aerosol distributions over both urban land areas and ocean. Wind back trajectories show how aerosol transport from surrounding areas can substantially affect the air quality in the Hampton-Norfolk-Virginia Beach region. The ocean lidar profiles generally showed notably lower aerosol loading than the land profiles showing the influence of urban pollution. The largest variation between land and ocean profiles was within the boundary layer. Above the boundary layer, each profile showed very similar characteristics.

In all cases, there was usually good agreement (R\(^2\) > 0.8) between lidar derived and MODIS AOD, especially at AOD values less than 0.3. Higher spatial resolution in the retrieval of MODIS optical depth, as with the 5x5-km product, can lead to improvements in this comparison. Results from the PM2.5-AOD correlations showed very little difference between the use of MODIS and lidar derived optical depth. With all cases included, both methods produce similar results with previous findings in correlating with PM2.5. However, large deviations are seen case by case in the ratio of AOD and PM2.5, reflecting large variations with height. The uncertainties of the relationship would be reduced if aerosol lidars are collocated well with the PM2.5 ground sites; in our analysis the distances are generally 10-24 km apart. Direct overflights of the PM2.5 monitors would also be helpful in obtaining collocated measurements of the AOD and PBL height.
with the PM2.5 mass concentration. By examining the correlation between lidar backscatter, MODIS AOD, and PM2.5 mass concentration, a better understanding of aerosol distribution and transport will be gained and better air quality forecasts and public policy decisions will be made in the future.

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REFERENCES


