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Editorial

Understanding the Roles of Aerosols and Clouds in Environment, Meteorology and Climate with Advanced Lidar Remote Sensing Techniques

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Abstract: This Special Issue lists nine publications, covering the topics of advanced atmospheric lidar techniques, lidar retrievals, and lidar applications. The investigations listed here are diverse, but they are all focused on atmospheric lidars. Some urgent issues, for instance low blind zone detection and polarization detection at a near-infrared wavelength band, were discussed and explored. The results are helpful for extending atmospheric lidar applications. In terms of lidar retrievals, a planetary boundary layer height retrieval and an automatic lidar retrieval for aerosol optical properties were investigated in some of the publications, which can strengthen the atmospheric lidar capabilities. For lidar applications, a detailed analysis of the evolution of stratospheric aerosol and dust–cloud interactions was presented. In this Editorial, the articles published within this Special Issue are reviewed to highlight their innovative contributions and main research findings.

Keywords: atmospheric lidar; blind zone; dust; Doppler lidar; lidar retrieval; planetary boundary layer

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1. Introduction

Aerosols are tiny particles and droplets that float in the air. Aerosols with diameters less than 2.5 µm can be harmful to human health, making them one of the primary pollutants in assessing air quality [1]. In addition, some particles can serve as agents triggering the formation of cloud droplets, ice crystals, and precipitation, known as “aerosol–cloud interactions” [2]. By doing so, aerosols can impose strong impacts on the Earth’s radiation balance through direct and in-direct effects, which ultimately affect the global climate [3]. All these effects make aerosols one of the most complex and fascinating components in atmospheric research. Understanding the roles of aerosols and clouds in the Earth system is of vital importance for improving air quality, numerical weather forecast, and future climate change projections.

Atmospheric lidar is an important active remote sensing instrument for monitoring the distribution of aerosols and clouds with a very high spatiotemporal resolution. Along with the development of laser technology, optical mechanics, and detectors, the capabilities of atmospheric lidars have been improved substantially over the past decade [4–6]. These improvements have also triggered research into lidar retrievals and the exploration of lidar applications in different fields in return. What are the latest developments in atmospheric lidars and how can they be applied to improve our understanding of aerosols and clouds in the Earth system? In this Special Issue, titled “Understanding the Roles of Aerosols and Clouds in Environment, Meteorology and Climate with Advanced Lidar Remote Sensing Techniques”, we attempt to fill the existing knowledge gaps by answering these two questions. In this Special Issue, nine original articles are included that showcase the latest developments in atmospheric lidars to promote our understanding of the effects of aerosols and clouds on climate, meteorology, and environment.

2. Overview of the Studies

This Special Issue consists of nine articles that showcase the latest research in atmospheric lidar technology, lidar retrievals, and lidar applications in atmospheric research. The authors and titles are listed below:

1. Voudouri, K.A.; Michailidis, K.; Koukouli, M.-E.; Rémy, S.; Inness, A.; Taha, G.; Peletidou, G.; Siomos, N.; Balis, D.; Parrington, M. Investigating a Persistent Stratospheric Aerosol Layer Observed over Southern Europe during 2019. Remote Sens. 2023, 15, 5394. https://doi.org/10.3390/rs15225394.
2. Yu, R.; Wang, Q.; Dai, G.; Chen, X.; Ren, C.; Liu, J.; Li, D.; Wang, X.; Cao, H.; Qin, S.; et al. The Design and Performance Evaluation of a 1550 nm All-Fiber Dual-Polarization Coherent Doppler Lidar for Atmospheric Aerosol Measurements. Remote Sens. 2023, 15, 5336. https://doi.org/10.3390/rs15225336.
3. Gao, L.; Chen, H.; Chen, G.; Deng, J. Particle Size Distributions and Extinction Coefficients of Aerosol Particles in Land Battlefield Environments. Remote Sens. 2023, 15, 5038. https://doi.org/10.3390/rs15205038.
4. Zhang, S.; Huang, Z.; Alam, K.; Li, M.; Dong, Q.; Wang, Y.; Shen, X.; Bi, J.; Zhang, J.; Li, W.; et al. Derived Profiles of CCN and INP Number Concentrations in the Taklimakan Desert via Combined Polarization Lidar, Sun-Photometer, and Radiosonde Observations. Remote Sens. 2023, 15, 1216. https://doi.org/10.3390/rs15051216.
5. Mao, S.; Yin, Z.; Wang, L.; Wei, Y.; Bu, Z.; Chen, Y.; Dai, Y.; Müller, D.; Wang, X. Aerosol Optical Properties Retrieved by Polarization Raman Lidar: Methodology and Strategy of a Quality-Assurance Tool. Remote Sens. 2024, 16, 207. https://doi.org/10.3390/rs16010207.
6. Xie, H.; Wang, Z.; Luo, T.; Yang, K.; Zhang, D.; Zhou, T.; Yang, X.; Liu, X.; Fu, Q. Seasonal Variation of Dust Aerosol Vertical Distribution in Arctic Based on Polarized Micropulse Lidar Measurement. Remote Sens. 2022, 14, 5581. https://doi.org/10.3390/rs14215581.
7. Wang, L.; Yin, Z.; Zhao, B.; Mao, S.; Zhang, Q.; Yi, Y.; Wang, X. Performance of Wide Dynamic Photomultiplier Applied in a Low Blind Zone Lidar. Remote Sens. 2023, 15, 4404. https://doi.org/10.3390/rs15184404.
8. Liu, J.; Li, M.; Zhou, L.; Ge, J.; Liu, J.; Guo, Z.; Liu, Y.; Wang, J.; Yan, Q.; Hua, D. Analysis of Aerosol Optical Depth and Forward Scattering in an Ultraviolet Band Based on Sky Radiometer Measurements. Remote Sens. 2023, 15, 4342. https://doi.org/10.3390/rs15174342.
9. Xian, J.; Zhang, N.; Lu, C.; Yang, H.; Qiu, Z. Novel Method for Determining the Height of the Stable Boundary Layer under Low-Level Jet by Judging the Shape of the Wind Velocity Variance Profile. Remote Sens. 2023, 15, 3638. https://doi.org/10.3390/rs15143638.

The innovative technical breakthrough and novel findings of each article are highlighted below:

Volcanic aerosols are harmful for aviation safety and can be important drivers of global radiative forcing and ozone depletion. Atmospheric lidar techniques are the only things that can monitor the vertical distributions of volcanic aerosols in the stratosphere with very high spatial and temporal resolution. Voudouri et al. present the temporal evolution, geometrical boundary layers, and AODs at 532 and 1064 nm of the stratospheric aerosol layer over Southern Europe based on ground-based Raman lidar and spaceborne observations, which was traced to be a mixture of volcanic aerosols emitted by the Raikoke volcanic eruption from the Kuris Islands in June 2019 and biomass burning aerosols over northern latitudes. After taking polarization measurements from spaceborne lidar, the morphological properties of the stratospheric volcanic aerosols were analyzed. A small particle depolarization ratio at 532 nm of 0.03 ± 0.04 indicates spherical aerosols such as sulfate aerosols. This study shows the benefits of conducting a combination analysis of ground-based, space-borne, and modeling results to aid out understanding of the impacts of stratospheric aerosols on the Earth system.

Polarization observations of atmospheric aerosols are beneficial to differentiate the particle types and phases of hydrometeors. Such a capability has been standardized for direct detection lidar over the past two decades; however, for coherent detection lidar, the polarization detection capability is still under technical development. Yu et al. present the design of a dual-polarization coherent Doppler lidar (DPCDL) with a paraxial telescope. Details of the transmitting and receiving modules were described. A calibration procedure was introduced to ensure high-quality polarization measurements. The overall performance of the DPCDL was evaluated by Allan deviation analysis, and comparisons were made with a polarization micro-pulsed lidar system. These results are meaningful for extending the capabilities of traditional coherent Doppler lidar.

Particle size distribution (PSD) is a key property in assessing the intensity of laser beam attenuation at different wavelength bands. The attenuation caused by fog, smoke screens, dust, and other aerosol particles determines the available detection range of lidars. However, very limited studies are available for the variation of aerosol particle attenuation at different laser wavelengths, in particular ground dust, soil explosion dust, as well as smoke screens, in a land battlefield. Gao et al. present a method to make measurements of the PSDs of different particles using laser diffraction and fit the measured PSD functions by their experiments, where they analyzed the applications and relationships of six common unimodal PSD functions. The fitting goodness of the six functions was assessed, and the spectral-dependent attenuation produced by ground and soil explosion dust particles was analyzed. This study provides a baseline for understanding and improving the detection performances of lidars in land battlefield environments.

Applications of atmospheric lidar on meteorological and climatic studies depend on the lidar retrievals of an ice-nucleating particle (INP) and cloud condensation nuclei (CCN), which is a central player in aerosol–cloud interactions. Zhang et al. show an excellent example of how polarization Raman lidar can be used for such studies. In their work, POLIPHON retrieval to derive CCN and INP concentrations was described with updated conversion factors of dust particles, which were calculated with the assistance of the GRASP algorithm. The vertical profiles of the CCN and INP number concentrations were analyzed to reveal the potential effects of East Asian dust on the cloud formation at Tazhong, close to the Taklimakan Desert. These results provide good references to investigate dust–precipitation–climate feedback and to demonstrate the capabilities of the Silk Belt Road Lidar Network on the research of regional and global climate change.

The atmospheric lidar data quality assessment and quality control (QA/QC) are vital for data application from single or multiple lidar networks. However, due to the complexity of lidar systems and the diversity of lidar components, it is very difficult to guarantee the homogeneity of lidar outputs. Mao et al. analyzed the effects of various factors on lidar outputs and introduced a weigh-assignment scheme scoring method to assess the quality of retrieved aerosol optical properties. In addition, to exclude the influence of manual analysis on the lidar outputs, an automatic retrieval algorithm was designed. These methods can be applied in the QA/QC procedure of atmospheric lidar networks and help to ensure the data quality reliability of the aerosol optical properties retrieved by different lidar systems.

The long-term observation datasets of aerosol in the Arctic region are very limited, and in particular, they pay less attention to dust aerosols from long-range transportation over the Arctic region. Xie et al. present four-year micro-pulsed lidar retrieval results to investigate the seasonal and vertical variations in Arctic duct. The particle depolarization ratio obtained from micro-pulse lidar is used as the main indicator for dust identification. Observations over the Arctic can be used for global modeling validation and to help understand the influence of dust particles on the Arctic climate by aerosol–cloud–radiation interaction processes, especially mixed-phase cloud processes.

Lidar measurements suffer from the insufficient signal dynamic range of the detectors, which leads to a blind zone close to the surface due to a strong backscatter signal. Wang et al. present a new aerosol lidar technique with a new wide dynamic customized PMT module to obtain extensive dynamic outputs. This method includes using the combination of two analog detection chains and one photon counting detection chain. It can avoid lidar saturation in the near range while having the same performance in the far range compared with commonly used single photon counting PMT. This approach can extend the detection dynamic range to eight orders of magnitude, which covers the detection range from a hundred meters to ten kilometers.

The accuracy of aerosol contributions from anthropogenic pollutants in megacities is necessary for regional climate studies. Liu et al. verified the accuracy of the Monte Carlo method in calculating forward scattering effects using simulated data from three typical aerosol particles. This is based on the long-term sky-radiometer datasets (2015–2020) collected in Xi'an, a typical megacity where heavy pollution weather commonly occurs. The results indicate that the correction factors of aerosol optical depth (AOD) are closely related to wavelengths, solar zenith angles, the value of AODs, and the optical properties of aerosol particles. The results also indicate that the forward scattering effect in heavily polluted areas of Xi'an cannot be ignored for the significance of short waves.

Obtaining a stable boundary layer height is important for air quality forecasts, emergency response, and numerical weather predictions. By comparing multiple meteorological element data from meteorological gradient observation towers, Xian et al. found that the existing methods for the calculation of stable boundary layer height have limitations in terms of their dynamic and thermal effects. A variance method of wind speed profile shape was proposed to obtain the stable boundary layer height. Misjudgment and missed judgment (about 20%) in the existing methods were found and then improved by investigations into four types of wind speed variance profile shapes under a low-level jet. The results indicate that the proposed method can be extended to various wind field detection tools for stable boundary layer height inversion generally.

3. Outlook

The articles collected in this Special Issue demonstrate that the capabilities and performance of atmospheric lidar can be improved by incorporating the latest technologies of optical detectors and optical designs and proposing new retrievals, while the optical properties of dust in the Arctic region, stratospheric aerosol, and the effects of dust on cloud formation can be investigated by applying advanced atmospheric lidars. Following the setups of multiple national and cross-continental lidar networks, lidar data quality and homogeneity are becoming important issues for lidar data applications. Therefore, these research articles are timely and important for addressing such issues.

Atmospheric lidar, as an important active remote sensing technique, is faced with great challenges because the fundamental principles have not been changed since the 1990s. How to apply and improve the current lidar technologies to address the most urgent issues are the next paths in this technique's future development. As one of the most urgent issues associated with atmospheric science, climate change is the most striking and urgent challenge for all human beings. Measuring the spatial distributions and fluxes of greenhouse gases (GHGs) is crucial for controlling emissions and a key step in achieving the Paris Agreement. A focus of this purpose is how to improve the current atmospheric lidar technologies for the large-scale and accurate measurement of GHGs and an atmospheric dynamic field. For future research in atmospheric lidars, differential absorption atmosphere lidars working in coherent detection mode are promising to address these issues. This also requires new technologies with high-power lasers with specific central wavelengths at near-infrared bands and sensitive detectors at similar wavelengths, such as superconducting nanowire single-photon detectors [7].

4. Further Reading

Readers who are interested in the lidar remote sensing of atmospheric aerosols and clouds and aerosol–cloud interactions, in addition to this Special Issue, are encouraged to read the publications in other recent Special Issues of *Remote Sensing*, for instance, "High Resolution Active Optical Remote Sensing Observations of Aerosols, Clouds and

Aerosol-Cloud Interactions and Their Implication to Climate" (I and II) issued in 2020–2022 (https://www.mdpi.com/journal/remotesensing/special_issues/HRAO_rs and https://www.mdpi.com/journal/remotesensing/special_issues/opticalrs_cloudnaerosolII), "Lidar for Advanced Classification and Retrieval of Aerosols" (https://www.mdpi.com/journal/remotesensing/special_issues/lidar_aerosol_retrieval) published in January 2023, and "Selected Papers of the European Lidar Conference" closed in June 2022 (https://www.mdpi.com/journal/remotesensing/special_issues/elc_2020) (all accessed on 22 January 2024). In these Special Issue, more aspects of advanced atmospheric lidar techniques, lidar retrieval algorithms, applications, and feature observations are explored, with a combination of lidar and other tools focused not only on aerosol, clouds, and their related atmospheric phenomenon but also water vapor, wind, temperature, as well as other GHGs.

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