A preliminary study on pollution characteristics of surfactant substances in fine particles in the Beibu Gulf Region of China

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Abstract

The pollution characteristics of surfactant substances in fine particles (PM₂.₅) in spring were studied in the Beibu Gulf Region of China, 68 samples of PM₂.₅ were collected at Weizhou Island in Beihai City from March 12 to April 17, 2015. The Anionic Surfactant Substances (ASS) and Cationic Surfactant Substances (CSS) in the samples were analyzed using Byethyl Violet Spectrophotometry and Disulfide Blue Spectrophotometry, respectively. Combined with the data from backward trajectory simulation, the effects of air pollutants from remote transport on the pollution characteristics of surfactant substances in PM₂.₅ in the Beibu Gulf Region were analyzed and discussed. The results showed that the daily mean concentrations of ASS and CSS in spring in the Beibu Gulf Region were 165.20 pmol/m³ and 8.05 pmol/m³, and the variation ranges were 23.21–452.55 pmol/m³ and 0.65–31.31 pmol/m³, accounting for 1.82%±1.65% and 0.12%±0.11% of the mass concentration of PM₂.₅, respectively. These concentrations were lower than those in comparable regions around the world. There was no clear correlation between the concentrations of ASS and CSS in PM₂.₅ and the mass concentrations of PM₂.₅. Tourism and air transport had a positive contribution on the concentrations of ASS. The concentration of surfactant substances in PM₂.₅ was significantly impacted by wind speed and wind direction. Atmospheric temperature, air pressure and precipitation had little effect on the concentrations of surfactant substances. Surfactant substances in PM₂.₅ significantly impacted visibility. Results also showed that the main sources of surfactant substances were from the southern China and Southeast Asia.

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Introduction

Since the discovery of surfactant substances in atmospheric particulate matters (Blanchard et al., 1964; Hoffman and Duce, 1974; Barger and Garrett, 1976), a large number of studies have confirmed that they are a type of surfactant, mainly composed of polyacids, polyesters, proteins and humic-like substances (Giovannelli et al., 1988; Latif et al., 2011; Latif and Brimblecombe, 2004, 2007; Kiss et al., 2005; Levent Kuzu et al., 2013; McNeill et al., 2014; Li et al., 2018), mainly from marine droplets (natural sources), combustion of fossil fuels, combustion of biomass and emissions of human pollution sources (Blanchard, 1964; Tervahattu et al., 2005; Frka et al., 2012; Wahid et al., 2013). Surfactant substances in atmospheric particulate matters can affect the characteristics of atmospheric aerosols such as surface tension, hygroscopicity and solar radiation, and change the heterogeneous reaction and cloud condensation processes on the surface of the aerosols, significantly impacting atmospheric environment, human health and global climate change (Latif and Brimblecombe, 2004; Kiss et al., 2005; Wahid et al., 2013; Yu Y., 2014).

Surfactant substances are composed of different groups (hydrophilic group and hydrophobic group), divided into anionic surfactant substances (ASS) and cationic surfactant substances (CSS) (Latif and Brimblecombe, 2004; Wahid et al., 2013; Shen at el., 2012; Yu, 2014). These substances are attached to the surface of fine particles (PM$_{2.5}$) and directly affect the hygroscopic properties of PM$_{2.5}$ (Frka et al., 2012). Current analysis methods for these substances are methylene blue spectrophotometry (MBAS), ethyl violet spectrophotometry (EVAS) and liquid chromatography–mass spectrometry/mass spectrometry (LC-MS/MS) to analyze ASS, and disulfide blue spectrophotometry (DBAS) to analyze CSS (Latif and Brimblecombe, 2004, 2007; McNeill et al., 2014; Frka et al., 2012; Wahid et al., 2013). The concentration of surfactant substances in PM$_{2.5}$ is very low, generally less than 1% (Latif and Brimblecombe, 2004; Wahid et al., 2013; Yu et al., 2014; Zhang et al., 2016), however, simulation results show that surfactant substances can affect the surface properties of PM$_{2.5}$ (Smoydzin and Von Glasow, 2007; Zelenyuk et al., 2007). For example, Baduel et al. (2012) studied the surface tension of aerosol samples in summer and winter and found that different types of surfactant substances on aerosol surfaces can lead to a change of surface tension during different seasons. Facchini et al. (2000) analyzed the surface tension of aerosols or cloud drops of neutral organic compounds, monocarboxylic acids, dicarboxylic acids, or polycarboxylic acids. The results showed that polycarboxylic acids had the greatest effect on the surface tension of aerosols or cloud drops, followed by monocarboxylic or dicarboxylic acids, and neutral organic compounds. Schwier et al. (2012) found that oleic acid and stearic acid on the surface of aerosols lowered the surface tension between aerosols and the atmosphere, further affecting the heterogeneous reaction of aerosols and the activity of cloud condensation nodules.

The composition and sources of surfactant substances have been studied extensively around the world (Latif and Brimblecombe, 2004, 2007; McNeill et al., 2014; Frka et al., 2012; Wahid et al., 2013), but only a few studies were carried out on surfactant substances in PM$_{2.5}$ in China. Wu et al. (2009) studied water-soluble organic substances in aerosols in Xiamen and identified that the contribution from traffic sources and urban living area was high. Yu et al. (2014) optimized the method of analysing ASS in PM$_{2.5}$, and studied the pollution characteristics and sources of ASS in PM$_{2.5}$ in Beijing. They found that the concentration of surfactant substances in PM$_{2.5}$ in Beijing was higher than in other countries, and identified that the main sources were motor vehicle exhaust, biomass combustion and coal combustion. In order to enrich the understanding of the surface chemistry of aerosols, and clarify the impact of aerosols on air quality, human health and climate effects in China, it is necessary to carry out regional studies on surfactant substances in atmospheric particle matters.

In this article, EVAS and DBAS were used to analyze the surfactant substances in PM$_{2.5}$ in Beibu Gulf Region in China. Based on meteorological factors and data from backward trajectory simulations, the impact factors of surfactant substances in aerosols and the contribution of atmospheric transport were discussed. This provides baseline data on surfactant substances on the surface of fine particles in coastal areas of China.

1. Materials and methods

1.1. Field observations

The sampling site was located on the roof of a five-story building in Dishui village of Weizhou Island, Haicheng District, Beihai City, Guangxi Province (21.0147°N, 109.0900°E). The sampling point was about 23 meters high from the ground and surrounded on three sides by sea (Fig. 1). Weizhou Island is

Fig. 1 – Location of the sampling site.
a national geological park. Tourism is its main industry and there is no obvious pollution source.

PM$_{2.5}$ samples were collected using a high volume PM$_{2.5}$ sampler TE-6070VFC-PM$_{2.5}$ (Thermofisher Company, USA) with 8 inch $\times$ 10 inch (203 mm $\times$ 254 mm) quartz membranes (Whatman Company, USA) in the daytime and at night during March to April in 2015. The sampling times were from 7:00 to 18:30 (Marked as ‘D’) and 19:00 to 6:30 (Marked as ‘N’) of the next day. Total 68 samples were collected, and the surrounding environment and weather data were also recorded during the sampling.

Before sampling, the quartz membranes put in a dryer providing constant temperature and humidity for 24 hr, which were heated in a muffle furnace (SX$_2$-8-10, Beijing Kewei Yongxing Instrument Co., LTD, China) at 450°C for 4 hr, then numbered and weighed. The membranes were then flattened, sealed and cryopreserved for further use. During analysis, the samples were put in the dryer again and then weighed using an analytical balance (CPA225D, Sartorius, Germany) of one hundred thousandths to obtain the mass concentration of PM$_{2.5}$.

Turbidity of the atmosphere was measured by using a turbidimeter (Ecotech Company, Australia) during the observation period (March 12 to April 10, 2015). The weather data used (wind speed, wind direction, relative humidity, barometric pressure, temperature, visibility and precipitation) were from Weizhou Island National Reference Climate Station. The wind data were the daily mean data under 1000 hPa of the Beibu Gulf Region from the US National Oceanic and Atmospheric Administration (NOAA) (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). The backward trajectory used were from Hybrid-Single Particle Lagrangian Integrated Trajectory 4 (HYSPLIT4) modelled data from NOAA (http://ready.arl.noaa.gov/hypub-bin/trajtype.pl?runtype=archive).

During the observation period from March 12 to April 15, the sampling site was impacted by typhoon “Maysak” between March 23 and April 6, 2015 (China Meteorological Administration, http://www.cma.gov.cn/).

1.2. Sample treatment and analysis

1.2.1. Determination of ASS in PM$_{2.5}$

Yu et al. (2014) optimized the MBAS and EVAS method for ASS analysis. The principle of this method is that ASS can form a hydrophobic organic association with a cationic chromogenic agent (MBAS or EVAS), and the extraction liquid can be analyzed by UV-Vis photometry (wavelength 652 nm for MBAS and wavelength 615 nm for EVAS) (Secagli et al., 2011). The results showed that EVAS was easier to operate and the standard curve was more linear, which is more suitable for the determination of ASS. So, the EVAS reagent was chosen for our analysis.

We cut the quartz membranes collected into quarters and then put them into an extraction bottle (PET, 50 mL), added ultra-pure water to completely submerge the pieces, and then put the bottle into an ultrasonic cleaner to extract the sample. The extracted solution was vacuum-filtered with a polycarbonate membrane (Millipore, pore size 0.45 μm), and then the filtrate was diluted to 100 mL and stored in a refrigerator until analyzed.

1.2.2. Determination of CSS in PM$_{2.5}$

The determination of CSS was carried out using the optimized DBAS method (Yu et al., 2017). The principle of this method is that CSS reacts with the anionic chromogenic agent to form a hydrophobic association compound (DBAS). The extraction liquid can be analyzed by UV-Vis photometry (Wavelength 628 nm). Then, according to the Beer-Lambert law, we can make a standard curve to obtain the concentration of CSS in PM$_{2.5}$.

The membranes were cut into quarters, ultra-pure water added to completely submerge the pieces, then they were put into an ultrasonic cleaner to extract the sample. The PM$_{2.5}$ sample extracted solution was put into an extraction bottle, acetate buffer solution added to adjust the pH value, dithio- blue solution added. The mixture was shaken, and chloroform was added for extraction. The absorbance of CSS in PM$_{2.5}$ sample at 628 nm was measured by spectrophotometry (Latif and Brimblecombe, 2004; Wahid et al., 2013; Li and Wei, 2006; Liu and Zhang, 2010). The standard curve was established using tetradeyl dimethyl benzyl ammonium chloride (TDBAC) as a reference (Fig. 3).

1.3. Data processing

The backward trajectory simulation was drawn for 34 days by HYSPLIT4 model, every trajectory simulated in 36 hr, 12 hr intervals. According to the distribution of backward trajectories, the period could be divided into four periods during which the sources of atmospheric particulate matters were mainly from one direction: in period I (March 12 to March 19) and period III (March 29 to April 7) and in period II (March, 20 to March 28) and period IV (April 8 to April 15).
Fig. 3 – Absorbance standard curve of tetradecyl dimethyl benzyl ammonium chloride.

1.4. Quality assurance

To ensure the reliability of the data, laboratorial operating procedures were strictly complied during sampling and analyzing. These measures will reduce the errors and improve the accuracy of the data.

(1) Sampling Wear disposable latex gloves. Scrub the filter screen of the sampler with alcohol. Use the clean tweezers to put / remove the quartz filter membrane. Fold the collected samples of quartz filter membrane in half and wrap it in tin foil paper, then Put it into self-sealing bag for preservation.

(2) Weighing Weigh the samples according to HJ 618-2011 ambient air - Determination of PM10 and PM2.5 - Gravimetric method.

(3) Sampler Before sampling, check the sampler to ensure that the flow of each sampling system is normal.

(4) Blank sample during samples collection, use a blank sample, and store and analyze it with the collected sample at the same time.

(5) During samples test and analysis, analyze instrument blank every time. Use disposable syringes for sample injection to avoid cross contamination between samples.

2. Results and discussion

2.1. Changes of air quality and meteorological conditions during observation

As shown in Fig. 4, during the observation period, the daily mean air temperature in Weizhou Island was 16.2°C at the lowest and 26.3°C at the highest, with an average temperature of 22.3°C. The daily mean environmental relative humidity was 68.8% at the lowest, 96.8% at the highest, 84.4% on average. The daily mean wind speed near the ground was 1.37 m/s at the lowest and 6.88 m/s at the highest, with an average wind speed of 3.15 m/s. There was a heavy rainfall event, from April 7 to April 10, during typhoon Maysak, accompanied by a rapid rise of relative humidity, a temperature dropped and high wind speed near the ground. During this period, the air temperature and relative humidity were high, and the wind speed and direction changed frequently, which created some favourable conditions for the accumulation and possible sources of PM2.5 and surfactant substances.

2.2. Concentration of surfactant substances in PM2.5

The variation of PM2.5, ASS and CSS concentrations in spring in the Beibu Gulf Region are shown in Fig. 5. The daily mean concentration of PM2.5 in Beibu Gulf was 53.03±18.16 μg/m³. The daily mean concentrations of ASS and CSS in PM2.5 were 165.20 pmol/m³ and 8.05 pmol/m³ and the variation ranges were 23.21–452.55 pmol/m³ and 0.65–31.31 pmol/m³ respectively, accounting for 1.82%±1.65% and 0.12%±0.11% of PM2.5, respectively.

During the sampling observation, the concentration of ASS increased first and then decreased twice, from March 15 to March 24 and April 9, reaching a peak of 394.86 pmol/m³ (March 24, day) and 452.59 pmol/m³ (April 9, day). The diurnal concentration difference was large on March 18, 21, 24 and April 7, maximum difference up to 190 pmol/m³, while other fluctuations were small in other time. The results showed that the diurnal concentration variation of PM2.5 fluctuates; the concentration was high at night on March 19, 2015, and in the daytime on April 4, 2015, attributed to biomass combustion. During March 12 to March 24, the diurnal variation of ASS showed an overall upward trend, and the concentration reached peaks, at 338.57 pmol/m³ and 394.86 pmol/m³ at night on March 21 and in the daytime on March 24, respectively. During March 25 to April 7, the diurnal variation of ASS was low and reached a peak of 394.89 pmol/m³ at night on April 7. From April 8 to April 15, the concentration of ASS decreased slowly; the concentration was a little higher from April 8 to April 11 and was 242.15–452.55 pmol/m³, then decreased to 37.84 pmol/m³ on April 13.

During the observation period, the concentration of CSS in PM2.5 decreased slightly (0.65-12.87 pmol/m³). At night on March 19, March 29, April 11 and April 12, the concentrations were abnormally high; the diurnal variation was low in other days. The daytime concentration peaked at 29.6 pmol/m³.
on March 13, and the night concentration peaked at 31.31 pmol/m$^3$ on April 12.

Fig. 6 shows the concentration of ASS in the Beibu Gulf Region compared with other regions in China and other countries (Latif and Brimblecombe, 2004; Wahid et al., 2013; Yu, 2014). ASS in the Beibu Gulf Region was significantly lower than in Beijing, China (504 pmol/m$^3$), Norwich, England (464.9 pmol/m$^3$), Colorado, United States (318.5 pmol/m$^3$) and Kuala Lumpur, Malaysia (289.73 pmol/m$^3$); and higher than in Edinburgh, England (109.8 pmol/m$^3$) and Bangi, Malaysia (153.12 pmol/m$^3$). The concentration of CSS in PM$_{2.5}$ in the Beibu Gulf Region was much lower than in Kuala Lumpur (51.3 pmol/m$^3$) and Bangi (37.6 pmol/m$^3$), slightly lower than in Edinburgh (10.5 pmol/m$^3$), and higher than in Norwich (5.57 pmol/m$^3$). Overall, the concentration of ASS and CSS in PM$_{2.5}$ was lower in the Beibu Gulf Region than in other comparable regions around the world.

2.3. Impact factors of surfactant substances in PM$_{2.5}$

The relationships of the concentration of PM$_{2.5}$, ASS and CSS during March 12 to April 15, 2015 are shown in Fig. 7. It can be seen from Fig. 7 a that the linear $R^2$ values between the concentration of ASS in PM$_{2.5}$ and PM$_{2.5}$, and between the concentration of CSS in PM$_{2.5}$ and PM$_{2.5}$, were 0.005 and 0.025, respectively. There was no obvious linear relationship between the concentrations of ASS and PM$_{2.5}$ and between the concentrations of CSS and PM$_{2.5}$. And as shown in Fig. 7 b, there was no linear relationship between concentration between ASS and CSS in PM$_{2.5}$ ($R^2 = 0.006$). The results are consistent with those of Wu et al. (2009) and Huang et al. (2015). Therefore, the mass concentration of PM$_{2.5}$ had little effect on ASS and CSS, and there was no obvious relationship between ASS and CSS during the whole observation period.

The relationships between the concentration of surfactant substances and meteorological factors (temperature, air pressure, relative humidity, precipitation, wind direction, wind speed) in spring in the Beibu Gulf Region are shown in Fig. 8. In our study, the observation period was divided into four periods according to meteorological factors and wind field changes. During period IV, the temperature was the lowest; the relative humidity was high (about 90%) at the sampling site, higher at night and lower in the daytime. As shown in Fig. 8 c Wind speed, the wind speed was maintained at 3-5 m/sec most of the time during periods I, II, and III; the wind speed reduced in period IV impacted by the typhoon. Then the wind direction was mainly north, northeast and southeast; and west and southwest winds occurred in period III and the later part of period IV. The diurnal mass concentration of PM$_{2.5}$ decreased first and then increased in period I; increased, decreased rapidly and increased slowly in period II; increased gradually to a peak (107 μg/m$^3$), decreased and then increased in period III; increased gradually in period IV.

During periods I, II, and III, ASS and CSS were not significantly affected by wind speed, relative humidity, rainfall, temperature and air pressure (Fig. 8). In period IV, the wind speed...
reached 8–10 m/s, and the wind direction was mainly north-easterly with humidity as high as 90%. When the wind direction was northerly, northeasterly to easterly, and the wind speed was higher than 3 m/sec, ASS concentration increased significantly. When the wind direction was southerly, southwesterly to northwesterly, CSS concentration increased significantly. The results indicated that ASS and CSS were affected by wind speed and direction as well as high humidity (Yu, 2014). Therefore, atmospheric temperature, atmospheric pressure and precipitation had little effect on the ASS and CSS, but wind speed, wind direction and humidity had a great influence on these concentrations.

The relationships of the concentration of PM$_{2.5}$, ASS and CSS on working days, at weekends and on holidays and during the Maysak tropical storm period are shown in Fig. 9. Our analysis found that the concentration of ASS was not significantly correlated with the mass concentration of PM$_{2.5}$ during working days. During typhoon Maysak, ASS increased significantly (Fig. 8), and CSS did not significantly change from its low value (< 0.1 ‰). Their concentrations showed a positive correlation (Fig. 9 i), which indicates that ASS and CSS had common sources (Wu et al., 2009). During typhoon Maysak, atmospheric particulate matters were transported from marine droplets by the wind (8–10 m/sec) in large quantities, which
significantly contributed to ASS concentration and also had a certain impact on CSS concentration. At weekends and during holidays, tourist visits to the island increased, catering activities were more active. During this time ASS increased significantly. This increase in ASS could be related to an increase in cleaning agents from catering activities (Sukhapan and Brimblecombe, 2002; Yu, 2014). ASS concentration was greatly affected by the marine environment and human activities, while there was no clear influence of these factors on CSS.

In summary, there was no obvious relationship between the concentration of ASS and CSS and the mass concentration of PM$_{2.5}$ (Wu et al., 2009; Wahid et al., 2013; Sukhapan and Brimblecombe, 2002). As wind direction determined the source of atmospheric particulate matters and wind speed determined the distance of transport, the concentrations of ASS and CSS were significantly related to the source of atmospheric particulate matters (Wu et al., 2009; Frka et al., 2012; Wahid et al., 2013; Sukhapan and Brimblecombe, 2002) and were impacted by air transport. Relative humidity affected ASS but the impact of air temperature, air pressure and precipitation were not significant.

2.4. Effects of surfactant substances of PM$_{2.5}$ on atmospheric visibility

During the observation period, there was a significant negative correlation between visibility and turbidity, especially in period III (Fig. 10). The variations of ASS concentrations followed variations of turbidity. Visibility increased in period I and III, but decreased in period II and IV. In period IV, ASS concentration increased suddenly, and visibility decreased under the influence of typhoon Maysak. During this period, a correlation between visibility and surfactant substances was observed: a negative correlation with ASS, but not with CSS, as shown in Table 1. According to other studies (Cserháti et al., 2002; Vejrup and Wolkoff, 2002; Liu and Zhang, 2010; Schwier et al., 2012; Wang et al., 2013; Ye and Chen, 2013), surfactant substances belonging to amphiphilic
polar organic matter, which adhere to the surface of PM$_{2.5}$, can change the surface hygroscopicity and tension of PM$_{2.5}$ and affect the heterogeneous reaction and radiation characteristics of fine particles. Therefore, it was speculated that surfactant substances in PM$_{2.5}$, especially ASS, had an impact on atmospheric visibility by affecting the surface extinction characteristics of PM$_{2.5}$. When the concentration of surfactant substances in PM$_{2.5}$ was relatively high, atmospheric visibility decreased significantly.

2.5. Effect of air transport on the concentration of surfactant substances in PM$_{2.5}$

ASS and CSS in the Beibu Gulf Region during the spring season arise mainly from water-soluble organic substances in PM$_{2.5}$. Therefore, the sources of air mass have key effects on the concentration of surfactant substances in PM$_{2.5}$. It can be seen from Fig. 11 that the sources of atmospheric particulate matters were mainly from one direction: in period I and period III, originated primarily from Southeast Asia; and in period II and period IV the source was mainly from Hainan, the South China Sea and southern China. Based on Table 2, we can see that, in periods I and III, the concentration of ASS was relatively low, at 111.18 pmol/m$^3$ and 147.03 pmol/m$^3$ respectively; the concentration of CSS was higher (13.09 pmol/m$^3$)

in period I (mainly southeast wind with low speed) and low (4.80 pmol/m$^3$) in period III (mainly west and southwest wind with low speed). This indicated that the particles transported from Southeast Asia were mixed with the sea salt particles of the Beibu Gulf (Roslan et al., 2010; Wahid et al., 2013), and the concentration of ASS was relatively low. The concentration of CSS was high in period I and low in period III. The reason may

<table>
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<th>Table 1 – Correlations between surfactant substances in PM$_{2.5}$ (x) and atmospheric visibility (y) in Beibu Gulf Region</th>
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<td>Substance</td>
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<td>ASS</td>
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<td>CSS</td>
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<td>Surfactant Substances</td>
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Fig. 10 – Daily change trend of visibility, turbidity and surfactant substances.

Fig. 11 – Backward trajectory of air mass in Beibu Gulf Region (Period 1: March 12 to March 19, Period 2: March, 20 to March 28, Period 3: March 29 to April 7 and Period 4: April 8 to April 15).
be that the wind speed was low, and atmospheric particulate matters were impacted by an air mass from Hainan in period I while particles from remote transport increased in period III. During periods II and IV, the concentration of ASS was relatively high, at 154.83 pmol/m$^3$ and 249.50 pmol/m$^3$, respectively. This may be because human activities were frequent in the mainland and organic detergents were used in large quantity during period II (Wu et al., 2009; Vejrup and Wolkoff, 2002; Yu, 2014), while during period IV, wind speed and humidity were high accompanied by precipitation caused by the tropical storm, the air mass transport was very fast and the high humidity accelerated the coagulation network sediment. The concentration of CSS was high in periods II and IV, reaching 7.72 pmol/m$^3$ and 8.56 pmol/m$^3$ respectively. In period IV, the concentration surged after the storm. The reason may be that the particulate matters were mainly from Hainan and the west of Guangdong in period II, human activity increased and the wind speed was low after the storm, CSS were discharged in large quantity to the atmosphere and were transported to the sampling site.

In summary, air transport had a significant effect on the concentration of ASS and CSS. Atmospheric particulate matters from the mainland area contained more surfactant substances, while those from Southeast Asia contained less.

3. Conclusions

(a) The daily mean concentration of PM$_{2.5}$ in the spring in the Beibu Gulf Region of China was 53.03 ± 18.16 μg/m$^3$. The daily mean concentrations of ASS and CSS were 165.20 pmol/m$^3$ and 8.05 pmol/m$^3$ and the variation ranges were 23.21-452.55 pmol/m$^3$ and 0.65-31.31 pmol/m$^3$, respectively, accounting for 1.82% ± 1.65% and 0.12% ± 0.11% of the PM$_{2.5}$, respectively. Concentrations of ASS and CSS were relatively lower in the Beibu Gulf Region than in other regions of China and other countries.

(b) During the observation period, there was no clear linear relationship between the concentrations of ASS and CSS and the mass concentration of PM$_{2.5}$. The concentration of ASS had a certain positive correlation with the concentration of PM$_{2.5}$ during weekends, holidays and the Maysak cyclonic event. The concentration of CSS had a certain positive correlation with that of ASS during this event. This suggested that tourist influx on the island and organic surfactants from the catering industry significantly impacted the concentration of surfactant substances during weekends and holidays. The concentration of surfactant substances in PM$_{2.5}$ was significantly impacted by wind speed and wind direction. Relative humidity had a certain impact on ASS and the impact of air temperature, air pressure and precipitation were not significant.

(c) When the concentration of surfactant substances in PM$_{2.5}$ was relatively high, atmospheric visibility decreases significantly. It is speculated that the surfactant substances in PM$_{2.5}$, especially the ASS, have a certain impact on atmospheric visibility by affecting the surface extinction characteristics of PM$_{2.5}$ during the observation period of this study.

(d) Air transport had a significant effect on the concentration of ASS and CSS. Atmospheric particulate matters from the mainland area contained more surfactant substances (as shown during the Maysak event), while those from Southeast Asia contained less surfactant substances.

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