Satellite-Based Analysis of Aerosol Impacts on Ice Clouds and Their Distribution Characteristics (Postprint)

Authors: Fan Xuewei

Date: 2021-04-14T00:00:00+00:00

Abstract

By utilizing CALIOP (the Cloud-Aerosol Lidar with Orthogonal Polarization) Level 3 monthly mean ice cloud and aerosol products and MODIS (Moderate-Resolution Imaging Spectroradiometer) Level 3 daily mean atmospheric products from January 2010 to December 2016, this study investigates the spatial distribution characteristics of aerosols and ice clouds and the influence of aerosols on ice clouds. The results demonstrate that latitude is closely correlated with ice cloud distribution, with a maximum region of ice cloud sample counts occurring in high-altitude areas near the tropics; as latitude increases, the altitude of both the maximum and high-value regions of ice cloud sample counts gradually decreases, with notable differences between the Northern and Southern Hemispheres; aerosols exhibit a maximum near the surface in low-latitude regions symmetric about the equator, extending to approximately 5 km in the Northern Hemisphere and about 3 km in the Southern Hemisphere; the temporal variation trends of aerosols and ice clouds are relatively consistent, whereas ice water content and ice cloud particle radius display an inverse relationship over time, with poor temporal correspondence between aerosol variations and changes in ice water content and ice cloud particle radius; clean regions exhibit relatively large aerosol optical depths due to the influence of sea salt particles, yet these regions still maintain smaller ice cloud optical depths; aerosols promote ice cloud formation in the temperature ranges of 0°C to -10°C and -20°C to -40°C; as temperature decreases, cloud ice water content decreases while ice cloud particle radius increases; in polluted regions, ice water content is smaller and ice cloud particle radius is also smaller compared to clean regions.

Full Text

Preamble

Based on Satellite Data: Analysis of Aerosol Effects on Ice Clouds and Their Distribution Characteristics

FAN Xuewei[1], ZHENG Youfei[1,2,3], WANG Liwen[1]
[1]School of Atmospheric Physics, Nanjing University of Information Science & Technology, Nanjing 210044, Jiangsu, China
[2]Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, Nanjing 210044, Jiangsu, China
[3]Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment Technology, Nanjing University of Information Science & Technology, Nanjing 210044, Jiangsu, China

Abstract

This study investigates the spatial distribution characteristics of aerosols and ice clouds and the influence of aerosols on ice clouds using CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) level-3 monthly mean ice cloud and aerosol products and MODIS (Moderate Resolution Imaging Spectroradiometer) level-3 monthly mean products. The results indicate that latitude is closely correlated with ice cloud distribution, with maximum ice cloud sample numbers occurring in high-altitude regions near the tropics. As latitude increases, both the maximum value and the altitude of the high-value region gradually decrease, with notable differences between the Northern and Southern Hemispheres. Aerosols exhibit maximum values near the surface in low-latitude regions symmetric about the equator, and can develop up to approximately 5 km in the Northern Hemisphere versus about 3 km in the Southern Hemisphere. Temporal variations of aerosols and ice clouds show consistent trends, while ice water content and ice cloud particle radius display an inverse relationship. However, temporal correspondence between aerosols and changes in ice water content and particle radius is weak. Clean regions show large aerosol optical thickness due to sea salt particles, yet this does not affect the smaller ice cloud optical thickness observed in these areas. Aerosols promote ice cloud formation in the temperature range of -20 ℃ to -10 ℃. As temperature decreases, cloud ice water content decreases while ice cloud particle radius increases. In polluted regions, ice water content is lower and ice cloud particle radius is smaller compared to clean regions.

Keywords: ice clouds; aerosols; satellite data; ice water content; effective particle radius

1. Introduction

The interaction between aerosols and radiation represents one of the most uncertain factors in the climate system and poses a significant challenge in current climate research. Aerosol particles can serve as cloud condensation nuclei or ice nuclei, altering cloud microphysical and radiative properties as well as cloud lifetime. Ice clouds cover approximately 20%-30% of the global area and play an important role in Earth's energy balance and climate system. Ice cloud formation is closely related to ice nuclei, and aerosols acting as effective ice nuclei exert a crucial influence on ice cloud development.

Ice cloud formation involves homogeneous and heterogeneous nucleation (contact freezing, immersion freezing, condensation freezing, and deposition freezing). Ice particles form through both homogeneous and heterogeneous nucleation at temperatures below -38 ℃, whereas they form exclusively through heterogeneous nucleation at temperatures above -38 ℃. Laboratory studies since the 1970s have demonstrated that mineral dust particles are efficient ice nuclei that may significantly impact cloud and precipitation processes. Research indicates that increased aerosol concentrations can suppress warm cloud precipitation while enhancing ice cloud precipitation. Previous studies have extensively investigated aerosol interactions with water clouds, but research on aerosol effects on ice cloud macro- and microphysical properties remains limited.

In recent years, climate modeling has become an important method for studying aerosol indirect effects, though significant uncertainties persist. Satellite-borne active and passive sensor data have been widely applied in scientific research due to their high spatial and temporal coverage, enabling comprehensive high-resolution observations of ice cloud and aerosol properties. The A-Train satellite constellation, comprising multiple satellites in similar orbits, provides complementary measurements of aerosols, clouds, temperature, relative humidity, and radiative fluxes, offering a relatively complete view of Earth's atmospheric layers. This study focuses on ice clouds forming at temperatures above -40 ℃, which require aerosol participation as ice nuclei through heterogeneous nucleation.

1.1 Study Area

In mid-to-high latitude regions of the Northern Hemisphere, free tropospheric aerosol conditions are largely determined by anthropogenic pollution from North America, Europe, and East Asia, desert dust emissions from Africa, the Americas, and Asia, and biomass burning smoke from latitudes above 50°N. These aerosols can serve as effective ice nuclei. In contrast, aerosol concentrations are considerably lower in remote marine regions of the Southern Hemisphere mid-to-high latitudes (>50°S). Although the primary particle source is oceanic, these regions are situated within the Antarctic low-pressure belt and experience prevailing westerlies throughout most of the year, resulting in clean marine conditions where large particles have likely been removed through dry and wet deposition.

Based on these differences, we selected four study regions: Region A (40°-60°S, 60°-90°E) and Region B (40°-60°S, 120°-150°E) representing clean areas, and Region C (40°-60°N, 90°-120°E) and Region D (40°-60°N, 90°-120°W) representing polluted areas.

1.2 Data Sources

The CALIPSO satellite carries three Earth observation instruments: the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), an infrared imaging radiometer, and a wide field camera. CALIOP is a spaceborne polarization lidar that observes the global spatial structure and properties of aerosols and clouds. It measures aerosol particle content and size, and its 532 nm depolarization information can distinguish between ice and water clouds while accurately determining the altitude of aerosol layers and clouds. CALIOP provides high vertical resolution (30-60 m) and horizontal resolution (333 m) measurements of global aerosols and clouds.

The MODIS instrument aboard the Terra satellite is an important tool for observing global biological and physical processes. This "图谱合一" (spectrum-image integrated) optical remote sensor conducts comprehensive observations of solar radiation, atmosphere, ocean, and land across 36 discrete spectral bands ranging from 0.4 m to 14.4 m. This study uses MODIS level-3 monthly mean products (MOD08_D3) to determine ice cloud effective particle radius.

1.3 Methods

This study employs CALIOP level-3 monthly mean ice cloud products (CAL_{LID}L3_{{{Ice}}*{{Cloud}}}) and aerosol products (CAL*{LID}L3_{APro}) along with MODIS level-3 monthly mean products (MOD08_D3) to investigate aerosol effects on ice cloud formation from January 2010 to December 2016. The CALIOP ice cloud level-3 product parameters are derived from the CAL_{LID}L3_{{{Ice}}_{{Cloud}}} profile product with horizontal resolution of 5°$×2°*andverticalresolutionof*180*m*, *covering*40*verticallayersfromapproximately*0− 12*kmaltitude.TheCALIOPaerosollevel*−3*productparametersarederivedfromtheCAL*$_{LID}$*L*3$_{APro}$*productwit* 20*kmaltitude.MODISlevel* − 3*productsarestatisticallyderivedfromlevel* − 2*productswith*1°×$1° horizontal resolution, providing parameters including cloud phase, particle size, optical thickness, water path, and aerosol optical thickness.

The methodology for studying aerosol effects on ice clouds involves comparing ice cloud properties in the lower and middle troposphere between Northern and Southern Hemisphere mid-to-high latitude regions. The fraction of ice clouds (F_{ice}) is defined as: F_{ice} = N_{ice}/(N_{ice} + N_{water} + N_{mixed}), where N_{ice}, N_{water}, and N_{mixed} represent sample numbers of ice clouds, water clouds, and mixed-phase clouds, respectively.

Data processing involves: (1) analyzing global distribution of aerosols and ice clouds using the four study regions; (2) obtaining aerosol optical thickness, ice cloud optical thickness, and ice cloud effective particle radius from MODIS data, and aerosol sample numbers, ice cloud sample numbers, and ice water content from CALIOP data; (3) investigating aerosol effects on cloud properties by linking CALIOP and MODIS cloud and aerosol characteristics.

---

2. Results

2.1 Spatial Distribution of Aerosol and Ice Cloud Samples

The spatiotemporal distribution of ice clouds significantly impacts Earth-atmosphere system radiation. Figure 1 shows the annual mean global distribution of ice cloud samples in latitude-vertical cross-sections. Latitude is closely correlated with ice cloud distribution. Near the tropics, ice cloud sample numbers are substantially higher than other regions, with maximum values concentrated at altitudes of 14-16 km, relatively higher in the Southern Hemisphere than the Northern Hemisphere. As latitude increases, both the maximum value and the altitude of the high-value region gradually decrease, reaching approximately 6-8 km at 60°N/S. The minimum altitude of ice cloud occurrence also decreases with increasing latitude, with ice clouds forming near the surface in polar regions. Except in polar areas, ice clouds rarely occur above 20 km, with most located below 15 km. Overall, higher temperatures and vigorous water vapor evaporation in equatorial regions lead to higher ice cloud occurrence probabilities but at greater altitudes, with all parameters gradually decreasing toward the poles.

Figure 2 presents the annual mean global distribution of aerosol samples in latitude-vertical cross-sections. Aerosols show substantial differences between hemispheres. Maximum values occur near the surface in low-latitude regions symmetric about the equator, with high-value zones located over oceans where sea spray contains abundant sulfates and sea salt particles that serve as effective aerosols. Land areas show smaller aerosol numbers compared to oceans. Some continental regions above 4 km altitude show blank samples as satellites cannot detect aerosols there. In the upper troposphere, Northern Hemisphere aerosols can develop to approximately 5 km, while Southern Hemisphere aerosols reach only about 3 km. Notably, in the Northern Hemisphere, continents with smaller aerosol sample numbers exhibit high-value zones extending to greater heights (up to 6 km), whereas in the Southern Hemisphere, oceans with higher aerosol numbers show high-value zones remaining near sea level.

2.2 Temporal Distribution of Microphysical Parameters

Figure 3 illustrates temporal variations of ice cloud microphysical parameters and aerosol samples. Ice cloud sample numbers peak in February-March and reach minima in August-September in Region A, while Region B shows peaks in July and minima in December. Ice water content (IWC) and ice cloud effective particle radius show inverse relationships: when IWC peaks, particle radius reaches minima, and vice versa. Three key findings emerge: (1) Aerosol and ice cloud sample numbers show consistent temporal trends, with peaks and valleys corresponding closely though with slight temporal differences; (2) IWC and effective particle radius exhibit inverse temporal relationships; (3) Except for Region C, temporal correspondence is weak between aerosol sample numbers and peaks/valleys of IWC and particle radius.

2.3 Aerosol Effects on Ice Cloud Microphysical Parameters

Figure 4 shows horizontal distributions of aerosol optical thickness (AOT), which ranges between 0.0-1.2. Region C exhibits relatively high AOT (0.15-0.25) with an average of 0.18, while Region D shows smaller, more uniform AOT (0.10-0.15, average 0.12). Despite containing abundant continental aerosols, land areas show relatively small and uniform AOT distributions. Region A and B show AOT values of 0.10-0.20 (average 0.14) and 0.10-0.15 (average 0.12), respectively.

Ice cloud optical thickness (IOT) affects the amount of solar shortwave radiation reaching the surface. Figure 5 presents IOT spatial distributions, ranging 0-8. Region A shows relatively uniform IOT distribution (2.0-3.0, average 2.5), while Region B shows higher IOT (2.5-4.0, average 3.2) due to abundant sea salt particles contributing numerous ice nuclei. Region C and D show larger average IOT values of 3.8 and 3.5, respectively, with a maximum band between 52°-56°N.

Figure 6 shows the fraction of ice clouds (F_{ice}) as a function of cloud top temperature at 1 ℃ intervals between 0 ℃ and -40 ℃. As temperature decreases, ice cloud fractions increase in all regions, but with distinct regional differences. Region B, representing clean marine conditions, shows lower ice cloud fractions despite high near-surface aerosol numbers, indicating minimal aerosol effects. Region C and D, with significant continental aerosol impacts, show higher ice cloud fractions. Notably, Region C's ice cloud fraction exceeds Region D's between -10 ℃ and -20 ℃, while Region D leads between -20 ℃ and -30 ℃. Overall, aerosols clearly promote ice cloud formation in the 0 ℃ to -10 ℃ and -20 ℃ to -40 ℃ temperature ranges.

Figure 7 displays regional vertical distributions of annual mean aerosol sample numbers with temperature. Aerosol sample numbers decrease as cloud top temperature decreases. Region C shows the highest aerosol sample numbers, followed by Region D. Below -10 ℃, westerlies and dry/wet deposition reduce aerosol numbers significantly, making Region B's aerosol sample numbers notably lower than Region A's below -25 ℃.

Figure 8 shows regional vertical distributions of IWC with temperature. The largest IWC differences between regions occur between 0 ℃ and -10 ℃: Region

C IWC is 0.19 $g \cdot m^{-3}$, Region D is 0.15 $g \cdot m^{-3}$, Region A is 0.12 $g \cdot m^{-3}$, and Region B is 0.10 $g \cdot m^{-3}$. As temperature decreases, IWC decreases and regional differences diminish, reaching approximately 0.02 $g \cdot m^{-3}$ below -40 ℃ with only minor differences between regions.

Figure 9 presents regional vertical distributions of ice cloud effective particle radius with temperature. Particle radius increases as temperature decreases. Between 0 ℃ and -15 ℃, Region B shows the largest radius (28-32 m) because abundant sea salt particles do not participate in ice crystal formation, eliminating competition for water vapor. Region C shows the smallest radius (20-24 m) due to numerous mineral dust particles competing for water vapor during ice nucleation, consistent with Twomey effects. Between -15 ℃ and -40 ℃, aerosol sample numbers correlate well with particle radius, satisfying the principle that increased aerosols competing for ice nucleation leads to smaller particle sizes.

---

3. Conclusions

This study yields four main conclusions:

(1) Latitude is closely correlated with ice cloud distribution. Maximum ice cloud sample numbers occur in high-altitude regions near the tropics, with the altitude and magnitude of these maxima decreasing as latitude increases. Southern Hemisphere mid-to-high latitudes show higher average ice cloud occurrence altitudes than the Northern Hemisphere. Aerosols exhibit maximum values near the surface in low-latitude regions symmetric about the equator, with high-value zones over oceans. Northern Hemisphere continents with smaller aerosol sample numbers show high-value zones extending above 5 km, while Southern Hemisphere oceans with higher aerosol numbers show high-value zones remaining near sea level.

(2) Temporal variations of aerosol and ice cloud sample numbers are consistent, while ice water content and ice cloud effective particle radius show inverse relationships. However, temporal correspondence is weak between aerosol sample numbers and peaks/valleys of ice water content and particle radius.

(3) Clean regions show high aerosol optical thickness due to marine surface aerosols, but these oceanic aerosols have minimal impact on ice clouds, resulting in smaller ice cloud optical thickness in clean regions. As temperature decreases, aerosol sample numbers and ice water content decrease, while ice cloud fraction and particle radius increase. Polluted regions show higher aerosol sample numbers and ice cloud fractions than clean regions between 0 ℃ and -10 ℃ and -20 ℃ and -40 ℃, but clean regions exhibit higher ice water content and effective particle radius overall.

(4) Aerosol particles as primary ice nuclei sources significantly impact ice cloud formation. Sea salt and sulfate particles near the ocean surface

do not contribute to ice nuclei formation, while mineral dust particles in polluted regions compete for water vapor, resulting in smaller ice cloud particle radii.

References

[1] Shi Guangyu, Wang Biao, Zhang Hua, et al. The radiative and climatic effects of atmospheric aerosols[J]. Chinese Journal of Atmospheric Sciences, 2008, 32(4): 826-840.

[2] Liou K. Influence of cirrus clouds on weather and climate processes: A global perspective[J]. Monthly Weather Review, 1986, 114(6): 1167-1199.

[3] Yang Jun, Chen Baojun, Yin Yan. Physics of clouds and precipitation[M]. Beijing: China Meteorological Press, 2011.

[4] Hoose C, Mohler O. Heterogeneous ice nucleation on atmospheric aerosols: A review of results from laboratory experiments[J]. Atmospheric Chemistry and Physics, 2012, 12(20): 9817-9854.

[5] Zhang D, Wang Z, Heymsfield J, et al. Quantifying the impact of dust on heterogeneous ice generation in midlevel supercooled stratiform clouds[J]. Geophysical Research Letters, 2012, 39(18): L18805.

[6] Seifert P, Ansmann A, Mattis I, et al. Saharan dust and heterogeneous ice formation: Eleven years of cloud observations at a central European EARLINET site[J]. Journal of Geophysical Research: Atmospheres, 2010, 115(D20): D013222.

[7] Fan Xuewei, Zheng Youfei, Wang Liwen, et al. Differences in the fractions of heterogeneous ice clouds over China based on CALIPSO data[J]. Arid Land Geography, 2020, 43(5): 1210-1219.

[8] Yang Lei, Yin Yan, Yang Shaozhong, et al. Characteristics of atmospheric ice nuclei and their relationship to aerosols in winter in Nanjing[J]. Chinese Journal of Atmospheric Sciences, 2013, 37(5): 983-993.

[9] Wang Wencai, Huang Jianping, Minnis Patrick, et al. Dusty cloud properties and radiative forcing over dust source and downwind regions derived from A-Train data during the Pacific dust experiment[J]. Journal of Geophysical Research: Atmospheres, 2010, 115(D4): D014109.

[10] Ma Yue, Xue Huiwen. A study of aerosol effects on stratocumulus clouds using CloudSat and MODIS data[J]. Acta Scientiarum Naturalium Universitatis Pekinensis, 2012, 48(2): 239-245.

[11] Peng Jie, Zhang Hua. Impact of aerosol on cloud properties at typical sites[J]. Transactions of Atmospheric Sciences, 2015, 38(4): 465-472.

[12] Zheng Qian, Zheng Youfei, Wang Liwen, et al. Macrophysical and microphysical properties of ice clouds during heavy rainfalls in Beijing-Tianjin-Hebei region in summer[J]. Arid Land Geography, 2019, 42(1): 67-76.

[13] Deng Junying, Ding Mingyue, Wang Wencai, et al. Vertical distributions of microphysical properties of ice particles in a heavy rain[J]. Arid Land Geography, 2016, 39(1): 590-599.

[14] Koren I, Kaufman Y J, Rosenfeld D, et al. Aerosol invigoration and restructuring of Atlantic convective clouds[J]. Geophysical Research Letters, 2005, 32(14): L14828.

[15] Shi Rui, Wang Tijian, Li Shu, et al. The spatial and temporal characteristics of aerosol-cloud-precipitation interactions during summer in East Asia[J]. Chinese Journal of Atmospheric Sciences, 2015, 39(1): 12-22.

[16] Yang Bingyun, Zhang Hua, Peng Jie, et al. Analysis on global distribution characteristics of cloud microphysical and optical properties based on CloudSat data[J]. Plateau Meteorology, 2014, 33(4): 1105-1118.

[17] Mattis I, Müller D, Ansmann A, et al. Ten years of multiwavelength Raman lidar observations of free tropospheric aerosol layers over central Europe: Geometrical properties and annual cycle[J]. Journal of Geophysical Research: Atmospheres, 2008, 113(D20): D009636.

[18] Bigg E. Ice nucleus concentrations in remote areas[J]. Journal of the Atmospheric Sciences, 1973, 30(30): 1153-1157.

[19] Liu Gang, Shi Weizhe, You Rui. Cloud aerosol lidar of America[J]. Spacecraft Engineering, 2008, 17(1): 78-84.

[20] Zhao Jian, Sun Xuejin, Zhang Riwei, et al. Application of CALIPSO in global aerosol detection[J]. Meteorological, Hydrological and Marine Instruments, 2014, 31(1): 50-54.

[21] Su Xingtao, Xu Liren, Wei Qiang, et al. Study of impacts of dust aerosol on precipitation over East Asia[J]. Plateau Meteorology, 2016, 35(1): 211-219.

[22] Ebert M, Worringen A, Benker N, et al. Chemical composition and mixing state of ice residuals sampled within mixed phase clouds[J]. Atmospheric Chemistry and Physics, 2011, 11(6): 2805-2816.

[23] Zobrist B, Marcolli C, Peter T, et al. Heterogeneous ice nucleation in aqueous solutions: The role of water activity[J]. The Journal of Physical Chemistry A, 2008, 112(17): 3965-3975.

[24] Twohy C H, Petters M D, Snider J R, et al. Evaluation of the aerosol indirect effect in marine stratocumulus clouds: Droplet number, size, liquid water path, and radiative impact[J]. Journal of Geophysical Research: Atmospheres, 2005, 110(D8): D005116.

[25] Twomey S. The influence of pollution on the shortwave albedo of clouds[J]. Journal of the Atmospheric Sciences, 1977, 34(7): 1149-1152.

Note: Figure translations are in progress. See original paper for figures.