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Emission and Flux of DMS from the Australian Antarctic and Subantarctic Oceans during the 1988/89 Summer

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Abstract. DMS emissions and fluxes from the Australasian sector of the Antarctic and Subantarctic Oceans, bound by 46–68° S and 65.5–142.6° E, were determined from a limited number of samples ($n = 32$) collected during three summer resupply voyages to Australian Antarctic continental research bases between November 1988 and January 1989 (a 92 day period). The maximum DMS emission from this sector of the Antarctic Ocean was in an area near the Antarctic Divergence (60–63° S) and the minimum DMS emission was from the Antarctic coastal and offshelf waters. The greatest emission of DMS from this sector of the Southern Ocean was from the Subantarctic waters. DMS flux from the Australasian Antarctic Ocean was 64.3×10^6 (± 115) mol d^{-1} or 5.9 (± 10.6) $\times 10^9$ mol based on an emission of 10.9 (± 19.5) μmol m^{-2} d^{-1} ($n = 26$). The flux of DMS from the Australasian sector of the Subantarctic Ocean was probably twice the flux of DMS from the adjacent Antarctic Ocean.

Key words: DMS, emission and flux, Australasian Antarctic and Subantarctic Oceans.

1. Introduction

The global average DMS emission varies from 0.5–5.5 μmol m^{-2} d^{-1}, based predominantly on samples taken from middle and lower latitudes of the Atlantic and Pacific Ocean (Andreae, 1986; Andreae, 1990). The emission of DMS from the Antarctic Ocean during the austral summer is estimated to be 12.3 μmol m^{-2} d^{-1} calculated according to the seasonal ratios between the (column integrated) primary productivity (Berresheim, 1987). Based on the extrapolation of regional and seasonal fluxes for the North Pacific Ocean, the marine biogenic flux of DMS into the atmosphere is $0.5 \pm 0.33 \times 10^{12}$ mol $year^{-1}$ (Bates *et al.*, 1987; Bates *et al.*, 1990; Bates *et al.*, 1992). At present, 14% of the total marine biogenic flux is estimated to come from the Antarctic Ocean (Berresheim, 1987).

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The purpose of this work was to determine the emission and flux of DMS from the Australasian Antarctic and Subantarctic Ocean, bound between 46–68° S and 65.5–142.6° E during the austral summer of 1988/89 using DMS concentrations from McTaggart and Burton (1992), wind speeds and seawater temperatures measurements. Sampling was carried out during transects in the Australasian Antarctic Ocean adjacent to the Prydz Bay region and during a transect across the Australasian Southern Ocean. In this work, the Southern Ocean is defined as being the water masses between 40° S and the Antarctic continent in agreement with Berresheim (1987). The Antarctic Convergence (AC) divides the Southern Ocean into the Subantarctic and Antarctic Oceans. The Antarctic Ocean is further subdivided by the Antarctic Divergence (AD) (Deacon, 1982). The Antarctic Convergence in the Australasian Southern Ocean is located around 53° S (Edwards and Emery, 1982; Nagata *et al.*, 1988). DMS emission has units of μmol m^{-2} d^{-1} and DMS flux has units of mol d^{-1} (Bates *et al.*, 1992).

2. Sampling and Method

Seawater samples were collected on three resupply voyages to Australian Antarctic stations on the 6 November, between 17–20 December and, between 15–24 January of 1988/89 (see Figure 1). In brief, samples were collected from the stern of the ship using a lead weighted plastic bucket. A sub-sample was placed unfiltered into a high density polyethylene bottle containing 0.1 w/v $HgCl_2$ and stored in the dark at 0 °C. Samples (10 ml) were analysed for DMS at the laboratory at Davis station, Australian Antarctic Territories, using a purge and cryogenic trap GC/FPD method. A discussion of the influence of sample handling on the stability of DMS during storage and details of the analytical procedure are contained in McTaggart and Burton (1992). Experimental results from a comparison of preserved and unpreserved samples taken at an Antarctic coastal water site in January 1989 during a bloom of the colonial alga *Phaeocystis pouchetii* suggest that there was no significant difference in DMS concentration between preserved and unpreserved samples using our sample preservation and storage method (see Table I). The overall sample error for our sample handling including the analytical errors is ±17% (McTaggart and Burton, 1992). Only one sample was taken in open water in November before the pack ice was entered and likewise, in December only four samples were taken. In January, all samples were taken from the open water. The temperature of the seawater in the bucket was measured using a mercury thermometer graduated to ±0.05 °C. Wind speed was taken from the ship's bridge anemometer (uncertainty not known).

3. Results

A total of 32 samples were taken in open seawater and measured for DMS concentration. The position of each sample, the date and the concentration of DMS in

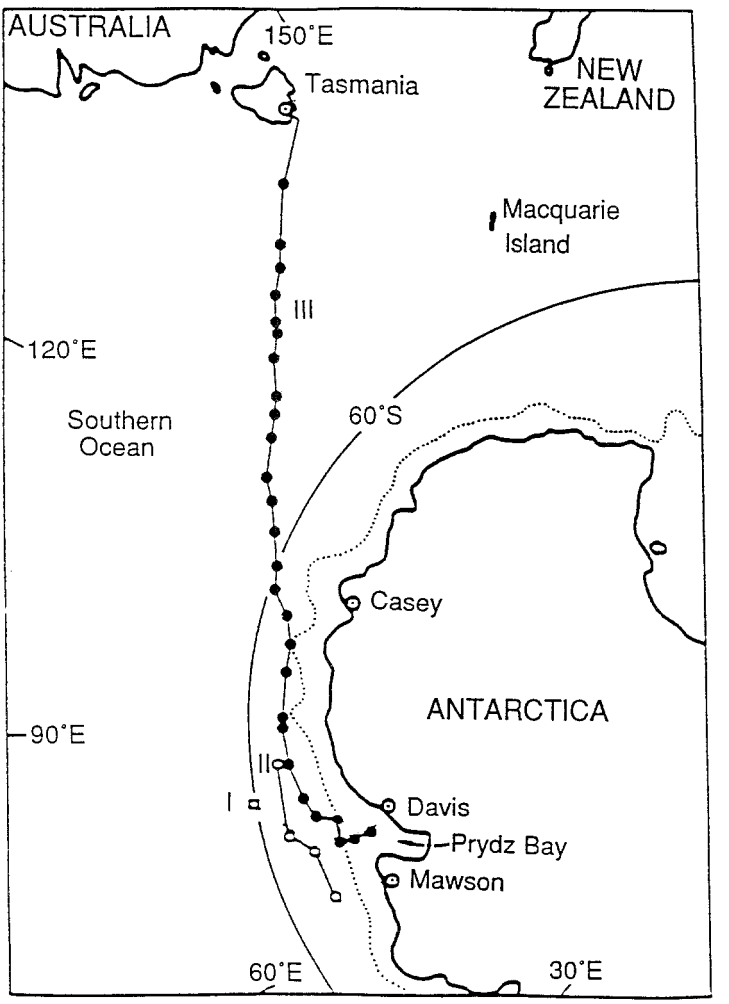

Fig. 1. Map of DMS sampling locations and voyage tracks in the Australasian sector of the Southern Ocean during the austral summer 1988–1989. Voyage I (squares), 6 November; Voyage II (open circles), 17–20 December; Voyage III (solid circles), 15–24 January. The continental shelf edge is shown by the dotted line.

TABLE I. Average DMS concentration (nM) in samples[a] with and without $HgCl_2$ added

Sample	Depth (m)	With $HgCl_2$	Without $HgCl_2$
3/1/89 ($n = 3$)	5	196 ± 11	203 ± 9
17/1/89 ($n = 3$)	15	189 ± 8	203 ± 13

[a] Samples were taken at an inshore site 10 km north of Davis station (68°31.8′ S 77°47.9′ E) and stored unfiltered in the dark for about 24 hr at –1 °C.

each sample are shown in Table II. The emission (F) can be estimated from gas exchange models (Liss, 1973) which assumes that the emission (F) of the gas is proportional to the difference between its concentration in the surface water C_w and its equilibrium solubility concentration, i.e. $F = K_w(C_a/H - C_w)$, where K_w is the piston (or transfer) velocity across the interface, C_a is the gas concentration above the water surface, and H the dimensionless Henry's constant. For the sea to air emission of DMS, this equation can be reduced to $F = -K_w c_w$, since the ocean is supersaturated with DMS compared to the boundary layer (Barnard *et al.*, 1982; Andreae and Raemdonck, 1983) therefore $C_a/H \ll C_w$ is always fulfilled.

The piston velocity K_w can be determined by using the following three relationships (Nguyen *et al.*, 1990)

$$K_w = 0.17[A(T)]^{-2/3}u \tag{1}$$

for wind speed $u \leq 3.6$ ms^{-1},

$$K_w = 0.17[A(T)]^{-2/3}u + 2.68[A(T)]^{-1/2}(u - 3.6) \tag{2}$$

for wind speed $3.6 \leq u \leq 13$ ms^{-1}

$$K_w = 0.17[A(T)]^{-2/3}u + 2.68[A(T)]^{-1/2}(u - 3.6) + 3.05[A(T)]^{-1/2}(u - 13) \tag{3}$$

for wind speed $u > 13$ ms^{-1},
which are derived from the three relationships, K_w versus wind speed u, of Liss and Merlivat (1986) obtained from laboratory experiments (Broecker *et al.*, 1978; Merlivat and Memery, 1983) and from 'in situ' experiments using different tracers such as Radon, SF_6 (Peng *et al.*, 1979; Wanninkhof *et al.*, 1985).

In Equations (1)–(3), $A(T)$ is the ratio of $Sc_T/Sc_{(20)}$, where $Sc_{(T)}$ is the Schmidt number of DMS at T °C and $Sc_{(20)}$ is the Schmidt number of CO_2 at 20 °C (equal to 595 (Liss and Merlivat, 1986)). The Schmidt number, Sc, is defined as the ratio of v/D, where v is the kinematic viscosity and D is the molecular diffusivity. Both v and D are a function of temperature, and so is Sc, and is computed using the diffusivity data of Saltzman *et al.* (1993). We note that a large uncertainty exists in the calculation of the exchange coefficient and that different approaches can give results differing by a factor of 1.8 (Erickson *et al.*, 1990). The uncertainty in wind speed measurements may also be large as there was no calibration available for the ship's anemometer.

Wind speeds and water temperature were measured throughout each voyage and shown in Table III. Based on seawater temperature change, the Antarctic Convergence was crossed at 53.3° S and the Antarctic Divergence was crossed at 62.0° S as observed also in previous reports made in the same water masses (Edwards and Emery, 1982; Smith *et al.*, 1984; Nagata *et al.*, 1988). The calculated DMS diffusivity, DMS piston velocities and DMS emissions are shown in Table III.

The wind speeds measured across the Australasian Antarctic and Subantarctic Ocean in 1988/89 are shown in Figure 2. High wind speeds were measured between

TABLE II. Sample date, location and concentration of DMS[a]

Sample number	Sample date	Location		DMS (nmol) C_w
		Lat. °S	Long. °E	
1	6.11.88	60.0	81.35	6.2
2	17.12.88	61.45	86.06	24.8
3	18.12.88	61.27	76.32	12.9
4	19.12.88	63.56	71.28	1.9
5	20.12.88	64.13	65.50	1.9
6	15.1.89	46.43	142.56	25.9
7	15.1.89	48.59	139.41	20.0
8	16.1.89	49.56	138.05	28.2
9	16.1.89	50.57	136.17	17.5
10	16.1.89	51.54	134.19	17.4
11	17.1.89	52.21	133.37	14.3
12	17.1.89	53.21	131.42	4.7
13	17.1.89	54.51	128.46	5.2
14	18.1.89	55.23	127.01	3.4
15	18.1.89	56.11	124.27	0.8
16	18.1.89	57.18	120.44	4.0
17	19.1.89	58.03	118.19	3.4
18	19.1.89	58.52	115.33	4.0
19	19.1.89	59.59	111.35	6.3
20	20.1.89	60.29	108.41	4.2
21	20.1.89	61.42	105.46	26.9
22	20.1.89	62.15	101.57	14.0
23	21.1.89	62.21	98.13	18.5
24	22.1.89	62.35	92.02	20.3
25	22.1.89	62.30	90.48	6.8
26	22.1.89	62.51	86.03	23.2
27	23.1.89	63.48	80.33	3.1
28	23.1.89	64.16	77.58	7.7
29	23.1.89	65.51	77.01	15.8
30	24.1.89	65.43	74.02	11.7
31	24.1.89	66.57	73.54	16.1
32	24.1.89	68.14	74.23	121.7

[a] Taken from McTaggart and Burton (1992).

52 to 54° S averaging 16 m s^{-1} while further north near southern Tasmania and further south between 55 and 59° S, the winds decreased to less than 2.5 m s^{-1}. Wind speed increased up to 12 m s^{-1} crossing the Antarctic Divergence between 60 and 62° S, before decreasing to 2.5 m s^{-1} in the shallower waters of Prydz Bay.

TABLE III. Wind speed and water temperature mesurements and, calculated DMS diffusivity, piston velocity (K_w) and emission for seawater samples taken during the austral summer of 1988/89 in the Australasian sector of the Southern Ocean

No.	Wind speed ($m\ s^{-1}$)	Water temp. (°C)	DMS diffusivity ($\times 10^{-5}\ cm^2\ s^{-1}$)	Piston velocity K_w ($cm\ h^{-1}$)	DMS emission ($\mu mol\ m^{-2}\ d^{-1}$)
1	12.7	−1.8	0.65	11.7	17.4
2	12.3	−0.6	0.68	11.6	68.8
3	6.0	−0.7	0.67	3.3	10.3
4	5.0	−1.4	0.66	2.0	0.9
5	1.0	−1.5	0.66	0.1	<0.1
6	1.2	14.3	1.02	0.1	0.8
7	1.2	10.9	0.93	0.1	0.5
8	10.0	10.2	0.92	11.6	78.6
9	10.0	9.6	0.90	11.4	48.1
10	10.0	8.7	0.88	11.1	46.5
11	16.0	8.7	0.88	32.3	111.0
12	16.0	6.9	0.84	30.7	34.4
13	16.0	6.6	0.83	30.4	37.6
14	2.5	6.9	0.84	0.2	0.2
15	2.5	6.6	0.83	0.2	<0.1
16	2.5	5.6	0.81	0.2	0.2
17	2.5	4.8	0.79	0.2	0.2
18	2.5	4.0	0.77	0.2	0.2
19	2.5	3.3	0.76	0.2	0.3
20	10.0	2.9	0.75	9.5	9.5
21	10.0	3.0	0.75	9.5	61.2
22	10.0	2.2	0.73	9.3	31.1
23	2.5	2.2	0.73	0.2	0.8
24	2.5	2.9	0.75	0.2	0.8
25	2.5	2.8	0.75	0.2	0.3
26	2.5	2.2	0.73	0.2	0.9
27	2.5	2.6	0.74	0.2	0.1
28	2.5	1.8	0.73	0.2	0.3
29	2.5	0.7	0.70	0.2	0.6
30	2.5	1.8	0.73	0.2	0.5
31	2.5	0.6	0.70	0.2	0.6
32	2.5	2.6	0.74	0.2	5.0

DMS emissions for all voyages ranged from <0.1–111.0 $\mu mol\ m^{-2}\ d^{-1}$ (see Figure 3). On the second and third voyages, sample locations between about 50 and 54.5° S and at the Antarctic Divergence (61.4–62.2° S), were affected by high wind

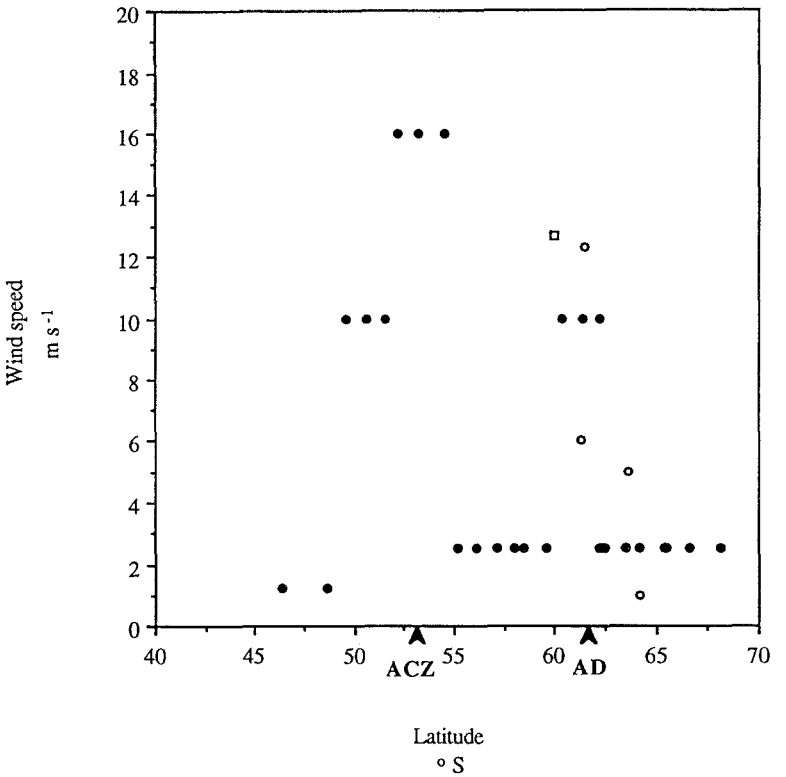

Fig. 2. Latitudinal change of wind speed (m s^{-1}) for all voyages during the summer of 1988/89. Voyage symbols same as Figure 1. ACZ: Antarctic Convergence Zone. AD: Antarctic Divergence.

speeds (> 10 ms^{-1}). DMS emissions were generally greater than 25 μmol m^{-2} d^{-1} in these regions. At 60.0–61.4° S, between November and January, the average DMS emission was 12.3 (±4.3, $n = 3$) μmol m^{-2} d^{-1}. During January, between 54.52–60.0° S, DMS emission was below 0.3 μmol m^{-2} d^{-1}. From 62.2° S to the Antarctic coast (ca. 68° S) during December and January, DMS emissions were less than 1.0 μmol m^{-2} d^{-1}.

4. Discussion

4.1. WIND SPEEDS IN THE AUSTRALASIAN ANTARCTIC AND SUBANTARCTIC OCEAN

Typically, there is a single sinusoidal wind speed trend across the Australasian part of the Southern Ocean (Taljaard and Van Loon, 1984). The January zonal geostrophic wind at sea level between 35°and 65° S, averaged between 20°and 115° E, has been shown to be at a maximum around 50° S at ca. 14 m s^{-1} decreasing to ca. 3 m s^{-1} at 35° S and ca. 1.5 m s^{-1} at 62° S. During the transects across

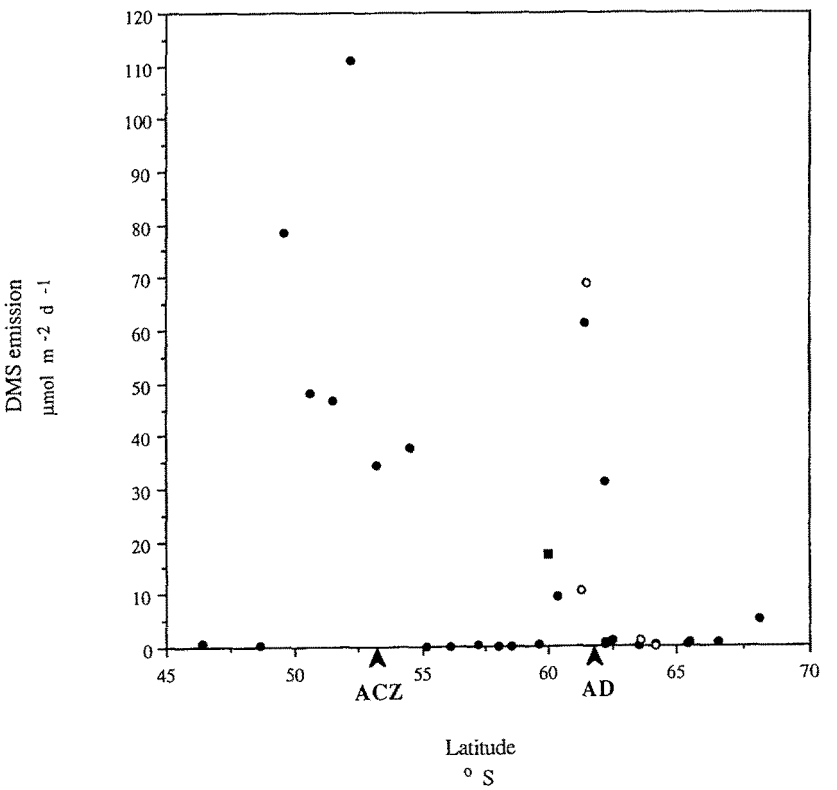

Fig. 3. Latitudinal change of the emission of DMS (μmol m^{-2} d^{-1}) for all voyages during the summer of 1988/89. Voyage symbols same as Figure 1. ACZ: Antarctic Convergence Zone. AD: Antarctic Divergence.

the Australasian Antarctic and Subantarctic Ocean between November 1988 and January 1989, the wind speeds showed two sinusoidal trends. The main difference compared to Taljaard and Van Loon (1984) was the shift to the south of the lower wind speed regions and the observed increase in wind speed at the Antarctic divergence.

4.2. EMISSION AND FLUX OF DMS FROM THE AUSTRALASIAN ANTARCTIC OCEAN

DMS emissions for the water masses of the Australasian Antarctic Ocean from November to January 1988/89 are shown in Table IV. The maximum DMS emission from the Antarctic Ocean during the summer of 1988/89 was at the Antarctic Divergence probably due to the high winds generated from the permanent low pressure trough in this region coupled with the higher productivity from upwelling. The minimum DMS emission was from the coastal and offshelf waters due to the light winds and the probable lack of DMS producing phytoplankton. Based on

TABLE IV. DMS emission and flux from the Australasian Antarctic Ocean (65.5°–142.6° E) from November to January, 1988/89

Region of the Antarctic Ocean	DMS emission[a] (μmol m^{-2} d^{-1})	Open ocean surface area[b] ($\times 10^6$ km^2)	DMS flux[a] 10^6 mol d^{-1}	DMS flux[a] 10^9 mol summer^{-1}
53–61° S open ocean	10.0 (±14.8) $n = 10$	3.9 (±0.2)	38.9 (±56.1)	2.6 (±4.4)
61–63° S Antarctic Divergence	21.8 (±28.7) $n = 8$	0.9	19.6 (±25.8)	1.6 (±2.1)
63–68° S offshelf waters and coastal waters	1.0 (±1.6) $n = 8$	1.1 (±0.5)	1.1 (±1.83)	0.1 (±0.2)

[a] Mean values, standard deviation in parenthesis, n = number of samples.
[b] Water area free from ice cover = ((long. East–long. West)/360) $\times$ $2\pi R^2$(sin(lat. North)–sin(lat. South)), where long. stands for longitude, lat. stands for latitude, R stands for radius of the earth.

these field measurements, the emission of DMS during the austral summer across the Australasian Antarctic Ocean [10.9 ± 19.5 μmol m^{-2} d^{-1} (n = 26)] agrees reasonably well with Berresheim (1987). The summer DMS flux from Antarctic waters north of AD (53–61° S) during November to January 1988/89 was an order of magnitude greater than from the Antarctic coastal and offshelf waters (see Table IV). On the other hand, the flux of DMS from the Antarctic Divergence in December and January, despite the much smaller surface area, was similar to Antarctic waters north of AD.

4.3. EMISSION AND FLUX OF DMS FROM THE AUSTRALASIAN SUBANTARCTIC OCEAN

High DMS emissions occurred in the Australasian Subantarctic Ocean transect coincident with strong winds (see Figures 2 and 3) and high DMS concentrations. Coccolithophores, DMS-producing phytoplankton, may contribute to the DMS concentrations as they were observed to increase in numbers to the north of the Antarctic Convergence on a transect from the Campbell Plateau (48° S) to the Antarctic continent (Rat'kova, 1987). This group of phytoplankton has been shown to produce high levels of the DMS precursor, dimethylsulfoniumpropiothetin (Keller *et al.*, 1989). The average DMS emission from the Subantarctic Ocean between 15–17 of January was 47.5 ± 43.3 μmol m^{-2} d^{-1} (n = 6). The average wind speed over these three days was around 8 ms^{-1}, a windspeed expected about 30% of the time during the summer over this region, i.e. one in three days (Taljaard and Van Loon, 1984). Assuming this represented the prevailing conditions in the Subantarctic Ocean, and the surface area of the Australasian Subantarctic Ocean between longitudes 65.5°to 142.6° E is ca. 8.5 $\times$ 10^6 km^2, then the estimated flux of DMS would be 12.1 ± 10.3 $\times$ 10^9 mol DMS. This suggests that,

during the 1988/89 summer, the flux of DMS from the Subantarctic Ocean could be as much as twice the DMS flux from the Antarctic Ocean.

5. Conclusion

A limited number of field measurements ($n = 32$) of DMS concentration, wind speed and seawater temperature taken during transects across the Australasian Antarctic and Subantarctic Oceans between November 1988 to January 1989 have been used to estimate the mean summer DMS emission and flux in this region. The maximum DMS emission was from the Antarctic Divergence (61–63° S) and the minimum DMS emission was from Antarctic coastal and offshelf waters. The flux of DMS from the Australasian Antarctic Ocean for the 1988/89 summer was about 1.2 ($\pm$2.3)% of the annual global biogenic flux of DMS and supports the recent DMS flux estimate in this region of the Southern Ocean (Bates *et al.*, 1992). The flux of DMS from the Subantarctic Ocean in this region was probably twice the flux from adjacent Antarctic waters.

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