Determinant of Sea Salt Aerosol Emission in the Southern Hemisphere in Summer Time

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Abstract High-resolution time (1h) aerosol composition measurements were performed in the Southern Hemisphere during February 2018–April 2018. Na+ was the most abundant water-soluble ion (WSI) species, accounting for 67% of the total WSIs. The highest Na+ levels were observed in low-middle latitudes (20°–40°S) with an average concentration of 2.69 ± 2.16 μg m⁻³. This was 2–3 times greater than in other regions. Low temperature (T) and strong short-term variations of wind speed (WS) were associated with relatively low Na+ concentrations in high-middle latitudes (40°–60°S), where there was a strong mean WS (9.1 m s⁻¹). When WS < 7 m s⁻¹, Na+ concentrations were low in all T ranges. Temperature and Na+ concentrations were moderately positively correlated when 10 ≤ WS < 13 m s⁻¹ and WS ≥ 13 m s⁻¹ (R² = 0.48 and 0.34, respectively). Na+ concentrations were very low when relative humidity (RH) < 60% and significantly increased when RH was between 70% and 90%. However, Na+ concentrations under high RH (90%–100%) were not higher than those with RH between 70% and 90%, implying that a number of fine particles will increase their mass and convert to coarse particles and lead to a greater gravity sedimentation in high RH. Close to the Antarctic, Na+ concentrations decreased significantly under high WS levels, suggesting that sea ice cover reduces the production of sea salt aerosols (SSAs). What's more, air mass trajectory and the source of air mass also had an effect on the concentrations of SSAs. The results presented here extend the knowledge of the impact of sea salt on atmospheric aerosols above the Southern Hemisphere Ocean.

1. Introduction

Marine aerosols are one of the most important components of atmospheric aerosol particles at the global scale (Vignati et al., 2010) and potentially influence global climate change (O'Dowd & de Leeuw, 2007). They directly and indirectly alter the Earth's radiative budget by absorbing and scattering solar radiation and acting as cloud condensation nuclei (CCN) (Quinn & Bates, 2011; Quinn et al., 1998). Marine aerosols are commonly divided into primary aerosols and secondary aerosols. Sea salt aerosols (SSAs) are one of the largest sources of primary aerosols in the marine atmosphere. SSAs are defined as that aerosol component consisting of seawater drops and dry sea salt particle (Lewis & Schwartz, 2004). Mostly it consists primarily of NaCl and a mixture of one or more other salts, such as Mg, K, Ca sulfates and traces of organic material (Thomas et al., 2022). The mass flux of SSAs is about 1–3 × 10⁶ Tg yr⁻¹ at a global scale (Quinn et al., 2017). Marine secondary aerosols are often associated with marine biogenic sulfur cycles and the emission of marine organic compounds (Gantt et al., 2009). Dimethylsulphide (DMS) is derived from marine phytoplankton and then oxidized by radicals to form sulfate (SO₄²⁻) and methane sulfonic acid (MSA) in the atmosphere (Ghalamremaninzhad et al., 2016).

SSAs play significant roles in the climate and chemistry of the marine atmosphere. SSAs have great effect on the global clear-sky radiative forcing over the oceans at the top of the atmosphere (Haywood et al., 1999) and are the primary source of CCN (Pierce & Adams., 2006). In addition, SSAs are considered to be the dominant contributor to aerosol light scattering in the marine boundary layer (Jacobson, 2001). The major mechanism of SSA production, by air bubbles bursting at the surface of the ocean as a result of wind stress, has been described in previous studies (Monahan & Muircheartaigh, 1980; Stokes et al., 2013). Breaking waves entrain air to various degrees, bubbles are formed and then come back to the surface where they form whitecaps and burst, leading to the injection of sea water films and jet droplets into the atmosphere. Wind speed has been found not to be the sole condition affecting SSA concentrations, as humidity and temperature difference also affects their distribution (Cole et al., 2003). In recent years, a lot of research have been done for the relationship between SSAs and meteorological parameters. A combination of data from the active aerosol lidar in space and reanalysis was used
to study the optical properties of SSAs in different meteorological conditions in Southern Ocean winter (Thomas et al., 2022). The large sea-air temperature difference in the Southern Ocean may promote the emission of SSA (Jiang et al., 2021). However, the relationships between SSA concentration, wind speed (WS), and temperature under different wind speeds and relative humidity (RH) in the Southern Ocean summer still remain uncertain.

The Southern Hemisphere is an origin of monsoons and a key region of the global climate system. In the mid and high latitudes of the Southern Hemisphere, westerlies fundamentally control regional patterns of air temperature, storm tracks, and precipitation while also regulating ocean circulation, heat transport, and carbon uptake (Goyal et al., 2021). The Southern Ocean, located at high latitudes in the Southern Hemisphere, plays an important role in global carbon cycles and thus climate change (Gruber et al., 2019; Landschutzer et al., 2015). Sea ice around the Antarctic has a great influence on ocean circulation and glacial climates (Ferrari et al., 2014). Sea ice melt has increased the emissions of SSAs and biogenic aerosols in the Southern Ocean (Yan, Jung, et al., 2020). Many large field measurement programs, which have made significant progress in aerosol science, have been carried out over Antarctica (Detrich et al., 2012; Wilson et al., 2019; Zhao et al., 2014). High-time resolution online observations over the Southern Ocean and Antarctica have been made in recent years. Such as Temme et al. (2003) measured atmospheric mercury species at a coastal site in the Antarctic during summer time. The conversion of DMS to MSA and SO$_4^{2-}$ in the Southern Ocean was carried out with high time resolution observation (Yan, Zhang, et al., 2020). However, high-resolution onboard observations of SSAs over the Southern Hemisphere, especially in the Southern Ocean is still rare.

Aerosol studies commonly use offline sampling methods (Xu et al., 2013; Ye et al., 2015). However, it is difficult to analyze atmospheric evolution processes using this method (Fu et al., 2015) as long sampling intervals are required in order to meet the determination limits of such methods which consequently result in the loss of unstable sample components (Yan et al., 2017). Continuous observation technology can greatly improve the temporal and spatial resolution of aerosol particle measurements, allowing for the characterization of atmospheric aerosol behavior.

In this study, we aim to determine the spatial distribution of aerosol compositions and how changes in WS, temperature, WS short-term variation, and RH impact the concentrations of SSAs. Observations were conducted using online high time-resolution (1 hr) instruments in different regions of the Southern Hemisphere between February 2018 and April 2018. In addition, we also examine the effect of air mass trajectory transmission and sea ice in the Southern Ocean. The results from this study should help to fill existing knowledge gaps and enrich the SSA database for the Southern Hemisphere. It is hope that the new data set may also be used to improve and test the parameterizations of aerosol properties used in global climate models.

2. Experiments and Observation Regions

2.1. Observation Region

High-resolution observations of aerosols were carried out on-board the Xuelong research vehicle (R/V) during the 34th Chinese Antarctica Expedition Research Cruise from 18 February 2018 to 13 April 2018. The cruise started from New Zealand on 18 February 2018 and arrived the Western Pacific on 13 April 2018. The cruise covered a large range of latitudes from 16°N to 76°S and longitudes from 131°E to 110°N (Figure S1 in Supporting Information S1).

2.2. Instrument and Methods

To measure gases and water-soluble aerosols, including sea salts, an in situ gas and aerosol composition (IGAC) system was used (Model S-611, Machine Shop, Fortelice International Co., Ltd., Taiwan; http://www.machineshop.com.tw/). To minimize the impact of ship emissions, the sampling inlet connected to the monitoring instruments was fixed 20 m above the sea surface on the mast located at the bow of the research vessel. A total suspended particulate sample inlet was also positioned at the top of the mast. All aerosol observation instruments were connected by conductive silicone tubing with an inner diameter of 1.0 cm. Meteorological data such as WS and temperature were measured continuously using an automated meteorological station. The time resolution of meteorological data is 1 hr.
In the IGAC system, gases and aerosols were separated and streamed into liquid effluent for on-line chemical analysis at an hourly temporal resolution (Young et al., 2016). The analytical design and methodologies used for the determination of gases and aerosol water-soluble ions have been described in a previous study (Yan et al., 2019). In the sampling process, fine particles were first enlarged by vapor condensation and subsequently collected on an impact plate. The samples were then analyzed for anions and cations by an on-line ion chromatography system (DionexICS-3000). Six to eight concentrations of standard solutions were selected for calibration, depending on the target concentration \(R^2\) values above 0.997, Figure S2 in Supporting Information S1. The detection limits for MSA, \(\text{SO}_4^{2-}\), \(\text{Na}^+\), \(\text{Cl}^-\), \(\text{NO}_3^-\), and \(\text{NO}_2^-\) were 0.09, 0.12, 0.03, 0.03, 0.0015, and 0.002 \(\mu\text{g} \text{ L}^{-1}\) (aqueous solution), respectively.

The concentrations of nss-\(\text{SO}_4^{2-}\) in the aerosols were calculated using the following equation:

\[
\text{[nss − SO}_4^{2−}\text{]} = \text{[SO}_4^{2−}\text{]} − \text{[Na}^+\text{]} \times 0.252
\]

where 0.252 is the mass ratio of \(\text{SO}_4^{2−}/\text{Na}^+\) in seawater (Hall & Wolff, 1998).

2.3. Satellite Data of Sea Ice and Air Mass Trajectories

Meteorological data such as WS and temperature were measured continuously using an automated meteorological station deployed in the R/V “Xuelong.” Remote sensing data was used to show the spatial and temporal distributions of sea ice concentrations in Antarctica during the survey. Daily sea ice concentration data was obtained from the 3.125-km resolution AMSR2 data set (available at https://seaice.uni-bremen.de).

Seventy-two-hour air mass backward trajectories (AMBTs) were calculated using the Hybrid Single Particle Lagrangian Integrated Trajectory (HY-SPLIT) model from the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (Stein et al., 2015). In order to trace the air mass source that influenced the study areas during the observation period, AMBTs were computed at three different altitudes (20, 500, and 1,000 m) every 6 hr. The 20 m height was used to represent the actual observing altitude, while 1,000 m was considered to be the boundary layer of the marine atmosphere.

3. Results and Discussion

3.1. Spatial Distributions of Marine Aerosols

The spatial distributions of the aerosol mass, \(\text{Na}^+, \text{MSA}, \text{and SO}_4^{2−}\) along the cruise track of the R/V Xuelong are shown in Figure 1. In this study, \(\text{Na}^+\) was found to be the most dominant cation in the aerosols, accounting for 67% of the key WSIs. Spatial distributions of aerosol mass, \(\text{Na}^+\) As can be seen in Figures 1a and 1b, the spatial distribution of \(\text{Na}^+\) concentrations were consistent with that of the aerosol mass. \(\text{Na}^+\) concentrations ranged from 0.014 to 7.4 \(\mu\text{g m}^{-3}\) with a mean of 0.996 ± 1.22 \(\mu\text{g m}^{-3}\).

Our results are compared with values from other areas reported in previous studies in Table 1. The \(\text{Na}^+\) levels in this study were comparable with previous values (i.e., Xu & Gao, 2014, with an average of 1.10 \(\mu\text{g m}^{-3}\)). High levels of \(\text{Na}^+\) were observed in low-middle latitudes (20–40°S), averaging 2.69 ± 2.16 \(\mu\text{g m}^{-3}\), which was 2–3 times that found in other regions in this study. High temperatures, strong and steady wind speeds (10–13 m s\(^{-1}\)), suitable RH (70%–90%) in this region maybe the reasons for the high levels of \(\text{Na}^+\) concentrations. This is discussed further in Section 3.3 below.

\(\text{SO}_4^{2−}\) concentrations ranged from 0.034 to 0.45 \(\mu\text{g m}^{-3}\), with an average of 0.162 ± 0.06 \(\mu\text{g m}^{-3}\). The concentrations of \(\text{SO}_4^{2−}\) in the Southern Ocean in this study were comparable with those previously recorded at the Halley Station (0.115 \(\mu\text{g m}^{-3}\)) but were lower than that found at the Dumont d’Urville Station (0.372 \(\mu\text{g m}^{-3}\)). Unlike MSA, the source of \(\text{SO}_4^{2−}\) includes marine SSAs, marine bio-genic sources, anthropogenic sources, and volcanic emissions (Hayashida et al., 2017). In high-latitude regions of the Southern Ocean, \(\text{SO}_4^{2−}\) is mainly associated with sea salt and biogenic sources (Berresheim et al., 1998). However, the distribution of \(\text{SO}_4^{2−}\) (Figure 1d) had a similar trend with \(\text{Na}^+\) (Figure 1b), but differed noticeably from the change in MSA concentration (Figure 1c).

This result suggests that \(\text{SO}_4^{2−}\) is highly impacted by SSAs over the Southern Hemisphere Ocean especially where high levels of sea spray aerosols occur.
Both NH$_4^+$ and NO$_3^-$ are mainly derived from anthropogenic sources, thus this may reflect human-induced changes in the atmosphere (Quan et al., 2014). In general, NH$_4^+$ and NO$_3^-$ distributions are characterized by high values in coastal sea areas and low levels in the open ocean. In this study (Table 1), the levels of NH$_4^+$ were very low throughout the observation period, ranging from 0.004 to 0.11 μg m$^{-3}$ with a mean concentration of 0.03 ± 0.01 μg m$^{-3}$. Different from MSA, NH$_4^+$ is more evenly distributed in the Southern Hemisphere and is lower than in the Northern Hemisphere, which may due to less human activity in the Southern Hemisphere. It is important to note that the NO$_3^-$ levels measured here (Table 1) were extremely low. This was probably caused by the different acquisition methods.

Correlation analysis of WSI in aerosols over the Southern Hemisphere Ocean was performed using SPSS 24.0 software (Table 2). Strong positive correlations were found between Na$^+$, K$^+$, Mg$^{2+}$, Ca$^{2+}$, Cl$^-$, SO$_4^{2-}$, indicating the same source for these species in the Southern Hemisphere Ocean. Na$^+$ derived from SSA is an important component of marine atmospheric aerosols (Teinila et al., 2014). Note that the ratio of Mg$^{2+}$ to Na$^+$ is 0.130, consistent with the mass ratio of Mg$^{2+}$ to Na$^+$ (0.121) in sea water. This, combined with their high correlation (0.997), indicates that Mg$^{2+}$ was derived from SSAs in this study. Similar to Mg$^{2+}$, positive correlation between Na$^+$ and Cl$^-$ ($R = 0.993$) indicated that Na$^+$ and Cl$^-$ had the same source. Source of SO$_4^{2-}$ and Ca$^{2+}$ are complex (Zhang et al., 2007), but they still have strong correlations with Na$^+$ (correlation coefficients 0.873 and 0.862, respectively) which suggested that oceanic aerosol over the Southern Hemisphere is mainly derived from sea salt in this study. This result is consistent with Figure 1.

![Figure 1. Spatial distributions of aerosol mass, Na$^+$, methane sulfonic acid (MSA), and SO$_4^{2-}$ in the Southern Hemisphere observed between 18 February 2018 and 13 April 2018. (a) Aerosol mass concentrations (ng m$^{-3}$), (b) Na$^+$ concentrations (ng m$^{-3}$), (c) MSA concentrations (ng m$^{-3}$), and (d) SO$_4^{2-}$ concentrations (ng m$^{-3}$).](image-url)
3.2. Latitudinal Distributions of Sea Salt Aerosols

MSA forms exclusively from the oxidation of DMS in the marine atmosphere (Sorooshian et al., 2007), hence MSA is regarded as a useful marker for marine biogenic sources. Grouping together WSIs with correlations and source, the aerosols are divided into SSAs (Na\(^+\), K\(^+\), Mg\(^{2+}\), Ca\(^{2+}\), Cl\(^-\), and ss-SO\(_4^{2-}\)), biogenic aerosols (nss-SO\(_4^{2-}\) and MSA) and inorganic nitrate aerosols (N-aerosols, i.e., NO\(_2^-\), NO\(_3^-\)). The temporal along-track change in these three aerosol groups is shown in Figure 2 in order to examine the influence of latitude. Except for the occasional temporary fluctuation, N-aerosols remained low overall during the cruise, probably due to the Southern Hemisphere atmospheric aerosols being little affected by anthropogenic sources. Different to N-aerosols, the concentrations of biogenic aerosols showed a significant increase in the second half cruise, which was consistent with previous observations that MSA and nss-SO\(_4^{2-}\) levels decrease rapidly at the end of austral summer (Read et al., 2008). As latitude decreases northwards (Figure 2), biogenic aerosols reach their maximum at the

| Study area                                      | Na\(^+\) | MSA\(^-\) | SO\(_4^{2-}\) | NH\(_4^+\) | NO\(_3^-\) | Reference       | Time             |
|------------------------------------------------|----------|-----------|--------------|-----------|------------|----------------|------------------|
| New Zealand (41°25S, 174°53E)                  | 0.024    | 0.073     | 0.249        |           |            | Allen et al. (1997) | 1991–1992        |
| Australia-East Antarctica (32–69°S)            | 1.10     | 0.077 (0.008) | 0.588       | 0.04 (0.03) | 0.04 (0.008) | Xu et al. (2013) and Xu and Gao (2014) | 2009–2010        |
| Halley Station (75°S, 26°W)                    | 0.035    | 0.115     |              |           |            | Minikin et al. (1998) | 1991–1992        |
| Dumont d’Urville Station (66°S, 140°E)         | 0.049    | 0.372     |              |           |            | Minikin et al. (1998) | 1991–1995        |
| Equatorial region (20°N–20°S)                  | 1.12 (1.27) | 0.176 (0.26) | 0.20 (0.06) | 0.048 (0.004) | 0.00018 (0.00025) | This study | 5–13 April       |
| Low-middle latitudes (20–40°S)                 | 2.69 (2.16) | 0.05 (0.037) | 0.253 (0.097) | 0.04 (0.003) | 0.0003 (0.00017) | This study | 1–5 April        |
| High-middle latitudes (40–60°S)                | 0.80 (0.89) | 0.015 (0.012) | 0.136 (0.054) | 0.037 (0.009) | 0.00027 (0.00055) | This study | 18–25 February    |
| The Southern Ocean (60–74°S)                   | 0.76 (0.8) | 0.017 (0.016) | 0.145 (0.03) | 0.026 (0.009) | 0.00028 (0.00067) | This study | 28–31 March       |
| All regions                                     | 0.996 (1.22) | 0.045 (0.12) | 0.162 (0.06) | 0.03 (0.01) | 0.0003 (0.0006) | This study | 25 February–28 March |

Note. Standard deviations given in parentheses.

Table 1

Main Water-Soluble Ion Concentrations (μg m\(^{-3}\)) Over the Southern Hemisphere From This Study Compared With Previously Reported Values From Other Areas

Table 2

Correlation Coefficients Between Water-Soluble Ion Concentrations in the Atmospheric Aerosols Recorded in the Southern Hemisphere During This Study

\(^a\) Coefficients at 0.05 Significance Level, \(P < 0.05\). \(^b\) Coefficients at 0.01 Significance Level, \(P < 0.01\).
equatorial region and this may be related to temperature and the enhancement of phytoplankton photosynthesis due to the increase of radiation intensity (Ye et al., 2015).

As the dominant source of the Southern Hemisphere oceanic aerosol, SSAs exhibit multiple fluctuations with the variation of latitude. The concentration of SSAs is generally low in most regions of the Southern Ocean (60°–74°S), suggesting that they were significantly affected by sea ice concentration. What is noteworthy is that the levels of SSAs were very low in the equatorial region, suggesting that SSAs may be influenced by the Inter-tropical Convergence Zone, characterized by low pressure, maximum surface temperature, high cloudiness, high rainfall, and trade-wind convergence (Nicholson, 2009). Moreover, along with WS and sea ice concentration, temperature may also be a factor affecting SSA concentrations (May et al., 2016).

3.3. Influences on Sea Salt Aerosol Formation

SSAs are generally produced from bubble-bursting and foam breaks (Spiel, 1998), while bubble-bursting and foam breaks are in turn affected by WS. In this study, the variation of Na⁺ concentrations (Figure 3), were mostly consistent with WS in the low-middle latitudes (20°–40°S). Positive correlations between Na⁺ concentrations and wind speeds were present here ($R^2 = 0.47$, Figure 4), implying that SSAs were greatly influenced by the WS. The increase of WS will lead to a rise in marine whitecaps, which consequently increase SSA concentrations (Exton et al., 1985). However, correlations between Na⁺ concentrations and wind speeds were relatively low in the Equatorial region (20°N–20°S) and high-middle latitudes (40°–60°S) ($R^2 = 0.26$ and 0.20, respectively), suggesting that the wind-driven wave-breaking mechanism is insufficient to explain the variability of SSA concentrations.

The roles of other parameters such as temperature, humidity, WS short-term variation (gusts), and sea surface temperature (SST) remain controversial (Lewis & Schwartz, 2004; Liu et al., 2021; Renjian et al., 2001). Noting the prevailing high-middle latitude (40°–60°S) westerlies, land accounts for little proportion in this region where there are very strong wind speeds. However, westerlies are much more variable than the trade winds and prone to form cyclones, which lead to reduced SSAs emissions for the same mean WS (Jaeglé et al., 2011). High-resolution observations found that daily variations in westerlies were much stronger than in other regions (Figures S3 and S4 in Supporting Information S1) and strong wind speeds were typically transient occurrences of less than several
hours duration. This result is in reasonable agreement with a previous study (Lewis & Schwartz, 2004), while the Na\(^+\) concentrations were much lower than in low-middle latitudes (20–40°S) under the same level of mean WS (9.07 and 8.96 m s\(^{-1}\), respectively). The observation results suggest that strong and steady wind speeds may benefit SSA emissions, but strong wind speeds with short-term variation may reduce SSA emissions. Moreover, there was no obvious correlation between sea salt and WS in the Antarctic (65–80°S), which has a very low temperature and is covered by sea ice, indicating that under the influence of temperature and sea ice coverage, the influence of WS on sea salt particles is weakened.

To determine the relationship between Na\(^+\) concentrations, WS, temperature, and RH, Figure 5 presents the distribution of averaged Na\(^+\) concentrations with temperature under different wind speeds. Wind speed of 7 m s\(^{-1}\) is the fourth level on the Beaufort scale, which the small waves start to appear. Wind speed of 7–10 m s\(^{-1}\) are mainly classified as the fifth level in Beaufort scale. At this level, Moderate waves, many white horses are formed. When the WS between 10 and 13 m s\(^{-1}\) (mainly sixth level), Large waves begin to form; the white foam crests are more extensive everywhere. Under the condition of WS greater than 13 m s\(^{-1}\) (Level seven or above), sea

**Figure 3.** The variation of wind speed and Na\(^+\) concentrations with latitude.

**Figure 4.** Correlation between Na\(^+\) and wind speed in regions of different latitude.
heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. Wind speeds were classified into four levels above and then the concentrations of Na$^+$ were averaged every 2°C for each classification level. The concentrations of Na$^+$ were low in all temperature ranges when WS $<$ 7 m s$^{-1}$, indicating that temperature had little effect on concentrations of SSAs at low WS. This may be due to low wind speeds producing less bubble-bursting and foam breaks, reducing the impact of temperature indirectly.

Similarly, for sea ice coverage (i.e., $T$ $<$ $-2.5^\circ$C), Na$^+$ concentrations were all low. Under the condition of $T$ $>$ 0°C and WS $\geq$ 7 m s$^{-1}$, both temperature and WS have positive effects on SSA concentrations. Moderately positive correlations between temperature and Na$^+$ concentrations ($R^2$ = 0.48 and 0.34, respectively) were present under the condition of 10 $\leq$ WS $< 13$ m s$^{-1}$ and WS $\geq$ 13 m s$^{-1}$. The concentration of the larger particles increases much more rapidly with WS than does the total salt concentration. McDonald et al. (1982) reported that as the WS increased from 3.4 to 10 m s$^{-1}$, a 7–10 fold increase in atmospheric salt concentration was observed, but the salt deposition rate also increased by 50 times. When the size of SSAs is greater than 1 $\mu$m, or even greater than 0.5 $\mu$m, the residence time of the SSAs is rapidly reduced to several hours (Huang & Jaeglé., 2017).

Higher temperatures may lead more moisture in particles to be vaporized and hence reduce their mass before descending to the ocean, thereby decreasing their fall speed. Furthermore, temperature will affect the sea water temperature. The kinematic viscosity of seawater has strong dependence on SST, decreasing by factor of 2.2 between 0°C and 30°C (Chen et al., 1973), and hence bubbles in warm water will rise more quickly to the surface (Lewis & Schwartz, 2004) which increases the production of SSAs. However, WS and temperature have little effect on the concentrations of Na$^+$ when $T$ is between 12.5°C and 20°C (mainly in 40–60°S), which may due to the low RH and negative sea-air temperature difference (Figures S5 and S6 in Supporting Information S1).

Under negative sea-air temperature differences, the region L (Figure S4 in Supporting Information S1) exhibits strong WS short-term variations. Here, a mass of air reaching an upper layer adiabatically would have a lower temperature and higher density than the surrounding air and hence would tend to come back to its previous height (Tedeschi & Piazzola, 2011). Under such conditions, the formation of SSAs will be inhibited.

The distribution of Na$^+$ concentrations with RH under different WS level is shown in Figure 5b. Na$^+$ concentrations were very low under the condition of RH $<$ 60%. The main constituents of marine aerosols are NaCl and MgCl$_2$, with each salt wetting at 35% and 75% RH (at 20°C) (Cole et al., 2003). Low RH makes it difficult to finish gas-to-particle conversion. Na$^+$ concentrations show a significant increase when RH is between 70% and 90%, indicating that the increase of RH is beneficial to forming fine particles (Gengchen, 1982). However, the concentrations of Na$^+$ under high RH (90%–100%) is not higher than that with RH between 70% and 90%, implying that a number of fine particles will increase their mass and convert to coarse particles, leading to higher terminal velocity and a greater fall out (Cole et al., 2003; Renjian et al., 2001; Tang et al., 1997).

In this study, Na$^+$ concentrations with high wind speeds (WS $\geq$ 13 m s$^{-1}$) were lower than those when 10 $\leq$ WS $< 13$ m s$^{-1}$ and 7 $\leq$ WS $< 10$ m s$^{-1}$ under the same RH conditions. High WSs were mainly present in
high-middle latitudes (40–60°S) and in the Southern Ocean (60–74°S) (Figure S4 in Supporting Information S1), where low temperatures and strong daily wind variation was not conducive to the formation of SSAs. Besides WS, humidity, WS short-term variation, and temperature can also affect SSA emission. However, more observations are required to clarify the relationship between SSA concentrations, temperature, RH, and other factors.

3.4. Sea Salt Aerosols Characteristics on the Sea Ice Margin

A notable characteristic of the Southern Ocean is that it is covered with sea ice. Ice cover strongly affects marine biota, air-sea exchanges and thus climate (Clarke & Ackley, 1984). The relationship between sea ice concentrations and Na\(^+\) concentrations is illustrated in Figure 6. It is readily apparent that the concentrations of Na\(^+\) increased as sea ice concentrations decreased.

Air mass backward trajectories were calculated using the HY-SPLIT model to establish the origin of air mass for some representative regions (see maps in Figure 7 for labeled representative areas). At the same level of WS, Na\(^+\) concentrations in the region far away from sea ice (H1, 14.82 m s\(^{-1}\)) were significantly higher than in the regions close to sea ice (L1, 17.51 and L2, 15.28 m s\(^{-1}\)). According to the air mass back trajectory analyses, air mass for representative open ocean area H1 mainly came from the marine atmosphere (Figure 7a), suggesting that a marine source was more significant in this area. However, for areas L1 and L2, source areas were covered by sea ice (Figure 6), and the air mass was mainly derived from sea ice and the Antarctic continent (Figures 7b and 7e), implying that sea ice and continental source has a non-negligible impact on SSAs. However, region H2 (WS = 15.19 m s\(^{-1}\)) close to the sea ice that had high Na\(^+\) concentrations, compared with L1 and L2. This

Figure 6. Spatial distributions of Na\(^+\) concentrations and sea ice concentrations in the Southern Ocean, Antarctica during the cruise; (a) Na\(^+\) concentrations during legI (25 February–7 March) (ng m\(^{-3}\)), (b) Na\(^+\) concentrations during legII (8–27 March) (ng m\(^{-3}\)), (c) average sea ice concentrations during legI from satellite data, and (d) average sea ice concentrations during legII from satellite data.
Figure 7. Backward 72 hr air-mass trajectory analysis for five representative regions. (a) Region H1, (b) region L1, (c) region H2, (d) region L3, and (e) region L2.
suggests that the differences in air mass trajectories also had an effect on the concentrations of SSAs. Figure 7c shows that although near to the sea ice, the air mass of region H2 mostly came from a marine source.

In addition to being affected by WS, the L3 region was a long way away from sea ice (6.25 m s⁻¹) and had a low level of sea salt particles. A marine source was the dominant source for this region (Figure 6d), but low wind speeds almost eliminated the effect of the source. Concentrations in the perimeter zone (longitude 130.6°–144.4°W) were roughly consistent with those in L3, where wind speeds with a mean value of 5.5 m s⁻¹, and the mean Na⁺ concentrations were 0.29 μg m⁻³. In summary, the results suggest that over the Southern Ocean, WS is a critical factor that affects SSAs by impacting bubble-bursting and foam breaks, but the role of sea ice and air mass trajectories cannot be ignored.

4. Conclusions

A high-resolution (1h) aerosol monitoring system was used during the 34th Chinese Antarctica Expedition Research Cruise (18 February 2018–13 April 2018) to present the relationship between SSA concentration and temperature under different wind speeds, RH, sea ice, and air mass trajectory in the Southern Ocean summer.

The spatial distributions of SSAs change significantly with the latitude in the Southern hemisphere. The highest Na⁺ concentrations were present in low-middle latitudes (20–40°S), which was 2–3 times than that in other regions. But low Na⁺ levels were observed in the low latitude (<20°S) and high latitude (>70°S). At low WS levels (WS < 7 m s⁻¹), Na⁺ concentrations were low in all temperature ranges. Temperature and Na⁺ concentrations had moderately positive correlations under the conditions of 10 ≤ WS < 13 m s⁻¹ and WS ≥ 13 m s⁻¹. Na⁺ concentrations were very low with RH < 60%, and significantly increased when RH rose to between 70% and 90%. However, Na⁺ concentrations decreased when the RH was over 90%. The formation of sea salt particles was significantly impacted by the sea ice coverage, the Na⁺ levels were extremely low at the sea ice margin even with high wind speeds.

Data Availability Statement

The data used in the figures, tables, and water-soluble ions mass concentrations are available online (https://doi.org/10.5281/zenodo.7253577).

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