Research Article

Characteristics of Aerosols over the Summer Monsoon Transition Zone

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Received 5 August 2019; Revised 5 October 2019; Accepted 17 October 2019; Published 29 December 2019

Academic Editor: Theodore Karacostas

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A survey was conducted in the summer monsoon transition region of China. By combining data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSOs) and Moderate Resolution Imaging Spectroradiometer (MODIS), the effects of East Asian summer monsoon circulation on the spatial distribution of aerosol, as well as the response mechanisms of different aerosols in an abundant and a deficient summer monsoon year, were analyzed. It was found that, in the summer monsoon transition region, the aerosol optical depth (AOD) in abundant monsoon years was lower than that in deficient years. Only in the Gobi Desert region of the Loess Plateau, the AOD in abundant monsoon years was significantly larger than that in deficient years. When the AOD was less than 0.06, the frequency of dust aerosol was higher than that of polluted aerosol in both the abundant and deficient monsoon years. When the AOD was over 0.06, the frequency of polluted aerosol was higher than that of dust aerosol in both the abundant and deficient monsoon years. In summer, the AOD was larger and the frequency of polluted aerosol in abundant monsoon years was higher than that in deficient years.

1. Introduction

Aerosol is a general term used to describe solid and liquid particles suspended in the atmosphere. Atmospheric aerosols are the primary atmospheric pollutants affecting human health. Atmospheric aerosols could also affect the radiative equilibrium and cloud microphysical process of the earth-atmosphere system through direct [1] and indirect [2] climatic effects, which will have an impact on climate. Based on observations, Zhang et al. [3] reported a rising trend in the aerosol concentration in Eastern China, with a concentration only slightly less than that in the South Asia Region. This was mainly due to anthropogenic aerosol. Zang et al. [4] improved a neutral-network algorithm, called the principal component analysis-general regression neural network (PCA-GRNN) model, to estimate hourly PM1 concentrations in China. They found that the regions most severely polluted with PM1 were largely located in the North China Plain and northeast China, in accordance with the distribution of industry and urban centers. Lu et al. [5] investigated the properties of aerosols over central China based on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSOs) and the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model. They found that approximately 60% of the aerosols over central China originated from local areas, whereas non-locally produced aerosols accounted for approximately 40%. Anthropogenic aerosols constituted the majority of the aerosol pollutants (69%) that were mainly distributed less than 2.0 km above the mean sea level.

In China, the aerosol concentration is higher compared to other regions of the world. In addition, the East Asia is in the monsoon region; thus, the climate characteristics, including temperature, precipitation, and atmospheric
circulation, display obvious seasonal changes. The variation over different time scales has a direct impact on regional precipitation and temperature variations. East Asia is a critical area for studies of global climate change. The transportation of atmospheric materials such as water vapor and droplets is also directly affected by the monsoon circulation. Thus, the processes involved in the generation, emission, and transportation of aerosol are also influenced by the atmospheric circulation factor. The temporal variations of aerosol concentrations are significantly impacted by changes in the monsoon circulation.

In recent years, many studies have investigated the interaction between atmospheric aerosols and the Asian monsoon [6], especially the East Asian monsoon [7]. There are concerns about the effect of aerosols over the East Asia region. Due to the summer monsoon, the East Asia region is wet and warm. Atmospheric aerosols may reinforce convection and precipitation. Using an air-sea coupling model (GCM), Bollasina et al. [8] conducted a series of simulation experiments and found a reduction of precipitation that was attributed to the emission of anthropogenic aerosol in South Asia. Pan et al. [9] evaluated the average radiative forcing by the intrinsic aerosol-cloud interaction for warm liquid clouds during the annual, monsoon, and nonmonsoon periods in South Asia and determined their effects on radiative forcing and climate in South Asia. Mao et al. [10] demonstrated the vertical physical and radiative impacts of aerosol loading on ice clouds. The overall effect was mainly a decrease in longwave cloud emissions back toward the surface and consequently weakened radiative forcing of ice clouds during the Indian summer monsoon season. Moreover, there is no doubt that many factors can affect the response of ice clouds to aerosol, including convective intensity, relative humidity (RH), aerosol type, cloud intrinsic characteristics, and other environmental conditions.

Many previous studies considered the effects of aerosols on the intensity and precipitation of the East Asian summer monsoon, but there have been few reports on the influence of the East Asian summer monsoon on atmospheric aerosols. Especially, few people regarded the response mechanisms of different aerosols to abundant and deficient monsoon years and the distribution characteristics of the summer monsoon at different propulsive phases in East Asia. This is also a very prominent scientific problem. It is necessary to conduct thorough systematic research to resolve the issue. In this study, using satellite and reanalysis data, the effects of the East Asian summer monsoon circulation on the spatial distribution of atmospheric aerosol and the response mechanisms of different aerosols to abundant and deficient summer monsoon years in East Asia were studied.

2. Description and Experimental Design

2.1. Selection of Study Area. Generally, the effects of the summer monsoon gradually weaken from southeast to northwest in China, and it will transition to the influence area of westerlies. The transition zone is the line representing the edge of summer monsoon activity, and the change of the line determines the drought and flood conditions in China. In the past, various different definitions have been proposed for the edge of the summer monsoon. Based on these previous definitions, Ran and Qian et al. [11] developed a definition of the edge of the summer monsoon that considered many elements, such as precipitation (hourly average precipitation ≥20 mm), wind field (southwesterly), and pseudoequivalent potential temperature (850 hpa potential temperature ≥335 K). This definition can objectively reflect the propulsive process of the summer monsoon. Figure 1 shows the distribution of the edge of the summer monsoon in China in the last 44 years according to the definition. The northern edge of the summer monsoon extended northward from the eastern side of the Tibetan Plateau. It passed through the northwest of China, the north of China, and finally reached the northeast of Asia. There was an overall trend of "southwest-northeast," and the edge movement across the hinterland of China.

However, it is concerned that the northern edge of the summer monsoon is not fixed, and there is always an obvious interannual and interdecadal swing [12]. The range of the swing range is about 33°~44°N around 110°E. The interannual scope of the swing of the summer monsoon can reach 11 latitudes, while the interdecadal swing scope can reach 1.5 latitudes. The range of the swing is referred to as the "summer monsoon transition zone," as shown in Figure 1. It is both the active boundary region for the effects of the summer monsoon and the coupling region for the system of the summer monsoon and westerlies [13]. The region is very sensitive to summer monsoon activity, and the effects are extremely prominent. The summer monsoon precipitation makes a key contribution to the total annual precipitation. In recent decades, with global warming, the summer monsoon index has displayed a remarkable decreasing trend in China [14, 15]. The most serious region affected by the weakening of summer monsoon is the monsoon transition zone. Under the background of the variation of the summer monsoon, the summer monsoon transition zone has become the heartland of aridification and desertification in China [16, 17].

2.2. Data and Methods. Under the conditions of any landform, a bright surface, thin clouds, and clear sky, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) was carried by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSOs) satellite, which was launched successfully on April 28th, 2006. It can observe the vertical distribution of aerosol and monitor the vertical features of dust in the transfer process. However, the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging Spectroradiometer (MISR) cannot provide vertical data. CALIPSO makes up for these shortcomings and provides the vertical distribution of aerosol in different scales. Pan et al. [18] investigated the possible effect of the three-dimensional (3D) variations of cloud during daytime on climate warming over the TP from 2007 to 2015 based on CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. The changes in the total
measured cloud properties were mostly attributed to the changes in low clouds, whose fractions and geometrical depths decreased by approximately 4.2% and 130 m, respectively. Young et al. [19] found that CALIOP opaque cloud optical depth estimates cannot be compared with cloud optical depths measured by using passive instruments. CALIOP opaque cloud optical depth depths are considerably underestimated.

The datasets used in this study included the following products: (i) the grid data of the three-level daily data product MOD08, with a 1° × 1° horizontal resolution; (ii) the NCEP daily data of U-wind, with a 2.5° × 2.5° horizontal resolution and from 1000 to 100 hpa; and (iii) a daily dataset of the aerosol layer at level 2 from the CALIPSO. All datasets covered a total period of more than one year (from January 2008 to December 2017).

The backscattering data at different heights, a series of characteristic Lidar signals, the depolarization ratio of volume, backscattering coefficient at 532 nm, type of area, and lift phenomenon were derived from the CALIPSO dataset. The type of aerosol in different heights could be differentiated. Six types of aerosol were determined: clean marine, dust, polluted continental, clean continental, polluted dust, and smoke. The classification rules are shown in Table 1. Because the study area was located inland, the study focused on four types of aerosols: dust, polluted dust, polluted continental, and smoke.

The East Asian summer monsoon (EASM) and its variability involve circulation systems in both the tropics and midlatitudes, as well as in both the lower and upper troposphere. Considering this fact, a new EASM index (NEWI) has been proposed based on 200 hPa zonal wind [20]. Compared with 15 indices defined in previous studies based on different variables, the NEWI has a good correlation with precipitation and temperature, and it can capture the dominant modes of rainfall and temperature. Because the East Asian summer monsoon has an obvious interannual variation, the aerosol characteristics under the background of monsoon intensity in extreme years were investigated. We calculated the NEWI (2008–2016), and four typical extreme years were selected for this study. The abundant monsoon years were 2010 and 2013, and the deficient monsoon years were 2008 and 2015 (Figure 2).

In this study, the effects of summer monsoon circulation on the distribution of atmospheric aerosols were investigated in abundant and deficient monsoon years. The summer monsoon transition zone was compared with other regions. The frequency of dust and polluted aerosol with different aerosol optical depths (AODs) and altitude were determined.

3. Results

3.1. Distribution of the AOD in Abundant and Deficient Monsoon Years. Figure 3 shows the difference between the AOD in the abundant and deficient monsoon years. The red area was the East Asian summer monsoon transition zone. At the beginning of the summer monsoon in June, most of the positive anomalies occurred in the transition area, which indicated that the average AOD in abundant years was lower than in deficient years. The distribution of AOD in the southwest-northeast direction was positive-negative-positive. Only in the Loess Plateau region, the AOD was larger in abundant years than that in deficient years. In July, the

![Figure 1: Distribution of the summer monsoon border zone in China (the area marked by the oblique line represents the summer monsoon transition zone).](image-url)
Table 1: Level 2 dataset aerosol classification.

<table>
<thead>
<tr>
<th>Mark</th>
<th>Aerosol</th>
<th>$\delta V$</th>
<th>$\beta_{532}$ (km$^{-1}$sr$^{-1}$)</th>
<th>Area</th>
<th>Lift phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clean marine</td>
<td>&lt;0.075</td>
<td>&lt;0.0015</td>
<td>Ocean</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Dust</td>
<td>&gt;0.20</td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Polluted continental</td>
<td>&lt;0.075</td>
<td>&gt;0.0005</td>
<td>Land</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Clean continental</td>
<td>&lt;0.075</td>
<td>&lt;0.0005</td>
<td>Land</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Polluted dust</td>
<td>0.075–0.20</td>
<td></td>
<td>Land</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>Smoke</td>
<td>&lt;0.075</td>
<td>&gt;0.0005</td>
<td>Land/ocean</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Figure 2: New East Asian summer monsoon index (NEWI) of 2008–2016.

Figure 3: Continued.
summer monsoon developed to the mature stage. There were obvious negative anomalies in the northeast and southwest region of the transition zone, indicating that the AOD in abundant years was larger than that in deficient years. The southwest-northeast direction showed a "negative-positive-negative" distribution. In August, there was no obvious distribution of the AOD in the transitional zone. Throughout the summer, the AOD in abundant monsoon years was lower than that in deficient monsoon years. Only in the Gobi Desert region of the Loess Plateau, the AOD was significantly larger in abundant years than that in deficient years. These characteristics indicated that the spatial distribution of the AOD varied significantly at different stages of monsoon development and under different monsoon intensity backgrounds.

3.2. Frequency of Dust and Polluted Aerosol in Abundant and Deficient Monsoon Years.

Some previous studies had investigated the frequency of dust aerosol in East Asia [21]. They found that there was an obvious seasonality for the occurrence of dust in the region. The maximum frequency of dust was reported in the source region, with the height of suspended dust being highest in spring. In general, the higher the dust particles are lifted, the farther they will travel. In this study, the frequency characteristics of dust and polluted aerosol with different optical depths in the summer monsoon transition zone were investigated in terms of the different aerosol classifications. Moreover, in different extreme summer monsoon years, the frequency of the two aerosols throughout year and summer was compared and analyzed.

As shown in Figure 4, when the AOD was less than 0.06, the frequency of dust aerosol was higher than that of polluted aerosol in both the abundant and deficient monsoon years. Moreover, the frequency of dust aerosol and polluted aerosol in the deficient monsoon years was higher than in the abundant monsoon year. When the AOD was over 0.06, the frequency of polluted aerosol was higher than that of dust aerosol in both the abundant and deficient monsoon years. The frequency of dust aerosol was higher in the deficient monsoon years than that in abundant monsoon years. However, there was no obvious tendency of polluted aerosol in either the abundant or deficient monsoon years.

As shown in Figure 5, in summer, when the AOD was less than 0.12, the frequency of dust aerosol in deficient monsoon years was higher than that in the abundant monsoon years. When the AOD was over 0.12, there was no obvious difference between the abundant and deficient monsoon years. The frequency of polluted aerosol in the abundant monsoon years was higher than that in the deficient monsoon years when the AOD was over 0.14. The water vapor in the strong summer troposphere promoted moisture absorption by hygroscopic aerosols (e.g., sulfate), which increased the optical depth. The AOD was larger, and the frequency of polluted aerosol in the abundant monsoon years was higher than that in the deficient monsoon years.
Variation in the summer monsoon can change the transmission, sedimentation, concentration, distribution, and chemical reactivity of atmospheric aerosols. In this study, the effect of the East Asian summer monsoon circulation on the distribution of atmospheric aerosols, and the response mechanisms of different aerosols in abundant and deficient summer monsoon years were investigated. The following conclusions were obtained:

(1) The distribution of AOD in the transition zone varied in the different stages of the monsoon. At the beginning of the summer monsoon, the distribution of AOD in the southwest-northeast direction was positive-negative-positive. Only in the Loess Plateau region, the AOD was larger in abundant years than that in deficient years. In July, the summer monsoon developed to the mature stage, and there were obvious negative anomalies in the northeast and southwest region of the transition zone, indicating that the AOD in abundant years was larger than that in deficient years. The southwest-northeast direction displayed the “negative-positive-negative” distribution. In summer, the AOD in abundant monsoon years was lower than that in deficient monsoon years. Only in the Gobi Desert region of the Loess Plateau, the AOD was significantly larger in abundant years than that in deficient years.

(2) When the AOD was less than 0.06, the frequency of dust aerosol was higher than that of polluted aerosol in both the abundant and deficient years. Moreover, the frequency of dust aerosol and polluted aerosol in the deficient years were higher than that in the abundant years. When the AOD was over 0.06, the frequency of polluted aerosol was higher in both the abundant and deficient monsoon years. In summer, the AOD of polluted aerosol was larger and the frequency was higher in the abundant years than that in deficient years.

The summer monsoon transition zone investigated in this study is very special. In this region, the temperature is low, and is heavily influenced by the winter monsoon. This has an impact on atmospheric pollution in winter, especially the haze that occurs in China. Our next work focuses on the effects of winter monsoon intensity on the distribution of aerosol and the frequency of different aerosols.

Data Availability

The CALIPSO and MODIS data used to support the findings of this study are available from the corresponding author upon request. The MODIS dataset used in this study is available from the Atmosphere Archive and Distribution System (LAADS) of the Distributed Active Archive Center (DAAC) (https://ladsweb.modaps.eosdis.nasa.gov/search/order/). The CALIPSO dataset used in this study is available at the Atmospheric Science Data Center (ASDC) at NASA Langley Research Center (DAAC) (https://www-calipso.larc.nasa.gov/tools/data_avail/).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.
Acknowledgments

This work was jointly supported by the Natural Science Foundation of China (41630426) and the National Basic Research Program of China (2013CB430200).

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