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Distributions and Direct Radiative Effects of Different Aerosol Types in North China

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Abstract: Different aerosol types exhibit distinct radiative effects in different regions, attributed to their unique optical characteristics and regional distributions. This study focuses on North China, which is impacted by both natural and anthropogenic aerosols with high concentrations and a variety of aerosol types. While many studies on aerosol direct radiative effects have been conducted in this region, the majority have focused on a specific type of aerosol or overall aerosol, leaving limited research on the direct radiative effects and contributions of different aerosol types. In this study, we use CALIPSO satellite data from 2011 to 2020 to investigate concentrations and distributions of different aerosol types. The results reveal that dust, polluted dust, polluted continental/smoke, and elevated smoke are the dominant aerosol types in North China. Based on the radiative closure experiment, we systematically calculate the radiative effects of different aerosol types and their corresponding contributions to the energy budget by combining satellite data with the Fu–Liou radiative transfer model. The annual average net aerosol direct radiative effect (ADRE) of North China is $-6.1$ and $-13.43 \text{ W m}^{-2}$ at the TOA and surface, respectively, causing a net warming effect of $7.33 \text{ W m}^{-2}$ in the atmosphere. For each main aerosol type, dust contributes $93\%$ to the shortwave ADRE in the western dust source region, while polluted dust mainly contributes $31\%$ and $45\%$ of the total ADRE, in Northwest China and North China Plain, respectively. Anthropogenic pollutant aerosols account for $58\%$ of the total ADRE in Northeast China. This study holds great significance in elucidating the dominant aerosol types and their concentrations in North China, comprehending the impacts of different aerosol types on the local energy balance.

Keywords: aerosol type; aerosol optical depth; aerosol radiative effect; North China; radiative closure experiment

1. Introduction

Aerosols play an important role in the climate system, directly affecting the Earth’s radiation balance by absorbing and scattering solar radiation and infrared radiation, or indirectly affecting climate by acting as cloud condensation nuclei or ice nuclei to influence cloud properties [1–3]. Some research has estimated that the increase in the burden of atmospheric aerosols has masked approximately one-third of the continental warming from greenhouse gases from 1964 to 2010, with important implications for global and regional climate [4]. However, aerosols are also a leading contributor to climate prediction uncertainty because of their complex properties and inhomogeneous distributions [5–8], especially against the background of accelerated global urbanization and rapid environmental change. Therefore, ongoing research with the latest improved observation data is important for reducing these uncertainties, enhancing our understanding of aerosol–climate interaction, and offering scientific support for achieving sustainable development under the “dual carbon” targets.

The direct aerosol radiative effect (ADRE) is commonly used to investigate the interaction between aerosol particles and radiation in both shortwave (SW) and longwave...
(LW). The magnitude and spatial distribution of this effect are highly associated with the variation of aerosol composition, size and distribution. The aerosol optical properties of aerosol optical depth (AOD), single scatter albedo (SSA), and asymmetry factor (g) are used to parameterize these characteristics [9]. Therefore, different types of aerosols with distinctive optical properties exhibit significant disparities in radiative effects [10–13]. For example, sulfate, nitrate, and sea salt aerosols with relatively high values of SSA, which exhibit strong scattering characteristics, can reduce the solar radiation reaching the Earth’s surface by scattering the incident solar radiation, thus producing a cooling effect. The global total ADRE of sulfate was estimated to be $-0.42 \ \text{W} \ \text{m}^{-2}$ [14]. Black carbon (BC), as a strongly absorbing aerosol with a relatively low value of SSA, significantly heats the atmosphere by absorbing solar radiation, showing a significant warming effect on the climate [15]. Compared to sulfate, the sign of BC radiative effect is positive, with a global total ADRE value of $0.19 \ \text{W} \ \text{m}^{-2}$ [16]. In addition, absorbing aerosols can also accelerate glacier melting by depositing on snow and ice surfaces, thereby impacting the local radiative energy balance by altering the underlying albedo [17]. It was reported that BC could reduce the snow albedo by 0.01–0.20 at the visible wavelength band in Northwest China [18]. Moreover, even the same type of aerosols can exhibit different optical characteristics and associated radiative effects owing to their diverse sources and compositions [19]. Su and Toon [20] found that the average SSA of dust from Asia is larger than that from Africa due to different dust compositions. The value of ADRE is also influenced by the solar zenith angle (SZA), surface albedo, cloud fraction, and so on [21]. Therefore, precisely quantifying the composition ratios and radiative effects of different aerosol types in various regions is of great significance for accurately evaluating the contributions of different aerosol types to regional radiative energy budget.

China, as the largest developing country, has maintained a high level of AOD and encompasses various types of aerosols due to its vast territory, dense population, rapid economic growth, and dramatic urbanization rate over recent decades [22,23]. It is well-known that aerosol loadings not only affect the regional energy budget but also have influences on global climate change [24–28]. There are already some studies that characterized aerosol optical properties and quantified the ADRE in China [29–32]. According to Filonchyk et al. [33], the distribution of AOD decreases gradually from east to west in China. The highest annual mean AOD (>0.7) was observed in populous regions with the highest density of agricultural and industrial activities, while the lowest values (<0.25) of the annual mean AOD are found in sparsely populated regions on the Tibetan Plateau and in the north forest ecosystems in the northeastern part of China. Li et al. [5] estimated the values of nationwide diurnal mean aerosol radiative effects across China are $-15.7 \ \text{W} \ \text{m}^{-2}$ at the surface and $+0.3 \ \text{W} \ \text{m}^{-2}$ at the top of atmosphere (TOA) using 25 ground-based stations and satellite observational data. Huang et al. [3] investigated the dust aerosol by studying dust storm cases and found that dust aerosol produces an average daily mean net radiative effect of $44.4$, $-41.9 \ \text{W} \ \text{m}^{-2}$ at the TOA and surface in Taklimakan, respectively. However, previous studies mostly focused on overall aerosols or only a single type of aerosol; radiative effects and contributions of different aerosol types to regional energy budgets have not been systematically studied. Also, with the adjustment of the industrial structure and implementation of pollution prevention and control measures in recent years, the content and composition of aerosols have undergone significant changes [34–39]. These changes have exerted a notable impact on aerosol characteristics, especially in North China, a region that not only includes areas impacted by high population density and significant industrial emissions but also covers natural source areas such as the Taklimakan Desert and Gobi Desert, displaying a more intricate distribution of aerosols. Therefore, we conducted a study on aerosol types and their radiative effects in this region using the latest observation data.

In this study, we systematically analyzed the types and proportions of different aerosols in typical regions of North China by using satellite data from 2011 to 2020, calculated the ADRE of different aerosols, and quantified the associated respective radiative
contributions by combing satellite data with the Fu–Liou radiative transfer model. This study enables a comprehensive assessment of aerosol species distribution and variation in North China within the context of air pollution control actions. By quantifying radiative effects of different aerosol types, we can evaluate their contributions to the regional energy budget and help formulate local emission policies. The remainder of this paper is organized as follows. The datasets and methods used are introduced in Section 2. The results are presented in Section 3, exploring the distributions of different aerosols in North China and estimating the radiative effects of these aerosols based on radiative closure experiment. Discussion and conclusions are provided in Section 4.

2. Materials and Methods

2.1. Study Area

In this study, we focus on North China, and divide it into four typical regions based on geographical type and distributions of population and industry: the central Xinjiang Uyghur Autonomous Region of China (Region 1, R1), Northwest China (Region 2, R2), the North China Plain (Region 3, R3), and Northeast China (Region 4, R4), as shown in the bottom panel of Figure 1. They include both natural dust source regions and pollution source regions with high population density and significant industrial emissions, and corresponding transitional zones. Distinctive distributions of aerosols exist in these regions, as shown in the top panels of Figure 1. A detailed analysis will be presented in Section 3.1.

Figure 1. Averaged percentage of the main aerosol types (top panel) in the four regions and spatial distribution of AOD (bottom panel) over North China of 2011–2020.

2.2. Datasets

Aerosols, surface albedo, and instantaneous radiative flux data used in this study are obtained from multiple satellite sources, with the aerosol data primarily from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). The CALIPSO satellite was launched in April 2006 with a repeat cycle of 16 days, which provides long-term, large-scale vertical observations of aerosols and clouds. CALIPSO level 2 products distinguish aerosols into seven types, including: “clean marine (CM)”, “dust (DD)” “polluted continental/smoke (PC/S)”, “clean continental (CC)”, “polluted dust (PD)”, “elevated smoke (ES)”, and “dusty marine”. The aerosol classification from CALIPSO products over East Asia is sufficiently reliable according to the evaluation by [40]. In this study, aerosol extinction coefficients at 0.532 µm are calculated from CALIPSO level-2 profile products, and AOD is the integral of aerosol extinction coefficients in the vertical direction. Apart from using daytime CALIPSO data in radiative closure experiment (in Section 3.2.1), the
rest of this study primarily relies on nighttime CALIPSO data to mitigate the influence of sunlight noise during daytime observations. To further minimize the uncertainties associated with the aerosol extinction profile, high-quality data are selected based on the following quality control: (1) cloud-free; (2) $-100 \leq$ cloud aerosol discrimination score $\leq -70$; (3) extinction quality control flag = 0, 1; (4) $0 <$ Extinction coefficient $\leq 1.25$; (5) extinction uncertainty $< 99$ km$^{-1}$; and (6) “clear-air” was set to 0 km$^{-1}$ [41–44].

Moderate-Resolution Imaging Spectroradiometer (MODIS) and Multi-Angle Imaging Spectro Radiometer (MISR) level 3 products were also utilized to describe the change of aerosol content in different regions. MODIS data are from the Level-3 Aqua MODIS Collection dataset (MYD08_M3), which is more accurate in capturing the annual average AOD change than Terra AOD products [45]. The SW and LW instantaneous radiative fluxes at the TOA from the Clouds and the Earth’s Radiant Energy System (CERES) Single Scanner Footprint (SSF) Level-2 products are used in radiative closure experiment to validate the results from the transfer model. The surface albedo used in the model simulation is from CERES SYN1deg products. The fifth generation of European Centre for Medium-Range Weather Forecasts Reanalysis 5 (ERA5) provides the profile of atmosphere at 37 levels in the model, which includes pressure, temperature, water vapor, and columnar ozone.

2.3. Fu–Liou Radiative Transfer Model

The Fu–Liou radiative transfer model was used in this study to estimate radiative fluxes and heating rates in the presence and absence of aerosols under clear-sky conditions. The model was developed by Fu and Liou [46,47], and subsequently modified by Rose et al. [48] and Kato et al. [49]. The delta-four-stream radiation transmission scheme is used to calculate 15 spectral bands from 0.175 to 4.0 μm SW flux and 12 spectral bands between 2850 and 0 cm$^{-1}$ in LW flux. The correlated k-distribution method is adopted to parameterize the non-gray gaseous absorption by H$_2$O, CO$_2$, O$_3$, N$_2$O, and CH$_4$ [47], with the addition of CFCs and CO$_2$ in the window region [50]. The model has been used widely [51–55].

In this study, the main parameters inputted into the model included monthly averaged atmospheric profiles (pressure, temperature, water vapor, and columnar ozone) from ERA5 reanalysis data, monthly averaged surface albedo from MODIS satellite data, and SZA from calculation. Note that instantaneous SZA is used for radiative closure experiment, while average calculation of daytime-mean SZA [56] in a month is used to obtain the aerosol radiative effects during 2011–2020. AOD is from CALIPSO data, while SSA and g are selected based on the optimal simulations derived from radiative closure experiments.

2.4. Calculation Methods

The ADRE at the TOA and surface (SFC) is defined as the result of the difference in radiative flux with and without aerosols. The atmospheric (ATM) ADRE is defined as the ADRE at the TOA minus the ADRE at SFC.

The SW and LW fluxes are defined as follows:

\[
T_{SW} = F_{SW}^a - F_{SW}^{clr}
\]  

\[
T_{LW} = F_{LW}^a - F_{LW}^{clr}
\]

where “$\downarrow$” and “$\uparrow$” denote the directions of radiative flux.

The SW, LW, and NET ADRE at the TOA and surface are calculated using

\[
A_{SW} = T_{SW}^{air} - F_{SW}^{clr}
\]  

\[
A_{LW} = T_{LW}^{air} - F_{LW}^{clr}
\]  

\[
A_{NET} = A_{SW} + A_{LW}
\]
where “aer” and “clr” denote aerosol and aerosol-free scenes, respectively. At the ATM, it is given by

\[ A_{ATM} = A_{TOA} - A_{SFC} \]  

(6)

The heating rate (HR) is defined as follows:

\[ HR_{sw} = HR_{sw,aer} - HR_{sw,clr} \]  

(7)

\[ HR_{Lw} = HR_{Lw,aer} - HR_{Lw,clr} \]  

(8)

3. Results

3.1. Distributions of Aerosol Types

Using CALIPSO data, we obtain the spatial distributions of total aerosol concentration at 1° × 1° resolution in North China, and the predominant aerosol types observed in different regions and their corresponding proportions, as shown in Figure 1. The results illustrate that the study area is dominated by four aerosol types: dust (DD), polluted continental/smoke (PC/S), polluted dust (PD), and elevated smoke (ES), which account for over 97% of the total aerosol concentration in the study area. “Other” in the figure represents other aerosol types provided by CALIPSO in addition to the four types mentioned in Section 2.2, such as clean continental, dusty marine, and so on.

Figure 1 shows a significant discrepancy in the distribution of aerosol loading and the proportion of aerosol types in different regions of North China, due to differences in natural environments and anthropogenic/industrial activities [57]. There are two high aerosol concentration centers: one is in region R3 with the largest annual mean AOD value of 0.59, and the other one is located in region R1 with the annual mean AOD value of 0.4. Because region R1 includes the Tarim Basin, which is the largest dust emission source in Asia [58], the contribution of dust aerosols can reach 84%, establishing their absolute dominance in this region. Compared to region R1 with predominate natural aerosols by local dust activities, the aerosols in region R3 are mainly derived from high levels of pollutant emissions and regional transports [59]. The proportion of PD is up to 53%, more than half of the total AOD, while PC/S is the second largest contributor (24%). The aerosol concentrations in regions R2 and R4 are relatively smaller, compared to those in the other two regions. As an intermediate region between dust source area and population-dense area, region R2 is dominated by DD (42%) and PD (41%); both contribute equally. In region R4, which is a traditional old industrial area, the total contribution of PC/S and ES is over 51%, which are generally emitted from local industrial activities and biomass burning, and from transported pollutants [60].

We then investigated the variation of the annual mean AOD from 2011 to 2020 in the four regions using multisource satellite data, as shown in Figure 2. The values of AOD from CALIPSO data show similar trends from other satellite AODs in each region and notable spatial variability from region to region, although there is a discrepancy in the AOD values between CALIPSO and the other satellite retrievals. Compared to the mean AOD values from MODIS (MYD_DB, MYD_DTB) and MISR data, the AOD values from CALIPSO are systematically larger in regions R1 and R2. Passive sensors, such as MODIS and MISR, will encounter difficulties in accurately retrieving aerosol properties under bright surface conditions due to complex interaction between sunlight, surface reflectance, and the atmosphere. Unlike passive remote sensing, CALIPSO, as an active sensing, can overcome the limitation of passive sensors; it can observe thin aerosol layers and obtain relatively accurate optical properties of aerosols under the bright surface condition. Gui et al. [61] concluded that the long-term AOD from CALIPSO can capture spatial patterns of aerosol loading over East Asia. The annual values of AOD exhibit an apparent decreasing trend after 2014, especially in region R3, with high anthropogenic emissions. The annual AOD changes of each aerosol type are also provided in the Supplementary Materials (Figure S1). It reveals that the reduction of total aerosol in region R3 is mainly due to the decrease in PD aerosol after 2014, when the clean policy was implemented.
Vertical distribution of aerosols is one of the critical parameters in the assessment of aerosol radiative effect [3]. CALIPSO observations provide a direct measure of the vertical structure of aerosols, which is one of its most distinct advantages. Therefore, we investigate the vertical distribution of seasonal and annual mean extinction coefficients of the four predominant aerosol types by using CALIPSO data, shown in Figure 3. The vertical resolution is 100 m from the ground up to 8 km above ground level (AGL). From the figures, all types of aerosols are primarily concentrated near the surface and decrease rapidly with altitude, except for the aerosol type of ES. In region R1, the DD and PD were observed below 4 km, with the maximum extinction appearing at 0.2 and 0.1 km, respectively, and reached the largest values (~0.15 and 0.03 km$^{-1}$, respectively). It clearly shows DD rose the highest (~5.2 km AGL) in spring, while it primarily existed under 2 km AGL in winter. The annual mean extinction coefficient profile of dust aerosol closely resembles the extinction profile of total aerosols, especially in spring, which corresponds to the period of the annual heavy dust storm in China [62,63]. The two profiles almost overlap. It indicates as the dust source region, aerosol vertical distribution in region R1 is mainly determined by local dust activities. In region R2, the value of the PD extinction coefficient is the largest in all seasons except for spring, when the region serves as the main pathway for transporting dust. The value of the extinction coefficient for PC/S is higher in summer and autumn than in winter and spring. The vertical distributions of DD and PD in regions R3 and R4 are consistent. The extinction coefficient of PD in region R3 reaches the highest value (0.32 km$^{-1}$) in winter, which may be associated with the intense temperature inversion in winter [64]. In regions R3 and R4, PC/S is primarily distributed under 2 km AGL. The extinction coefficient of PC/S reaches its maximum near the surface and gradually decreases as altitude increases. The ES, as one of the predominant aerosol types in regions R3 and R4 with high population densities and industries, shows significant differences in vertical distribution comparing to the other aerosols. The maximum extinction coefficient of ES does not occur near the surface, but is observed at approximately 2 km AGL, and then gradually decreased. ES is primarily distributed within the altitude range of 0 to 4 km AGL; and there is a noticeable enhancement in the overall distribution of its extinction coefficient in summer. The extinction coefficients of pollutants such as PC/S and ES aerosols show significant increases during the summer season, which can be attributed to the growth of aerosols through hygroscopic growth and straw burning [65].
3.2. Aerosol Radiative Effects

3.2.1. Radiative Closure Experiment

To achieve accurate simulation of radiative fluxes, we first conducted a radiative closure experiment under a clear sky to assess the accuracy of key parameters imported to the Fu–Liou model, including atmospheric profiles, surface albedo, and SZA. For “clear sky” identification, it is required that the proportion of clear sky in the field of view from the CERES SSF Level-2 product exceeds 90%, and the total AOD calculated from CALIPSO data is less than 0.1. The simulated results are compared with the instantaneous upward radiative fluxes at the TOA provided by the CERES SSF product under a clear sky, as shown in the two left columns of Figure 4. The comparison shows a good agreement between model simulations and satellite observations. The mean bias error (MBE) for SW ranges from $-5.1$ to $-1.1$ W m$^{-2}$ in the four regions, and the MBE for LW ranges from $-4.7$ to $-1.1$ W m$^{-2}$. The root mean squared error (RMSE) values for both LW and SW radiation are smaller than 10 W m$^{-2}$. It is evident that the model with these background parameters can appropriately represent the atmospheric and surface conditions of each region.

**Figure 3.** The extinction coefficient profiles of the main aerosol types at altitudes above ground levels (AGL). Letters (a–e) at the top left in each subplot represent annual, spring, summer, autumn and winter, respectively. Numbers 1–4 following the letters represent the four selected regions of R1–R4.
To evaluate aerosol radiative effects and heating rates, we need to know aerosol optical properties, such as the extinction coefficient, single-scattering albedo (SSA), and asymmetry factor (g). These properties depend on aerosol density, size distribution, and refractive index. In this study, the aerosol extinction coefficient is derived from the CALIPSO data. We select the aerosol type that determines the SSA and g and their spectral dependences in the model by comparing model-simulated instantaneous radiative fluxes at the TOA with those from the CERES data under all sky. For the “all sky” identification, the cloud-free criteria are the same as “clear sky”, while AOD is larger than 0.1. To optimize SSA and g of specific aerosol types in North China, we select specific aerosol types in the model corresponding to the CALIPSO aerosol type by comparing the CERES TOA instantaneous SW and LW fluxes with the Fu–Liou model simulations along the CALIPSO orbit. We find that for DD and PC/S, selecting the nucleation dust and urban mode in the model resulted in the smallest error when compared to observed radiative fluxes at the TOA. However, for PD and ES, there are no proper corresponding aerosol types in the model. So, we continually adjusted two different aerosol types and their proportions based on the simulation results, revealing that PD corresponds to a mixture of nucleation dust and soot modes, while ES corresponds to a mixture of continental and soot modes. The corresponding values of SSA...
and $g$ at 0.532 $\mu$m of the four aerosol types used in the model are listed in Table 1, and more details of SSA and $g$ in the model can be found in Figure S2 in the Supplementary Materials. The two right columns of Figure 4 compare the SW and LW fluxes at the TOA derived from the model with the CERES measurements. The model-simulated results agree reasonably well with those from the CERES. The averaged MBE between the two are 1.60 and 0.75 W m$^{-2}$ for SW and LW, respectively, while the RMSE ranges from 12.0 to 13.5 for SW and from 5.1 to 8.5 for LW. Compared to clear-sky conditions, the relatively larger RMSE for SW under all-sky conditions indicates unavoidable errors in the optical properties of aerosol types. Generally, the comparison demonstrates the reliability of the optical properties of aerosols and suggests that the radiative transfer model constrained by the CERES observations can be used to reliably simulate the aerosol radiative effects and heating rates.

Table 1. SSA and $g$ at 0.532 $\mu$m for the CALIPSO aerosol subtypes used in Fu–Liou model.

<table>
<thead>
<tr>
<th></th>
<th>DD</th>
<th>PD</th>
<th>PC/S</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSA</td>
<td>0.9647</td>
<td>0.8893</td>
<td>0.9384</td>
<td>0.8875</td>
</tr>
<tr>
<td>$g$</td>
<td>0.6649</td>
<td>0.6322</td>
<td>0.6389</td>
<td>0.6110</td>
</tr>
</tbody>
</table>

3.2.2. Distributions of ADRE and Aerosol Heating Rate

Aerosol radiative effects are commonly used to quantitatively evaluate the impact of aerosols on the energy balance of the Earth–atmosphere system. Based on the radiative closure experiment results, we simulated the SW and LW radiative fluxes at the TOA and surface by using the Fu–Liou model. The ADRE is calculated according to Equations (1)–(6). Figures 5 and 6 exhibit the spatial distributions of ADRE at $2^\circ \times 2^\circ$ resolution for the total aerosols and the primary aerosol types in North China. Regions R1 and R3 are two centers with strong ADRE corresponding to their abundant mineral dust and elevated concentrations of anthropogenic aerosols, respectively. The total ADRE values in regions R1 and R3 are $-8.5$ and $-12.9$ W m$^{-2}$ at the TOA, and $-17$ and $-31$ W m$^{-2}$ at the surface, respectively. Our surface result in region R3 is consistent with that in Xia et al. [66]. They used the ground-based observation data of Xianghe station (located in region R3) to obtain the surface ADRE value of $-32.8$ W m$^{-2}$. The ADRE of all the aerosol types manifests as a cooling effect at the TOA and surface while it has a warming effect on the ATM. The annual average SW ADRE in North China is $-6.39$ W m$^{-2}$ at the TOA and $-14.24$ W m$^{-2}$ at the surface, while it is 7.85 W m$^{-2}$ in the ATM, which indicates the presence of aerosols over North China leads to more energy being retained in the atmosphere and, thereby, warming the atmosphere.

Significant differences exist in the distribution of aerosol radiative effects due to their distinct spatial characteristics and physical properties. The seasonal ADRE values of individual aerosol types for each region are presented in Tables 2 and 3. Dust aerosols, which originate from the Tarim Basin, can impact the entire northern part of China along the downwind regions. The radiative cooling effect of dust is the strongest in region R1 due to the location in the source region, and its averaged SW ADRE can reach $-7.95$ W m$^{-2}$ at the TOA and $-14.77$ W m$^{-2}$ at the surface. Furthermore, in region R1, the SW ADRE of dust can reach $-11.78$ W m$^{-2}$ at the TOA and $-22.77$ W m$^{-2}$ at the surface in spring, when dust storms are most frequent. As the dust particles are transported downstream to areas with more human and industrial activities, dust particles are coated with pollutants along their pathways [67], causing a decrease in dust loading and an increase in polluted dust loading. Therefore, the strongest radiative effect of PD aerosol is observed in the North China Plain (region R3) with most frequent anthropogenic activities and industrial emissions, where the SW ADRE at the TOA and surface can reach $-5.77$ and $-17.83$ W m$^{-2}$, respectively. The effects of PD aerosol with the ADRE of $-1.71$ (TOA) and $-5.70$ W m$^{-2}$ (surface) in Northeast China (region R4) are much weaker than those in North China Plain, where large-scale industries are present, which is primarily attributed to the limited
amount of dust transported from the dust source region. Note that the ADRE of PD in the northern part of region R1 also shows relatively large values, which is due to the high local dust loading and relatively concentrated population and industries compared to the other parts in this region. As anthropogenic aerosols, PC/S and ES are mainly generated by human production. Therefore, the radiative effects induced by these two aerosols mainly occur in densely populated and industrially developed regions, especially ES that only affects the North China Plain and Northeast China. The ADRE value of ES in region R4 is $-1.11 \text{ W m}^{-2}$, which is comparable to $-1.73 \text{ W m}^{-2}$ in region R3, indicating that the pollutant aerosols generated by local daily life and production also have a significant impact on the local radiation balance.

Figure 5. Annual spatial distributions of aerosol types for SW ADRE in North China at TOA (left panel), SFC (middle panel) and ATM (right panel). Letters a–c at the top left in each subplot represent total, DD, PD, PC/S, ES aerosols. The value at the top right is the average of ADRE in North China under the given conditions.
For the LW radiation, the magnitude of its ADRE is much smaller than that of the SW, due to the relatively smaller particle sizes. The LW ADRE of all the aerosol types (in Figure 6) manifests as a warming effect at the TOA and surface, with mean values of only 0.29 and 0.81 W m\(^{-2}\), respectively.

The ADRE in the ATM indicates that aerosols can keep the energy in the atmosphere to change the entire atmospheric column’s energy. To describe how these effects influence the fluxes at different levels, we calculated the changes in SW and LW heating rates. Figure 7 shows that aerosols absorb the SW radiation, and heat the atmosphere layer in all four seasons. In region R1, a strong and thick heating rate layer from dust is present in all seasons. The maximum heating rate (0.26 K day\(^{-1}\)) from DD occurs in spring at 1 km AGL. In region R2, the heating effects of DD and PD aerosols are below 4 km AGL. The maximum SW heating effect of PD occurs near the surface in summer, reaching approximately 0.2 K day\(^{-1}\).

In regions R3 and R4, the value of the heating rate from DD aerosols is generally small, except in spring, and the heating effect is driven by PD and PC/S near the surface. ES is mainly observed in summer, with its peak occurring around 2 km AGL instead of near the surface.

**Figure 6.** Same as Figure 5, except for LW ADRE.
Table 2. Seasonal ADRE (W m$^{-2}$) in four regions at the TOA, SFC and ATM for SW. “−” denotes the value smaller than 0.01 W m$^{-2}$.

<table>
<thead>
<tr>
<th></th>
<th>TOA</th>
<th>SFC</th>
<th>ATM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAM</td>
<td>JJA</td>
<td>SON</td>
</tr>
<tr>
<td>R1</td>
<td>DD</td>
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<td>−9.41</td>
</tr>
<tr>
<td></td>
<td>PD</td>
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<td>−0.32</td>
</tr>
<tr>
<td></td>
<td>PC/S</td>
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<td>−0.03</td>
</tr>
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<td></td>
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<td>−</td>
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<td>R3</td>
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<td>PD</td>
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<tr>
<td></td>
<td>PC/S</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>ES</td>
<td>−1.43</td>
<td>−2.50</td>
</tr>
</tbody>
</table>

Table 3. Same as Table 2 except for LW.

<table>
<thead>
<tr>
<th></th>
<th>TOA</th>
<th>SFC</th>
<th>ATM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAM</td>
<td>JJA</td>
<td>SON</td>
</tr>
<tr>
<td>R1</td>
<td>DD</td>
<td>1.08</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>PD</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>PC/S</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>ES</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>R2</td>
<td>DD</td>
<td>0.38</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>PD</td>
<td>0.14</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>PC/S</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>ES</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>R3</td>
<td>DD</td>
<td>0.24</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>PD</td>
<td>0.39</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>PC/S</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>ES</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>R4</td>
<td>DD</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>PD</td>
<td>0.16</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>PC/S</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>ES</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>

To evaluate the contributions of different types of aerosols to the radiative energy budget over North China, we calculated the percentage of ADRE attributed to the main aerosol types to the total ADRE over the four regions (Figure 8). We can see significant variation in the radiative budget contributions of the four major aerosol types in different regions. First, we focus on the SW ADRE. DD exerts a dominant influence on the local radiative effect in region R1, which accounts for 93% of the total radiative effect in this area. Due to the limited industries in this region, the radiative contribution of PD is only 6%. The other two anthropogenic aerosol types have negligible impacts on the radiative balance of this region. For region R2, despite comparable concentrations of DD and PD, the radiative effect of PD is much larger at the surface and ATM. The percentage of DD ADRE in the ATM is only 28%, while that of PD is as high as 60%. This is because PD has relatively strong absorption characteristics, which results in larger warming effects in the ATM. Due to the
influence of dust transportation from the source region, the contribution of radiative effects attributed to PD dominates in the densely populated region R3. The proportion can reach 45% and 58% at TOA and surface, respectively, allowing for the retention of 12.07 W m$^{-2}$ of radiative energy in the atmosphere to alter the atmospheric heating rate. The percentages of PC/S and ES contribution to radiative effect in region R3 are much larger compared to those in region R2. The ADRE of PC/S contributes 27% and 23% to the TOA and surface radiative budgets, respectively, which are the second-largest contribution of aerosol radiative effect.

In region R4, the radiative effect is driven by PC/S and PD, accounting for 39% (35%) and 29% (42%) at the TOA (surface). The radiative contribution of ES surpasses that of DD, reaching 19% at the TOA. These results indicate that in Northeast China, known for its traditional heavy industrial activities, aerosols from industrial production have a significant impact on local radiative energy. The LW radiative contribution of aerosol types in different regions is consistent with the SW’s.

Figure 7. The heating rates of main aerosol types at altitude above ground level (AGL). Letters (a–e) at the top left in each subplot represent annual, spring, summer, autumn and winter, respectively. Numbers 1–4 following the letters represent the four selected regions of R1–R4.
4. Discussion and Conclusions

North China, which includes the world’s second-largest source region of dust, is the most densely populated region in China. It is impacted by both natural and anthropogenic aerosols with high concentrations and a variety of aerosol types. In this study, we use the latest CALIPSO satellite data to classify aerosols in the study area, and investigate associated radiative effects by combining satellite data with the radiative transfer model. Dust, polluted dust, polluted continental/smoke, and elevated smoke are dominant aerosol types in North China, which account for over 97% of the total AOD. In terms of spatial distribution, there is a transition from natural aerosols to anthropogenic aerosols from west to east. Dust aerosols contribute 84% of the total aerosols in the western region. As the dust particles are transported downstream, natural aerosol concentrations decrease while pollution aerosol concentrations increase. In the northeastern area, pollution aerosols become the dominant type, while dust aerosols account for only 11%. As one of the most densely populated regions and highly impacted areas by dust transportation from the Taklimakan Desert and Mongolian Gobi, the Northern China Plain is dominated by polluted dust and polluted continental aerosols, which account for 53% and 24%, respectively. It is worth noting that although the frequency of the influence of dust from Mongolia has increased in this region during recent years [68,69], the total AOD has been decreasing, which is mainly due to the pollution control measures implemented in the last decade.

For the radiative effects of different aerosol types, the most important factors are AOD and SSA. We obtained the AOD of the four main types of aerosols from the CALIPSO data, which can provide extinction coefficients of individual aerosol types and whose accuracy has already confirmed in many studies. For single-scattering properties of individual types of aerosols, we cannot obtain these parameters directly from ground-based and satellite observations, which only provide total aerosols. Therefore, we optimized the SSA and g of specific aerosol types by selecting the aerosol type and adjusting its corresponding scattering parameters in the Fu–Liou model by comparing with the CERES instantaneous flux at the TOA. Although we attempted to minimize the errors by using reliable observations for the model inputs and to constrain the single-scattering properties of specific aerosol types in the model, the calculated aerosol radiative effects still have some unavoidable uncertainties.
Some studies investigated the uncertainties induced by the aerosol extinction coefficient, surface albedo, and single scattering properties. Take dust aerosols as an example. The range of uncertainties in CALIPSO lidar ratio is about 20%, which can lead to uncertainties of about $\pm 6.8$, $\pm 7.6$, and $\pm 14.4$ W m$^{-2}$ in the net dust radiative effect at the TOA, ATM, and surface, respectively [3]. The SSA was found to be the major cause of uncertainty in SW radiative effect estimate. An uncertainty of $\pm 0.03$ in the AERONET SSA can lead to 12% uncertainty in SW TOA forcing [70]. For the radiative heating rate, these parameters can only regulate the magnitude, but not the pattern, of the heating rate.

Based on the radiative closure experiment, we investigated the SW, LW, and Net radiative heating rates and radiative effects at the TOA and surface for different aerosol types in the study area. We found that different aerosol types have varying radiative contributions in different regions. Taking the significant impact of SW aerosol radiation effects as an example, dust aerosols in the western dust source region contribute the highest radiative effect ($-7.95$ W m$^{-2}$), accounting for 93% of the local ADRE. Polluted dust mainly affects Northwest China and the North China Plain, which are located downstream of dust transport, contributing 31% and 45% of the total ADRE, respectively. Anthropogenic pollutant aerosols (polluted continental/smoke and elevated smoke) are primarily distributed in regions with high population density and industrial concentration, contributing 58% of the total ADRE in Northeast China. On the whole, SW radiation has a cooling effect at the TOA and surface, with values of $-6.39$ and $-14.24$ W m$^{-2}$, respectively, while the LW radiation has a weak warming effect. The distributions of heating rates further illustrate how aerosols capture energy through the process of thermal absorption, contributing to a net radiative warming effect of 7.33 W m$^{-2}$ in the atmosphere.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs15235511/s1, Figure S1: The annual AOD variations for the four aerosol types in regions (a) R1, (b) R2, (c) R3, (d) R4.; Figure S2: The value of SSA (a) and g (b) at sub-bands of SW.

**Author Contributions:** Conceptualization, N.P. and J.S.; Data curation, X.H., X.D. and W.L.; Formal analysis, N.P., J.S. and J.W.; Methodology, N.P.; Software, N.P.; Supervision, J.S.; Validation, J.S.; Writing—original draft, N.P.; Writing—review and editing, J.S. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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