Antarctic Science 14 (3): 253–261 (2002) © Antarctic Science Ltd Printed in the UK DOI: 10.1017/S0954102002000100

Physical structure of epishelf lakes of the southern Bunger Hills, East Antarctica

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Abstract: Epishelf lakes, positioned between ice-free areas and floating ice shelves or glaciers, are unusual tidal, but largely freshwater, environments found in both the Arctic and the Antarctic. The greatest concentration of these lakes is in the Bunger Hills, East Antarctica (66°S, 100°E). We present and discuss temperature and salinity profiles for five epishelf lakes from this region, most of which show unusual properties. White Smoke Lake is fresh and cold (< 0.1°C) throughout; Lake Pol'anskogo has two basins, one fresh and cold, the other saline and warm; 'Southern' Lake is cold and saline at depth; Transkriptsii Gulf has a deep, warm saline layer; and 'Northern' Lake is relatively warm throughout. The structures of these lakes can be explained in terms of a simple model in which the isolated saline water evident in three of the lakes entered the basins through the connection to the marine waters during periods of reduced freshwater input. By dating these marine incursions, periods of reduced melt, presumably due to colder temperatures, can be determined.

Received 23 November 2001, accepted 10 June 2002

Key words: Bunger Hills, climate change, epishelf, stratification, salinity, temperature

Introduction

Beginning in the 1950s a series of unusual lakes located between rocky, ice-free areas and floating ice shelves was discovered in Antarctica (Korotkevich 1960, Simonov 1963, Kruchinin & Simonov 1967, Heywood 1977, Piskun & Klokov 1986). These lakes, which were fresh, tidal, and were often located many tens of kilometres from open marine waters, were termed epishelf lakes. They result from accumulation at the ice–rock margin of freshwater runoff from the rocky areas and the continental polar plateau, as well as from the surface of the floating ice shelf. These unusual environments have engendered interest from a number of viewpoints, including as indicators of climate change (Vincent *et al.* 2001), and the possibility that they may act as refugia for freshwater zooplankton such as copepods during glacial periods when most of the freshwater environments currently found in Antarctica would have been covered by glacial ice (Bayly & Burton 1993).

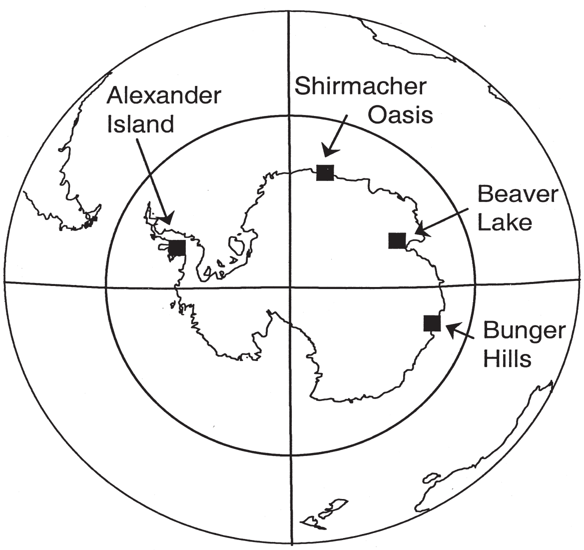

Fig. 1. Known locations of epishelf lakes in Antarctica. Further lakes probably occur around the margin of the continent.

Epishelf lakes have been recorded from northern Ellesmere Island in Arctic Canada (Van Hove *et al.* 2001, Vincent *et al.* 2001) and from four widely spread areas on the margin of the Antarctic continent (Fig. 1): Alexander Island (Heywood 1977), Schirmacher Oasis (Bormann & Fritzsche 1995), Beaver Lake (Wand *et al.* 1988, Laybourn-Parry *et al.* 2001), and the Bunger Hills and surrounding areas (Klokov *et al.* 1990, Gal'chenko *et al.* 1995, Doran *et al.* 2000).

Two types of epishelf lakes have been identified (Fig. 2). In the first, the freshwater layer floats directly on saline marine water, and the depth of the freshwater layer is controlled by the thickness of the ice-shelf. Examples of this type include Beaver Lake (Wand *et al.* 1988) and Disraeli Fiord in the Canadian Arctic (Vincent *et al.* 2001). Lakes of the second type are characterized by an indirect hydraulic connection with the marine environment, which presumably occurs at the land-ice contact or through cracks in the ice

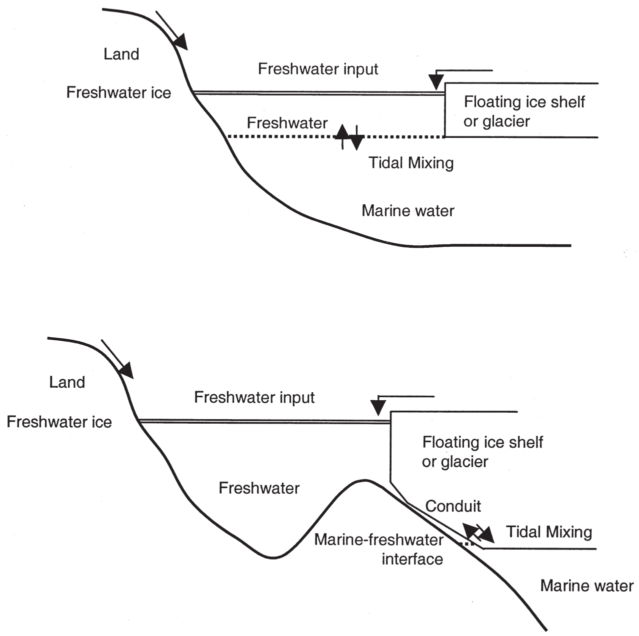

Fig. 2. Types of epishelf lake. **a.** Type 1, with freshwater directly overlying marine water (e.g. Beaver Lake), **b.** Type 2, with an indirect connection to the marine environment (e.g. the epishelf lakes of the Schirmacher Oasis)

sheet. Type 2 lakes may be entirely fresh, but are still tidal. Examples include the epishelf lakes of the Schirmacher Oasis, none of which contain salt water (Bormann & Fritzsche 1995).

Due in part to their isolation, the physical limnology of epishelf lakes is poorly known. Wand *et al.* (1988) presented limited data for Beaver Lake that showed the temperature of the freshwater portion of the water column to be -0.2 to +0.12°C, with colder temperatures in the marine zone. Laybourn-Parry *et al.* (2001) recorded warmer water near the surface of the lake (T_{max} = 2.3°C at 24 m), but the temperature dropped to near freezing deeper in the water column. Heywood (1977) also reported near freezing temperatures (< 0.3°C) throughout the water columns of Ablation and Moutonée lakes, Alexander Island. In contrast, Gal'chenko *et al.* (1995) recorded significantly warmer temperatures (> 5°C) in Lake Pol'anskogo in the Bunger Hills. This lake, as well as Transkriptsii Gulf, also in the Bunger Hills, was characterized by the presence of anoxic, saline water at the base of the water column. In order to gain insight into the processes that lead to these characteristics, detailed temperature and salinity profiles of five epishelf lakes in the Bunger Hills of contrasting physical structures were recorded in January 2000. These profiles, along with less-detailed profiles recorded in early 1992, were used to develop a model that explains the interesting limnological properties of these lakes.

Methods

Temperature and salinity profiles were recorded in January–March 1992 and January 2000. All of the lakes were covered by ice, which ranged in thickness from 1.8 m to 3.9 m (Table I). Holes were drilled through the ice with a motorized ice drill or by hand using an ice auger. The zero mark for all profiles was the piezometric water level in the hole. In 1992, temperature and conductivity profiles were recorded at metre or coarser intervals with a Hydrolab DataSonde 3 multiprobe (Hydrolab Corporation, Texas). Salinity was calculated from these parameters using equations provided in the instrument manual. In 2000, temperature and conductivity profiles were recorded with a Falmouth Instruments 3" MicroCTD unit (Falmouth Instrument, Massachusetts), which was lowered slowly into the water column while collecting data at *c.* 1 Hz (equivalent to a depth interval of *c.* 5 cm). Salinity was calculated using in-built algorithms. Theoretical freezing temperatures were calculated from salinity and depth by the algorithm given by Millero & Leung (1976). Under-ice water temperature in Transkriptsii Gulf was measured during January 2000 using a Tidbit temperature recorder

Table I. Morphological parameters of lakes visited during this study. The date of the measurement of the thickness of the ice-cover is noted.

Lake	Location	Area km^2	Maximum recorded depth (m)	Ice-cover 1992 (m)	Ice-cover 2000 (m)
White Smoke Lake	66°19'S 100°36'E	0.83	90[1]	2.3 (19 February)	3.7 (13 January)
Lake Pol'anskogo	66°19'S 100°30'E	2.0	69[2]	2.2 (9 March)	3.5 (13 January)
Southern Lake	66°17'S 100°29'E	0.83	68[3]	n.d.	3.8 (8 January)
Transkriptsii Gulf	66°15'S 100°35'E	14.4	122[4]	2.6 (17 March)	3.9 (11 January)
Northern Lake	66°13'S 100°39'E	0.55	22[3]	n.d	3.7 (9 January)

n.d. = not determined.
References: [1]Doran *et al.* 2000, [2]Gal'chenko 1994, [3]this study, [4]Klokov *et al.* 1990

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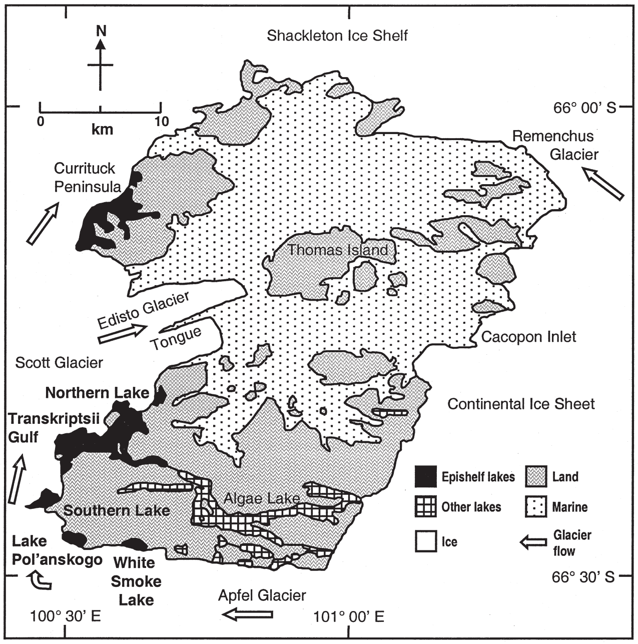

Fig. 3. Map of the Bunger Hills, showing the locations of the epishelf lakes profiled during this study.

Fig. 4. Aerial view of Lake Pol'anskogo, March 1992. North is to the top and right of the image. Tide cracks are clearly evident around the margins of the lake and around the islands within the lake. The line of islands that forms part of the sill that isolates the western basin is clearly visible.

(Onset Corporation, MA) positioned *c.* 1 m below the base of the ice cover.

The temperature and salinity profiles were recorded with different instruments in the two field seasons, and variations between profiles could, in part, be due to differences in the accuracy and resolution of the instruments, especially considering the small temperature and salinity gradients measured in some of the profiles. The Hydrolab 3 unit had a stated accuracy of ± 0.15°C and resolution 0.01°C; recalibration of the unit after the Antarctic field season by the manufacturer indicated that the difference between the measured and actual temperatures was within this tolerance. The accuracy of the Falmouth MicroCTD unit, which had been recalibrated prior to the 1999/2000 field season, was given as 0.002°C, with resolution 0.0001°C. Similarly, the algorithms used to calculate salinity from temperature and conductivity were different, and the data may not be strictly comparable at low salinity. For low salinity water (< 0.1 g l^{-1}), typical *in situ* conductivity is also given so that comparisons can be made.

Sample locations

The Bunger Hills, which, at 952 km^2, is the largest ice-free oasis on the coastline of East Antarctica (Wisniewski 1983), is completely surrounded by ice: to the east is the Remenchus Glacier and the Antarctic Ice Sheet, to the south the Apfel Glacier, to the west the Scott and Edisto glaciers, and to the north the floating Shackleton Ice Shelf (Fig. 3). Over 400 km^2 of the oasis is taken up by Cacapon Inlet, an area of marine water isolated (at least at the surface) from the Southern Ocean. The topography of the Bunger Hills *sensu stricto* is rugged, with a maximum altitude of 160 m. The exposed rock is dotted with numerous freshwater and saline lakes, including Algae (Figurnoe) Lake, one of the largest freshwater lakes in Antarctica.

A complete survey of the epishelf lakes of the Bunger Hills and surrounding areas has not been made, but it is possible that as many as twelve are present. Most of the epishelf lakes are located at sea level along the western and a section of the southern margins of the Bunger Hills, where the floating Apfel, Scott and Edisto Glaciers are adjacent to the exposed rock. The ice to the east is continental ice and rock-based glaciers, so no epishelf lakes occur in this region. Cacopon Inlet could also be considered an epishelf lake, but in this case runoff into the basin from the hills and the surrounding ice is at present insufficient to create a permanent freshwater layer (Melles 1994, Kulbe *et al.* 2001). Further epishelf lakes occur adjacent to nunataks surrounded by the Scott and Apfel Glaciers, and in the Obruchev Hills, *c.* 50 km to the south-west.

The five epishelf lakes profiled in this study were located along the southern and western margins of the southern Bunger Hills (Fig. 3). Some morphological characteristics of the lakes are presented in Table I. White Smoke Lake (unofficial name) is located between the southern margin of the Bunger Hills and the Apfel Glacier. The land margin is rugged, with many semi-permanent snow banks (see aerial photographs in Doran *et al.* 2000). The lake receives melt water from both terrestrial and supraglacial drainage systems. Tide cracks around the margins of the lake are clearly evident in photographs from 1947, and direct observation of a tidal range of *c.* 1 m was made in 1992 (Doran *et al.* 2000). In contrast, no tide cracks or other signs

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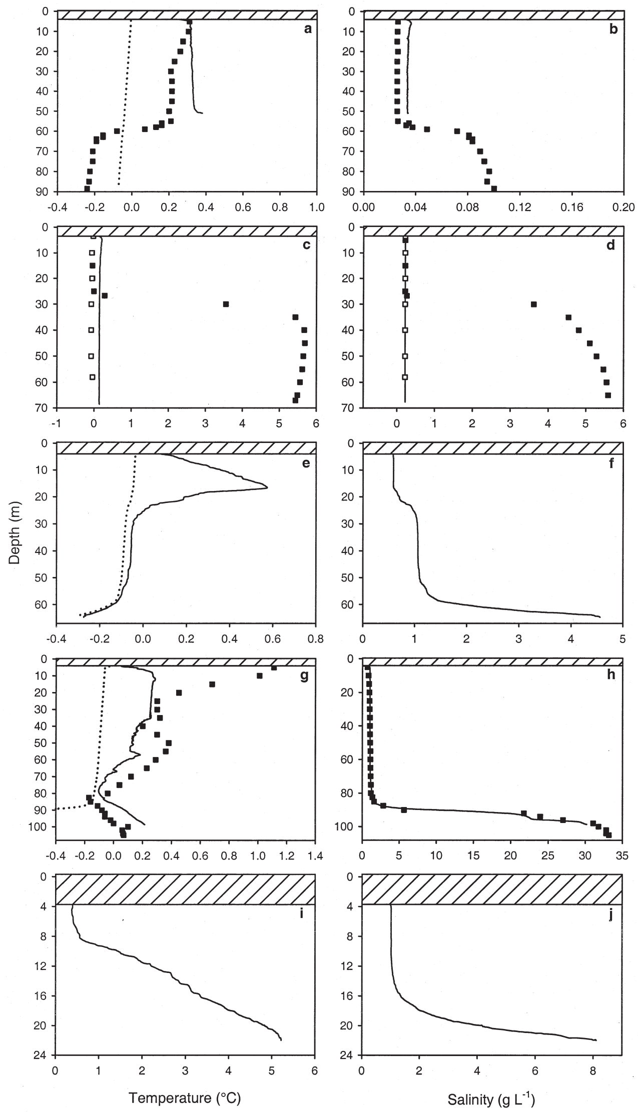

Fig. 5. Temperature and salinity profiles for epishelf lakes in the Bunger Hills. **a**. White Smoke Lake temperature, **b**. White Smoke Lake salinity; **c**. Lake Pol'anskogo temperature, **d**. Lake Pol'anskogo salinity, **e**. Southern Lake temperature, **f**. Southern Lake salinity, **g**. Transkriptsii Gulf temperature, **h**. Transkriptsii Gulf salinity, **i**. Northern Lake temperature, and **j**. Northern Lake salinity. The unbroken lines are the profiles recorded in 2000 and the squares data collected in 1992. The dotted line in panels **a**, **e** and **g** are the theoretical freezing temperature for the salinity and depth calculated from the data collected in 2000 (panels e & g) or 1992 (panel a). In panels **c** and **d**, the closed squares are data for the western basin of Lake Pol'anskogo, and the open squares the eastern basin. The hashed box at the top of the profiles represents ice thickness in 2000.

of tidal activity were observed during visits in January 2000.

Lake Pol'anskogo is situated at the south-western corner of the southern Bunger Hills (Figs 3 & 4). It is bordered to the south and west by deeply crevassed ice cliffs, and the land margin is similar to that of White Smoke Lake. A series of small islands in the lake divides it into two basins, one to the east, the other to the west (Fig. 4). Both of these basins are about 69 m deep (Gal'chenko 1994). Tidal measurements in Lake Pol'anskogo indicate a range of *c*. 1.3 m (Klokov & Verkulich 1994).

Southern Lake (unofficial name) is located between Lake Pol'anskogo and Transkriptsii Gulf. The local topography is rugged, with rocky cliffs bordering the lake at its southern end. Large, semi-permanent snow banks occur on the northern land margin, and the ice cliffs to the west are heavily crevassed. The lake cuts across the Edisto Moraines (Adamson & Colhoun 1992), which are clearly visible to both the north and the south of the lake.

Transkriptsii Gulf is the largest and deepest of the epishelf lakes of the southern Bunger Hills (Table I). The lake is bounded by the Edisto Ice Tongue and the Apfel Glacier to the west (except for two small islands at the glacier/lake margin) and by land to the east. It is probable that the Edisto Moraines continue under the surface of the lake along its western margin, as they are clearly evident on these islands. A long, sinuous and relatively shallow inlet, Izvilistaja Bay, extends from the main basin of the lake into the Bunger Hills, and the majority of the terrestrially derived water input flows into the lake at the head of this bay (Gibson *et al.* 2002). An extensive supraglacial stream system, draining a large area of Apfel Glacier, also enters Transkriptsii Gulf (Gibson 2000). Tidal measurements indicate a semi-diurnal range of *c.* 1.3 m (Klokov & Verkulich 1994).

Northern Lake (unofficial name) lies between Transkriptsii Gulf and Cacopon Inlet, the central marine basin of the Bunger Hills. It is bounded on one side by the heavily crevassed Edisto Glacier tongue, and on the other by relatively low-lying land. The lake occurs in a gap in the Edisto Moraines, which parallel the margin of the ice tongue (see fig. 7 in Adamson & Colhoun (1992), which shows an aerial view of the lake). No previous studies of this lake have been reported.

Results

White Smoke Lake

Temperature and salinity profiles were recorded in both 1992 (to a depth of 88.5 m) and 2000 (to 52 m). The ice-cover was markedly thinner in 1992 than in 2000 (Table I). On 19 February 1992 temperature varied only slightly throughout the water column (-0.24°C– +0.31°C) (Fig. 5a), with the warmest water occurring between 5 and 10 m. Below this slight peak, temperature was near constant at 0.21°C to a depth of 55 m, but then dropped relatively sharply to -0.19°C at 64 m and then more slowly to the sediment. The temperature below 60 m was beneath the calculated freezing temperature, but it may be that the

Hydrolab unit was reading a few tenths of a degree low (see methods). On 13 January 2000, the water temperature was coldest directly under the ice, with the majority of the water column between 0.32°C and 0.35°C. A slight temperature increase occurred close to the sediment.

The 1992 salinity profile (Fig. 5b) indicated that the upper 55 m of the water column was isohaline, with a calculated salinity of 0.026 g l^{-1} (*in situ* conductivity: 0.077 mS cm^{-1}). As the deeper portion of this water was also isothermal at 0.21°C, it appears that water was mixed to this depth at some time in the year. Below 55 m salinity increased sharply to 0.084 g l^{-1} (0.185 mS cm^{-1}) at a depth of 64 m, and then more gently to the base of the water column. Temperature and salinity were strongly negatively correlated between 30 m and 88.5 m, indicating conservative mixing between the warmer, fresher upper water and the cooler, more saline water below. The water column was close to isohaline in 2000.

Lake Pol'anskogo

Lake Pol'anskogo was profiled in both 1992 (the western basin to 65 m and the eastern basin to 58 m) and 2000 (the eastern basin only to 68 m). Ice thickness had increased markedly between 1992 and 2000 (Table I). On 3 March 1992 the eastern basin was isothermal (Fig. 5c) and isohaline (Fig. 5d) at a temperature of -0.08°C (with only slight warming to -0.03 °C immediately under the ice and at the sediment) and a salinity of 0.22 g l^{-1}. In contrast, the western basin had the same salinity and temperature as the eastern basin to 28 m, but below this depth both parameters increased, reaching 5.5 g l^{-1} and 5.69°C respectively (Fig. 5c & d). The shapes of the salinity and temperature profiles were similar, with a rapid increase between 25 and 30 m. However, the strong correlation between temperature and salinity evident in White Smoke Lake did not occur here, indicating that these variables behaved independently. Maximum temperature occurred at 45 m, and maximum salinity at the sediment.

Salinity in the eastern basin in 2000 was 0.22 g l^{-1} throughout the water column. A slight thermal maximum also occurred under the ice, but below this the water column was isothermal at 0.13°C to the sediment at 68 m.

Southern Lake

The temperature and salinity profiles recorded for Southern Lake on 8 January 2000 (Fig. 5e & f) indicated the presence of three different zones within the water column. From beneath the ice to 18 m the salinity was near constant at 0.59 g l^{-1}. In contrast, the temperature increased from just above freezing under the ice to 0.6 °C at 17 m, before dropping back to slightly above freezing at 25 m. A transition zone was present between 20 and 25 m, in which salinity increased to 1.03 g l^{-1} and temperature dropped to near freezing. These conditions extended to 50 m, below which salinity increased sharply and temperature dropped again. For much of the water column the temperature was only marginally above the freezing point calculated for the salinity and the depth, particularly at the base of the water column (Fig. 5e).

Transkriptsii Gulf

The temperature profile on 17 March 1992 was more complex than for the other lakes (Fig. 5g). The warmest temperatures occurred in the top 10 m, reaching 1.11°C. Between 25 and 60 m, the temperature was in the range 0.2–0.4°C, below which temperature dropped steadily to a minimum of -0.17°C at 87.5 m before beginning to increase. At this depth the water was close to its freezing temperature. A lens of low salinity water occurred just under the ice (Fig. 5h), below which salinity was near 1.05 g l^{-1} to a depth of 45 m, where a slight increase occurred. A further near isohaline section of the water column extended to approximately 80 m, where a sharp increase in salinity was evident. Salinity reached a maximum (33.3 g l^{-1}) at the sediment (105 m).

The more detailed profile recorded on 11 January 2000, when the ice-cover was significantly thicker than in 1992 (Table I), showed similar characteristics to the earlier profile (Fig. 5g). The maximum temperature in 2000 was only 0.29°C in a near isothermal section that extended from 10 m to 35 m. Below 35 m temperature generally decreased with depth, though local maxima occurred. Minimum temperature, which was close to -0.1°C, occurred at 79 m. Temperature in the bottom, saline water increased slightly to a maximum of 0.21°C. The salinity was 1.04 g l^{-1} for most of the water column, and increased sharply at 86–88 m (Fig. 5h). Maximum salinity recorded was 30 g l^{-1} at the sediment (98 m).

Under-ice temperature varied only slightly during January 2000 (± 0.1°C, data not shown), suggesting that, at least during this summer when the ice was over 4 m thick, limited intra-annual variation in temperature occurred.

Northern Lake

Temperature and salinity profiles on 9 January 2000 (Fig. 5i & j) were markedly different to those of the other lakes. The temperature was *c.* 0.5°C to about 8 m, but then rose roughly linearly to 5.3°C at the base of the water column. The salinity profile showed a narrow lens of low salinity water immediately under the ice, below which there was a near isohaline zone (salinity: 1.03 g l^{-1}) that extended from 4 to 13 m. Below this depth salinity initially rose slowly, and then more rapidly, to a maximum of over 8 g l^{-1} at the sediment.

https://doi.org/10.1017/S095410200200010X Published online by Cambridge University Press

Discussion

The five epishelf lakes profiled in this study had markedly different physical characteristics: White Smoke Lake was cold and fresh, with a slight but definite salinity increase deep in the water column; one of the basins of Lake Pol'anskogo was cold and fresh, the other relatively warm and saline; Southern Lake was cold throughout, but had saline water at the base of the water column; Transkriptsii Gulf was also cold, but had a distinctly warmer saline zone at depth; and Northern Lake was saline and warm. All these apparently disparate characteristics can be understood, however, using a simple model that involves gross control of salinity by ingress of salt water into the lake basins during periods of reduced freshwater input, and heat loss from the water column by contact with the marginal ice.

The major source of salt in the lakes is undoubtedly from the underlying marine system, with trivial input from terrestrial and glacial sources. The major process by which salt can enter the basins results from the need to retain water level in the lakes, which effectively act as sumps. Periods of negative water balance at the lake surface (i.e. input from glacial and terrestrial sources is less than that lost by ablation from the ice-cover) will result in the boundary between saline marine and low salinity lake water moving closer to the surface of the lake due to the need to maintain hydrostatic equilibrium (Fig. 6). The sub-shelf marine water that enters the lake will be close to its freezing point, and thus the presence of cold, saline water at the base of the water column, as observed in Southern Lake in January 2000, will be evidence of the interface being in, or close to, the lake basin.

Saline water entering the lake may flow over sills and into basins isolated from the marine connection. When the surface water balance returns to positive, the boundary between the saline and fresher water will be depressed, eventually re-entering the conduit. After an extended period of positive freshwater balance the maximum depth of the boundary will be defined by the depth of the floating ice shelf, similar to the situation in Beaver Lake (Piskun & Klokov 1986) and Disraeli Fiord (Vincent *et al.* 2001). Any isolated basins filled with saline water will remain salty, as this water is trapped (Fig. 6b). The clearest example of this is in Lake Pol'anskogo, in which the eastern and western basins are separated by a sill of maximum depth 28 m. Exchange with the marine water occurs in the well-mixed eastern basin. Water in the western basin below the sill depth is saline, and indicates that water of minimum salinity *c.* 5 g l^{-1} must have been present in the eastern basin to a minimum depth of 28 m at some time in the past. Some of this water flowed into the western basin where it remains trapped. It is also possible that the salinity at 28 m was significantly higher, but that only a relatively small amount flowed into the western basin and mixed with the freshwater prior to an increase in freshwater input and depression of

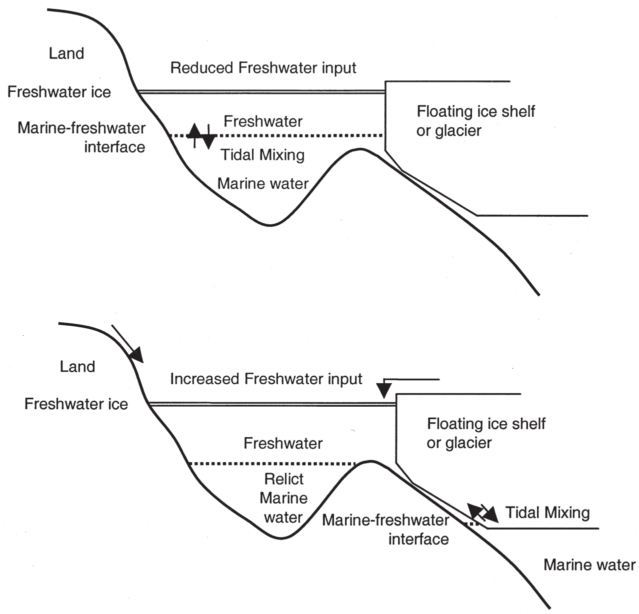

Fig. 6. General model of the epishelf lakes of the Bunger Hills; **a.** during periods of reduced freshwater input, **b.** during periods of increased freshwater input.

the fresh-saline interface below the sill. The lack of vertical mixing in this basin below the sill depth, which is evident from the salinity and temperature profiles (Fig 5c & d), has also resulted in the onset of anoxia (Gal'chenko *et al.* 1995). Similar processes must have occurred in Transkriptsii Gulf and Northern Lake. In the former, the sill depth is at *c.* 80 m, and, as the maximum salinity in the anoxic water is close to that of seawater, undiluted seawater must have invaded the lake to the depth of the sill at some stage. Northern Lake is probably split into two basins by the Edisto Moraines (Colhoun & Adamson 1996), and the depth of the sill in this smaller lake is clearly quite shallow.

Salt can also enter lake basins through turbulent mixing at the saline–freshwater boundary. Considering the tidal range (typically 1.3 m) and the area (0.55 to 14.4 km^2) of the lakes, between 7.2×10^5 and 1.9×10^7 m^3 water flows into and out of the lakes during each tidal cycle. The minimum cross-sectional area of the conduit between the lakes and the marine system is unknown, but is undoubtedly much smaller than the area of lakes. If the conduit has a cross sectional area 5% that of the area of the lake, the boundary will move backwards and forwards by *c.* 26 m during the tidal cycle, and further if the conduit is more constricted. This movement will create turbulence that will result in the halocline at the boundary becoming less intense, and salt will be mixed into the freshwater zone. It would be expected that turbulence would be greatest in lakes with the most constricted conduits. This may explain the presence of more saline water at the bottom of White Smoke Lake, and the moderate salinities (*c.* 1 g l^{-1}) recorded throughout most of

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the water columns in Southern Lake and Transkriptsii Gulf. The halocline will be 'reset' if freshwater input is sufficient to depress the interface to the depth of the ice barrier.

The water balance at the surface of the lakes will affect the salinity profile as well. During periods of negative water balance, the salt in the surface waters of the lake, which is largely excluded from newly forming ice, will become concentrated in a smaller volume, and thus the under-ice salinity will increase. When the balance returns to positive, the fresher water input at the surface will not mix with the more saline water below if the density difference is sufficiently large. The end result is the appearance of distinct steps in the salinity profile, as observed in the profiles of Southern Lake. The formation of similar steps has been observed in meromictic lakes in Antarctica as a result of changes in water balance (Gibson & Burton 1996, Webster *et al.* 1996, Gibson 1999).

It is unlikely that temperature plays a major role in structuring the water column due to the limited variation in temperature and the moderate salinity of the lakes (excepting, perhaps, White Smoke Lake). However, temperature does reflect both vertical and horizontal mixing processes in the lakes. The temperature of the water column is the result of the balance between heat sources, including solar radiation and geothermal fluxes, and losses, including conduction through the ice-cover and to melting ice at the ice margins. The contact with marine water is also a heat sink, as the temperature of inshore Antarctic seawater is -1.87°C for most of the year, reaching temperatures above zero only for short periods during summer, and then only near the surface (Gibson & Trull 1999).

The epishelf lakes are in the most part cold, being within a degree of freezing at most depths. This is in contrast to other large Antarctic freshwater lakes (e.g. Algae Lake, Bunger Hills: Markov *et al.* 1970; Crooked Lake, Vestfold Hills: Bayliss *et al.* 1997), in which temperatures throughout most of the water column, though cold, remain a few degrees above freezing. Significantly warmer temperatures do occur in the epishelf lakes, but only in isolated basins containing saline water (e.g. Lake Pol'anskogo).

The main heat source for the lakes is solar radiation. The ice-cover of the lakes is thick (up to 3.9 m), but is very clear. Measurements in 1992 indicated that *c.* 5–8% of incident visible radiation passed through the 2.2–2.6 m ice-cover of the lakes (Gal'chenko *et al.* 1995; D. Andersen, unpublished data). The heat produced by the absorption of this radiation in the water column can be lost via conduction through the ice, as dictated by the generally colder air than water temperatures, or by conduction to or melting of the ice boundary of the lake. While the former process can remove heat only from the surface water, the latter can cool the entire water column excluding isolated basins. However, it involves the removal of heat from a three-dimensional lake at a two-dimensional plane at the lake margin, and the effectiveness of the process will clearly depend on the efficiency of the advection of water, and therefore heat, to the ice by currents. Horizontal mixing has been shown to occur in ice-covered, stratified Antarctic lakes (Shirtcliffe & Bensemann 1964), and the heat loss to the ice and consequent change in water density is likely to enhance horizontal transport in the epishelf lakes. It is the dislocation between the points of heat gain and heat loss that allows limited accumulation of heat in a system that is striving to reach freezing point in an ice-water equilibrium. Water temperatures in Beaver Lake are higher than in the Bunger Hills lakes, reaching 2°C under a 4 m ice-cover (Laybourn-Parry *et al.* 2001). We argue that this is a result of the lower efficiency of heat loss to the ice shelf in this lake, which is significantly larger than the epishelf lakes in the Bunger Hills. This is also consistent with the relatively warm temperatures in Transkriptsii Gulf, the largest of the lakes considered here. Towards the base of all the freshwater portions of the lakes in the Bunger Hills water temperature decreases with depth to near freezing point. This is the result of reduced radiative heating at depth, but could also imply greater efficiency of transfer of heat to the ice margin and melting of the glacial ice at depths where the cross-sectional area of the lake is smaller than closer to the surface.

The warmer temperatures in the saline basins of Lake Pol'anskogo and Northern Lake are probably the result of solar heating in isolated basins in which the water is not in contact with glacial ice. This heliothermal behaviour is similar to that observed in meromictic saline lakes elsewhere in Antarctica (Spigel & Priscu 1998, Gibson 1999). The situation in Transkriptsii Gulf is less certain, as the warmer water is present only towards the base of the water column, to where little solar radiation would penetrate. It is possible that a geothermal heat flux plays some role in warming this water.

Lakes are a major source of information about climate change in the Antarctic. The sources of information include diatom stratigraphy and isotope analyses of sediment cores (Bird *et al.* 1991, Roberts *et al.* 1999, 2000, Doran *et al.* 2000), which provide longer term data, and observations of ice thickness, water level and lake structure changes (McKay *et al.* 1985, Chinn 1992, Wharton *et al.* 1992, Gibson & Burton 1996, Gibson 1999, Doran *et al.* 2002), which give a more immediate view of change. Short-term change in the Bunger Hills is clearly evident, notably in the thickness of the ice on the lakes. As shown in Table I, there was a significant increase in the thickness of the ice on all the lakes between 1992 and 2000, which can be interpreted in terms of increased ice formation in winter and/or decreased ablation in summer. These changes were not due to seasonal melt and reformation, as ice thickness on Transkriptsii Gulf did not change measurably over a period of four weeks in January 2000, and the thinner ice in 1992 was recorded during a period when new ice would be forming. Similar observations have been made for Beaver

Lake, which was free of ice during the summer of 1956/57 (Bowden 1997: p 161), and possibly again in the summer of 1976/67 (A. Ruddell, personal communication 2001), but which was covered by ice 4 m thick in January 2000 (Laybourn-Parry *et al.* 2001).

The invasion of significant amounts of marine water has occurred in at least three of the lakes sometime in the past, as ancient saline water has been trapped in basins distant from the point of water input into the lakes. These saltwater invasion episodes are interpreted as being a result of reduced input of freshwater at the surface of the lakes, due either to decreased precipitation or, more likely considering the vast freshwater resource of the ice-shelf systems, reduced melt as a result of colder temperatures. By determining the age of the trapped seawater it will therefore be possible to date significant periods of reduced freshwater inputs. Indications of three marine phases have been detected in sediment cores collected from quite shallow depths in Izvilistaja Bay in Transkriptsii Gulf, indicating that salt water has invaded this basin on a number of occasions (Melles 1994).

The structures of the epishelf lakes of the Bunger Hills provide an indicator of climate change in the area. Continued monitoring of the structures should be undertaken to determine the sensitivity of the basins to short-term change (years to decades). It appears that the Bunger Hills area is currently going through a cold, dry period, and it will be of interest to see what affect this has on the lake structures in the future.

Acknowledgments

This work was supported by the Australian Antarctic Division and NASA's exobiology program. We wish to thank D. Bol'shiyanov, V.F. Gal'chenko, N. Chernykh, P. Doran and J. Rice (1992), and B. Harding, G. Kuehn and D. Flynn (2000) for assistance in the field. Logistic support was provided by the 37th Soviet Antarctic Expedition, Arctic and Antarctic Research Institute, St Petersburg and the Australian Antarctic Division. We thank Dr Cynan Ellis-Evans and an anonymous referee for their constructive comments on the manuscript.

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