ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 39, DECEMBER 2022, 1983–1985

• Editorial Notes •

New Progress and Challenges in Cloud–Aerosol–Radiation–Precipitation Interactions: Preface for a Special Issue※

Chuanfeng ZHAO[1], Yuan WANG[2], and Husi LETU[3]

[1]*Department of Atmospheric and Oceanic Sciences*, *School of Physics*, *Peking University*, *Beijing* 100871, *China*
[2]*Department of Earth*, *Atmospheric*, *and Planetary Sciences*, *Purdue University*, *West Lafayette*, *IN* 47907, *USA*
[3]*State Key Laboratory of Remote Sensing Science*, *The Aerospace Information Research Institute*, *Chinese Academy of Sciences (CAS)*, *Beijing* 100101, *China*

Citation: Zhao, C. F., Y. Wang, and H. S. Letu, 2022: New progress and challenges in cloud–aerosol–radiation–precipitation interactions: Preface for a special issue. *Adv. Atmos. Sci.*, **39**(12), 1983−1985, https://doi.org/10.1007/s00376-022-2009-2.

Clouds play essential roles in the Earth's radiative energy balance and global hydrological cycle. Aerosols, the particles suspended in the air, can change cloud properties by interacting with radiation or serving as cloud condensation nuclei. However, the variations in cloud properties subjected to aerosol context, and their impacts on radiation and precipitation, are related to many complicating factors such as land types, meteorological conditions, cloud types, aerosol properties, and their co-varied relationships. Complication of cloud-aerosol-radiation-precipitation interactions makes representation of clouds one of the largest uncertainties in climate models for future climate prediction. It has also become a prevailing topic in atmospheric sciences over the past several decades.

Significant efforts have been made in China during the past 20 years in understanding cloud physics, aerosol hygroscopic growth, cloud in-situ measurements and remote sensing observations, human weather modifications, and aerosol-cloud-radiation-precipitation interactions (CARPI). Progress in CARPI highly depends on the development of new observation techniques and advancement of numerical models. Over the past 20 years, substantial progress has been made towards developing cloud remote sensing instruments and platforms, data processing algorithms, and weather and climate models. For example, high-quality aircraft with advanced world-standard instruments have been deployed. New satellites with more instruments, having more radiometric channels and higher sensitivity, also have been launched. Retrieval algorithms and numerical weather and climate simulation models with performance comparable to global models have been developed. State-of-the-art machine learning techniques have been applied. On the one hand, these new developments enable scientists to better examine the aerosol-cloud-radiation-precipitation interactions. On the other hand, new challenges emerge rapidly.

Motivated by those facts, we organized the special issue "Cloud-aerosol-radiation-precipitation interaction: progress and challenges" to recap new advances in cloud observation instruments and model development. The purpose is to share with the meteorological community the progress made in characterizing cloud properties, cloud processes and radiative impacts, the progress achieved in recognizing weather and climate model performance and simulations, and the challenges existing at the current time. Our special issue has solicited 16 articles, covering the following four research topics.

1. Cloud retrieval algorithms and characteristics

The new generation geostationary satellite observations, such as the Advanced Himawari Imager (AHI) on board the HImawari-8, have high temporal and spatial resolutions, enhancing investigation of cloud properties. Liu et al. (2022, Page 1994) developed a machine learning method based on a cloud detection algorithm for the Himawari-8 spectral imagery, which is among the most recent studies for AHI-based cloud retrievals. Three unique characteristics were introduced in this algorithm. First, different algorithms were applied to daytime and nighttime retrievals, one with and the other without solar band observations. Second, three models with different treatments for the earth's surface were introduced to eliminate the influence of surface conditions on cloud detection. Third, the surface variables were added into the machine learning algorithm

※ This paper is a contribution to the special issue on Cloud–Aerosol–Radiation–Precipitation Interaction: Progress and Challenges.

in a binary way to enhance the algorithm accuracy, which is about 5%. Comparison against the CALIOP observations confirms the reliability of this machine learning algorithm.

Li et al. (2022, Page 2008) revealed the fine-scale characteristics of daytime cloud regimes over coastal South China during the pre-summer rainy season (April–June) with high spatial-temporal resolution AHI data. They showed that optically thick warm clouds are the major cloud regime during the pre-summer rainy season, with higher frequencies over land than offshore, possibly influenced by the higher aerosol concentrations over land (particularly over cities). Specifically, convective clouds appear more frequently over the land, and optically thinner clouds occur mainly offshore. Further analysis showed that convective clouds are closely related to the synoptic flow patterns during the pre-summer rainy season.

Yu et al. (2022, Page 2024) applied a deep neural network (DNN, a deep learning scheme) to store and compute the optical properties of non-spherical particles. Based on the dataset of optical properties of super-spheroids with extensive shape parameters, size parameters, and refractive indices, the DNN architectures were trained; the results obtained had comparable prediction performance of particle optical properties with the original database while requiring much less storage size.

Zuo et al. (2022, Page 2203) further identified the convective and stratiform clouds based on weather radar observations using a density-based spatial clustering of applications with noise (DBSCAN) algorithm. This method reliably provides the classification of four types of clouds, which are deep-convective cloud (DCC), shallow-convective cloud (SCC), hybrid convective-stratiform cloud (HCS), and stratiform cloud (SFC), which also provide abundant cloud structure information to the users.

2. Cloud-associated physical properties and processes

Cloud physical properties and processes are often investigated with aircraft observations or ground-based remote sensing retrievals. Using observations from 22 aircraft observation flights in 2014, 2015, 2016, 2017, 2020 and 2021, Wu et al. (2022, Page 2056) investigated the microphysical characteristics of wintertime cold clouds in North China. This study showed the dominance of mixed-phase clouds, the common presence of aggregation and riming processes, and the dependence of cloud microphysical properties on temperature in the wintertime cold clouds in North China, which is highly valuable for better understanding of cloud properties over this region.

Also using aircraft observations, Li et al. (2022, Page 2040) showed distinct physical characteristics of different parts of mixed convective-stratiform clouds and their responses to seeding. Specifically, the convection was deeper and radar echoes were significantly enhanced with higher tops in the convective regions while radar echoes became weaker with lower tops in the stratiform regions in response to seeding. This helps to improve understanding of cloud seeding response.

Zheng et al. (2022, Page 2107) examined the heterogeneities of cloud and drizzle microphysical properties and the aerosol-cloud-precipitation interactions for closed-cell marine stratocumulus case during the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) aircraft field campaign. They found that the cloud and drizzle heterogeneities inside the same stratocumulus can significantly alter the sub-cloud aerosols and CCN budget, suggesting caution in the aircraft assessment of aerosol-cloud-precipitation interactions.

He et al. (2022, Page 2071) examined the ice nucleation of cirrus clouds related to the transported dust layer for 22 events observed by ground-based lidars over Wuhan, China in spring and winter from 2012 to 2018. They found that dust-related heterogeneous nucleation contributed to primary ice nucleation in cirrus clouds with the consumption of water vapor (reducing relative humidity and then further inhibiting homogeneous nucleation) by providing ice nucleating particle concentrations when the cloud top temperature is below −30°C.

Using the Explicit Mixing Parcel Model, Luo et al. (2022, Page 2087) investigated the relationships between cloud droplet spectral relative dispersion and entrainment rate and their impacting factors, including vertical velocity, relative humidity, liquid water content, and droplet number concentration. The findings enhance the understanding of relative dispersion and lays a foundation for the quantification of entrainment-mixing mechanisms.

3. Cloud and aerosol radiative impacts

Cloud and aerosols, by changing the radiation balance directly and indirectly, can modify local and even global climate. Zhou et al. (2022, Page 2124) investigated the performance of climatology and anomalies of surface cloud radiative effect using cloud property histograms and cloud radiative kernels (CRKs). They found that the cloud-induced surface radiative anomalies reproduced by surface CRKs and MODIS cloud property histograms are not affected by spurious trends that appear in Clouds and the Earth's Radiant Energy System (CERES) surface irradiance products, while its climatology along with cloud radiative effect (CRE) are well correlated with those calculated from surface radiative fluxes. This study provides a new method to understand the climatology of cloud radiative forcing.

Using the ground site observation at Xianghe in the north China plains from 2005 to 2009, Liu et al. (2022, Page 2213) investigated the cloud effect on surface irradiance. The cloud fraction (CF) demonstrates a distinct seasonal variation, with a minimum in winter (0.37) and maximum in summer (0.68), resulting in CRE ranging from –29.5 W m^{-2} in winter to –78.2 W m^{-2} in summer. When clouds do not obscure the sun, CF is a dominant factor affecting diffuse irradiance, causing a positive linear relationship between CF and CRE. When clouds obscure the sun, CF affects both direct and diffuse irradiance, resulting in a non-linear relationship between CF and CRE. The finding of this study provides better understanding of cloud radiative effect.

Zhao et al. (2022, Page 2137) showed the importance of high spatial resolution in climate models for the simulation of aerosols and aerosol radiative forcing. They found that, compared to the AERONET observations, a high-resolution model (HRM) can better reproduce the spatial distribution and seasonal cycles of aerosol optical depth (AOD) compared to a low-resolution model (LRM), with more reasonable aerosol radiative forcing. The better performance of HRM was found to be mainly related to its better simulation of relative humidity.

Zuo et al. (2022, Page 1986) investigated the potential climate impact of the Hunga Tonga-Hunga Ha'apai (HTHH) eruption near the South Pacific Island nation of Tonga on 15 January 2022, from a historical perspective. They estimated that the current HTHH eruption with an intensity of 0.4 Tg SO_2 injection will decrease the global mean surface temperature by only 0.004°C in the first year after eruption, which is within the amplitude of internal variability at the interannual timescale and thus not strong enough to have significant impacts on the global climate. This provides a quick answer to the great concern from the public.

4. Evaluation of weather and climate models

Zhao et al. (2022, Page 2156) investigated a long-standing issue in the latest CMIP6 models, namely underestimates cloudiness and overestimates of the absorption of solar radiation (ASR) over the Southern Ocean that lead to substantial biases in climate sensitivity. By employing 10 years of satellite observations to evaluate CRE and cloud physical properties in five CMIP6 models, they found that while the CRE and total cloud fraction are reasonably simulated by CMIP6 models, there are distinct biases in cloud macro- and micro-physical properties including liquid water path (LWP), cloud optical depth (COD), and cloud effective radius, as well as aerosol optical depth (AOD). Further analysis shows that the large underestimation of both LWP and cloud effective radius (regional means ~20% and 11%, respectively) results in relatively smaller bias in COD. Also, the impacts of the biases in COD and liquid cloud fraction (LCF) cancel each other, leaving CRE and ASR reasonably well predicted in CMIP6. The findings of this study call for more rigorous calibration of detailed cloud physical properties for future climate model development and climate projection.

Wang et al. (2022, Page 2172) investigated the influence of cloud microphysics schemes (one-moment versus two-moment schemes) and cloud overlap methods (observation-based versus a fixed vertical decorrelation length) on the simulated cloud fraction using the BCC_AGCM2.0_CUACE/Aero model. They found that both the use of observation-based approach and the two-moment cloud microphysics scheme can significantly improve the simulation of cloud fraction both globally and regionally, suggesting the interaction between clouds and climate through microphysical and radiation processes is a key contributor to simulation uncertainty.

Zhou et al. (2022, Page 2188) quantitatively analyzed the decomposed fast and slow responses of clouds to an abruptly quadrupled CO_2 concentration (approximately 1139 ppmv) in East Asia (EA) using a general circulation model, BCC–AGCM2.0. They found that the changes in the cloud forcing over EA related to the fast and slow responses opposed each other, with the final cloud forcing being dominated by the slow response. The mean net cloud forcing (NCF) in the total response over EA was –1.80 W m^{-2}, indicating a cooling effect which partially offset the warming effect caused by the quadrupled CO_2. The total responses of NCF in the TP, south China (SC), and northeast China(NE) were –6.74 W m^{-2}, 6.11 W m^{-2}, and –7.49 W m^{-2}, respectively. Thus, the local effects of offsetting or amplifying warming were particularly obvious.

Better understanding of cloud properties and cloud-aerosol-radiation-precipitation interactions requires further development of novel and improved instruments, retrieval algorithms, and weather and climate simulation models, along with more in-depth analyses of cloud-aerosol-radiation-precipitation interaction mechanisms. Additional efforts beyond that reported in the current special issue are being made by the cloud physics science community. National and international collaboration on cloud physics, including both observational experiments and model developments, are also essential for better understanding and representation of cloud-aerosol-radiation-precipitation interactions.