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Measurement and analysis of ozone, ultraviolet B and aerosol light scattering coefficients in the Arctic

LAI Xin[1], BIAN Lingen[1*], LU Changgui[1]& TANG Jie[2]

[1]Chinese Academy of Meteorological Sciences, Beijing 100081, China;

[2]Meteorological Observation Center of China, Meteorological Administration, Beijing 100081, China

Abstract Tropospheric ozone (O_3), ultraviolet B (UVB) radiation and aerosol light scattering coefficients (SC) were investigated on a cruise ship during the fourth Chinese National Arctic Research Expedition from July 1–September 20, 2010. The results showed that O_3, UVB and SC decreased with increasing latitude, with minimum values recorded in the central Arctic Ocean. Average O_3 concentrations were 15.9 ppbv and 15.1 ppbv in the Bering Sea and Arctic Ocean, respectively. Ozone concentrations increased to 17.5 ppbv in the high Arctic region. Average UVB values were 0.26 $W{\cdot}m^{-2}$ and 0.14 $W{\cdot}m^{-2}$ in the Bering Sea and Arctic Ocean, respectively. The average SC in the Bering Sea was 4.3 $M{\cdot}m^{-1}$, more than twice the value measured in the Arctic Ocean, which had an average value of 1.7 $M{\cdot}m^{-1}$. Overall, UVB and SC values were stable in the central Arctic Ocean.

Keywords **Arctic Ocean, tropospheric ozone, ultraviolet B radiation, aerosol light scattering coefficient**

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0 Introduction

Over recent decades, the Arctic atmosphere and environment have experienced rapid changes. Anthropogenic greenhouse gases and aerosols have contributed to warming in the Arctic[1−2]. Since China began Arctic research expeditions in 1999, a variety of greenhouse gases have been measured during the Arctic cruise[3−6]. During the first voyage to the Arctic and the sixteenth to the Antarctic in 1999–2000, Lu et al.[7] determined cruising ozone concentrations and revealed differences between surface ozone concentrations in the Arctic and Antarctic. Some researchers have suggested that an "ozone depletion episode" (ODE) occurs during the spring, since the generation of first year ice releases bromine gas and halogenated hydrocarbons into the troposphere, consuming tropospheric ozone during spring[8−10].

An inverse correlation exists between ultraviolet B (UVB) radiation and total ozone. Although UVB only accounts for a small proportion of the total radiation, it has a significant impact on ecosystems and human health[11−12]. This makes the measurement of UVB in fragile polar region ecosystems very important.

The aerosol light scattering coefficient (SC) is an important optical parameter. Understanding the SC helps to estimate the radiative climate forcing of aerosols and the global radiation budget. The optical properties of aerosols are determined by their chemical compositions and particle sizes and shapes. These characteristics are dependent on the atmospheric relative humidity, meaning the hydrophilicity of the aerosols present could impact their SC. For example, hydrophilic aerosols will increase in size with increasing humidity, which enhances

*Corresponding author (email: blg@cams.cma.gov.cn)

the scattering ability of the aerosols[13−14].

Because no permanent observation station exists in the Arctic Ocean, research and exploration vessels are an important way to obtain measurements in the Arctic. During the fourth Chinese National Arctic Research Expedition from July–September 2010, we used advanced standard equipment to perform on-line measurements of O_3, UVB and the SC on-board the R/V *XUE LONG* icebreaker during its voyage to the Arctic. This manuscript presents the analysis of measurements obtained during the voyage and provides a scientific basis for the understanding and assessment of the mechanism responsible for the rapidly changing climate and environment in the Arctic.

1 Sampling locations and experimental methods

1.1 Cruise summary

The R/V *XUE LONG* icebreaker, for the fourth Chinese National Arctic Research Expedition, arrived at Xiamen on June 27 from Shanghai and began the trip to the Arctic from Xiamen port on July 1. It cruised through the Tsushima Strait, the Sea of Japan, the Soya Strait, the Sea of Okhotsk, the northwest Pacific Ocean, the Bering Sea and finally entered the Arctic Ocean (Figure 1). From August 8–19 the comprehensive scientific expedition was carried out in selected ice floes, with the most northern point (88.43°N, 176.98°W) reached on August 20. The icebreaker then returned through the Bering Sea, entered the Sea of Japan along the Kamchatka Peninsula and cruised through the Sea of Okhotsk. Finally, it arrived at the Yangtze estuary anchorage in Shanghai on September 18.

1.2 Equipment and data analysis

Ozone measurements were obtained using an ultraviolet absorption ground-level ozone analyzer (EC9810A, Ecotech). The sampler flow rate was 0.5 L·min^{-1}. Zero calibrations were performed every second day. During data processing, zero compensations were performed on the original measurements according to the zero calibration value. Measurements were recorded every 3 min. Overall, 41 640 measurements were obtained. After eliminating outliers, 79.6% of the measurements were used.

UVB measurements were obtained using an ultraviolet B radiation meter (280–320 nm) manufactured by

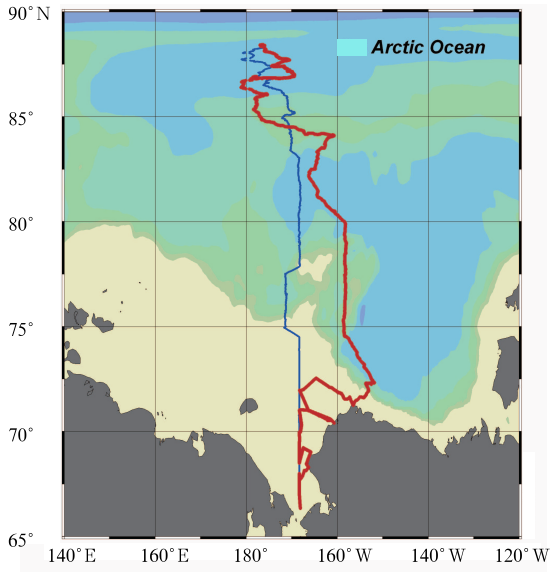

Figure 1 The Arctic portion of the fourth Chinese National Arctic Research Expedition. The thick red line indicates the arrival route and the thin blue line indicates the return route.

Yankee Environmental Systems, Inc. (USA). Measurements were taken every 10 min and were recorded by a data logger (DT600) with internal memory. Overall, 12 456 UVB measurements were obtained.

Aerosol light scattering coefficients were measures using an Aurora 1000 integrating nephelometer (Ecotech). This instrument calculated the SC by measuring the integrated light scattering of particles in the internal light source (10°–170°). The light source wavelength was 520 nm and the sample flow rate was approximately 5 L·min^{-1}. The instrument performed zero calibrations using a high efficiency particulate matter filter automatically each day. Span calibrations were performed every 15 d with 99.5% pure R-134 standard gas. Measurements were calibrated using the zero and span calibrations during processing. The inlet of the instrument was heated. The relative humidity of the sampled gas was maintained below 60% to eliminate particle growth resulting from water vapor in the instrument. Measurements were recorded every 5 min and 24 837 measurements were collected. After eliminating outliers, 90.5% of the measurements were used.

The instruments and data collection system were installed in the meteorological room on the top floor of the *XUE LONG* and dedicated inlets from the top of the ship were run into the room. The UVB radiation meter

was fixed to a balance bracket on the roof of the vessel. The instrument was 2.5 m above the deck and 30 m from the water surface. Power was produced in the rear of the ship. Generally, measurements during cruising were not affected by the chimney on the stern. The data may, however, be influenced by factors such as stopping, slowly moving forward and wind along the stern. Based on the ships speed and heading and the wind speed and direction, abnormal data were removed and smooth processing was performed.

2 Results and discussion

2.1 Ozone

Figure 2 presents changes in average ozone concentrations with latitude. The average ozone concentration during the monitoring period was 18.2 ppbv and the median concentration was 16.9 ppbv. Figure 2 shows that ozone concentrations in the eastern waters of China were significantly higher than those recorded away from China. Ozone concentrations were highest in the sea to the east of Shanghai, with an hourly average greater than 40 ppbv. Average ozone concentrations reached 55 ppbv during the first Chinese National Arctic Research Expedition in 1999, a much higher average concentration than in the other seas. For example, among the other seas, the maximum average surface ozone concentration was only 22.4 ppbv from 60°–69°N during July and August of the same year[7]. Ozone concentrations in the eastern Sea of China are most likely affected by on-land pollution. Ozone concentrations decreased sharply between the Sea of Japan and the northwest Pacific Ocean. Ozone concentrations were lowest between the Bering Sea and the Arctic Ocean, with an average concentration of 15.5 ppbv. Measurements made during the drift of the French schooner, TARA, from September 2006–January 2008 (81°–88°N latitude) were analyzed by Bottenheim et al.[10]. They found that ozone concentrations during the summer (15–20 ppbv; mid-June–mid-September) of 2007 were lower than during the winter (30–40 ppbv, October 2006–March 2007). Generally, ozone concentrations decreased with increasing latitude. However, an increase in ozone concentrations north of 75°N was observed, reaching a maximum of 17.5 ppbv near 87°N. This phenomenon was likely related to the density

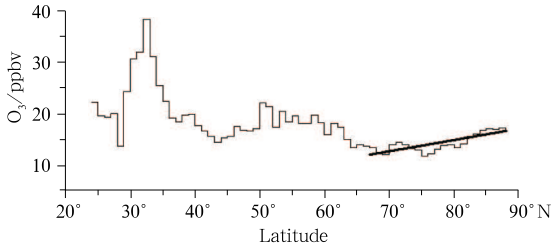

Figure 2 Average ozone concentrations (ppbv) at different latitudes over the expedition route (thin line) and a fitting line only in the Arctic region (thick line).

of sea ice. Lu et al.[7] also observed increased ozone concentrations with increasing latitude in the Arctic from 70°–74°N (the northernmost latitude that year). In their study of information from global stations, Helmiga et al.[15] suggested that although polar regions are far removed from human activities, they do not necessarily have the lowest ozone concentrations. The average ozone concentration in the middle of the Arctic Ocean during the summer was higher than that recorded at Antarctic coastal stations (12 ppbv)[16], indicating that ozone pollution in the Arctic is greater than in the Antarctic.

The expedition collected measurements at different times and spatial points in a Lagrangian method, rather than at the same time but different spatial points in an Eulerian method, therefore, ozone concentrations on the route should be functions of time and space. Table 1 presents average ozone concentrations in each sea on the arrival and return routes. From Table 1 it is apparent that average ozone concentrations consistently decreased with increasing latitude and dates. The highest ozone concentrations occurred in areas near land on the route, likely resulting from the spread of urban pollution, particularly the eastern area of Shanghai, which is adjacent to the economically developed Yangtze River Delta. The Arctic Ocean had the minimum difference between average ozone concentrations on the arrival and return routes. Though the measurement times in this study were different, compared with other seas, this study indicates that the Arctic Ocean has the least ozone pollution in the northern hemisphere.

2.2 Ultraviolet B radiation

Figure 3 presents changes in the average UVB irradiance with latitude. Similar to total radiation, UVB reaching the water surface is related to changes in the solar elevation angle after sunrise. It is apparent from

Table 1 Average O_3 concentrations (ppbv), UVB irradiance ($W \cdot m^{-2}$) and SC ($M \cdot m^{-1}$) in each sea on the arrival and return routes

Sea	Beijing time	O_3 Concentration/ppbv	UVB irradiance/($W \cdot m^{-2}$)	SC/($M \cdot m^{-1}$)
East China Sea and	Arrival: July 1–July 4	36.8±1.0	0.80	59.0±4.0
Yellow Sea	Return: September 12–September 17	29.6±0.5	0.75	95.4±3.5
Sea of Japan	Arrival: July 4–July 7	21.9±0.7	0.71	29.2±3.2
	Return: September 10–September 12	14.5±0.5	0.72	24.5±3.7
Northwest Pacific Ocean	Arrival: July 7–July 11	22.5±0.3	0.43	6.1±0.3
	Return: September 5–September 10	13.8±0.2	0.53	9.0±0.4
Bering Sea	Arrival: July 11–July 20	19.4±0.2	0.37	4.1±0.2
	Return: August 31–September 5	12.3±0.2	0.15	4.4±0.3
Arctic Ocean	Arrival: July 20–August 7	15.2±0.1	0.20	2.5±0.1
	Ice station: August 7–August 18	17.5±0.1	0.12	1.2±0.1
	Return: August 18–August 31	12.7±0.2	0.09	1.5±0.1
Whole cruise	Average	18.24	0.31	16.11
	Median	16.85	0.13	2.41

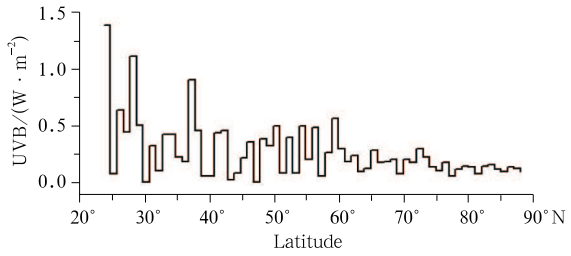

Figure 3 Changes in average UVB irradiance ($W \cdot m^{-2}$) with latitude during the expedition.

Figure 3 that UVB radiation decreased with increasing latitude. UVB values were high in the eastern Sea of China (24°–35°N), with a maximum hourly average of 2.68 $W \cdot m^{-2}$. The UVB irradiance did not significantly change with latitude between the Bering Sea and the Arctic Ocean. The UVB irradiance was still related to the solar elevation angle, but melting sea ice, high humidity and cloudy days during the expedition period resulted in little change in the observed UVB values. The average UVB value was 0.26 $W \cdot m^{-2}$ in the Bering Sea. The lowest UVB value measured was in the Arctic Ocean (0.14 $W \cdot m^{-2}$). From Table 1, the average UVB values on the arrival and return routes displayed some differences. Double or triple differences in UVB values between the arrival and return routes in the Bering Sea and the Arctic Ocean were observed, while differences were low in other regions. In addition to the reasons described above, differences in UVB values were also related to the different observation times. A clear statistical relationship between O_3 and UVB was not apparent from the analysis, consistent with the report by Lu et al.[17].

2.3 Aerosol light scattering coefficient

To study the radiative forcing of aerosols in the atmosphere, aerosol light scattering coefficients must be measured and analyzed for temporal and spatial variations and contributions to the overall mass concentration of aerosols. Few studies have measured the SC in the Arctic Ocean. To better understand the SC in China, measurements of SC during the Arctic expedition were performed.

Figure 4 presents changes in the average aerosol light scattering coefficient with increasing latitude. The average SC over the entire route was 16.1 $M \cdot m^{-1}$, with a median of 2.4 $M \cdot m^{-1}$. From Figure 4 it is apparent that the SC decreased with increasing latitude, including in the Arctic regions (fitting line in Figure 4). The maximum SC measured was in the eastern Sea of China (172.6 $M \cdot m^{-1}$) and the minimum SC, of 0.2 $M \cdot m^{-1}$, was measured in the middle of the Arctic Ocean. For comparison, we referred to measurements of aerosol light scattering coefficients from October 1997–September 2007 in Barrow, Alaska (71.32°N, 156.61°W), in the Arctic Circle. The average SC in Barrow was 10.4±11.1 $M \cdot m^{-1}$. A strong seasonal trend was evident, with low values during the summer and high values (10–15 times higher than the summer values) during the winter[18]. From July–September 2006, we calculated the average SC at Barrow to be 2.3 $M \cdot m^{-1}$ using data provided by NOAA/ESRL (http://wdca.jrc.it/data/parameters/data_sca-t.html). Measurements from the Pallas station (67.97°N, 24.12°E) in Finland, also in the Arctic Circle, also indicated

seasonal trends in SC values, but these measurements showed SC values to be at a minimum during autumn (October) and 4–5 times higher during the summer (July), when they were at a maximum. This result is different than measurements from Barrow. The SC values ranged from 0.2–94.4 $M{\cdot}m^{-1}$, with an average SC of 7.1±8.6 $M{\cdot}m^{-1}$[19]. Also, Table 1 shows that average SC values in different seas were impacted by pollutant emissions from East Asia. SC values measured in the East China Sea and the Sea of Japan were orders of magnitude different than SC values measured in the northwest Pacific Ocean, the Bering Sea and the Arctic Ocean. Among these, the average SC in the Bering Sea (4.3 $M{\cdot}m^{-1}$) was more than twice the average SC in the Arctic (1.7 $M{\cdot}m^{-1}$). The average SC at the Shangdianzi Background Station in Beijing during the summer from 2004 to 2006 was 200–250 $M{\cdot}m^{-1}$[20].

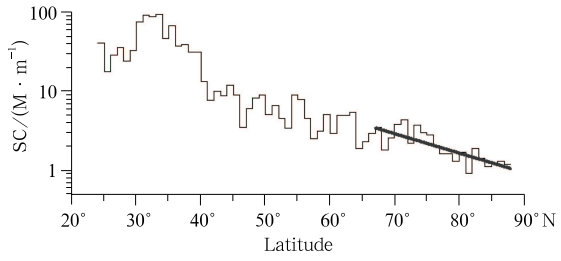

Figure 4 Changes in the aerosol light scattering coefficient ($M{\cdot}m^{-1}$) with latitude during the expedition (thin line) and fitting only in Arctic regions (thick line).

To better understand the background characteristics of the SC in the Arctic Ocean, hourly SC values between the Bering Sea and the Arctic Ocean are presented in Figure 5. Hourly average SC values showed significant fluctuations, particularly between 67°–76°N, when waters went from ice-free to having ice. This indicates that aerosols were not completely mixed in the Arctic Ocean. Aerosols observed in open water partially resulted from sea spray. The sea water consisted of 3.5% salt, with 85% of salt being NaCl. The evaporation of sea spray forms sea salt particles, largely made up of NaCl[21]. Aerosols affecting the observed changes in SC values in the Arctic Ocean could be mostly composed of sea salt. Areas north of 76°N were covered by ice floes, reducing sea salt particle emissions to the atmosphere and stabilizing the SC values in the central Arctic Ocean.

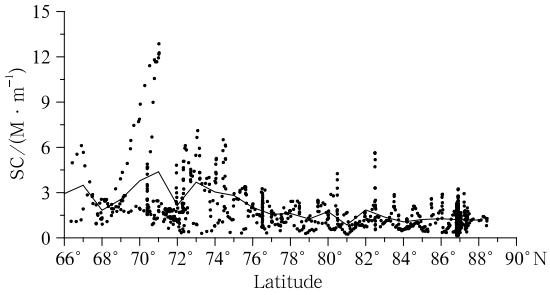

Figure 5 Distribution of aerosol light scattering coefficients in the Arctic Ocean (dots are hourly averages corresponding to the latitude, while the line is the meridional average).

3 Conclusions

We studied ozone concentrations, ultraviolet B radiation and aerosol light scattering coefficients in Arctic regions and have improved the understanding of background atmospheric characteristics in the Arctic, laying the foundation for further research on environmental changes in the Arctic.

Ozone concentrations were highest in the eastern Sea of China, where the hourly average concentration was greater than 40 ppbv. Ozone concentrations in this area were likely affected by urban pollution. Ozone concentrations decreased sharply with increasing latitude, from the Sea of Japan to the northwest Pacific Ocean and the Bering Sea. Ozone concentrations were at a minimum between the Bering Sea and the Arctic Ocean. Average O_3 concentrations were 15.9 ppbv and 15.1 ppbv in the Bering Sea and Arctic Ocean, respectively. Ozone concentrations increased with increasing latitude north of 75°N, reaching 17.5 ppbv at 87°N. These increasing concentrations were related to the sea ice density.

Ultraviolet B radiation was intense in the eastern Sea of China, with a maximum hourly average of 2.68 $W{\cdot}m^{-2}$. UVB irradiance showed little variation with latitude between the Bering Sea and the Arctic Ocean. Average UVB irradiances were 0.26 $W{\cdot}m^{-2}$ and 0.14 $W{\cdot}m^{-2}$ in the Bering Sea and the Arctic Ocean, respectively.

Aerosol light scattering coefficients decreased with increasing latitude. The maximum SC was 172.6 $M{\cdot}m^{-1}$ in the eastern Sea of China and the minimum value was 0.2 $M{\cdot}m^{-1}$ in the central Arctic Ocean. The average SC in the Bering Sea was 4.3 $M{\cdot}m^{-1}$, more than twice that measured in the Arctic Ocean. Ice floes north of 76°N

resulted in stable SC values.

Because of limitations in the spatial and temporal distributions of the measurements, background atmospheric characteristics in the Arctic must be studied further.

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