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Impacts of mineral dust on ice clouds in tropical deep convection systems

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ABSTRACT

Multi-platform and multi-sensor observations are used to study the impacts of mineral dust on ice clouds of tropical deep convection systems based on one massive Sahara dust event. The comparisons of cloud properties between dust-laden and dust-free conditions support the hypothesis that the presence of large concentrations of mineral dust produces more ice particles at warmer temperature through heterogeneous nucleation processes. Water vapor competition limits ice particles' growth and results in relatively small sizes of ice particles and a narrow distribution of effective particle diameter in non-precipitating ice clouds, particularly at upper layer with temperatures colder than −40 to −50 °C. On the other hand, precipitating ice clouds with sufficient water vapor supply have greater ice water paths under dust-laden conditions than under dust-free conditions. The results also suggest that mineral dusts may invigorate the convection and enhance water vapor supply in deep convective precipitating clouds, lifting ice particles to higher altitudes. Additional study illustrates that the observed microphysical changes of ice clouds in the deep convection systems are not simply due to the differences of large-scale dynamics and thermodynamics.

1. Introduction

The role of aerosols in modifying clouds and precipitation has been one of the most uncertain and challenging problems in both cloud physics and climate study (Denman et al., 2007). Ice clouds significantly influence both shortwave and longwave radiation, and thus exert strong radiative forcing on the Earth climate system. Since most precipitation originates from the ice phase, the formation and evolution of ice clouds significantly impact the spatial and temporal distributions of global precipitation and consequently the latent heating, which is an important energy source for driving atmospheric circulations (Simpson et al., 1988; Tao et al., 2006, 2007). Therefore, it is critical to understand the processes involved in ice nucleation and their impact on ice clouds and precipitation.

Although aerosols are mostly present in the lower atmosphere, i.e., within the boundary layer, several modeling studies suggested that deep convection can transport aerosols vertically from the lower troposphere to the upper troposphere (Yin et al., 2005; Cui and Carslaw, 2006). The enhancement of aerosol abundance in the lower atmosphere thus may have significant consequences on upper level clouds and precipitation. Furthermore, there is a possible linkage among humidity in the stratosphere and the upper troposphere, ice crystal size in towering cumulus clouds, and aerosols associated with tropical biomass burning on yearly time scales (Sherwood, 2002). Recent studies show that aerosols change both microphysical and macrophysical properties of ice clouds (Jiang et al., 2009, 2011; Ou et al., 2009, 2012; Min and Li, 2010; Jackson et al., 2012).

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However, direct observational evidence of aerosol impacts on deep convective clouds and precipitation is still very limited.

Mineral dust is one of the main natural aerosols in the atmosphere and has been observed in the most remote regions in the world (Prospero, 1999). Dust can serve as effective ice forming nuclei (IN), and cloud condensation nuclei (CCN), giant CCN after being coated by soluble material such as sulfate aerosol. The measurements from the Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment (CRYSTAL-FACE) suggested extremely high numbers of heterogeneous ice nuclei in high clouds associated with the Saharan dust (DeMott et al., 2003; Sassen et al., 2003). Min et al. (2009) and Li and Min (2010) have shown that microphysical effects of dusts may alter precipitation vertical structure, shift the precipitation size spectrum from heavy precipitation to light precipitation, and even suppress precipitation. Changes in cloud microphysics may have strong feedbacks to cloud thermodynamics by altering the vertical gradient of heating profiles in both convective and stratiform regions (Rosenfeld et al., 2008). Furthermore, with strict constraints on cloud dynamics and thermodynamics, Li et al. (2010) found that dust aerosol indirect effect on warm clouds strongly depends on the cloud precipitation regime and cloud top height, indicating the importance of aerosol vertical transport and aerosol–cloud interaction. Min and Li (2010) also found that changes of the partitioning of homogeneous and heterogeneous nucleation processes in ice clouds due to dust aerosols would result in substantial changes in the cloud top distribution and such macrophysical changes would have a strong cooling effect of thermal infrared radiation of up to 16 W m^{-2} on cloud systems. In this study, we focus on ice cloud microphysical properties and use dust aerosols as a surrogate for understanding aerosol-ice cloud interaction.

2. Data and method

2.1. Observations and re-analysis dataset

It is challenging to retrieve optical properties of ice clouds, particularly of cold, precipitating cloud systems (Lin and Rossow, 1996). Optical remote sensing from satellites, such as from Moderate Resolution Imaging Spectroradiometer (MODIS), are generally insensitive to precipitation-sized particles. Furthermore, the significant amount of cloud liquid droplets underneath the ice clouds or mixed with ice particles can result in large uncertainties in satellite retrievals of ice clouds (Kaufman et al., 2005; Horvath and Davies, 2007). In spite of the relative large uncertainty of satellite remote sensing for ice clouds as compared to that for liquid clouds, systematic characteristics of ice clouds derived from satellite nevertheless provide important information for understanding the aerosol effects and associated climate consequence of ice clouds. In this study, we use MODIS retrieved cloud thermodynamic phase, cloud top temperature (CTT), ice water path (IWP), ice cloud effective diameter (De), and aerosol optical depth (AOD) to analyze the potential impacts of dust aerosol on cloud micro- and macro-physical properties. In addition, we further separate precipitating ice clouds from non-precipitating clouds based on the collocated rainfall retrievals from the Advanced Microwave Scanning Radiometer (AMSR-E Aqua L2B rain rate and type product, at 5.4 km resolution).

Ice cloud formation strongly depends on temperature, moisture, and convective strength. Direct estimation of in-cloud moisture saturation ratio and convective strength from satellite observation is currently impossible. The cloud top temperature is a good indicator of cloud top height and cloud thermodynamic conditions, which also provides an important constraint on cloud convection strength. Since the cloud top temperature is readily available from MODIS retrievals, this study classifies ice cloud optical properties in terms of cloud top temperature. Cloud top temperature of ice clouds retrieved by MODIS in these regions generally varies from −10 to −90 °C. In order to minimize potential misclassification and contamination by super cooled liquid clouds, we exclude samples with cloud top temperatures warmer than −20 °C. Satellite observations have showed that at this temperature more than 50% of clouds are glaciated (Curry et al., 1990; Lin and Rossow, 1996; Choi et al., 2010).

Deep convective clouds, associated with precipitation, can also be profoundly influenced by mineral dust through ice nucleation and growth processes (Min et al., 2009; Li and Min, 2010). However, optical measurements saturate over those thicker, brighter clouds, and are only sensitive to the characteristics of the top cloud layer. Furthermore, water vapor availability is another critical factor in ice nucleation and ice particle growth, which is difficult to monitor by optical sensors in the presence of clouds. Passive microwave measurements, on the other hand, have proven more useful in thick precipitating ice clouds. Upwelling brightness temperature at 89 GHz (Tb89, vertically polarized microwave radiation in this study) can be strongly depressed due to the scattering of precipitation-sized ice particles, while brightness temperatures at 18.7 GHz (Tb18.7) and 23.8 GHz (Tb23.8) are generally proportional to column integrated liquid water (precipitation and cloud liquid water) and water vapor amount (Wilheit et al., 1977; Spencer et al., 1989; Petty, 1994; Lin and Rossow, 1996 and references therein). To further investigate the impacts of mineral dust on ice clouds for given column liquid water path and water vapor, the relationships between Tbs at 89, 18.7 and 23.8 GHz (Fig. 4) are studied, using Advanced Microwave Scanning Radiometer-EOS L2A Spatially-Resampled Brightness Temperatures data (at 21 km resolution).

Cloud formation and evolution are affected not only by aerosol, but also by large scale dynamics and thermodynamics. To investigate possible impacts of large scale dynamics on cloud properties, we use multiple datasets of observation and re-analysis. We colocate the sea surface temperature (SST) retrievals from Advanced Microwave Scanning Radiometer-EOS (Wentz and Meissner, 2004), Convective Available Potential Energy (CAPE), temperature difference between 850 and 500 hPa, $\Delta T_{850-500\,\text{hPa}}$, from NCEP FNL Operational Global Analysis data (the closest one to the satellite overpass time). All of those dataset are at 1° × 1° resolution, we pair all associated cloud retrievals in the box with those information to study the possible impacts from large scale dynamics and thermodynamics, as done in Min and Li (2010). Although the real environmental conditions surrounding clouds are different from those reanalysis data due to the coarse resolution and time difference, the collocated SST and NCEP data provide the best estimation of background dynamics and thermodynamics conditions which can be used to understand meteorological impacts on clouds.