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Limnological features of the saline lakes of the Bunger Hills (Wilkes Land, Antarctica)

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Abstract: Twelve saline lakes 5–35 m above sea level in Bunger Hills (66°10'S, 101°00'E) were investigated from January to April in 1987–89. Some lakes may be relict and all were subject to wind-borne marine salts with present salinities between 3.4–79.0 $^{\circ}/_{\circ\circ}$ and $\delta^{18}O$ values mostly between -10 to -14%. Temperatures up to 17.7°C were measured at the bottom of Lake Polest where a sharp thermohalocline was observed during the period of open water. Mg^{2+} dominated over Ca^{2+} in all the lakes. Phosphates concentration was 3–10 μgP l^{-1} and total phosphorus 8–16 μgP l^{-1}. The concentrations of nitrates and nitrites were often equal, ranging between 1–4 μgN l^{-1}. Dissolved O_2 was usually near saturation levels but peaked at more than 230% of saturation in the hypolimnion of Lake Polest as a result of temperature-enhanced photosynthesis with an assimilation rate of 23.9 mgC (mg Chl *a*)$^{-1}$h^{-1}. The values for chlorophyll *a* were 0.26–1.93 mg m^{-3} and for primary production 0.013–0.171 gC m^{-3}d^{-1}, the latter being an order of magnitude higher than in the freshwater lakes of the Bunger Hills.

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Introduction

Bunger Hills, one of the largest of the Antarctic ice-free areas (952 km^2) is *c.* 50 km from the Mawson Sea (Fig. 1). The two largest coastal bays, Edisto Strait and Cacapon Bay, with islands of different size, are located in the north and the central parts of the oasis. The largest massif of exposed bedrock, with an area of 262 km^2, is in the southern part of the oasis (Korotkevich 1958). Hundreds of lakes fill the valleys and bedrock depressions. The freshwater lakes (the biggest of them being Lake Figurnoye, 14.3 km^2) are concentrated mostly in the southern part and along the periphery of the oasis. Most of the lakes on the islands and in the northern part of the largest massif are saline.

The first data on physico-chemical and biological properties of the lakes were collected during the International Geophysical Year (Vinogradov 1957, Korotkevich 1958, Grigoryev 1961). Systematic limnological studies, initiated in January 1987, have been carried out every year since during January–April around the Soviet summer base Oasis-2 (Klokov *et al.* 1989, Kaup *et al.* 1990, Bolshiyanov *et al.* 1991, Verkulich 1991). Freshwater lakes with total salts as low as 6 mg l^{-1} and lakes of relict seawater with salinity up to 32$^{\circ}/_{\circ\circ}$ have been found. This paper presents data on the physical, chemical and biological parameters of 12 saline lakes in the Bunger Hills.

Materials and methods

Sampling and measurements were carried out in lakes on Thomas Island (a), on Cachalot Island (b) and on the main southern massif (c, Fig. 2). Most of the lakes studied are situated in relatively flat valleys running mainly east-west with surrounding hills up to 100 m a. s. l. Characteristic of this region is the Six Lakes Valley which extends from Rybiy Khvost Bay to Transcription Bay. Transcription Bay is a perennially ice-covered ocean-connected water body where the meltwater, with small seawater additions, overlies diluted seawater. Rybiy Khvost Bay contains only slightly diluted seawater. Here the ridges between saline lakes Sredneye, Krugloye, Vostochnoye and Zapadnoye (Table I) are at *c.* 20–60 m a.s.l. Lakes Polest, Sredneye and Jaw are separated from the Cacapon Bay by ridges of *c.* 10 m a.s.l. The other lakes studied are at higher elevations (Table I). The lakes are 50–2000 m long and up to 6 m or possibly 10 m deep in some cases.

There were no streams feeding the lakes (except Lake Sredneye which received inflow from a freshwater lake) and the amount of snowfield meltwater entering the lakes was relatively small. In some lakes, such as Drying and Shallow, evaporation clearly exceeded the current meltwater inflow and salts were deposited on their beaches. All the 12 lakes are within 0.5–1.5 km from the coastal bays, which are ice-free for several weeks in summer when wind-borne seaspray certainly contributes to the chemistry of the lake waters. On

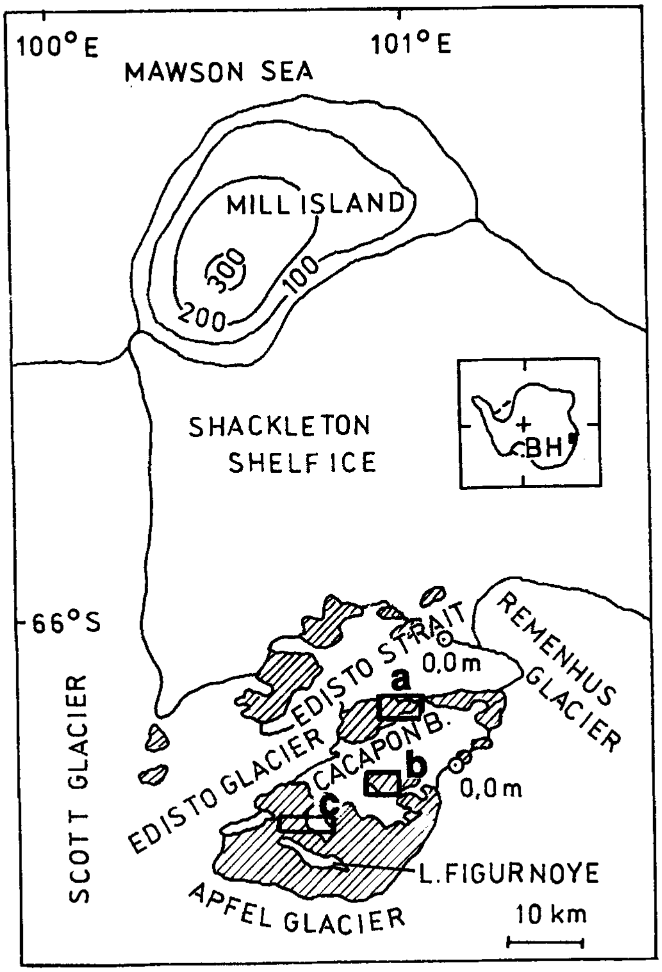

Fig. 1. Location of Bunger Hills and of the areas **a**, **b**, **c** with saline lakes studied. The hatched areas represent ice-free areas of the oasis and islands.

Table I. Some morphometric data of the lakes studied.

Locality, lake	Height above sea level, m	Length, m	Max depth, m
Thomas Island (a)			
Little	15	160	-
[13 m a.s.l.]	13	2000	-
Cachalot Island (b)			
Jaw	8	300	-
Shallow	20	100	0.5
Main landmass (c)			
Eolovoye	30	120	-
Drying	35	50	0.5
Grill	25	350	-
Polest	6	800	6.0
Sredneye	5	150	-
Krugloye	30	230	3.0
Vostochnoye	15	400	6.0
Zapadnoye	15	250	5.0

the other hand, in mid-Holocene (5–6000 years B.P.) the sea level around Bunger Hills was *c.* 10 m higher and at least Lakes Polest, Jaw and Sredneye may have retained relic seawater from that period. A minor sea-rise of 3 m occurred 1400 y B.P.(Bolshiyanov *et al.* 1991). The cryptogamic vegetation on the catchments is rather poor. For example, there were no lichens either on Thomas Island or on the coastal areas SW of the Rybiy Khvost Bay. The vegetation is more developed on the SW and W slopes of the hills protected from the strong and salt laden winds of the E and N directions (Andreyev 1991). There can thus be only minor inflow of nutrients and organic substances into the saline lakes from their catchments.

Most of the data originate from 1987 and 1989 with additional field data on water temperature, oxygen, salinity and pH from 1988 collected by Dr A. Loopmann. A Ruttner bathometer was used to draw water samples from the deepest parts of the lakes through holes drilled in the ice or from an inflatable boat. The water was stored at 0–5°C in polyethylene bottles. The same type of bottle was also used for direct sampling from the littoral parts of the lakes.

Shortly after sampling the carbonates were titrated potentiometrically with HCl and the pH was determined with a glass electrode. These field camp tests also established: (1) salinity to $\pm 0.1^{0}/_{00}$ (2) nutrients, (3) dissolved and particulate organic matter as permanganate oxidation potential (COD) and (4) chlorophyll *a* (Carlberg 1972).

The major ions were determined in Leipzig within 8 months of collection. For the cations atomic absorption spectrophotometry (Mg^{2+}, Ca^{2+}) and flame emission photometry (Na^{+}, K^{+}) were used on a Perkin-Elmer 5000. Cl^{-} was determined with silver nitrate after Mohr and SO_4^{2-} with the barium chromate method (Haendel & Kaup 1986). The $\delta^{18}O$ was determined in the Isotope Geology Laboratory in Tallinn on a Finnigan MAT Delta E mass-spectrometer with internal precision of 0.05%. The dissolved oxygen distribution with depth was recorded with an Oxymet electrode (precision of 0.1 mg l^{-1}), calibrated in distilled water saturated with atmospheric oxygen at a known temperature to allow the *in situ* O_2 values to be corrected according to the O_2 solubility in saline water (Hitchman 1978).

The distribution of the photosynthetically active radiation (PAR, 380–710 nm) at various depths was determined at about noon from the boat or through an 18 cm hole in the ice cover with a phytopyranometer. The coefficients of vertical extinction of PAR in the water were calculated, assuming an exponential decrease in the radiation intensity with increasing depth, by means of the equation

$$I_x = I_0 e^{-kx}$$

where I_0 is intensity of PAR at initial level, I_x at depth x m, and k is the coefficient of extinction of PAR.

The daily primary production of phytoplankton (PP) was determined for several levels in the lake. Water from each

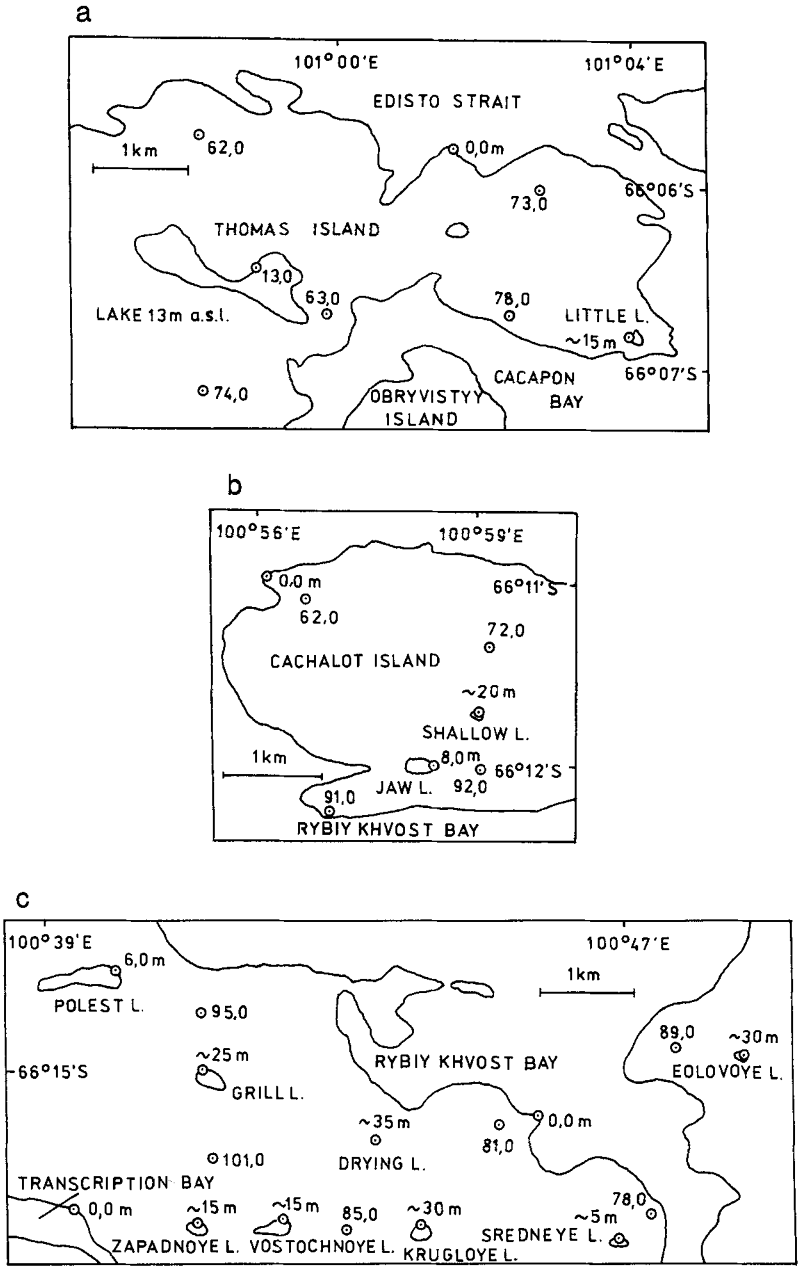

Fig. 2. Location of saline lakes: **a.** on Thomas Island, **b.** on Cachalot Island, **c.** between Rybiy Khvost Bay and Transcription Bay. Lake position and altitude is from the map of SAE 1:50 000, compiled by air photography in 1957; thus most altitudes are approximate.

level was poured into three 100 ml light bottles (one of them contained formalin) and one 100 ml dark bottle. 1 ml of Na$_2$H^{14}CO$_3$ solution, (activity *c.* 4 Ci) was added to each bottle which were then exposed for 24 h. After exposure each bottle was passed through 0.45 μm Millipore filters. The filters were treated with 10 ml distilled water and 1 ml 0.1% HCl. Rack-Beta counter was used to determine the radioactivity. The total inorganic carbon in the water was derived from titrations with HCl. As the dark fixation of carbon frequently proved to be quite high (up to 37% of the fixation in light bottles), the values of non-biological fixation of carbon in the light bottles (those with formalin) were subtracted from the mean values of carbon fixation in the light bottles.

Phytoplankton was sampled from the lake bottom to the surface with of a 15 cm diameter net (mesh size of 10 μm); phytobenthos samples were taken using a bathometer lowered onto the bottom. Samples preserved in 4% formalin were analysed by Prof. H. Pankow, Rostock University.

Results and discussion

Salinity, major ions and isotopes

The salinity of lake waters ranged between 3.4–79.0 $^{\circ}/_{\circ\circ}$ (Table II) and higher salinities occurred in lakes on islands and near Rybiy Khvost Bay. The southernmost Lakes Zapadnoye, Vostochnoye and Krugloye which run from west to east in the Six Lakes Valley, had salinities of 4.5, 5.2–7.2 and 11.0 $^{\circ}/_{\circ\circ}$, respectively. As strong easterly winds are

Table II. Chemical and isotopic composition of waters in saline lakes

Locality	Lake	Date	Depth m	Salinity ‰	pH	Na	K	Ca	Mg	Cl	SO_4	HCO_3+ +CO_3	$\delta^{18}O$ ‰
									gl^{-1}				
Thomas	Little	22.02.89	0.2	27.2	8.11	10.63	0.38	0.50	0.77	-	-	0.15	-12.1
Island	[13m asl]	22.02.89	0.2	23.7	7.89	7.51	0.36	0.44	0.62	-	-	0.13	-14.0
Cachalot	Jaw	04.02.89	0.2	22.7	8.37	6.75	0.33	0.10	0.49	-	-	0.29	-14.4
Island	Shallow	04.02.89	0.2	17.5	7.85	5.39	0.15	0.14	0.13	-	-	0.11	-5.4
Main	Eolovoye	27.02.87	0.2	22.4	8.05	-	-	-	-	-	-	-	-10.8
landmass	Sredneye	01.02.87	0.2	3.4	8.37	1.68	0.08	0.08	0.15	2.0	0.18	0.19	-
	Krugloye	23.02.88	0.2	11.0	8.46	-	-	-	-	-	-	-	-13.1
	Drying	23.02.88	0.2	26.0	8.08	-	-	-	-	-	-	-	-4.2
	Grill	14.02.89	0.2	18.6	8.46	5.40	0.20	0.11	0.44	-	-	0.22	-12.2
	Zapadnoye	09.03.87	2.5	4.5	8.58	1.60	0.10	0.06	0.15	2.1	0.12	0.23	-
			4.5	4.5	8.71	1.60	0.10	0.06	0.15	2.7	0.12	0.23	-13.4
	Vostochnoye	09.03.87	2.0	5.2	8.77	1.70	0.10	0.06	0.17	2.4	0.12	0.27	-10.6
			5.0	5.2	8.82	1.75	0.10	0.06	0.18	3.1	0.14	0.27	-10.1
		19.02.88	0.2	7.2	8.38	-	-	-	-	-	-	-	-
		20.02.89	0.5	5.9	8.64	-	-	-	-	-	-	0.28	-11.3
	Polest	08.02.87	0.2	31.8	8.12	8.50	0.44	0.28	1.16	20.5	1.68	0.14	-11.2
		23.02.88	0.2	48.0	8.08	-	-	-	-	-	-	-	-10.5
		13.02.89	0.5	58.0	8.04	19.2	0.83	0.28	1.28	-	-	0.20	-10.4
			3.0	57.2	8.08	20.7	0.93	0.26	1.19	-	-	-	-
			3.5	77.0	8.00	28.2	1.16	0.40	1.62	-	-	0.30	-11.2
			5.5	79.0	7.97	27.7	1.16	0.40	1.64	-	-	0.32	-12.0
		23.03.89	0.5	65.5	8.11	-	-	-	-	-	-	0.21	-11.0
			3.0	67.0	8.05	-	-	-	-	-	-	0.20	-10.9
			4.0	68.5	8.06	-	-	-	-	-	-	0.24	-10.9
			5.5	68.5	8.02	-	-	-	-	-	-	0.25	-11.2

normal in February–March when Rybiy Khvost Bay is ice-free, the sequence of increasing salinity may illustrate the impact of wind blown sea-spray. This phenomenon is certainly influenced by snowfield meltwater dilution, as in the case of Lake Sredneye.

Wind driven water circulation gave a rather uniform salinity profile in Lakes Zapadnoye and Vostochnoye in February–March (Table II), but its values varied from season to season and year to year (Fig. 3). In Lake Vostochnoye the salinity increase of 0.2–0.3 ‰ after the establishment of ice cover can be explained by the freeze-out of salts. The salinity may also be affected by pressure exerted by the weight of snow accummulation. An observation made on 19 January 1987 showed that the surface salinity of partly ice-covered Lake Zapadnoye was only 0.7 ‰ and that of ice-free Lake Vostochnoye 3.4‰, much less than on 9 March 1987 (Table II). The surface salinities were clearly decreased by melting ice and there was probably a salinity increase with depth also in Lake Vostochnoye.

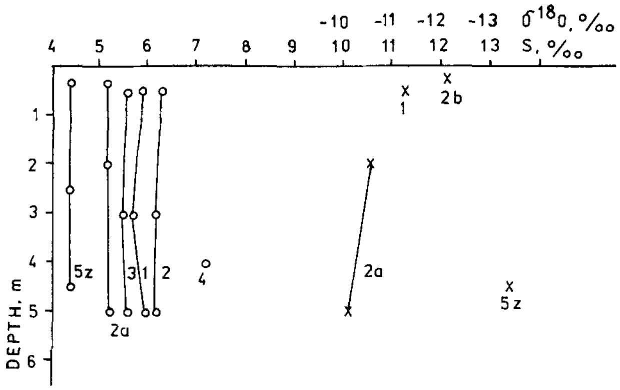

Fig. 3. Salinity (o) and $\delta^{18}O$ (x) in Lake Vostochnoye in 1987–89: **1** 19.02.89, **2** 09.03.89, **2a** 09.03.87, **2b** 19.01.87, **3** 26.03.89, **4** 19.03.88. **5z** represents L. Zapadnoye 09.03.87.

Until mid-February wind-driven turbulence did not destroy the sharp thermohalocline in Lake Polest (Fig. 4). This difference between the stability of the two lakes apparently arose from differences in their salinity. The reasons for thermohalocline and for the year-to-year variability in surface salinity in Lake Polest are discussed below.

The comparison with saline lakes in other oases of East Antarctica shows that the lakes of Bunger Hills are of lower salinity than the lakes in the vicinity of Syowa Station where chlorinities up to 158 g l^{-1} were rendered (Fukui *et al.* 1985). In Vestfold Hills the salinities of several lakes were found to be 100–200 g kg^{-1}, with a maximum in Deep Lake at 224 g kg^{-1}, (Burke & Burton 1988).

The dominance of Na^+ and Cl^- in all the samples indicates the mainly marine origin of salts in lake waters and is further confirmed by the distinct domination of Mg^{2+} over Ca^{2+}. In the water of Lakes Polest, Jaw and Grill the Mg^{2+}/Ca^{2+} ionic ratios exceeded 5.24, a typical value for Antarctic seawater (Meyer *et al.* 1962) which indicates a possible precipitation of $CaCO_3$ at low temperatures. The Lakes Zapadnoye and Vostochnoye had intermediate ratios of 4.1–4.9 and other lakes 2.1–2.5. However, the Shallow Lake on Cachalot Island had a ratio of 1.5, representing the minimum marine influence among the saline lakes studied. The freshwater lakes of the Bunger Hills with glacial meltwater input and positive water balance had Mg^{2+}/Ca^{2+} ratios of 0.44–0.72 (Kaup *et al.* 1990).

The isotopic composition of lake water mainly depends on the origin of the water and on the local climatic conditions. Most of the small saline lakes in the oasis originate from hollows filled with seawater which became separated from the sea during isostatic uplift. Nowadays they are usually fed from the meltwater of snow and firn fields in the oasis with average $\delta^{18}O$ values of about -18 to -20$^{\circ}/_{00}$ (Kaup & Vaikmäe, unpublished). Thus, the lake water is usually a mixture of sea water and freshwater. Besides these two components the isotopic composition of lake water strongly depends on the intensity of evaporation. The lakes of higher salinity freeze at lower temperature and are, therefore, influenced by evaporation for longer period. This might be one of the reasons, why the lakes with higher salinity have heavier isotopic composition (Table II). However, exceptionally heavy isotopic composition (-4.2 and -5.4$^{\circ}/_{00}$, respectively) in Lakes Drying and Shallow is most probably caused mainly by strong prevailing intensive evaporation over feeding with meltwater.

In Lake Polest the two $\delta^{18}O$ profiles measured at different times indicate the role of wind-driven turbulence in the water column, leading to more homogeneous isotopic composition throughout the water body. At the same time the existing unlinearity between the $\delta^{18}O$ values and salinity in Lake Polest (Fig. 4, lines 1) shows that the water in this lake is not a simple mixture of seawater and freshwater. Obviously original seawater has gone through several freezing cycles, resulting in the concentration of salts. That kind of process is well known in many Antarctic saline lakes (Matsubaya *et al.* 1979).

Light climate

The monthly total radiation changes from 783 MJ m^{-2} in December to zero in June and does not exceed 113 MJ m^{-2} from April–August (Dolgin *et al.* 1976). Radiation measurements for this study during February and March gave mean monthly total radiation of 452 and 293 MJ m^{-2}, respectively.

Radiation levels in the water column depend on the ice and snow cover on the lakes. Most of the saline lakes freeze during the first 10 days of March. A curious exception is a lake in the central part of Cachalot Island which was ice-free on 19 March 1987 and partly frozen on 10 April 1989 (air observations), suggesting that even higher salinities than in Lake Polest may occur (indeed on 7 March 1992 the salinity of 139$^{\circ}/_{00}$ was fixed, personal communication D. Bolshiyanov). Evidence of late freezing of more saline lakes was obtained from Lake Polest. On 16 March there was only 4 cm of white, rather opaque ice. On 23 March the ice (covered by 6 cm of frozen snow) attained a 9 cm thickness. Lake Vostochnoye was covered with an ice thickness of 9–11 cm on 9 March 1987 and 1989, but the ice cover was 2–4 cm thinner and more opaque than that on the freshwater Lake Figurnoye. On 7 April 1989 the ice thickness on Lake Vostochnoye achieved 30 cm (cf. 40 cm on Lake Figurnoye on the same day).

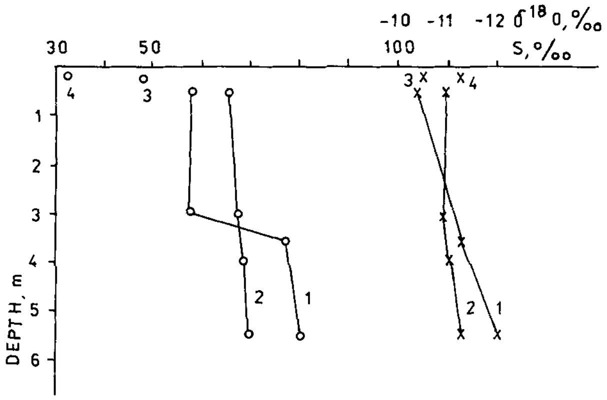

Fig. 4. Salinity (o) and $\delta^{18}O$ (x) in Lake Polest in 1987–89: **1** 13.02.89, **2** 23.03.89, **3** 23.02.88, **4** 09.02.87.

The data of 1987–89 (unpublished meteorological records of SAE) show that heavy snowfalls occurred in the Bunger Hills in March, but this snowcover on the lakes was mostly blown away by strong winds at the beginning of April. The snow cover on Lake Vostochnoye was 2 cm on 9 March, 13 cm on 26 March and again zero on 5 April 1989.

The PAR levels in lakes decreased in the course of the autumn (Fig. 5). Besides total radiation which penetrates the water surface they depend on the content of particulate material in the water, kept in circulation by wind-driven currents. Stronger winds result in higher content of particulate material in the water, churned up from the bottom and blown in from the surrounding rocks. On 9 March 1989 the extinction coefficient k was 0.488 m^{-1} in Lake Vostochnoye compared with 0.244 m^{-1} on 9 March 1987, and 0.271 m^{-1} in Lake Zapadnoye on the same day. The difference can be explained by the difference in wind speeds: the mean values for February in 1989 and 1987 were 5.2 and 3.5 ms^{-1}, respectively. The snow cover dramatically reduced the PAR levels under ice. While 8% of incident light reached the lake bottom at 5.4 m through open water in February 1989 (by measured Secchi transparency of 4.8 m) and 12% through 9 cm of ice in March 1987, in March 1989 the snow cover of 2 cm decreased this to 1%.

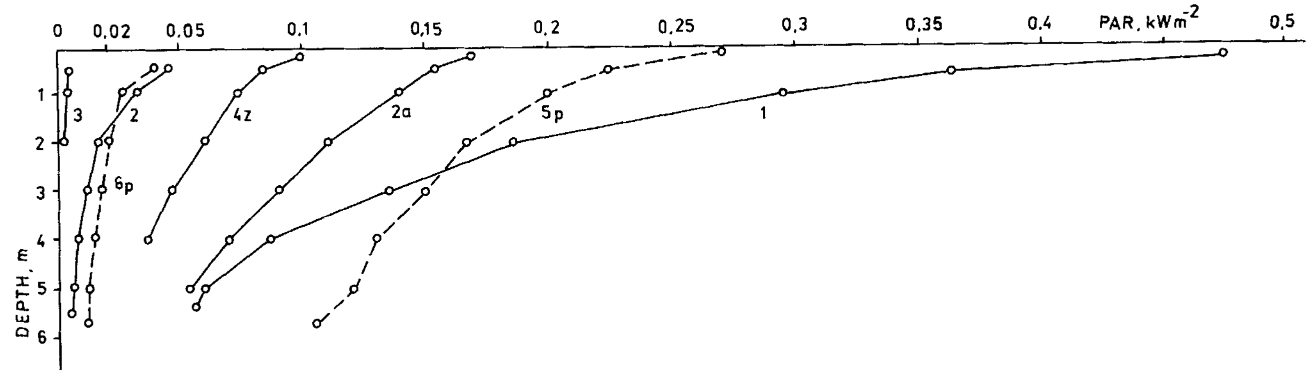

Fig. 5. Distribution of PAR in the water column. Lake Vostochnoye: **1** 19.02.89 (incident total radiation 0.69 kWm^{-2}), **2** 09.03.89 (0.60); **2a** 09.03.87 (0.40), **3** 26.03.89 (0.53). **4z** represents Lake Zapadnoye 09.03.87 (0.30). Lake Polest (dotted line): **5p** 14.02.89 (0.57), **6p** 23.03.89 (0.38).

Similar results were obtained in Lake Polest (Fig. 5) where the water was more transparent than in Lake Vostochnoye with Secchi transparency of 6.0 m and an extinction coefficient of 0.167 m^{-1}. The thermohalocline had kept the bottom sediment in place during February but after the mixing of the water column, k increased to 0.232 m^{-1} at the end of March. The values of k appeared to be of similar magnitude to those in saline Ace Lake of Vestfold Hills (0.17–0.52 m^{-1}) (Burch 1988). The phytoplankton can have played only a minor role in the extinction of PAR in saline lakes of the Bunger Hills as the concentration of chlorophyll *a* was *c.* 1 mg m^{-3} in Lake Vostochnoye and 0.5 mg m^{-3} in Lake Polest (see below).

Temperature

Temperatures were measured during the autumnal cooling from mid-February to the beginning of April. Lake Vostochnoye followed that trend closely (Fig. 6) and any solar heating after the establishment of ice cover at the beginning of March was terminated by a snowfall on 7 March. The cooling continued and by 5 April the temperature of the upper layers of water was -0.3°C.

Rather higher water temperatures were recorded in Lake Polest. On 13 February the temperature of the 3 m of epilimnion was 5.2°C but after a sharp thermocline coinciding with a halocline of 20 ‰ it reached 11.7–11.8°C at depths of 3.5–5.8 m. At the very bottom the temperature was as high as 17.7°C (Fig. 7), suggesting a salinity higher than the 79.0 ‰ observed at 5.5 m (Table II). After quite a cold and windy night the temperature of the epilimnion fell to 4.5°C but at greater depths it was unchanged. Hence the hypolimnion of the shallow Lake Polest acts as an efficient solar energy trap, at least during meromictic conditions in summer, resulting in higher bottom water temperatures than those recorded in saline lakes of Vestfold Hills (Burke & Burton 1988) and in the vicinity of Syowa Station (Fukui *et al.* 1985). By 23 March the temperature had fallen sharply, and was -3°C in the upper 5 m but 4.7°C at the very bottom. The stratification was probably destroyed by storms on 23–24 February when the wind speed peaked at 35 m s^{-1}.

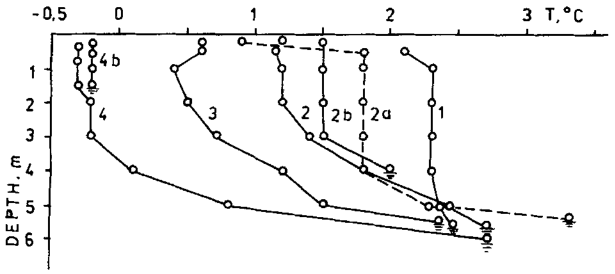

Fig. 6. Temperature in the water column of Lake Vostochnoye in 1987–89: **1** 20.02.89, **2** 09.03.89, **2a** 09.03.87, **2b** 19.03.88, **3** 26.03.89, **4** 05.04.89, **4b** 08.04.88. Underlined points represent values on lake bottom.

The data allowed prediction of the year-round development of stability of Lake Polest and to a lesser extent also of Lake Vostochnoye and other lakes. In the course of autumn a further decline of temperature occurred, demonstrated also by the data of Dr A. Loopmann from 1988 (Fig. 7). Since the growing ice cover (40 cm was observed on 8 April 1988 and a maximum thickness of 1.0–1.5 m could be predicted) was depleted in salts, the salinity of the rest of water column increased substantially. During the vernal and summer solar heating the melting ice diluted the surface layers of water. The lake bottom and near-bottom layers of water were heated but because of their higher density the vertical convection was restricted by a halocline and nearly all the solar heat penetrating into the hypolimnion was used to increase the temperature of the bottom and the water under halocline. After the disappearance of ice cover (probably at the end of December) the situation will be as observed on 13–14 February but at the end of January due to higher solar angles and higher air temperatures the water temperatures will probably be higher (on 1 February 1992 a water temperature of 21.1°C was measured at a depth of 5–6 m, personal

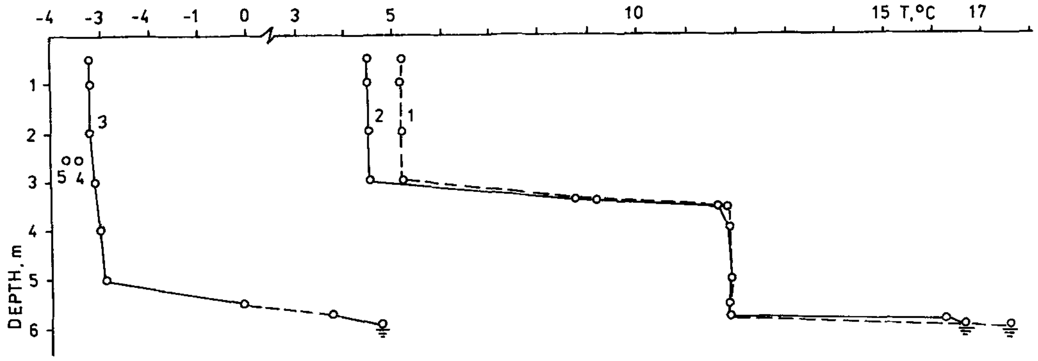

Fig. 7. Temperature in the water column of Lake Polest in 1988-89: **1** 13.02.89, **2** 14.02.89, **3** 23.03.89, **4** 30.03.88, **5** 08.04.88. Underlined points represent values on lake bottom.

communication D. Bolshiyanov). If the halocline is not destroyed by autumnal storms, the temperature and salinity gradients may become more marked in the following summer. This is also the explanation for the different salinities of surface waters, observed in Lake Polest in February of the years 1987–1989 (Table II). Thus at present Lake Polest possesses substantial meromictic features which may strengthen if the duration of ice cover is extended by the climatic cooling. Due to their lower depth and salinity the saline lakes of Bunger Hills have not yet achieved meromixis, as is usually the case in saline lakes of Vestfold Hills and Syowa Coast.

Dissolved oxygen and pH

During the open water period and shortly after the establishment of the ice cover in 1989 oxygen concentration was 2–6% below saturation in Lake Vostochnoye (Fig. 8). The saturating concentrations at the observed salinities of 5.9 and 6.2 $^{\circ}/_{00}$ and water temperatures of 2.3 and 1.2–1.8°C were 13.1 and 13.5 mg O_2 l^{-1}, respectively. However, on 9 March 1987 (the period of snowless ice cover) the water was oversaturated with oxygen by 2–5%, probably due to algal photosynthesis in the lake. By 26 March, with 13 cm of snow, the oxygen concentration had declined to 75–80% of saturation. After two days the snow was blown away by strong winds and by 5 April the oxygen concentration had risen to 111–113% of saturation. The decline of oxygen near the bottom shows a bottom uptake while the increasing oxygen concentration under the ice indicates freezeout from the ice cover.

The epilimnion of Lake Polest was 100% saturated with oxygen on 13 February (Fig. 9), the saturation value being 8.5 mg O_2 l^{-1} at 5.2°C and a salinity of 59 $^{\circ}/_{00}$. At the depth of 3.4 m, the lower part of the thermohalocline, the water was nearly 200% saturated with oxygen and at greater depths the oxygen level was more than 14.3 mg l^{-1} (>230%). Such very high oxygen values were apparently due to the algal photosynthesis in this almost closed system, represented by the hypolimnion with high temperatures and sufficient light as well as adequate nutrients. These were higher saturation values than in saline lakes in the vicinity of Syowa Station (Fukui *et al.* 1985) and in Lake Fryxell where a maximum oxygen concentration of 23 mg l^{-1} or 170% of saturation was measured under the ice at the depth of 7 m (Matsumoto *et al.* 1989). On 23 March only 6.4 mg O_2 l^{-1} (*c.* 75% of saturation) remained near the bottom and, as the ice was rather opaque and the polar night was approaching, a further decline could be predicted.

pH values of *c.* 8 were obtained from most of the saline lakes of Bunger Hills. Only in Lakes Zapadnoye and Vostochnoye did they range between 8.4–8.8. In the latter lake the pH values gradually decreased during the observation period of 1989 (Fig. 8), probably from the freeze-out of salts and dissolved gases from growing ice cover.

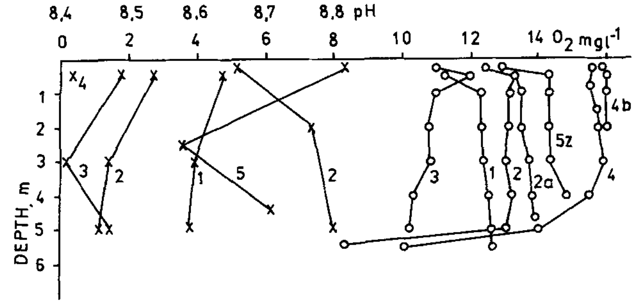

Fig. 8. Dissolved oxygen (o) and pH (x) in Lake Vostochnoye in 1987–89: **1** 19.02.89, **2** 09.03.89, **2a** 09.03.87, **3** 26.03.89; **4** 05.04.89, **4b** 08.04.88. **5z** represents Lake Zapadnoye 09.03.87.

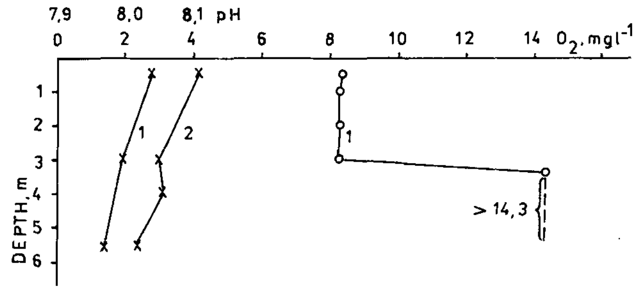

Fig. 9. Dissolved oxygen (o) and pH (x) in Lake Polest: **1** 13.02.89, **2** 23.03.89.

Nutrients and organic matter

The depth-time distribution of nutrients levels was generally uniform in most lakes (Table III). The concentration of phosphates was low (3–10 μgP l^{-1}) in all the lakes. Total phosphorus was usually 8–16 μgP l^{-1}, except in Lake Polest where the levels were 28–39 μgP l^{-1}. Phosphate constituted 13–24% of total phosphorus in Lake Polest but significantly more (the total range 27–83%) in other lakes.

The very low levels of nitrates (typically 1.1–3.8 μgN l^{-1}, omitting the extreme values) were remarkable, often being even lower than the levels of nitrites (1.2–3.9 μgN l^{-1}). A typical feature of nitrite distribution was an increase after the establishment of ice cover, particularly in under-ice samples, which may indicate freeze-out.

The values of ammonium were available only from Lakes Zapadnoye and Vostochnoye from 9 March 1987 and here, as the concentrations of 120–130 μgN l^{-1} were recorded under the ice cover, the freeze-out seems to increase the levels of ammonium in lake water. Rather high values of silica (mostly 4–10 mgSi l^{-1}) were recorded, though after the establishment of ice cover the silica values decreased in Lakes Vostochnoye and Polest.

In general the nutrient levels were similar to those observed in saline lakes of Syowa Coast (Fukui *et al.* 1985) and of Vestfold Hills (Burch 1988), except for much higher phosphorus and ammonia values in the anaerobic monimolimnia of the referenced lakes.

The total organic carbon was high in the three lakes studied. The marked accumulation of organic matter in hypolimnion of Lake Polest can be explained by intensive algal primary production and low degradation rates due to the onset of low temperatures after the disappearance of stratification.

Algal species composition, chlorophyll a *and primary productivity*

Phytoplankton and phytobenthos composition was available only from Lake Polest. On 14 February 1989 a phytobenthos sample from 6 m depth showed dominance by the pennate diatom *Navicula cryptocephala* var. *intermedia* Grun.; another pennate *Achnanthes brevipes* var. *intermedia* (Kütz.) Cleve was also present. On 23 March 1989 a phytoplankton sample (from bottom at 6 m to surface) showed the continued presence of *N. cryptocephala*, with two centric diatoms, *Coscinodiscus oculus iridis* Ehrenb. and *C. centralis* Ehrenb. Thus, all the species recorded are typical marine diatoms. This is not surprising as Rybiy Khvost Bay is only 0.5 km distant and strong winds from the sea are frequent. In a phytobenthos sample at 30 m depth in the Bay of the many diatom species identified only *C. centralis* Ehrenb. was found in Lake Polest.

The flora of the hypersaline (> 35°/$_{oo}$ salinity) Antarctic lakes is known to be poor. Only three algal species have been found (Wright & Burton 1981). This short list includes also

Table. III. Nutrients in saline lakes, in μg l^{-1}; silica and permanganate oxidation potential (COD) in mg l^{-1}.

Lake	Date	Depth m	N-NH$_4$	N-NO$_2$	N-NO$_3$	Si	P$_t$	P-P0$_4$	COD
Grill	14.02.89	0.2	-	1.9	2.6	6.5	18	6	-
Zapadnoye	09.03.87	0.3	120	2.2	3.0	7.0	11	3	6.0
		2.5	10	1.9	3.0	8.0	13	7	5.5
		4.5	30	1.9	3.5	9.0	0	3	5.2
Vostochnoye	09.03.87	0.3	130	1.6	3.8	11.0	16	5	6.8
		2.0	50	2.2	0.3	10.8	15	6	12.5
		5.0	10	1.8	2.8	10.0	12	7	12.0
	20.02.89	0.5	-	1.9	1.9	6.8	12	9	-
		3.0	-	1.2	1.8	6.8	12	7	-
		5.0	-	0.9	1.5	6.8	10	6	-
	09.03.89	0.5	-	3.3	1.3	3.0	14	9	-
		3.0	-	3.3	1.6	5.0	12	10	-
		5.0	-	2.8	3.6	3.5	12	7	-
	26.03.89	0.5	-	3.9	2.0	7.0	12	8	-
		3.0	-	2.6	1.4	4.5	10	6	-
		5.0	-	3.4	1.1	6.5	8	6	-
Polest	08.02.89	0.2	-	1.0	4.2	3.4	33	12	-
	13.02.89	0.5	-	1.6	2.4	4.0	28	5	43.2
		3.5	-	1.9	2.6	5.5	38	6	61.6
		5.5		1.9	3.6	5.8	39	5	61.6
	23.03.89	0.5	-	5.0	1.1	4.1	34	6	-
		3.0	-	3.8	3.1	4.2	35	5	-
		4.0	-	2.6	3.5	4.2	33	8	-
		5.5	-	3.3	2.8	3.0	34	6	-

A. brevipes var. *intermedia* Kütz. found in Lake Polest but both the above-mentioned Coscinodiscaceae and *N. cryptocephala* var. *intermedia* Grun. represent additions.

The levels of chlorophyll *a* (0.26–0.63 mg m^{-3}) in Lake Polest (Fig. 10) were quite stable both under the surface and near the bottom in February–March. The maximum values of 0.6 mg m^{-3} were observed at intermediate depths and may reflect accumulation of the phytoplankton cells on the 'liquid bottom' of the thermohalocline.

Higher chlorophyll *a* levels were recorded in Lake Vostochnoye (Fig. 11) where distinct vertical differences were found on 9 March 1989. On 9 March 1987 the mean values of three depths were quite close to those on the former date. Values (Lake Zapadnoye) were slightly lower at 0.6–0.7 mg m^{-3}. A two-fold increase was observed at the end of March and at the beginning of April in Lake Vostochnoye. Similar increases have been recorded in the freshwater lakes of the Bunger Hills, where the chlorophyll *a* levels were mostly 2–3 times lower (Kaup, unpublished). The chlorophyll *a* values in the saline lakes of Bunger Hills thus appeared rather low if compared with Ace Lake (an April–January range of 0.5–10 mg m^{-3}) or with 11.3 mg m^{-3} in Plus 14 Lake in Vestfold Hills (Burch 1988).

Primary productivity (PP) patterns were similar in both lakes in the open water (Figs 12 & 13). As the underwater PAR levels were very high photoinhibition in the epilimnion was apparent. In the hypolimnion of Lake Polest high water temperatures probably enhanced photosynthesis. Substantially lower values of PP were recorded in this lake at low PAR levels and very low temperatures at the end of March, although nutrients and chlorophyll *a* levels were largely unchanged.

A remarkable, nearly four-fold, difference in PP was observed in Lake Vostochnoye comparing 9 March 1987 and 9 March 1989. While a probable photoinhibition was observed under the ice (also in Lake Zapadnoye) on the former date, the PAR values on the latter date were probably insufficient (Fig. 5) for the same chlorophyll *a* levels and nearly the same temperatures.

The 20 measurements of PP in three saline lakes in February–March ranged 0.013–0.171 gC $m^{-3}d^{-1}$, an order of magnitude higher than in the freshwater lakes of Bunger

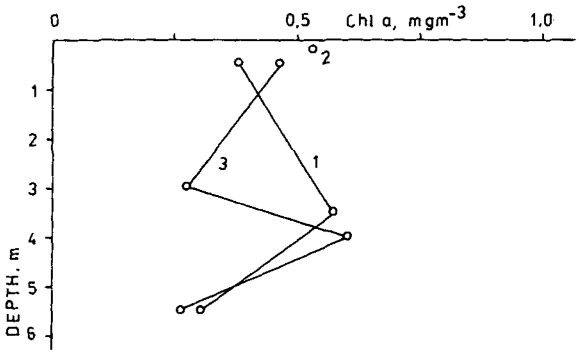

Fig. 10. Concentration of chlorophyll *a* in Lake Polest: **1** 13.02.89, **2** 16.03.89, **3** 23.03.89.

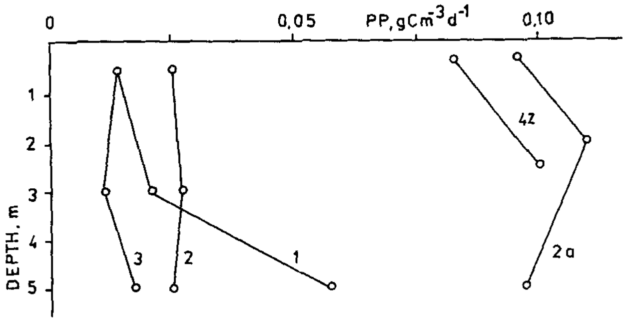

Fig. 12. Primary production of phytoplankton (PP) in Lake Vostochnoye: **1** 19.02.89, **2** 09.03.89, **2a** 09.03.87, **3** 26.03.89. **4z** represents Lake Zapadnoye 09.03.87.

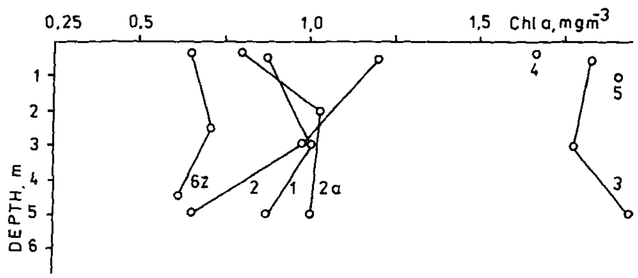

Fig. 11. Concentration of chlorophyll *a* in Lake Vostochnoye: **1** 19.02.89, **2** 09.03.89, **2a** 09.03.87, **3** 26.03.89, **4** 05.04.89, **5** 06.04.89. **6z** represents Lake Zapadnoye 09.03.87.

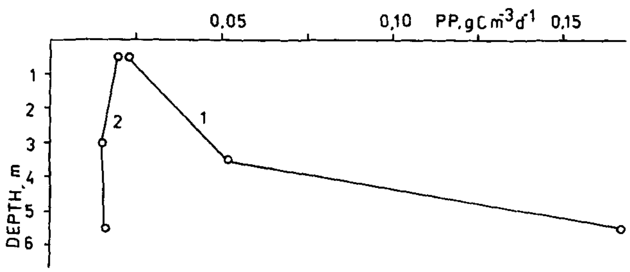

Fig. 13. Primary production of phytoplankton (PP) in Lake Polest: **1** 13.02.89, **2** 23.03.89.

Hills with measurements between 0.0006–0.019 gC m^{-3}d^{-1} (Kaup, unpublished).

The assimilation rates differed markedly between Lakes Vostochnoye and Polest. In open water the rates in the epilimnion were 0.7–0.9 mgC (mgchl *a*)$^{-1}$h^{-1} in Lake Vostochnoye and 2.4–3.7 in Lake Polest, at the end of March they fell to 0.3–0.4 in the former and 1.8–2.6 in the latter. A very high assimilation rate of 23.9 was recorded in the hypolimnion of Lake Polest in the mid-February (cf. 2.7 in Lake Vostochnoye), reflecting very favourable conditions for photosynthesis. High assimilation rates of 4.3–5.9 were found also on 9 March 1987 in Lakes Zapadnoye and Vostochnoye.

The few measurements of the PP in saline lakes elsewhere in the Antarctic (0.004–0.011 gC m^{-3}d^{-1} in Ace Lake in February and 0.003–0.008 gC m^{-3}d^{-1} in Lake Bonney) (Wright and Goldman, Wright & Burton 1981) are much lower. A range of assimilation rates of 0.05–0.10 mgC [mg Chl *a*]$^{-1}$h^{-1} was measured at the sediment/water interface in Deep Lake in Vestfold Hills (Wright & Burton 1981) again lower than in the Bunger Hills. The shallower depths and consequently higher summer temperatures in the saline lakes of the Bunger Hills may be the cause of higher PP and assimilation rates than in other lakes.

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