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Cloud invigoration and suppression by aerosols over the tropical region based on satellite observations

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Abstract

Aerosols may modify cloud properties and precipitation via a variety of mechanisms with varying and contradicting consequences. Using a large ensemble of satellite data acquired by the Moderate Resolution Imaging Spectroradiometer onboard the Earth Observing System's Aqua platform, the CloudSat cloud profiling radar and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite over the tropical oceans, we identified two distinct responses of clouds and precipitation to increases in aerosol loading. Cloud-top temperatures decrease significantly with increasing aerosol index (AI) over oceans and aerosol optical depth (AOT) over land for mixed-phase clouds with warm cloud bases; no significant changes were found for liquid clouds. The distinct responses are explained by two mechanisms, namely, the aerosol invigoration effect and the microphysical effect. Aerosols can significantly invigorate convection mainly through ice processes, while precipitation from liquid clouds is suppressed through aerosol microphysical processes. Precipitation rates are found to increase with AI for mixed-phase clouds, but decrease for liquid clouds, suggesting that the dominant effect differs for the two types of clouds. These effects change the overall distribution of precipitation rates, leading to more or heavier rains in dirty environments than in cleaner ones.

1 Introduction

Several studies suggested that suppression of warm rain by aerosols may allow more cloud particles to ascend above the freezing level, initiating an ice process in which more latent heat is released thus invigorating convection (Andreae et al., 2004; Khain et al., 2005). A further study using a parcel model suggests that this effect exists when ice processes are involved. The effect is much stronger for clouds with warm bases because cloud particles have longer distances to grow before freezing (Rosenfeld et al., 2008). The invigoration effect was exhibited as systematic increases in cloud-top heights or rain rates (Lin et al., 2006; Bell et al., 2008; Koren et al., 2005). However, the lack of full cloud geometry information in these studies, i.e. cloud top and base heights, makes it hard to verify if the invigoration effect really occurs for mixed-phase clouds with warm bases.

In this study, we provide direct evidence of the aerosol invigoration effect by classifying clouds according to their top and base heights as detected by space-borne active sensors, in combination with the aerosol index (AI) or aerosol optical thickness (AOT) retrievals from a passive sensor aboard the A-Train constellation. We also show that clouds and precipitation respond differently to increases in aerosol loading for different types of clouds and how these different responses modify the overall precipitation rate distribution.

2 Data and methodology

Satellite products employed in this study include one year's worth (2007) of observations from CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) as well as the Aqua/MODerate resolution Imaging Spectroradiometer (MODIS) over the tropical region extending from 20° N to 20° S. The MODIS products include Level 3 AOT at 550 nm and the Angstrom exponent (Kaufman et al., 1997a; Remer et al., 2005). The Level 3 products were generated by averaging the daily Level 2 data with a resolution of 10 km to 1° × 1° grids. The validation of Level 2 aerosol products with ground-based observations shows very good agreement (Li et al., 2007; Mi et al., 2007; Levy et al., 2007a, 2010). The CloudSat/CALIPSO products include cloud bases and top heights, cloud ice water paths, and precipitation rates (Stephens et al., 2002; Haynes et al., 2009). The ECMWF-AUX data set is also used for atmospheric state variables interpolated to each CloudSat cloud profiling radar (CPR) bin. The variables include atmospheric pressure, temperature, and specific humidity at each level. These data are used to convert cloud top and base heights to cloud top and base temperatures. The column water vapor and lower tropospheric static stability

(LTSS), defined as the potential temperature difference between the surface and the 700 hPa pressure level (Klein and Hartmann, 1993), are calculated from the data set to constrain meteorological conditions. These products are summarized in Table1.

All data from CloudSat/CALIPSO products are averaged over 1° × 1° grids in order to match the MODIS Level 3 aerosol product. Only data within 20° S–20° N are used to ensure that the dominant cloud type is convective cloud. Grids with AOT >0.6 are excluded in our study because AOT retrievals may be tainted with cloud contamination. Cloud top and base heights are converted to temperatures using temperature profiles from the ECMWF-AUX product. This information is used to define different cloud types: mixed-phase clouds with cloud-base temperatures (CBT) >15 °C and cloud-top temperatures (CTT) < −4 °C, mixed-phase clouds with CBT in the range of 0–15 °C and CTT < −4 °C, and liquid clouds with CBT>0 °C and CTT >0 °C. Only clouds classified as single-layered by the CloudSat algorithm are considered here. Table 2 summarizes the cloud types under study.

The AI, which is a product of AOT and the aerosol Angstrom exponent, is binned and the dependencies of averaged cloud properties in each bin on the AI are examined over the ocean. AI serves a better proxy for cloud condensation nuclei (CCN) than the AOT (Nakajima et al., 2001; Feingold et al., 2006). How the precipitation rate and its distribution change with AI is also examined. Over land, AOT is used instead of AI because the Angstrom exponent retrieved from MODIS over land is not quantitative and much less reliable than over oceans (Levy et al., 2010). Tests on the dependencies of LTSS and column water vapor on AI or AOT are also done over both land and ocean.

3 Results

Figure 1 shows the cloud-top temperature and ice water path as functions of AI over oceans and AOT over land for different cloud types as defined in Table 2. The CTT for mixed-phase clouds with warm bases decreases dramatically with AI, whereas the CTT for liquid cloud does not change at all. The results for mixed-phase clouds with cold bases lie somewhere in-between. The ice water path (IWP) also increases with increasing AI for mixed-phase clouds at higher rate than that for water clouds. The increasing IWP indicates enhanced ice processes, in which more latent heat is released to invigorate the convection when liquid cloud particles are freezing. Similar results are obtained over land using AOT instead of AI (bottom panels of Fig. 1). Note that a logarithmic scale is used on the x-axis in the top panels. These observational findings support the invigoration theory of Rosenfeld et al. (2008), which states that the aerosol invigoration effect is more significant for mixed-phase clouds with warm bases than those with cold bases because the former generate more latent heat which fuels cloud convection into deeper heights.

Deeper clouds and enhanced ice processes in dirty conditions could lead to enhanced rainfall as suggested by previous studies (Khain et al., 2005; Lin et al., 2006). Therefore, the relation between AI and the precipitation rates from the CloudSat radar is also examined.

The precipitation rates from mixed-phase and liquid clouds show very different responses to increasing AI (Fig. 2). Note that only clouds with precipitation rates greater than 1 mm/h are studied here because the aerosol invigoration effect is significant chiefly for deep clouds which favor the production of heavy rain (Rosenfeld et al., 2008). To increase the sample size, only two types of clouds are differentiated here: mixed-phase and liquid clouds, regardless of cloud-base heights. As the AI increases, the precipitation rate increases for mixed-phase clouds, but decreases for liquid clouds. This finding confirms that aerosols enhance precipitation from mixed-phase clouds by inducing stronger convection, but suppress precipitation from liquid clouds because of the microphysical effect that reduces cloud particle size and thus precipitation rate.

In theory, precipitation may remove aerosols due to the scavenging effect, which could lead to a false aerosol effect on the precipitation rate. We would argue that if this were the case, similar trends would be observed for both mixed-phase and liquid clouds, because the scavenging effect works the same way for both types of clouds.

However, the precipitation rates for the two types of clouds respond differently to increasing AI, which cannot be explained only by the scavenging effect of rain.

The increase in precipitation rate with increasing AI for mixed-phase clouds and the decrease in precipitation rate for liquid clouds should change the overall distribution of precipitation rate, as shown in Fig. 3. In relatively dirty environments (AI>0.3), the frequency of occurrence of high precipitation rates is greater than that under clean conditions (AI<0.3). Conversely, the frequency of occurrence of low precipitation rates is slightly higher under more pristine conditions than under more dirty ones. This result indicates that aerosols could greatly change the hydrological cycle by changing the frequency of heavy or light rain, even though the mean precipitation rates may remain unchanged.

We examined the dependencies of several meteorological variables on AI or AOT to make sure that AI or AOT are not proxies of some meteorological variables. Two important atmospheric conditions affecting cloud formation are correlated with AI or AOT: column water vapor and LTSS. The results are presented in Fig. 4. For mixed-phase clouds over oceans (red and blue curves), column water vapor and LTSS are generally invariant with respect to the AI and the AOT so neither meteorological variable can explain the changes in cloud-top temperature or precipitation rate shown in Fig. 2. For mixed-phase clouds over land, the LTSS is positively correlated with AOT, which means that the atmosphere becomes more stable as AOT increases. Clouds tend to develop higher in the atmosphere under unstable conditions, therefore, the positive correlation between LTSS and AOT cannot explain the decrease of cloud-top temperature with increasing AOT. This is not surprising given that the LTSS is computed based on large-scale variables that seem not be affected by the aerosol invigoration effect.

Tests on column water vapor and LTSS under clean and dirty conditions were also conducted but no systematic differences were found. These tests rule out the premise that the change in the precipitation rate distribution is caused by systematic differences in meteorological conditions.

4 Concluding remarks

Strong but conditional dependencies of cloud-top temperature, cloud ice water path, and precipitation rate on the AI and AOT are observed from one year's worth of satellite data acquired by the CloudSat and EOS Aqua platforms over the tropical regions. Results show that cloud-top temperatures decrease with increasing AI over the ocean (or increasing AOT over land) for both warm and cold base mixed-phase clouds, but the decreasing rate is higher for the former. Cloud ice water path also increases with increasing AI/AOT for mixed-phase clouds. Enhanced ice processes generate heavier precipitation under hazy conditions. However, for liquid clouds, there is no significant decrease in cloud-top temperature, indicating the absence of the invigoration effect. Also, the precipitation rate decreases with increasing AI.

The finding of stronger invigoration for mixed-phase clouds with warm bases than with cold bases stems from the fact that cloud particles in clouds with warmer bases have more chances to grow before freezing. Therefore, more liquid water is frozen to release more latent heat. For liquid clouds, the dearth of ice processes does not incur any significant invigoration, and precipitation from these clouds is most likely suppressed due to the aerosol microphysical effect. Tests on the dependencies of column water vapor and LTSS on AI/AOT show that the above results cannot be explained by any changes in meteorological conditions.

The findings reported here may have great implications for studying both the Earth's radiation budget and the global hydrological cycle. Smaller cloud particles caused by higher aerosol loading reflect more solar radiation and result in negative forcing at the top of the atmosphere (the Twomey effect). However, this effect can be compensated by changes in the overall distribution of cloud geometries. Clouds with higher tops, which occur more frequently under dirty conditions, emit less longwave radiation than do clouds with lower tops, leading to a warming instead of a cooling effect (Koren et al. 2010). The suppression and enhancement of precipitation from shallow and deep clouds change the overall distribution of precipitation rates. Heavy rain becomes more frequent and light rain becomes less frequent under dirty than under cleaner conditions. This change could have a very large impact on the hydrological cycle, leading to more frequent flooding or drought events under a dirty environment.

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Table 1. Summary of satellite and model datasets employed in this study.

Geophysical Parameter	Product	Sensor	Spatial Resolution
AOT	MYD08	MODIS	1 × 1 degree
Cloud Geometry	2B-GEOPROF-LIDAR	CloudSat and CALIPSO	Horizontal: 1.4 km × 2.5 km Vertical: ∼250 m
Cloud Ice Water	2B-CWC	CloudSat	1.4 km × 2.5 km
Column Water Vapor	ECMWF-AUX	N/A	1.4 km × 2.5 km
Atmospheric Temperature Profiles	ECMWF-AUX	N/A	1.4 km × 2.5 km

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Table 2. Definitions of warm and cold base mixed-phase clouds and liquid clouds in this study.

	Mixed-phase clouds with warm bases	Mixed-phase clouds with cold bases	Liquid clouds
Cloud base temperature	> 15°C	0–15°C	> 0°C
Cloud top temperature	< −4°C	< −4°C	> 0°C

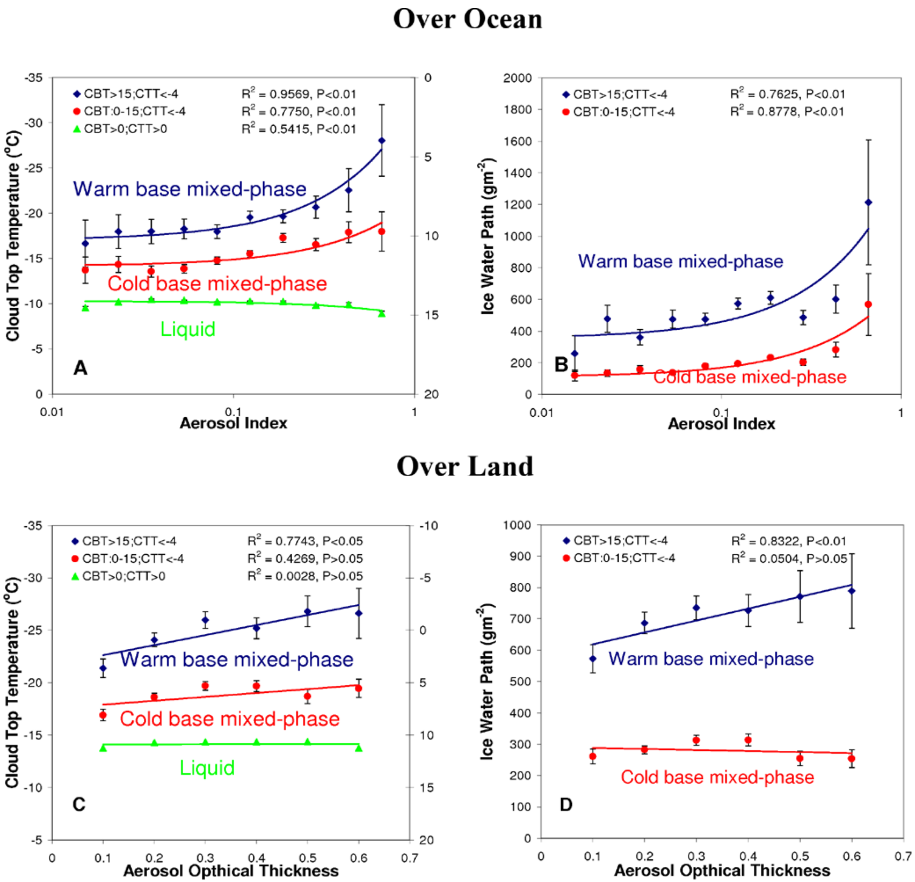

Fig. 1. Cloud-top temperature **(A)** and **(C)** and ice water path **(B)** and **(D)** as functions of AI/AOT for warm (blue dots) and cold (red dots) base mixed-phase clouds and liquid clouds (green dots) over ocean (upper panels) and land (lower panels). The right-hand axes of **(A)** and **(C)** are for liquid clouds. The AI is plotted using a logarithmical scale.

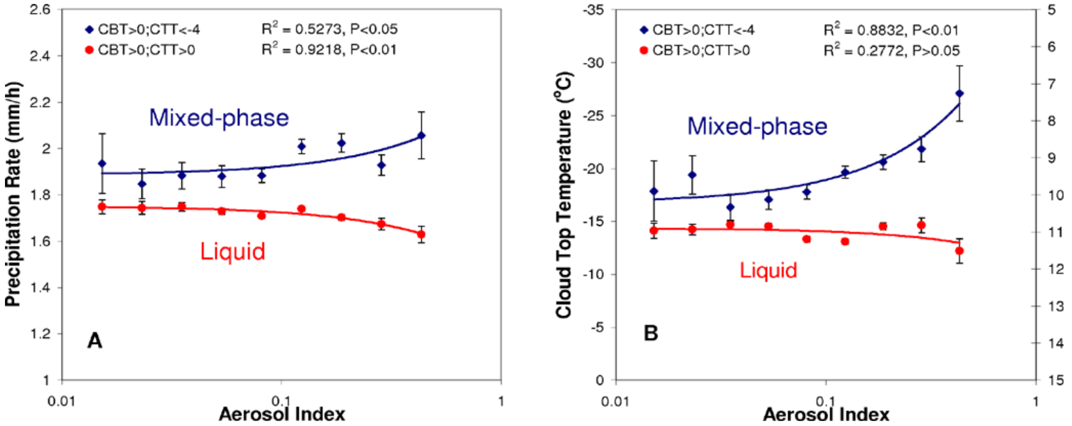

Fig. 2. Precipitation rate **(A)** and corresponding cloud-top temperature **(B)** as functions of AI for mixed-phase (blue dots) and liquid clouds (red dots) over the ocean. Note that only clouds with precipitation rates greater than 1 mm/h are included here. The right-hand *y*-axis of **(B)** represents the cloud-top temperatures of liquid clouds.

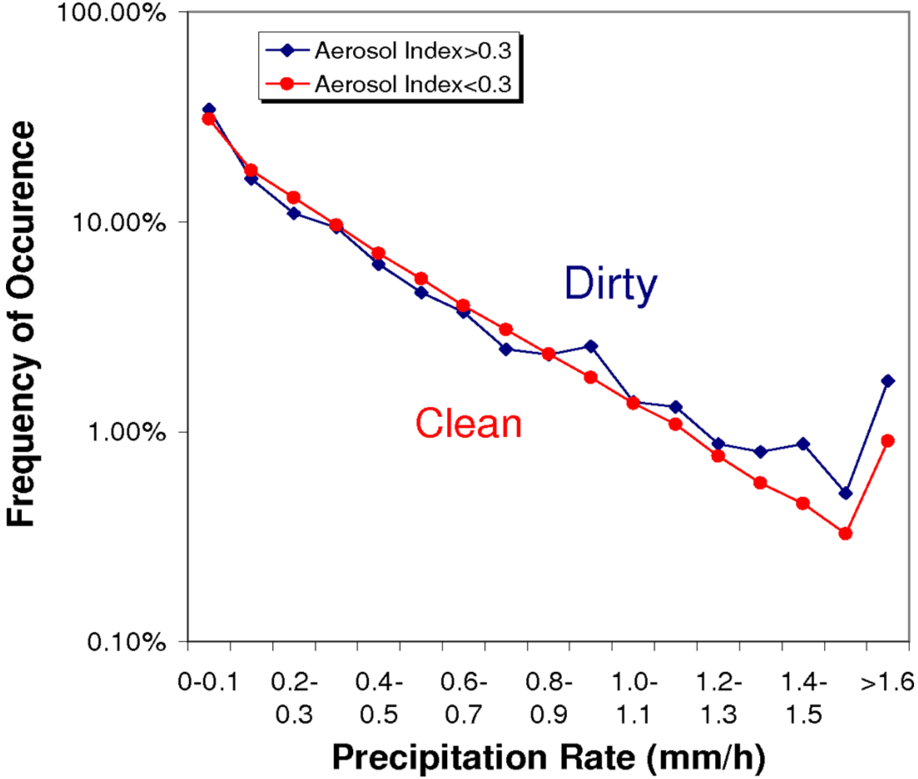

Fig. 3. Frequency of occurrence of different precipitation rates under relatively clean and dirty conditions.

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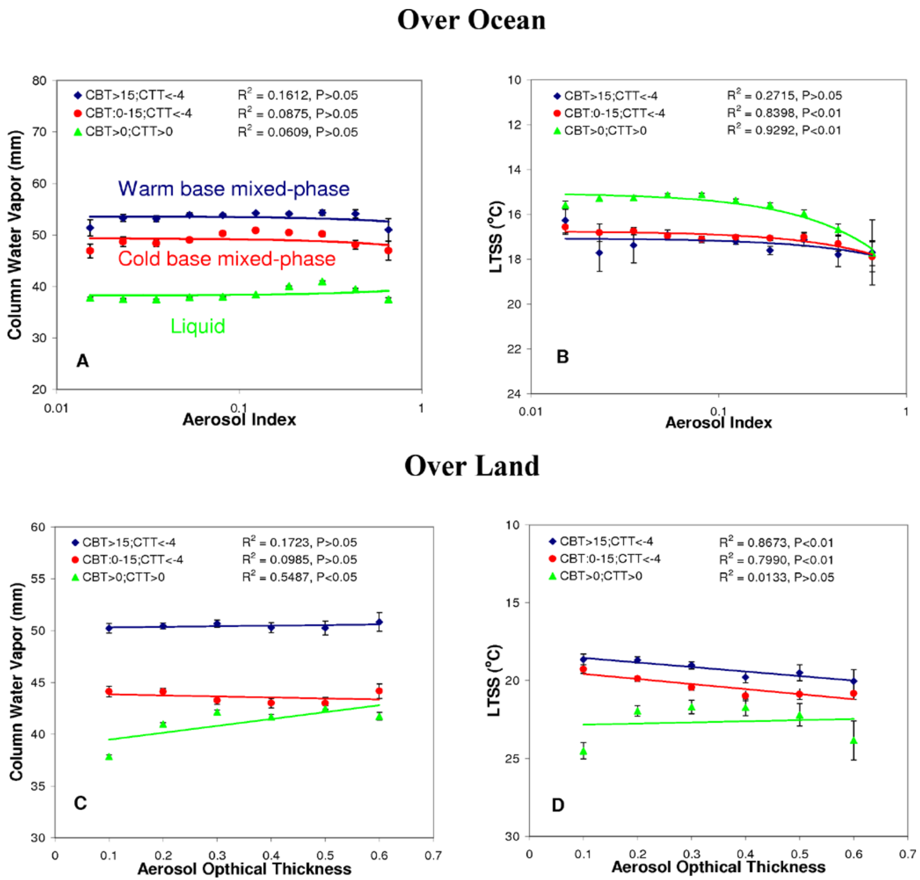

Fig. 4. Column water vapor **(A)** and **(C)** and LTSS **(B)** and **(D)** as a function of AI over the ocean (upper panels) and AOT over land (lower panels) for warm (blue dots) and cold (red dots) base mixed-phase clouds and liquid clouds (green dots). LTSS is plotted in descending order; smaller values (top part of the *y*-axis) indicate a more unstable atmosphere.