Chinese Journal of Polar Science, Vol. 14, No. 2, 138 - 148, December 2003

# Atmospheric nitrous oxide observations above the oceanic surface during the first Chinese Arctic Research Expedition

Zhu Renbin(朱仁斌)[1], Sun Liguang(孙立广)[1], Xie Zhouqing(谢周清)[1] and Zhao Junlin(赵俊琳)[2]

*1 Institute of Polar Environment, University of Science and Technology of China, Hefei 230026, China*

*2 Institute of Environmental Science, Beijing Normal University, Beijing 100875, China*

Received November 28, 2002

**Abstract** 339 gas samples above oceanic surface were collected on the cruise of "Xuelong" expeditionary ship and nitrous oxide concentrations were analyzed in the laboratory. Results showed that Atmospheric average $N_2O$ concentration was 309 ± 3.8nL/L above the surface of northern Pacific and Arctic ocean. $N_2O$ concentrations were significantly different on the northbound and southbound track in the range of the same latitude, 308.0 ± 3.5 nL/L from Shanghai harbor to the Arctic and 311.9 ± 2.5 nL/L from the Arctic to Shanghai harbor. $N_2O$ concentration had a greater changing magnitude on the mid- and high-latitude oceanic surface of northern Pacific Ocean than in the other latitudinal ranges. The correlation between the concentrations of the compositions in the aerosol samples and atmospheric $N_2O$ showed that continental sources had a great contribution on atmospheric $N_2O$ concentration above the oceanic surface. Atmospheric $N_2O$ concentration significantly increased when the expeditionary ship approached Shanghai harbor. The average $N_2O$ concentrations were 315.1 ± 2.5 nL/L, 307.2 ± 1.4 nL/L and 306.2 ± 0.7 nL/L, respectively, at Shanghai harbor, at ice stations and at floating ices. The distribution of $N_2O$ concentrations was related with air pressure and temperature above the mid- and high-latitude Pacific Ocean.

**Key words** Arctic Ocean, Northern Pacific Ocean, Nitrous oxide, Atmosphere.

## 1 Introduction

Nitrous oxide ($N_2O$) is one of the most important gases for heat budget of the terrestrial atmosphere, and its radiative effect on climate change is thought to be about 200 times as strong as $CO_2$ on a per molecule basis (IPCC 1990). In addition, $N_2O$ plays an important role in the depletion of stratospheric ozone (Ramanathan 1988). From the results of polar ice core analyses and recent direct atmospheric measurements, it is well known that the tropospheric $N_2O$ concentration has been increasing due to human activities, and its increase rates for the last few decades are observed to be 0.5-.2 nL $L^{-1}$ $yr^{-1}$ (IPCC 1990). Such a concentration increase is generally ascribed to direct emissions of $N_2O$ into the atmosphere through fertilizer production, crop production, fossil fuel combustion, biomass

burning, nitric acid production and sewage, as well as to enhancement of biogenic $N_2O$ emissions by additional fixation of nitrogen by cultivation of leguminous plants and deposition of anthropogenic nitrogen compounds in the open atmosphere (Xing 1998; Xing and Zhu 1997; Mosier *et al.* 1997; IPCC 1990). Of the sources of atmospheric $N_2O$, the oceans are considered significant, though not dominant. McElroy and Wofsy (1986) calculated the oceanic contribution to be about 13% of all sources, with an estimated error of about 50%. Cohen and Gordon (1979) estimated oceanic $N_2O$ concentration arrived at a mean supersaturation of 9%. At the other extreme, studies by Elkins (1978) and Singh *et al.* (1979) reported mean saturation anomalies of 25% and 34%. Butler *et al.* (1989) reported $N_2O$ in the surface water and marine troposphere showed a latitudinally weighted, mean interhemispheric difference of 0.97 nL/L, which suggested that 2/3 of the global flux of $N_2O$ into the atmosphere derived from sources in the northern hemisphere. Zhu *et al.* (2003) estimated that 2/5 of the global flux of $N_2O$ is derived from the sources in the southern hemisphere. Stratospheric $N_2O$ has been observed above the ocean in the past few years (Strahan *et al.* 1999; Kondo *et al.* 1999).

Climatic and environmental characteristics, physical and chemical processes in Arctic areas have good connections with global climatic and environmental changes. This area corresponds and feedbacks to global climatic and environmental changes very sensitively, being one important background area for global atmospheric environmental monitoring, and therefore it is considered important for the studies about human activities and global climatic and environmental changes. At present, the data for $N_2O$ concentrations from mid- and high-latitude oceanic surface of northern Pacific Ocean to Arctic Ocean are very sparse. During the first Chinese Arctic Research Expedition (FCARE), we collected gas samples above oceanic surface from Shanghai harbor to Arctic Ocean and analyzed atmospheric $N_2O$ concentrations in the lab. The purpose of this study is to research how oceanic atmospheric $N_2O$ concentrations change with the latitudes and the affecting factors.

## 2 Gas sampling and $N_2O$ determination

"Xuelong" expeditionary ship set out from Shanghai harbor in China on July 1, 1999. Its cruise was Shanghai harbor—Japanese Sea—Bering Sea—Chukchi Sea—Areas approaching Arctic ices—Chukchi Sea—Bering Sea—Japanese Sea—Shanghai harbor. Latitudinal and longitudinal ranges included 31°N-7°N, 123°E-33°W (i. e Northern Pacific Ocean and the Arctic Ocean). Bering Sea, Chukchi Sea, Canadian Oceanic Basin and areas approaching Arctic ices were the main expedition and research areas (Fig. 1).

We used vacuum vials made in the institute of Japanese agricultural environment, which had been vacuumized to close to zero Pa in advance to collect atmospheric samples above oceanic surface on the cruise. The sampling height was about 2 m above the ship deck. To avoid the effects of anthropogenic factors and expeditionary ship, we collected gas samples upwind on the fore. 3 duplicate gas samples were collected every time to ensure the accuracy of determination and sampling time was 8:00 AM and 20:00 PM every day. The air temperature and pressure on the oceanic surface were simultaneously recorded to investigate the effects of these climatic factors on $N_2O$ concentrations. In addition, more gas sa –

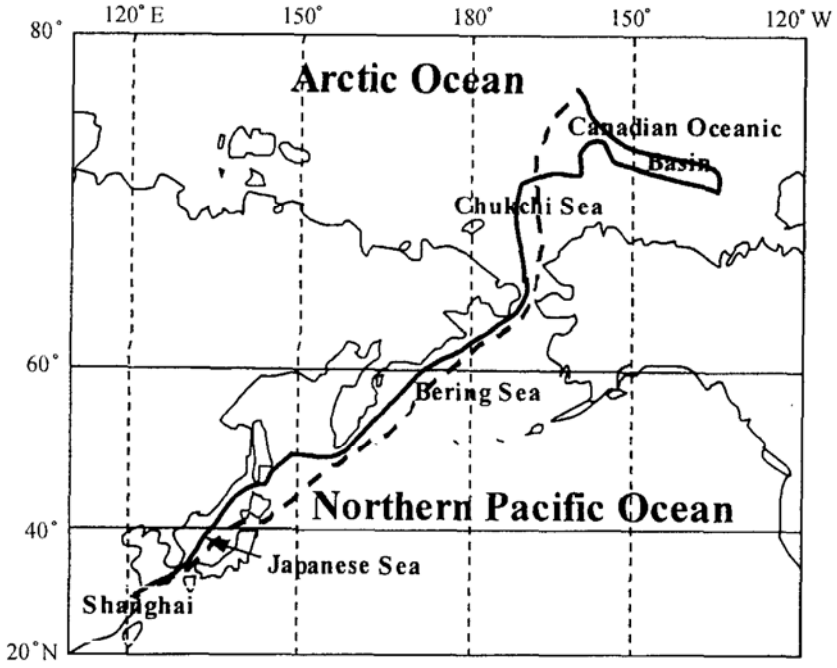


Fig. 1 The cruise track of "Xuelong" expeditionary ship during the first Chinese Arctic Research Expedition. The bold line indicates the northbound track and the ordinary line indicates southbound track.

mples concentrated in the areas approaching Arctic ice, ice stations and floating ices. 339 gas samples on the oceanic surface were collected on the cruise (including northbound and southbound tracks) from July 2 to September 9, 1999. These vials was sealed with a butyl rubber septum and then covered by a plastic cap. High vacuum inside the vial can maintain at least for a year (Xing 1998; Xing and Zhu 1997). In addition, standard gas samples stored in the vials showed no significant change in concentration during 3 months of storage in the laboratory or during transport from the field site to the laboratory, suggesting that the quality of sample air in the vials did not change during the sampling and transport period as well (Sun *et al.* 2000).

The collected gas samples were brought back to China and analyzed in the laboratory of Material Cycling in Pedosphere, Institute of Soil Science, Academia Sinica of China, for the $N_2O$ concentrations. $N_2O$ concentrations were determined by HP5890 Ⅱ GC using a $^{63}$Ni electron capture detector (ECD) (Xing and Zhu 1997; Sun *et al.* 2000). GC-ECD was equipped with back flush system with 10-port valves. A pre-column (2m) and a main-column (Porapak Q, 100 mesh) were used with an argon-methane (95%: 5%) mixture as the carrier gas at a flow rate of 30mL/min. The detector and column temperatures were 330℃ and 85℃, respectively. The back flush time was 2.8 min. The injecting gas volume was set up as 3.0ml by using an adjustable pressure syringe injector. Compressed air was used as standard gas with the value of 303 nL/L demarcated by the National Institute of Japanese Agricultural Environment. The variance coefficient for standard samples was within 0.1%-0.4% in ten hours.

To identify the sources for atmospheric $N_2O$, aerosol sampling was conducted using a

high-volume bulk aerosol sampler (Tianhong Instruments, Wuhan, China) on the cruise of the expeditionary ship. Bulk aerosol samples were collected on $20 \times 25$ $cm^2$ Whatman 41 filters at a flow rate of $1.05 m^3 min^{-1}$. All filter samples were retrieved from the sampler with strict contamination control procedures. They were sealed into clean plastic bags and kept at 4℃ until lab analysis. Aerosol sample preparation and chemical analysis (including $MSA^-$、$Cl^-$、$Na^+$、$SO_4^{2-}$ etc) were conducted at the Byrd Polar Research Center of the Ohio State University (Columbus, OH, USA) using DX500 (Dionex, Sunnyville, CA) ion chromatography (IC). The experimental procedures were described in details by Xie *et al.* (2002).

## 3 Results and discussion

### *3.1 The latitudinal distribution of atmospheric $N_2O$ above oceanic surface*

Fig. 2 is a scatter plot of atmospheric $N_2O$ for the cruise, which had measured mixing ratios between 301 and 318 nL/L for the entire cruise and a mean $N_2O$ mixing ratio of $309.0 \pm 3.8$ nL/L. Atmospheric $N_2O$ mixing ratios above oceanic surface may be divided into three areas according to the latitudes on the northbound track of expeditionary ship: The first area was in the range from 30-35° N, where $N_2O$ mixing ratios were above 309.0 nL/L and the average was 312.0 nL/L ($n = 9$); This latitudinal range contained noticeably higher mean $N_2O$ mixing ratios. The second area was in the range of 35 ~ 65°N, where $N_2O$ mixing ratios were generally lower than 307.0 nL/L and the average fell down to about 304.0 nL/L ($n = 60$); This range was the area in which the inflow and outflow regions of Typhoon Mireille were sampled (Newell *et al.* 1996; Collins *et al.* 1996). Therefore the lower $N_2O$ levels may be attributed to encountering some air masses brought from the mid-Pacific near the equator within the typhoon. In addition, Collins *et al.* (1996) proposed that this latitudinal range appeared to be preferentially influenced by the stratosphere/troposphere exchange, which would reduce the $N_2O$ mixing ratio at higher latitudes. The third area was from 65° N to the Arctic, where $N_2O$ concentration significantly increased and the average was about 309.3 nL/L ($n = 123$). Atmospheric $N_2O$ concentrations generally appeared a linearly rising trend on the southbound track from the Arctic back to Shanghai harbor and most of the values were above 309 nL/L with the exception of $N_2O$ concentrations in the range of 40-45°N (Fig. 2). The distribution of atmospheric $N_2O$ concentrations was also different in the same latitudinal range on the cruise. Atmospheric $N_2O$ concentrations on the northbound and southbound tracks had no apparent distinction in the ranges of 31-35° N and 70-77° N (2.6 nL/L and 0.5 nL/L, respectively), whereas the greater differences appeared in the other latitudinal ranges, especially in the range of 35-45°N (10 nL/L), which may be relate with the effects of continental sources because of the different sampling time. The wind direction was from southeast and the continental sources had little effects on atmospheric $N_2O$ concentrations above the oceanic surface on the northbound track, whereas the wind direction switched, and was from the Eur-Asia continent (northwest) and the concentrations were more greatly affected by continental sources on the southbound track.

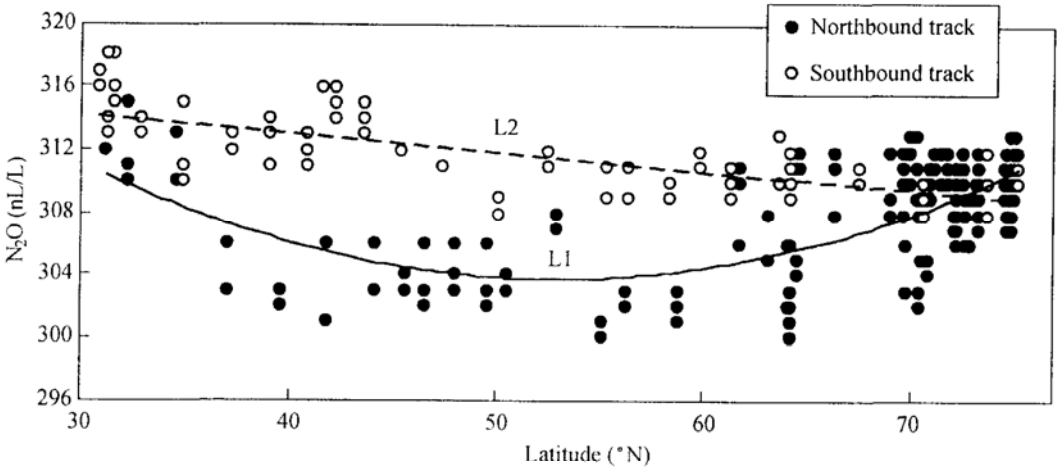


Fig. 2 The latitudinal distribution of $N_2O$ above the oceanic surface along the cruise of "Xuelong" expeditionary ship ($L_1$: $y_1 = 0.0142x_1^2 - 1.5064x_1 + 343.64$, $r_1 = 0.67$ $n = 198$; $L_2$: $y_2 = -0.1217x_2 + 318.15$, $r_2 = 0.68$ $n = 81$).

The atmospheric average mixing ratio of nitrous oxide were listed in table 1 above the seas in continental margin, Arctic Ocean and on Antarctic Fildes Peninsula. The atmosphere above the East China Sea (31-35°N) contained noticeably higher $N_2O$ mixing ratios than those above the rest oceanic regions. During September-October 1991 as part of the NASA Pacific Exploratory Mission (PEM)-West A, airborne $N_2O$ observations over the western Pacific Ocean were conducted between the equator and the 40°N latitude. This latitude survey indicated that the latitude ranges between 20°N and 35°N contained significantly higher mean $N_2O$ mixing ratios due to the continental sources (Collins *et al.* 1996). Our observation was consistent with the results reported by Collins *et al.* (1996). Mean $N_2O$ mixing ratios above Japanese Sea were above 2 nL/L higher than those above Bering Sea. Japanese Sea is located in the mid-latitudes and closer to the Asian continent. Since the sampled air mass were significantly influenced by Asian continental sources (biogenic and urban-anthropogenic), contained larger mean $N_2O$ and other pollutant mixing ratios. Bering sea is located out of more remote locations, and the lower mean $N_2O$ mixing ratio is indicative of (1) being farther away from the dominant land sources and (2) stronger center Pacific influences. High atmospheric $N_2O$ concentrations were also observed above Chukchi Sea and Canadian Oceanic Basin due to the effects of continental sources from Siberian and northern American. In addition, the mean $N_2O$ concentration on Antarctic Fildes Peninsula was slightly higher than that above high-latitude oceanic surface of northwestern Pacific Ocean, and almost equal to that above Arctic Ocean. The atmospheric $N_2O$ concentration on Antarctic Nelson Icecap was 0.8 nL/L higher than those for Arctic floating ices and ice stations, indicating that atmospheric $N_2O$ concentrations in two pole regions had no significant distinctions.

### *3.2 Comparison of $N_2O$ concentrations above ocean surface at 8:00 AM and 20:00 PM*

The changing trend of atmospheric $N_2O$ concentrations above oceanic surface is con-

sistent at 8:00 AM and 20:00 PM (Fig. 3). The average concentrations were 307.8 ±3.3 nL/L (n=96) and 307.9 ±1.5 nL/L (n=96), respectively, for the observations at 8:00 AM and 20:00 PM on the northbound track, and the difference of $N_2O$ concentrations was insignificant according to t test ($t=0.21 < t_{0.1,62}=1.64$); The average concentrations were 312.3 ±2.2 nL/L (n=42) and 311.9 ±2.7 nL/L (n=42), respectively, on the southbound track. The difference of $N_2O$ concentrations was also insignificant by t test ($t=0.24 < t_{0.1,26}=1.71$), indicating that the daily variation of atmospheric $N_2O$ concentrations may be very small above northern Pacific and Arctic Ocean surface. However, $N_2O$ concentrations on the southbound track were significantly higher than those on the northbound track at 8:00 A. M or 20:00 P. M, suggesting that the seasonal variations may be large in the study areas.

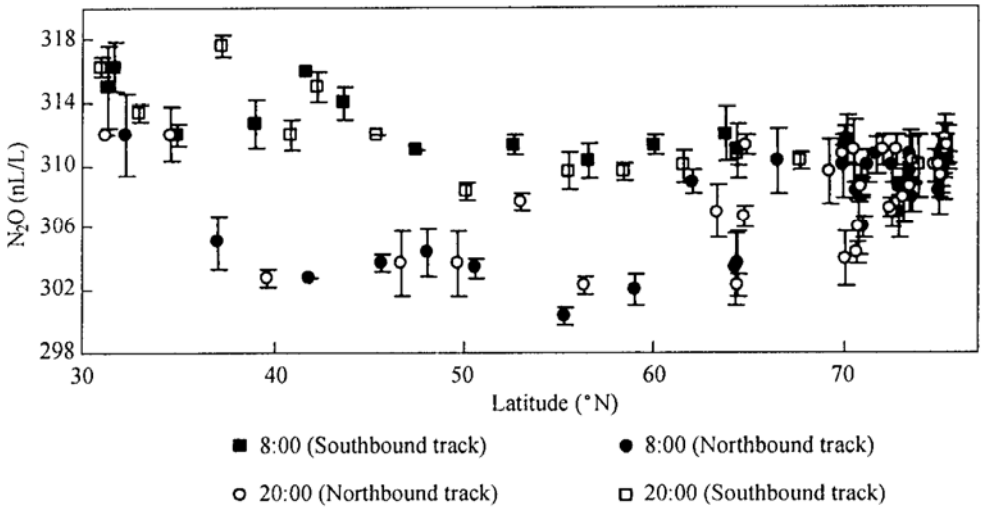


Fig. 3 The comparisons of average $N_2O$ concentrations above oceanic surface at 8:00 AM and 20:00 PM.

### *3.3 Influencial factors of $N_2O$ concentrations above oceanic surface*

#### *3.3.1 Source analyses and assessment for atmospheric $N_2O$*

The concentrations for nss-$SO_4^{2-}$、$SO_4^{2-}$、MSA、$Cl^-$、$Na^+$ in atmospheric aerosol were also observed. The correlations were analyzed between average $N_2O$ concentrations and the content of these aerosol compositions in the ranges of corresponding latitudes. The weak correlations were observed between $N_2O$ concentrations and the content of $Na^+$、$Cl^-$ (Fig. 4a and Fig. 4b), indicating that atmospheric $N_2O$ had different sources. However, the negative correlation was significant between $N_2O$ and MSA (Fig. 4c). Study showed that biogenic sulfur in atmospheric aerosol above oceanic surface was mainly from nss-$SO_4^{2-}$ and MSA, which were produced by the processes of biological oxidation of marine Dimethyl sulfide (DMS). DMS production in oceans has been seen to covary with biological activity. $N_2O$ production in oceans is also related to biological activity, particularly microbial metabolism (Elkins and Wofsy 1978; Collins *et al.* 1996). However, $N_2O$ can accumulate in the marine boundary layer for days, while DMS has a lifetime of less than a day

in the marine boundary layer, which means that DMS is not a perfect tracer for determining the $N_2O$ source from the oceans. MSA production by DMS is related with the productivity for marine organisms and their activities and MSA is more stable in the marine boundary layer (Gao *et al.* 1996). Therefore MSA is a more rational tracer for determining the $N_2O$ source for the oceans. The negative correlation indicates that atmospheric MSA and $N_2O$ have the different sources and $N_2O$ is an artifact of the continental sources. The positive correlation between $N_2O$ and nss-$SO_4^{2-}$/MSA、$SO_4^{2-}$、nss-$SO_4^{2-}$ are also obtained, indicating that the emissions from the continental sources have a great contribution to atmospheric $N_2O$ above oceanic surface. Anthropogenic sources from Eur-Asian continent may have an important effect on $N_2O$ concentration above oceanic surface. The concentrations significantly increased while the expeditionary ship approached Shanghai harbor on the cruise. $N_2O$ concentrations in the range of 30-35°N were higher than those in the other areas above oceanic surface (Fig. 2), 3-5 nL/L higher than the areas approaching Arctic ices (Table 1). In addition, the concentrations in Shanghai harbor were also significantly higher than those at Arctic ice stations and floating ices (Table 2). The average $N_2O$ concentration for three different sites in Shanghai harbor was 315.1 ±2.5 nL/L. The averages for ice stations and floating ice were 307.2 ±1.4 nL/L and 306.2 ±0.7 nL/L, respectively, 7.9 nL/L and 8.9 nL/L lower than that in Shanghai harbor, further suggesting that continental sources may have a significant contribution to the global atmospheric $N_2O$.

Table 1. The comparisons of atmospheric mean $N_2O$ concentrations in the ranges of different latitudes for the cruise and Antarctic Fildes Peninsula.

| Latitudinal range | Sampling areas | Mean $N_2O$ concentration for Northbound track (nL/L) | Mean $N_2O$ concentration for southbound track (nL/L) | The cruise (nL/L) |
|---|---|---|---|---|
| 31 ~ 35°N | East China Sea | 312.0 ±1.9 | 314.6 ±2.4 | 314.3 ±2.6 |
| 35 ~ 45°N | Japanese Ssea | 303.6 ±1.9 | 313.3 ±1.8 | 309.2 ±5.2 |
| 45 ~ 55°N | | 304.4 ±1.9 | 310.5 ±1.5 | 306.5 ±3.6 |
| 55 ~ 65°N | Bering Sea | 304.1 ±3.3 | 310.6 ±1.3 | 307.2 ±4.0 |
| 65 ~ 70°N | Chukchi Sea<br>Canadian oceanic basin | 307.9 ±1.5 | 309.7 ±1.2 | 308.1 ±2.9<br>309.9 ±1.6 |
| 70 ~ 77°N | Areas approaching Arctic ices<br>Ice stations and floating ices | 309.3 ±2.3 | 309.8 ±1.3 | 307.2 ±1.4<br>307.2 ±1.7 |
| 31 ~ 77°N | The cruise | 308.0 ±3.5 | 311.9 ±2.5 | 309.0 ±3.9 |
| 62°12′S | Antarctic Fildes Peninsula | | 310.7 ±4.4 | |
| 62°12′S | Antarctic Nelson Icecap | | 308.0 ±0 | |

Note: The data for atmospheric $N_2O$ concentrations in Antarctica are from Sun *et al.* (2001).

Table 2. Comparisons of atmospheric $N_2O$ concentrations at Shanghai harbor, ice stations and floating ices.

| Sampling area | Latitude | Longitude | Average $N_2O$ concentration (nL/L) |
|---|---|---|---|
| Shanghai harbor 1 | 31°14.4′N | 123°14.48′E | 312.0 ±0 |
| Shanghai harbor 2 | 30°59.45′N | 122°26.38′E | 316.0 ±0.6 |
| Shanghai harbor 3 | 31°23.38′N | 121°36.1′E | 317.3 ±0.6 |
| Ice station 1 | 73°6.05′N | 165°22.48′W | 306.3 ±0.6 |
| Ice station 2 | 73°24.93′N | 164°54.05′W | 308.7 ±1.2 |
| Ice station 3 | 73°27′N | 165°1.8′W | 306.7 ±1.2 |
| Floating ice 1 | 73°25′N | 158°57′W | 306.3 ±1.2 |
| Floating ice 2 | 73°28.13′N | 158°56.97′W | 305.7 ±0.6 |
| Floating ice 3 | 72°28′N | 155°30.03′W | 306.7 ±0.6 |
| Floating ice 4 | 72°26.20′N | 153°29.42′W | 306.0 ±0.6 |

Note: Sampling numble n = 3

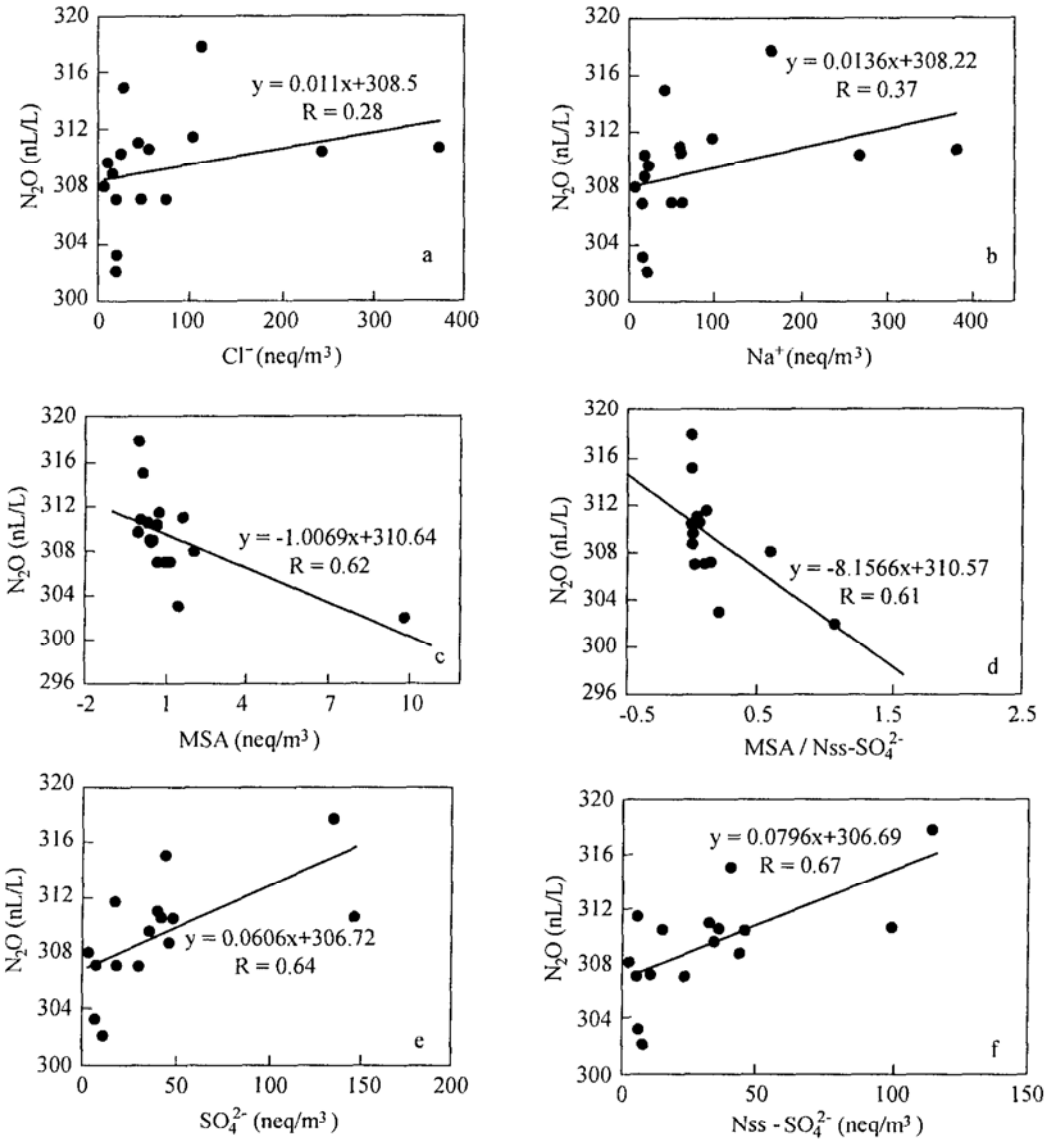


Fig. 4. The identification of atmospheric $N_2O$ sources above the oceanic surface. Note: The data for $N_2O$ concentrations are the average values corresponding to the same latitudinal rang of the aerosol compositions.

### *3.3.2 The relationship between the distribution of $N_2O$ concentrations and air pressure, air temperature above oceanic surface*

The distribution of atmospheric $N_2O$ concentration may be related with air pressure above the oceanic surface. Air pressure was lower in the range from 30-35°N, but the $N_2O$ concentrations were the highest, which was mainly related with anthropogenic emissions because the sampling sites approached the continent. However, $N_2O$ concentrations and air pressure had a good corresponding relationship in the range from 35-70°N where their changing trends were generally consistent, only a few values existing in advancing or lagging response while their changes were relatively smaller in the range from 70-77°N (Fig. 5a and

Fig. 5b). Therefore air pressure may be one of the main factors affecting atmospheric $N_2O$ concentrations above mid-and high-latitude oceanic surface. The movement of atmospheric circumfluence is controlled by polar high pressure and subpolar low pressure in the Arctic areas approaching the sea ice. The areas from 65°N to 77°N were located in the confluent zone of prevailing western wind and polar eastern wind and $N_2O$ strong exchange in marine boundary layer may occur, which was responsible for the increased $N_2O$ concentrations.

The solubility for $N_2O$ increases in the seawater under the conditions of low air temperature, which prevents $N_2O$ in deeper water from diffusing and transferring to the surface water, therefore its exchanging amount decreases at the interface between the ocean and atmosphere (Butler *et al.* 1989). Therefore atmospheric $N_2O$ concentration is indirectly affected by air temperature. Higher $N_2O$ concentration may be related with the emissions from oceanic sources as a result of high air temperature in the range of 30-35°N besides the effects of continental sources. The variations of $N_2O$ concentration and air temperature above the oceanic surface were generally simultaneous in the range of 40-60°N, especially for the southbound track (Fig. 5c and Fig. 5d). The changes of air temperatures above the oceanic surface were consistent on the northbound and southbound tracks, suggesting the effects of ocean on the air temperatures. However $N_2O$ concentrations were significantly different, indicating that they were influenced by other environmental factors.

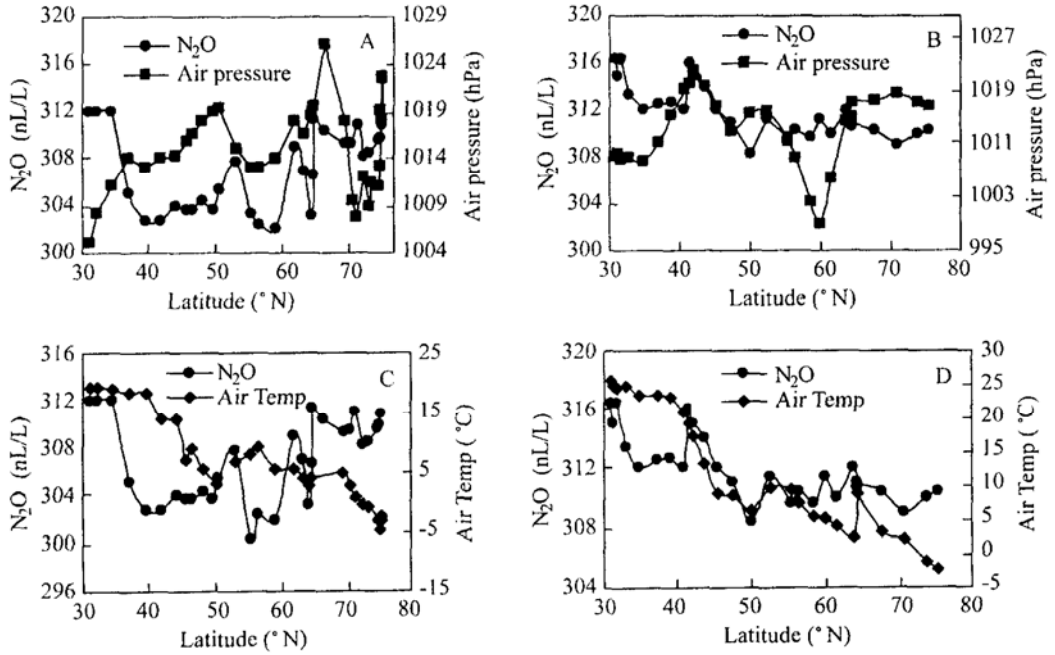


Fig. 5 The changing relationships between atmospheric average $N_2O$ concentration, air pressure and temperature above the oceanic surface with the latitude. Fig A and C indicate the northbound track and Fig B and D southbound track.

## 4 Conclusions

On the cruise of "Xuelong" expeditionary ship, atmospheric average $N_2O$ concentra-

tion was 309.0 ±3.9 nL/L above the surface from mid- and high-latitude Northern Pacific Ocean to Arctic ocean. Atmospheric average $N_2O$ concentrations in Arctic ocean, at ice stations and floating ices were 309.3 ±2.3 nL/L, 307.2 ±1.4 nL/L and 306.2 ±0.7 nL/L, respectively. $N_2O$ concentrations were significantly different in the same latitudinal area of Northern Pacific Ocean on the northbound and southbound. In addition, the distribution of atmospheric $N_2O$ concentration was related with the effects of continental sources, air temperature and pressure.

**Acknowledgments** Acknowledgements We would like to thank the Polar Office of the National Oceanic Bureau of China and members on "Xuelong" expeditionary ship for support and assistance. This study was supported by the Knowledge Innovation Project of CAS (No. KZCX2-302) and the National Natural Science Foundation (Grant No. 40076032).

## References

Butler JH, Elkins JW, Thompson TM(1989): Tropospheric and dissolved $N_2O$ of the West Pacific and East Indian Oceans During the EI Nino Southern Oscillation Event of 1987. J. Geophys. Res., 94(14): 865 - 14877..

Cohen Y, Gordon LI (1979): Nitrous oxide production in the ocean. J. Geophys. Res., 84:347 - 353.

Collins JrJE, Sachse GW, Anderson BE, Harris RC, Bartlett KB, Sandholm S, Wade LO, Burney LG, and Hill GF (1996): Airbone nitrous oxide observations over the western Pacific Ocean: September-October 1991. J. Geophys. Res., 101:1975 - 1984.

Elkins JW *et al.* (1978): Aquatic sources and sinks for nitrous oxide, Nature, 275: 602 - 606.

Gao YR, Arimoto RAD, Chen LQ, Zhou MY, Gu DY (1996): Atmospheric non-sea-salt sulfate, nitrate and methanesulfonate over the Chinese Sea. J. Geophys. Res., 101(1):2601 - 12611.

IPCC (1990): Climate Change, The IPCC Scientific Assessment. Edited by Houghton J T, Jenkins GJ and Ephraums JJ, New York: Cambridge Univ Press.

Kondo Y *et al.* (1999): NOy-$N_2O$ correlation observed inside the Arctic vortex in February 1997: Dynamical and chemical effects, J. Geophys. Res., 104, 8215 - 8224.

McElroy MB, Wofsy SC (1986): Tropical forests: Interactions with the atmosphere, In Tropical Rain Forests and World Atmospheres. Edited by France GT, Boulder, Colo: Westview Press, 33 - 60.

Moiser *et al.* (1997): Impact of agriculture on soil consumption of atmospheric CH4 and $N_2O$ flux in subarctic, temperate and tropical grasslands. Nutrient Cycling in Agroecosystems, 49:71 - 83.

Newell RE *et al.* (1996): Atmospheric sampling of super-typhoon Mireille with the NASA DC-8 aircraft on September 27, 1991, during PEM-West A. J. Geophys. Res., 101(D1): 1853 - 1871.

Ramanathan V (1988): The greenhouse theory of climate change: A test by an inadvertent global experiment, Science, 240: 293 - 299.

Singh HB, Salas LJ, Shigeishi H (1979): The distribution of nitrous oxide ($N_2O$) in the global atmosphere and the Pacific Ocean. Tellus, 31(4): 313 - 320.

Strahan SE, Loewenstein M, Podolske JR (1999): Climatology and small-scale structure of lower stratospheric $N_2O$ based on in situ observations, J. Geophys. Res., 104: 2195 - 2208.

Sun LG, Xie ZQ, Zhao JL, Xing GX, Shi SL, Du LJ (2000): Monitoring the concentration of $N_2O$ in the Fildes Peninsula, maritime Antarctica. Chinese Science Bulletin, 45(21): 2000 - 2004.

Sun LG, Zhu RB, Yin XB, Zhao JL, Xing GX, Shi SL, Du LJ (2001): Contrast between nitrous oxide concentrations in Antarctic Fildes Peninsula in 1999 and 2000 summers, Chinese Journal of Polar Research, 13(2): 83 - 90 (in Chinese).

Xie ZQ, Sun LG, Wang JJ, Liu BZ (2002): A potential source of atmospheric sulfur from penguin colony emissions, J. Geophys. Res., 107 (D22): 4617 - 4626.

Xing GX (1998): $N_2O$ emission from cropland in China. Nutrient Cycle in Agroecosystem, 52: 249 – 254.

Xing GX, Zhu ZL (1997): Preliminary studies on $N_2O$ emission fluxes from upland soil and paddy soils in China. Nutrient Cycle in Agroecosystems, 49: 249 – 254.

Zhu RB, Sun LG, Liu XD (2003): Atmospheric nitrous oxide observations above the oceanic surface during CHINARE-18, Progress in Natural Science, 13 (8): 615 – 619.