Postprint: Seasonal Distribution Characteristics of Precipitation Ice Clouds in the Beijing-Tianjin-Hebei Region Based on MODIS and CloudSat

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Abstract

Using Aqua MODIS and CloudSat satellite data from September 2008 to August 2016, precipitating ice clouds in the Beijing-Tianjin-Hebei region were identified and divided into four subregions for analysis, yielding seasonal distribution characteristics of these clouds to provide a basis for weather modification in the area. The results indicate that the occurrence frequency of precipitating ice clouds across the entire Beijing-Tianjin-Hebei region is relatively high in summer and exhibits an increasing trend. Regionally, the cloud top height of precipitating ice clouds is lowest in winter and highest in summer, while the minimum cloud top temperature is highest in winter and lowest in summer. Precipitating ice clouds are predominantly single-layer clouds in spring, summer, and autumn, whereas double-layer clouds dominate in winter. The number of precipitating ice cloud types is 7, 7, 6, and 5 in spring, summer, autumn, and winter, respectively, with deep convective clouds being predominant in summer (accounting for 48.3%) and nimbostratus clouds dominating in other seasons. The primary distribution heights of microphysical parameters (including ice water content, particle number concentration, and particle effective radius) are 0-13.5 km (spring), 3.5-17.0 km (summer), 1.0-14.0 km (autumn), and 0-11.0 km (winter). The distribution heights and maximum values of ice water content, particle effective radius, and particle number concentration are all highest in summer; however, particle effective radius is lowest in autumn, while ice water content and particle number concentration are lowest in winter. The vertical distribution characteristics of these three microphysical parameters are relatively consistent across subregions in summer, all exhibiting a single-peak structure, but differ substantially in other seasons.

Full Text

Preamble

The Beijing-Tianjin-Hebei region faces significant water scarcity, making research on precipitating ice clouds crucial for understanding precipitation mechanisms and assessing potential for weather modification. Ice clouds play a vital role in precipitation processes, yet their study has been limited by insufficient research duration and analysis. This study addresses this gap by examining the seasonal distribution characteristics of precipitating ice clouds across the region.

Using Aqua MODIS and CloudSat satellite data from September 2008 to August 2016, we screened for precipitating ice clouds in the Beijing-Tianjin-Hebei area and divided the region into four sub-regions for detailed analysis. The CloudSat 2B-CLDCLASS product provides precipitation indicators that have been validated in previous research, allowing us to identify both precipitating and non-precipitating ice clouds. By combining MODIS cloud phase information with CloudSat' s vertical resolution capabilities, we can investigate cloud internal structures that are essential for understanding ice cloud characteristics. This comprehensive seasonal analysis provides a foundation for weather modification operations in the region.

1. Data and Methods

This study utilizes CloudSat 2B-CLDCLASS and 2B-CWC-RO products, along with MODIS MYD06_{L2} cloud product data. The MODIS data have a spatial resolution of 5 km × 5 km and include latitude/longitude, cloud phase, cloud top height, and cloud top temperature information. Cloud phase is identified using the Cloud_{{{Phase}}_{{Infrared}}} parameter, where values of 1, 2, 3, 4, and 5 represent ice clouds, water clouds, mixed-phase clouds, clear sky, and undetermined conditions, respectively. The high-resolution, multi-spectral characteristics of MODIS enable reliable cloud phase identification for both simple single-layer and complex multi-layer cloud systems.

CloudSat data include latitude/longitude, altitude, cloud type, precipitation indicators, cloud layer count, ice particle number concentration, ice particle effective radius, and ice water content, with a spatial resolution of 2.5 km (along-track) × 1.4 km (cross-track) and 240 m vertical resolution. Cloud type and precipitation indicators are derived from the 2B-CLDCLASS product, where a precipitation flag value of 1 indicates precipitation occurrence. Cloud layer information comes from the cloud_{scenario} parameter in 2B-CWC-RO, with values of 1, 2, 3, and 4 representing single-layer, double-layer, triple-layer, and more than three-layer cloud systems, respectively.

The study period spans September 2008 to August 2016, with seasons defined as spring (March-May), summer (June-August), autumn (September-November), and winter (December-February). Based on CloudSat orbital paths, the Beijing-Tianjin-Hebei region (36.02°-42.62°N, 113.06°-119.88°E) is divided into four sub-regions: Region 1 (114.12°-115.69°E, 37.37°-42.11°N) covering Zhangjiakou; Region 2 (114.63°-116.12°E, 37.98°-41.95°N) covering Hengshui, Baoding, Shijiazhuang, Handan, and Xingtai; Region 3 (116.26°-117.52°E, 39.19°-42.60°N) covering Cangzhou, Tianjin, Langfang, and Beijing; and Region 4 (117.56°-118.66°E, 39.19°-42.11°N) covering Tangshan and Chengde [Figure 1: see original paper].

2. Results Analysis

2.1 Occurrence Probability of Non-Precipitating and Precipitating Ice Clouds

Following Li et al.' s definition of ice cloud occurrence probability, we define the precipitating ice cloud occurrence probability (Fp) as:

$$Fp = (Nice\_p / (Nclear\_p + Nice\_p + Nliquid\_p + Nmix\_p)) \times 100\%$$

where Nclear__p, Nice__p, Nliquid__p, and Nmix__p represent clear-sky, ice cloud, water cloud, and mixed-phase/undetermined cloud pixels under precipitation conditions, respectively.

The non-precipitating ice cloud occurrence probability (Fn) is similarly defined as:

$$Fn = (Nice\_n / (Nclear\_n + Nice\_n + Nliquid\_n + Nmix\_n)) \times 100\%$$

where the subscript n denotes non-precipitating conditions.

Table 1 shows the sample quantities of non-precipitating and precipitating ice clouds across the Beijing-Tianjin-Hebei region and its four sub-regions for all four seasons. Precipitation samples are significantly fewer than total ice cloud samples.

Table 2 presents the seasonal distribution of occurrence probabilities. Non-precipitating ice clouds show their lowest occurrence in winter and highest in spring for most sub-regions, except Region 2 where spring has the highest probability. Precipitating ice clouds demonstrate a clear seasonal pattern with lowest occurrence in winter and highest in summer, though sub-regional variations exist. Region 1 shows higher occurrence in winter and summer, while Region 2 exhibits lower occurrence in winter and higher in autumn. Region 3 displays the most pronounced seasonal differences. These results align with previous MODIS-based studies showing higher ice cloud occurrence in summer and lower in winter across Beijing. Ice clouds readily form in regions with vigorous convection and moisture-rich storm tracks, and precipitation in Beijing-Tianjin-Hebei is strongly influenced by topography, particularly during summer. Notably, 2012 shows exceptionally high occurrence probability, correlating with numerous heavy precipitation events that year.

2.2 Cloud Top Height and Temperature of Precipitating Ice Clouds

Understanding macrophysical cloud properties such as cloud top height and temperature is essential for evaluating conditions for weather modification operations. Table 3 summarizes the mean, minimum, and maximum values of cloud top temperature and height across the region and sub-regions.

Overall, precipitating ice cloud top temperatures range from 216-273 K, with heights between 10.1-17.2 km. Mean cloud top temperature is lowest in winter and highest in summer, while the minimum temperature shows the opposite pattern (highest in winter, lowest in summer). Cloud top height is lowest in winter (10.1 km) and highest in summer (17.2 km), a pattern consistent across both extreme and mean values.

Sub-regional differences in cloud top temperature are substantial. Except for Region 1 where maximum height occurs in spring, all other sub-regions show peak values in summer across mean, minimum, and maximum metrics. For mean values, Region 1 shows lowest temperatures in winter and highest in autumn, Region 2 shows lowest in spring and highest in autumn, and Region 3 shows lowest in autumn and highest in winter. Minimum temperatures are highest in summer across all sub-regions.

2.3 Cloud Layer Structure of Precipitating Ice Clouds

Cloud layer number is a critical structural parameter for understanding vertical cloud architecture. Using CloudSat data, we categorize cloud systems into single-layer, double-layer, triple-layer, and more than three-layer configurations.

Figure 3 [Figure 3: see original paper] reveals that triple-layer and higher cloud systems are extremely rare across all seasons. For the entire Beijing-Tianjin-Hebei region, the probabilities of triple-layer clouds are 19.3% (spring), 29.7% (summer), 30.1% (autumn), and 0% (winter). Double-layer clouds occur with probabilities of 56.1% (spring), 40.9% (summer), 67.8% (autumn), and 67.0% (winter). Single-layer clouds dominate in spring (79.9%), summer (67.8%), and autumn (67.0%), while winter shows a different pattern with double-layer clouds being most prevalent (79.9%).

At the sub-regional scale, most areas and seasons show single-layer dominance, except for Region 1 in autumn and winter, and Region 2 in winter where double-layer clouds are more common. The proportion of triple-layer clouds is lowest in summer across the region. Previous research indicates that stratiform clouds have been primary targets for weather modification operations in Hebei Province, suggesting that single-layer precipitating ice clouds are preferred for cloud seeding operations.

2.4 Cloud Types of Precipitating Ice Clouds

Cloud type and development stage directly influence precipitation distribution patterns. The CloudSat 2B-CLDCLASS product categorizes clouds into eight types, though we focus on ice cloud types relevant to precipitation: deep convective clouds, nimbostratus, cumulus, stratocumulus, altocumulus, altostratus, and cirrus (stratus being water clouds are excluded).

Figure 4 [Figure 4: see original paper] shows the seasonal distribution of cloud types. Precipitating ice clouds exhibit the greatest type diversity in spring and summer (7 and 6 types respectively), with fewer types in autumn and winter (6 and 5 types). Deep convective clouds dominate in summer, accounting for 48.3% of precipitating ice clouds, while nimbostratus prevails in other seasons (71.0% in spring, 67.7% in autumn, 77.5% in winter). Other cloud types including cumulus, stratocumulus, altocumulus, altostratus, and cirrus contribute smaller proportions.

Sub-regionally, spring shows highest nimbostratus proportions across all areas. Cumulus and altocumulus peak in summer and minimize in winter, while stratocumulus and cirrus show the opposite pattern. Altostratus peaks in spring and autumn. Region 1 has relatively lower nimbostratus proportions, while Region 2 and 3 are dominated by deep convective clouds in summer. Region 4 shows the fewest cloud types in winter (only 2 types), with nimbostratus reaching 98.9% in that season.

2.5 Vertical Distribution of Microphysical Properties

The CloudSat 2B-CWC-RO product provides ice water content data essential for understanding ice particle distribution during precipitation development. We analyzed vertical profiles of three microphysical parameters: particle number concentration, ice water content, and particle effective radius.

2.5.1 Particle Number Concentration Particle number concentration serves as a key indicator for precipitation initiation and development. Overall, the distribution heights for precipitating ice cloud particle number concentration across Beijing-Tianjin-Hebei are 0-11.0 km (spring), 3.5-17.0 km (summer), 1.0-14.0 km (autumn), and 0-13.5 km (winter). Maximum concentrations are 67.6 L^{-1} (spring), 171.8 L^{-1} (summer), 142.1 L^{-1} (autumn), and 52.1 L^{-1} (winter), occurring at altitudes of 8.6 km, 9.8 km, 8.3 km, and 6.7 km respectively [Figure 5: see original paper].

Summer exhibits the highest distribution altitude and maximum values, consistent with higher temperatures and moisture availability promoting vertical water vapor transport. Sub-regional analysis shows spring concentrations in Region 1 are significantly higher than other areas, with maximum differences reaching 60 L^{-1}. Summer shows uniform single-peak structures across all regions with maximum differences of approximately 40 L^{-1}. Autumn displays multiple peaks in most regions except Region 1, which maintains a single-peak structure. Winter shows multiple peaks across all sub-regions, with Region 3 showing the largest values but at lower altitudes.

2.5.2 Ice Water Content Ice water content represents the mass of ice crystals within clouds. The vertical distribution patterns closely follow those of particle number concentration. Distribution heights are 0-11.0 km (spring), 3.5-17.0 km (summer), 1.0-14.0 km (autumn), and 0-13.5 km (winter). Maximum values are 139.1 $\mathrm{mg \cdot m^{-3}}$ (spring), 297.8 $\mathrm{mg \cdot m^{-3}}$ (summer), 85.9 $\mathrm{mg \cdot m^{-3}}$ (autumn), and 88.1 $\mathrm{mg \cdot m^{-3}}$ (winter), occurring at 6.0 km, 8.3 km, 5.2 km, and 3.1 km respectively [Figure 6: see original paper].

Summer shows the highest distribution altitude, maximum values, and peak heights, correlating with abundant moisture and high temperatures. Sub-regionally, spring shows single-peak structures in Regions 1, 2, and 3, but multiple peaks in Region 4 with maximum differences of 135 $\mathrm{mg \cdot m^{-3}}$. Summer exhibits consistent single-peak structures across all regions with maximum differences of 140 $\mathrm{mg \cdot m^{-3}}$. Autumn shows Region 1 with higher distribution and maximum values, differing by up to 140 $\mathrm{mg \cdot m^{-3}}$ from other regions. Winter shows Region 4 with significantly greater distribution height and values, differing by up to 140 $\mathrm{mg \cdot m^{-3}}$.

2.5.3 Particle Effective Radius Particle effective radius influences cloud microphysical processes and precipitation development. Distribution heights are 0-11.0 km (spring), 3.5-17.0 km (summer), 1.0-14.0 km (autumn), and 0-13.5 km (winter). Maximum values are 92.0 m (spring), 103.1 m (summer), 85.9 m (autumn), and 88.1 m (winter), occurring at 6.0 km, 8.3 km, 4.1 km, and 5.2 km respectively [Figure 7: see original paper].

Summer shows the highest distribution altitude, maximum values, and peak heights. Sub-regionally, spring effective radius in Region 1 exceeds other regions with a single-peak structure and maximum differences of 20 m. Summer shows uniform single-peak structures across all regions with small maximum value differences of about 10 m. Autumn shows Region 1 with larger distribution heights and values in a single-peak structure, while other regions show multiple peaks with maximum differences of 25 m. Winter shows Region 4 with the largest maximum values, but the altitude difference is only 25 m.

3. Conclusions

Using CloudSat and Aqua MODIS data from September 2008 to August 2016, we investigated seasonal variations in precipitating ice cloud characteristics across four sub-regions of Beijing-Tianjin-Hebei, including occurrence probability, cloud top height and temperature, cloud layer structure, cloud types, and microphysical properties (ice water content, particle number concentration, and particle effective radius). The findings have important applications for precipitation forecasting and cold cloud seeding operations.

Key conclusions are:

1) The occurrence probability of precipitating ice clouds peaks in summer across the entire Beijing-Tianjin-Hebei region, with particularly high val-

ues in 2012. The difference in occurrence probability before and after 2012 indicates significant interannual variability.

2) The minimum cloud top temperature of precipitating ice clouds is highest in winter and lowest in summer, while cloud top height is lowest in winter and highest in summer. Sub-regional differences in these parameters are substantial, with Region 1 showing maximum heights in spring rather than summer.

3) Single-layer cloud structures dominate in spring, summer, and autumn, while double-layer structures prevail in winter across the region.

4) Cloud type diversity is greatest in spring and summer (7 and 6 types respectively) and lowest in autumn and winter (6 and 5 types). Deep convective clouds dominate in summer (48.3%), while nimbostratus clouds prevail in other seasons. This pattern aligns with previous studies of precipitating clouds in East and South Asian monsoon regions.

5) The main distribution altitudes of microphysical quantities are 0-11.0 km (spring), 3.5-17.0 km (summer), 1.0-14.0 km (autumn), and 0-13.5 km (winter). Ice water content and particle number concentration show lowest values in winter and highest in summer, with maximum altitudes also lowest in winter and highest in summer. Particle effective radius is lowest in autumn and highest in summer. Notably, all three microphysical parameters show consistent single-peak vertical structures across all subregions in summer, but display more complex, seasonally varying patterns in other seasons.

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