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Water soluble dicarboxylic acids and related compounds in Antarctic aerosols

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Abstract. Antarctic aerosols collected at Syowa Station were studied for water soluble organic compounds by employing a water extraction and dibutyl ester derivatization and using a capillary gas chromatography (GC) and GC/mass spectrometry (GC/MS). Total carbon and nitrogen were also determined. A homologous series of α,ω -dicarboxylic acids (C₂-C₁₁), ω -oxocarboxylic acids (C₂-C₉), and α -dicarbonyls (C₂-C₃) were detected, as well as pyruvic acid and aromatic (phthalic) diacid. Succinic (C₄) or oxalic (C₂) acid was found to be the dominant diacid species, followed by azelaic (C₉), adipic (C₆), or malonic (C₃) acid. Concentration range of the total diacids was 5.9-88 ng m⁻³, with an average of 29 ng m⁻³. Highest concentrations were observed in the summer sample with a predominance of succinic acid (61.5 ng m⁻³), which comprised approximately 70% of the total diacids and accounted for 3.5% of total aerosol carbon (1020 ng m⁻³). The succinic acid (C₄) is likely produced by photooxidation of 4-oxocarboxylic acids, which are present in the atmosphere as intermediates of the photooxidation of unsaturated fatty acids. These results indicate that the Antarctic organic aerosols originate from marine-derived lipids and are transformed largely by photochemical oxidations. ω -Oxocarboxylic acids (C₂-C₉, 0.36-3.0 ng m⁻³) also showed the highest concentration in the summer sample, again suggesting a secondary production in the atmosphere of the Antarctic and in the Southern Ocean.

Introduction

Antarctica is the continent surrounded by the Southern Ocean, in which long-range atmospheric transport of anthropogenic pollutants is insignificant, whereas natural sources such as seawaters are important contributors to the marine aerosols through sea/air interaction. This is in contrast to the Arctic, which is surrounded by the Eurasian and North American continents and is a cold sink for anthropogenic organic and inorganic materials transported long distance through the atmosphere from midlatitudes [Barrie, 1986; Barrie

and Barrie, 1990]. In analogy, midlatitudinal aerosols in the southern hemisphere may also be transported to the far south and deposited on the Antarctic ice sheet. Thus the chemical species stored in an ice core, from which past atmospheric information can be reconstructed [Delmas, 1992], are largely dependent on the aerosol chemical composition in the Antarctic region. Antarctic aerosols have been studied mostly for inorganic constituents [e.g., Itoh, 1989], and there are very few studies on the organic chemistry.

In a previous study [Nishikiori *et al.*, 1996], we analyzed Antarctic aerosols for the distributions of solvent extractable fatty acids and related lipid compounds. Their molecular distributions showed that the Antarctic aerosols are largely contributed from biological sources; however, labile compounds such as unsaturated fatty acids are depleted, and photochemical reaction products such as nonanoic acid and azelaic acid are abundantly detected. Although this study showed a significant photochemical transformation of the organic aerosols in the Antarctic region, water soluble organic compounds such as small diacids (e.g., oxalic acid) were

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not determined due to the limitation of the methodology used (solvent extraction and methyl ester derivatization).

Oxalic, malonic, and succinic and other dicarboxylic acids are ubiquitous organic aerosol constituents in the urban, marine, and Arctic atmosphere [e.g., Grosjean *et al.*, 1978; Norton *et al.*, 1983; Kawamura and Kaplan, 1987; Li and Winchester, 1993]. In the midlatitudes, their concentrations show a diurnal distribution with a daytime maximum [Satsumabayashi *et al.*, 1990; K. Kawamura and O. Yasui, unpublished results, 1990] and increase in the summer of the year [Kawamura and Ikushima, 1993]. On the contrary, in the Arctic atmosphere, the diacids show a concentration maximum in early April as a result of enhanced photochemical production at a polar sunrise [Kawamura *et al.*, 1995a]. Photochemical oxidations of anthropogenic hydrocarbons and biogenic organic matter are the sources of atmospheric dicarboxylic acids [Grosjean *et al.*, 1978; Hatakeyama *et al.*, 1985, 1987; Yokouchi and Ambe, 1986; Kawamura and Gagosian, 1987; Kawamura and Ikushima, 1993], as well as direct emission from internal combustion engines [Kawamura and Kaplan, 1987]. Thus dicarboxylic acids accumulate in the aerosols and account for up to 1.1% of the total aerosol carbon in the urban Tokyo atmosphere [Kawamura and Ikushima, 1993], 9.1% in the Arctic atmosphere (K. Kawamura *et al.*, manuscript in preparation, 1996), and 15% in the remote Pacific atmosphere (F. Sakaguchi and K. Kawamura, High abundance of oxalic and malonic acids in the remote marine aerosols from equatorial to western North Pacific, submitted to *Geophysical Research Letters*, 1996 (hereinafter referred to as Sakaguchi and Kawamura, submitted manuscript, 1996)).

In this paper, we studied Antarctic aerosol samples for low molecular weight dicarboxylic acids, ketocarboxylic acids, and α -dicarbonyls using gas chromatography and mass spectrometry. The aerosols were also analyzed for total carbon and nitrogen contents. Here we present molecular distributions of these water soluble organic compounds and a large increase of their concentrations during summertime. We also discuss the source of the dicarboxylic acids in the Antarctic aerosols, in comparison with their molecular distributions in the Arctic and in the northern hemisphere.

Samples and Methods

Submicron aerosols ($<0.7 \mu\text{m}$) were collected at Syowa Station ($69^{\circ}00'$, $39^{\circ}35'$; altitude, 21 m) in February to December 1991 using a high-volume impactor sampler (Kimoto model CPS-105) on a precombusted (450°C , 3 hours) quartz fiber filter (Pallflex, $20 \text{ cm} \times 25 \text{ cm}$). Larger aerosols ($>0.7 \mu\text{m}$) were collected only for X ray microanalyses and were not available in this study. Air sample volumes were 2000–2600 m^3 . Filters were stored in a clean glass jar with a Teflon-lined screw cap before and after air sampling. Aerosol filters were stored at -20°C prior to analysis.

The filter samples and field blank were analyzed by the method of Kawamura and Ikushima [1993] and

Sempéré and Kawamura [1994]. Briefly, an aliquot of the filters was extracted for low molecular weight dicarboxylic acids and other water soluble organic compounds with pure water prepared by distillation after KMnO_4 oxidation of Mili Q water. The water extracts were concentrated using a rotary evaporator under vacuum and dried by a nitrogen blow down system. The diacids and related compounds were reacted with a 14% $\text{BF}_3/\text{n-butanol}$ at 100°C for 60 min to derive dibutyl esters for carboxyl group and dibutoxy acetal for aldehyde group. After the reaction, the derivatives were extracted with n-hexane, washed with pure water, and dissolved in 50 μL n-hexane.

Dicarboxylic acid dibutyl esters and related compounds were determined using a Hewlett Packard (HP 5890) gas chromatograph (GC) equipped with a split/splitless injector, a HP-5 fused silica capillary column ($0.32 \text{ mm ID} \times 25 \text{ m long}$, $0.52\text{-}\mu\text{m}$ film thickness) and an FID (flame ionization detector). Identification of the compounds was performed by comparing GC retention times of authentic $\text{C}_2\text{-C}_{11}$ diacid dibutyl ester standards. The identifications were confirmed by examination of mass spectra, which were obtained with a Finnigan MAT ITS40 GC/MS system. Mass spectral information of the compounds reported here are given elsewhere [Kawamura and Ikushima, 1993; Kawamura, 1993]. Recoveries of authentic diacids spiked to a quartz fiber filter were 71% for oxalic acid and better than 90% for malonic, succinic, and adipic acids. Part of the filter samples (approximately 20 cm^2) were cut off and subjected to an elemental analyzer (Yanagimoto model MT-3) for the measurement of total carbon and nitrogen contents [Sempéré and Kawamura, 1994].

Results and Discussion

Table 1 presents total carbon (TC) and total nitrogen (TN) contents for the Antarctic aerosol samples, as well as sampling dates, ambient temperature, and solar radiation. Concentration ranges of TC and TN were 440–1020 ng m^{-3} and 11–170 ng m^{-3} , respectively. The Antarctic aerosol TC contents (average 750 ng m^{-3}) are 1 order of magnitude lower than those (average 22,000 ng m^{-3}) of urban Tokyo aerosols, whereas the TN contents (average 56 ng m^{-3}) were 2 orders of magnitude lower than those (average 5,300 ng m^{-3}) of the Tokyo aerosols [Kawamura *et al.*, 1995b]. However, TC contents in the Antarctic aerosols are similar to or even higher than those of the Arctic aerosols from Alert (February to June 1991: 88–639 ng m^{-3} , average 359 ng m^{-3} (K. Kawamura *et al.*, manuscript in preparation, 1996). The Antarctic submicron aerosols showed very high C/N weight ratios of 36–89 for the autumn to winter samples (S2 and S3) and a high C/N ratio of 15 for the winter to spring sample (S4). However, the summer aerosols showed a C/N ratio of 6.0 (S5, see Table 1), which is similar to Redfield-Richards ratio (C/N weight ratio of 5.7 [Libes, 1992]). This suggests that the summer aerosols mainly originate from marine organisms. This is consistent with the predominance of C_{12} , C_{14} , C_{16} , and C_{18} monocarboxylic acids in the distributions

Table 1. Total Carbon and Total Nitrogen Contents in the Antarctic Aerosols from Syowa Station with Sampling Dates and Solar Radiation

	S2	S3	S4	S5
Sampling dates	March 19 to April 29, 1991	May 13 to June 9, 1991	Aug. 29 to Oct. 29, 1991	Nov. 28 to Dec. 31, 1991
Ambient temperature, deg	-10.7	-17.1	-17.8	-0.8
Solar radiation, MJ m ⁻²	6.5	0.6	28.9	58.0
Air volume, m ³	2457	2017	2643	2330
Total Carbon, ng m ⁻³	570	980	440	1020
Total Nitrogen, ng m ⁻³	16	11	29	170
C/N ratio	35.6	89.1	15.2	6.0

of lipids in the Antarctic summer aerosols [Nishikiori *et al.*, 1996]. The C/N ratios in the Antarctic aerosols are much greater than those of the urban atmosphere (approximately 2 [Kawamura *et al.*, 1995b]), where a gas to particle conversion of anthropogenic NO_x is significant.

A homologous series of α,ω -dicarboxylic acids (C₂-C₁₁), and aromatic acid (phthalic acid) were detected in the Antarctic aerosols, as well as ω -oxocarboxylic acids (C₂-C₆, C₈-C₉), α -ketoacid (pyruvic acid), and α -dicarbonyls (C₂-C₃), as shown in Figure 1. Among these water soluble compounds, dicarboxylic acids are the most abundant compound class (5.9-88.6 ng m⁻³, average 29 ng m⁻³), followed by ω -oxocarboxylic acids (0.70-3.05 ng m⁻³, average 1.4 ng m⁻³) and α -dicarbonyls (0.15-0.97 ng m⁻³, average 0.40 ng m⁻³) (see Table 2). Succinic (C₄) or oxalic (C₂) acid was found as the most abundant diacid species. The diacids with more carbon numbers are generally less abundant. The concentrations of the total diacids in the Antarctic aerosols are much lower than those of diacids in the urban aerosols from midlatitudes (90-1400 ng m⁻³, average 480 ng m⁻³ [Kawamura and Ikushima, 1993]) and marine aerosols from western North Pacific (20-1040 ng m⁻³, average 245 ng m⁻³, [Kawamura and Usukura, 1993]). However, their concentration levels are com-

parable to or even higher than those from the central North Pacific (16-53 ng m⁻³, average 35 ng m⁻³ [Kawamura and Usukura, 1993]).

Highest concentrations of the total diacids (88.6 ng m⁻³) were obtained in the summer aerosol sample (Table 2). In the summer sample, succinic acids (61.5 ng m⁻³) accounted for 69 % of the total diacids. Although succinic acid (C₄) has often been detected at a high concentration level in the continental aerosols, the predominance of this acid has not been obtained in the marine and continental atmosphere from the northern hemisphere [Kawamura and Usukura, 1993; Kawamura and Ikushima, 1993]. Previous studies showed that oxalic acid (C₂) is always the most abundant diacid and that relative abundances of succinic acid (C₄) are less than 8% of the total diacids [Kawamura and Ikushima, 1993; Kawamura and Usukura, 1993; Kawamura *et al.*, 1995a]. In contrast, the ice core samples from south Greenland showed a predominance of succinic acid [Kawamura and Yasui, 1991]. This suggests that C₄ diacid is produced from a specific source and reaction mechanism in the remote atmosphere free from pollution sources.

Although diacids with more carbon numbers are generally less abundant, azelaic acid (C₉) was detected as a relatively abundant species, and its highest concentration was observed in the summer sample. The C₉ diacid has been considered as a specific product in the photochemical oxidation of unsaturated fatty acids, which contain a double bond, predominantly at C-9 position [Yokouchi and Ambe, 1986; Kawamura and Gagosian, 1987]. Branched chain dicarboxylic acids such as methylmalonic (iso C₄) and methylsuccinic (iso C₅) acids were also detected; however, their abundances are far less than those of the corresponding straight chain diacids. Unsaturated diacids including maleic acid were detected in the aerosol samples as minor diacid species. In all the samples, the *cis* configuration is more abundant than the *trans* configuration. Aromatic (phthalic) acid was detected as a relatively abundant diacid. These diacids also showed the highest concentrations in the summer aerosols, suggesting that they are photochemically produced from aromatic structures which may be produced in the ocean and emitted to the atmosphere.

The diacid carbon concentrations in the total carbon (TC) contents ranged from 0.46% to 3.5% (average 1.35%). The highest value was obtained in the sum-

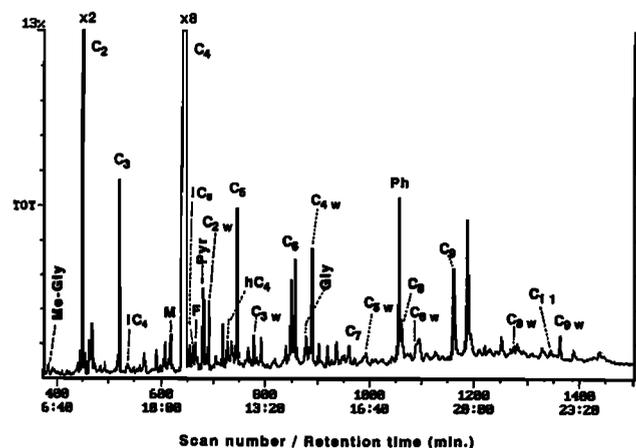


Figure 1. A reconstructed total ion chromatogram (TOT) of dicarboxylic acid dibutyl esters and related compounds isolated from the Antarctic submicron aerosols (S-5).

Table 2. Concentrations of Dicarboxylic Acids, Oxocarboxylic Acids, and α -Dicarbonyls in the Antarctic Aerosols Collected From Syowa Station in 1991

Compounds	Abbreviation	S2	S3	S4	S5
Dicarboxylic acids					
Oxalic (Ethanedioic)	C ₂	1.59	3.12	3.26	10.29
Malonic (Propanedioic)	C ₃	0.13	0.38	0.52	2.69
Methylmalonic	iC ₄	0.05	0.05	0.05	0.24
Maleic (<i>cis</i> Butenedioic)	M	0.19	0.38	0.18	0.96
Succinic (Butenedioic)	C ₄	0.63	5.77	1.18	61.53
Methylsuccinic	iC ₅	0.10	0.13	0.11	0.18
Fumaric (<i>trans</i> Butenedioic)	F	0.04	BDL	0.23	0.23
Methylmaleic	mM	BDL	BDL	0.06	BDL
Malic (Hydroxybutanedioic)	hC ₄	0.15	0.03	0.00	0.70
Glutaric (Pentanedioic)	C ₅	0.31	0.58	0.34	2.26
Adipic (Hexanedioic)	C ₆	0.49	0.85	0.33	1.81
Pimelic (Heptanedioic)	C ₇	0.46	0.52	0.23	0.94
Suberic (Octanedioic)	C ₈	0.21	0.28	0.21	0.96
Phthalic	Ph	0.92	1.68	0.87	2.61
4-Oxopimelic	C _{7,4-oxo}	BDL	0.41	0.09	0.53
Azelaic (Nonanedioic)	C ₉	0.55	1.09	0.30	2.22
Sebacic (Decanedioic)	C ₁₀	BDL	0.06	0.08	0.17
Undecanedioic	C ₁₁	0.14	0.10	0.04	0.28
Subtotal		5.96	15.43	8.08	88.60
ω-Oxocarboxylic acids					
Glyoxylic (Oxoethanoic)	C _{2ω}	0.22	0.30	0.36	0.38
3-Oxopropanoic	C _{3ω}	0.07	0.06	0.05	1.03
4-Oxobutanoic	C _{4ω}	0.18	0.28	0.19	1.00
5-Oxopentanoic	C _{5ω}	BDL	BDL	0.02	0.09
6-Oxohexanoic	C _{6ω}	0.08	0.39	0.01	0.11
7-Oxoheptanoic	C _{7ω}	BDL	BDL	BDL	BDL
8-Oxooctanoic	C _{8ω}	0.05	0.12	0.02	0.18
9-Oxononanoic	C _{9ω}	0.18	0.08	0.05	1.16
Subtotal		0.78	1.23	0.70	3.05
α-Ketoacid					
Pyruvic	Pyr	0.32	0.22	0.14	0.78
α-Dicarbonyls					
Glyoxal (Ethanedial)	Gly	0.05	0.05	0.16	0.08
Methylglyoxal	MeGly	0.10	0.10	0.81	0.23
subtotal		0.15	0.15	0.97	0.31
total		7.21	17.03	9.89	92.74

Values are in nanograms per cubic meter.

BDL, below detection limit (approximately 0.01 ng m⁻³).

mer aerosol sample, suggesting an enrichment of the diacids in the Antarctic aerosols by photochemical reactions. The relative abundance of diacid-carbon in the aerosol TC is much higher than those of urban aerosols from Tokyo (0.06-1.1%, average 0.46% [Kawamura and Ikushima, 1993]). The lower values in urban aerosols may be due to the abundant presence of elemental carbon. The diacid-C/TC ratios in the Antarctic aerosols are comparable to those of the Arctic aerosols collected from February to June at Alert (1.5-9.1%, average 3.6% (K. Kawamura et al., manuscript in preparation, 1996) and the remote marine atmosphere from central and North Pacific (1.2-16%, average 9.1% (Sakaguchi and Kawamura, submitted manuscript, 1996)). These results suggest that in the remote atmosphere, organic aerosol composition is largely controlled by photochemical reactions.

Solar radiation and ambient temperature showed maxima during the S-5 (summer) sample collection (Table 1). Figure 2 plots concentrations of major diacid-carbon and ω -oxoacid-carbon normalized by total aerosol carbon (TC) as a function of solar radiation. Oxalic (C₂) and malonic (C₃) acids showed a strong positive correlation with solar radiation ($r > 0.97$), suggesting that they are in situ produced in the atmosphere by photochemical reactions of precursor organics. Longer chain diacids greater than or equal to C₄ also showed positive correlation with solar radiation ($r = 0.73-0.94$), although confidence levels are relatively low. Abundant presence of succinic acid (C₄) in the Antarctic summer aerosols suggests that the C₄ diacid is produced by the photochemical oxidation of marine organic precursors, whose sea-to-air emission should be enhanced due to a retreat of sea ice near the Antarctic coasts. Concentrations of

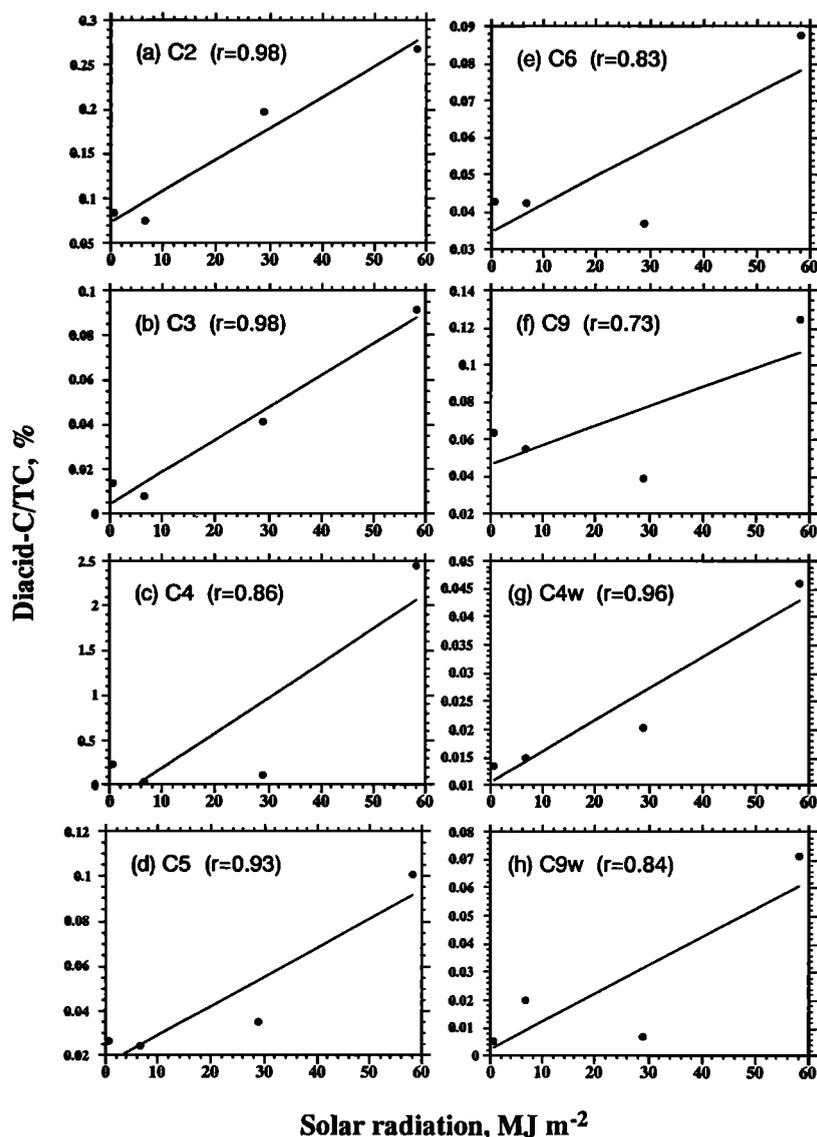


Figure 2. Relationships between concentrations of dicarboxylic acid-carbon and ω -oxocarboxylic acid-carbon normalized by total aerosol carbon contents (TC) and solar radiation in the Antarctic atmosphere. For abbreviations, see Table 2.

ω -oxocarboxylic acids ($C_{4\omega}$ and $C_{9\omega}$) in TC also positively correlate with the solar radiation. The highest values of both C_9 diacid and C_9 ω -oxoacid in the summer sample (Figure 2, Table 2) suggest that they are produced by the oxidation of particulate unsaturated fatty acids containing a double bond predominantly at C-9 position [Kawamura and Gagosian, 1987].

As a precursor of succinic acid, we consider that mid-chain oxocarboxylic acids with keto group at C-4 position are likely candidates. Homologous series of mid-chain ketocarboxylic acids with keto group at different positions have been reported in the remote marine aerosols from North Pacific [Kawamura and Gagosian, 1988] and the equatorial and South Pacific (K. Kawamura and K. Tanaka, unpublished results, 1995). Interestingly, 4-oxooctanoic and 4-oxononanoic acids were also detected in the Antarctic aerosols as major ke-

toacids [Nishikiori *et al.*, 1996]. These midchain ketoacids have been considered to be produced by the atmospheric oxidation of semivolatile fatty acids which are the counterparts of α, ω dicarboxylic acid (azelaic acid, C_9), or ω -oxononanoic acid, produced by photooxidation of unsaturated fatty acids [Kawamura and Gagosian, 1990]. Further oxidation of positional isomers of midchain ketoacids probably produce a homologous series of α, ω -dicarboxylic acids by heterogeneous reactions on aerosol surfaces (Figure 3). Enhanced concentrations of C_4 and other diacids (C_5 , C_6 , C_7 , and C_8) in the summer aerosols (Table 2) seem to support the reaction pathways described in Figure 3.

Also detected in the Antarctic atmosphere was 4-oxopimelic acid, C_7 dicarboxylic acid with an additional keto group at C-4 position. The keto diacid showed the highest concentration in the summer aerosols. This

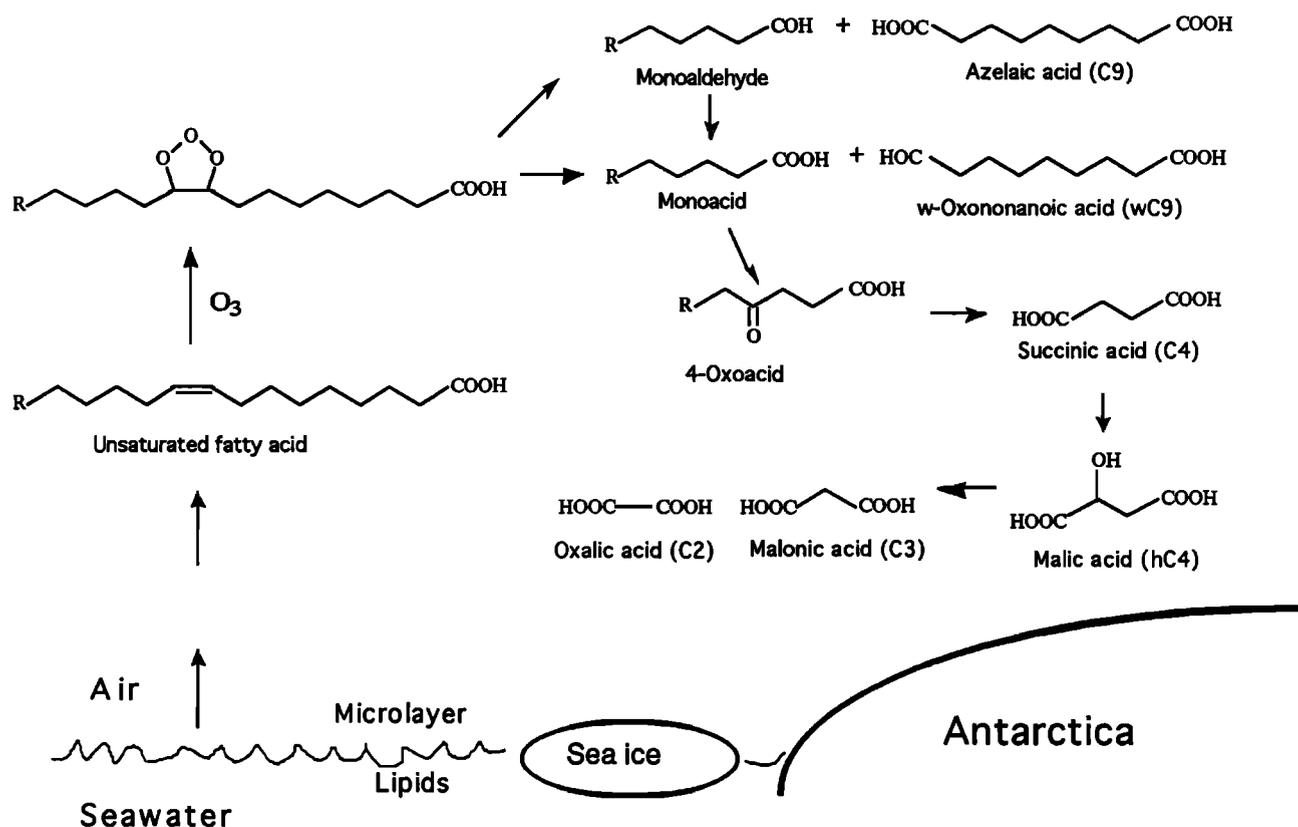


Figure 3. A proposed reaction scheme for the production of succinic acid (C₄) and other low molecular weight dicarboxylic acids from unsaturated fatty acids and their photooxidation intermediates in the atmosphere of the Southern Ocean and Antarctica.

compound has been detected in the remote marine atmosphere [Sakaguchi and Kawamura, 1994] and is considered as a photooxidation product of C₇ diacid. Also, 4-oxopimelic acid could be further oxidized in the atmosphere to result in succinic acid (C₄).

Highest concentrations of ω-oxocarboxylic acids and pyruvic acid were also obtained in the summer aerosol sample (Table 2). ω-Oxononanoic acid has been proposed as a photochemical oxidation product of unsaturated fatty acids [Kawamura and Gagosian, 1987]. In the Antarctic aerosols, 9-oxononanoic acid was detected as the most abundant ω-oxoacids, and its concentration was found to be highest in the summer aerosols (S-5), again supporting the reaction scheme on the atmospheric oxidation of unsaturated fatty acids (Figure 3).

These considerations lead to the conclusion that organic aerosols over the coast of Antarctica are significantly influenced by the sea-to-air emission of marine organic matter and subsequent photochemical transformation. The sea-to-air emissions should be enhanced during summer season due to a retreat of sea ice, as stated above. Unsaturated fatty acids are major lipids compounds in the marine micro algae and are enriched in the microlayers of sea surfaces [Marty *et al.*, 1979]. Enhanced emission of seawater microlayer lipids as aerosol particles to the marine atmosphere, coupled

with intensified solar radiation in the Austral summer, probably cause a significant photochemical production of dicarboxylic acids and modifies the chemical constituents of the marine aerosols near Antarctica. Alternatively, it is likely that the diacids and related compounds which are produced in the Southern Ocean atmosphere are transported long distances over the Antarctic coast with a seasonality of summer maximum. This observation at Syowa Station suggests that the marine aerosols containing photooxidation products may be transported farther to inland Antarctica and deposited over the ice sheet by dry and/or wet precipitation processes.

As stated above, the molecular distributions of dicarboxylic acids in the Antarctic submicron aerosols are different from those of the Arctic aerosols (82°N [Kawamura *et al.*, 1995a]). This suggests a difference in the source organic matter between the Arctic and Antarctic aerosols. In the Arctic atmosphere, a major portion of oxalic acid is produced by the photochemical oxidation of anthropogenic aromatic hydrocarbons such as benzene and toluene and their reaction intermediates, which are transported long-range from midlatitudes toward the Arctic during winter to spring [Kawamura *et al.*, 1995a]. In contrast, the diacid distributions of the Antarctic aerosols indicate that anthropogenic organics are not the major precursors, rather, biogenic organic

precursors such as unsaturated fatty acids significantly contribute to the Antarctic aerosol constituents. However, the aerosols collected in autumn to spring sometimes indicate a predominance of oxalic acid. This may suggest that except for Austral summer, atmospheric transport of aerosols from midlatitudes to the south occurs, and organic aerosols are subjected to photochemical transformation to produce oxalic and malonic acids during a long-range atmospheric transport to the Antarctica.

Conclusions and Summary

GC and GC/MS study of the Antarctic aerosols showed the presence of a homologous series of dicarboxylic acids (C_2 - C_{11}), ω -oxocarboxylic acids (C_2 - C_9), and α -dicarbonyls (C_2 - C_3). The maximum concentrations of diacids and ω -oxoacids were observed in the Austral summer sample. The molecular distribution of the summer aerosols is characterized by a predominance of succinic acid (C_4), which differs from the distributions in the Arctic and other northern hemisphere aerosols, in which oxalic acid (C_2) is always dominant. The distributions of dicarboxylic acids and ω -oxocarboxylic acids and their seasonal trend suggest that the Antarctic aerosols are not contributed from pollution sources, rather, their organic constituents are significantly controlled by sea-to-air emission of marine-derived organic matter and their subsequent atmospheric photochemical oxidation. These water soluble organic compounds should be present in the ice sheet and could be used as potential tracers to reconstruct past changes in the atmospheric environments.

Appendix

CA registry numbers are as follows: oxalic acid, 144-62-7; malonic acid, 141-82-2; methylmalonic acid, 516-05-2; maleic acid, 110-16-7; succinic acid, 110-15-6; methylsuccinic acid, 498-21-5; fumaric acid, 110-17-8; methylmaleic acid, 498-23-7; malic acid, 6915-15-7; glutaric acid, 110-94-1; adipic acid, 124-04-9; pimelic acid, 111-16-0; suberic acid, 505-48-6; phthalic acid, 88-99-3; azelaic acid, 123-99-9; sebacic acid, 111-20-6; undecanedioic acid, 1852-04-6; glyoxylic acid, 298-12-4; pyruvic acid, 127-17-3; and methylglyoxal, 78-98-8.

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