Impact of mineral dust on summertime precipitation over the Taiwan region

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Abstract

Dust particles are effective ice nuclei and are known to affect precipitation. Here, the possible impacts of mineral dusts on summertime cloud and precipitation over the Taiwan region are investigated through analysis of 25 years (1989 – 2013) of multiple observational and modeling datasets. Due to the unique mechanism, typhoon precipitations are excluded in this study. Statistical methods are used to untangle the influences of dust from the co-varying water vapor conditions. The results suggest a statistically significant positive correlation between non-typhoon precipitation and number concentration of dust particles larger than 0.5 µm () in July and August in the regions with heavy precipitation. From clean (0.008 cm) to dusty days (0.2 cm), averaged ice (liquid) water paths and precipitation increase by ˜25% (˜20%) and ˜70% over the orographic region, and vertically, ˜30% more cloud ice content is generated at ˜ 350 hPa (T = ˜-20), enhancing the development of the mixed-phase cloud and precipitation. The results also indicate critical role of the atmospheric water vapor in the responses of precipitation to , with precipitation increasing more significantly with in higher water vapor circumstances.

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Key Points:

- Long-term multiple observational and modeling datasets are used to study the correlation between mineral dust and summertime precipitation
- The analysis suggests a positive correlation between dust number concentration and precipitation in the orographic region
- The impact of mineral dust on precipitation is more significant in environments with higher water vapor concentrations

Abstract

Dust particles are effective ice nuclei and are known to affect precipitation. Here, the possible impacts of mineral dusts on summertime cloud and precipitation over the Taiwan region are investigated through analysis of 25 years (1989 – 2013) of multiple observational and modeling datasets. Due to the unique mechanism, typhoon precipitations are excluded in this study. Statistical methods are used to untangle the influences of dust from the co-varying water vapor conditions. The results suggest a statistically significant positive correlation between non-typhoon precipitation and number concentration of dust particles larger than 0.5 μm (N_d) in July and August in the regions with heavy precipitation. From clean (N_d = ~0.008 cm^{-3}) to dusty days (N_d =~0.2 cm^{-3}), averaged ice (liquid) water paths and precipitation increase by ~25% (~20%) and ~70% over the orographic region, and vertically, ~30% more cloud ice content is generated at ~ 350 hPa (T = ~−20℃), enhancing the development of the mixed-phase cloud and precipitation. The results also indicate critical role of the atmospheric water vapor in the responses of precipitation to N_d, with precipitation increasing more significantly with N_d in higher water vapor circumstances.

1 Introduction

Ice particles play significant roles in the formation and development of cloud and precipitation by altering atmospheric water vapor (Lindzen, 1990), latent heat release (Fan et al., 2018) and cloud radiation properties (Yang et al., 2015). In the mixed-phase clouds (T > −37℃), ice nucleating particles (INPs) are indicated to influence cloud ice formation by catalyzing heterogeneous freezing (Hoose & Möhler, 2012; Murray et al. 2012). At higher temperatures, the number concentration of ice particles can rapidly increase by orders of magnitudes through the rime-splintering process (secondary ice production) (Mossop & Hallett, 1974; Hallett & Mossop, 1974; Field et al., 2017). Among various aerosols, mineral dusts are considered as one of the most important sources of INPs owing to their large emission rate (up to 5000 Tg yr^{-1}), long-range transport ability and high ice nucleating efficiency (Husar et al., 2004; Engelstaedter et al., 2006; Uno et al., 2009; Heymsfield et al. 2007). Previous laboratory studies establish the close association of the ice nucleating process with mineral dust in the air (Roberts & Hallett, 1968; Hoose & Möhler 2012; DeMott et al., 2010, 2015). The indirect influences of dust aerosols on clouds have also been demonstrated by a series of observation and numerical studies (Tao et al., 2012; Liu et al., 2012; Fan et al., 2016; Zamin et al., 2017). Mineral dust aerosols were observed to contribute to ice nuclei populations over areas at great distance from dust sources (DeMott et al., 2003; Richardson et al., 2007). The intermittent long-term transport of dust from Asia was shown to impact the cloud and precipitation, enhancing the accumulated precipitation by ~20% and snowfall by ~40% in California when there are adequate water vapor inputs (Ault et al., 2011; Creamean et al., 2013). Modeling studies indicate that the presence of mineral dust leads to the initiation of mixed-phase cloud and increases precipitation efficiency (Muhlbauer & Lohmann, 2009; Fan et al., 2014).

Located in the East Asia, Taiwan is influenced by the long-range transport of mineral dust from mainland China, Middle East, and Sahara (Chen et al., 2003; Hsu et al. 2012; Lin et al., 2012; Chou et al., 2017). The long-range transport of dust into East Asia during late winter and spring has been investigated by numerous observation and modeling studies (Duce et al., 1980; Chen et al., 2004; Lin et al., 2012), and has been shown to influence public health, environment, biogeochemical cycles, and the atmospheric radiation budget (Uematsu et al., 1983; Li et al., 1996; Cheng et al., 2005; Liu et al., 2006; Chiu et al., 2008). Recent research also indicates the winter-time river-dust event as a local source of dust aerosols (Lin et al., 2018). However, there are very few studies on summertime dust aerosols in Taiwan, likely as a result of generally very low concentrations of dust particles.

During the summer season, the Taiwan region is highly influenced by episodes of extreme precipitation caused by various meteorological factors. Previous studies suggest that the extreme precipitations are generally associated with the east Asian monsoon system (Tao, 1987; Chen et al. 2010), Meiyu front (Xu et al., 2009; Yim et al., 2015), typhoon systems (Shieh et al. 1998), and afternoon thunderstorms and local severe convection (Jou 1994; Chen & Chen 2003; Lin et al., 2011). To our knowledge, no previous studies have examined the possible impacts of dust on precipitation in Taiwan. The main objective of the present work is to study the potential influence of mineral dust on the summertime orographic precipitation over the Taiwan region, through analysis of 25-year (1989–2013) of model, observation, and reanalysis data.

2 Data

In this work, multiple datasets are used to study the potential influence of dust particles on cloud and precipitation in summer over Taiwan area.

(1) Precipitation: The 1×1 km gridded daily precipitation dataset collected by the Taiwan Climate Change Projection and Information Platform (TCCIP, http://tccip.ncdr.nat.gov.tw/NCDR/main/index.aspx) project (1989–2013) and the hourly site precipitation observation from Taiwan Central Weather Bureau (CWB) (1998–2013). This dataset has been widely used to study the Taiwan region precipitation (Chen & Chen, 2002; Chen et al., 2007; Su et al., 2012; Lin et al., 2015; Kuo et al., 2016). Due to the unique mechanism, typhoon precipitation days (http://photino.cwb.gov.tw/tyweb/tyfnweb/table/completetable.htm) are excluded in this study.

(2) Dust Number Concentrations: Previous measurements indicate the dependence of ice particle formation rate on the dust number concentration with diameter larger than 500 nm (N_d) (DeMott et al., 2010; Creamean et al., 2013). Because of the lack of long-term quantitative observations, N_d simulated by a global chemical transport model (GEOS-Chem) with size-resolved advanced particle microphysics (APM) (Yu & Luo, 2009) is used in this study. The model is driven by Global Modeling and Assimilation Office (GMAO) Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) meteorology fields. The GEOS-Chem-APM model was run globally at $2^o\times2.5^o$ horizontal resolution with 47 vertical layers for the preiod from 1989 to 2018. N_d values at a grid box representing the long-range transported regional dust concentration in Taiwan area (23°N–25°N, 118.75°E–121.25°E) were output at every chemistry time step (30 minutes). The maximum daily mean N_d in the vertical is used to represent the strength of daily dust aerosol loading in the region.

(3) Dust Ratios: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Lidar Level 2 Vertical Feature Mask Data (https://www-calipso.larc.nasa.gov) from 2006 to 2018 with satellite track passing through Taiwan region (21.7°–25.5° N, 119.8°–122.2° E). CALIPSO level 2 classified aerosol data provides information on the vertical properties of dust, polluted dust, biomass burning, polluted continental, clean continental, and clean marine aerosols, which are widely used in the previous studies of atmospheric dust aerosols (Omar et al., 2006; Omar et al., 2009; Huang et al., 2007, 2008; Schuster et al., 2012). In this study, the classified “dust” and “polluted dust” pixels are treated as observed dust signals. The dust ratios, defined as the ratios of dust pixels to all pixel within 23°–25°N under 6 km, are used to represent atmospheric dust loading in the region for comparison with the GEOS-Chem N_d simulations. The observations with more than 15% missing data in this region are excluded.

(4) Cloud properties and Meteorology: 25-year (1989–2013) ERA-Interim reanalysis from European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al. 2011) are used in the present analysis.

(5) PM10 Aerosol Speciation: In-situ measurements (2006–2017) of aerosol speciation for particular matter smaller than 10 µm (PM10) at the Cape Fuguei Research Station (25.30°N, 121.54°E, 10 m) at the northern tip of Taiwan Island (Chou et al., 2017). Calcium ion concentration is used as a proxy for dust. We follow the method of Song and Carmichael (2001) and assume a calcium/dust ratio of 6.8% to estimate the mass loading of dust particles (Song & Carmichael, 2001). The derived dust mass concentrations are compared with the surface dust concentrations simulated by GEOS-Chem model in the same region.

In this study, the GEOS-Chem simulation and ECMWF data have been processed into local time (LT), same as the precipitation observation. A 24-hour (0000 to 2400 LT) period is defined as one event day.

3 Analysis and Results

The intermittent long-range transport is a major source of mineral dusts over the Taiwan area (Chen et al., 2003; Hsu et al. 2012; Lin et al., 2012; Chou et al., 2017). During dust transport events, dust aerosols can reach high concentrations as can be observed by the CALIPSO satellite lidars, even in the summer season (Fig. 1). In July and August from 2006 to 2018, the CALIPSO satellite passed over Taiwan region (21.7°–25.5° N, 119.8°–122.2° E) on forty-six days.

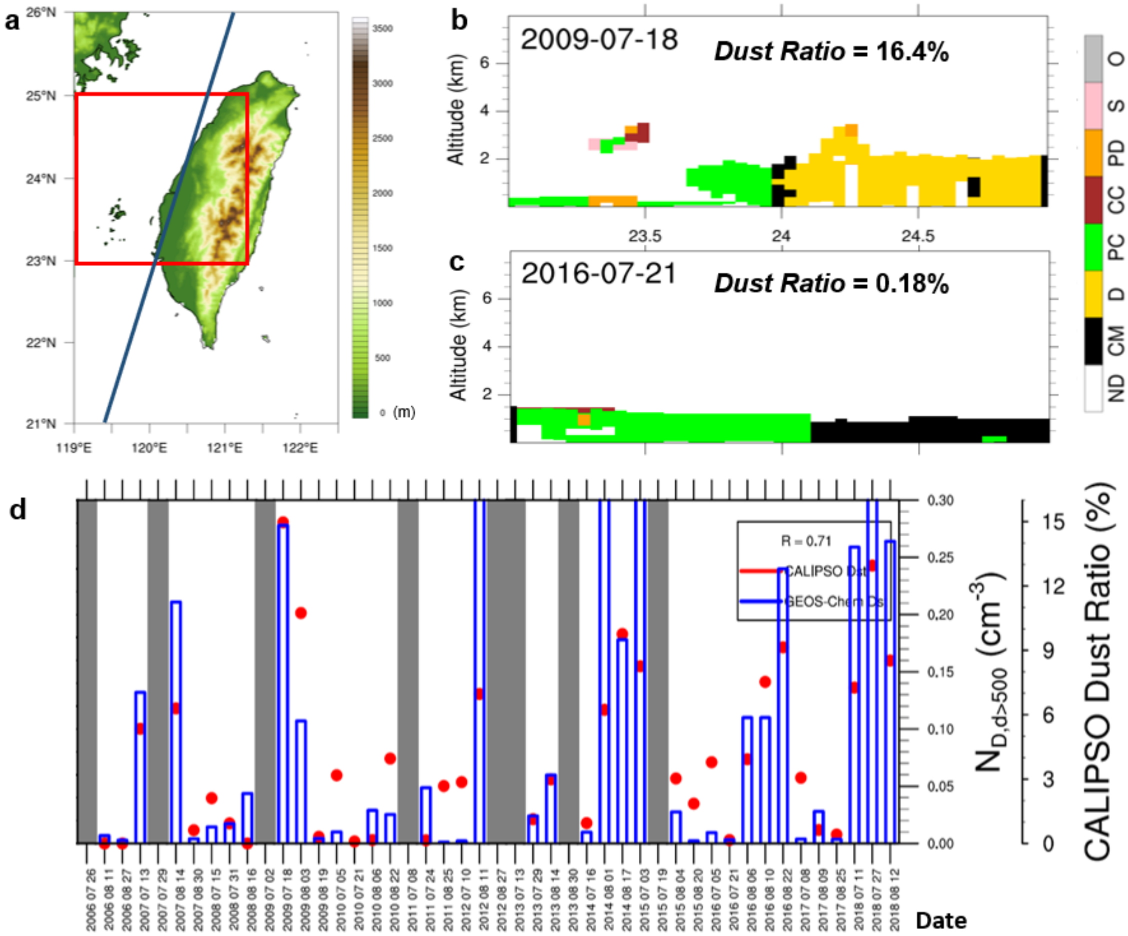

Figure 1. (a) Satellite tracks (red line) and the terrain height of the Taiwan region; Examples of (b) dusty and (c) clean days observed by the CALIPSO satellite (ND = “not determined”, CM = “clean marine”, D = “Dust”, PC = “Polluted continental”, CC = “clean continental”, PD = “Polluted dust”, S = “smoke” O = “other”); and (d) 46 days in July and August (2006–2018) when the CALIPSO satellite track passed Taiwan region: the red spots are the CALIPSO observed dust pixel ratios, blue columns are model predicted N_d at the corresponding date, and grey shades are those days CALIPSO has over 15% missing data (not used in the comparison).

Fig. 1 a, b and c show the tracks and vertical profiles of the CALIPSO observations passing the Taiwan region. Both dust (D) and polluted dust (PD) in the CALIPSO observations are considered as dust signals. Examples of one strong dust event (dust ratio = 16%) on July 18, 2009 (Fig. 1b) and one case of clean atmosphere (dust ratio = 0.18%) on July 21, 2016 (Fig. 1c). show that, in the Taiwan region, although the summertime atmospheric dust loading is substantially lower than in spring, strong dust signals can still be detected by the satellite, indicating that CALISPO observations can be used to identify the occurrence of dust events in summer. The comparisons between CALIPSO observations and GEOS-Chem simulations for all 46 days (given in Table S1 and Fig. 1d) suggest that N_d simulations are generally consistent with the CALIPSO observations and that the GEOS-Chem model can simulate the strong dust events in July over the Taiwan area.

Dust concentration simulations are also compared with the long-term site measurements (shown in Fig. S1). The PM10 dust mass concentration observed at the northernmost tip of Taiwan Island (Chou et al., 2017) is compared with the simulated surface-level PM10 dust mass (2003–2017) at the nearby Taipei site (25°–27°N, 121.25E°–123.75°E). It should be noted that observed dust mass concentrations shown in Fig. S1 are dominated by those from spring months. Nevertheless, the comparison shows a high correlation coefficient between surface dust site observation and GEOS-Chem simulations of mass concentrations in the region (r = 0.7), indicating that although the GEOS-Chem dust mass simulation is higher than the observation, the model is able to simulate the dust events and the variations of dust concentration.

The comparisons of model simulations of dust concentrations in Taiwan region with site (Fig. S1) and satellite (Fig. 1d) data show that the dust simulations by GEOS-Chem can reasonably capture the strong dust events. As pointed out earlier, although the summertime atmospheric dust loading over Taiwan region is lower than that in spring and winter, dust aerosols can still reach high enough concentrations to be detected by CALIPSO during strong dust event days. In summer (JA), the mean N_d simulation during dusty days (top 50% dust days) is ~0.2 cm^{-3}. According to previous laboratory experiments which suggest mineral dust activation ratio of about 0.5–3% at ~−20 °C (Zimmermann et al., 2008; Niemand et al., 2012), the dust-contributed INP number concentration in Taiwan summer season can reach about 1–6 L^{-1}, high enough to substantially influence the development of cloud and precipitation (Creamean et al., 2013; Fan et al., 2014).

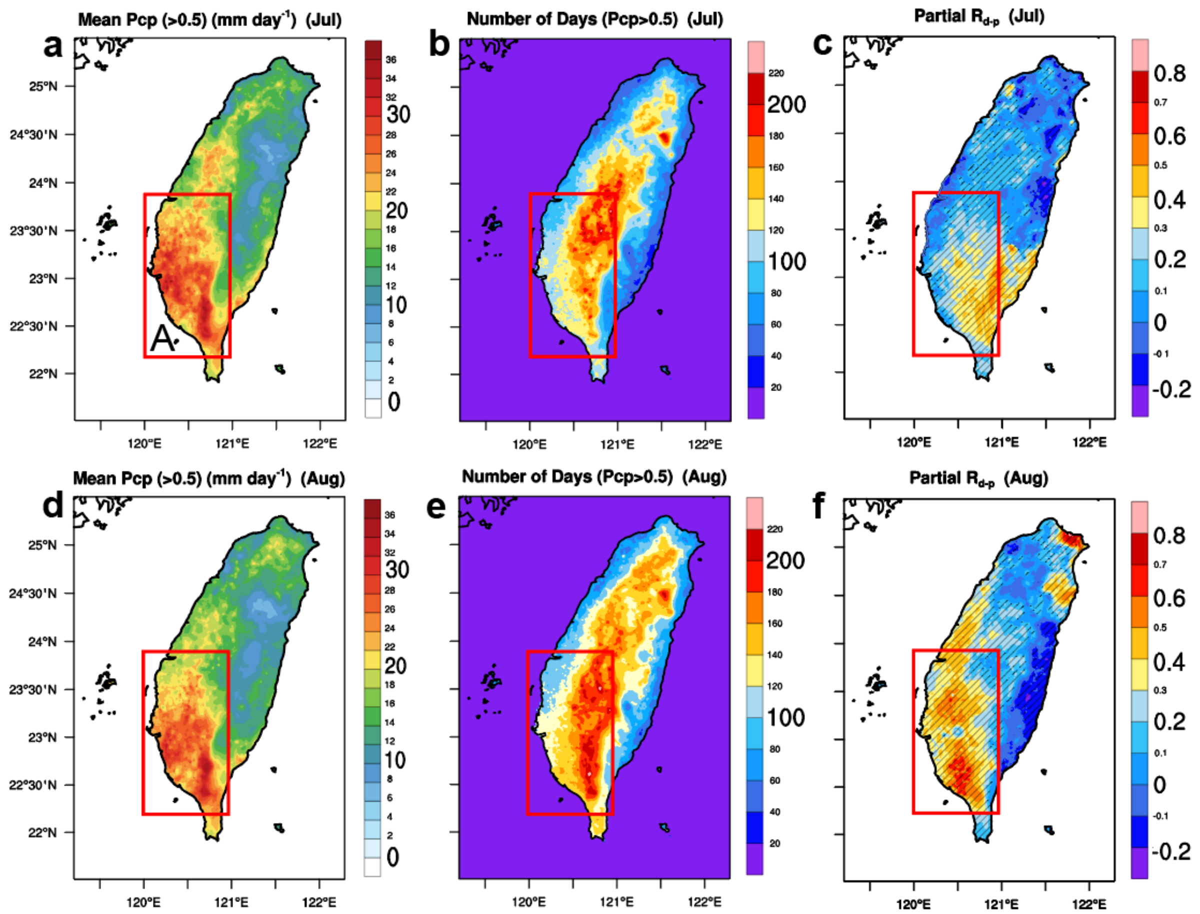

Figure 2. Mean precipitation amount (a) and frequency (b) of non-typhoon precipitation days (> 0.5 mm day^{-1}) in July (1989–2013); d, e same as a, b but in August. (c) Partial correlation (R_{dp}) between N_d and precipitation and the area at significance level of 0.05 ($p < 0.05$, the shaded area) in July; f same but in August. The red box in each panel marks the region (A) with heavy summer precipitation.

To investigate the possible impacts of dust particles on precipitation in Taiwan summer months, we have analyzed the 25-year (1989–2013) dataset of precipitation from TCCIP and N_d from GEOS-Chem-APM simulations. Because of the unique mechanisms of typhoon cases, recorded typhoon cases are not considered in our analysis. Figs. 2 a, b, d, and e show the mean rainfall amounts and the frequencies of non-typhoon precipitations for all days with daily mean precipitation >0.5 mm day^{-1}. Figs. 2 a & d show that the heavy summer rainfall mainly occurs over the southern part of Taiwan, on the western slope of the mountain range (region A, 22.25°N-23.75°N, 120°E-121°E). In July and August, the daily mean precipitation averaged in region A are over ~24 mm day^{-1} and can reach ~40 mm day^{-1}. With consideration of terrain effect, our study focuses on the dust-cloud-precipitation correlation on west-wind days. Directly related to the model dust transport, the GEOS-Chem (MERRA-2) daily u and v wind speed under 4 km are vertically averaged to represent the regional scale wind direction in the lower troposphere in the region. Our analysis indicates that the wind simulation is consistent with wind from ERA-Interim reanalysis in this region (23°N–25°N, 118.75°E–121.25°E).

Model simulations and CALIPSO observations show that, in July and August, the dust aerosols over this region are generally long-range transported at low altitude over the ocean; dust events may be entangled with water vapor, which is one of the controlling factors of cloud and precipitation. To analyze the relationship of precipitation and dust, the Pearson's partial correlation between N_d and precipitation (R_{dp}) is used to eliminate the influences of vapor, which was used by previous studies (Engström & Ekman, 2010; Zhao et. al., 2019). R_{dp} is calculated by equation 1:

$$R_{dp} = \frac{R_{dp0} - R_{vp}R_{vd}}{\sqrt{1-{R_{vp}}^2}\sqrt{1-{R_{vd}}^2}} \qquad (1)$$

where R_{dp0} is the Pearson's total correlation between daily N_d (simulations by GEOS-Chem) and precipitation (gridded precipitation observation), R_{vp} is the Pearson's total correlation between daily total column water vapor (TCWV) (ERA-Interim reanalysis) and precipitation, and R_{vd} is the linear correlation between N_d and TCWV.

R_{dp} in July and August are given in Fig. 2 c, f. The results suggest that, in both months, the orographic precipitation is positively correlated with N_d in region A (at significance level of 0.05, $p < 0.05$), and the correlations are significant at the precipitation centers, with highest R_{dp} = 0.5 in July and 0.6 in August, respectively. The result suggests that the summer precipitation increases with mineral dusts, indicating dust aerosols may play important roles in the formation and development of orographic precipitation, especially in heavy rainfall regions. It should be noted that, in June, the non-typhoon precipitation (Fig. S2 a) is stronger than in July and August, while the long-term analysis shows no correlation between precipitation and N_d (Fig. S2 c). The possible reason is that, in June, Taiwan region is high influenced by heavy

Meiyu-front precipitations with different controlling mechanisms. Based on this statistical result, our study focuses on the dust-precipitation interactions in July and August in region A.

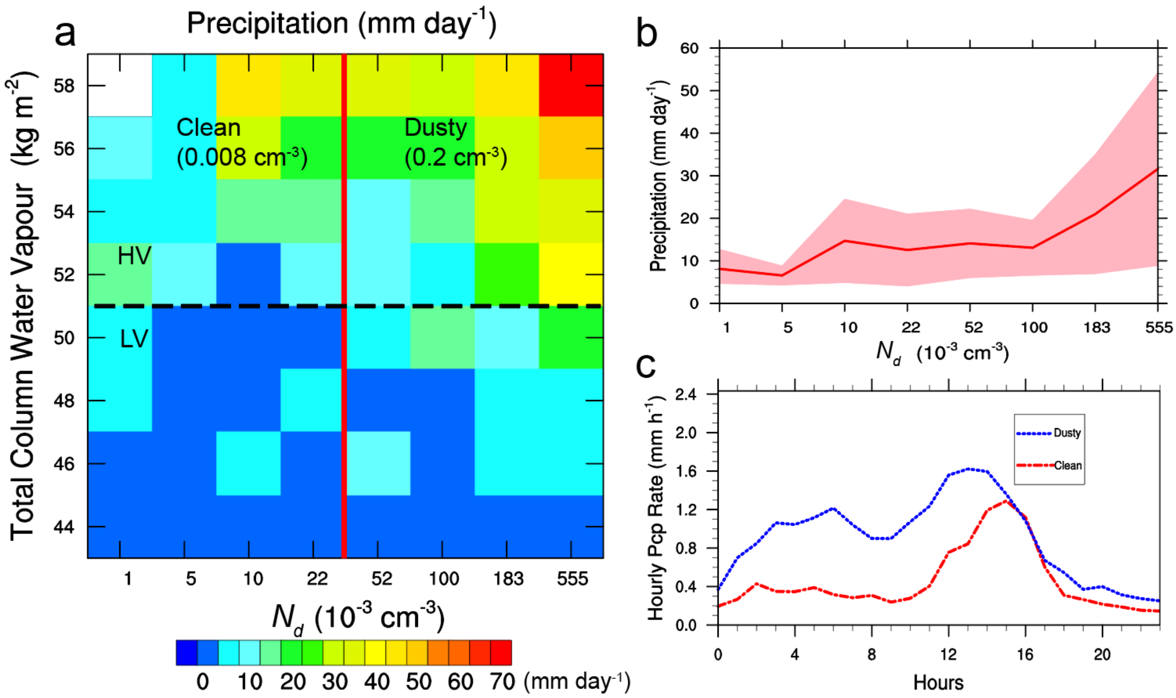

Figure 3. (a) Daily precipitation averaged in dust-vapor bins; (b) Precipitation versus N_d: the solid red line represents the precipitation averaged over all vapor conditions (44–58 kg m^{-2}) in each dust-bin, the pink shade represents the range of precipitation change between low (44–50 kg m^{-2}) and high (52–58 kg m^{-2}) vapor conditions; (c) Hourly precipitation averaged in clean (1–22 $\times$ 10^{-3} cm^{-3}, dust-bin 1–4) (red line) and dusty (52–555 $\times$ 10^{-3} cm^{-3}, dust-bin 5–8) (blue line) bins.

To untangle the influences of mineral dust from the co-varying water vapor concentrations, non-typhoon precipitation averaged in the southwest Taiwan region marked as A in Fig. 2 (averaged rainfall larger than 0.5 mm day^{-1}) in 507 selected days (JA) are stratified into 8 vapor bins by the mean TCWV. The daily precipitations are stratified into 8 dust bins, according to N_d at intervals of 12.5% of total case number. The precipitation matrix is summarized in Fig. 3a. The value in each N_d -TCWV bin in Fig. 3a represents the averaged rainfall intensity under the corresponding dust-vapor conditions. To better understand the relationship between precipitation and N_d under different vapor conditions, the precipitation bins are defined as "clean" (with lower 50% N_d, dust-bins 1–4) and "dusty" (top 50% N_d, dust-bins 5–8). The mean N_d increases by a factor of ~25 (from 0.008 to 0.2 cm^{-3}) from clean to dusty conditions and by ~2 orders of magnitude from the lower 25% (dust bins 1–2) to the top 25% (dust bins 7–8) conditions. With the precipitations divided into high vapor (HV) and low vapor (LV) conditions according to TCWV, Fig. 3a shows that, with similar water vapor condition (in each vapor-bin), the precipitations generally increase with N_d. High values of rainfall (> 30 mm day^{-1}) are mainly distributed in the dusty-HV quadrant, indicating that strong precipitations are related to the appearances of both high N_d and vapor. In Fig. 3b, the precipitations in each dust-bin are averaged in HV (upper edge), LV (lower edge) and all vapor conditions (solid line). Fig. 3b shows that from clean to dusty cases, the mean precipitation shows a significant increasing trend with N_d, increasing from 11 to 19 mm day^{-1} by ~72%. Fig. 3a shows that the precipitation increases with N_d more significantly in HV than in LV conditions. The different variation trends of precipitation responding to N_d in HV and LV conditions suggest the atmospheric moisture appears to influence the dust–precipitation interactions.

The hourly observations at 27 sites in region A (site information is given in Table S2) are selected to further study the responses of rainfall to the variation of N_d. According to the selection of precipitation days in Fig. 3a, hourly precipitation data are also stratified into dust-vapor bins. Fig. 3c gives the rain rate averaged in clean and dusty conditions. The hourly precipitation rates show that, from clean to dusty days, the summertime precipitation rate on average increases by ~100% in the morning and early afternoon (before 1400 LT), and the late afternoon precipitation (after 1400 LT) does not show clear differences. The different responses of precipitation to the dust changes before and after 1400 LT may be caused by the diverse precipitation types and mechanisms in the two periods. Previous studies indicate that the diurnal precipitations are influenced by the interaction between land–sea breeze and orography (Kishtawal & Krishnamurti, 2000; Huang & Wang, 2014), additionally, afternoon precipitations are highly impacted by afternoon thunderstorms and local severe convections (Chen et al., 2003; Lin et al., 2010).

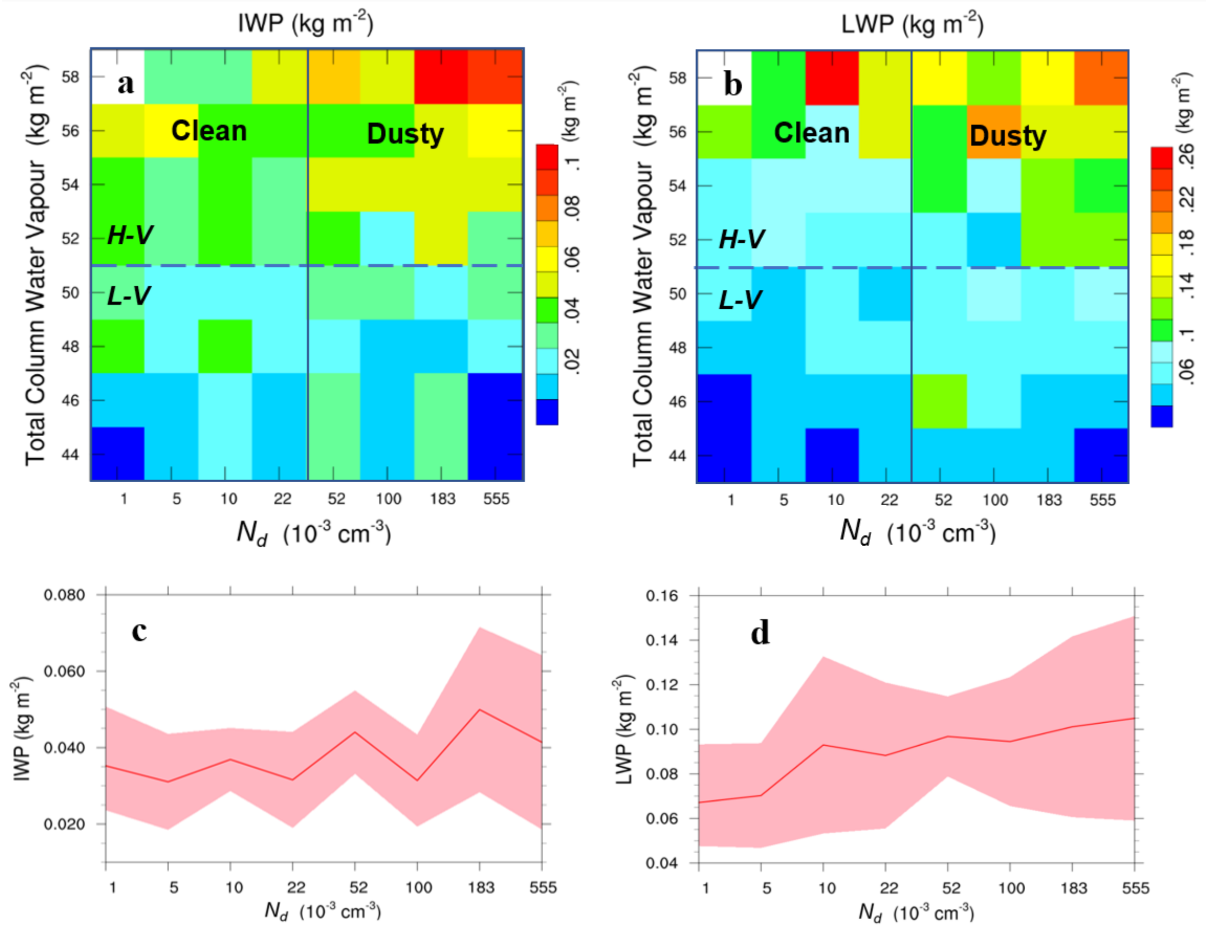

Figure 4. Same dust-vapor matrix as Fig. 3a, for IWP (a) and LWP (b); Same as Fig. 3b, for IWP (c) and LWP (d)

ERA-Interim reanalysis of cloud properties are analyzed to provide insights on the physical mechanism of possible impacts of dust on the summertime precipitations over the southern Taiwan region. In Figs. 4 a & b, the ice water path (IWP) and liquid (LWP) averaged in region A on the corresponding days of selected precipitations are stratified into dust-vapor bins as in Fig. 3a. The results indicate that, under similar vapor conditions, the IWP (Fig. 4a) and LWP (Fig. 4b) increase with N_d: consistent with the orographic precipitations. In Figs. 4c & d, IWP and LWP in the matrixes are averaged in HV (upper edge), LV (lower edge) and all vapor conditions (solid line). Figs. 4 c & d show that, the IWC and LWC have increasing trends with increasing N_d. From clean to dusty cases, the averaged IWP increases by ~25% (0.033 to 0.041 kg m^{-2}) and the LWP increases by ~21% (0.08 to 0.10 kg m^{-2}), suggesting a positive impact of mineral dust on the cloud development possibly through an enhanced glaciation and release of latent heat, which is similar to the convective invigoration effect (Andreae et al., 2004). Figs. 4 c & d also show different responses of LWP and IWP to the increasing N_d under HV and LV conditions; with adequate water vapor, IWP and LWP increase more significantly in HV than in LV conditions. This suggests that the atmospheric water vapor plays an important role in the dust-cloud-precipitation interactions, likely because for dust to be effective IN, the convection must reach about the −15 ~ −20 °C levels and rich columnar water vapor is an important condition for such strong convections. Taiwan's orography may also play a role in invigorating the convection.

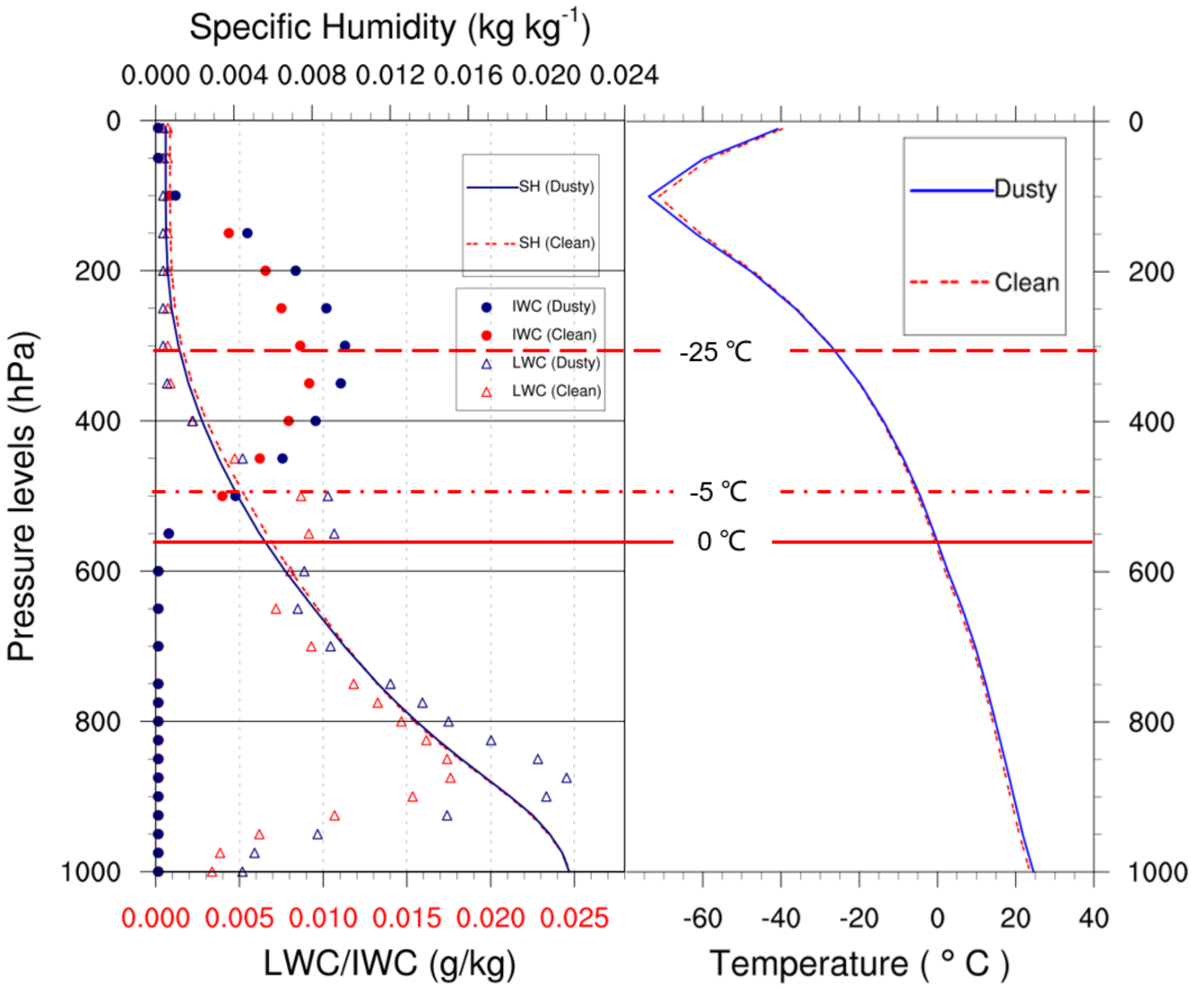

Figure 5. Daily vertical profile averaged over region A of (a) specific humidity (line), LWC

(triangles), IWC (dots) and (b) atmospheric temperature in clean (red) and dusty (blue) conditions, according to the case selection in Fig. 4.

To gain further insight into the dust-cloud-precipitation interactions and to provide more detailed physical explanations, we examine the vertical structures of cloud properties averaged in region A. Fig. 5 shows the vertical profiles of ERA-Interim reanalysis of specific humidity, ice (IWC) and liquid water content (LWC), and temperature averaged in clean and dusty conditions, according to the case selection of the upper matrixes. After controlling for the co-varying conditions, the vertical structures of atmospheric vapor and temperature are similar in different N_d cases. From clean to dusty conditions, with N_d increasing by a factor of ~25, IWC increases by ~30% in the midlevel cloud (−5 > T > −30 °C). At lower and warmer level, both IWC and LWC are enhanced in the mixed-phase cloud, possibly through the rime-splintering and melting processes of ice particles. The generated larger cloud droplets and raindrops with higher accretion efficiency may ultimately lead to the enhancement of precipitation. Previous measurements have indicated a direct link between long-range transported dust aerosols and cloud ice formation (Creamean et al., 2013), suggesting that mineral dust can serve as effective INPs (DeMott et al., 2003; Eidhammer et al., 2010). In orographic clouds, the presence of mineral dust has been recognized to enhance ice and mixed-phase clouds because of the earlier initiation of the cloud ice (Muhlbauer & Lohmann, 2009). Due to increased cloud ice number concentrations, the more intensive rime-splintering process and stronger deposition growth occur in the dust-enriched air (Fan et al., 2014), resulting in more water vapor converting into cloud hydrometeor particles. Larger cloud droplets could be generated through ice particle melting, leading to stronger coalescence growth and enhanced rain formation as the result (Freud & Rosenfeld, 2012; Gerber 1996). The convective invigoration by mineral dust could also be an important reason of the enhancement of the cloud water content and precipitation (Koren et al., 2005; Storer et al., 2013; Storer et al., 2014).

4 Conclusions and Discussion

This study explores the possible influence of atmospheric mineral dusts on summertime (JA) mixed-phase cloud and precipitation over the southern Taiwan region, using 25-year GEOS-Chem N_d simulations, gridded daily precipitation (TCCIP) measurement, and ERA-Interim analysis data. The model-simulated dust events and concentrations in the region are generally consistent with CALIPSO satellite and in-situ surface measurements. The GEOS-Chem N_d simulations indicate that the long-range transport of dust has significant influences on the atmospheric dust loading over the Taiwan region. The mean N_d in dusty conditions is ~25 times higher than in clean cases, which could be high enough to impact cloud development and precipitation.

Statistical analysis of the 25-year data of precipitation and N_d shows significant positive correlation between dust number concentrations and the non-typhoon precipitations over the windward side of the mountain ranges in summer (JA). As dust events may be entangled with events of enriched atmospheric water vapor, the regional averaged precipitations and cloud water paths are stratified into dust-vapor bins. The results indicate that the orographic cloud and precipitation are influenced by both N_d and vapor. Under similar vapor conditions, precipitation and cloud water generally increase with N_d. From clean to dusty cases, the hourly precipitation rates almost doubled in the morning to the early afternoon (before 1400 LT) and no clear differences are found in the late afternoon or nighttime. The results also suggest that atmospheric vapor plays a critical role in the dust-cloud-precipitation interactions, that in high water vapor conditions, precipitation and cloud water paths show more significant increasing trend with N_d than with low total column water vapor. The vertical structure of cloud variables suggest that, under similar meteorological conditions (specific humidity and temperature), heterogeneous nucleation in the mid-level cloud is enhanced in the dust-rich atmosphere, resulting in stronger mixed-phase processes and cold rain processes. Besides the microphysical effect, the convective invigoration and indirect effects by mineral dust could also be important for the enhancement of the summertime precipitation. This study indicates that mineral dusts play a critical role in altering ice formation, cloud development, and precipitation efficiency in the orographic cloud in summer (JA) over the Taiwan region. We also found that some extreme non-typhoon precipitations and strong dust events occur concurrently over the mountain region. Thus, accounting for dust influences may improve the accuracy of numerical weather prediction models, most of which only consider the influences of temperature and supersaturation, but not of the actual number of ice nuclei on heterogeneous freezing.

In this study, the mineral dust impact on cloud is isolated from the co-varying atmospheric water vapor by using partial correlation and water vapor stratification. However, other controlling factors such as dynamics and other species of aerosol are hard to identify. In addition, the statistical results cannot prove direct and detailed physical mechanisms and processes of the dust-cloud interactions. To solve these remaining problems, more detailed numerical simulations are needed to carry out sensitivity experiments to investigate the dust-cloud-precipitation interaction, which will be the subject of further study.

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- The 1×1 km gridded daily precipitation dataset collected by the Taiwan Climate Change Projection and Information Platform (TCCIP, http://tccip.ncdr.nat.gov.tw/NCDR/main/index.aspx) project.
- European Centre for Medium-Range Weather Forecasts. 2009, updated monthly. ERA-Interim Project. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6CR5RD9. Accessed Dec. 26, 2019.

- The GEOS-Chem model is a community model managed by the Atmospheric Chemistry Modeling Group at Harvard University with support from NASA. The work described in this paper is based on GEOS-Chem version 10-01. GEOS-Chem is a freely accessible community model that can be downloaded from http://acmg.seas.harvard.edu/geos/.
- The long-term measurement of dust concentration at the Cape Fuguei Research Station is conducted by the Research Center of Environmental Changes (RCEC) with support from the Academia Sinica and the MOST, Taiwan.

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