https://doi.org/10.1016/j.atmosenv.2017.01.051

Continuous ground-based aerosol Lidar observation during seasonal pollution events at Wuxi, China

Man Sing Wong [a], Kai Qin [b,*], Hong Lian [a], James R. Campbell [c] , Kwon Ho Lee [d], Shijie Sheng [e]

[a] Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[b] School of Environment Science and Spatial Informatics, China University of Mining and Technology, Xuzhou, China

[c] US Naval Research Laboratory, U.S.

[d] Department of Atmospheric and Environmental Sciences, Gangneung-Wonju National University, Korea

[e] Wuxi CAS Photonics CO., Ltd, Wuxi, China

*corresponding author: Kai Qin, email: qinkai20071014@163.com

---

Abstract:

Haze pollution has long been a significant research topic and challenge in China, with adverse effects on air quality, agricultural production, as well as human health. In coupling with ground-based Lidar measurements, air quality observation, meteorological data, and backward trajectories model, two typical haze events at Wuxi, China are analyzed respectively, depicting summer and winter scenarios. Results indicate that the winter haze pollution is a compound pollution process mainly affected by calm winds that induce pollution accumulation near the surface. In the summer case, with the exception of influence from $PM_{2.5}$ concentrations, ozone is the main pollutant and regional transport is also a significant influencing factor. Both events are marked by enhanced $PM_{2.5}$ concentrations, driven by anthropogenic emissions of pollutants such as vehicle exhaust and factory fumes. Meteorological factors such as wind speed/direction and relative humidity are also contributed. These results indicate how the vertical profile offered by routine regional Lidar monitoring helps aid in understanding local variability and trends, which may be adapted for developing abatement strategies that improve air quality.

Key words: Aerosol; Backward trajectory; Ground-based Lidar; Haze.

1. Introduction

Atmospheric aerosols are an important part of the earth-atmosphere-maritime system. They affect the climate through three primary components: (i) direct scattering or absorption on short-wave and long-wave radiation, namely direct radiative forcing; (ii) varying aerosol concentrations change the characteristics of clouds: perturbed numbers of aerosol particles acting as cloud condensation nuclei influence the number of the cloud particles per unit volume, which can also impact effective cloud droplet radii, cloud shortwave reflectance, and cloud lifetime, known as indirect radiative forcing; (iii) aerosols can also change various atmospheric chemical processes, affect the concentration and distribution of greenhouse gases, and thus impact climate (Kaufman et al., 1997). Aerosol radiation forcing remains a key factor driving current uncertainties relating to manifestations of climate change (IPCC, 2013).

With the recent acceleration of industrialization and urbanization processes in China, rapid economic development and expansion has caused environmental problems to become more apparent. Continuous emissions of greenhouse gases enhance global warming through positive feedback, inducing long-term changes in each part of the climate system that will increase the possibility of serious, widespread and irreversible impact on human and ecological system (IPCC, 2014). The growth and relevance of satellite and ground-based remote sensing observations of regional and urban aerosols in the most susceptible regions of China has led to a rapid characterization of chemical and physical aerosol properties there (e.g., Zhang et al., 2015; Qin et al., 2016; Zhang et al., 2016), allowing for the research community to quickly devise strategies that help urban officials design strategies that mitigate hazardous conditions (Wong et al., 2015; Xiao et al., 2015).

Light Detection and Ranging (Lidar) is an effective and reliable method to monitor and profile geometric and optical properties of aerosols and clouds. Lidar instruments are predominantly used for profiling the structure of aerosol particles throughout the troposphere, either from ground (e.g., Livingston et al., 1999; Campbell et al., 2001) or satellite (Spinhirne et al., 2005; Winker et al., 2010). Commercial and prototype Lidars are currently deployed in global federated network for aerosol and cloud measurement activities such as the Micro Pulse Lidar Network (MPLNET) (Welton et al., 2001), the European Aerosol Research Lidar Network (EARLINET, Matthias et al., 2004; Pappalardo et al., 2014), and the Asian Dust Network (ADNET, Murayama et al., 2001). Coupled with the sun photometers operated by the AErosol RObotic NETwork (AERONET), synergistic observations based on ground-based profiling and column-integrated optical property measurements have provided the community with an example paradigm for how routine monitoring and long-term climatological evaluation of aerosol properties is possible. Further, these observations provide critical ground verification for aerosol satellite-observing missions (e.g., Fromm et al., 2015).

Significant progress in the theory and application of Lidar aerosol detection has occurred in China. The Institute of Atmospheric Physics of Chinese Academy of Sciences developed the first atmospheric aerosol detection Lidar system in the mid-1960s. The Institute further developed a Mie-scattering backscatter instrument and large multi-wavelength Lidar for measuring aerosol extinction and atmospheric slant visibility (Zhang, 2007). In 1995, Anhui Institute of Optics and Fine Mechanics (AIOFM) developed a portable dual-wavelength (532 nm and 1064 nm) Mie-scattering Lidar, L300, which was used in the observation with aerosol extinction coefficient, depolarization ratio of dust and clouds, and horizontal visibility (Zhou et al., 1998). The Ocean University of China completed the first non-coherent Doppler wind Lidar system in China, featuring the high spectral resolution Lidar technique (HRSL) (Liu et al., 1996, 1997, 1999; Zhang, 2007).

In addition, the China Meteorological Administration began building the Chinese Aerosol Observation Network (CAeroNet) in 2002, establishing twenty observing stations mainly in the dust source regions to the north and west near the primary deserts. Chemical and particle aerosol air monitoring data, including SO_2, NO_x, CO, PM_{10} concentrations, have been collected in China since 2000. Other air quality parameters, such as $PM_{2.5}$, have been monitored in China since approximately 2012. The Chinese government released data from 367 stations in 2015. CAeroNet also uses CIMEL sun photometers (Model CE318 - II) for atmospheric aerosol column-integrated monitoring (Yan et al., 2006). The Institute of Atmospheric Physics (IAP) at the Chinese Academy of Sciences (CAS) established the Chinese Sun Hazemeter Network (CSHNET) in August 2004 (Xin et al., 2007), based on the measurements of column-integrated aerosol optical thickness. These observations better describe the temporal and spatial distribution of atmospheric aerosol optical properties in China (Wang et al., 2007). However, due to the sparse geographical locations of these stations, as well as their ground-based observations, the vertical distribution, formation, sources and trends of aerosols are difficult to analyze.

This paper introduces continuous aerosol monitoring observations from Lidar at Wuxi, China (30°30'N, 120°21'E). Observations similar to that collected by MPLNET are made there with an autonomous Lidar-D-2000, developed by Wuxi CAS Photonics Co., Ltd. Observations began in 2012 and are collected in a relatively continuous manner. Here, we describe two case studies investigated using these data, combining measurement profiles of aerosol extinction estimated from the Lidar with backscatter depolarization measurements that help estimate those aerosol types present. These data are paired with a series of chemical and particle sampling measurements of surface-based aerosols as well as surface meteorology. We further analyze air mass backward trajectories so as to analyze the pollution trajectories and likely sources. Our goal is to conceptualize how Lidar measurements, and in particular continuous network-based Lidar profiling, can be adapted to in order to help better understand aerosol formation and transport mechanisms, as well as the physical and optical characteristics of regional aerosols, in China.

2. Data and Methods

2.1 Ground-based Lidar

The Lidar-D-2000 is a dual-wavelength three-channel Mie scattering Lidar. The Lidar operates at two wavelengths (355 nm and 532 nm), with backscatter measured in three channels: 355 nm total, 532 nm parallel-polarized and 532 nm orthogonal. Thus, the 532 nm channels are polarized so as to detect and profile the morphological characteristics of particulate matter (e.g., Sassen 1991; Song et al., 2012). The 355 nm channel, in contrast, is used for analysis of fine particulate matter and ratio measurements relative to the 532 nm channel that help resolve size characteristics. The detection range of Lidar-D-2000 can reach to 30 km, with a standard temporal resolution of one minute, and standard range resolution of 7.5 m.

The Lidar backscatter equation is written as

$$P_r(r) = P_0 k r^{-2} \beta_T(r) exp\left\{-2\int_0^{r'} \alpha_T(r')dr'\right\} \qquad (1)$$

Here, $P_r(r)$ is the atmospheric backscatter signal at height r, P_0 is the emitted Lidar energy, k is Lidar system constant, $\beta_T(r)$ is total atmospheric backscatter coefficient at 532 nm from both polarized channels, and $\alpha_T(r)$ is the range-integrated atmospheric extinction term. The ratio of $\alpha(r)$ and $\beta_T(r)$ is the so-called '*Lidar ratio*', or extinction-to-backscatter ratio, which represents a practical mean for converting measured backscatter to extinction, since the two unknown terms in (1) cannot be solved directly. The extinction coefficient is estimated using the 532 nm parallel channel (Dong et al., 2015). As Lidar-D-2000 is a Mie-backscatter Lidar, outputs for aerosol extinction here are unconstrained and thus estimates, meaning that we apply a static value of the extinction-to-backscatter ratio of 50 sr (assuming urban and mineral mixtures at 532 nm; e.g., Ackerman, 1998) to initiate the retrievals (e.g., Fernald, 1984). The data have not been cloud-cleared, with such elements referred to in the text to avoid confusion.

As a polarization Lidar, the Lidar-D-2000 receives two separate channels: the parallel (with respect to the emitted light) and the perpendicular light. The volume depolarization ratio is defined as the ratio of the total perpendicular to the total parallel-polarized backscatter coefficient at 532 nm channel. It should be noted that the calculations of depolarization ratio were based on relative measurements with assumption of single scattering condition, and no multiple scattering corrections have been applied to the data analyzed here.

In December 2013, Yun et al. (2015) used Lidar-D-2000 and an Air Quality Index (AQI) parameter to analyze the formation and characteristics of atmospheric pollutants at Wuxi, China. Wu et al. (2015) combined Lidar-D-2000 and meteorological data to analyze a dust transport event at Wuxi during 9-10 April 2014. Dong et al. (2015) used Lidar-D-2000 to analyze the vertical distribution of atmospheric particulate matter, correlating horizontal and vertical displacement in local winds with pollutant dispersion (Dong et al., 2015). Song et al. (2016) incorporated local convection, humidity and wind speed corrections on the MODerate resolution Imaging Spectroradiometer (MODIS) aerosol optical thickness (AOT) products, finding that there is good correlation between revised MODIS AOT data and Lidar-D-2000-based estimates.

2.2 Location and Observation Period

Lidar-D-2000 is deployed on the roof of the 11th floor, Block C, 200 Linghu

Road, Wuxi City, Jiangsu Province (31.5° N, 120.37° E), about 20 m above the ground with no surrounding residential and/or industrial impediments. Observation periods for the two pollution episodes described here are 3-6 December 2013 and 11-16 June 2014, respectively. The first event corresponded with a large anthropogenic pollution event that advected the East China region, including Wuxi. Air quality was severely degraded and polluted (Huang et al., 2016). The second event varied in terms of amount of processed pollution, ranging from good air quality to lightly- and then moderately-polluted.

Aerosol conditions during the December event were influenced by anthropogenic pollution, like vehicle emissions and industrial exhaust, with the primary contribution being observed at the surface as $PM_{2.5}$. Unlike winter, local air pollution during summer is mainly comprised of high O_3 concentrations from photochemical processing, that converting NOx and VOCs from vehicle emissions and industrial exhaust into O_3. (Geng et al., 2008; Geng et al., 2009). Accordingly, and after factoring in local synoptic meteorological conditions during each period, the summer event was a significant and prolonged pollution episode, compared with a relatively short period during winter corresponding with broad-scale subsidence between continental frontal boundaries. These two events are highly representative, however, providing a comprehensive overview of air pollution events at Wuxi and the value added to post-event studies by Lidar profiling.

2.3 HYSPLIT Trajectory Model

The U.S. National Oceanic and Atmospheric Administration (NOAA) HYSPLIT air mass trajectory model makes use of the four-dimensional data in meteorological fields to simulate the transport, diffusion, and deposition processes (Draxler & Rolph, 2003). HYSPLIT can be applied to simulate transmission paths of pollutants, and has been widely used in the research of atmospheric pollutant transport (e.g., Brankov et al., 1998; Klemn et al., 1998; Campbell et al., 2003; Kato et al., 2004; Kindap et al., 2006; Wong et al., 2013; Zhang et al., 2016). The model is applied similarly here, serving as context for understanding regional and potentially long-scale transport of aerosols to Wuxi from which to interpret surface and Lidar profile aerosol observations.

2.4 Air Quality Data and Meteorological Data in China

AQI as well as $PM_{2.5}$ and PM_{10}, from December 2013 to December 2014, provided by the China's Air Quality Online Monitoring Analysis Platform (http://www.aqistudy.cn/historydata/) were analyzed. AQI is a non-dimensional index to quantitatively describe the air quality status. The major pollutants in regional air quality assessment are fine particulate matter, respirable particulate matter (PM with particle sizes less than or equal to 10 microns diameter), sulfur dioxide, nitrogen dioxide, ozone and carbon monoxide. When AQI is 0-50, the air quality is considered excellent; AQI is 51-100, the air quality is considered good; AQI is 101-150, the air quality is considered lightly polluted; AQI is 151-200, the air quality is considered moderately polluted; AQI is 201-300, the air quality is considered heavily polluted; AQI is larger than 300, the air quality is severely polluted (Ministry of environmental protection of the people's Republic of China, 2012).

Corresponding meteorological data, including daily relative humidity and wind speed in hourly increments for December 2013 to December 2014, were measured and collected by the Wuxi Environmental Protection Station.

3. Case Studies

Figure 2 shows the temporal distribution of different air quality conditions in Wuxi city for December 2013 to December 2014. The average AQI during this period is 108, generally defined as lightly-polluted air quality. During 2014, there were 217 days with good and excellent air quality, or around 60 percent of the year. Polluted days mainly occurred during winter and early summer. Pollution was most serious from 16 to 20 January 2014, with an average AQI near 138. There were six months (January, May, June, July, November and December) in 2014 that were defined as lightly polluted, with other months generally defined as good. The winter of 2013-2014 experienced the most serious air pollution conditions compared with other seasons in 2014. The two cases studies below represent, as defined above, typical heavily-polluted events with extreme AQI.

Figure 3 shows the annual, June and December monthly-averaged climatological profile values for 532 nm aerosol extinction coefficient (km^{-1}) and volume depolarization ratio derived at 5° x 5° resolution centered at 22.5 °N and 122.5 °E from 2006 to 2015 Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) satellite based observations. The methods used to solve these profiles from available Level 2 Aerosol Profile products are described in Campbell et al. (2012). These profiles are shown as context for the events derived from Lidar-D-2000 measurements shown in each of the case studies below.

3.1 3rd – 6th December 2013

The first case study occurred during winter, featuring the high daily air quality indices. No rainfall occurred during the episode, meaning little in the way of synoptic/mesoscale mixing and/or particle fallout driven through precipitation and washout. Figure 4(a) shows the temporal variation of ground-based AQI during the event. Air quality was heavily or severely-polluted through the entire period. Shown in Figure 5 are Lidar-D-2000 profiles of 532 nm aerosol extinction coefficient estimates and volume depolarization ratio. Much of the aerosol structure is confined near the surface, suggesting little in the way of external pollutant transport during the episode. Therefore, we characterize this event as representing local pollution.

On 3rd December, near-surface extinction was approaching climatology while depolarization was relatively high, indicating the likely dominance of relative non-spherical particles. Wind speeds were low, resulting in a likely low dispersion rate. Relative humidity was general relatively low through the period, excepting for an obvious increase in the morning of 5th of December. The densest pollution occurred on both the 4th and 5th/6th, with extinction values near the surface approaching 1.0

km^{-1}, which was well above the CALIOP climatological values. From Figure 3, increases and/or decreases of NO_2 exhibit a similar pattern as $PM_{2.5}$ and PM_{10}, indicating contaminating gases likely undergoing conversion to pollutant particles.

Throughout the episode, NO_2, $PM_{2.5}$ and PM_{10} exceeded urban air quality standards of China Technical Regulation on Ambient AQI. $PM_{2.5}/PM_{10}$ was about 0.8 during this period. $PM_{2.5}$, PM_{10}, and NO_2 began increasing in correlation with aerosol extinction late on 4th December. Relative humidity (Figure 4 (d)) increased overnight with radiational cooling, while $PM_{2.5}$, PM_{10}, and NO_2 all decreased but still remained at high concentrations (Figure 4 (b) and (c)). In the morning of 5th December, the extinction coefficient maintains certainly high, though $PM_{2.5}$ and PM_{10} decreased lightly. This portion of the period corresponded with higher relative humidity, greater than 80%. It is known that both high aerosols and relative humidity can increase extinction coefficient. Zhang et al. (2015) found that the visibility was exponentially decreased with the increase of $PM_{2.5}$ concentrations when RH was less than 80%. However, when RH was higher than 80%, the relationship was no longer following the exponentially decreasing trend, and the visibility maintained in very low values, even with low $PM_{2.5}$ concentrations. Hence, hygroscopic growth was expected to increase extinction coefficient. On the other hand, with low and moderate wind speeds, the air mass was relatively stagnant with little means for dispersion. By the time of the second pulse occurring on 5th and 6th December, depolarization dropped significantly, indicating a shift to mostly spherical particles, in spite of relatively stable $PM_{2.5}$, PM_{10} and chemical concentrations. The Lidar depicts the clear shift in the aerosol physics near the surface that the samplers could not.

The depolarization ratio was high (0.3) near 2.0 km altitude as 6th December began, with corresponding extinction depicting a sustained layer there on both 5th and 6th December. Using HYSPLIT, we calculated a 72-hr back trajectory ending near the site at 1.0, 1.5 and 2.0 km, with the results shown in Figure 6. The trajectories show that the air mass origins were mostly similar among all levels, with the air advecting from northwest to southeast.

3.2 11th – 16th June 2014

A second event occurred in summer, between 11th and 16th June 2014. Conditions were generally stable over the six days, though rain fell around midnight on the 16th and then again later during the day. Figure 7 (a) displays AQI for the period, which indicates that relatively high pollution loading was observed occurred from the 12th through 15th. Good-to-heavy pollution was characterized between the 13th and 15th in surface measurements. Yet, $PM_{2.5}$ and PM_{10} concentrations (Figure 7 (c)) were lower than the previous event.

Figure 7 (b) shows the hourly variation of NO_2 and O_3, showing an anti-correlation: as NO_2 decreased, O_3 increased, and these variations mainly occurred around afternoon and evening with increased photochemical production of O_3 from NO_2. NO_2 is mainly produced by automobile exhaust on sunny summer afternoons and early evenings through photochemical reaction, which can further be converted into O_3 (Schauer et al., 1996; Saito, Nagao, & Tanaka, 2002).

Wind speeds in the morning and night were low during the event (Figure 7 (d)), but relatively high during midday before the 15th. On the 11th and 12th, average wind speeds were relatively high (>2 m/s), which is favorable for the horizontal diffusion of pollutants. On the morning of 14th June, wind speeds were less than 1.5 m/s, presumably enhancing the accumulation of $PM_{2.5}$ and PM_{10} that increased to about 150 μg/m^3 and 250 μg/m^3. This easily exceeded the respective national air quality standards of 75 μg/m^3 and 150 μg/m^3 (Ministry of Environmental Protection of the People's Republic of China, 2012). Meanwhile, the depolarization ratio increased (nearly 0.3) on 14th June, indicating near-surface dust driving local pollution. Relative humidity was relatively low on 14th June, especially near noon (40%). Rain occurring on 16th June would wash the scene out.

The 532 nm extinction began increasing from the beginning of the event (Figure 8), with values well over background climatology near 0.5 km^{-1} in two distinct peaks approaching the surface on the 12th and 13th, subsiding thereafter as rainfall commenced on 16th June. This variability was consistent with ozone tendencies, which were consistent, though in a broader sense considering the noise, with AQI. Corresponding 532 nm extinction generally followed the same trend. Depolarization near the surface throughout the event was relatively low, near and slightly below background climatological values, again consistent with relatively small particles and low complexity. Some elevated structure in aerosol transport is evident in Figure 8, particularly on the 11th and 12th, which corresponded with the lesser AQI values observed during the event. The concentration of O_3 exceeded the standard during this period of time (200 μg/m^3 per hour), likely due to photochemical reactions that contributed main component of the pollution.

Air mass back trajectories (Figure 9) indicate northerly transport, including transects over East China Sea. Its plausible that the air mass was maritime in nature, given the relatively low depolarization values, though the primary transport routes include the major urban anthropogenic sources along the eastern China coastline. Here again, the Lidar data provide unique context relative to the surface observations in distinguishing the potential mixture of pollutant aerosols regionally. The depth of the haze, approaching 2.0 km and the top of the planetary boundary layer on the 13th June, enhances what were potentially hazardous conditions to aviation interests, in addition to surface exposure.

4. Discussion

Wuxi is located in the Yangtze River Delta region in the eastern China, which is deemed as one of the seriously polluted regions in China. Different from dust outbreaks that are more frequent in northern China, pollution in this region is primarily caused by anthropogenic emissions associated with the dense cities. Urban industrial emissions and automobile exhaust are primary contributes, while the dense urban agglomeration ensures that the pollution cannot easily be diffused.

The two cases in this paper exhibit obvious seasonal characteristics. In winter, depolarization ratio is high from the near-surface to near 1.5 km, which indicates a higher proportion of non-spherical particles that are primarily dust particles.

Meanwhile, wind speeds are low in winter, making it difficult to diffuse local pollutants and recycle the air mass. This results in accumulation and the outbreak of severe pollution events. The prevalence of northwest winds in winter advect dust, which aggravates the pollution. Thus, pollution observed at Wuxi during this season with a combination of local pollution and external dust input, and the Lidar profile aids significantly in providing such thorough characterization.

The extinction coefficient estimated during the summer case was high from near the surface through and elevated altitude (2 km), with corresponding low depolarization. Summer pollution is mainly the result of by photochemical reactions, primarily that converting NO_2 into O_3 that is driven by vehicle exhaust. Increasing surface $PM_{2.5}$ and depolarization ratio in 14th June indicated the introduction of dust into the event, again highlighting the role of the Lidar in depicting the elevated nature of the complicating agent. The complex mixture inherent during this event necessitates a broad observing structure be in place to help with characterization, and eventually with urban planning and hazard mitigating strategies.

5. Conclusions

Using 532 nm extinction coefficient and depolarization ratio measurements from a continuously-running ground-based commercial Lidar, integrated with ground-based air quality monitoring and surface meteorological data, two typical pollution events are characterized at Wuxi, China from 2013 and 2014. Climatological context from the CALIOP satellite-based Lidar instrument are shown from which to consider the evolving Lidar measurement profiles over each event: one during winter, and another during summer. The causes of these episodes are seasonally-based, wherein the winter haze event conceptualizes typical compound pollution events driven by broad-scale subsidence and relative stability that enhances pollutant accumulation and chemical processing near the surface. During summer, pollutant contributors to a regional haze are $PM_{2.5}$ and ozone. Air mass backward trajectories help in this analysis, depicting favorable transport routes corresponding with each event. The result is an abstract depiction of the value of continuous Lidar monitoring in reconciling the unique surface and shallow-layer aerosol conditions endemic to East Asia and the China coastlines.

The observation capabilities and relevance of atmospheric Lidar monitoring, are optimized with synergistic surface air quality and meteorological data. Together, they help analyze the entire pollution process systematically and comprehensively. In unique regions like East Asia, it is necessary to consider many potential mechanisms for urban pollution, combining the potential transport of myriad regional sources with enhanced photolytic chemistry near large anthropogenic centers. Combining these data leads to a more thorough monitoring capability for air quality, which can find a role in preventing air pollutants or at least better advisories for public hazard. Unlike dust transport in the northern China, pollution in the south and east is mainly contaminated by anthropogenic photochemical enhancement. Whereas the region and its scientists have a valuable history in the development of practical Lidar monitoring, there exists little infrastructure or commitment to continuous long-term observation and data dissemination on a scale consistent with projects like the NASA Micro-Pulse Lidar Network.

Aerosol extinction coefficient and depolarization ratio can determine the severity of contamination, the evolution of the profile structure through the free troposphere, and whether or not the particles are non-spherical or spherical. Combined with $PM_{2.5}$ and PM_{10} concentrations, the composition of pollution particulate matter can be further analyzed. Further application of NO_2, SO_2, O_3 and other polluting gases data, and their role in secondary particle formation and haze activation, can help accurately determine the sources and causes of pollution. With the grown ease and practicality in Lidar development and deployment for long-term air quality management, the gains in hazard monitoring for urban planning and mitigation can be significant. In regions with persistent air quality degradation, Lidars can provide a highly synergistic measurement that compliments such strategies.

Acknowledgments

This research was supported in part by the grant of General Research Fund (project id: 15205515) from the Research Grants Council of Hong Kong; the grant PolyU 1-ZVAJ from the Faculty of Construction and Environment, the Hong Kong Polytechnic University; the grants PolyU 1-ZVBP, PolyU 1-ZVBR from the Research Institute for Sustainable Urban Development, the Hong Kong Polytechnic University; and National Natural Science Foundation of China (41401495). We thank for the Wuxi CAS Photonics CO., Ltd for the Lidar data and ground-based meteorological data in

Wuxi, the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model, and China's Air Quality On-line Monitoring Analysis Platform (http://www.aqistudy.cn/historydata/) for the ground-based air quality data in China.

References

Ackermann, J. (1998). The extinction-to-backscatter ratio of tropospheric aerosol: a numerical study. *Journal of Atmospheric and Oceanic Technology*, *15*, 1043-1050.

Brankov, E., Rao, S. T., & Porter, P. S. (1998). A trajectory-clustering-correlation methodology for examining the long-range transport of air pollutants. *Atmospheric Environment*, *32*(9), 1525-1534.

Campbell, J. R., Hlavka, D. L., Welton, E. J., Flynn, C. J., Turner, D. D., Spinhirne, J. D., Scott, V. S., and Hwang I. H. (2002). Full-time, eye-safe cloud and aerosol Lidar observation at Atmospheric Radiation Measurement program sites: instruments and data analysis, *Journal of Atmospheric and Oceanic Technology* 19, 431-442.

Campbell, J. R., Welton, E. J., Spinhirne, J. D., Ji, Q., Tsay, S. -C., Piketh, S. J., Barenbrug, M., and Holben, B. N. (2003). Micropulse Lidar observations of tropospheric aerosols over northeastern South Africa during the ARREX and SAFARI-2000 Dry Season experiments, *Journal of Geophysical Research: Atmospheres*, 108(D13), 8497, doi:10.1029/2002JD002563.

Campbell, J. R., Tackett, J. L., Reid, J. S., Zhang, J., Curtis, C. A., Hyer, E. J., Sessions, W. R., Westphal, D. L., Prospero, J. M., Welton, E. J., Omar, A. H., Vaughan, M. A., and Winker, D. M. (2012). Evaluating nighttime CALIOP 0.532 μm aerosol optical depth and extinction coefficient retrievals, *Atmospheric Measurement Techniques*, 5, 2143-2160, doi:10.5194/amtd-5-2143-2012.

Collis, R. T., Ligda, M. G. (1964). Laser radar echoes from the clear atmosphere. *Nature*, 203(4944), 508-508.

Dong, M., Wang, J., Zhao, D., Chen, C. (2015). The Study of Vertical Distribution of Particulate Matter in summer, Wuxi City. *Journal of Nanjing University (Natural Sciences), 51*(3), 490-498.

Draxler, R. R., & Rolph, G. D. (2003). HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model access via NOAA ARL READY website (http://www. arl. noaa. gov/ready/hysplit4. html). NOAA Air Resources Laboratory, Silver Spring.

Fernald, F.G. (1984). Analysis of atmospheric Lidar observations: Some comments. *Applied Optics*, 23, 652–653.

Fromm, M., Kablick III, G., Nedoluha, G., Carboni, E., Grainger, R., Campbell, J., and Lewis J. (2014). Correcting the record of volcanic stratospheric aerosol impact: Nabro and Sarychev Peak, *Journal of Geophysical Research: Atmospheres*, *119*, doi:10.1002/2014JD021507.

Geng, F., Tie, X., Xu, J., Zhou, G., Peng, L., Gao, W., ... & Zhao, C. (2008). Characterizations of ozone, NOx, and VOCs measured in Shanghai, China.

Atmospheric Environment, 42(29), 6873-6883.

Geng, F., Zhang, Q., Tie, X., Huang, M., Ma, X., Deng, Z., ... & Zhao, C. (2009). Aircraft measurements of O 3, NOx, CO, VOCs, and SO 2 in the Yangtze River Delta region. *Atmospheric Environment, 43*(3), 584-593.

Goldsmith, J. E. M., Blair, F. H., Bisson, S. E., and Turner D. D. (1998). Turn-Key Raman Lidar for profiling atmospheric water vapor, clouds, and aerosols, *Applied Optics*, 37, 4979–4990.

Huang, F., Chen, R., Shen, Y., Kan, H., & Kuang, X. (2016). The Impact of the 2013 Eastern China Smog on Outpatient Visits for Coronary Heart Disease in Shanghai, China. *International Journal of Environmental Research and Public Health*, *13*(7), 627.

Kato, S., Kajii, Y., Itokazu, R., Hirokawa, J., Koda, S., & Kinjo, Y. (2004). Transport of atmospheric carbon monoxide, ozone, and hydrocarbons from Chinese coast to Okinawa island in the Western Pacific during winter, *Atmospheric Environment*, *38*(19), 2975-2981.

Kaufman, Y. J., Tanré, D., Remer, L. A., Vermote, E. F., Chu, A., & Holben, B. N. (1997). Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer. *Journal of Geophysical Research: Atmospheres*, 102(D14), 17051-17067.

Kindap, T., Unal, A., Chen, S. H., Hu, Y., Odman, M. T., & Karaca, M. (2006). Long-range aerosol transport from Europe to Istanbul, Turkey. *Atmospheric Environment*, *40*(19), 3536-3547.

Klemm, O., Ziomas, I. C., Balis, D., Suppan, P., Slemr, J., Romero, R., & Vyras, L. G. (1998). A summer air-pollution study in Athens, Greece. *Atmospheric Environment*, *32*(12), 2071-2087.

Ligda, M. (1963). Meteorological observations with a pulsed laser radar. In *Proceedings 1st Conference on Laser Technology*, San Diego, United State, pp. 63-72.

Liu, Z., Chen, W. B., Hair, J. W., & She, C. Y. (1996). Proposed ground-based incoherent Doppler Lidar with iodine filter discriminator for atmospheric wind profiling. In *SPIE's 1996 International Symposium on Optical Science, Engineering, and Instrumentation* (pp. 128-135). International Society for Optics and Photonics.

Liu, Z. S., Chen, W. B., Zhang, T. L., Hair, J. W., & She, C. Y. (1997). An incoherent Doppler Lidar for ground-based atmospheric wind profiling. *Applied Physics B: Lasers and Optics*, *64*(5), 561-566.

Liu, Z., Matsui, I., & Sugimoto, N. (1999). High-spectral-resolution Lidar using an iodine absorption filter for atmospheric measurements. *Optical Engineering*, *38*(10), 1661-1670.

Liu, J., Hua, D. X., & Li, Y. (2007). Ultraviolet Lidar for profiling of the urban atmospheric aerosol in spatial and temporal at Xi'an. *Acta Photonica Sinica*, *36*(8), 1534-1537.

Liu, J., Hua, D. X., Li, Y., & Xu, L. M. (2007). Design of a compact Mie Lidar system. *Journal of Xi'an University of Technology*, *23*(1), 1-5.

Matthias, V., Balis, D., Bösenberg, J., Eixmann, R., Iarlori, M., Komguem, L., Mattis, I., Papayannis, A., Pappalardo, G., Perrone, M. R., & Wang, X. (2004). Vertical aerosol distribution over Europe: statistical analysis of Raman lidar data from 10 European Aerosol Research Lidar Network (EARLINET) stations, *Journal of Geophysical Research*, 109, D18201.

Ministry of environmental protection of the people's Republic of China, (2012). Technical Regulation on Ambient Air Quality Index (on trial). Ministry of environmental protection of the people's Republic of China, p.3.

Murayama, T., Sugimoto, N., Matsui, I., Liu, Z., Sakai, T., Shibata, T., Iwsasaka, Y., Won, J.-G., Yoon, S.-C., Li, T., Zhou, J., & Hu, H. (2001). Lidar Network Observation of Asian Dust, in: Advances in Laser Remote sensing, Selected papers 20th Int. Laser Radar Conference (ILRC), Vichy, France, 10–14 July 2000, edited by: Dabas, A., Loth, C., and Pelon, J., Vichy, France, 169–177.

Pappalardo, G., Amodeo, A., Apituley, A., Comeron, A., Freudenthaler, V., Linné, H., Ansmann, A., Bösenberg, J., D'Amico, G., Mattis, I., Mona, L., Wandinger, U., Amiridis, V., Alados-Arboledas, L., Nicolae, D., & Wiegner, M. (2014). EARLINET: towards an advanced sustainable European aerosol lidar network, *Atmospheric Measurement Techniques*, 7, 2389-2409.

Qin K., Wu L. X., Wong M. S., Letu H., Hu M. Y., Lang H. M., Sheng S. J., Teng J. Y., Xiao X., Yuan L. M. (2016), Trans-boundary aerosol transport during a haze episode in China in January 2015 observed by ground-based Lidar and CALIPSO satellite, *Atmospheric Environment*, 141, 20-29.

Saito, S., Nagao, I., & Tanaka, H. (2002). Relationship of NOx and NMHC to photochemical O_3 production in a coastal and metropolitan areas of Japan. *Atmospheric Environment, 36*(8), 1277-1286.

Sassen, K. (1991). The polarization Lidar technique for cloud research: a review and current assessment, *Bulletin of the American Meteorological Society*, 72, 1848–1866.

Schauer, J. J., Rogge, W. F., Hildemann, L. M., Mazurek, M. A., Cass, G. R., & Simoneit, B. R. (1996). Source apportionment of airborne particulate matter using organic compounds as tracers. *Atmospheric Environment,30*(22), 3837-3855.

Song, Y. H., Hua, D. X., Li, S. C., Wang, Y. F., Di, H. G., & Qiang, L. H. (2012). Detection of Bottom Aerosol in Urban Area using Micro-pulse Polarization Lidar. *Acta Photonica Sinica, 41*(10), 1140-1144.

Song, T., Liu, J. Z., Hu, T. T., et al, (2016). Application of Atmospheric Particles Monitoring based on MODIS Aerosol Optical Thickness Products and Lidar. *Remote Sensing Technology and Application. 31*(2), 397-404

Spinhirne, J. D. (1993). Micro pulse Lidar. *IEEE Transactions on Geoscience and Remote Sensing*, *31*(1), 48-55.

Spinhirne, J. D., Palm, S. P., Hart, W. D., Hlavka, D. L., and Welton E. J. (2005). Cloud and aerosol measurements from GLAS: overview and initial results, *Geophysical Research Letter*, *32*, L22S03, doi:10.1029/2005GL023507.

Wang, L. L., Xin, J. Y., Wang, Y. S., Li, Z. Q., Wang, P. C., Liu, G. R., & Wen, T. X.

(2007). CSHNET Assess the Applicability of MODIS Aerosol Products in China. *Chinese Science Bulletin, 52*(4), pp.477-486

Winker, D.M., Pelon, J., Coakley Jr., J. A., Ackerman, S. A., Charlson, R. J., Colarco, P. R., Flamant, P., Fu, Q., Hoff, R., Kittaka, C., Kubar, T. L., LeTreut, H., McCormick, M. P., Megie, G., Poole, L., Powell, K., Trepte, C., Vaughan, M. A., and Wielicki, B. A. (2010). The CALIPSO mission: a global 3D view of aerosols and clouds, *Bulletin of the American Meteorological Society*, 91, 1211–1229.

Wong M. S., Nichol J. E. and Lee K. H. (2013), Estimation of aerosol sources and aerosol transport pathways using AERONET clustering and backward trajectories, a case study of Hong Kong, *International Journal of Remote Sensing*, 34(3), 938-955.

Wong M. S., Xiao F., Nichol J. E., Fung J., Kim J., Campbell J., Chan P. W. (2015), A Multi-Scale Hybrid Neural Network Retrieval Model for Dust Storm Detection, a study in Asia, *Atmospheric Research*, 158-159, 89-106.

Wu, D. X., Zhang, T. S., Wan, X. P., & Sun, X. H., (2015). Monitoring and Analysis of Spring Dust Importing Using Lidar in Wuxi. *Environmental Science & Technology 38*(6), 303-306.

Xiao F., Wong M. S., Lee K. H., Campbell J. R., Shea Y. K. (2015), Retrieval of dust storm aerosols using an integrated Neural Network model, *Computer and Geoscience*, doi:10.1016/j.cageo.2015.02.016.

Xin, J. Y., Wang, Y. S., Li, Z. Q., Wang, P. C., Hao, W. M., Nordgren, B. L., Wang, S. G., Liu, G. R., Wang, L. L., Wen, T. X., Sun, Y., Hu, B. (2007). Aerosol optical depth (AOD) and Ångström exponent of aerosols observed by the Chinese Sun Hazemeter Network from August 2004 to September 2005. *Journal of Geophysical Research: Atmospheres, 112*(D5).

Yan, H., Jiao, M.Y., Bi B.G., & Liu, G.Q. (2006). Advances in Aerosol Observation Network and Corresponding Science Plan. *Scientia Meteorologica Sinica, 26*(1), 110-117.

Yun, L. L., Zhang. T. S., Lu, F., Wu, D. X., Sheng, S. J., Lu, Y. H., & Liu, J.G., (2015). Analysis of Air Pollutants during Process of a Haze in Wuxi City. *Journal of Atmospheric and Environmental Optics, 10*(1), 22-30.

Zhang, B. (2007). Study of atmosphere extinction properties over Qingdao with ground-based and space borne Lidar (Master thesis, Ocean University of China, 2007). *China Knowledge Resource Integrated Database.*

Zhang, Y. C., Li, D., Chen, B. L., Chen, S. Y., Chen, H., & Guo, P. (2013). Research of Atmospheric Aerosol Properties over Beijing Region Based on Rotational Raman-Mie Lidar and CALIPSO. *Transactions of Beijing Institute of Technology, 33*(5), 634-637+643.

Zhao, Y. M., Pan, C., Wang, L. D., Zhang, Y. S. (2015). Aerosol Monitoring by Lidar at Wang Du, Hubei. *Journal of Telemetry, Tracking and Command, 36*(4), 64-70.

Zhang, Z. Y., Wong, M. S., Lee, K. H. (2015). Estimation of potential source regions of PM2.5 in Beijing using backward trajectories, *Atmospheric Pollution Research*, 6, 173-177. doi: 10.5094/APR.2015.020.

Zhang Z. Y., Wong M. S., Nichol J. E. (2016), Global trends of aerosol optical thickness using ensemble empirical mode decomposition method, *International Journal of Climatology*, doi: 0.1002/joc.4637.

Zhou J., Y. Guming, Q. Fudi, J. Chuanjia, W. Yongha, X. Liming, and H. Huanling (1998).Optical Properties of Aerosol Derived from Lidar Measurements. C*hinese Journal of Quantum Electronics*, *15*(2), 140-148.