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Optical and Physical Characteristics of Aerosol Layers in Australia Based on CALIPSO

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Abstract: Atmospheric aerosols have important impacts on global radiative forcing, air pollution, and human health. This study investigated the optical and physical properties of aerosol layers over Australia from 2007 to 2019 using the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Level 2 aerosol products. Australia was divided into three sub-regions (western highlands, central plains, and eastern ranges). Interannual and seasonal optical property variations in aerosol layers in the three sub-regions were analyzed and compared. Results showed that annual mean values of AOD_L (lowest aerosol layer AOD) and AOD_T (total AOD of all aerosol layers) were always higher in the eastern ranges region than the other two regions from 2007 to 2019. The reason could be that Australian population was predominantly located in the eastern ranges region, where more human activities could bring significant aerosol loadings. B_L (base height of the lowest aerosol layer), H_L (top height of the lowest aerosol layer), and H_H (top height of the highest aerosol layer) all showed trends of “western highlands > eastern mountains > central plains”, indicating that the higher the elevation, the higher the B_L, H_L, and H_H. T_L (thickness of the lowest aerosol layer) was higher during the day than at night, which might account for increased diurnal atmospheric convection and nocturnal aerosol deposition. DR_L (depolarization ratio of the lowest aerosol layer) was higher in the western highlands and central plains than the eastern mountains, probably because these two regions have large deserts with more irregularly shaped dust aerosols. CR_L (color ratio of the lowest aerosol layer) had slightly higher values in the eastern ranges than the other two regions, probably due to the wet climate of the eastern ranges, where aerosols were more hygroscopic and had larger particle sizes. This study can provide technical support for the control and management of regional air pollutants.

Keywords: aerosol; particle; lidar; vertical distribution; optical property



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1. Introduction

Atmospheric aerosols are suspended microscopic particles in the air, typically with aerodynamic diameters of 10^{-3} – 10^2 μm [1–3]. Atmospheric aerosols have a strong impact on global radiative forcing, air pollution, and human health [4–7]. Atmospheric aerosols can absorb or scatter solar short-wave and long-wave radiation, altering the radiation balance between the Earth and the atmosphere. Aerosols can also act as cloud condensation nuclei, altering the life cycle of clouds and affecting local or regional weather conditions [8–12]. Therefore, studies of atmospheric aerosols are of great importance, which can help scientists and government departments to understand global radiation changes and formulate air pollution control policies.

Many aerosol observation stations have been established around the world, which are helpful for the study of aerosols. For example, the AERONET (Aerosol Robotic Net-

work), established by NASA, can obtain a continuous observation of aerosols' physical and optical properties around the world [13,14]. The MODIS sensors on board TERRA and AQUA satellites can obtain large-scale aerosol optical parameters but still cannot obtain the vertical distribution properties of aerosols [15]. With the development of observation technology, lidar has become a more popular remote sensing device for atmospheric aerosol and gas observations [16–21]. Not only can it obtain information on the vertical distribution of aerosols, but it can also work continuously at nighttime and during the daytime [22–24]. The NASA Micro-pulse Lidar Network (MPLNET), the European Lidar Observation Network (EARLINET), and the Asian Dust Lidar Observation Network (AD-NET) have been established worldwide in recent years [25–27]. NASA and CNES jointly launched the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) in April 2006, which was equipped with the orthogonal polarization cloud aerosol lidar CALIOP [28,29]. The CALIOP can provide vertical distribution, particles size, particle classification, and information on aerosols and clouds [30–32].

Australia is located between the South Pacific Ocean and the Indian Ocean. It is the only country in the world that is also a continent. In total, 70% of Australia is arid and semi-arid, with 3.4 million square kilometers of desert and semi-desert. Strong westerly winds can carry large amounts of dust from northern Australia, resulting in increased aerosol loadings in the middle part of Australia [33–35]. Australia has both a savannah climate and a tropical desert climate with high summer temperatures and low precipitation in the midwestern part [36]. As there have been no studies on the vertical distribution of aerosol layers in Australia, we took the opportunity to analyze the optical and physical properties of aerosol layers in Australia in this study utilizing CALIPSO Level 2 aerosol layer products. This study can provide scientific understanding and technical support to scientists and atmospheric environmental management departments. Research methods are explained in Section 2, results and discussions are presented in Section 3, and conclusions are in Section 4.

2. Methodology

2.1. Study Area

Figure 1 showed the topographic map of Australia. The total area of Australia is 7,692,000 square kilometers, and the coastline is 36,735 km long [37]. The landform of Australia consists of mountains in the east, plains in the center, and plateaus in the west. The average annual temperature is 27 °C in the north and 14 °C in the south. Australia straddles two climate zones, with the north being tropical and the south being temperate [33]. The mid-west has barren deserts with little rain, high temperatures, and large diurnal temperature differences. The coastal zone has plenty of rain and a humid environment. Due to the topography and climate, the Australian population is concentrated along the eastern seaboard. The western seaboard is less populated, and the middle part is almost uninhabited (Figure 2).

2.2. Materials and Methods

CALIPSO (Cloud-Aerosol Lidar and Infrared Path and Satellite Observation) carries three instruments (CALIOP, IIR, and WFC). The CALIOP is a visible and near-infrared polarimetric lidar used for observing the phase state of Earth's aerosols and clouds [38]. The CALIOP has one 1064 nm channel and two channels of 532 nm horizontal polarization and vertical polarization, respectively [29,31]. The signal spanning is six orders of magnitude. The satellite orbit is sun-synchronous with 705 km elevation and 7 km/h orbital speed. The orbital period is 96 min, with a repeat period of 16 days. There are three levels of CALIOP data, and this paper uses the Level 2 (L2) aerosol layer datasets [39]. L2 aerosol layer datasets have a horizontal resolution of 5 km, and the parameters used are the AOD of the lowest aerosol layer (AOD_L), the total AOD of all aerosol layers (AOD_T), the base height of the lowest aerosol layer (B_L), the top height of the lowest aerosol layer (H_L), the top height of the highest aerosol layer (H_H), the thickness of the lowest aerosol layer (T_L),

the number of aerosol layers (N), the AOD proportion for the lowest aerosol layer ($PAOD_L$), the receding ratio of the lowest aerosol layer (DR_L), and the color ratio of the lowest aerosol layer (CR_L). AOD_L , H_L , B_L , H_H , DR_L , CR_L , and N can be obtained directly from L2, while AOD_T , TL , and $PAOD_L$ are obtained indirectly, using the following equations:

$$AOD_T = \sum_{i=1}^N AOD_{N_i}; N = 1, 2, \dots, 7, 8 \quad (1)$$

$$T_L = H_L - B_L \quad (2)$$

$$PAOD_L = \frac{AOD_L}{AOD_T} \times 100\% \quad (3)$$

where $N = 1$ represents the lowest aerosol layer, i.e.:

$$AOD_L = AOD_1 \quad (4)$$

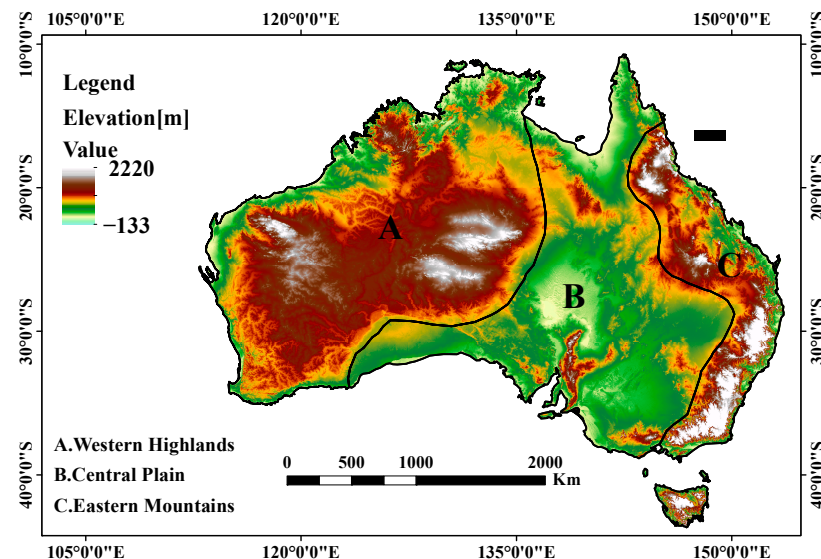


Figure 1. A topographic map of Australia. The color change represents the elevation.

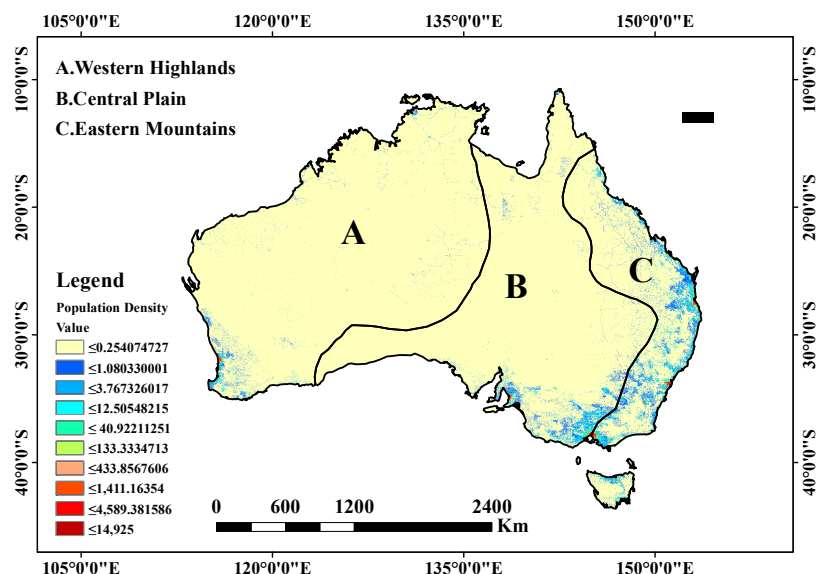


Figure 2. The distribution of population in Australia. Different colors represent population density differences.

To extrapolate temporal and spatial variabilities of aerosol characteristics conveniently in Australia, we divided Australia into three regions based on topography (Figure 1): western highlands (A), central plains (B), and eastern ranges (C). Seasons were defined as spring (September to November), summer (December to February), autumn (March to May), and winter (June to August). Annual and seasonal statistical information of aerosol variables were calculated over three subregions from 2007 to 2019. Null and negative values were removed first in this study; AOD_L and AOD_T values greater than 10, B_L , H_L , H_H , and T_L greater than 100 and DR_L , and CR_L greater than 10 were removed second, because these datasets were false noise interferences; then, the remaining datasets were utilized in the next step.

3. Results and Discussions

3.1. Interannual Variations in Aerosol Layer Optical Properties over Australia

Annual mean AOD_T values for the A, B, and C subregions were analyzed from 2007 to 2019. Figure 3b (daytime) and Figure 4b (nighttime) revealed that a slight increase in the annual mean AOD_T over Australia. The C region had a higher AOD_T than the A and B regions. The annual mean AOD_T (daytime: 0.20; nighttime: 0.16) was higher in the eastern mountains region, followed by the central plains (daytime: 0.16; nighttime: 0.13), and finally the western highlands (daytime: 0.14; nighttime: 0.13). This might be because Australia was controlled by the subtropical high-pressure belt and the effect of narrow eastern ranges, which could result in wet conditions in the east and arid conditions in the mid-west parts of Australia all year round [35,36]. Previous studies had shown that humidity had a positive correlation with AOD; therefore, AOD_T and AOD_L were higher in the eastern ranges than in the other two regions [33,40]. It might also be related to the distribution of population (Figure 2), economic development, and industrial activity in Australia. Figure 2 revealed that the population density in the east was high, and more populous cities existed in the eastern ranges region, such as Sydney, Melbourne, and Brisbane. High populations could lead to high anthropogenic particulate emissions, and therefore, high aerosol AOD_T and AOD_L values existed in the east [33].

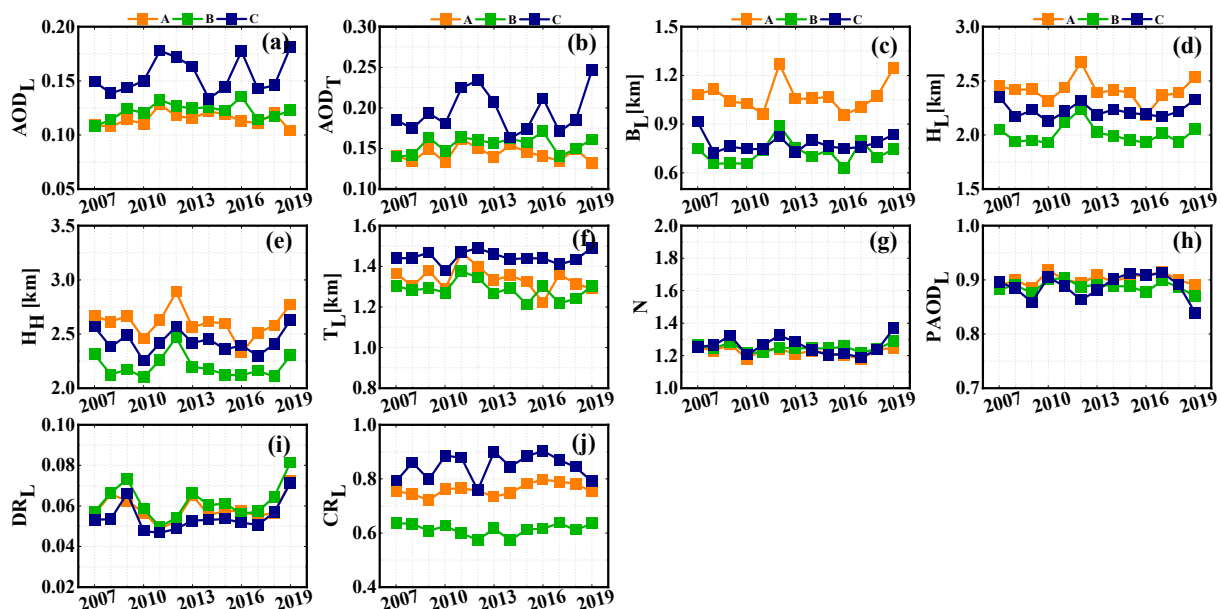


Figure 3. Interannual variation in aerosol layer optical properties in Australia during the daytime from 2007 to 2019 (A: western plateau, B: central plains, and C: eastern ranges). (a) AOD of the lowest aerosol layer (AOD_L); (b) total AOD of all aerosol layers (AOD_T); (c) base height of the lowest aerosol layer (B_L); (d) top height of the lowest aerosol layer (H_L); (e) top height of the highest aerosol layer (H_H); (f) thickness of the lowest aerosol layer (T_L); (g) number of aerosol layers (N); (h) specific gravity of the AOD of the lowest aerosol layer ($PAOD_L$); (i) declination ratio of the lowest aerosol layer (DR_L); (j) color ratio of the lowest aerosol layer (CR_L).

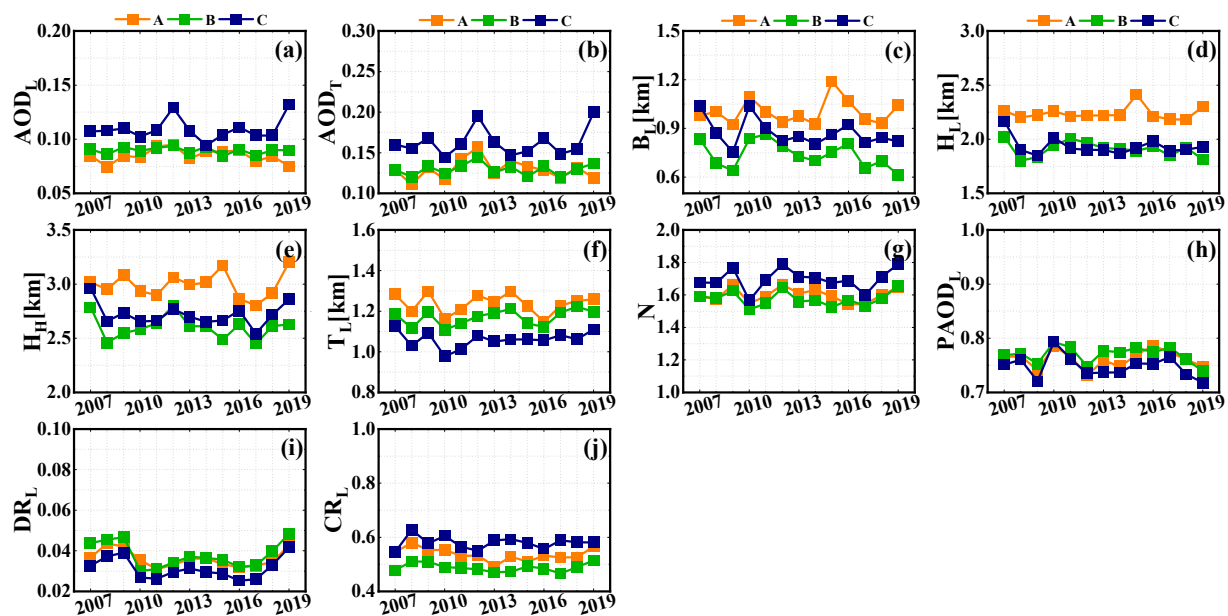


Figure 4. Interannual variation in aerosol layer optical properties in Australia at nighttime from 2007 to 2019 (A: western plateau, B: central plains, and C: eastern ranges). (a) AOD of the lowest aerosol layer (AOD_L); (b) total AOD of all aerosol layers (AOD_T); (c) base height of the lowest aerosol layer (B_L); (d) top height of the lowest aerosol layer (H_L); (e) top height of the highest aerosol layer (H_H); (f) thickness of the lowest aerosol layer (T_L); (g) number of aerosol layers (N); (h) specific gravity of the AOD of the lowest aerosol layer ($PAOD_L$); (i) declination ratio of the lowest aerosol layer (DR_L); (j) color ratio of the lowest aerosol layer (CR_L).

The increase in AOD_T values between 2010 and 2012 might be due to forest fires (Margaret River Bushfires and Carnarvon Bushfires) resulting in the release of large amounts of organic matter and aerosols into the atmosphere. During this time, Australia experienced several dust storms resulting in large amounts of dust also being released into the atmosphere resulting in increased AOD values [33,35,36]. It might also be due to the rapid economic development of Australia during this period and the increase in human activities such as industrial production and transport, which may have led to increased concentrations of aerosols in the atmosphere and hence higher AOD values [33]. From 2012 to 2014, international cooperation might have contributed to reduced emissions of pollutants in the atmosphere, resulting in lower AOD values. Between 2014 and 2016, Australia experienced continued economic growth. Increased human activities, such as energy consumption, industrial production, and transport, led to increased aerosol concentrations in the atmosphere and consequently higher AOD values. It should be noted that decreases in AOD_L in 2012–2014 and in 2016–2018, as well as the increase in 2013–2016 in the C region (Eastern Australia), could be due to interannual variability in air humidity in this region. Also, it may be one of the reasons for the lower interannual variation in nighttime AOD_L compared to daytime in the C region.

Analysis was carried out on the AOD_L , which was strongly influenced by natural and anthropogenic activities [41,42]. Figure 3a,b (daytime) and Figure 4a,b (nighttime) showed that the annual mean AOD_L over Australia has a similar annual variability pattern to AOD_T , i.e., the annual mean AOD_L was higher in the eastern ranges (daytime: 0.16; nighttime: 0.11), followed by the central plains (daytime: 0.12; nighttime: 0.09), and finally the western highlands (daytime: 0.11; nighttime: 0.08). This might be because Australia is surrounded by sea, with cold currents in the west and warm currents in the east, creating a spatial distribution of a wetter climate in the east and a drier climate in the west, resulting in a higher AOD_L in the eastern ranges [33].

Figure 3c (daytime) and Figure 4c (nighttime) showed the interannual variation in B_L , which is mainly influenced by elevations [41]. Results showed that B_L was highest in the western highlands (daytime: 1.07 km; nighttime: 1.00 km), followed by the eastern mountains region (daytime: 0.78 km; nighttime: 0.87 km) and the central plains (daytime: 0.72 km; nighttime: 0.74 km). The main reason was the influence of elevation, with higher B_L values in higher elevation areas. Annual mean H_L and H_H values (Figures 3d,e and 4d,e) were also higher in the western highlands (daytime: 2.41 km; nighttime: 2.24 km), followed by the eastern mountains (daytime: 2.23 km; nighttime: 1.93 km) and the central plains (daytime: 2.01 km; nighttime: 1.91 km). This result showed that H_L and H_H were also more related to topography, with higher elevation regions having higher H_L and H_H values. This result was similar to that of Zhang's study [41–43]. Figure 3f (daytime) and 4f (nighttime) showed the interannual variation in T_L in the western highlands (daytime: 1.34 km; nighttime: 1.24 km), the central plains (daytime: 1.29 km; nighttime: 1.17 km), and the eastern mountains (daytime: 1.46 km; nighttime: 1.06 km). As shown, values at night were relatively small compared to the daytime. This should be due to the mixed layer that was thicker in the daytime due to convective processes driven by solar radiation [44]. At the same time, low temperatures and weak vertical convection in the atmosphere at night could lead to thinner aerosol layers [41,42,45]. Figure 3g (daytime) and Figure 4g (nighttime) showed that there was little difference between annual averaged N values for the eastern ranges (daytime: 1.26; nighttime: 1.70), central plains (daytime: 1.25; nighttime: 1.58), and western highlands (daytime: 1.23; nighttime: 1.60) regions of Australia. However, annual averaged N values were slightly greater in the eastern ranges region than in the central plains and western highlands regions. One plausible reason for this was that the Australian population is predominantly distributed in the eastern ranges region, where anthropogenic factors contribute to the large atmospheric aerosol loadings, resulting in significant vertical stratifications of atmospheric aerosols [33].

According to Figures 3h and 4h, it can be seen that there was little difference in $PAOD_L$ values between the eastern mountains region (daytime: 89%; nighttime: 75%), the central plain region (daytime: 89%; nighttime: 77%), and the western plateau region (daytime: 90%; nighttime: 76%). $PAOD_L$ was the ratio of AOD_L to AOD_T and was mainly influenced by N . Results showed that $PAOD_L$ had a negative correlation with N . The larger the value of N , the smaller the $PAOD_L$. This was similar to the results of the Yellow River basin in China and Pakistan [41,43]. The DR_L reflected the aerosol particle degree of non-sphericity in the lowest aerosol layer. The larger DR_L values mean more non-spherical particles; smaller DR_L values mean more spherical particles [41]. Results showed that annual mean DR_L values were higher in the western highlands (daytime: 0.06; nighttime: 0.04) and the central plains (daytime: 0.06; nighttime: 0.04) than in the eastern mountains (daytime: 0.05; nighttime: 0.03), which indicated that more non-spherical particles were present in the A region and the B region, as these two regions had large areas of deserts with irregularly shaped dust aerosols. These results also indicated that more non-spherical particles were present during the daytime compared to the nighttime, which may be due to nighttime aerosol depositions. In addition, it may also be caused by nighttime water condensation on non-spherical particles. The water coating will make a particle more spherical, increasing the total sphericity of the particles [34,41]. CR_L values represented particle sizes; the higher the CR_L values, the larger the particle sizes. Figures 3j and 4j reflected the annual mean variations in CR_L in the lowest aerosol layer during the daytime and at nighttime. Results showed that larger CR_L values existed in the eastern mountains region (daytime: 0.85; nighttime: 0.58) and western highlands region (daytime: 0.76; nighttime: 0.54) compared to the central plain region (daytime: 0.61; nighttime: 0.49). The larger size of aerosol particles in C region may be caused by sea salt [37]. The medium-sized aerosol particles in the A region may be due to sandy and dusty aerosols (the Great Sandy Desert, Great Victoria Desert, Gibson Desert, and Simpson Desert are all located in the western highlands region of Australia) [34].

3.2. Seasonal Variations in Aerosol Layer Optical Properties over Australia

Seasonal variations in aerosol layer optical properties over Australia were conducted during the daytime and nighttime (Figures 5–8). Results showed that AOD_T was more variable in the eastern mountains region, reaching its highest value in summer (daytime: 0.23; nighttime: 0.20). And AOD_T values were highest in the western highlands (daytime: 0.17; nighttime: 0.16) and the central plains (daytime: 0.18; nighttime: 0.14) in spring because of dust. This may be due to the influence of southeasterly trade winds in summer and the tall eastern mountains blocking the warm and humid airflow, resulting in more rain in the east and less rain in the mid-west. Hence, the highest AOD_T values in the eastern mountains was in summer, which was similar to the study results of Mitchell et al., where AOD and scattering coefficients peaked in the central plains of Australia in spring and summer [35]. Overall, AOD_T values were lowest in winter (daytime: 0.15; nighttime: 0.11) over most of the Australian continent, because high pressures can lead to a dry atmosphere and low humidity over most of the continent [35]. From spatial distribution maps (Figures 5 and 6), AOD values were relatively high in the eastern ranges region of Australia compared to the other two regions, which may be because the Australian population was predominantly located in the eastern ranges region, leading to high anthropogenic pollution emissions, which was consistent with the findings of Mitchell et al. [36].

As shown in Figures 5 and 6, H_L and H_H values were higher in the western highlands compared to the other two regions. Notably, H_L and H_H values were higher in spring in the western plateau region compared to the other three seasons, which may be the reason that the western plateau region had large areas of desert and was significantly affected by sand and dust aerosols in spring [33]. The seasonal plots showed gradual decreases in H_L and H_H values from spring to winter. These can be attributed to the intensification of vertical convection caused by seasonal temperature gradients, which can result in the enhanced vertical movement of the aerosol layers [37].

As shown in Figures 7g and 8g, the highest N values were observed in spring (daytime: 1.31; nighttime: 1.76), and the lowest N values were observed in winter (daytime: 1.19; nighttime: 1.45). This may be due to a stronger vertical convection in spring and a weaker vertical convection in winter [37]. The nighttime N values were higher than those in the daytime (~ 0.37); the reason for this could be that atmosphere convection increased and fully mixed during the daytime, leading to a decrease in N and an increase in T_L ; during the night, atmospheric convection weakened and residual layer appeared, resulting in the stratification of the atmosphere and an increase in N [45]. High values of N were mainly found in the eastern ranges region, which is characterized by a dense population, high economic activity, and more industrial units and agricultural activities, resulting in more aerosol stratification [36]. The seasonal mean of T_L was highest in spring (daytime: 1.42 km; nighttime: 1.22 km) and lowest in winter (daytime: 1.27 km; nighttime: 1.05 km). As T_L was calculated from B_L and H_L , its variation mainly depended on the distribution of B_L and H_L (Figures 7d,e and 8d,e). In addition, the T_L values were slightly lower at nighttime than during the daytime (~ 0.2 km).

As shown in Figures 7h and 8h, $PAOD_L$ mean values for all seasons were almost the same for the whole of Australia (daytime: 89%; nighttime: 76%). The higher $PAOD_L$ values in winter compared to the other seasons may be related to the properties of AOD_T (AOD_L) and N as discussed above. In addition, $PAOD_L$ values were higher during the daytime than at nighttime, which may be due to higher aerosol loadings in the lowest aerosol layer, where coarse particles dominated [34,41]. Seasonal mean values of DR_L were slightly higher in spring (daytime: 0.06; nighttime: 0.04) and summer (daytime: 0.07; nighttime: 0.04) than in autumn (daytime: 0.05; nighttime: 0.03) and winter (daytime: 0.05; nighttime: 0.03). This might be due to relatively heavy dust transports during these two seasons, resulting in a higher number of non-spherical aerosol particles [37]. DR_L values were higher in the western highlands and central plains regions than in the eastern ranges region, which may be due to the high number of deserts and dust aerosols in the western highlands and central plains regions. Seasonal mean values of CR_L did not vary significantly between the seasons

(daytime: 0.74; nighttime: 0.54), and its spatial distribution showed higher CR_L values in the eastern ranges and western highlands regions, indicating that larger aerosol particle sizes existed in these two regions. Mitchell et al. showed that as the atmospheric humidity increased, the aerosol particle sizes increased [33]. The eastern mountainous region was wet and rainy leading to larger CR_L values. The larger CR_L values in the western highlands may be due to the influence of sand and dust aerosols.

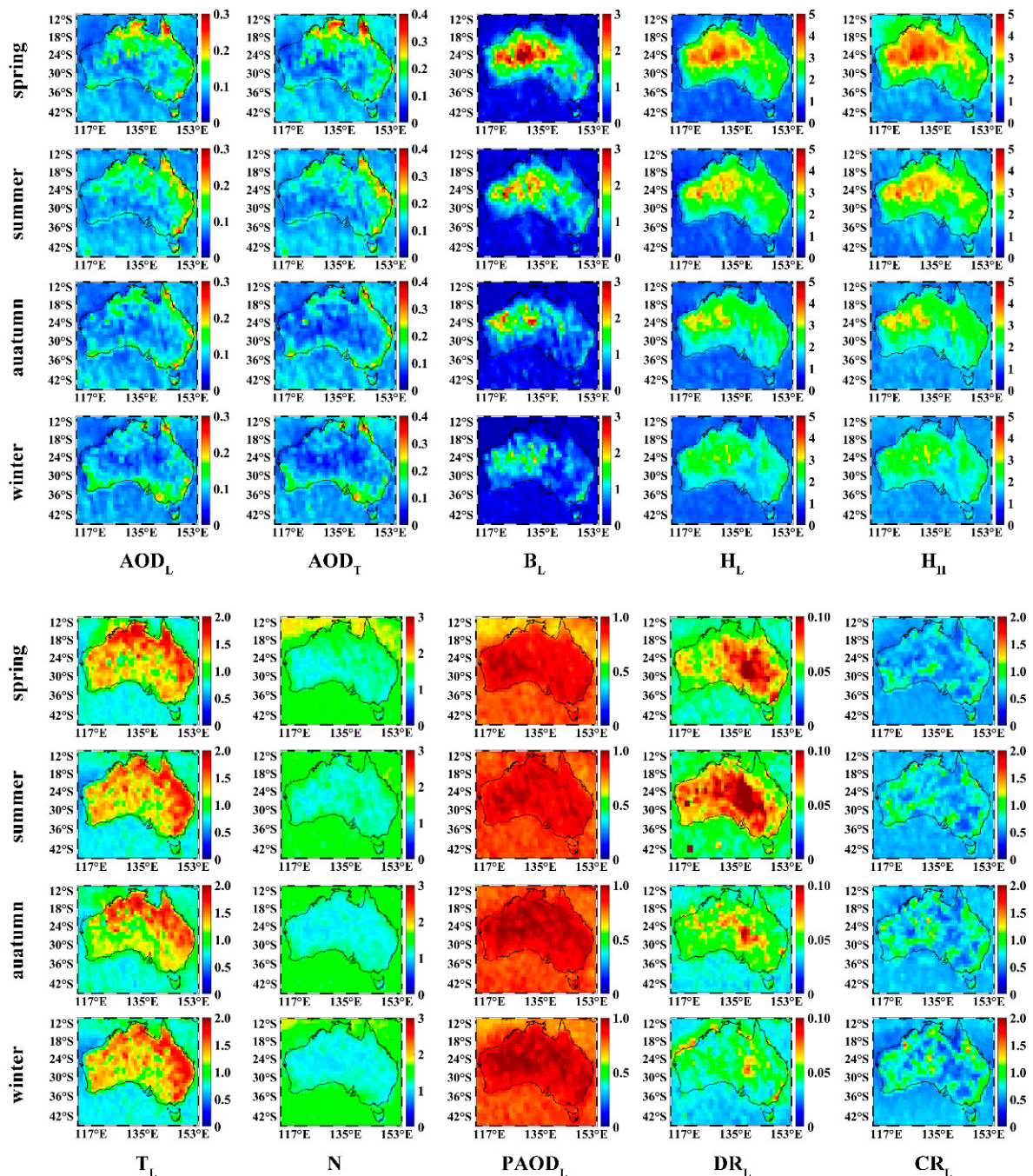


Figure 5. Seasonal spatial distribution of AOD of the lowest aerosol layer (AOD_L), total AOD of all aerosol layers (AOD_T), base height of the lowest aerosol layer (B_L), top height of the lowest aerosol layer (H_L), top height of the highest aerosol layer (H_H), thickness of the lowest aerosol layer (T_L), number of aerosol layers (N), specific gravity of the AOD of the lowest aerosol layer ($PAOD_L$), declination ratio of the lowest aerosol layer (DR_L), and color ratio of the lowest aerosol layer (CR_L) over Australia during the daytime.

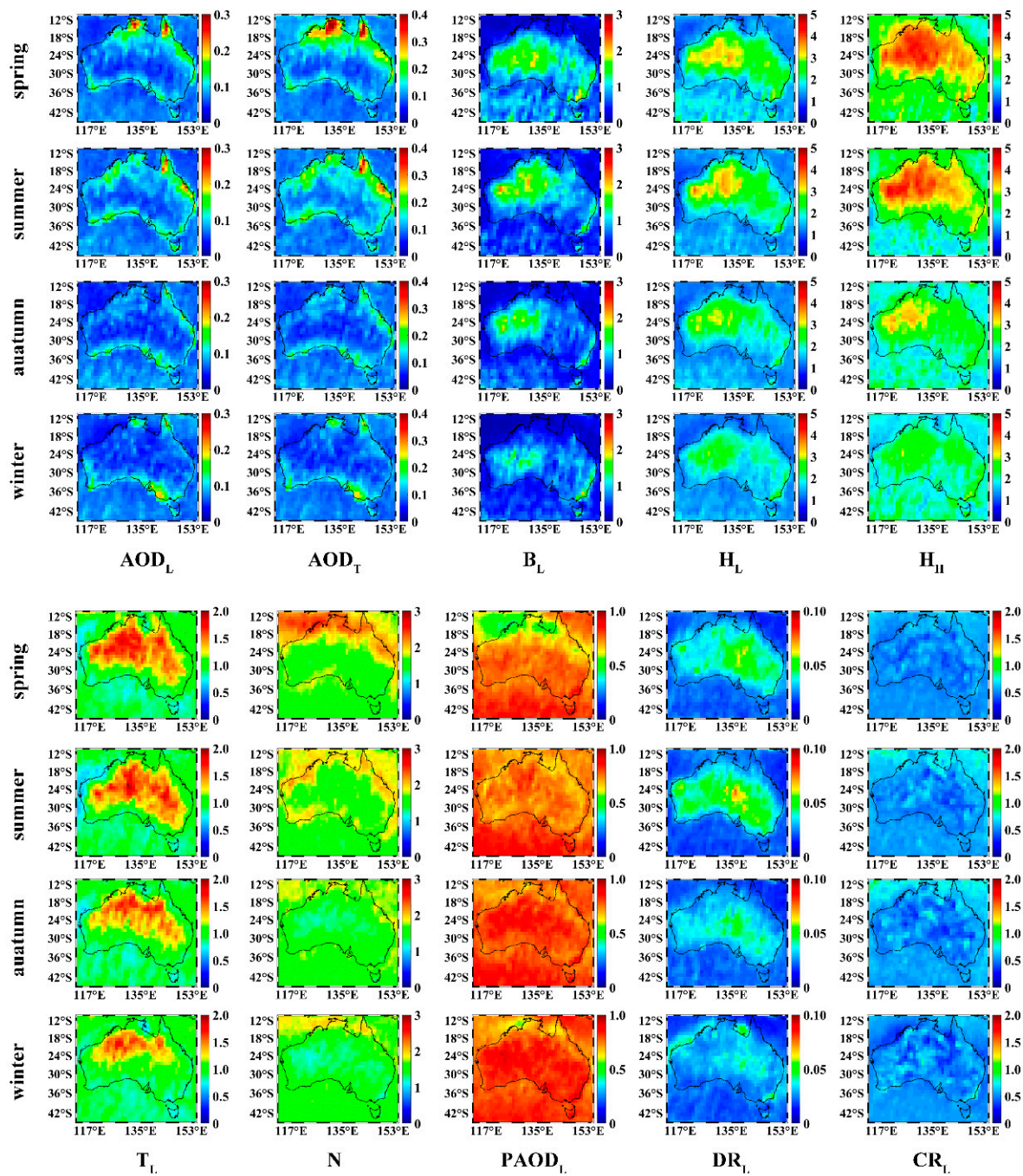


Figure 6. Seasonal spatial distribution of AOD of the lowest aerosol layer (AOD_L), total AOD of all aerosol layers (AOD_T), base height of the lowest aerosol layer (B_L), top height of the lowest aerosol layer (H_L), top height of the highest aerosol layer (H_H), thickness of the lowest aerosol layer (T_L), number of aerosol layers (N), specific gravity of the AOD of the lowest aerosol layer (PAOD_L), declination ratio of the lowest aerosol layer (DR_L), and color ratio of the lowest aerosol layer (CR_L) over Australia at nighttime.

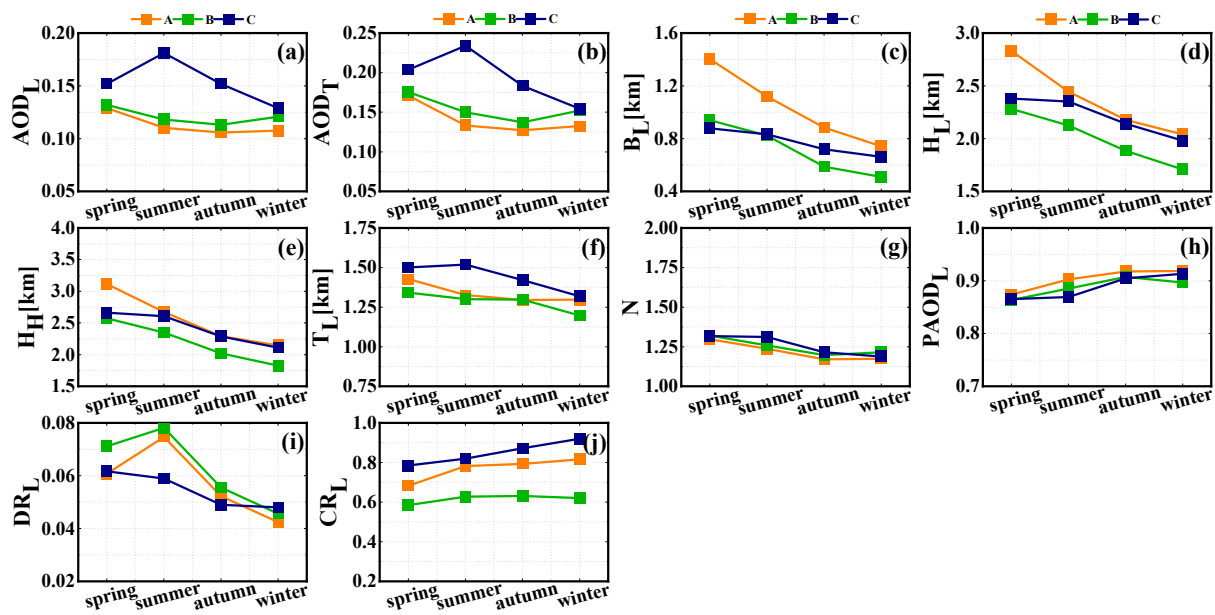


Figure 7. Seasonal variation in the optical properties of aerosol layers over Australia during the daytime from 2007 to 2019 (A: western plateau, B: central plains, C: eastern ranges). (a) AOD of the lowest aerosol layer (AOD_L); (b) total AOD of all aerosol layers (AOD_T); (c) base height of the lowest aerosol layer (B_L); (d) top height of the lowest aerosol layer (H_L); (e) top height of the highest aerosol layer (H_H); (f) thickness of the lowest aerosol layer (T_L); (g) number of aerosol layers (N); (h) specific gravity of the AOD of the lowest aerosol layer ($PAOD_L$); (i) declination ratio of the lowest aerosol layer (DR_L); (j) color ratio of the lowest aerosol layer (CR_L).

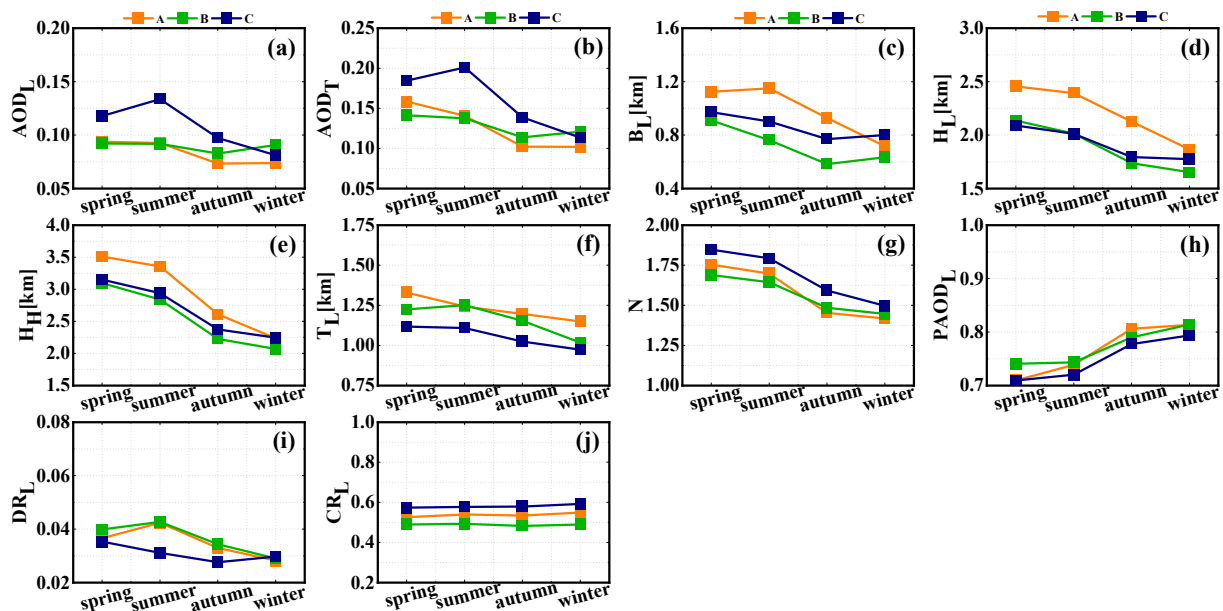


Figure 8. Seasonal variation in the optical properties of aerosol layers over Australia at nighttime from 2007 to 2019 (A: western plateau, B: central plains, C: eastern ranges). (a) AOD of the lowest aerosol layer (AOD_L); (b) total AOD of all aerosol layers (AOD_T); (c) base height of the lowest aerosol layer (B_L); (d) top height of the lowest aerosol layer (H_L); (e) top height of the highest aerosol layer (H_H); (f) thickness of the lowest aerosol layer (T_L); (g) number of aerosol layers (N); (h) specific gravity of the AOD of the lowest aerosol layer ($PAOD_L$); (i) declination ratio of the lowest aerosol layer (DR_L); (j) color ratio of the lowest aerosol layer (CR_L).

3.3. Correlation of Aerosol Properties in Australia

To better understand the spatial and temporal distribution of aerosol properties over Australia, seasonal correlations between some aerosol layer parameters during the daytime and at nighttime were carried out (Figures 9–11). We used the Pearson correlation coefficients in this part [46]. The results showed a more significant positive correlation between AOD_L and T_L . And these relationships varied during the daytime and at nighttime and also changed at different seasons. Daytime correlations were mostly higher than nighttime correlations, which may be related to reduced anthropogenic factors at night. In terms of seasonal distribution, the highest correlations for the three Australian regions were found in spring, followed by summer and autumn, and the lowest correlations were found in winter, because aerosol contents in spring and summer were relatively high compared to those in autumn and winter. This was consistent with the results of the Yellow River basin in China and Pakistan [41,43].

Figure 10 depicts the correlation between N and H_H in Australia. N was mainly distributed between 1 and 7 in regions A, B, and C, all of which had strong positive correlations with H_H . This phenomenon revealed that the higher the H_H , the greater the N values. This result was consistent with the existing knowledge reported for the Yellow River Basin and the Qinghai-Tibet Plateau [42,43]. Figure 11 depicts the correlation between N and $PAOD_L$ in Australia. The results showed that N exhibited a significant negative correlation with $PAOD_L$. Based on the current knowledge, the larger the N value, the smaller the $PAOD_L$ value, which was consistent with the previous research [41,42].

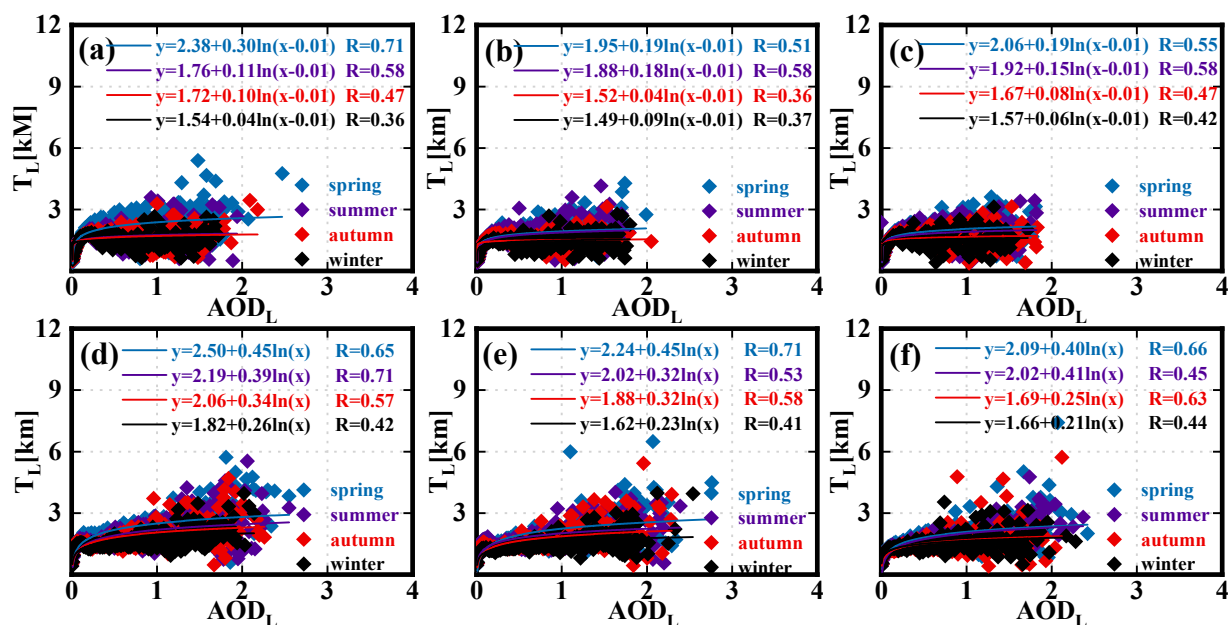


Figure 9. Correlation of AOD_L and T_L over Australia from 2007 to 2019: (a) western plateau daytime; (b) central plains daytime; (c) eastern ranges daytime; (d) western plateau nighttime; (e) central plains nighttime; (f) eastern ranges nighttime.

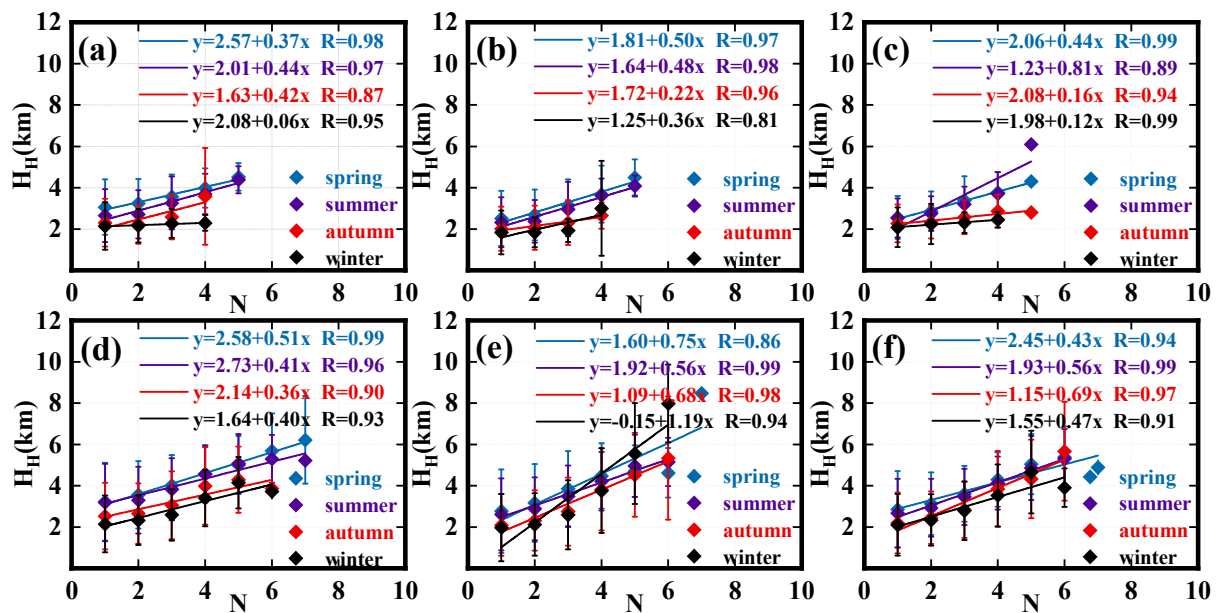


Figure 10. Correlation of N and H_H over Australia from 2007 to 2019: (a) western plateau daytime; (b) central plains daytime; (c) eastern ranges daytime; (d) western plateau nighttime; (e) central plains nighttime; (f) eastern ranges nighttime.

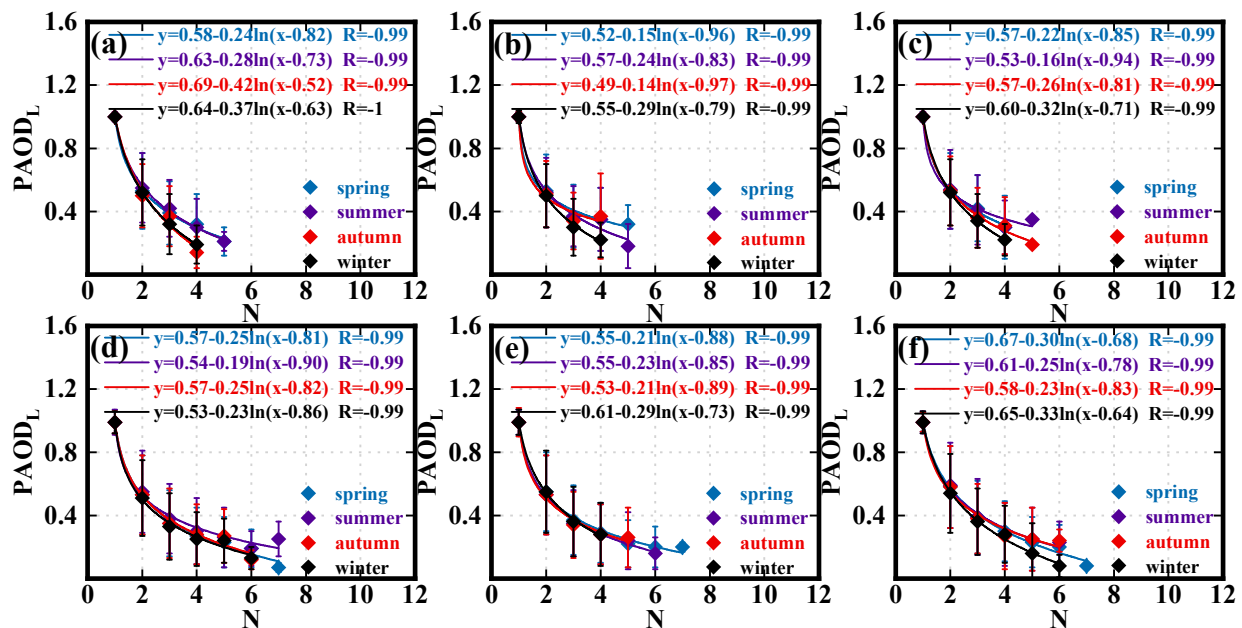


Figure 11. Correlation of N and $PAOD_L$ over Australia from 2007 to 2019: (a) western plateau daytime; (b) central plains daytime; (c) eastern ranges daytime; (d) western plateau nighttime; (e) central plains nighttime; (f) eastern ranges nighttime.

4. Conclusions

In this article, the optical and physical properties of aerosol layers over Australia were investigated using CALIPSO level 2 products from 2007 to 2019. The interannual, seasonal variabilities of AOD_L , AOD_T , B_L , H_L , H_H , T_L , N , $PAOD_L$, DR_L , and CR_L were analyzed and discussed for the daytime and the nighttime. The main conclusions are as follows:

(1) The annual mean values of AOD_T were highest in the eastern ranges. This may be related to Australian climatic characteristics (wet and rainy in the east, dry and low rainfall in the mid-west) and population distributions.

(2) AOD_T values reached maximum levels in the summer in the eastern range region and in the spring in the other two regions. This may be due to high atmospheric humidity in the summer over the eastern range region, while the other two regions had more frequent dusty weather in spring.

(3) B_L , H_L , and H_H had clear correlations with elevation: the higher the elevation, the higher the values of B_L , H_L , and H_H . B_L , H_L , and H_H values gradually decreased from spring to winter. H_H had a positive correlation with N .

(4) T_L values were smaller at nighttime than during the daytime. This may be related to nocturnal aerosol depositions.

(5) DR_L values were higher in the western highlands and central plains than in the eastern mountain ranges. This was because the central and western regions were dotted with large areas of deserts and because there were large amounts of non-spherical dust aerosols. More non-spherical particles were present during the daytime than at nighttime.

(6) CR_L values were higher in the eastern mountainous regions and the western highland regions than in the central plain regions. This indicated that aerosol particles in the first two regions were of a larger particle size.

In future work, we will investigate dust emissions in the A and B regions using CALIOP data. Meanwhile, we will use more in situ datasets to observe more optical and physical parameters over Australia.

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