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ENVIRONMENTAL GEOCHEMICAL AND BIOLOGICAL FEATURES OF ANTARCTIC OASES

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Abstract: Distinctive geochemical and biological features of Antarctic oases are discussed from an environmental viewpoint. The increase of lake water level and the decrease of lake ice thickness in the McMurdo Oasis, and the increasing numbers of population and colonies of native vascular plants in the Argentine Islands of the Antarctic Peninsula region probably reflect global warming by human activity.

Distributions of organisms in Antarctica are controlled mainly by extremely low air temperatures. Cryptoendolithic microbial communities distributed in the near-surface layers of porous rocks of the McMurdo Oasis are the best adapted form for the extremely cold and dry environment.

Extraordinary high pH (>9) and dissolved oxygen concentrations (>20 m*l*/*l*) are often detected in perennially ice-covered lakes and ponds. Extremely high total organic carbon (>20 mgC/*l*) correlated with chloride ion content is found in the bottom waters of saline lakes. Chlorophyll-*a* data in Lake Vanda of the McMurdo Oasis reveal that the lake has the highest Secchi transparency, greater than 45 m, the clearest water in the world.

Long-chain ($>C_{19}$) *n*-alkanes and *n*-alkanoic acids, and C_{29} sterols (*e.g.*, 24-ethylcholest-5-en-3β-ol), which are believed to be characteristic of vascular plants, are often the predominant compounds in lake sediments and soils, in spite of the absence of vascular plants in the oases. These compounds are probably derived from micro-algae and/or cyanobacteria. Novel long-chain (C_{20}-C_{33}) *anteiso*-alkanes and *anteiso*-alkanoic acids found in cryptoendolithic microbial communities may be attributed to certain bacteria in unique microbial communities.

The monitoring of lake water level, lake ice thickness in the McMurdo Oasis, and the date of total surface ice-cover formation of lakes in the Syowa Oasis, such as Lake Ô-ike, as well as the changes in biological distributions, such as vascular plants, mosses and/or lichens in Antarctica are important to estimate environmental changes, in particular global warming.

1. Introduction

There are 16 major ice-free areas, so-called oases, in and around the coastal regions of Antarctica (SIMONOV, 1971; Fig. 1), although most of Antarctica is covered by a thick ice sheet with an average thickness of 2450 m (DREWRY *et al.*, 1982). Antarctica is located in high latitudes, sensitive to climate changes, and is an ideal field to monitor global warming. Antarctica also lies farthest from industrialized areas, is the least polluted continent, and therefore is the most suitable landmass for global background studies of human activity (*e.g.*, MATSUMOTO, 1993, 1994).

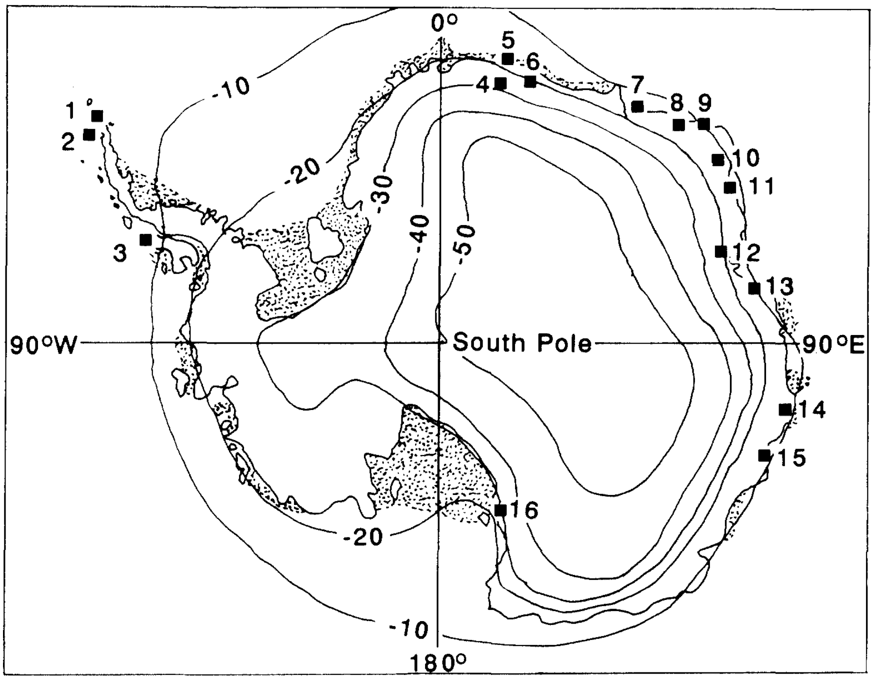

Fig. 1. Oases (SIMONOV, 1971) and mean annual surface air temperatures (NATIONAL WEATHER RECORDS CENTER and WEYANT, 1967) in Antarctica. Oases: 1, Snow Hill. 2, Bellingshausen. 3, Alexander. 4, Zimmermann. 5, Schirmacher. 6, Insel. 7, Syowa. 8, Molodezhnaya. 9, Thule. 10, Øygarden. 11, Stefansson. 12, Amery. 13, Vestfold Hills. 14, Bunger. 15, Greason. 16, McMurdo.

Antarctica is characterized by extremely low air temperature and a sunshine cycle that varies from the whole day dark in winter to whole day light in summer. These conditions are extremely harsh for biological activity, and thus vascular plants are absent, except in the Antarctic Peninsula (GREENE *et al.*, 1967). Only cryptogamic organisms, *e.g.* mosses, lichens and microorganisms are distributed in the oases. Antarctic ecosystems lack higher organisms, are simple and labile, and thus small changes in environmental conditions cause a large influence on the ecosystems.

Since the International Geophysical Year, 1957–58 (IGY), scientific studies of Antarctic oases have been extensively carried out by many scientists of the SCAR nations. A number of characteristic environmental geochemical and biological features of lakes and ponds, and terrestrial vegetation in the oases have been discovered. The present paper mainly discusses climate changes, in particular global warming, distributions of organisms and their environments, high concentration of organic carbon in lake waters, clearness of lakes, unusual organic compounds, and environmental monitoring in Antarctic oases.

2. Climate Changes and Global Warming

2.1. Lake water level and ice thickness

The increase of greenhouse gasses, such as carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide in the atmosphere by human activity may cause

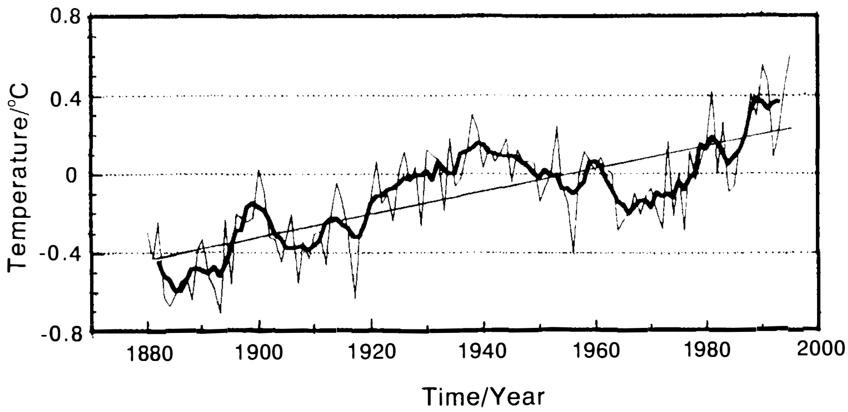

Fig. 2. Global mean air temperature changes during 1880–1995 (JAPAN METEOROLOGICAL AGENCY, 1995). Bold solid line: 5-year running mean. Straight line shows trend of temperature change.

global warming. For instance, since the Industrial Revolution (*ca.* 1760), carbon dioxide concentrations have increased from ca. 280 ppm to 358 ppm in 1994 (IPCC, 1995). Figure 2 shows the annual mean air temperatures from 1880 to 1995 for the world's land areas recorded at 1300–1400 meteorological stations. It reveals that the annual mean air temperatures rose approximately 0.6° C/100 years (JAPAN METEOROLOGICAL AGENCY, 1995). This may be caused by the increase of greenhouse gasses in the atmosphere by human activity.

Antarctic lakes may serve as a sensitive indicator of climate changes, because summer temperatures are close to the freezing point of water, therefore, small changes in climate are expected to cause large differences of lake water level and ice thickness (*e.g.*, CHINN, 1982; MCKAY *et al.*, 1985; MATSUMOTO, 1994).

Generally, Antarctic saline lakes are meromictic, and have no outflows. Thus the lake water level is balanced between the amount of meltwater supply from permafrost, glacier and snow, and the ablation and sublimation losses of waters. Lake Bonney in

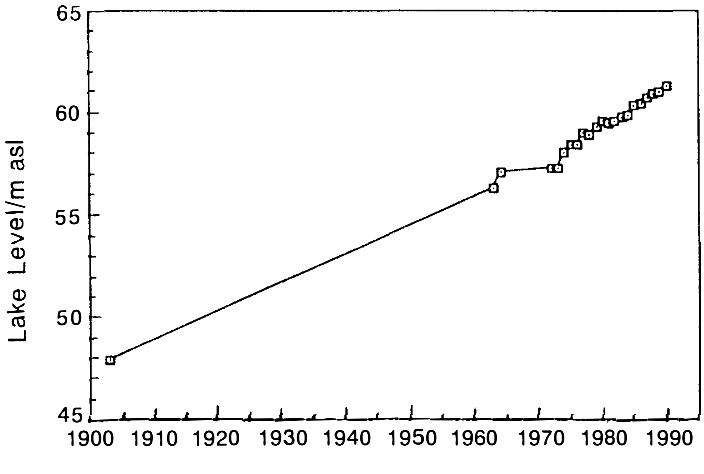

Fig. 3. An 87-year record of water levels for Lake Bonney in the McMurdo Oasis (CHINN, 1993).

the McMurdo Oasis is divided into two (east and west) lobes by a narrow isthmus (Fig. 1). It is noteworthy that the lake level of Lake Bonney estimated by a measurement of the width of the isthmus (5.2 m) by the western party of Scott's Discovery Expedition in 1903 (Scott, 1905) lies on the straight line of lake level increases recorded by the New Zealand Antarctic Research Program (NZARP, now NZAP) from 1960 to 1990 (Fig. 3; Chinn, 1993). In the last 97 years the lake level increased by 13 m at a rate of 15 cm/year. Water levels in Lakes Vanda and Hoare in this region also have increased considerably in the last 30 years (Chinn, 1993). Especially, water levels in Lake Vanda increased strikingly in the last 10 years, by about 5 m. These data probably reflect global and/or local warming. There are a number of paleolake shorelines on the valley walls around the Lake Vanda basin up to approximately 52 m above present lake water level (Chinn, 1993). Carbon fourteen dating has shown that these paleolake shorelines were formed during 1300–2900 yr B.P., and thus the lake water levels varied several times, largely due to climate changes (Yoshida *et al.*, 1975).

As discussed before, mean annual air temperatures for the boundary of the presence

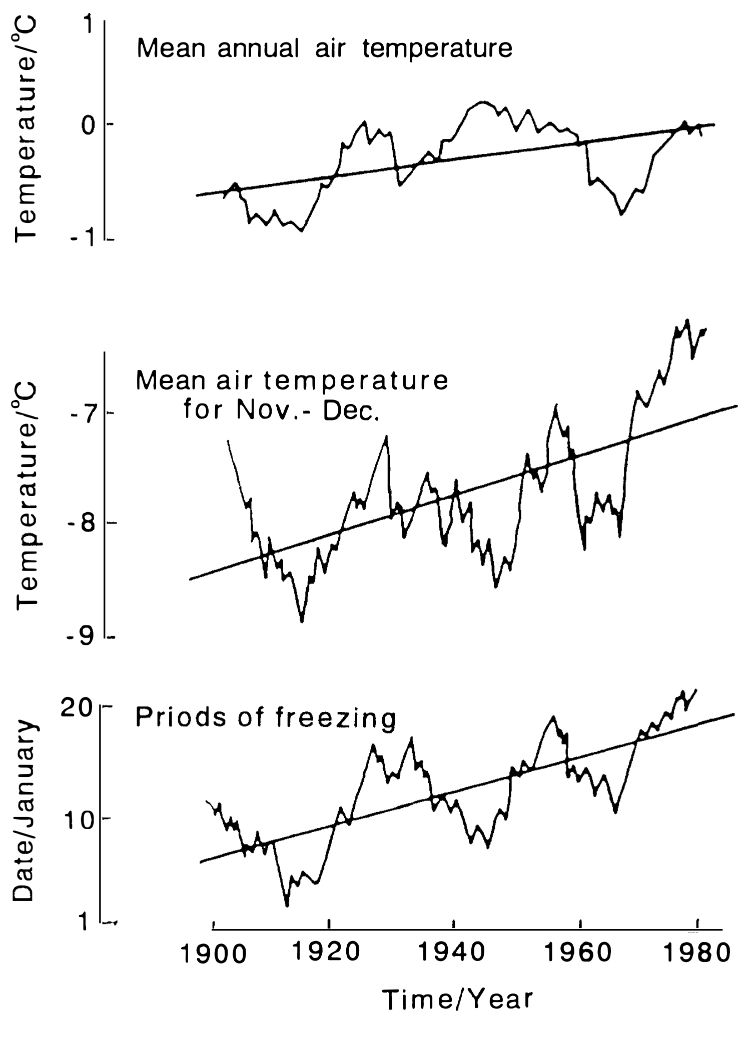

Fig. 4. Changes in mean air temperatures and freezing periods in Lake Baikal of Siberia, Russia (revised from Okuda, 1994; Shimaraev et al., 1994).

of perennial lake ice are approximately −20°C (MATSUMOTO, 1994). The −20°C isotherm lies several kilometers inland from the coastline of Antarctica (Fig. 1). During 1977–88 the ice thickness of Lake Hoare of the McMurdo Oasis decreased greatly, at a rate of 22.5 cm/year, reflecting again local and/or global warming (WHARTON *et al.*, 1992, 1993).

The date of total ice-cover formation on Lake Baikal (52–56°N) in Siberia was delayed approximately from the 5th to 20th of January during 1900 and 1980 (Fig. 4; OKUDA, 1994; SHIMARAEV *et al.*, 1994). This result is well correlated with the mean air temperature of November-December rather than mean annual air temperature in the Baikal region. Also, they probably reflect global warming in the Northern Hemisphere. In the Syowa Oasis, lakes have no perennial ice cover, although mean air temperature in mid-summer (January) is slightly lower than 0°C (−0.7°C; NATIONAL INSTITUTE OF POLAR RESEARCH, 1985). It is, therefore, expected that fluctuations of the date of total ice-cover formation of lakes, such as Lake Ô-ike in the Syowa Oasis, reflect climate change (MATSUMOTO, 1994).

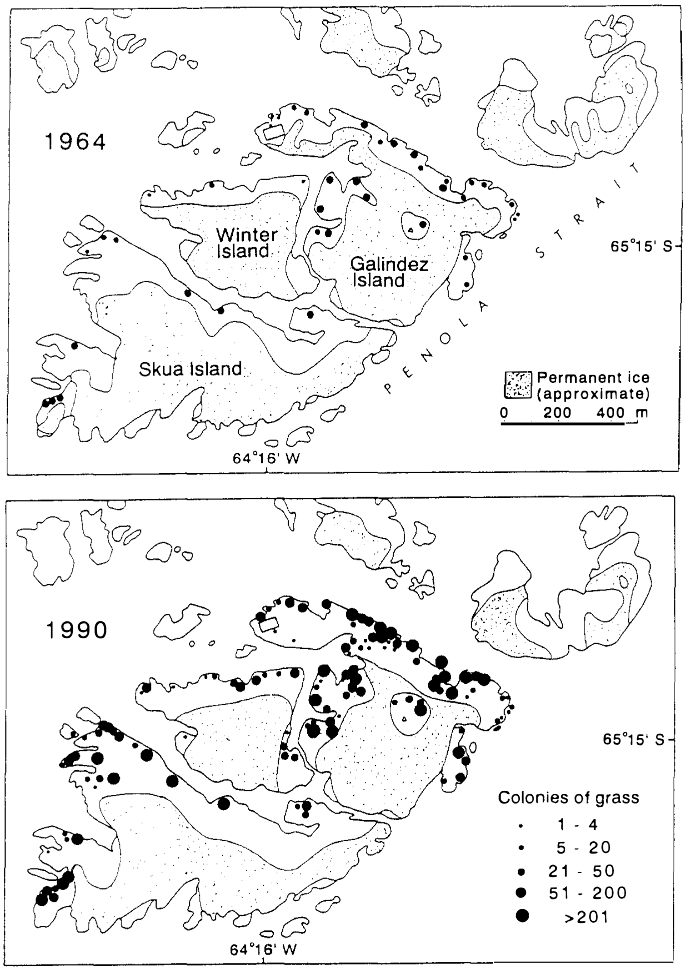

Fig. 5. Distribution and approximate numbers of individual Deschampsia antarctica plants on Galindez, Winter, and Skua Islands in 1964 and 1990 (revised from FOWBERT and LEWIS-SMITH, 1994).

2.2. Vascular plants

Two Antarctic native vascular plants, *Colobanthus quitensis* and *Deschampsia antarctica*, are distributed in the Antarctic Peninsula region. The number of individual plants and colonies of these native vascular plants have been monitored between 1964 and 1990 on three islands of the Argentine Islands archipelago in the Antarctic Peninsula region (FOWBERT and LEWIS-SMITH, 1994). The *Deschampsia* population increased by nearly 25-fold (Fig. 5) and *Colobanthus* by over 5-fold. The number of *Deschampsia* colonies also increased, but no additional *Colobanthus* colonies were recorded. The rapid increase of the numbers of individual plants and colonies of these plants are considered to be a response to the rising summer air temperature in this region of the maritime Antarctic (FOWBERT and LEWIS-SMITH, 1994; Fig. 6). This fact probably reflects global and/or local warming as in the case of the McMurdo Oasis.

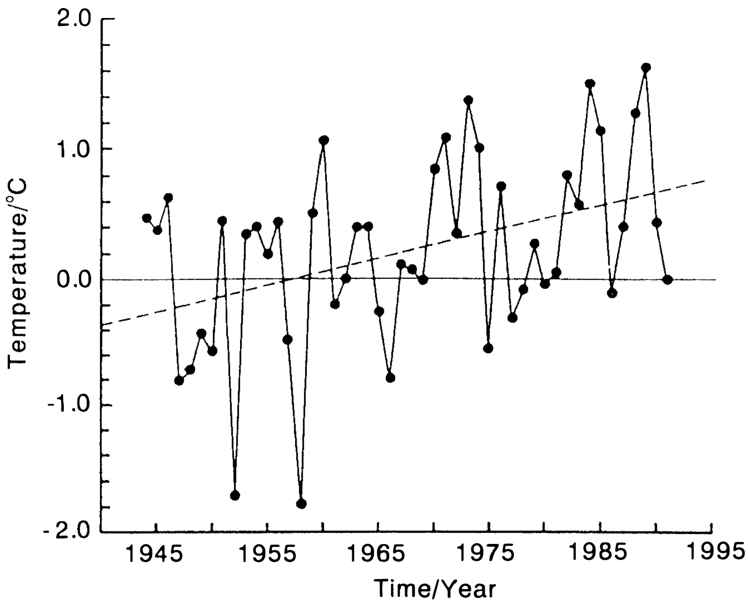

Fig. 6. Mean summer (December-February) air temperature at the British Antarctic Survey Faraday Station, Galindez Island of Argentine Islands in the Antarctic Peninsula region, 1944-1992 (FOWBERT and LEWIS-SMITH, 1994). $r^2=0.16$. $P<0.005$.

Surprisingly, a vascular plant (*Poa trivilis*) was found in the Langhovde ice-free area of the Syowa Oasis by the 36th JARE members (1993-94; KANDA *et al.*, unpublished). It is uncertain whether the seed of the plant was introduced by birds or contained in cargo of the JARE members. However, this result indicates that the present environmental conditions of the Syowa Oasis support the survival of vascular plants. This probably reflects warming of this region.

The evidences of warming in the McMurdo Oasis, the Antarctic Peninsula region and the Syowa Oasis strongly suggests that the warming has been progressing throughout the Antarctic.

3. Distribution of Terrestrial Organisms and Their Environments

Distributions of organisms in Antarctica are controlled by various environmental factors, such as extreme low temperatures, special daylight cycle, water availability (aridity), substrate stability and nutrient conditions. Thus, the terrestrial organisms in Antarctica are mainly distributed in lakes, ponds, meltwater streams and soils in oases (*e.g.*, KAPPEN, 1993; SIMMONS *et al.*, 1993; VINCENT, 1988; VISHNIAC, 1993; KANDA and KOMÁRKOVÁ, 1997), but a small quantity of microorganisms is found near the surface of snow (*e.g.*, snow algae, KAWECKA, 1986) and inside of porous rocks in oases.

Microorganisms certainly remain viable for long periods at low temperatures (*e.g.*, MEYER *et al.*, 1962). Viable microorganisms are found in Antarctic permafrost cores 1 million years old (CAMERON and MORELLI, 1974). ABYZOV (1993) summarizes numbers of viable microorganisms at various depths (0–2405 m) in the ice core obtained from the inland ice sheet at Vostok Station in central Antarctica, representing 0 to 0.2 million year-old ice. These include fungi, yeasts, bacteria and actinomycetes. Fungal spores and especially bacterial spores are able to survive for many thousands of years, and the latter have been found in the oldest layers.

The relationships between distributions of organisms and environmental conditions in Antarctica are summarized in Fig. 7 (revised from CAMERON, 1969; CAMPBELL and CLARIDGE, 1987). Although the most unfavorable environmental conditions are sterile, with the increasing favorable environmental conditions, bacteria, actinomycetes, cyanobacteria, algae, molds, yeasts and protozoa, lichens, mosses and then vascular plants appeared. Vascular plants are distributed only in the Antarctic Peninsula region. Mosses are less widely distributed than lichens (Fig. 8; GREENE *et al.*, 1967). Antarctica is the coldest continent on the earth, and low temperatures are believed to be the fundamental factor controlling the distribution of organisms. Global warming provides more favorable environmental conditions for organisms, and their monitoring is important to assess environmental changes.

In marked contrast to the marine ecosystems, diatoms are rarely the dominant biomass in Antarctic terrestrial aquatic environments, where the main phototrophs are cyanobacteria, phytoflagellates and chlorophytes. Cyanobacteria are present in all

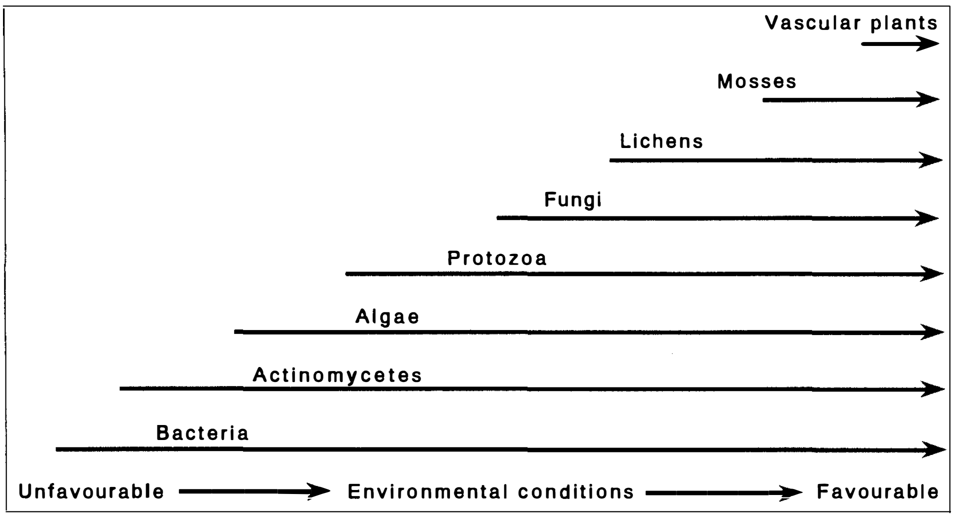

Fig. 7. Relationship between distributions of organisms and environmental conditions in Antarctica (revised from CAMERON*, 1969).*

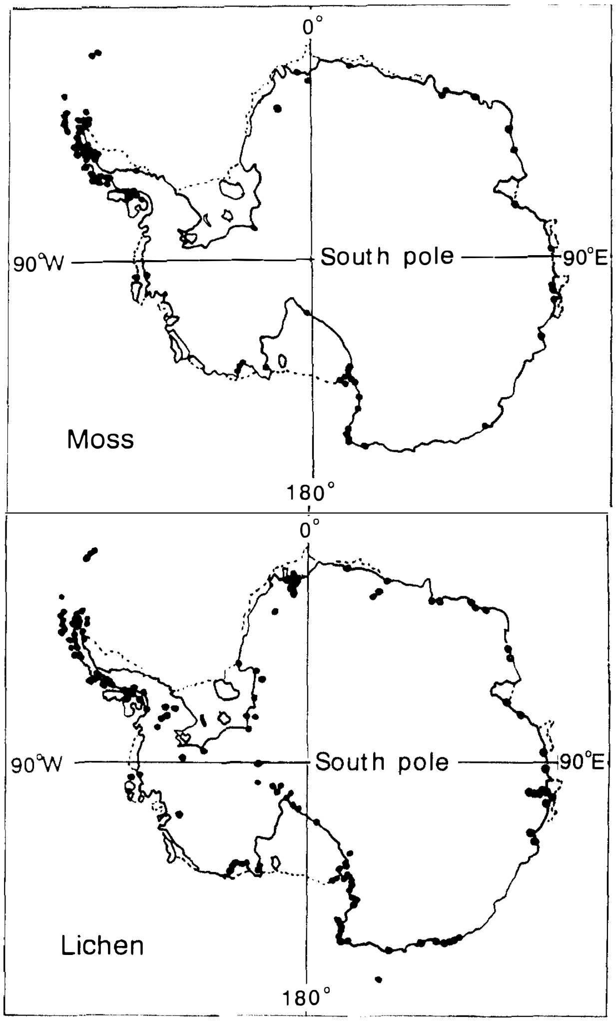

Fig. 8. Moss and lichen distributions in Antarctica (GREENE et al., 1967).

types of freshwater habitat, and are often the microbial biomass which dominates in streams, overlying lake sediments (mats) and plankton communities in Antarctica (VINCENT, 1988).

Microorganisms found in Antarctica are generally cosmopolitan, widely distributed in the temperate and subantarctic zones, and simply cold-tolerant or desiccation-tolerant species. These microorganisms show large differences from those in temperate and subarctic zones in their ability to withstand freezing, and a number of adaptive strategies may minimize or eliminate damage by ice during the freezing process, such as production of extracellular substances, increased solute content, increase in membrane water permeability and changes in membrane water permeability (VINCENT, 1988). A few endemic species of organisms, such as yeasts in soils, cryptoendolithic alga (*Hemichloris antarctica*) from the McMurdo Oasis, a bacterium (*Halomonas subglaciescola*) from a hyper saline lake in the Vestfold Hills Oasis and a wide range of microalgae are distributed in the oases (*e.g.*, VINCENT, 1988; NIENOW and FRIEDMANN, 1993; VISHNIAC, 1993).

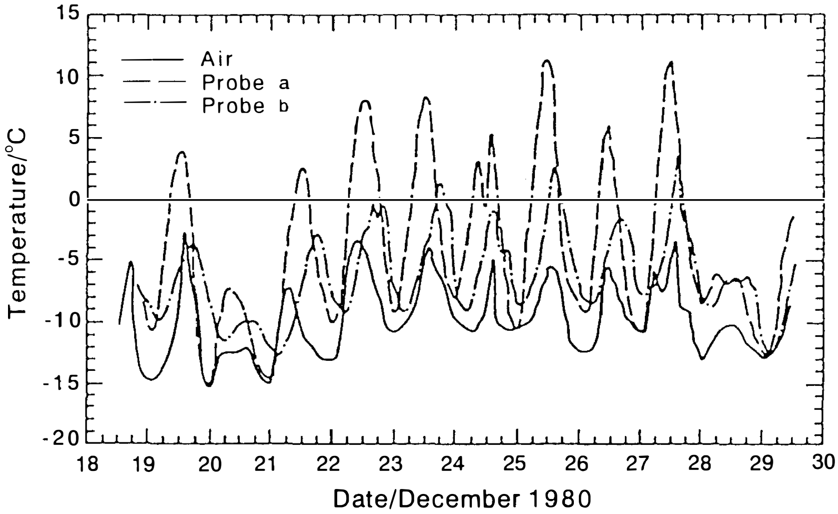

Fig. 9. Low-frequency (diurnal) temperature oscillations: Daily temperature variations of air and inside of porous rock colonized by cryptoendolithic microbial communities from the McMurdo Oasis during 18 to 30 December 1980 (revised from McKAY and FRIEDMANN, 1985). Temperatures are plotted as running means of 2 h periods to eliminate short-term fluctuations. Probe A: Vertical rock surface facing north at 22.9 mm depth. Probe B: Horizontal rock surface at 23.7 mm depth.

Of special interest is the occurrence of cryptoendolithic microbial communities in the near-surface layers of porous rocks, such as Beacon sandstone in the mountainous regions of the McMurdo Oasis, although the rock surfaces are extremely cold and dry, and are virtually abiotic (FRIEDMANN, 1982; NIENOW and FRIEDMANN, 1993). This is a model of microbial distributions on Mars in the past. The inside of the rock is warmed by insolation to temperatures above the ambient (Fig. 9). Moisture and nutrient conditions in the inside of the rock are more favorable than those of the rock surface. In addition, organisms in the inside of the rock are protected from strong UV light. Several distinct cryptoendolithic microbial communities exist there. These communities are classified into 5 groups: (a) lichen-dominated community consisting of lichen-forming fungi and green algae, parasymbiotic fungi, free-living fungi and green algae and cyanobacteria; (b) *Hemichloris* community (*H. antarctica*); (c) red *Gloeocapsa* community (various *Gloeocapsa* species and other cyanobacteria); (d) *Hormathonema-Gloeocapsa* community (*Hormathonema* sp., *Gloeocapsa* sp. and other cyanobacteria); (e) *Chroococcidiopsis* community (*Chroococcidiopsis* sp.; FRIEDMANN, 1982; NIENOW and FRIEDMANN, 1993). A number of unidentified heterotrophic bacteria occur in all these communities. These microbial communities exist near the temperature limit below which maintenance of life is impossible; even slight changes in the environmental conditions cause death and extinction, and various stages of fossilization occur.

4. Lakes and Ponds

4.1. Lake water chemistry

Lakes and unnamed water pools (ponds) are widely distributed in valley depressions of oases. These lakes and ponds have a wide variety of geochemical and biological properties. Dissolved salt contents in lake and pond waters vary widely from those of nearly pure water to 13 times higher than the seawater (TORII and YAMAGATA, 1981; MATSUMOTO, 1993). Don Juan Pond in the McMurdo Oasis has the highest salt content (392 g/kg) of all lakes and ponds in the world, because the major ionic component is calcium chloride (TORII and YAMAGATA, 1981): the solubility of calcium chloride in water is much greater than that of sodium chloride. The salt composition of lakes and ponds in coastal regions is similar to that of seawater, while that of lakes and ponds in inland regions of the McMurdo Oasis vary widely. This reflects the disintegration of rocks in the drainage basin, including hydrothermal saline water-rock interaction, and thus Mg and Ca are abundant (*e.g.*, TORII and YAMAGATA, 1981; MATSUMOTO, 1993; TAKAMATSU *et al.*, 1998).

Dissolved oxygen (DO) contents in perennially ice covered lake and pond waters in the McMurdo Oasis are often extremely high, ranging from 5.5 to 35.0 m*l*/*l* (except for anoxic bottom waters) with an average of 15.1 m*l*/*l*, which is much higher than the saturation (*e.g.*, YOSHIDA *et al.*, 1975; WHARTON *et al.*, 1987; MATSUMOTO, 1993). WHARTON *et al.* (1987) explained that the supersaturation of DO and dissolved nitrogen results from the exclusion of air during freezing of aerated meltstream water at the bottom of the ice-cover. They suggested that about half of the net DO production in Lake Hoare is the result of biological processes. CRAIG *et al.* (1992), however, showed that 89% of DO in Lake Hoare is derived from meltwater inflow, while only 11% of DO in the lake is from biological processes.

The relative contributions of physical and biological processes to DO concentrations vary perhaps in lakes and ponds as well as seasons. The extremely high DO concentrations are also caused by DO evolution by continuous photosynthetic activity under ice-cover, as evidenced by the extremely high pH of waters, as discussed below (MATSUMOTO *et al.*, 1992a). In the Syowa Oasis, in contrast, no extraordinarily high DO concentrations ($>$20 m*l*/*l*) in waters of lakes and ponds which have no perennial ice-cover are observed, although the supersaturation of DO in Lake Ô-ike on West Ongul Island is detected, and explained by the intense photosynthetic activity in the austral summer (YOSHIDA *et al.*, 1975).

Extraordinarily high pH values (pH$>$9) maximizing at 10.8 are found in perennially ice-covered lakes and ponds of the McMurdo Oasis (MATSUMOTO *et al.*, 1992 a). Generally, pH values decrease with increasing of chloride ion contents. These results can be explained by the combination of three factors: (1) low chloride ion contents mean small buffer capacity of water; (2) continuous photosynthetic activity consumes carbonate in water; (3) perennial ice-cover prevents the exchange of gases between air and water. As expected, extremely high pH values are not found in lakes and ponds in the Syowa Oasis, and are consistent with the absence of ice-cover in the austral summer (MATSUMOTO *et al.*, 1992a).

4.2. High concentration of organic carbon

Total organic carbon (TOC) and dissolved organic carbon (DOC) in saline lakes and ponds are generally high, up to 186 mgC/*l*, in spite of the absence of pollution sources in drainage basins of Antarctic oases (Table 1; MATSUMOTO, 1989). Generally,

Table 1. High concentration of total organic carbon (TOC) in Antarctic lakes (revised from MATSUMOTO, 1989).

Lake (Depth, m)	TOC (mgC/*l*)
McMurdo Oasis	
Pony Lake (surface)	110
Lake Vanda (66)	63.8
Lake Bonney, east lobe (4)	50
Lake Bonney, east lobe (33)	28.0
Lake Bonney, west lobe (24)	30
Lake Bonney, west lobe (28)	18.6
Lake Fryxell (18)	29.1
Syowa Oasis	
Lake Nurume (11)	30*
Lake Hunazoko (0–7)	103–186*
Lake Suribati (10–29)	10^2*
Vestfold Hills Oasis	
Ace Lake (no data)	>60
Deep Lake (no data)	50

* Dissolved organic carbon.

high TOC and DOC contents are found in the anoxic bottom layers of saline lakes. The correlation coefficients between TOC and chloride ion contents for Lakes Vanda, Bonney and Fryxell and Labyrinth ponds from the McMurdo Oasis are 0.83 ($n=28$), 0.91 ($n=16$), 0.84 ($n=8$) and 0.85 ($n=12$), respectively (MATSUMOTO, 1993). Also, a high correlation coefficient between DOC and chloride ion contents is observed in Lakes Hunazoko, Nurume and Suribati in the Syowa Oasis (TOMINAGA and FUKUI, 1981). As discussed above, saline lakes and ponds have no outflows. Organic matter and dissolved salts supplied from snow and glacial meltwaters are first concentrated by freezing. In addition, *in situ* photosynthetic activity produces organic matter, although organic matter undergoes microbial degradation, and refractory organic matter is concentrated in the saline waters. Furthermore, dissolved organic matter and salts in lake and pond waters are concentrated through ablation and sublimation of waters. Consequently, high concentration of organic matter correlated with chloride ion is formed in Antarctic saline lakes and ponds (MATSUMOTO, 1993). High TOC content in Pony Lake on Ross Island can be, however, explained by the influence of penguins and skuas nesting around the lake (MATSUMOTO *et al.*, 1979).

4.3. Clearest lakes in the world

Transparency measured by Secchi disk is an indicator of clarity of lake water. Lake Mashu (41.6 m), Japan and Lake Baikal (41 m), Russia are generally accepted as

Table 2. High Secchi transparency lakes in the world with reference to seawater records.

Lake (locality)	Maximum Secchi transparency/m (year)
Lake water	
Lake Mashu (Japan)	41.6 (1931)[1]
Lake Baikal (Russia)	40.5 (1911)[1]
Crater Lake (U.S.A.)	40 (1984)[2]
Lake Tahoe (U.S.A.)	32.7 (1873)[1]
Lake Tazawa (Japan)	30.0 (1926)[1]
Lake Vanda (Antarctica)	45 (1987)[3]
	65 (1987)[4]
Lake Untersee (Antarctica)	77 (1980)[5]
Seawater	
Southeastern Mediterranean Sea	53 (1987)[6]
Eastern Weddell Sea	79 (1987)[7]

[1] National Astronomical Observatory (1992).
[2] LARSON (1984).
[3] Calculated by chlorophyll-*a* concentration by CARLSON's equation (1977).
[4] Calculated by chlorophyll-*a* concentration by AIZAKI *et al.*'s equation (1983).
[5] Calculated by extinction coefficient of visible light (KAUP, 1988).
[6] MEGARD and BERMAN (1989).
[7] GIESKES *et al.* (1987).

the clearest lakes in the world (NATIONAL ASTRONOMICAL OBSERVATORY, 1992; Table 2). LARSON (1984) reported high transparency lake (40 m) in Crater Lake in Oregon, U.S. A. Direct measurements of Secchi transparency in Antarctic lakes are often impossible, because the lake surfaces are covered with perennial ice. Here the Secchi transparency of a perennially ice-covered lake, Lake Vanda of the McMurdo Oasis, is calculated based on the relationship between Secchi transparency and chlorophyll-*a* concentration in the water column.

CARLSON (1977) reported the relationship between Secchi transparency and chlorophyll-*a* concentrations for lakes in North America shown in eq. (1).

$$\ln \text{Secchi transparency } (m) = 2.04 - 0.68 \ln \text{chlorophyll-}a \ (\text{mg/m}^3). \quad (1)$$

AIZAKI *et al.* (1981) summarized the relationship between Secchi transparency and chlorophyll-*a* concentrations for 24 lakes in Japan with a good correlation coefficient ($r = -0.96$) as shown in eq. (2).

$$\ln \text{Secchi transparency } (m) = 2.41 - 0.654 \ln \text{chlorophyll-}a \ (\text{mg/m}^3). \quad (2)$$

VINCENT (1987) reported extremely low chlorophyll-*a* concentrations in the water column ranging from 0.04 to 0.20 mg/m^3 with an average of 0.074 mg/m^3 for 0–50 m depths in Lake Vanda (Fig. 10). The lake has an ice-cover with a thickness of approximately 3 m in the austral summer. The Secchi transparency is calculated here based on the average chlorophyll-*a* concentration of 0.074 mg/m^3 in the lake using eqs. (1) and

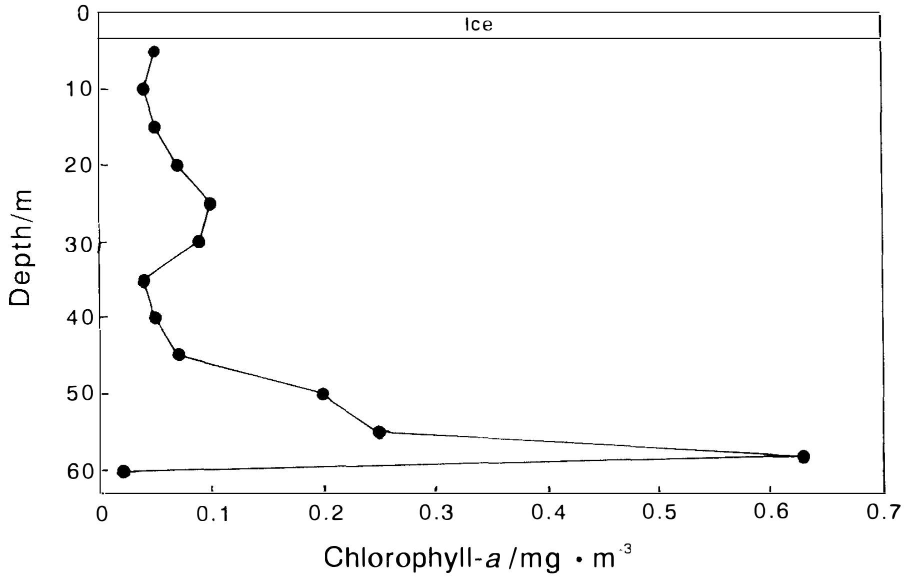

Fig. 10. Vertical distribution of chlorophyll-a concentrations in Lake Vanda, Antarctica (VINCENT et al., 1987).

(2), and the values of 45 and 61 m are obtained, respectively. These Secchi transparency values are much higher than the previously reported world records (Table 2).

MEGARD and BERMAN (1989) reported a relationship between the Secchi transparency (m) and the extinction coefficient of the dominant waveband (*Kd'*) estimated by light measurements at depths near the Secchi depth in very transparent waters of the southeastern Mediterranean Sea which has maximum transparency of 53 m, as shown in eq. (3).

$$\text{Secchi transparency } (m) = 1.70/Kd'. \qquad (3)$$

KAUP (1988) measured extremely low *Kd'* of 0.022/m at 25–35 m depths of Lake Untersee in the Schirmacher Oasis (Fig. 1), and estimated the Secchi transparency to be 77 m. This Secchi transparency is extraordinarily high. It is close to the world record value of 79 m found in a coastal polynya of the eastern Weddell Sea, where the water is believed to be nearly pure, being derived from recently melted ice and snow (GIESKES *et al.*, 1987). However, there is a question of this Secchi transparency value, because the *Kd'* of Lake Untersee was measured at 25–35 m depths. Therefore, it is necessary to measure the *Kd'* for deeper water layers.

Lake Vanda and probably Lake Untersee have the highest Secchi transparency among the world lakes. These lakes have perennial ice-cover, and thus the water exchange is very poor. These features favor high transparency (HERMICHEN *et al.*, 1985; KAUP, 1994). The chlorophyll-*a* maximum in Lake Vanda is observed at a depth of approximately 60 m, just above the anoxic bottom layer (*e.g.*, VINCENT, 1987), where nutrients are supplied only by molecular diffusion from the lake bottom. Phytoplankton in Lakes Vanda and Fryxell of the McMurdo Oasis are photoadapted to the lowest photosynthetic photon flux density of any community reported so far (PRISCU *et al.*, 1987).

5. Occurrence of Unusual Organic Compounds

Antarctic oases lack vascular plants, and are suitable for the study of microbial biomarkers. Various organic compounds, including hydrocarbons, fatty acids, hydroxy acids, sterols and phenolic acids have been reported to be present in waters, sediments, soils and rocks in Antarctica (*e.g.*, MATSUMOTO, 1989, 1993; MATSUMOTO *et al.*, 1990a, b). These organic compounds are widely distributed in natural environments of the world. Generally, long-chain ($>C_{19}$) *n*-alkanes and *n*-alkanoic acids as well as C_{29} sterols (*e.g.*, 24-ethylcholesterol) are accepted as characteristic compounds of vascular plants. However, they are often predominant compounds in Antarctica in spite of the absence of vascular plants in the oases (*e.g.*, MATSUMOTO, 1989, 1993; MATSUMOTO *et al.*, 1990a, b).

Long-chain *n*-alkanes and/or *n*-alkenes with the predominance of odd-carbon numbers are found in lake sediments and soil samples. Long-chain *n*-alkenes, however, are unusually abundant in soil samples from the McMurdo Oasis, although their source organisms are not yet clear (MATSUMOTO *et al.*, 1990a). Long-chain *n*-alkenes are detected in a cultured green alga (*Scotiellopsis* sp.) which is believed to be an important source of long-chain *n*-alkenes in Antarctica (MATSUMOTO *et al.*, unpublished). In addition, long-chain *n*-alkanoic acids and/or *n*-alkenoic acids are detected in lake sediment samples. These long-chain compounds are probably synthesized by microorganisms, including microalgae (MATSUMOTO, 1989, 1993). Very long-chain *n*-alkanoic acids extending up to C_{40} discovered in soil samples from the McMurdo Oasis may be, however, attributed to the ancient vascular plants derived from disintegrated sedimentary rocks, such as the Beacon Supergroup of a Gondwanaland sediment which is widely distributed in the mountainous regions of the oasis (MATSUMOTO *et al.*, 1981, 1990b).

It is noteworthy that novel long-chain (C_{20}-C_{33}) *anteiso*-alkanes and *anteiso*-alkanoic acids are distributed in the cryptoendolithic microbial communities from the McMurdo Oasis (Fig. 11; MATSUMOTO *et al.*, 1992b). However, these compounds could not be detected in any water, sediment or soil samples from this area or other oases in Antarctica. These compounds may be attributed to certain bacteria in unique microbial communities. Recently, long-chain *anteiso*-compounds have been found in sediment samples from an acid lake (Lake Tazawa) in Japan (FUKUSHIMA *et al.*, 1996). They suggest that these *anteiso*-compounds are synthesized by organisms in moderately acidic conditions (pH=3–6), although source organisms are not yet identified.

A ternary diagram shows the distribution of C_{27} (cholesta-5,22-dien-3β-ol, cholest-5-en-3β-ol, 5α-cholestan-3β-ol), C_{28} (24-methylcholesta-5,22-dien-3β-ol, 24-methylcholest-5-en-3β-ol and 24-methyl-5α-cholestan-3β-ol) and C_{29} (24-ethylcholesta-5,22-dien-3β-ol, 24-ethylcholest-5-en-3β-ol and 24-ethyl-5α-cholestan-3β-ol) sterols in Antarctic samples, as compared with those in mid- and lower latitudes (Fig. 12; MATSUMOTO, 1993). Unexpectedly, C_{29} sterols are abundant in some Antarctic samples, in spite of the absence of vascular plants in the areas studied. These sterols are probably derived from cyanobacteria and green algae (MATSUMOTO *et al.*, 1982; VOLKMAN, 1986; MATSUMOTO, 1993).

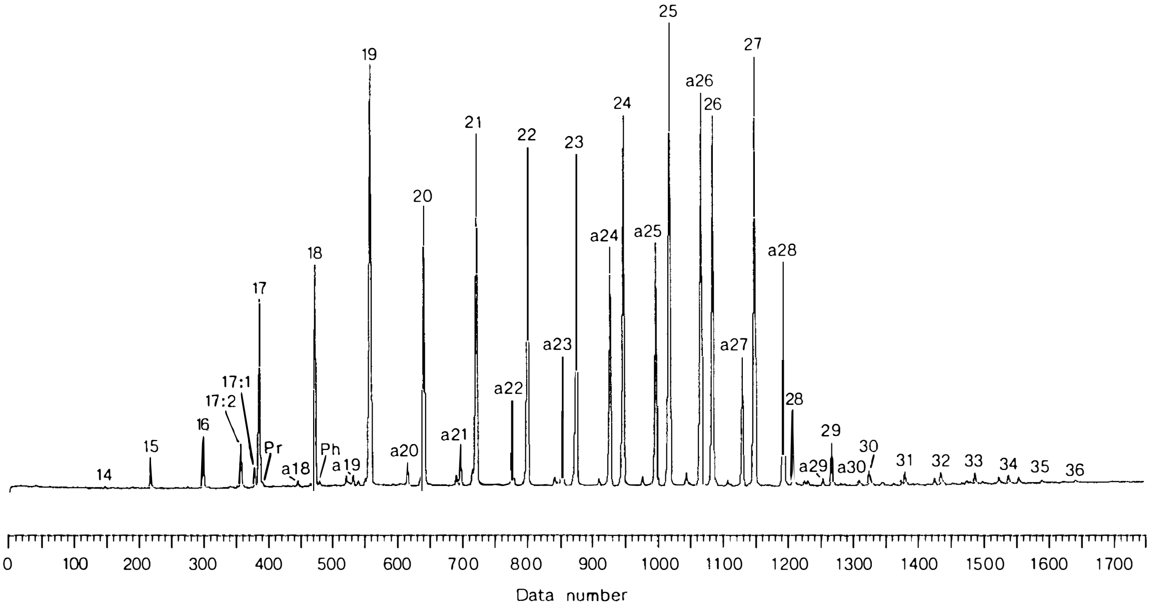

Fig. 11. Capillary gas chromatogram (TIC) of the hydrocarbon fraction from cryptoendolithic microbial communities from the McMurdo Oasis (MATSUMOTO et al., 1992b). Arabic figures on the peaks denote carbon-chain length of n-alkanes. a = Anteiso-alkanes. Pr = Pristane. Ph = Phytane. m:n = Carbon chain length: number of double bonds.

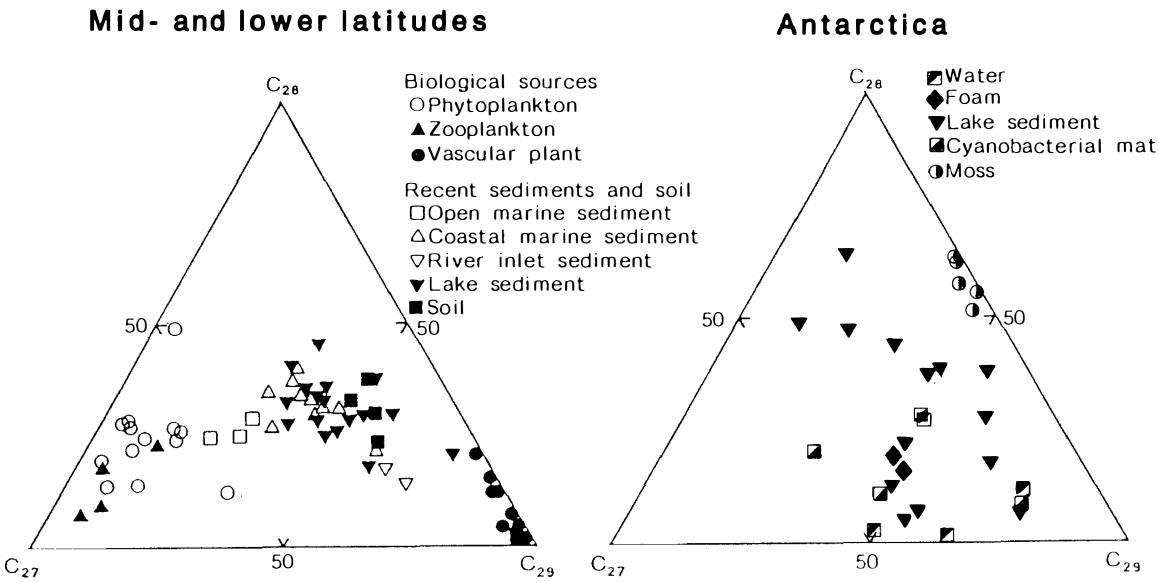

Fig. 12. Relative abundances of C_{27}, C_{28} and C_{29} sterols from the mid- and lower-latitudes, and Antarctica (MATSUMOTO, 1993).

6. Environmental Monitoring

6.1. Global environmental change

Changes in $\delta^{18}O$ values in marine sediment and Antarctic deep ice core samples indicate the occurrence of the cycles of glacial and interglacial periods (*e.g.*, EMILIANI and SHACKLETON, 1974; JOUZEL *et al.*, 1993). Also, the ice core samples show that the concentrations of greenhouse gases of carbon dioxide and methane are well correlated with paleotemperatures estimated from $\delta^{18}O$ values, and are high during the interglacial periods, but are low in glacial periods (JOUZEL *et al.*, 1993). These greenhouse gases seem to play an important role in the formation of glacial and interglacial periods.

Figure 13 shows the changes in temperatures during the past 125000 years and the future 25000 years (IMBRIE and IMBRIE, 1979). In this scenario increasing carbon dioxide will cause super-interglaciation and continuing for several thousand years until the next ice age. Antarctica, as a high latitude area, is sensitive to global warming. In the future, it is probable that coastal regions of Antarctica will be widely covered with vascular plants. Therefore, the monitoring of lake water level, ice thickness and the date of the whole surface-ice formation of lakes is important to estimate global and/or local climate changes. Monitoring of the changes in distributions of native vascular plants, mosses and lichens is also necessary to assess the climate changes. In order to clarify the influence of global warming in high latitude areas, the monitoring of vegetation, including mosses and lichens enclosed by pentagonal open top chambers made of transparent acrylic resin boards (a small greenhouse, diameter 70 cm, height 30 cm, open top diameter 50 cm, NAKASHINDEN *et al.*, 1997) to keep warmer conditions than the outside is being conducted simultaneously in the Antarctic (the Syowa Oasis)

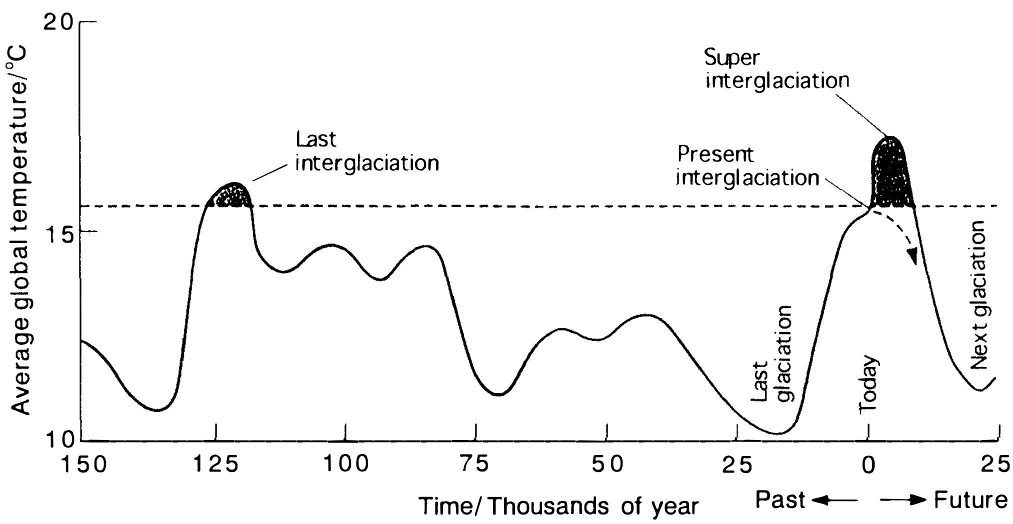

Fig. 13. The course of average global temperature during the past 150000 years and 25000 years from present (IMBRIE and IMBRIE, 1979). According to the astronomical theory of the ice ages, the natural course of future climate (shown by the dashed line) would be a cooling trend. The warming effect of carbon dioxide may well interpose a super-interglaciation, with global mean temperatures reaching levels several degrees higher than those experienced at any time in the last million years.

and the Arctic (Spitsbergen Island).

6.2. Human activities in Antarctica

Recent human activities in Antarctica, including logistics, research and tourism, use various kinds of living and life support materials, and discharge several gaseous, liquid (sewage) and solid wastes. These activities influence the environment, although at present their direct influence is not serious except for research station areas. However, a large number of solid wastes, such as plastics, wood and paper are found in the McMurdo Oasis and on Ross Island due to the logistic and scientific activities (*e.g.*, personal observation; VINCENT, 1988). It is likely that solid wastes are widely distributed at around research stations and research sites throughout Antarctica, although solid wastes may have been reduced by recent environmental management.

Liquid wastes contain organic pollutants, and thus measurements of organic matter indicators, such as chemical oxygen demand (COD), biological oxygen demand (BOD) and TOC contents in waters receiving liquid wastes may be useful for the monitoring of water pollution. Petroleum-derived hydrocarbons (gasoline, diesel fuels, lubricating oils, etc.) are also widely used at all Antarctic research stations. Thus the measurement of hydrocarbons is believed to be a suitable marker of human activity, as discussed before (MATSUMOTO, 1994).

PARKER and HOWARD (1977) proposed an environmental impact matrix for the assessment of the influence of the Dry Valley Drilling Project (1971-76). This approach incorporates an assessment of the relative magnitude of the environmental impacts for 5 stages from 0 (no impact) to 4 (complete destruction) on 5 time scales (1 day, seasonal, 1-5 years, 5-15 years and >15 years). This approach is useful for the assessment of human impacts on the oases. Table 3 shows the revised environmental impact matrix for oases.

Environmental management of the cold desert ecosystem of the McMurdo Dry Valleys in the McMurdo Oasis was discussed in detail at a workshop held at Santa Fe, New Mexico (VINCENT, 1995). These reports include a proposed Environmental Code of Conduct for Field work in the McMurdo Dry Valleys. To minimize or eliminate impacts on the environment in the McMurdo Dry Valleys, the code should be implemented as soon as possible for the field camps, sampling and experimental sites,

Table 3. Environmental impacts for land surface in Antarctica[1].

Human impact	Surface[2] properties	Surface[2] environment	Indigenous[2] microbiota
Vehicle movements	11111	32211	42111
Diesel fuels and lubricants	43321	33333	43211
Disposal of sewage and other waste	44444	33333	44444
Introduction of aeolian microorganisms	00000	10000	44433

[1] Modified from PARKER and HOWARD (1977).

[2] Each effect is rated on a scale from 0 (no impact) to 4 (complete destruction). In each group of five digits the first number refers to the impact over the first day, the second to impacts at the seasonal level, the third to 1-5 year impact, the fourth to the 5-15 year impact, and the fifth to impacts at time scales longer than 15 years.

travel, lakes, streams, valley floor and side, mountains, and glaciers. Also, a system-wide geographical information system (GIS) should be developed for the management of the environment in the oasis. This is a suitable model for the management of all Antarctic and Arctic desert environments.

7. Summary and Conclusions

Distinctive geochemical and biological features of Antarctic oases are discussed from an environmental viewpoint, and summarized as follows:

(1) Increasing of lake water levels and decreasing of lake ice thickness in the McMurdo Oasis, as well as the increasing of the numbers of population and colonies of native vascular plants on the Argentine Islands of the Antarctic Peninsula region probably reflect global warming.

(2) Biological distributions in Antarctica are believed to be principally controlled by extremely low temperatures of their habitats. Cryptoendolithic microbial communities are the best adapted form for extremely dry and low temperature environment on the earth.

(3) Extraordinary high pH values (>9) and DO concentrations ($>20\,\mathrm{m}l/l$) are often observed in perennially ice-covered lakes and ponds.

(4) Very high TOC concentrations correlated with chloride ion concentrations are widely found in the bottom waters of saline lakes.

(5) Lake Vanda of the McMurdo Oasis and probably Lake Untersee of the Schirmacher Oasis have Secchi transparency greater than 45 m and are the clearest lakes ever reported in the world.

(6) Long-chain *n*-alkanes and *n*-alkanoic acids as well as C_{29} sterols are often abundant in Antarctic oases in spite of the absence of vascular plants, and are derived from microorganisms including microalgae. Long-chain *anteiso*-compounds in cryptoendolithic microbial communities are synthesized by certain bacteria in unique microbial communities.

(7) The monitoring of water level and ice thickness of perennially ice-covered lakes in the McMurdo Oasis and the date of whole surface-ice formation of lakes in the Syowa Oasis, as well as the distributions of native terrestrial organisms (vascular plants, mosses and lichens) are important to estimate environmental changes, in particular global warming.

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