Remote Sensing of Environment 216 (2018) 171–182

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Vertically resolved physical and radiative response of ice clouds to aerosols during the Indian summer monsoon season

Feiyue Mao[a,b,c], Zengxin Pan[b,*], David S. Henderson[d], Wei Wang[e], Wei Gong[b,c]

[a] School of Remote Sensing and Information Engineering, Wuhan University, Wuhan 430079, China
[b] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China
[c] Collaborative Innovation Center for Geospatial Technology, Wuhan 430079, China
[d] University of Wisconsin-Madison, Space Science and Engineering Center, Madison, Wisconsin, USA
[e] School of Geoscience and Info-Physics, Central South University, Changsha 410083, China

ARTICLE INFO

Keywords:
Ice clouds
Three dimension observations
Indirect effect
Semi-direct effect
Indian summer monsoon

ABSTRACT

Changes in aerosol loading affect cloud albedo and emission and Earth's radiative balance with a low level of scientific understanding. In this study, we investigate the vertical response of ice clouds to aerosols within the Indian subcontinent during monsoon season (2006–2010) based on multiple satellite observations. As a function of aerosol loading, we find that the cloud optical depth, cloud geometrical depth and ice water path decrease by 0.23 (from 0.39 to 0.16), 0.8 km (from 2.6 to 1.8 km), 5.1 g/m^2 (from 7.9 to 2.8 g/m^2), respectively, and that ice particles possibly decrease in size and become more spherical in shape as aerosol optical depth (AOD) increases from 0.1 to 1; these changes tend to plateau as AOD increases beyond 1. The absolute negative response between ice clouds and aerosols under moist and unstable atmospheric conditions is stronger than that under drier and stable atmospheric conditions, and vice versa. Moreover, the negative impact of smoke on ice clouds is stronger than dust and polluted dust, which is likely related to the strong absorption properties and poor ice nucleation efficiency of smoke. Aerosol impacts on ice clouds lead to a decrease in the net cloud radiative effect of 7.3 W/m^2 (from 18.5 to 11.2 W/m^2) as AOD increases from 0.1 to 1. This change in ice cloud properties mainly results in the decrease in downwelling LW radiation to the surface and consequently weakened radiative forcing of ice clouds during the Indian summer monsoon season.

1. Introduction

Ice clouds are widely dispersed throughout the upper troposphere and play an important role in the Earth's radiation balance by reflecting solar radiation and absorbing thermal radiation (Mace et al., 2009; Sassen et al., 2008). Ice clouds play an active role across the Indian subcontinent, particularly during the monsoon season (June–-September), where the ice cloud fraction is close to 70% (Luo et al., 2009). The Indian subcontinent is severely contaminated by dust and polluted dust, as well as large contributions from biomass burning aerosols (Gautam et al., 2011; Pan et al., 2018). Observational and laboratory studies have demonstrated how various types of aerosol particles can act as ice nuclei (Alam et al., 2014; Atkinson et al., 2013); however, the impact of ice cloud and aerosol interactions related to aerosol radiative absorption and scattering remains uncertain (Mcfarquhar et al., 2014).

Generally, ice clouds can form either by homogeneous ice nucleation or by heterogeneous ice nucleation. Exclusive homogeneous nucleation occurs when supercooled solution droplets freeze spontaneously, and is limited to temperatures below about −38 °C and supersaturations above 45%, producing many small ice crystals (Koop et al., 2000). However, exclusive heterogeneous nucleation requires lower relative humidity (RH) than homogeneous nucleation with atmospheric ice nuclei (IN) aiding the phase transition, producing fewer but larger ice crystals (Hoose and Möhler, 2012). Diverse aerosol particles can act as IN to some extent, including dust, polluted dust, smoke and biological particles (Hoose and Möhler, 2012). In the presence of IN, heterogeneous nucleation can commence at lower supersaturations and the subsequent ice crystal growth can suppress homogeneous nucleation by reducing the supersaturation and depleting water vapor, which generates an optically thinner cloud (Barahona and Nenes, 2009). Thus, with the competition of homogeneous and heterogeneous ice nucleation, aerosol perturbations substantially alter the optical properties of ice clouds, and thereby can alter Earth's radiation budget and climate (Storelvmo, 2017). Unfortunately, the long-standing and fundamental question of what and how much effect aerosols have on ice

---

[*] Corresponding author.
E-mail address: pzx@whu.edu.cn (Z. Pan).

https://doi.org/10.1016/j.rse.2018.06.027
Received 18 April 2017; Received in revised form 20 May 2018; Accepted 18 June 2018

Table 1
Observations used in analysis along with their sources and spatial resolutions.

Sensor	Spatial resolution	Products	Parameter
CALIPSO	5 × 5 km	Level 2 Cloud Layer V3	Cloud optical depth; cloud fraction; cloud top/base height; ice water path; integrated color/depolarization ratio
		Level 2 Aerosol Layer V3	Aerosol optical depth; aerosol top/base height; ice water path; vertical feature mask
CloudSat	1.3 × 1.7 km	2B-FLXHR-LIDAR R04	Vertical SW/LW heating rate; TOA SW/LW radiative fluxes
		2B-CLDCLASS-LIDAR R04	Cloud fraction; cloud top/base height
MODIS	1° × 1°	Level 3 MYD08_M3 006	Monthly average aerosol optical depth
ECMWF	1.3 × 1.7 km	ECMWF-AUX R04	Pressure; temperature; relative humidity

cloud formation and variation in today's atmosphere remains largely uncertain.

To investigate the interactions of ice clouds and aerosols, previous research has focused on case analysis to estimate aerosol impacts on ice clouds through the use of passive satellite and in situ observations. Su et al. (2008) verified the importance of the indirect and semi-direct effects of low-level dust aerosols on ice cloud microphysical and optical properties using passive satellite observations, but with large uncertainty due to the lack of vertically resolved atmospheric profiles. Using observations from the Microwave Limb Sounder and Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aura and Aqua satellites, respectively, Jiang et al. (2011) demonstrated that ice cloud effective radius increases with convective intensity, but decreases with column aerosol loading based over South Asia. However, meteorological stations, reanalysis, and passive remote sensing data (such as MODIS) used by previous studies are not sensitive enough to accurately detect ice clouds, and do not explicitly observe the vertical distributions of cloud and aerosol. This results in large uncertainty when quantifying the aerosol effect on the three-dimensional (3D) distribution of clouds (Guo et al., 2016; Pan et al., 2015). Due to this uncertainty, there is still a need for a quantitative and pervasive study of the effect of aerosols on the vertical distribution of ice clouds. Combined CloudSat and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite datasets are currently the only available satellite-based observations that can acquire the vertical distribution of clouds and aerosols, and also provide information regarding the type and phase of aerosols and clouds with high confidence (Omar et al., 2009; Pan et al., 2017; Winker et al., 2010).

Combined CloudSat and CALIPSO data have enhanced our knowledge of globally dispersed aerosols, clouds, and their interactions with each other. Sassen et al. (2008) found a global average frequency of cirrus cloud occurrence of 16.7% through combined CloudSat and CALIPSO cloud masks. Das and Jayaraman (2011) found that a 40% enhancement of black carbon could increase atmospheric heating rates up to 50% based on CALIPSO and ground-based stations over western India during premonsoon periods. Tan et al. (2014) determined the ice-nucleating potential of dust, polluted dust, and smoke aerosols individually by analyzing their vertical profiles based on ~5 years of CALIPSO observations. When observing the radiative impacts of clouds and aerosols, Haynes et al. (2013) illustrated the necessity of vertically resolved sensors when deriving atmospheric heating rates, and Matus and L'Ecuyer (2017) demonstrated the importance of separating cloud phase when deriving the radiative effects of various clouds types. These studies are examples that indicate the usefulness of CloudSat and CALIPSO observations when examining aerosols, clouds, and their interactions.

The primary motivation of this work is to quantify the vertical microphysical and radiative effect of aerosols on ice clouds. In this study, we investigate the vertical response of ice clouds to aerosols during monsoon seasons from 2006 to 2010 using CloudSat, CALIPSO, MODIS, and reanalysis environmental data. The vertical physical and radiative of responses of ice clouds to aerosol loading, derived using the increased vertical information content provided by CALIPSO and CloudSat, will be discussed and evaluated.

2. Data and methodology

2.1. Data and uncertainties

CloudSat and CALIPSO were launched into the A-Train constellation in April 2006 (Winker et al., 2010). Until early April 2011, CloudSat and CALIPSO were maintained in tight orbital coordination; temporal differences between two satellites were nominal at 15 s (Mace et al., 2009). CloudSat has a 1.3 km cross-track and a 1.7 km along-track footprint resolution, and its effective vertical resolution at nadir is 240 m; CALIPSO has a spatial and vertical resolution of 333 m and up to 30 m, respectively. The CALIPSO lidar is more sensitive to optically thin clouds and aerosols, however, the CloudSat radar (CPR) is more suitable for probing optically thick clouds (Mace et al., 2009). Therefore, the combined CloudSat and CALIPSO observations provide comprehensive 3D information from optically thin and thick layers (Mace et al., 2009).

In this study, we implement five years of A-Train data during the monsoon season (June 2006–September 2010) to analyze the vertical response of ice clouds to aerosols (Table 1). These data include the physical parameters of ice clouds and aerosols from the CALIPSO Level 2 cloud and aerosol layer products with the spatial resolution of 5 km, the spatial average aerosol optical depth (AOD) from MODIS MYD08_M3 monthly product of Aqua, and corresponding cloud radiative characteristics from the CloudSat 2B-FLXHR-LIDAR R04 product (L'Ecuyer et al., 2008; Remer et al., 2005; Wang et al., 2017; Winker et al., 2010). Environmental conditions are obtained from the European Center for Medium range Weather Forecast-AUXiliary analysis (ECMWF-AUX) product (Uppala et al., 2005). Further, the CloudSat 2B-CLDCLASS-LIDAR R04 data are used to supplement the conclusions of this study (Fig. 1a).

Ice clouds are identified using the CALIPSO ice/water phase flags from the vertical feature mask (VFM) and require high quality assurance flags (confidence probability > 75%) (Avery et al., 2012). Only ice clouds are selected to remove impacts from mixed-phase clouds. The ice clouds detected by CALIPSO consist of sub-visible, thin, and opaque cirrus. The cloud-aerosol masks from CALIPSO have been shown to correctly identify cloud or aerosol at ~90% accuracy (Sassen et al., 2009). For 2B-FLXHR-LIDAR, quality control flags are used to screen data. Following the 2B-FLXHR-LIDAR R04 screening in Matus and L'Ecuyer (2017), CloudSat profiles are removed if there is: missing CALIPSO information, missing MODIS observations, missing solar zenith angle, or when out-of-bounds fluxes exist.

Henderson et al. (2013) demonstrated that the global mean outgoing shortwave (SW) and longwave (LW) radiation from the CloudSat observations agree within 4 (approximately 4%) and 5 W/m^2 (approximately 2%) on monthly/5° scales, respectively, when compared to the collocated data from the Clouds and the Earth's Radiant Energy System (CERES); these uncertainties decrease significantly for longer temporal-scale averages (L'Ecuyer et al., 2008). SW and LW heating rates have been recorded to have errors of 12.5% at the global level (Haynes et al., 2013), however, when directly comparing gridded column heating rates between CERES and 2B-FLXHR-LIDAR, SW and LW heating rate root mean square errors are 4% and 7%, respectively (Matus and L'Ecuyer, 2017). For thin cirrus detected only by CALIPSO,