Regional Impact of Inter-Continental Aerosol Transport

Leona Charles*¹,², Barry Gross¹, Fred Moshary¹, Yonghua Wu¹, Viviana Vladutescu¹,², Sam Ahmed¹
¹Optical Remote Sensing Lab., 140th Street at Convent Ave., T553, CCNY, New York, NY, 10031; ²SBIRS Program Northrop Grumman Corporation Azusa CA 91702

ABSTRACT

In this paper, we present results showing the usefulness of multi-wavelength lidar measurements to study the interaction of aerosols in the PBL with long range advected aerosol plumes. In particular, our measurements are used to determine the plume angstrom exponent, which allows us to differentiate smoke events from dust events, as well as partitioning the total aerosol optical depth obtained from a CIMEL sky radiometer between the PBL and the high altitude plumes. Furthermore, we show that only if the optical depth from the upper level plumes is taken into account, the correlation between the lidar derived PBL aerosol optical depth and surface PM2.5 is high. In addition, we also observe the dynamic interaction of high altitude plumes interacting with the PBL, resulting in a dramatic rise in surface PM10 concentrations without a corresponding dramatic rise in PM2.5 concentrations. These observations strongly suggest the deposition of large particulates into the PBL which is consistent with both lidar angstrom coefficient measurements and back-trajectory analysis. These studies are useful in identifying the vertical length scales in which spaced based lidars such as Calipso can be used to probe surface PM2.5.

Keywords: Multi-wavelength lidar, Planetary Boundary Layer, angstrom exponent, PM2.5/10, backscatter

1. INTRODUCTION

Aerosols transported over long distances can affect air quality on a local, regional, and even intercontinental scale. Therefore, global monitoring of aerosols is important, not only because of aerosol effects on the Earth radiation budget, but also because of the potential impacts on air quality and human health, cloud properties, and precipitation. Airborne particulate matter (PM) is one of the principal components of the atmosphere that has been singled out as a major air pollutant concern. Air pollution caused by such particulates has been a major problem since the beginning of the industrial revolution, and have the greatest influence on our activities due to a reduction in visibility because of their ability to scatter light. An increased PM2.5 concentration also causes concerns for the stability of our global environment due to “Greenhouse effects”.

In an effort to improve Air Quality Forecasting, the EPA together with NASA and NOAA, implemented an ambient air quality-monitoring program to determine the composition of airborne PM2.5 in urban air, in an effort to assimilate satellite measurements of aerosol column optical depth into air quality transport models. These regulations are designed to bring most urban areas of the U.S. into attainment by the year 2015. In order to improve our knowledge and quantify the aerosol impact on the environment, aerosol monitoring and modeling have become a significant scientific challenge.

Although the Intergovernmental Panel on Climate Change (IPCC) has foreseen pollution emissions in the United States to curtail in the next century, long-range transport mixing with surface air can increase particulate concentrations and may consequently reduce the benefits of local emission control. With increasing measures taken to reduce ambient concentrations of air pollutants at a regional level, there continues to be an increased interest in atmospheric particulates due to concerns over the effects on climate and the environment, in particular surface air quality.

* Leona.Charles@ngc.com
Chin et al. [2007] studied the implications on air quality by intercontinental transport of pollution and dust aerosol, where he focused on the quantification of fine aerosol mass concentrations on US surface air from regional emissions, natural sources, intercontinental transport, and the impact of transported from one major source region on surface fine aerosol mass. Their results revealed that long-range transport of dust adds significant amounts of fine particulates (>0.5µg/m$^3$ annual average) over the eastern US. Collette et al. [2006] studied the transpacific transport of Asian anthropogenic aerosols and its impact on surface air quality in the United States. One of the focuses of this study was to improve their understanding of the mechanics for transpacific transport of Asian pollution and to quantify its impacts on North American air quality.

It has been documented by many authors that East Asian dust can be transported over the Northern Pacific reaching Canada and the United States. A comprehensive evaluation of the April 2008 dust storm was done by Husar et al. by using a combination of satellite multi-sensor observations (AVHRR aerosol optical depth, TOMS aerosol index, etc.), and ground based observations, including AERONET sun-photometer measurements. Recently, Darmenova et al. examined the capabilities of TOMS, MODIS, and SeaWiFS measurements to track dust plumes and constraining the areas affected by dust transport over land and ocean.

Of particular interest in this paper is the usefulness of multi-wavelength lidar to study aerosol interactions in the Planetary Boundary Layer (PBL) with long-range advected plumes. In particular, our measurements are used to determine the plume angstrom exponent, which allows us to differentiate smoke events from dust events, as well as partitioning the total aerosol optical depth obtained from a CIMEL sky radiometer between the PBL and the high altitude plumes. Furthermore, we show that only if the optical depth from the upper level plumes is taken into account, the correlation between the lidar derived PBL aerosol optical depth and surface PM2.5 is high. In addition, we also observe the dynamic interaction of high altitude plumes interacting with the PBL, resulting in a dramatic rise in surface PM10 concentrations without a corresponding dramatic rise in PM2.5 concentrations. These observations strongly suggest the deposition of large particulates into the PBL, which is consistent with both lidar angstrom coefficient measurements and back-trajectory analysis.

Lidar provides a method to quantitatively evaluate the spatial and temporal variability of smoke and dust plumes as they are transported downwind from their sources at a single convenient location and has the ability to detect the complex vertical structure of the atmosphere and can therefore identify the existence and extent of aerosols that have undergone long-range transport. It has been demonstrated that East Asian dust could be transported over the Pacific reaching Canada and the United States. Husar et al. [2001] performed a detailed analysis on an East Asian dust episode of April 1998 using data from multiple satellites, including AERONET sun photometer and TOMS aerosol index. This paper will report the Asian dust episode of April 6-21, 2006, which traversed the Pacific reaching Canada and the Eastern United States by 18, April 2006. The focus is on qualifying and quantifying the use of lidar techniques, multi-sensor satellite observations, and other ground based measurements to provide useful evaluations of the dust event.

2. MOTIVATIONS FOR AEROSOL MONITORING AND ASSESSMENTS

Air quality in New York City and elsewhere is highly dependent on the meteorological conditions that govern the transport and mixing of trace gases and aerosol particles. These processes occur on a variety of scales, namely; the atmospheric boundary layer (ABL), regional, intra-continental and inter-continental scales. Previous studies have demonstrated on all of these scales, the impact of transport processes on the United States, in particular the impact on surface air quality. A clear understanding of transport on these scales will allow us to assess the impact from local, regional, and distant sources on air quality of air masses as they traverse over NYC and transported to downwind locations. The event discussed in this paper was observed by continuous multi-sensor satellite observations, lidars, sun photometer measurements, and surface aerosol monitors on the east coast, NYC in particular.
Lidar has the capability to characterize particle optical properties on both a horizontal and vertical scale, which makes it an applicable tool for boundary layer aerosol properties. Lidar also serves as a means to quantify the effects of the boundary layer structure and dynamics on plume incursion and dispersion, and its AOD retrievals also serves as a proxy indicator of PM2.5 concentrations, making it a key parameter for various aerosol related studies. To assess the need for lidar measurements to predict PM2.5, we examine a case of a plume advecting and mixing with the planetary boundary layer.

The large-scale event of free tropospheric transport of dust particles that occurred in April of 2006 provided an excellent opportunity to gain new insight on the influence of such lofted plume layers. In support of this prediction, the CCNY lidar system observed some reasonable transport activity over its location, which contributed to reasonable aerosol loadings in the free troposphere.

3.1. Model Predictions and Satellite Observations

Transport models can be very useful forecasting tools for predicting inter-continental aerosol transport. The Infusing Satellite Data into Environmental Applications (IDEA) 48-hour aerosol trajectory forecast which plots the latest high MODIS aerosol optical depth (AOD) and the potential vertical movement of high aerosol loads in the troposphere, reported very low aerosol optical depth ($\tau_a<0.2$) over New York City (NYC) and its immediate vicinity (not shown). These low AOD’s are indicative of low column aerosol loadings, nonetheless; the parcel trajectory forecast patterns were in agreement with the HYSPLIT back-trajectory models displayed in figure 1. However, in the trajectory forecast areas of elevated MODIS AOD ($\tau_a>0.4$) are seen over parts of southeastern Canada (north of US east coast) on April 18 and 19; projecting wind patterns towards the eastern US with particle trajectories directed towards high pressure within the boundary layer on April 19. The backward trajectories also show that the dust observed at all levels above the planetary boundary layer on April 19 (figure 1a) and April 18 (figure 1b) originated from East Asia. This shows that transport source can be predicted to some degree of accuracy. This evidence for long-range transport of continental aerosols prompted our examination of satellite imagery for pre-lidar observation days.

Fig. 1: NOAA/ARL 13-day HYSPLIT model backward particle trajectories for three altitudes (indicated) ending at 2200 UTC on April 18 and 19, 2006 respectively showing source for continental layers from East.
3.2. Satellite Observations

It is well documented that aerosol plumes can at times be transported over large distances from their source regions, and can also affect the air quality of the earth’s climate system, and monitoring of their constituents on a global scale is necessary. Although ground based remote sensing provides accurate aerosol information at high temporal resolution, their spatial coverage is limited which therefore limits our ability to monitor aerosol concentrations and their properties across the United States. Surface monitoring is limited over the United States, particularly over coastal regions which are very often niche by polluted air approaching over water. Long-range plume layers can also be transported aloft, undetected by ground monitors, and can also descend to influence surface air.

3.2.1. MODIS

Dust plumes are readily seen in satellite imagery, and many satellite sensors like GOES, MODIS \(^\text{15}\) and TOMS \(^\text{16,17}\) have been widely used to map the geographical distribution and to characterize aerosol (dust) transport on a global scale. MODIS and TOMS (sun synchronous polar orbiting satellites) provide global coverage approximately once a day and can only provide snap-shots of large-scale aerosol spatial distribution during the time of satellite overpass, which is impractical for daily tracking and monitoring of large scale aerosol events.

The 8-day mean aerosol optical depth retrieved from MODIS (Level-3 global product) was used in this analysis, which is derived from Level-2 data and spatially averaged to a 1° x 1° equal angle grid over 24 hours. To better illustrate the MODIS spatial coverage and spatially assess the dust transport event, a fusion of eight days of data becomes useful to obtain a cloudless composite image. In figure 2, we show an 8-day MODIS composite image (16-23 April, 2006) indicating how well this event was captured from its source region (East Asia) and its transport across the northern Pacific to Canada and the United States. We can observe that the instance of incursion by the Asian-sourced dust was transported along the extent of the U.S. eastern seaboard. Although it appears to have been a large scale dust event which spanned over 13 days, by the time the dust particulates reached the eastern U.S. it was at a reduced scale, which is indicative of reasonably low aerosol loadings (< 0.2). It is also very likely that the dust particulate concentrations may have been reduced by precipitation scavenging along its transport path, although HYSPLIT model shows no precipitation except for April 14 (< 1 inch). We can also see in figure 2 that the largest enhancements in aerosol optical depth is over the source region and its immediate surroundings and of a lower order along its trajectory path compared to the much lower aerosol loadings in the background.

Fig.2 Dust pollution from source region and transport pathway from MODIS AOD (550nm) image (8-day composite level-3 product) in 16-23 April, 2006.
3.2.2. OMI

The Aura Ozone Mapping Instrument (OMI) provides daily information on absorbing aerosols using a retrieved aerosol index (AI) and is continuously being used to track long-range transport events globally. However, because its sensitivity to aerosols decreases with increasing pressure (lowest near surface), this limits its use for air quality monitoring. The main mission of the Aura OMI instrument is to monitor atmospheric aerosols and smoke from biomass burning; in particular, to differentiating UV-absorbing aerosols such as dust and biomass burning aerosols from the weakly absorbing aerosols and clouds. Absorbing and non-absorbing aerosols are separated based on the UV aerosol index, which is positive for absorbing (e.g. dust) and negative for non-absorbing aerosols. OMI also has the unique capability to detect aerosols mixed with clouds. The aerosol index is simply a measure of the absorption of UV radiation by aerosols.

As was done with the MODIS AOD data, we used the OMI TOMS-Like daily global 1°x1.25° UV aerosol index (dust only) for 12-20 April of the dust event and computed an 8-day global composite of UV Aerosol Index with the goal of being able to fill in the gaps of missing meaningful data. Figure 3 shows the results of the 8-day UVAI composite, with the HYSPLIT trajectory projected on the map. We can see that the air parcel trajectory clearly follows the transport path of the dust plume which was observed by the CCNY lidar system, particularly over northern Canada, because OMI has the capability over other satellite sensors of detecting aerosols mixed with clouds.

![Aura OMI TOMS-Like Global 1°x1.25° UV 8-day composite Aerosol Index over 12-20 April, 2006.](image)

3.3. CCNY Multi-wavelength Lidar Observations

During 6-21 April, 2006, a severe dust storm wiped over East Asia, where waves of dust washed out of the Asian deserts and progressed over the northern Pacific Ocean reaching Canada and eastern United States, and arriving NYC by April 19. Figure 5 and 6 shows the measured lidar signal (range corrected) on April 18 at 1064 nm and April 19 at 532, 355, and 1064 nm respectively, measured by the CCNY lidar system, which clearly illustrates the complex vertical structure of the observed atmosphere over CCNY. These observed features are consistent with the upper air
meteorological soundings displayed in figure 6, which was obtained using the NOAA Air Resources Laboratory HYSPLIT model. Although the retrieved backscatter was reasonably small on both days, aerosols have been detected up to altitudes of 10,000m on April 18 and 6000m on April 19 above CCNY, with the majority of the optical depth carried in aloft plumes. In addition, we observe a well-mixed (homogeneous) PBL in the CCNY Lidar image, except for the mid-day haze on April 18, indicating a shallow PBL (~ 1 km) in the morning with a gradual increase to about 2 km during the afternoon, allowing for an interaction between the PBL and the aloft plume. Upper air soundings provide a means to confirm the detailed vertical structure of the atmosphere as observed by the CCNY Lidar system. The PBL is topped by a temperature inversion, which can be seen in the upper air soundings in figure 6. The lidar also reveals how multiple clean and continental influenced aerosol layers can coexist over a particular location, and how variable the column physical, chemical, and optical properties can be. In figure 4, the aerosol layers appear to be entrained between 5 and 10km, with no evidence of decent. However, in figure 5, during most of the day the aerosols were concentrated in layers above 3km and by 4:00PM demonstrated to be entrained into the planetary boundary layer from aloft. The incursion of the transported aerosol plume into the boundary layer was clearly a cause for air quality concerns.

Fig. 4: Time-to-height indication of range-corrected power (logarithmic) obtained by the CCNY lidar on April 18, 2006 at 1064nm.

Fig. 5: Time-to-height indication of range-corrected power obtained by the CCNY lidar on April 19, 2006. (a) Visible at 532 nm, (b) UV at 355 nm, and (c) IR at 1064 nm
4. PLUME PROPERTIES AND IDENTIFICATION

4.1. Plume Properties from Ground Observations

Figure 7 shows the near surface particulate loadings on April 19 obtained from the New York State Department of Environmental Conservation (NYS DEC). April 18 showed low PM2.5 loading within the CCNY lidar observation window (not shown), which is expected since the plumes remained lofted, and also indicating the absence of local transport. On the other hand, since a plume incursion into the PBL was evident on April 19, it was practical to examine the influence of these incursions on near surface air quality. PM2.5 levels showed a very small increase in mass loads but as seen in figure 7, the small PM2.5 loading occurred simultaneously with a distinctively large increase in the PM10 loadings during the incursion period, which is identifiable with the PBL. This finding is consistent with the hypothesis that the plume is comprised mainly of large dust particulates undergoing large-scale transport from a remote source. Additionally, we have analyzed coincident data obtained from the CCNY Mobil Lidar stationed at Princeton University in New Jersey, which is downwind from New York City, which also captured the same transport event seen over NYC at a later time (image not shown).
To test the dust particulate hypothesis, we have processed our lidar signals at both the 532nm and 1064nm channels in order to derive the wavelength dependence of the backscatter within the plume. To obtain the absolute backscatter on the 532nm channel, we use the traditional Frenauld processing scheme, where the far end calibration is determined by the molecular profile while the 1064nm channel is calibrated using a cirrus cloud feature within the scene. This approach is similar to that described in Schneider et al 2002, where it is assumed that the cloud backscatter from cirrus clouds between the 532nm and 1064 nm channels is to a good approximation, a white scatterer independent of wavelength so that the backscatter color ratio is near unity. In this case, an accurate measurement of the backscatter below the cloud base at the 532nm channel can be used to obtain the calibration of the 1064 channel. While the main idea is the same, the approach in Schneider et al 2002 is somewhat different technically than our approach and does not discuss the uncertainties inherent in the calibration scheme, due to uncertainties in the 532nm channel; therefore, we briefly describe it below.

I. To begin, a reference height is chosen which is sufficiently clear, based on match-ups with the molecular only signal obtained from meteorological radiosonde data.

II. Given this reference layer, we then “forward” integrate the Frenauld equation from the reference layer through the cloud base using a large range of viable parameter values for both the reference aerosol lidar ratio ($Z_{ref}(532)\leq 1.2$) and aerosol S ratio ($30\leq S_{532}\leq 70$) values.

III. Since it is well known that the forward integration method may become unstable for sufficiently large optical depths, we utilize an iterative scheme for the integration of the Frenauld equation, which allows us to ensure stability by calculating the solution at different iteration orders and only penetrating into the cloud when the 10th iterate is the convergent solution.

IV. For all convergent solutions, we then calculate the mean and standard deviation of the backscatter retrieval over all lidar parameter sets, to identify the optimal depth in to the cloud that maximizes the backscatter retrieval, while maintaining a sufficiently small retrieval uncertainty.

V. Once the optimal altitude is determined, we can easily obtain the calibration constant as

\[
C_{1064} = \frac{\bar{P}(z)}{\beta_n(z, \lambda(532)) + \beta_a(z, \lambda(1064)) T_0^2(R, \lambda(1064)) T_m^2(R, \lambda(1064))}
\]  

(1)

Where $\bar{P}(z)$: received backscatter signal (1064) from altitude z.

Once the 1064nm calibration is performed, and the backscatter signal is constructed, the vertical estimate of the plume Angstrom coefficient ($\alpha$), can be derived using the Angstrom Relation in equation 2, where, given the backscatter coefficients at two wavelengths $\lambda_1$ and $\lambda_2$, where $\lambda_1 < \lambda_2$ are known.

\[
\alpha(\lambda_1/\lambda_2) = -\frac{\ln[\beta(\lambda_1)/\beta(\lambda_2)]}{\ln(\lambda_1/\lambda_2)}
\]  

(2)

The dust event can easily be distinguished from its background conditions by examining the angstrom exponent as a function of backscatter. During those days the angstrom exponent was approximately 0.5, with minimum values near zero on April 19 when the dust mixed with the boundary layer. We show the lidar aerosol extinction for April 18 and 19, which is a product of the aerosol backscatter and lidar scattering ratio. For the dust, our S ratios were based on the dust aerosol model from AERONET. Then using the 532-1064 nm wavelengths we derived the plume angstrom exponent. Figure 8, shows the aerosol backscatter and angstrom exponent as a function of altitude for the 15:20 EST time slice on April 18. We can observe that for the plume layers between 5-8 km (figure 8a), the large plume backscatter coefficient compared to the background, and an angstrom exponent near zero (figure 8b). Because of the small angstrom exponent (<0.5), smoke clouds can instantaneously be ruled out. Small angstrom exponents are indicative of an
abundance of large characteristic particle size with large aerosol backscatter. However, in the April 18 case, since the angstrom exponent is closer to 0.5 we can safely conclude that the plume layer was not purely dust, but mixed with other particulates along the transport pathway. Unlike smoke, dust plumes are made of very large absorbing particles, which are representative of angstrom coefficients smaller than unity. In spite of the impression from lidar, that the major plume is dust-like (small angstrom exponents), elevated values of angstrom exponent at other layers (figure 8) clearly indicates other particulate (e.g. smoke from fires) contributions.

![Graph 1](image1)

Fig. 8 April 18, 2006 (a) Plume vertical estimate of aerosol extinction at 15:20 EST, and (b) Plume vertical estimate of angstrom exponent at 15:20 EST.

In figure 9(a) and (b) we show the aerosol extinction and angstrom exponent for April 19, respectively. We can clearly see larger plume backscatter than the background, where the larger aerosol backscatter coincides with much smaller angstrom exponents than background (~0). The small values of the angstrom coefficient (A ~ 0) insure that the particles in the plume are consistent with dust particles. In this case it is evident that the dust particulates dominate.

![Graph 2](image2)

Fig. 9: April 19, 2006 (a) Plume vertical estimate of aerosol extinction at time of plume incursion into the boundary layer 16:00 EST, and (b) Plume vertical estimate of angstrom exponent at 16:00 EST.
Finally, once we have identified the altitude of the observed plumes, further analysis based on extended backward trajectory ending at 2200 UTC, on April 19, 2006, at an altitude of 2000 m over the CCNY site (latitude 40.8, longitude -73.9). The ending altitude was determined from the lidar observations of the plume incursion in the boundary layer, shown in figure 6. We can see that the 2 km wind trajectory (green trajectory in figure 1b) traces back to the source regions (East Asia). A careful examination of the results reveal that the dust plume traversed over the Pacific Ocean, across to south eastern Canada, and downwind to the eastern US (as shown in the OMI 8-day UVAI composite). The wind parcel trajectory is also consistent with the wind patterns on that day in question, and there was no rainfall reported along the parcel trajectory path (not shown), which would effectively reduced the possibilities of aerosol scavenging if modeled correctly. This event was also captured by Aura’s Ozone Monitoring Instrument (OMI); refer to figure 3, with winds patterns conforming to previous findings (wind patterns not shown in image)16. We can also see in figure 4 high positive aerosol index along most of the trajectory path, which is indicative of colored absorbing aerosols (dust).

4.2. Plume Properties from Satellite Observations

Numerous passive instruments on space-borne platforms (such as MODIS, OMI, and GOES etc.) are being used to measure the column dust aerosol optical thickness on a global scale. The dust episode was captured by MODIS, GOES, and OMI. MODIS images are multi-spectral products and are captured daily and can be used for real time applications such as identifying plume transport and their properties. Because of cloud cover, assessing transport events may at times be difficult or impossible using daily multi-spectral imagery, as is the case with the dust event over Northern Canada. Multi-day composite products can also provide meaningful global pictures since the data over several days can fill the gaps compared to daily averaged data, although on the downside we loose the temporal evolution of the dust on a shorter timescale.

4.2.1. MODIS

We have assumed a global transport path confined between 30° and 75° latitude, and performed a latitude averages AOD and weighted averaged Angstrom exponent, to observe how these plumes vary along the transport path (longitudes) for the MODIS 8-day AOD composite shown in figure 2. In figure 10, we display the average AOD for the above defined latitudes across all longitudes in the upper panel (blue profile), average AOD across latitudes 90°N to 90°S (red profile), and average over all latitudes outside the 35-75° window. We can safely conclude that the largest aerosol loadings were in the source region, however, the AODs reduced in magnitude by the time it arrived the western U.S, which is consistent with the low aerosol loadings retrieved from MODIS, sun-photometer and lidar. The aerosol loading again increased along its path to the U.S east coast which may be largely due to mixing with local transport. The averaged AOD for 35-75°N and 73.9°W which includes CCNY, is on the same order as the obtained from AERONET sun-photometer and out multi-wavelength lidar system, bearing in mind that MODIS at times overestimates the aerosol loadings over land19. Similarly, the Angstrom exponent is smaller at the source than over the United States.
4.2.2. **OMI**

OMI aerosol index is useful for identifying the aerosol type. In figures 3 we showed the OMI UV aerosol index for the dust particulates only, where we can clearly see large plumes with high absorption index (~3) over the source region. In the 8-day composite (figure 3) we can also see the larger AI’s over the source region and the transport path. This shows that aerosol index can serve as a tracer of transport.

We also looked at the daily global variability of the UV aerosol index for April 2006, averaged over 90S-90N, 180W-180E using the GIOVANNI interface developed by the NASA Goddard Earth Science Data and Information Service Center (GES DISC). It is event that the UV absorbing aerosol index is highest during the time of the Asian dust event (figure 11).
5. LIDAR DERIVED AOD APPORTIONMENT

Lidar data can provide insight on the amount of pollution above and below the boundary layer, and can further aid in particulate matter estimates. In order to be able to estimate PM2.5 based on optical depth, it is important to understand the connection between AOD and particulate matter. An approach to the latter is currently being used in the Infusing satellite Data into Environmental Applications (IDEA) product for the north-east, where it is assumed that 1 AOD ~ 60 μgm-3 of PM2.5. This allows an evaluation of the impact of elevated aerosol optical depth on near surface by using the optical depth below the boundary layer as a precursor for PM2.5 concentration estimates. This can be done by examining how well the lidar AOD apportionment below the boundary layer and the total column AOD agrees with the PM2.5 surface measurements.

Figures 12 (a) and (c) shows lidar column integrated AOD (green) and AOD apportionment above the PBL (blue) for April 18 and 19. We can also see that lidar derived column optical depth is in good agreement with the sun-photometer AOD on both days. The trends seen in the aerosol loadings on April 18 and 19 are well in agreement with the features observed in the CCNY lidar images, aloft plumes with no surface interaction and plume interaction with the PBL respectively. The plume layers appear relatively stable on April 18, and remained lofted and entrained at high altitudes.

Figures 12 (b) and (d) show the fraction of the lidar total column AOD solely due to the plumes above the PBL. We can see that on April 18, the largest percentage of the total column AOD contribution are due to the lofted plumes above the boundary layer, with less than 20% due to PBL contributions. This is also in agreement with the lidar image, since there is no evidence of boundary layer interaction on this day. However, April 19 was quite the contrary. As the plume descended towards the surface, the PBL optical depth contribution increased from less than 5% between 3 and 3:30 PM to almost 40% by 5PM at the time of the plume incursion. The rise in PBL AOD is expected during episodes of boundary layer plume interactions.

Fig. 12: (a) Lidar column AOD (blue), Layer column AOD (red), and sun-photometer column AOD (black) April 18, 2006 (b) Lidar layer fractional AOD April 18, 2006; (c) Lidar column AOD (blue), Layer column AOD (red), and sun-photometer column AOD April 19, 2006; (d) Lidar layer fractional AOD April 19, 2006.
To estimate the contribution of aerosols to the boundary layer to a reasonable accuracy, we integrated (as a function of altitude) the lidar derived aerosol extinction at 532nm above the boundary layer and subtracted those retrievals from the sun-photometer column AOD at 500nm. We are able to a good approximation, estimate the PBL AOD contributions. The lidar retrieved AOD’s is consistent with that retrieved from the sun-photometer. In figure 13, the blue profile represents the sun-photometer aerosol optical depth, the green and the red profiles showing the plume column integrated and PBL AOD respectively. In figure 13, we can see that on April 19, the largest contribution of the total column aerosol loading was due to the lofted layers, but as the plumes descended and mixed with the boundary layer, the PBL equally contributed to the total column loadings.

We applied the IDEA PM2.5 estimator described earlier to the AOD loadings derived from the CCNY lidar below the PBL. Figure 14 shows the hourly PM2.5 concentrations (measured) and the lidar PM2.5 concentrations (estimated) below the boundary layer are in reasonably good agreement with the TEOM measurements for April19, indicating acceptable PM2.5 estimator performance. Therefore, assuming a linear relationship between aerosol optical depth and PM2.5 concentrations show that AOD’s can be used (to a reasonable approximation) as a good predictor of PM2.5. This can be said with reservations, because there are cases where there is no obvious relationship between AOD and PM2.5. This may have been the case for April 18 (not shown) where the PM2.5 measurements were high compared to the low PBL AOD’s, resulting in a corresponding low PM2.5 estimations. A possible reason may be due to the majority of the aerosols being lofted and does not influence the surface air.
6. CONCLUSIONS

We showed that, predicting air quality requires accurate satellite measurements of aerosols. However, column integrated optical depth is not sufficient to predict PM2.5, and is impractical to use in daily surface monitoring and forecasting. In particular, passive satellites cannot determine the vertical layering of aerosols and therefore the connection with air pollution is poor. Furthermore, the vertical structure of aerosols is very important in assessing transport events and how they interact with the PBL as demonstrated.

Analysis of lidar AOD illustrated good correlations with sun-photometer column integrated optical depth measurements. Multi-wavelength lidar can provide vertical information, and have demonstrated its usefulness in identifying large scale incursions of high altitude aerosol plumes into the Planetary Boundary Layer, and plume properties and classification through the optically derived angstrom coefficient.

Backward trajectory analysis indicated east Asian origins and estimates a travel time of 13 days, although the dust emissions at the source was intermittent. Also, combined with satellite measurements, the source of these plumes can be identified, where in our case the April 2006 dust episode was tracked back to the Deserts in East Asia. Lidar measurements also allow us the capability to apportion the PBL optical depth characteristics from the total column, which we found to be consistent with the column integrated sun-photometer AOD. It is only when the PBL is separated, do the PM2.5 measurements and predictions agree with aerosol optical depth.

We showed that surface monitors are limited spatially, and pollution layers and plumes can be transported aloft over long distances, undetected by surface monitors, and then advect downwards to influence the surface air. Therefore, satellite observations are useful to help address these limitations by fusing surface measurements with satellite measurements, and even by augmenting surface networks.

We have also shown how well near surface aerosol loadings correlate with PM2.5, which can be used as a proxy for PM2.5 predictions. The results presented in this paper show that a combination of data from lidar, satellite, and ground-based instruments looks promising and will soon be as reliably used as traditional weather forecasts.

ACKNOWLEDGMENTS

This work was partially supported under contracts from NOAA # NA17AE1625 and NASA # NCC-1-03009.

REFERENCES