

Measurement report: Analysis of aerosol optical depth variation at Zhongshan Station in Antarctica

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Three key findings:

- The AOD level over Zhongshan Station in Antarctica is low in summer and high in winter. AE indicates the dominance of fine (coarse) aerosols in summer (winter).
- In winter and spring, high AOD values are related to the increase of coarse mode particles, while in summer and autumn, high AOD values may be related to the growth of fine mode particles.
- AOD varied inversely with wind speed and showed an insignificant positive correlation with temperature but a significant negative correlation with relative humidity.

Abstract: Our understanding of aerosol optical depth (AOD) in Antarctica remains limited due to the scarcity of ground observation stations and limited daylight days. Utilizing data from the CE318-T photometer spanning from January 2020 to April 2023 at Zhongshan Station, we analysed the seasonal, monthly, and diurnal variations in AOD and Ångström exponent (AE). AOD median values increased from spring (0.033) to winter (0.115), while AE peaked during summer (1.010) and autumn (1.034), declining in winter (0.381), indicating a transition in dominant aerosol particle size from fine to coarse mode between summer and winter. Monthly mean AOD variation closely paralleled the proportion of $AE < 1$, suggesting fluctuations in coarse mode particle proportions drive AOD variation. The high AOD values during winter and spring were associated with increased contribution of coarse mode particles,

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28 while high AOD values during summer and autumn were associated with the growth of fine mode
29 particles. We observed a peak in AOD (~ 0.06) at 14:00 local time at Zhongshan Station, possibly
30 associated with a slight decrease in boundary layer height (BLH). Additionally, higher (lower) wind
31 speeds corresponded to lower (higher) AOD values, indicating the diffusion (accumulation) effect. The
32 temperature and AOD showed an insignificant positive correlation ($R = 0.22$, $p = 0.40$), relative humidity
33 exhibited a significant negative correlation with AOD ($R = -0.59$, $p = 0.02$). Backward trajectory analysis
34 revealed that coarse particles from the ocean predominantly contributed to high AOD daily mean values,
35 while fine particles on low AOD days originated mainly from the air mass over the Antarctic Plateau.
36 This study enhances the understanding of the optical properties and seasonal behaviors of aerosols in the
37 coastal Antarctic. Specifically, AOD measurements during the polar night address the lack of validation
38 data for winter AOD simulations. Additionally, we revealed that lower wind speeds, higher temperatures,
39 and lower relative humidity contribute to increased AOD at Zhongshan Station, and air masses from the
40 ocean significantly impact local AOD levels. These findings help us infer AOD variation patterns in the
41 coastal Antarctic based on meteorological changes, providing valuable insights for climate modeling in
42 the context of global climate change.

43 **1 Introduction**

44 Aerosols play an important role in impacting the climate system by absorbing and scattering solar
45 radiation (Li et al., 2022). Antarctica, considered one of the most pristine lands, serves as an ideal
46 background area for evaluating the climate effects of aerosols (Kamra, 2022). Marine aerosols emitted
47 from the Southern Ocean are a primary source contributing to the aerosol load in Antarctica (Thakur,
48 2019). The retreat of sea ice in Antarctica is expected to escalate the release of sea salt and secondary
49 biogenic aerosols (Yan et al., 2020). Sea salt particles with strong scattering may produce negative
50 effective radiative forcing or indirect radiative effect by influencing cloud condensation nuclei within
51 the marine boundary layer over Antarctica (Thornhill et al., 2021; Udisti et al., 2012). However, the
52 heating effect of absorbent aerosols, such as black carbon (BC), may be amplified by the high surface
53 albedo in Antarctica (Kang et al., 2020). In recent years, there has been a notable increase in BC
54 concentrations in Antarctica, with BC deposition on snow and ice surfaces contributing to reduced

55 surface albedo and increased solar radiation absorption, subsequently accelerating snow and ice melt
56 (Kannemadugu et al., 2023). Given the close connection between aerosol radiation effects and their
57 optical properties (Che et al., 2024), it is necessary to investigate the optical parameters of Antarctica
58 aerosols.

59 Aerosol optical depth (AOD), as a key parameters of aerosol optical properties, serves as an effective
60 measure of aerosol load and can influence the solar radiation components (Alghoul et al., 2009). AOD
61 observation records from Antarctica sites indicate that the values range from 0.006 to 0.220 in coastal
62 regions and from 0.007 to 0.034 in inland regions (Kannemadugu et al., 2023; Tomasi et al., 2007, 2012;
63 Yang et al., 2021). Typically, coastal aerosols consist primarily of coarse-mode sea salt particles during
64 austral winter, while fine-mode particles (such as dimethyl sulfide and its oxidation product mesylate,
65 DMS, and MSA) lead to elevated particle number concentrations in summer (20-100 times higher than
66 in winter) (Lachlan-Cope et al., 2020; Shaw, 1979). Conversely, aerosols over the Antarctic Plateau
67 predominantly comprise fine-mode particles of non-sea-salt sulfate (NSS) and DMS (Harder et al., 2000;
68 Walters et al., 2019).

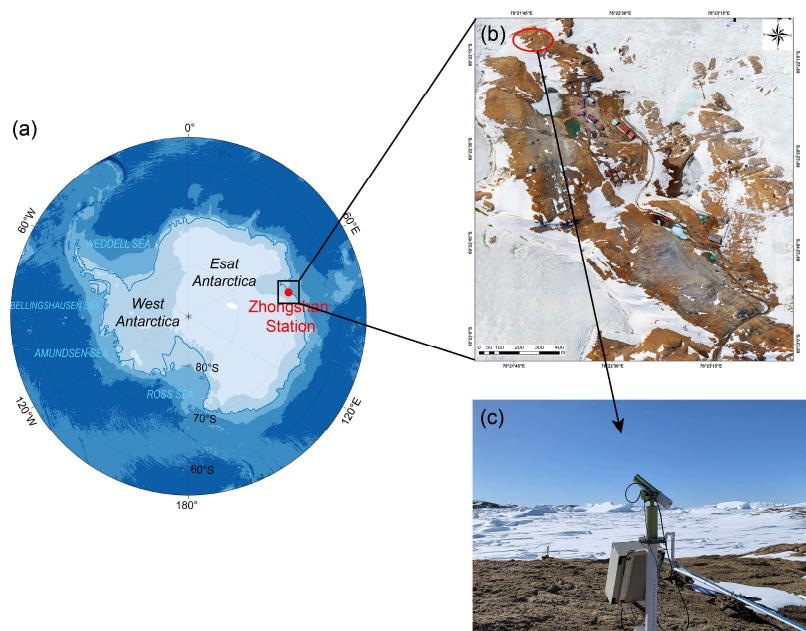
69 Additionally, particle size plays a significant role in aerosol extinction. The Ångström exponent (AE)
70 serves as an important indicator of aerosol size, with value greater (less) than 1 indicating a predominance
71 of fine (coarse) mode particles (Schuster et al., 2006). Weller and Lampert report that the mean AE at
72 Neumayer Station was 1.5 ± 0.6 and 1.2 ± 0.5 during summer and winter, respectively, suggesting an
73 increased contribution of fine-mode biological sulfate particles in summer (Weller and Lampert, 2008).
74 Virkkula et al. observed higher scattering AE estimate values during summer (~ 1.9) and lower values
75 during winter (~ 0.8) at Dome C on the Antarctic Plateau, indicating a prevalence of fine particles in
76 summer (Virkkula et al., 2022).

77 Currently, the challenging environment and the limited number of daylight days per year restrict the
78 availability of ground sites capable of obtaining adequate AOD and AE observations. Consequently, the
79 optical properties of aerosols across large parts of Antarctica remain unexplored. To improve our
80 comprehension of aerosol properties in Antarctica, we analyse the seasonal, monthly, and diurnal
81 variations of AOD and AE using data obtained from the recently installed sun-sky-lunar CE318-T
82 photometer at Zhongshan Station.

83 2 Site, Instrument, and Data

84 2.1 Site Introduction

85 Zhongshan Station ($69^{\circ}22'12''\text{S}$, $76^{\circ}21'49''\text{E}$, 18 m a.s.l.) is located at the Larsemann Hills of Prydz Bay
86 on the east Antarctic continent. The sun-sky-lunar CE318-T photometer is installed at Swan Ridge,
87 northwest of the Nella fjord (Fig. 1) (Tian et al., 2022). This location experiences 54 polar days and 58
88 polar nights annually, with snow covering the surrounding surface during winter and revealing bare rock
89 in summer. In this study, the austral spring, summer, autumn, and winter are referred to the season from
90 September to November (SON), December to February of next year (DJF), March to May (MAM), and
91 June to August (JJA), respectively. The average annual air temperature is $-10\text{ }^{\circ}\text{C}$, with a relative
92 humidity of 58% and prevailing wind speeds of 6.9 m s^{-1} , primarily from the east or east-southeast
93 direction (Ding et al., 2022).



94
95 **Figure 1 (a) The location of Zhongshan Station in Antarctica, (b) the aerial view of Zhongshan Station, and**
96 **(c) the sun-sky-lunar photometer CE318-T at Zhongshan Station.**

97 2.2 Instrument and Data

98 The AOD measurement data utilized in this study were obtained from the sun-sky-lunar CE318-T
99 photometer, manufactured by CIMEL Electronique, France. The CE318-T is a ground-based multiband
100 radiometer capable of inverting aerosol optical parameters by measuring the spectral data of direct solar
101 and lunar radiation extinction and the angular distribution of sky radiances (Barreto et al., 2016).

102 We collected AOD level 1.5 (cloud-screened) data across various wavelengths spanning from January
103 2020 to April 2023 (Fig. S1). However, the operation of CE318-T in polar environment is impeded by
104 solar radiation and weather conditions, leading to a significant number of missing measurements.
105 Consequently, we categorize daily observations with less than 20 measurements and the coefficient of
106 dispersion (CV) exceeding 1 as invalid data, which are systematically eliminated from our analysis.
107 Typically, these invalid data manifest with exceedingly high AOD values, often attributed to instrument
108 downtime caused by factors such as precipitation or cloudy weather. Moreover, to ensure the accuracy
109 of AOD measurement at Zhongshan Station, we refine our data by cross-referencing station operation
110 records and the time series of black carbon (BC) concentrations. This process allows us to exclude AOD
111 data associated with significant station activities and periods of elevated BC concentrations, thereby
112 enhancing the reliability of our analysis. It should be noted that there are uncertainties in the AOD
113 measurements of CE318-T during field observations due to atmospheric conditions, instrument noise,
114 and calibration. It is estimated that during daytime measurements, the AOD uncertainty ranges from
115 0.010 to 0.021. For night-time measurements, the AOD uncertainty depends on the calibration technique
116 used. Specifically, when calibrated using the Moon Ratio technique, the uncertainty ranges from 0.011
117 to 0.019. With the application of the new Sun Ratio technique, the uncertainty for the 440 nm channel is
118 between 0.012 and 0.015 (0.017), while for longer wavelengths, it ranges from 0.015 to 0.021. By
119 employing the new Sun-Moon gain factor technique and using the Langley-calibrated instrument for
120 calculation of the amplification between daytime and night-time measurements, the uncertainty range is
121 from 0.016 to 0.019 (Barreto et al., 2016).

122 The meteorology data, including temperature, relative humidity, wind direction, and wind speed, were
123 obtained from the Zhongshan Station meteorology observatory, with the temporal resolution of 1 hour.
124 BLH data was obtained from ERA5 reanalysis provided by European Centre for Medium Range Weather
125 Forecasts (ECMWF) with the temporal and spatial resolution of 1 hour and 0.25 (latitude) \times 0.25
126 (longitude).

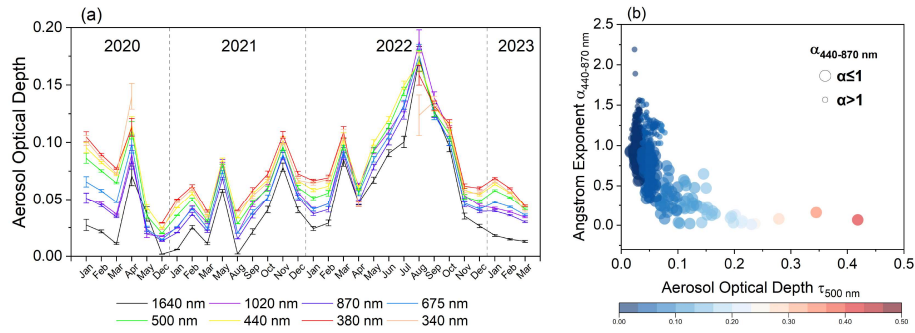
127 The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, is a comprehensive
128 model developed by the National Oceanic and Atmospheric Administration (NOAA) and the Air
129 Resources Laboratory (ARL) to calculate and analyse the source, transport, and diffusion trajectories of

130 atmospheric pollutants. The meteorological data used in the HYSPLIT model comes from the National
131 Center for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS). In this study,
132 the HYSPLIT model is utilized to calculate the 168h backward air mass trajectory from 3 altitudes of 50,
133 500, and 1000 m (amsl) to Zhongshan Station.

134 **3 Results**

135 **3.1 Variation Characteristics of AOD**

136 From January 2020 to March 2023, the monthly mean AOD values at various wavelengths varied from
137 0.00 to 0.20, with the lowest values in December 2020 and the highest values in August 2022 (Fig. 2a).
138 The monthly mean AOD values at 500 nm ($AOD_{500\text{ nm}}$) generally remained below 0.10, consistent with
139 findings by Gadhavi and Achuthan at the Maitri Station, where AOD variation fell within the range of
140 0.01 to 0.10 (Gadhavi and Achuthan, 2004). The annual mean \pm SD (standard deviation) values of the
141 $AOD_{500\text{ nm}}$ were 0.074 ± 0.090 , 0.051 ± 0.066 , 0.071 ± 0.117 , and 0.053 ± 0.031 in 2020, 2021, 2022, and
142 2023, respectively (Table 1). Similarly, the annual mean \pm SD values of the $AE_{440-870\text{ nm}}$ were
143 1.134 ± 0.411 , 0.953 ± 0.338 , 0.883 ± 0.374 , 0.753 ± 0.206 for the same years, respectively, suggesting that
144 the aerosols over Zhongshan Station were mainly dominated by fine mode particles in 2020, and coarse
145 mode particles in 2021, 2022, and 2023. The relationship between multi-year $AOD_{500\text{ nm}}$ and $AE_{440-870\text{ nm}}$
146 illustrates that fine mode particles are primarily concentrated in the range of $AOD_{500\text{ nm}} < 0.1$, while high
147 $AOD_{500\text{ nm}}$ values, which occur occasionally, are caused by coarse mode particles (Fig. 2b). Although
148 fine mode particles have a longer suspension time in the atmosphere and can efficiently scatter and absorb
149 sunlight, leading to lower AOD ranges, it is worth mentioning that in the coastal regions of Antarctica,
150 the dominant role in AOD is sometimes played by coarse mode particles. These particles, with larger
151 radii and higher volume concentrations, originate mainly from abundant sea salt sources. Their presence
152 results in increased scattering and absorption of sunlight, emphasizing the significance of coarse mode
153 particles in determining AOD levels in the Antarctic coastal areas (Su et al., 2022)



154
 155 **Figure 2 (a) Monthly variation of mean aerosol optical depth at different wavelengths measured over**
 156 **Zhongshan Station in Antarctica from 2020 to 2023. (b) Relationship between AOD_{500 nm} and AE_{440-870 nm} over**
 157 **Zhongshan Station from 2020 to 2023.**

158 **Table 1 Annual mean and standard deviation of aerosol optical depth at different wavelengths and Angstrom**
 159 **Exponent at 440-870 nm at Zhongshan Station from 2020 to 2023.**

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	2020	2021	2022	2023
AOD _{1640 nm}	0.028±0.102	0.026±0.079	0.050±0.141	0.016±0.036
AOD _{1020 nm}	0.049±0.095	0.045±0.073	0.067±0.131	0.040±0.034
AOD _{870 nm}	0.047±0.093	0.039±0.070	0.060±0.126	0.037±0.032
AOD _{675 nm}	0.059±0.091	0.042±0.068	0.063±0.122	0.044±0.031
AOD _{500 nm}	0.074±0.090	0.051±0.066	0.071±0.117	0.053±0.031
AOD _{440 nm}	0.081±0.089	0.057±0.065	0.077±0.116	0.057±0.031
AOD _{380 nm}	0.089±0.091	0.063±0.065	0.077±0.117	0.061±0.032
AOD _{340 nm}	0.088±0.095	0.059±0.064	0.073±0.118	0.058±0.032
AE _{440-870 nm}	1.134±0.411	0.953±0.338	0.883±0.374	0.753±0.206

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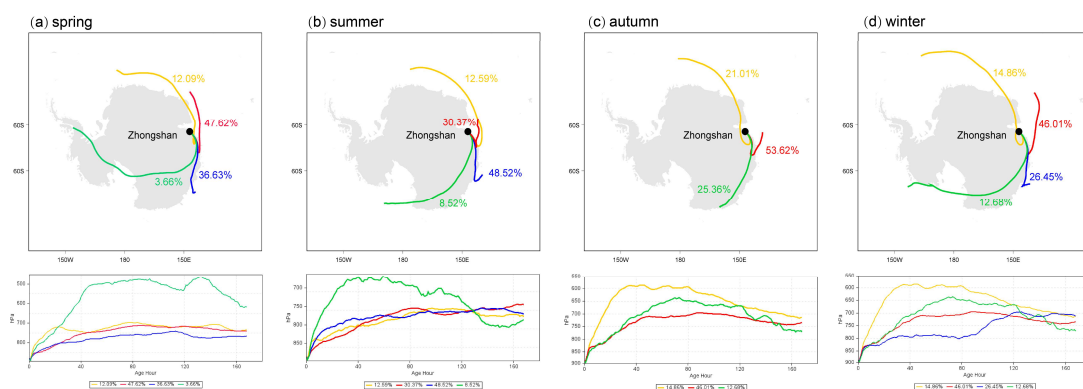
162 3.2 Seasonal and Monthly Variations in AOD and Ångström Exponent

163 The seasonal variation of AOD_{500 nm} and AE_{440-870 nm} over Zhongshan Station suggests the median AOD₅₀₀
 164 nm values are lower in spring (0.033), summer (0.036), and autumn (0.045), but higher in winter (0.115),
 165 while the AE_{440-870 nm} values are 0.908, 1.010, 1.036, and 0.381, respectively (Fig. 4a). The frequency
 166 histograms show that the highest frequency range of AOD_{500 nm} is 0.02 to 0.04 in spring, summer, and
 167 autumn, while 0.08 to 0.12 in winter (Fig. S2). The normal fitting curves of the frequency histograms of

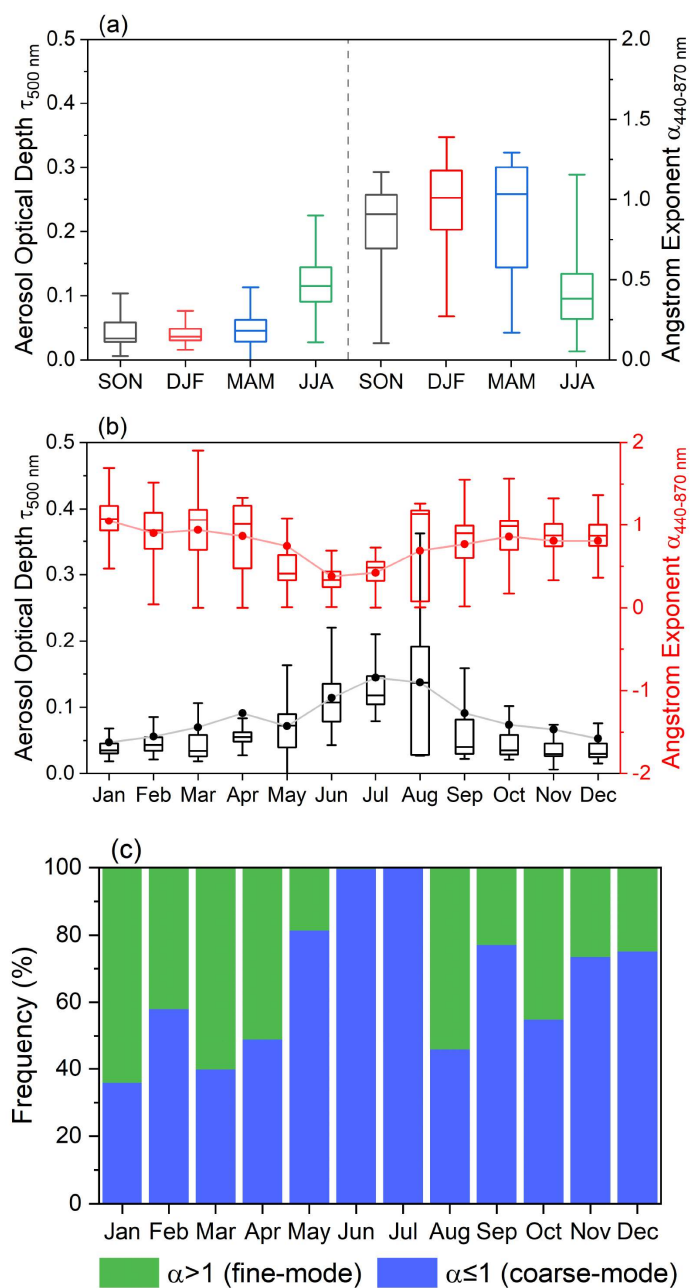
168 $AE_{440-870\text{ nm}}$ indicate that the peak in winter is in the low-value range (0.3~0.4), while the peaks in spring,
169 summer, and autumn are in the high-value range (1.0~1.2). To investigate the seasonal differences in
170 $AOD_{500\text{ nm}}$ and $AE_{440-870\text{ nm}}$, it is essential to understand the sources of air masses influencing aerosols at
171 Zhongshan Station. Therefore, we calculate the 168h backward trajectory once every 24h from January
172 2020 to December 2022, with the starting height of 500 m and the starting time of 18:00 (13:00 local
173 time at Zhongshan Station), and clustered by season (Fig. 3). We observed that the proportion of air
174 masses originating from the surrounding waters (red clusters) and the ice edge margin of ice sheet (blue
175 clusters) ranges from 50% to 80%, dominating throughout the year. These air masses are likely the
176 primary sources of local or natural aerosols in Antarctica. In contrast, the proportion of distant origin
177 (yellow and green clusters) is approximately 20%, but it significantly increases in autumn, reaching
178 around 45%. These air masses are associated with long-range transported aerosols. Therefore, the
179 seasonal differences in $AOD_{500\text{ nm}}$ and $AE_{440-870\text{ nm}}$ at Zhongshan Station are largely attributed to
180 variations in the types and concentrations of local aerosols.

181 The seasonal variations in AOD and AE are consistent with previous findings on sea salt aerosol
182 concentrations, although the mechanism behind this seasonal variation is multifaceted. Wang and Huang
183 et al. have indicated that higher winter wind speeds at Zhongshan Station can elevate marine source
184 aerosol concentrations, primarily composed of sea salt, potentially explaining the winter peak in sea salt
185 concentration (Hong et al., 2009; Huang et al., 2005). However, Hall and Wolff propose that the high
186 sea salt load correlates more with moderate wind speeds and shifts in wind direction, rather than high
187 wind speeds, with concentrated brine on freshly formed ice surfaces acting as a source of winter sea salt
188 (Hall and Wolff, 1998). Moreover, blowing snow over sea ice generates aerosols primarily made of sea
189 salt, contributing to the winter peak in sea salt aerosols (Frey et al., 2020). In summer, lower sea salt
190 concentrations lead to lower background levels of AOD, but the effect of enhanced marine biogenic
191 emissions on AOD may increase. In the marine boundary layer over the eastern Southern Ocean sector,
192 $nssSO_4^{2-}$ and MSA contribute approximately 40% of the total mass of fine aerosols (particle size < 0.56
193 μm) (Xu et al., 2021). Xu et al. reported the annual mean concentrations of $nssSO_4^{2-}$ and MSA at
194 Zhongshan Station were $0\text{-}79\text{ ng m}^{-3}$ and $19\text{-}41\text{ ng m}^{-3}$, respectively, with the maximum
195 concentrations were observed in summer (Xu et al., 2019). This increase in summer concentrations is

196 attributed to enhanced solar radiation, phytoplankton blooms in the polynyas releasing DMS (Zhang et
 197 al., 2015), and the DMS in the atmosphere is oxidized by radicals such as O₃ (significant at high latitudes),
 198 OH, and BrO in the gas phase (Boucher et al., 2003), resulting in elevated concentrations of MSA and
 199 $nssSO_4^{2-}$. The positive correlation between mean surface chlorophyll and AOD in the Southern Ocean
 200 confirmed the contribution of DMS flux to aerosol load during summer (Gabric et al., 2005).
 201 The monthly variations in AOD_{500 nm} and AE_{440-870 nm} at Zhongshan Station suggest an opposite trend,
 202 with the mean values of AOD_{500 nm} peaking in July and AE_{440-870 nm} reaching its lowest in June (Fig. 4b).
 203 Median AOD_{500 nm} values increase slightly from January to February, followed by a decrease in March
 204 and increase continuously from March to August, reach the maximum value, then gradually decrease,
 205 and reach the minimum in November and December. The percentages of AE_{440-870 nm} > 1.0 and AE_{440-870 nm}
 206 < 1.0 represent the proportion of the monthly occurrence frequency of fine and coarse mode particles
 207 (Fig. 4c). The monthly mean and median AOD_{500 nm} values are consistent with the proportion of coarse
 208 mode particles (AE_{440-870 nm} > 1.0), suggesting that the variation characteristics of AOD_{500 nm} at
 209 Zhongshan Station are primarily influenced by coarse mode particles. Given that Zhongshan Station is
 210 located in the coastal area of Antarctica, it is suspected that these coarse particles may be sea salt aerosols.
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 213 **Figure 3 Clusters of air mass backward trajectories in (a) spring, (b) summer, (c) autumn and (d) winter at**
 214 **Zhongshan Station from 2020 to2022.**



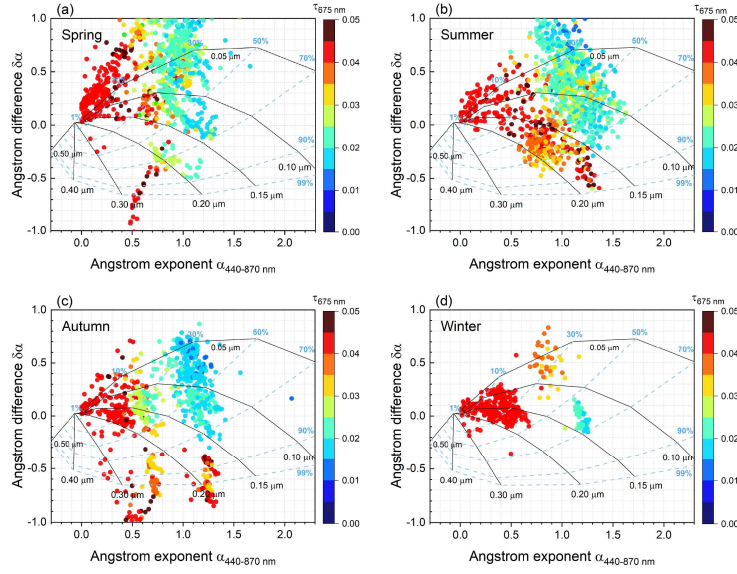
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216 **Figure 4 (a) Seasonal variation of aerosol optical depth at 500 nm and Angstrom exponent at 440-870 nm over**
 217 **Zhongshan Station. For each monthly box, the central line indicates the median; and the bottom and top edges**
 218 **of the box indicate the 25th and 75th percentiles, respectively. (b) Variations in monthly AOD_{500 nm} and AE₄₄₀₋**
 219 **870 nm at Zhongshan Station. For each monthly box, the central line indicates the median; the dot represents**
 220 **the mean; and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. (c)**
 221 **Monthly percentages of Ångström exponent >1.0 (green) and Ångström exponent ≤ 1.0 (blue) at Zhongshan**
 222 **Station from 2020 to 2023.**

223

Additionally, we used a graphical method proposed by Gobbi et al (Gobbi et al., 2007), which is based on Mie calculation and correlates Ångström exponent (α) and Ångström exponent spectral difference ($\delta\alpha$) with fine mode aerosol effective radius (R_{eff}) and fine mode fraction to investigate the aerosol

226 modification processes at Zhongshan Station in different seasons. Fig. 5 presents a schematic diagram of
227 the classification of aerosol types using the α and $\delta\alpha$ functions of a dual-mode, lognormal distribution
228 with refractive index = $1.4 - 0.001i$ as reference. It is known from Jurányi and Weller' research that the
229 refractive index of Antarctic coastal aerosol is about 1.4, so it seems reasonable to use this reference
230 (Jurányi and Weller, 2019). We utilized AOD_{440nm} , AOD_{675nm} , and AOD_{870nm} to calculate $\alpha_{440-675nm}$,
231 $\alpha_{440-870nm}$, and $\alpha_{675-870nm}$, and then get the $\delta\alpha = \alpha_{440-675nm} - \alpha_{675-870nm}$. The negative values of
232 $\delta\alpha$ indicate the dominance of fine mode aerosol, while positive values indicate the effect of two separate
233 particle modes (Kaufman, 1993). The solid black line represents the size of fine mode particles (R_{eff}),
234 and the dashed blue line represents the proportion of the contribution of fine mode particles to AOD (η).
235 In Fig. 5, increasing AOD_{675nm} is associated with the declining η (spring and winter) and increasing
236 R_{eff} (summer and autumn). This indicates that higher aerosol loads in spring and winter are attributed
237 to increased coarse-mode particle fractions, whereas in summer and autumn are primarily associated with
238 the increase of fine-mode particle size. Previous studies have indicated that sea salt dominates winter
239 aerosols in the coastal areas of Antarctica (Hall and Wolff, 1998; Weller et al., 2008), and Xu et al
240 observed that the highest mean concentration of sea salt in September at Zhongshan Station, these can
241 explain the $\delta\alpha$ values are mainly positive in spring and winter, and η is concentrated within the range
242 of less than 50% (Xu et al., 2019). In summer and autumn, apart from common sea salt aerosols ($\delta\alpha > 0$,
243 $\eta < 50$), the high AOD is mainly related to the particle growth such as hygroscopic growth or
244 condensation of fine mode aerosols ($R_{eff}: 0.10\mu m \sim 0.20\mu m$). This may be linked to the atmospheric
245 oxidation of (DMS) emitted by biological sources in coastal regions, or the aging process of aerosols
246 originating from other sources, as the rate of new particle formation and particulate matter growth in
247 summer is much greater than in winter in the Antarctica (Davison et al., 1996; Lachlan-Cope et al., 2020;
248 Weller et al., 2015).
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Figure 5 Ångström exponent difference ($\delta\alpha = \alpha_{440-675\text{ nm}} - \alpha_{675-870\text{ nm}}$) as a function of the $\alpha_{440-870\text{ nm}}$ and $\text{AOD}_{675\text{ nm}}$ (colour scale) during (a) spring, (b) summer, (c) autumn, and (d) winter at Zhongshan Station. The black lines indicate the R_{eff} of fine-mode aerosols, while the blue lines correspond to fine-mode fraction (η).

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3.3 Relationship between AOD, Ångström Exponent and Meteorological Conditions

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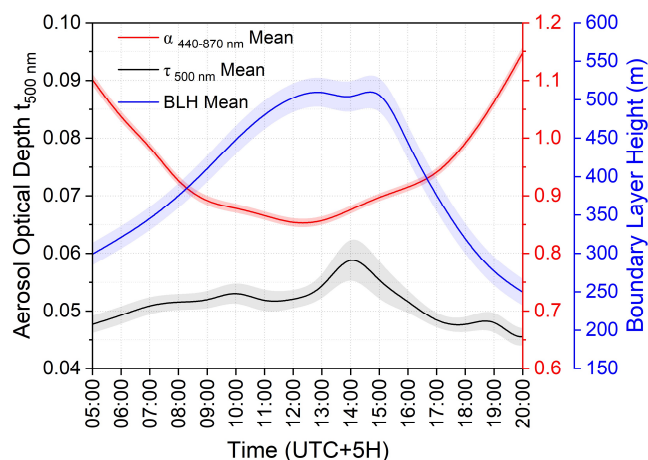
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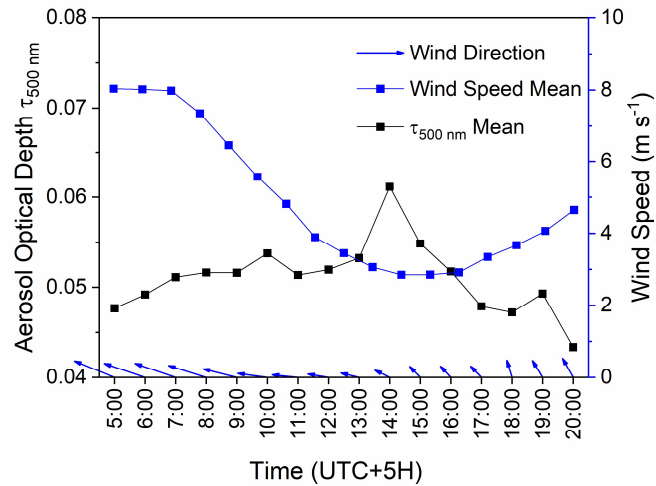
In this section, we analyse the diurnal variation characteristics of $\text{AOD}_{500\text{ nm}}$ and $\text{AE}_{440-870\text{ nm}}$ during summer and explore their correlation with meteorological variables within the planetary boundary layer (PBL), such as wind directions and speeds, temperature, and relative humidity. We calculated the diurnal variations of $\text{AOD}_{500\text{ nm}}$ and $\text{AE}_{440-870\text{ nm}}$ based on observations collected at Zhongshan Station during summer (December-February, 2020-2023), with each hourly mean containing at least one thousand individual observations (Fig. 6). The mean $\text{AOD}_{500\text{ nm}}$ exhibited an increase from 5:00 to 14:00 (local time of Zhongshan Station), reaching a maximum value (0.06 ± 0.04), and then decreased. The mean $\text{AE}_{440-870\text{ nm}}$ decreased from 5:00 to 12:00, reaching the lowest value (0.85 ± 0.25), and then increased. These results indicate that the highest aerosol load occurs at 14:00, accompanied by a larger aerosol particle size during this period. The diurnal variation of boundary layer height (BLH) is almost consistent with the variation of $\text{AOD}_{500\text{ nm}}$, which is inconsistent with the general conclusion that the negative correlation between BLH and particulate matter concentration in the mid-latitudes (Lou et al., 2019; Miao and Liu, 2019). However, a minor decline in BLH is noticeable when the $\text{AOD}_{500\text{ nm}}$ value reaches its peak at 14:00. Consequently, we suspect that the weak absorption and low content of Antarctic

270 aerosols typically do not suffice to form an “aerosol-boundary layer” positive feedback mechanism, but
 271 may contribute to reducing the BLH when AOD is high (Lou et al., 2019; Petäjä et al., 2016).



272
 273 **Figure 6 Diurnal variation of AOD_{500 nm} and AE_{440-870 nm} at Zhongshan Station. The black line indicates the**
 274 **mean of AOD_{500 nm}; the red line represents the mean of AE_{440-870 nm}; the blue line represents the mean of BLH.**
 275 **The shadow represents the standard deviation of the mean.**

276 Moreover, the 2-minute average wind direction at Zhongshan Station mainly comes from the southeast,
 277 with the diurnal variation of the 2-minute average wind speeds ranging from 2 to 9 m s⁻¹. There is a
 278 noticeable decline in wind speeds between 5:00 and 14:00, followed by a gradual increase thereafter (Fig.
 279 7). Given that the CE318-T is positioned westward of the main Zhongshan Station building, the eastward
 280 winds may carry emissions originating from western stations such as Zhongshan and Progress Station.
 281 The relationship between the diurnal variation of AOD_{500 nm} and wind speed is more obvious: AOD_{500 nm}
 282 exhibits a decline (increase) concurrent with increasing (decreasing) wind speeds. This correlation stems
 283 from the fact that higher wind speeds facilitate the dispersion of pollutants, leading to a reduction in
 284 AOD, and vice versa (Coccia, 2021; Liu et al., 2020; Wang et al., 2022).



285

286 **Figure 7 Diurnal variations of 2-minute average wind direction, 2-minute average speed, and AOD_{500 nm} in**
 287 **summer at Zhongshan Station.**

288 The influence of temperature and relative humidity on aerosol parameters is relatively complex.

289 Temperature affects aerosol particle concentration by influencing the air convection and influencing the

290 formation and optical properties of secondary by controlling chemical transformation (Han et al., 2007;

291 Li et al., 2020). Relative humidity affects the chemical composition, size distribution, and optical

292 properties of aerosol particles by affecting their aqueous-phase reactions and gas-particle partitioning

293 (Altieri et al., 2008; Ding et al., 2021; Hennigan et al., 2008; Sun et al., 2013). The diurnal variations of

294 AOD_{500 nm}, temperature, and relative humidity in summer at Zhongshan Station show that AOD_{500 nm} is

295 positively correlated with temperature with a correlation coefficient of 0.22, and AOD_{500 nm} is negatively

296 correlated with relative humidity with a correlation coefficient of -0.59 (Fig. 8). This indicates that rising

297 (declining) temperature and declining (rising) relative humidity during the day may contribute to an

298 increase (declining) in aerosol load. Previous studies have shown a positive correlation between

299 temperature and AOD (Basharat et al., 2023). During the summer at Zhongshan Station, high

300 temperatures may destroy the physical properties of bare rocks and promote the formation and diffusion

301 of particulate matter, thereby increasing the aerosol load (Zhang, 2024). However, there is a study

302 showing that higher temperatures may reduce methane sulfinic acid (MSIA) yield (Cecilia Arsene et al.,

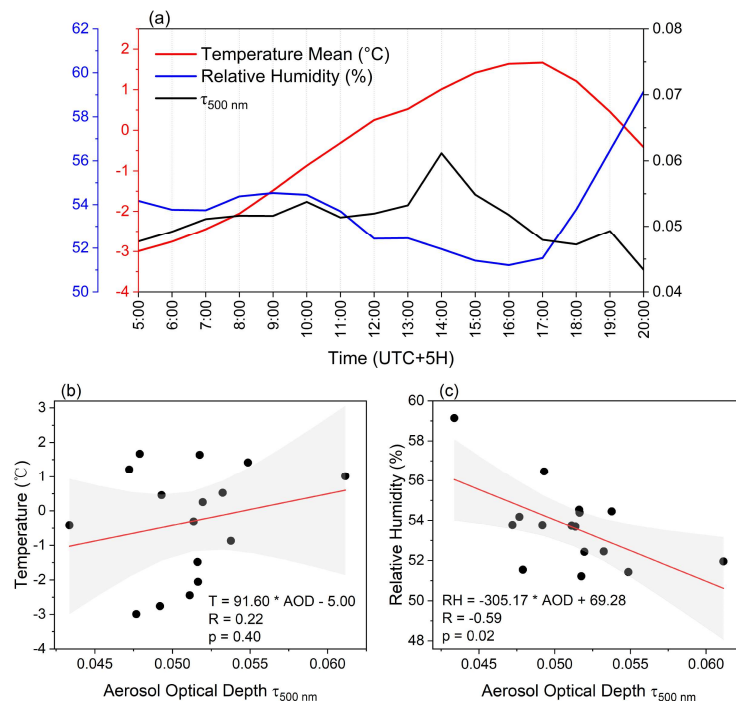
303 1999). Therefore, the effect of temperature on the AOD at Zhongshan Station is complex, resulting in an

304 insignificant positive correlation. The relationship between relative humidity and AOD is inconclusive

305 (Gautam et al., 2022), as high relative humidity may contribute to the increase of aerosol hygroscopic

306 properties leading to an increase in AOD (Meng et al., 2024), or it may contribute to a decrease in AOD

307 by reducing dust particles in the air (Zhang, 2024). Therefore, the influence of temperature and relative
 308 humidity on AOD may be related to the physicochemical properties of local aerosols and their sourcing
 309 and sink processes.



310
 311 **Figure 8 (a) Diurnal variations of AOD_{500 nm} (black), temperature (red), and relative humidity (blue) in**
 312 **summer at Zhongshan Station; (b) relationship between AOD_{500 nm} and temperature; and (c) relationship**
 313 **between AOD_{500 nm} and relative humidity. The red line indicates the regression line obtained by fitting a linear**
 314 **regression, and the grey bands indicate the confidence intervals for the linear regression.**

315 4 Discussion

316 4.1 Potential effects of aerosol sources on AOD levels

317 Besides meteorological conditions, aerosol sources may also influence the diurnal variation
 318 characteristics of AOD. We classified days with mean AOD below the 5th percentile as low AOD day
 319 and those above the 95th percentile as high AOD day (Fig. S3 and Table S1). Using the HYSPLIT
 320 backward trajectory model, we found that air masses on high AOD days primarily originated from the
 321 ocean, whereas those on low AOD days mostly came from the interior of Antarctica (Fig. S4). The
 322 altitudes of the backward trajectories show that during low AOD days, the air mass originating from the
 323 ocean usually starts at a lower altitude (<1000 m), rises to a higher altitude (~2000 m) and then descends
 324 to Zhongshan Station (2020-05-15 and 2020-12-25), while the air mass originating from the interior of

325 Antarctica usually starts at a higher altitude (~3000 m) and then descends to Zhongshan Station. This
326 indicates that particles from the Antarctic plateau or the free troposphere above the Antarctic interior are
327 transported to Zhongshan Station by katabatic winds. Researches show that the katabatic winds driven
328 by latent cooling occurring in the high-wind East Antarctic can rush the dense air from the interior plateau
329 to the coast (Simmons et al., 2021; Yu et al., 2020). Combined with the AE values, we can find that the
330 AE values of low AOD days are usually greater than 1, indicating the small particle size, thus, we suspect
331 that these fine particles may be $nssSO_4^{2-}$ from the Antarctic interior (Pei et al., 2021). In contrast, in
332 high AOD days, the air mass all originates in the ocean and usually starts at a lower altitude. The AE
333 values corresponding to high AOD moment on high AOD days are extremely low (<0.5), indicating that
334 the particle size is large, thus, we suspect that these aerosols may consist of coarse sea salt particles.

335 **4.2 Potential effects of aerosol particles on cloud and radiative forcing**

336 The optical properties of aerosols play a crucial role in their impact on radiative forcing, cloud formation,
337 and local climate. In our analysis of the variations in AOD and AE, we provided insights into the aerosol
338 loading, particle sizes, and possible formation and growth mechanisms in the atmosphere over
339 Zhongshan Station. During winter and spring, coarse mode particles are predominantly derived from sea
340 salt. Studies have shown that aerosols larger than 0.13 μm in the marine boundary layer contain sea salt,
341 contributing to most of the aerosol scattering and inducing cooling effects (Murphy et al., 1998).
342 Additionally, the size and inhomogeneity of sea salt particles are often associated with relative humidity.
343 Compared to remote oceans, the low relative humidity in coastal Antarctica may introduce more
344 inhomogeneous sea salt particles, resulting in up to a 12% change in direct radiative forcing due to
345 inhomogeneity (Wang et al., 2019).

346 However, we are particularly interested in the behaviour of aerosol particles during summer since solar
347 radiation is limited in winter. In summer and autumn, the increase in fine mode particles is closely related
348 to the release of biogenic aerosols, such as DMS, emitted by phytoplankton in the marginal ice zone.
349 When particles grow to a size suitable for cloud condensation nuclei or ice nucleating particles, they can
350 affect the formation of low-level mixed-phase clouds in coastal areas, contributing to the formation of
351 low-level ice clouds. At the same time, the increased number density of cloud droplets enhances cloud
352 reflectivity, resulting in negative radiative forcing (Satheesh and Krishna Moorthy, 2005). A recent study

353 revealed that in the shallow mixed-phase clouds over Antarctica, the concentrations of cloud-relevant
354 aerosol particles match the concentrations of ice crystals and cloud droplets (Radenz et al., 2024). the
355 number of particles plays a crucial role in cloud growth. Increasing particle concentration results in a
356 higher abundance of liquid droplets and ice crystals within clouds, which can impact cloud lifespan and
357 potentially influence local weather and climate. Therefore, continuous monitoring of aerosol optical
358 properties in coastal Antarctica is vital to improve our comprehension of aerosol radiative forcing
359 variations caused by changes in aerosol loading and particle size.

360 **5 Summary**

361 This study analysed the AOD and AE variations retrieved from CE318-T sun photometer data spanning
362 from January 2020 to April 2023 at Zhongshan Station in Antarctica. The main conclusions we draw are
363 as follows:

364 At Zhongshan Station, AOD varied from 0.00 to 0.20. Fine mode particles were predominantly found in
365 the lower AOD range, while higher AOD values were mainly attributed to coarse mode particles.
366 Seasonally, AOD exhibited a pattern of lower values in summer and higher values in winter, and the AE
367 displayed an opposite trend. The increases in AOD during summer and autumn may be linked to particle
368 growth, whereas the increases during spring and winter are associated with a decline in the fraction of
369 fine mode particles.

370 Low aerosol load over Zhongshan Station was not enough to form an “aerosol-boundary layer” positive
371 feedback mechanism, but the slight decrease in BLH may be related to AOD diurnal peak at 14:00.
372 Moreover, high (low) wind speeds facilitated pollutant dispersion (accumulation), leading to reduced
373 (increased) AOD. A weak positive correlation was noted between temperature and AOD ($R = 0.22$, $p =$
374 0.40), and a negative correlation between relative humidity and AOD ($R = -0.59$, $p = 0.02$). The
375 mechanisms underlying temperature and humidity's influence on aerosols remain unclear, possibly
376 linked to local aerosol properties at Zhongshan Station. In addition, we discuss the influence of aerosol
377 sources on AOD. The backward trajectories show that the air masses on high AOD days come from the
378 ocean, and the low AE values indicate that the particle size is larger, we speculate that the main
379 composition of the aerosols is sea salt. The air masses on the low AOD days mainly come from the

380 interior of Antarctica, and the high AE values indicate that the particle size is small. We speculate that
381 the katabatic winds rush the air from the Antarctic plateau to Zhongshan Station.

382 **Data availability**

383 The data included in this study can be accessed via <https://zenodo.org/records/10983098>. Boundary layer
384 height data downloaded from ECMWF ERA5 ([https://www.ecmwf.int/en/forecasts/dataset/ecmwf-](https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5)
385 [reanalysis-v5](https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5)). Backward trajectory of air mass and the meteorological data are obtained from NOAA
386 Air Resources Laboratory (https://www.ready.noaa.gov/HYSPLIT_traj.php).

387 **Author contributions**

388 The paper is a result of the lead author's research work under the supervision of MD, LZ, YS. ZZ and
389 YZ provided constructive comments. LZ participated in the offline discussion and made equal
390 contributions in responding to the review comments and revising the manuscript. MD, QW and BT
391 provided experimental data. ZL provided aerial photos of Zhongshan Station. LC wrote the first draft of
392 the paper with the help and support of all the authors. HC provided guidance for the manuscript revisions.

393 **Competing interests**

394 The contact author has declared that none of the authors has any competing interests.

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