ECOLOGY OF THE FRESH-WATER LAKES OF SIGNY ISLAND, SOUTH ORKNEY ISLANDS:
II. PHYSICAL AND CHEMICAL PROPERTIES OF THE LAKES

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ABSTRACT. The lakes of Signy Island contain soft water of pH about 7 which is contaminated to a varying extent by sea spray and effluent from seal wallows and bird colonies. The waters attain a maximum temperature of approximately 5°C and remain isothermal because they are completely and continually stirred by strong winds. The degree of transparency of the lake waters is largely determined by the amount of transported debris, which varies considerably from one lake to another in relation to the substrates of the various drainage basins. Photosynthesis by blue-green algae maintains the oxygen content of the lakes at saturation or supersaturation level throughout the summer.

The lake waters freeze to a depth of about 1 m. for 8–9 months of each year. The irradiance is reduced to a level thought to be below that necessary for photosynthesis for most of this time and the waters become almost anaerobic. The extraction of water molecules in the formation of the ice cover is mainly responsible for the remarkable increase observed in the concentrations of the major ions.

THE catchment areas and drainage systems of Signy Island (Fig. 1) and the morphology of the lake basins have already been described (Heywood, 1967*b*). The aim of the work presented

TABLE I. MEAN DAILY WIND SPEEDS (kt.) RECORDED ON SIGNY ISLAND DURING THE 1961–64 SUMMERS

Year	*Month*	*Monthly mean*	*Number of days with mean wind speeds of* <2	2–4	5–9	10–19	20–29	30+
1961	December	11·0	1	3	12	12	3	0
1962	January	11·0	0	7	9	11	3	1
1962	February	16·0	0	1	3	13	11	0
1962	March	11·0	0	2	10	18	1	0
1962	April	15·0	0	3	5	13	9	0
1962	December	13·0	2	2	13	12	2	0
1963	January	11·0	3	5	4	16	3	0
1963	February	14·0	0	2	6	14	6	0
1963	March	16·0	0	0	10	11	8	2
1963	April	14·0	1	3	8	10	6	2
1963	December	13·0	2	4	7	11	7	0
1964	January	12·0	0	4	10	12	5	0
1964	February	13·0	0	2	7	15	5	0
1964	March	15·0	2	1	9	7	10	2
Total of days			11	39	113	175	79	7

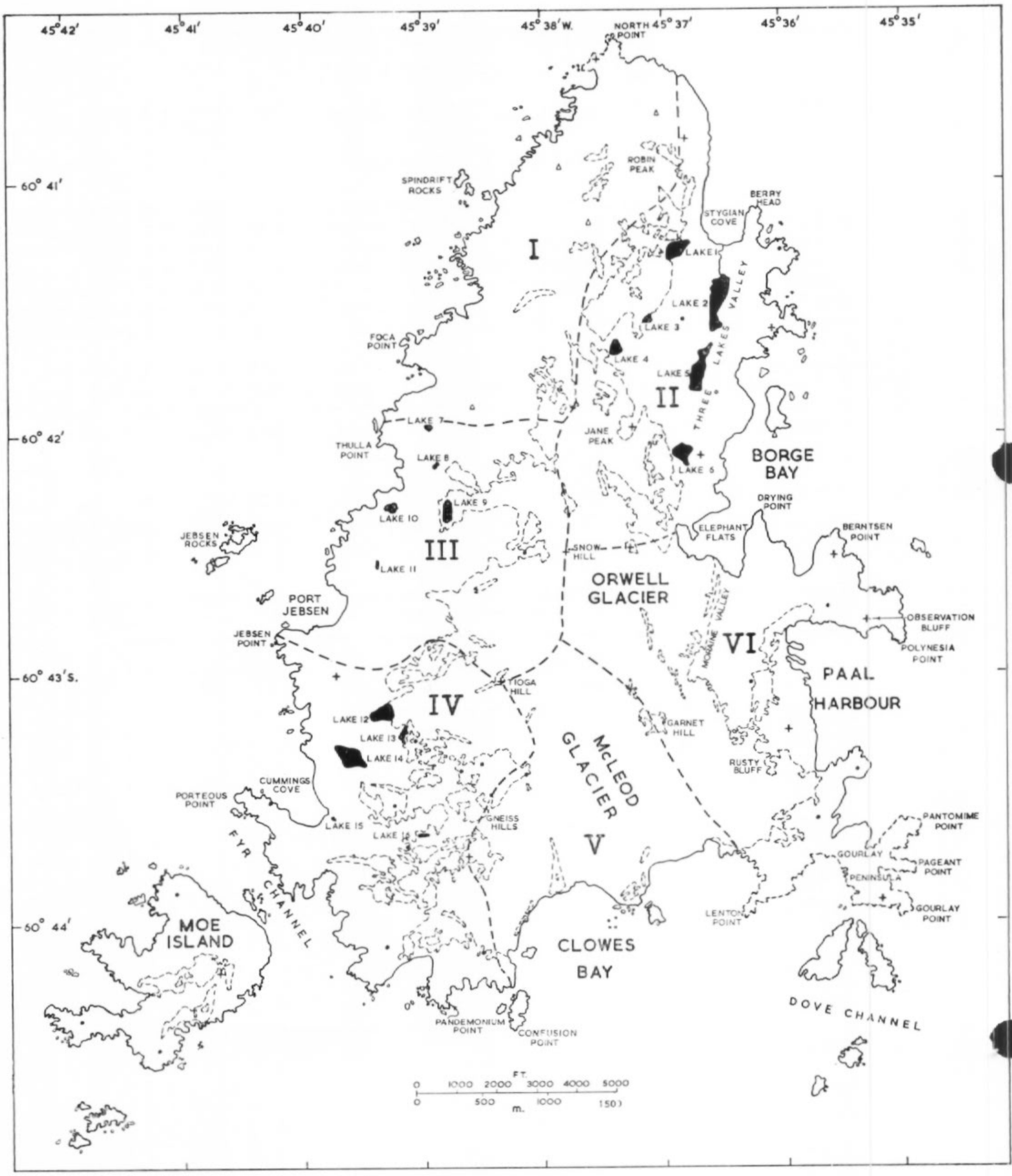

Fig. 1. Sketch map of Signy Island, South Orkney Islands, showing the limits of the six main catchment areas (I–VI) and the locations of the fresh-water lakes (1–16).

in this paper was to obtain a broad-based description of the abiota as an essential primary phase of research into a new ecosystem. Problems are presented, rather than explained in many cases, because no phenomenon was investigated in detail. In the chemical section, where a detailed discussion of the complex but often cyclic processes is difficult, the literature has been freely used to suggest probable reasons for the observed results.

Methods

The optical apparatus consisted of two selenium barrier-layer cells, the spectral response of which is given in Fig. 2; one cell was mounted for above-water and one for under-water exposure. The cosine collector was an opal glass filter, backed in bright conditions by a neutral filter which reduced the light intensity by 90 per cent. The under-water cell was used to measure vertical illumination and the surface cell to check variation in the incident illumination.

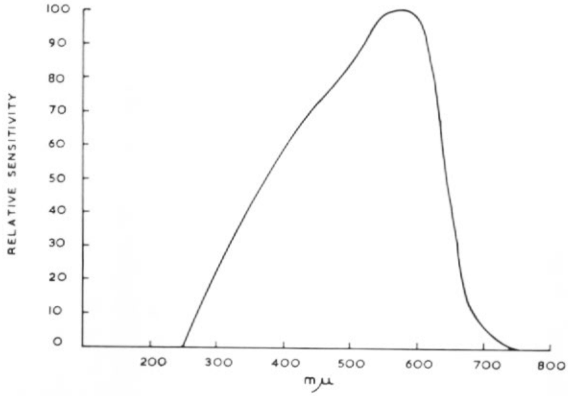

Fig. 2. Spectral response of the EEL selenium barrier-layer cells (made by Evans Electroselenium Ltd.).

The light-cell readings were to have been evaluated by comparison with readings of total solar and sky radiation measured with a recorder constructed at Signy Island by M. J. G. Chambers. The radiation recorder required calibration and it was unfortunately broken during shipment to the United Kingdom for this purpose. Therefore, the actual amounts of radiation energy entering the lakes are not known. Signy Island has an annual mean cloud cover of 7 oktas and, as high cloud amounts affect the distribution of energy in the visible spectrum of daylight (Taylor and Kerr, 1941), accurate information for this work cannot be obtained from radiation values measured at other Antarctic stations or from such general estimations as given by Perl (1935). The photocell readings were used to determine the vertical extinction coefficients (In units $m.^{-1}$; Poole and Atkins, 1926), the percentage of visible radiation available at various depths and the seasonal variation. The immersion effect on the under-water cell was not measured but errors were eliminated by calculating all spectral parameters from the irradiation measured at a depth of 5 cm. ($I_{5\ cm.} = 100$ per cent); this also cancelled errors arising from surface loss. The water surfaces were almost continually ruffled by strong winds (Table I) and surface loss as high as 40 per cent has been recorded.

The spectral composition of the irradiation was measured using glass colour filters (made by Jenaer Glaswerk) types BG12, VG9 and RG1. The optical properties of these, when used singly and in association with a selenium cell, have been described by Sauberer (1962) and Talling (1965).

Summer readings were taken with the under-water cell suspended from a 2 m. boom extending from the sunward side of the boat to reduce the shading effect to negligible proportions. During the winter, removal of only 1 $m.^2$ of ice and snow cover had a considerable effect on the amount of light available in the upper metres of water, and useful information could not be gained by suspending the photocell through a hole cut in the ice cover of the shallow lakes (Table II). The method adopted for winter work was burying the under-water cell below the ice layer using the apparatus shown in Fig. 3. The cable from the cell passed through a rubber bung which had been bored under very strong pressure to produce a tapering hole which was self-sealing round the cable. The whole apparatus was suspended through a small (30 $cm.^2$) hole in the ice and the collar was adjusted so that the bottom of the tube protruded far enough below the ice to allow for any increase in ice thickness. The cell was then left for 2–3 weeks to ensure that the ice cover had fully re-formed. The ice chippings were scattered away from the vicinity of the hole because they promoted drifting which produced an atypically thick snow layer. After the waiting period, readings were taken at regular intervals throughout several daylight periods; ammeter and operator were stationed sufficiently far away to avoid any shading effect. The bung was then knocked out and a series of readings were taken throughout the depth of the lake, at noon when the sun was at its zenith and the radiation intensity was at its highest. The apparatus was then freed and re-set. This method

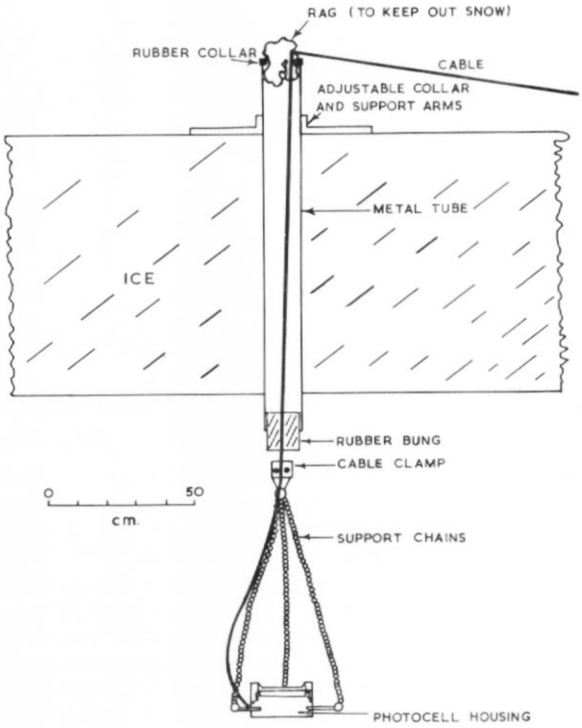

Fig. 3. Apparatus used for burying the photocell under the ice cover.

supplied very accurate information on the irradiation within the lake. Shortage of photocells restricted the winter investigations to the total visible irradiation present in one lake and the number of investigations to eight. Three of these attempts were frustrated by the wires within the cable breaking near the bung; it is not known whether this was the result of strain caused by supporting the heavy cell for long periods or of deterioration caused by cold.

Temperatures were measured with a reversing thermometer during 1962 and with a thermistor unit thereafter. The thermistor was incorporated into an oxygen probe (after the design of Mackereth (1964)).

Water samples for chemical analyses were obtained with a plastic sampling bottle supplied by the National Institute of Oceanography (reference number N10/4839). Additional care in the maintenance of the bottle was necessary because of the extreme conditions under which it was used. It had to be dried immediately after use to prolong the working life of the rubber seals which perished very rapidly if ice-covered (normal working life during the course of this work was 2–3 months). All detachable parts were tied to the main body of the instrument because the circlips retaining these parts were frequently forced off by ice actually forming while the bottle was in use.

TABLE II. COMPARISON OF TOTAL VISIBLE-LIGHT VALUES OBTAINED FOR LAKE 2 DURING THE 1963 WINTER WITH A PHOTOCELL (1) BURIED BENEATH THE ICE LAYER; (2) SUSPENDED THROUGH A HOLE CUT IN THE ICE; (3) SUSPENDED THROUGH A HOLE IN THE ICE COVERED BY A TENT

Station	*Date 1963*	*Experiment*	*Relative light intensity* (I_0 = 100 per cent) 1 m.	2 m.	3 m.	4 m.	*Percentile transmission per metre stratum of water* 1–2 m.	2–3 m.	3–4 m.
A	30 July	1	0·52	0·33	0·11	0·05	63	33	45
		2	13·00	2·23	0·58	0·17	17	26	29
		3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
E	22 August	1	0·13	0·07	0·02	—	54	29	—
		2	12·00	1·10	n.d.	—	9	n.d.	—
		3	0·59	0·12	0·04	—	20	33	—
A	3 October	1	0·76	0·52	0·36	0·22	68	69	61
		2	15·50	2·30	0·83	0·38	15	36	46
		3	0·15	0·04	0·03	0·02	27	75	67
E	28 October	1	0·05	0·02	0·01	—	40	50	—
		2	8·20	1·20	0·28	—	15	23	—
		3	0·92	0·12	0·04	—	13	33	—
A	14 November	1	6·50	2·90	1·30	0·78	45	45	60
		2	12·50	2·50	1·00	0·58	20	40	54
		3	2·15	1·10	0·74	0·43	51	67	58

n.d. Not determined.

Samples were stored in polythene bottles for transportation. The bottles were filled carefully to avoid trapping air and the samples were then allowed to freeze (10–15 min. during winter). The samples were slowly thawed out at room temperature in the laboratory. 7–10 days often elapsed between collection and analysis during the winter but it was assumed that loss of phosphate and nitrate was prevented by the samples being frozen.

Attempts to collect water in displacement bottles for accurate carbon dioxide analyses failed because the small (100 ml.) samples froze both in summer and winter, in the absence of effective insulation, and shattered the glass bottles. Measurement of pH in the field was prevented for similar reasons. The standard solutions froze on most field days and they were particularly difficult to thaw out in an open boat during the summer. There was also the ever-present risk of the liquid electrolyte freezing and breaking the delicate probe (portable unit made by Analytical Measurements Ltd.). Consequently, all carbon dioxide and pH measurements were made in the laboratory using aliquots taken from the main samples, and the results are of limited accuracy.

Dissolved oxygen was measured in the field using a probe after the design of Mackereth (1964). Although this probe had a liquid electrolyte, it was of a robust design and able to withstand transport inside inner clothing and storage in a sleeping bag during nights in the field. It was not possible to store the probe in de-oxygenated water as suggested by Mackereth and the probe consequently took 20 min., after immersion, to attain equilibrium with the oxygen content of the water, even though it was fitted with an extra-fine membrane.

The methods used for the analyses of free carbon dioxide and the radicals were those described by Mackereth (1963). The nitrate determinations were affected by the high chloride concentrations but, since neither literature nor other chemicals were available, the technique could not be modified.

The detailed temperature and chemical data obtained in this work are given in the Appendix (Tables XIV–XXIV; p. 41–44).

Optical Properties of the Lakes

Summer

Light penetration in the lake waters varies considerably (Fig. 4) and a comparison with other natural fresh-water bodies and with pure water emphasizes the wide range (Table III). Light in natural waters decreases in intensity with depth and changes in spectral composition

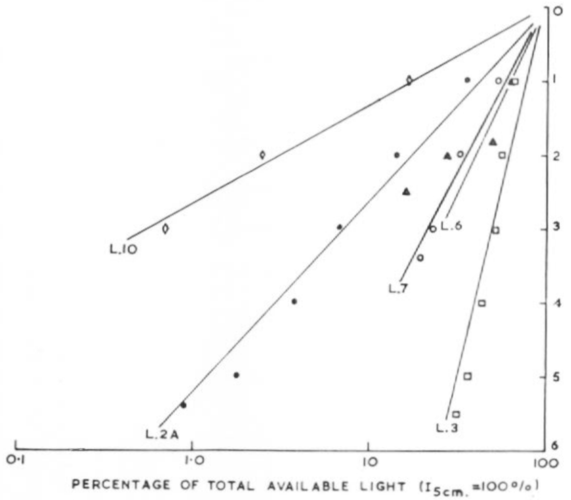

Fig. 4. The percentage transmission of total visible light in certain of the Signy Island lakes ($I_{5\ cm.}$ = 100 per cent).

Table III. Penetration of total visible light in certain lakes on Signy Island compared with distilled water and other natural fresh-water bodies

Location	*Authority*	*Vertical extinction coefficient* (ln units m.$^{-1}$)	*Percentage transmission* (per m.)
Distilled water	Hutchinson, 1957 (at 540 mμ)	0·030	—
Crater Lake, Oregon, U.S.A.	Utterback and others, 1942	0·075	—
Crystal Lake, Wisconsin, U.S.A.	Birge and Juday, 1930	0·160	85
Lake 3, Signy Island	Heywood	0·212	82
Lake 6, Signy Island	Heywood	0·394	69
Trout Lake, Wisconsin, U.S.A.	Birge and Juday, 1930	0·400	67
Lake 7, Signy Island	Heywood	0·496	61
Lake 2, Signy Island	Heywood	0·804	46
Midge Lake, Wisconsin, U.S.A.	Birge and Juday, 1930	1·530	22
Lake 10, Signy Island	Heywood	1·654	19

mainly because of the amount and nature of the dissolved and particulate material present (Birge and Juday, 1929). The drainage basins of the Signy Island lake system have widely differing substrates (Heywood, 1967*b*); the main water supplies of some lakes run wholly over ice, bare rock or scree, collecting only small quantities of inorganic material, and of other lakes, through luxuriant moss stands or across seal wallows, often carrying large quantities of organic detritus (Fig. 5). The lakes of moderate transparency (lake 6; Fig. 6)

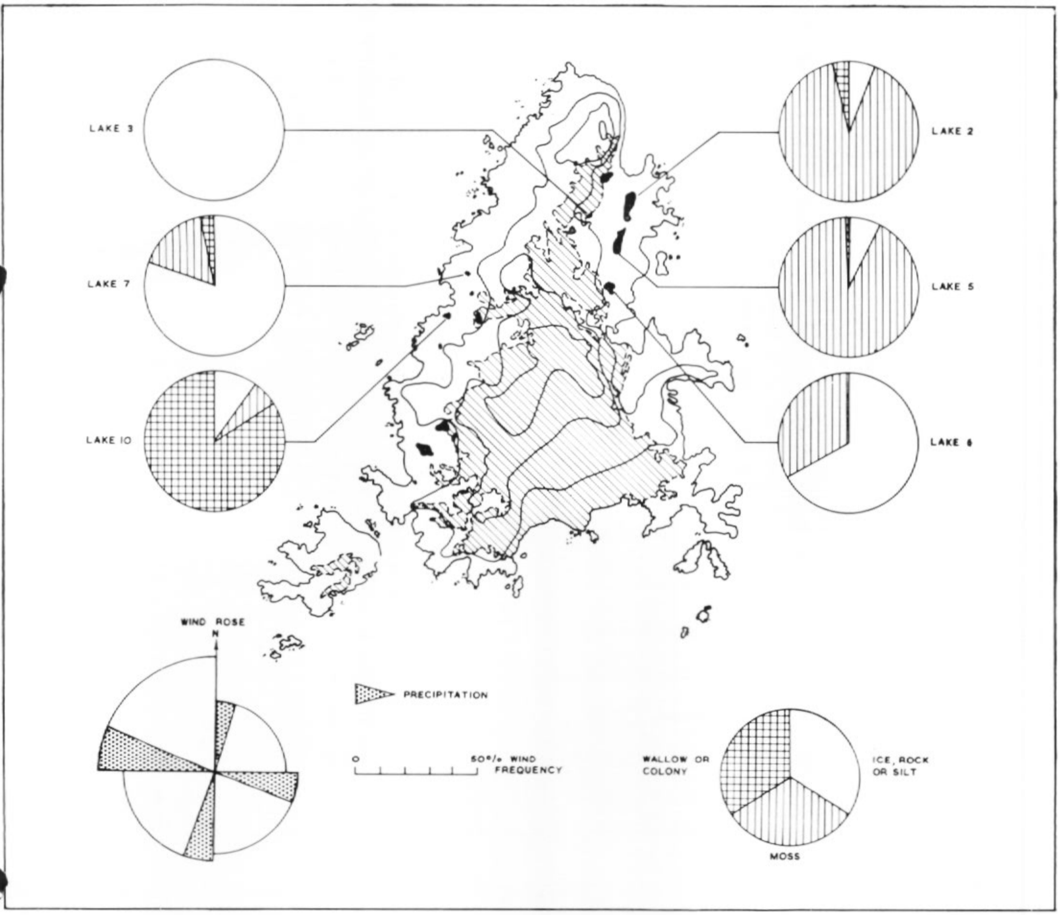

Fig. 5. The extent to which the lakes on Signy Island are protected from prevailing winds (the ice cap, indicated by the hatched area, covers most of the high upland area, which as yet has not been accurately surveyed). For certain lakes the relative proportions of run-off water, contaminated by passage through moss stands and seal wallows–bird colonies, are also shown.

contain only small amounts of suspended organic matter and silt, and radiation from the centre of the visible spectrum has the highest transmission. The large quantities of organic material suspended in the lakes of low transparency (lake 10; Fig. 6) absorb the longer-wave radiation the least. Work on lake 3 was always curtailed by bad weather during the summer and the only readings available from this period are for total visible light. This lake is far more transparent than lake 6 (Table III) and it contains only very small amounts of suspended silt. The absorption of light will approach that of pure water and will be least at the short-wave end of the visible spectrum. The relative amounts of visible solar and sky radiation

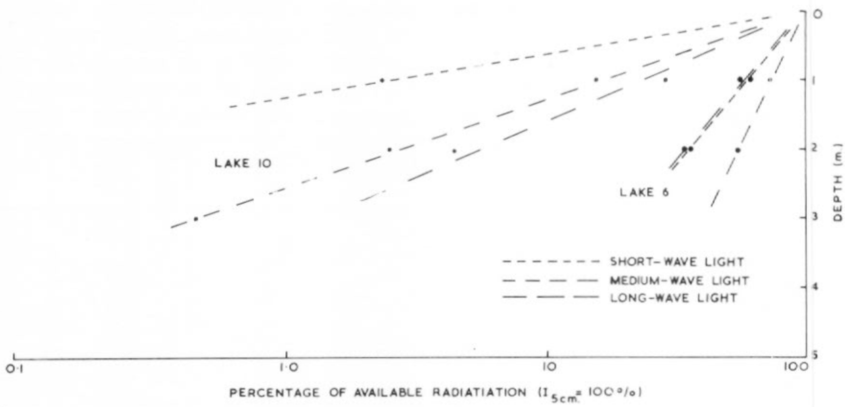

Fig. 6. Percentage transmission of various wave-lengths of visible light in lakes 6 and 10 ($I_{5\text{ cm.}}$ = 100 per cent).

energy which the lakes receive and the variation with depth of the spectral composition are shown in Fig. 7. The various vertical extinction coefficients for blue, green and red wave bands are given in Table IV.

TABLE IV. VERTICAL EXTINCTION COEFFICIENTS FOR THE SHORT-, MEDIUM-, AND LONG-WAVE BANDS OF THE VISIBLE SPECTRUM

Lake	*Vertical extinction coefficients* (ln units m.$^{-1}$) 460 mμ	540 mμ	640 mμ
Pure water (Hutchinson, 1957)	0·005	0·03	0·31
Lake 6; 20 January 1963	0·54	0·31	0·51
Lake 7; 27 February 1964	0·94	0·29	0·68
Lake 2 (A); 28 January 1964	1·89	0·84	1·18
Lake 10; 28 February 1964	3·77	1·84	1·56

The percentage transmission of total visible light varies with each metre stratum (Fig. 8) as the values for transmission become more and more characteristic of the wave-lengths predominating in the irradiance. The transmission profile of lake 3 is complicated by unusual factors. Snow settling in the upper centimetres of water reduced the transmission over the first metre. Light entering through the ice wall of the lake basin appeared to increase the transmission over the upper metres and particles carried into the lake by the inflowing stream (Heywood, 1967*b*) are presumed to have been responsible for the lowered transmission over the lowermost metre. In lake 2 the sudden reduction in transmission over the lowermost metre was caused by the photocell disturbing the bottom sediments. In most of the lakes transmission over the first metre was remarkably high (cf. Birge and Juday, 1929), probably reflecting the apparent paucity of phytoplankton in the lakes during the summer (Heywood, 1967*a*). In lake 10 the low value is thought to be more indicative of the quantity of tripton in the water than of phytoplankton.

The transparency of small lakes may vary with the precipitation, which determines the amount and rate of the inflowing water and therefore the amount of suspended matter, and the wind, which might promote currents to stir up the sediments. At Signy Island one can assume that these agencies produce little variation, for the frequency of precipitation is high (335 days/yr.), the total amount of precipitation small (40 cm./yr.) and the wind speeds are commonly high (Table I). The percentage transmission values for lake 2 (Table V) suggest

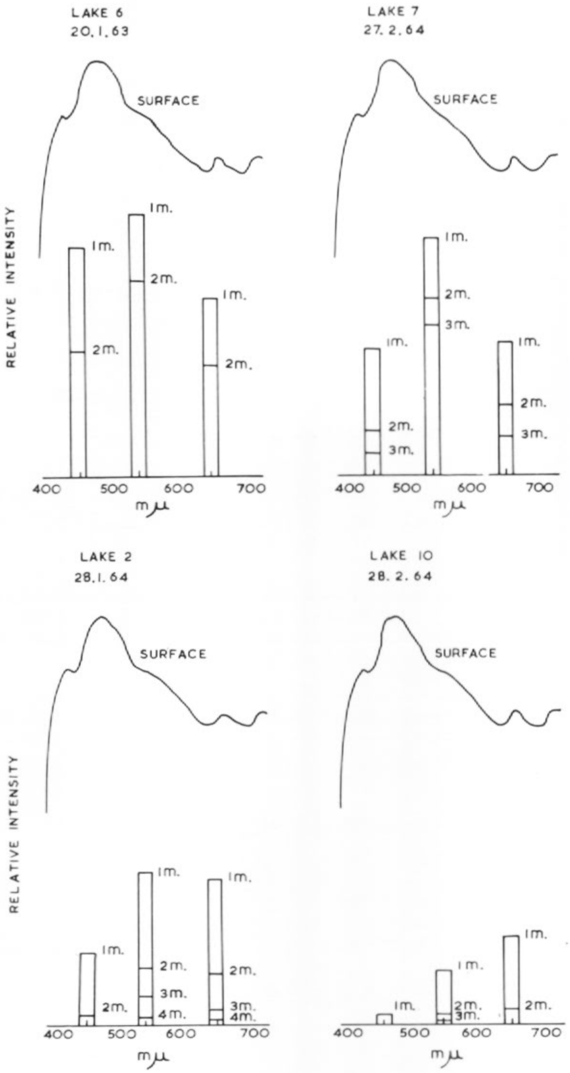

Fig. 7. The average, relative spectral-energy distribution at the Earth's surface under a totally overcast sky is given by the curve (from Taylor and Kerr, 1941). The reduction in intensity and the changes in spectral distribution at successive depths in the lakes are indicated by the columns. As the optical properties of a filter vary with depth, the *mean* position of the optical centre of gravity is indicated by the line crossing the x-axis.

that there is a marked seasonal variation in the lakes. The main inflow of detritus appears to occur during the latter half of the main thaw when the water which is released by snow melt sweeps rock and plant debris produced by frost action into the lakes. Very little of this material settles out during the summer because of the continual turn-over of lake water by the high

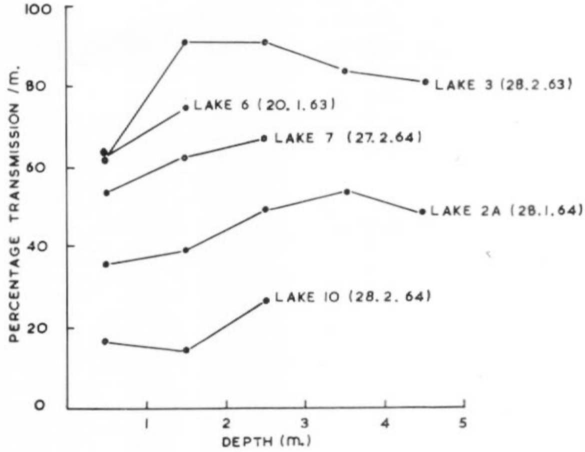

Fig. 8. Variation in percentage transmission of total visible light between the several metre strata of the lakes.

winds, but under the settled conditions that exist after the water surface has frozen, the water clears considerably (lake 2 attains the moderate transparency of lakes 6 and 7). Although the initial inflow of melt water in the spring is largely free of debris, the currents produced in the lake stir up the bottom sediments. Readings taken at station E (lake 2), which is near the main

TABLE V. SEASONAL CHANGES IN THE PERCENTAGE TRANSMISSION OF TOTAL VISIBLE LIGHT THROUGH THE SEVERAL METRE STRATA OF LAKE 2

Date	*Station A*						*Station E*			
	0–1 m.	1–2 m.	2–3 m.	3–4 m.	4–5 m.	*Mean*	0–1 m.	1–2 m.	2–3 m.	*Mean*
1963										
7 January	46	39	46	48	40	44	39	42	38	40
30 January	34	36	44	51	39	43	36	36	39	37
21 March	39	41	47	53	48	46	36	41	41	39
30 July	ice	63	33	45	n.d.	47	n.d.	n.d.	n.d.	n.d.
22 August	ice	n.d.	n.d.	n.d.	n.d.	n.d.	ice	54	29	42
3 October	ice	68	69	61	n.d.	66	ice	n.d.	n.d.	n.d.
28 October	ice	n.d.	n.d.	n.d.	n.d.	n.d.	ice	40	50	45
14 November	ice	45	45	60	n.d.	50	ice	n.d.	n.d.	n.d.
1964										
5 January	41	47	55	55	58	51	43	48	55	51
28 January	36	40	49	54	48	47	n.d.	n.d.	n.d.	n.d.

n.d. Not determined.

inflow, are invariably lower than those recorded at station A, the relationship reflecting directly the relative amounts of transported debris found in these areas (Heywood, 1967*b*).

Winter

Information already available shows that most of the incident light is reflected from or absorbed by snow layers and that the amount and spectral composition of visible light transmitted by snow and ice layers vary with the depth and nature of these substances (Croxton and others, 1937; Greenbank, 1945; and others). The ice cover of any water body will vary in nature from year to year and in depth from month to month. Snow cover is particularly ephemeral. At Signy Island it changed considerably both in depth and texture from day to day, varying from 1 m. of soft, freshly fallen flakes to a few centimetres of firm wind-packed crystals. The snow was frequently removed as drift by high winds. Minor thaws did not affect the snow cover directly because the lake ice had a high thermal capacity and nullified the effects of the air temperature, but melt water from the surrounding land occasionally ran on to parts of the lake surface where it formed with the snow cover a slushy mixture, which re-froze into a more durable layer. Further research, which is solely concerned with the amount and composition of light available in a lake under these extreme conditions, is consequently of limited value unless it is directly related to a quantitative study of productivity or to the actual

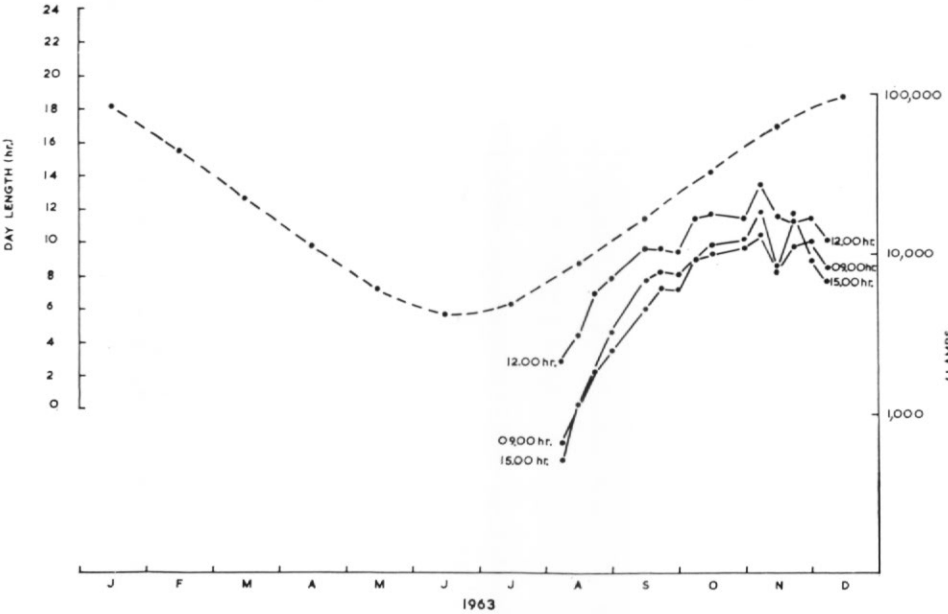

Fig. 9. Seasonal variation in day length and relative intensities of total visible radiation. Radiation figures are 7-day means. The fall recorded during November–December was due to extremely bad weather conditions.

mechanics of reflection and absorption (Thomas, 1963). Comment on the results obtained at Signy Island will therefore be brief.

The upper layers of ice covering the lakes are normally opalescent (p. 28) and the snow cover is granular and compacted by the wind, a combination least favourable for light penetration. During the early part of the winter, snowfall on Signy Island is generally associated with high winds which sweep the snow into the surrounding sea, but this period of thin or absent snow cover coincides with decreasing day length and low radiation intensity. As winter proceeds, snowfall becomes increasingly associated with light winds and the cover thickens, thus cancelling the effects of increasing intensity and duration of the radiation (Fig. 9). For approximately 6 months each year, therefore, the amount of light available in the lakes is severely reduced (Fig. 10) and it seems almost certain that, for most of the period that snow

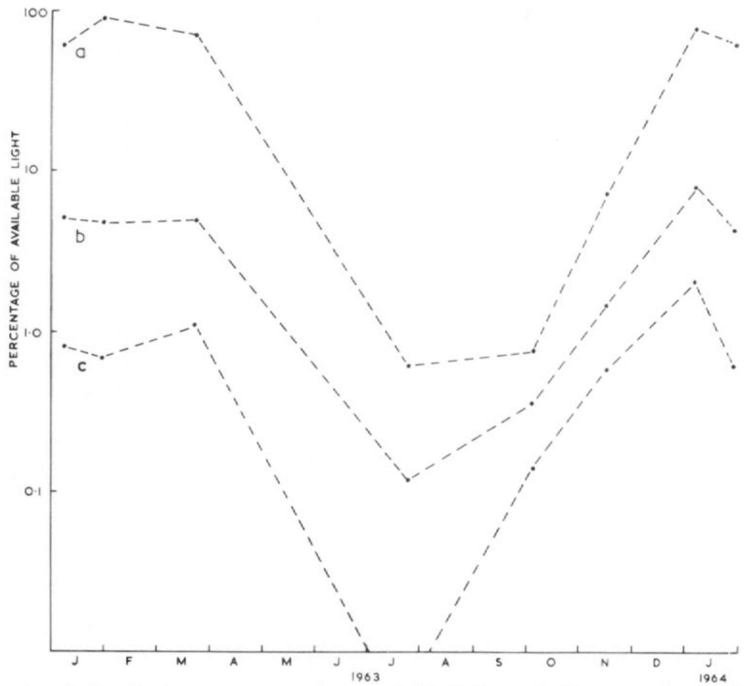

Fig. 10. Seasonal variation in the percentage of total visible light available at: a, 5 cm. depth or water–ice interface; b, 3 m. depth (mid-depth); c, lake bottom (5 m.), in lake 2; sampling station A.

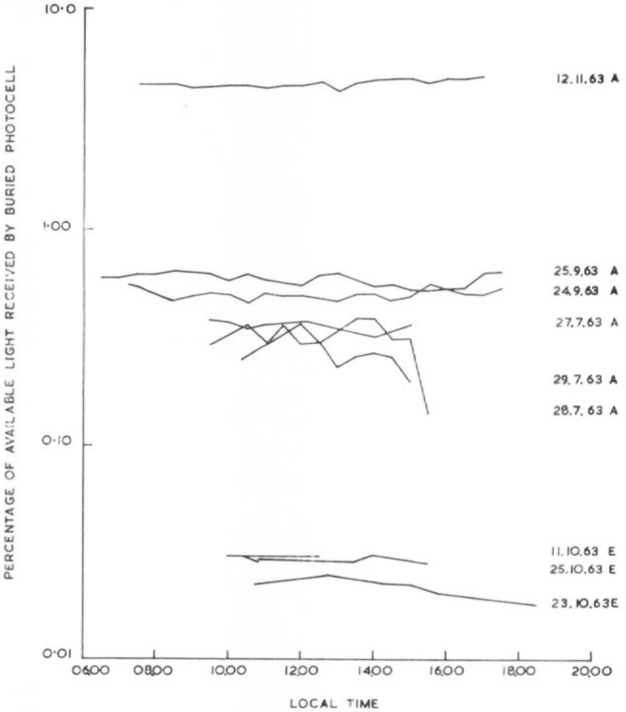

Fig. 11. Percentage of available visible light reaching a photocell buried beneath the ice cover of lake 2 during several day-length periods.

covers the lake ice, the amount of radiation energy available is below the level necessary for photosynthesis.

Work with the buried photocell suggested that change in the angle of the incident light and in the intensity of radiation did not affect the albedo of the snow cover or the percentage transmission of visible light through the snow and ice layers (Fig. 11)—a fact presumably reflecting the unevenness of the snow surface and the random arrangement of the snow crystals (and the crystals in the ice/snow mixture of the upper layers of ice (p. 28)).

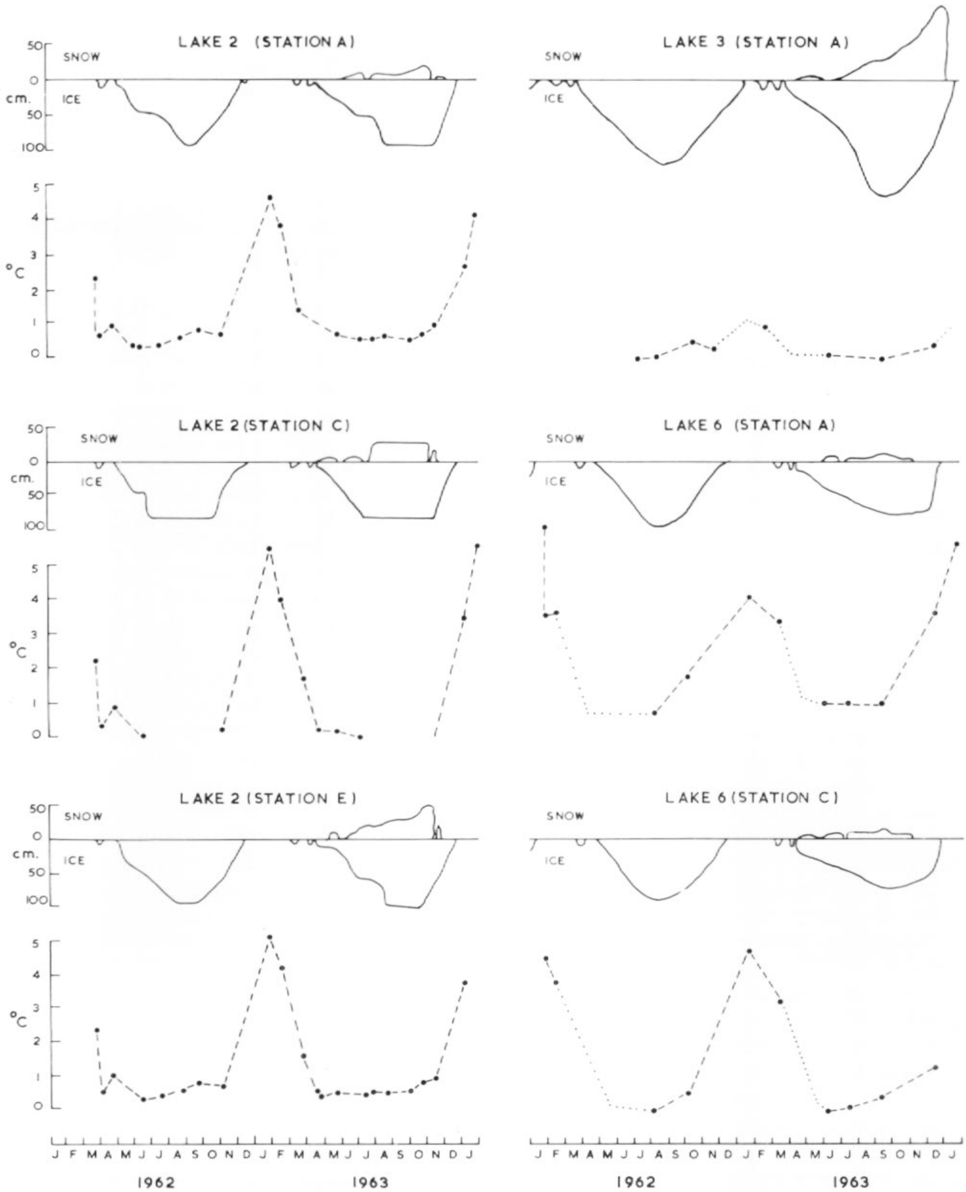

Fig. 12. Seasonal variations in the mid-depth temperatures of several lakes on Signy Island. The variation in thickness of ice and snow cover (1963 only) is also shown.

Thermal Properties of the Lakes

The lakes investigated presented a common pattern. After break-up of the ice in December or January, the main body of lake water quickly attained its summer maximum temperature (Fig. 12). The lakes began to lose heat during February and the temperature fell steadily until the surface waters froze in March or April. An inverse thermal gradient was maintained in the waters below the ice cover. The maximum ice thickness was attained in August and maintained for some weeks. By mid-October an increase in temperature became apparent in water remote from the ice cover. Shore leads appeared in late November or early December.

Summer

Maximum summer temperatures are quickly attained after the ice cover disappears because the long day-length period is well established, the amount of available solar radiation is at its maximum (Fig. 9) and the main body of lake water may have attained temperatures as high as 3–4°C under the ice cover. However, the actual rate of heating is low and the maximum summer temperatures were less than 6°C in the main water bodies of all the lakes examined. The maritime climate of the region promotes these low temperatures; the amount of available solar radiation reaching the water is reduced by the high average cloud cover; the frequent precipitation, mainly in the form of snow and freezing drizzle, cools the surface waters; the prevailing low air temperatures and high winds permit a considerable loss of heat from the lake.

There was rarely any variation of temperature with depth whenever the lakes were sampled during the summer (Fig. 13). The lake waters are subject to a number of conditions which promote isothermy. The inverse thermal gradient, which is present during the winter, practically disappears from the main water body several weeks before the lake opens, and so initially no density gradient is present and wind-generated turbulence mixes the waters of the various depths. As water attains its maximum density at 4·0°C, heating of the surface waters by solar radiation will promote water mixing by convection currents until the whole body of lake water is at 4·0°C. Even after this temperature has been attained, further surface heating will not create a very stable stratification because the increase in stability of thermal stratification per °C is not very great over the range of temperatures in the lakes. The predominant factor, however, is the almost continual strong wind that sweeps across the island. The mean wind speed during the summer months is normally in excess of 13 kt. (6·7 m. sec.$^{-1}$) and there are few calm days (Table I). Experience in the field suggests that the topography of the surrounding ridges increases the air turbulence in the vicinity of all the lakes and that they are commonly subjected to winds of a higher force than that recorded in the scientific station area. On several occasions the winds blew in almost directly opposing directions over the north and south basins of lake 2 with resultant chaos in the central area. Winds of this magnitude are sufficient to produce considerable turbulence and consequently mixing at all depths in the very shallow lakes on Signy Island.

Variation may exist between temperatures of the shallow waters of the sub-lacustrine shelves and those of the main water bodies during relatively calm periods (measurements of the summer temperature profiles are biased in that it was only possible to use the small portable boat when the wind velocity was less than 7 kt. (3·6 m. sec.$^{-1}$)). The waters of the two almost separate troughs of lake 2 may also act as independent water bodies under these conditions; the temperature differences are further influenced by the large amounts of water entering the southern basin (Table XXI). Temperature differences are small because the calm periods are of very brief duration. Variation in water density and stability of stratification will be slight; the gentlest breeze will promote isothermy. On Signy Island the factors affecting horizontal thermal gradients and the re-establishment of isothermal conditions are not unique, and hence lengthy discussion is not merited.

The lakes on the more exposed west coast of the island commonly open 2–4 weeks later than those on the east coast; they may also close a few days earlier. This shortened summer period suggests that the west coast lakes, in general, may have colder summer-temperature regimes. Unfortunately, few temperature measurements are available for these lakes.

General climatic conditions during December, January and February suggest that decrease in day length, and therefore of available solar radiation, is mainly responsible for the loss of heat from the lakes during February; the ambient temperatures and mean wind speeds vary only slightly. The waters remain more or less isothermal throughout the cooling period.

The morphology of two of the lakes suggested that they might not conform to the general pattern of isothermal summer regimes, but more detailed consideration indicated that this was unlikely. Lake 12 is a cirque lake and the high ridges and hills surrounding the cirque

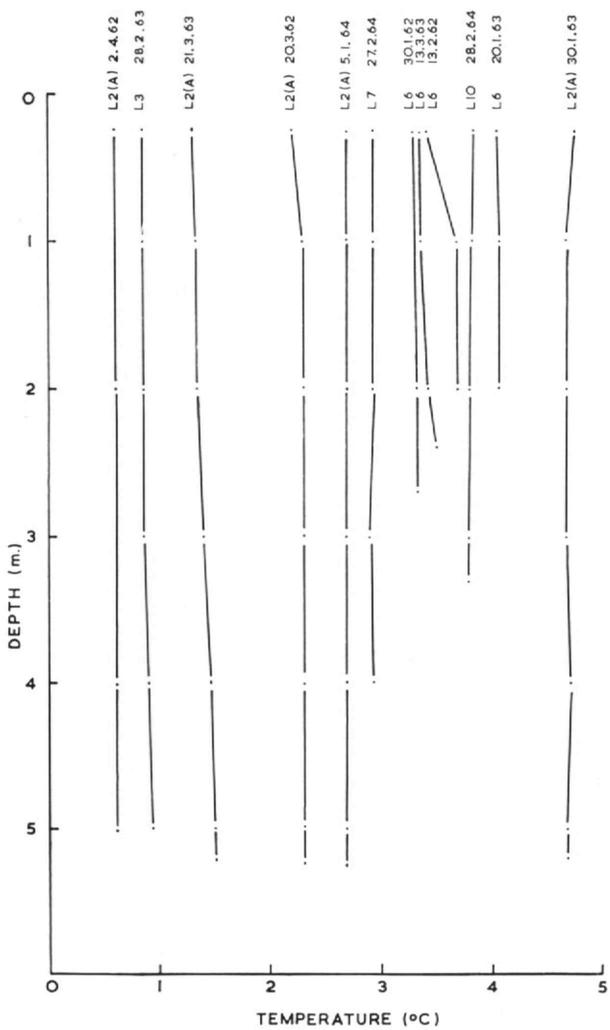

Fig. 13. Summer temperature profiles illustrating isothermal conditions in the various lakes.

afford a particularly sheltered site. The lake appears to be exposed to the main force of the wind on only 3–6 days during a typical summer month. A temperature profile obtained on 7 September 1963 revealed a bottom temperature of only 0·9°C (Table XIX). The lake is the deepest on the island, having a maximum recorded depth of 15 m. The sheltered nature of its position and its depth suggest that a thermocline could develop during the summer months (an attempt to study the lake during February 1964 failed because of personal injury). But the surrounding high ground also limits the amount of direct solar radiation and, as the lake receives practically all its water supply from a tongue of the ice cap which falls to its eastern shore, it seems unlikely that the lake temperature exceeds 4·0°C during the summer (the lake had only very short open periods during the years of this survey). It seems probable, therefore, that the whole body of lake water is mixed by convection currents, supplemented by some wind-generated turbulence, during a normal summer. The second possible exception is lake 9, which often remains ice-covered throughout the summer, but it always receives copious amounts of melt water from a small icefield forming part of its eastern shoreline. A comparison with lake 3 suggests that the maximum temperatures in lake 9 are unlikely to exceed 1·0°C. Although the ice cover obviously protects the water from the wind, sufficient turbulence should be provided by the inflowing water to remove the inverse thermal gradient of winter and any horizontal and vertical gradients produced by solar radiation during the summer.

Thermo-circulation types. Hutchinson (1957, p. 437) has reviewed the attempts to classify the thermo-circulation types of lakes and has discussed their limitations. The Signy Island lakes cannot be classified accurately under any of the available systems and withdrawal of the terms "cold monomictic" and "formally dimictic" (Heywood, 1967*a*) is suggested. The present classifications do not refer to the type of circulation found in these shallow lakes. It is considered more important that the mean annual temperature of the lakes is several degrees below 4°C than that for a brief period of the year the temperature rises slightly above this point. Only Paschalski (1964) has put forward a definitive and orderly classification for all probable forms of circulation (complete and continuous circulation, as present in the lakes of Signy Island throughout the ice-free period, is called "pleomictic"). It would be logical to base all future attempts to provide a thermo-circulation classification on this system.

Winter

When an ice cover has formed, water below 1–2 m. can have the temperature at which the water freely circulated just before freezing (Fitzgerald, 1895; Yoshimura, 1936). Results are not available to determine this exact temperature for any lake on Signy Island because temperature profiles were not obtained until several days after the surface waters had frozen. The available results suggest, however, that for most lakes on the island the minimum temperature of free circulation was below 0·4°C.

Hutchinson (1957, p. 454) has described the series of characteristic events which takes place once a lake has frozen over and which has the general effect of increasing the temperature of the main mass of water remote from the ice. Winter heating was recorded in lakes 2, 3 and 6 on Signy Island—and one may assume that it occurs in all the lakes on the island. For the greater part of the winter, however, the rate of heating was very low and all but obscured. Work on the optical properties of the lakes during 1963 (p. 21) suggested that, during most of the winter period, solar radiation had little effect on the lakes and that the inverse thermal gradient in the lake water reflected a balance between heat loss through the ice cover and heat gain from the bottom deposits.

The heat budget became balanced about August and the ice cover did not increase although its thickness was maintained. Experiments with the photocell showed that there was no appreciable increase in available radiation at this time and one must assume that the change in the heat budget was caused by the thickened ice and snow layers with their very low levels of thermal conductivity effectively insulating the water from the ambient temperatures. The additional radiation received during the brief time the lakes are free of snow in a normal mid-winter period appears to be small and its effects are not revealed in the temperature profiles. The bottom deposits may have released all their excesses of heat by this time because, although the lakes appeared well insulated, the temperature gradients remained constant.

During the latter part of the winter, the effects of the periodic removal of snow cover and the increase in available radiation were shown in the temperature profiles (Fig. 14), and as the periods of little or no snow cover increased winter heating became very apparent. The whole mass of lake water remote from the ice attained a temperature as high as 3–4°C in lake 6 (Fig. 12) before the ice cover disappeared.

Annual variation

The conditions prevailing in these lakes from day to day, and from year to year, reflect a delicate balance between ambient temperature, available solar and sky radiation, and snow cover. The climatic conditions in 1963 closely approached the means for the years 1947–66.

In 1963, winter heating only became effective after mid-October and the heat budget remained neutral for 6–8 weeks before this. These conditions contrast with those of 1962 when considerable periods of thaw occurred in every winter month, snow cover was often absent and winter heating became apparent as early as July. In 1961 the snow cover must have formed very slowly but once formed it must have persisted for most of the winter, thus affording maximum heat loss during the early part of the winter and considerable insulation thereafter; the ice on lake 6 was still 1·2 m. thick on 15 December 1961 and all the lakes seemed unaffected by thawing. In February 1966, 15 cm. of ice had re-formed on lake 6 following an unusually cold spell (personal communication from B. J. A. Goodman).

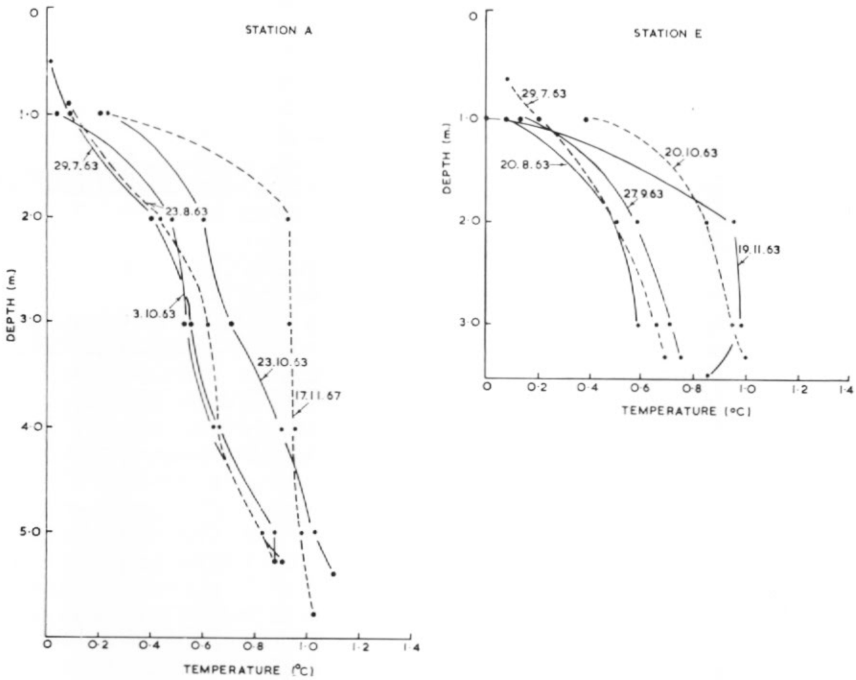

Fig. 14. Winter heating recorded at two sampling stations; lake 2.

Heat budget

Only a small proportion of the annual heat income is involved in actually heating the water of any lake on Signy Island. The main demands on energy are for the removal of the ice cover, for maintaining the water temperature against the cooling effects of melt water and wind, and for heating the lake sediments.

Only $\sim 40\times10^{10}$ cal. are required to heat the water of lake 2 to its maximum temperature (~ 5°C). But before this $\sim 20\times10^{10}$ cal. will have been used to raise the ice temperature to 0°C (assuming a minimum mean temperature of -7°C for the ice cover) and a further 200×10^{10} cal. will have been used to melt the ice cover. Removal of ice by sublimation will also have demanded energy at a rate of 620 cal. g.$^{-1}$. After removal of this ice cover, evaporation of water at a rate of 1–2 mm. day^{-1} (a value suggested for a free water surface by Penman (personal communication)) will result in a heat loss of 60–150 cal. cm.$^{-2}$ day^{-1}. A considerable amount of heat will also be lost by conduction to the air because the mean ambient temperature is 3–4°C lower than the water temperature and winds (with mean speeds of over 13 kt. (6·7 m. sec.$^{-1}$)) are completely and continually stirring the lake waters throughout the ice-free period. The amount of heat absorbed by the bottom sediments is not known; it will vary considerably from one lake to another (Fig. 7) but it should generally be in excess of the amount utilized in heating the lake water.

It is clear that no sensible figure can be presented for the annual heat budget of any lake on Signy Island until all of these factors have been investigated in detail or values for available radiation have been obtained. Rough calculations to determine the probable order of magnitude suggest that the heat budgets of these very shallow lakes are small compared with most of the known heat budgets of lakes in other areas of the world (Hutchinson, 1957, p. 496–500).

Ice cover

The process of freezing usually depends on a sudden loss of heat during a still night when an inverse thermal gradient is established in the top layers of water. On Signy Island, however, the surface layers of ice are generally formed under turbulent conditions. The climatic conditions at the times of freezing suggest that the ice forms from a layer of snow which, falling on to turbulent and perhaps supercooled surface waters, remains discrete and eventually precipitates the formation of ice crystals (the freshly formed surface layers of the ice cover always have a granular appearance). This conclusion is supported by the results of Wilson and others (1954) on a North American lake. After the second time of freezing in 1963 (Fig. 12), a 33-hr. period of intermittent rain and gale-force winds broke a 10-cm. ice cover on the lakes into large floes which eventually froze together and, with new ice, formed a floe-agglomeritic ice cover. Observations on the sub-lacustrine shelf of various lakes showed that anchor ice formed in a thin layer over the boulders after the water surface had frozen. The water over the shelf areas eventually freezes solid.

The ice on lake 10 was yellow and soft, suggesting that organic matter, perhaps in colloidal form, had been incorporated in or imprisoned within the ice matrix.

After periods during which the ambient temperature fell rapidly over a considerable range, the lake ice was scored with numerous cracks that formed two systems, one radial and the other at right-angles. This phenomenon is a very characteristic effect of rapid temperature change and it has been examined in detail by Zumberge and Wilson (1953) and Wilson and others (1954). Whereas a slow fall in temperature apparently permits the ice to flow over the water surface, a rapid temperature change subjects the ice to stresses during contraction which it cannot withstand. The unusual feature of this phenomenon on the Signy Island lakes is that the cracks were dry. Cracking often occurred whilst sampling was in progress but water did not well up through the cracks which are often 3 cm. wide. Therefore, the cracks could not have extended through the whole thickness of the ice. The explanation probably lies in the fact that a thermal gradient exists in the ice layer (the bottom temperature is always at 0°C whilst the surface temperature varies with the ambient temperatures). When the air temperature falls rapidly, a gradient of stress will exist throughout the ice. The bottom layers will be affected only slightly and they will be sufficiently plastic to withstand the stress transmitted by the contraction and cracking of the upper layers in ice of this thickness.

When a lake surface has frozen, cracked and the water in the cracks frozen, heating to 0°C, if sufficiently rapid, produces a sheet of ice of greater area than before. Pressure is therefore exerted on the shore, forcing gravel and boulders landwards. This phenomenon, ice push, was not observed on Signy Island. Two slight ripples were observed on the northern basin of lake 2. The ripples were present on either side of a radial crack which coincided with the edge of the sub-lacustrine shelf and are thought to have been produced by pressures resulting from the interaction between freely floating main ice and firmly anchored ice on the shelf.

Melt water does not gain access to the main body of lake water during minor thaw periods because the lake margins are frozen solid to a depth of 90–100 cm. The net effect of minor thaws is an increase in ice thickness. Melt water running on to the lake ice combines with the snow cover and further precipitation to form a slush which re-freezes into "*névé*". The addition of more melt water to the "*névé*" forms a layer of granular ice. This process can add considerably to the original ice thickness.

The ice cover first melts where streams enter and leave the lakes and the remaining ice may remain seemingly unaltered for several weeks. Pools then appear along the margins of the lake in the shallow water over the sub-lacustrine shelf, where the available radiation is concentrated on a small thickness of ice and not dissipated throughout a large water volume as elsewhere in the lake. Several of these pools were studied on lake 2 and they were found to have an unusual structure during the early stages of formation (Fig. 15). This structure may result

TABLE VI. MID-DEPTH VALUES OF THE CONCENTRATIONS OF THE COMMONER RADICALS AND DISSOLVED GASES

	Lake	*Date*	O_2 (per cent saturated)	CO_2 (p.p.m.)	pH	Alkalinity (meq./l.)	Ca^{++} (p.p.m.)	Mg^{++} (p.p.m.)	Cl' (p.p.m.)	SO_4'' (p.p.m.)	NO_3' (p.p.m.)	PO_4''' (p.p.m.)
		1964										
	2 (A)	29 January	104	1·9	6·7	0·12	3·6	3·1	44·0	6·0	0·07	0·013
	3						Not determined					
	5	29 January	105	1·9	6·9	0·12	2·7	2·0	29·5	4·3	0·04	0·007
Summer	6	29 January	102	1·5	7·1	0·14	2·1	1·3	17·5	1·6	0·03	0·002
	7	27 February	110	2·1	6·9	0·18	4·8	3·9	48·0	5·5	0·04	tr
	10	28 February	94	3·1	7·1	0·30	12·5	5·4	61·0	15·0	9·03	0·160
		1963										
	2 (A)	3 October	23	11·6	6·2	0·19	7·2	7·0	74·6	15·9	2·08	0·123
	3	13 September	84	4·0	6·7	0·22	5·3	4·0	42·8	6·0	0·18	0·002
	5						Not determined					
Winter	6	11 September	13	16·4	6·2	0·31	7·3	4·5	47·0	7·8	0·26	0·012
	7	5 September	4	6·3	6·2	0·14	4·6	3·6	36·0	7·1	0·13	0·043
	10	4 September	3	5·7	6·2	0·20	12·2	6·3	109·0	26·4	>8·00	>0·500

tr Trace.

from an unevenness of the shelf floor—the small area where the lake ice is fully penetrated coinciding with a jutting boulder. The pools enlarge until the sub-lacustrine shelf area is completely free of ice. The main ice mass may remain as a floe for several days. The melting of lake and river ice has been studied by Birge (1910) and Humphreys (1934).

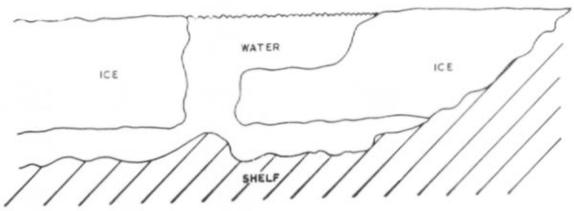

Fig. 15. An early stage in the formation of pools along the margins of the lake ice-cover.

A strange phenomenon was observed on lake 5 on 30 November 1963. The ice cover was broken into radial segments, the inner edges of which dipped into the depths of the lake and the outer edges remained firmly frozen to the narrow sub-lacustrine shelf. The water level of the lake had been raised by the addition of melt water, because the outflow stream which runs under-ice (Heywood, 1967*b*) was still frozen and there was no other exit from the small cirque. Ice is less dense than water and no explanation can yet be offered for this observation.

Chemical Properties of the Lakes

The lakes of Signy Island contain soft water which has a pH of about 7. Early summer values for the commoner radicals and dissolved gases of the selected lakes are given in Table VI. The most important single factor influencing the chemical composition of the lake waters is contamination by wind-borne sea spray. The ratios of sulphate and magnesium to chloride approached the oceanic values in all the lakes investigated during this period of the year (Table VII). Large amounts of these ions must be carried by the strong winds that sweep across the island. Some analyses of precipitation are given in Table VIII. Drischel (1940) in Europe and Conway (1942) in the U.S.A. have shown that the amount of chloride carried by the wind and present in precipitation decreases rapidly over even very short distances from the sea, and this is presumably true for salts such as sulphates in areas free of industrial pollution. The salinity differences of the various lakes can therefore be explained in part by their respective distances from the sea, the direction of the prevailing wind (which may be modified locally by the topography of the drainage basin (Heywood, 1967*b*)) and the degree to which the drainage basin is sheltered (Fig. 5).

Virgin mineral soil on Signy Island has a high base-rich calcium and sodium content (Holdgate and others, 1967). Leaching of calcium appears to have raised the calcium to chloride ratio in the lakes above that of sea-water and additional calcium from marble outcrops promotes amd maintains the slightly higher ratios of lakes 6 and 7.

Surface water flowing over areas of scree and silt, which are bare of vegetation, had a low nitrate and phosphate content (samples A and B, Table IX) unless contaminated by bird droppings (sample E). Water flowing through stands of moss gained appreciable amounts of these salts (samples C, D and G), which probably came from wind-borne fine particulate matter and aerosols (from seals wallows and bird colonies) trapped within the moss cover (Allen and Northover, 1967). Water flowing over seal wallows (and presumably through bird colonies) contained very large amounts of calcium, nitrate and phosphate, produced by the break-down of excreted waste and moulted fur (sample F). The chemical composition of the sub-soil water was not determined but analysis of soil samples and the simple geology of the drainage basins suggest that, in general, the composition of the water will vary only slightly from one area to another. The clay-like properties of the permanently waterlogged soil (Heywood, 1967*b*) ensure that most precipitation enters the lakes in the form of surface water. Consequently, the concentrations of nutrient salts within a lake are determined by the supplies of run-off water and the nature of the substrate over which they flow (Fig. 5; Table VI).

TABLE VII. RATIOS OF CERTAIN RADICALS TO CHLORIDE IN THE LAKE WATERS

	Lake	*Date*	SO_4''	Ca^{++}	Mg^{++}	NO_3'	PO_4'''
	Sea-water		0·1396	0·0211	0·0670	—	—
		1964					
	2 (A)	29 January	0·1393	0·0843	0·0700	0·0016	0·0003
	3				Not determined		
	5	29 January	0·1460	0·0913	0·0680	0·0014	0·0002
Summer	6	29 January	0·0910	0·1200	0·0700	0·0017	0·0001
	7	27 February	0·1100	0·1000	0·0800	0·0008	tr
	10	28 February	0·2500	0·2100	0·0900	0·1480	0·0026
		1963					
	2 (A)	1 October	0·2130	0·0970	0·0940	0·0278	0·0016
	3	13 September	0·1395	0·1240	0·0930	0·0042	0·00004
	5				Not determined		
Winter	6	11 September	0·1660	0·1550	0·0960	0·0055	0·0003
	7	5 September	0·1970	0·1280	0·1000	0·0036	0·0012
	10	4 September	0·2430	0·1120	0·0580	n.d.	n.d.

n.d. Not determined.
tr Trace.

TABLE VIII. CONCENTRATIONS OF CERTAIN RADICALS IN PRECIPITATION FALLING ON SIGNY ISLAND

Precipitation	*Date*	Cl' (p.p.m.)	SO_4'' (p.p.m.)	Ca^{++} (p.p.m.)	Mg^{++} (p.p.m.)	*Remarks*
Rain/sea spray	March 1965	51·0*	n.d.	2·64	tr	Collected over 7 days
	1963					
Snow	18 July	7·5	0·8	0·38	0·56	Sea frozen
Snow	28 August	33·3	n.d.	1·09	2·48	Sea frozen
Snow/sea spray	6 November	79·6	n.d.	n.d.	n.d.	Sea open

* Calculated from sodium concentration (figures by courtesy of M. J. Northover).
n.d. Not determined.
tr Trace.

TABLE IX. CONCENTRATIONS OF THE COMMONER RADICALS IN SURFACE-FLOWING WATERS

Sample	*Date*	*Description*	pH	Alkalinity (meq./l.)	Ca^{++} (p.p.m.)	Mg^{++} (p.p.m.)	Cl' (p.p.m.)	SO_4'' (p.p.m.)	NO_3' (p.p.m.)	PO_4''' (p.p.m.)
	1963									
A	15 December	Inflow of lake 6. Flows 120 m. from ice face at moderate speed over fine silt/scree	6·8	0·11	1·1	1·3	25·6	3·2	0·08	tr
	1964									
B	28 January	Inflow of lake 6. Flows 120 m. from ice face at moderate speed over fine silt/scree	7·2	0·19	1·7	0·6	7·6	0·8	0·08	0·001
C	28 January	Inflow of lake 5. Flows from snow bank at slow speed through luxuriant moss stands	6·4	0·07	1·8	1·8	26·6	5·9	0·89	0·002
D	28 January	Inflow of lake 2. Flows from snow bank 50 m. at moderate speed through luxuriant moss stands	6·8	0·16	3·6	2·0	32·8	8·7	1·13	0·003
E	5 March	Inflow of lake 7. Flows from 60 m. cliff and coarse scree. *Macronectes* colony nearby	6·7	0·10	1·9	2·3	31·4	4·8	0·01	0·072
F	5 March	Inflow of lake 10. Drainage from seal wallows	7·9	0·51	13·2	4·8	54·6	11·4	6·20	0·077
G	20 March	Inflow of lake 2. Flows from snow bank 50 m. at moderate speed through luxuriant moss stands	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3·26	0·025

n.d. Not determined.
tr Trace.

Photosynthesis in algal mats covering the shelf areas ensures that the whole body of water in each lake remains saturated and even supersaturated with oxygen throughout the period of complete and continual water circulation.

Seasonal variation

After the main spring flush of melt water, there was a gradual increase in concentration of the various ions and this continued after ice had sealed the lake from the external environment (Table X). The oxygen concentration fell rapidly under the ice cover and, for most of the winter, conditions were almost anaerobic in the lower levels of the trough. Oxygen loss was paralleled by an increase in carbon dioxide which lowered the pH. Entry of melt water re-established the early summer conditions. These events were observed in lake 2 but occasional work on four other lakes suggested that events were similar in all of the lakes.

Chloride. These ions are not normally affected by biological activity and consequently chloride analyses indicate the pattern of events occurring in the lakes through purely physical agencies, and can thus clarify the general picture of chemical and biochemical activity.

Chloride is replenished throughout the summer by ions from precipitation and wind-borne sea spray. Lake 2 appears to have had a net gain of 20 kg. day^{-1} over the 84-day period between 30 January and 25 April 1963. On a small island subjected to strong winds, the so-called precipitation amount is clearly the combined volumes of actual precipitation and wind-borne sea spray. Working from a figure of $\sim$ 40 cm. yr.$^{-1}$ precipitation/sea spray for Signy Island (Heywood, 1967*b*), water entering lake 2 would have to have had a mean concentration of 70 p.p.m.* chloride throughout the 84-day period discussed here. Precipitation/sea spray samples collected near the British Antarctic Survey station throughout the last week in March 1965 had a mean concentration of over 50 p.p.m. chloride (Table VIII). Field experience indicates that prevailing winds are deflected down the valley of lake 2 by the mass of Coronation Island, and that turbulence raises the mean wind speed above the 13 kt. (6·7 m. sec.$^{-1}$) recorded in the station area. Furthermore, the north basin of the lake lies only 200 m. from Stygian Cove and the whole lake must normally receive very large amounts of wind-borne sea spray. The mean chloride concentration in water entering lake 2 is most probably higher than that collected in the station area and a net gain of 20 kg. day^{-1} by the lake is therefore feasible.

A marked decrease in the chloride content of lake 2 was observed on 24 May (Table XI), suggesting that the lake water had been diluted by inflowing water after ice had sealed the surfaces of lakes, streams and soil. Water was heard flowing in the stream connecting lakes 2 and 5 for several days under these conditions. No change in the level of either lake was observed, implying that water was flowing out of lake 2 and that ground water was seeping into both lakes at this time. Chambers (1966) has reported that the freezing plane descends slowly through the soil at the beginning of winter, so the ambient temperatures are not an immediate barrier to the movement of ground water. No information is available on the amount of ground water involved or in its chloride concentration but certain points may be assumed. The relative amounts of glacial debris and bare rock surrounding the two lakes suggest that the greater part of the ground water must seep into lake 5 and into the southern basin of lake 2 (Heywood, 1967*b*). The greater distances of these areas from the sea (in the direction of the prevailing winds) will reduce the amount of contamination by sea spray, and, as lake 2 will be protected against direct contamination, ingress of seepage water will definitely cause dilution of its salt content. Furthermore, part of the ground water may have

* Calculated from the expression $ds = (\rho - \gamma)\, dM = V d\gamma$, which gives $V \ln (a-\rho)/(a'-\rho) = M$,

where s = total salt in lake at a given time,
γ = concentration of salt in lake at that time,
V = volume of lake,
ρ = concentration of salt in the precipitation,
M = volume of the precipitation,
a = initial concentration in lake,
a' = final concentration in lake.

(Kindly provided by Dr. Cohn, Mathematics Department, Queen Mary College, London University.)

TABLE X. SEASONAL VARIATION IN MEAN CONCENTRATIONS OF RADICALS, GASES, ALKALINITY AND pH IN LAKE 2

Date	Cl′ (p.p.m.)	SO_4'' (p.p.m.)	NO_3' (p.p.m.)	PO_4''' (p.p.m.)	Ca^{++} (p.p.m.)	Mg^{++} (p.p.m.)	O_2 (p.p.m.)	CO_2 (p.p.m.)	Alkalinity (meq./l.)	pH
1963										
7 January	43·9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0·1109	n.d.
30 January	41·4	6·1	0·32	n.d.	n.d.	n.d.	12·6	n.d.	0·1220	6·7
17 February	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	13·0	n.d.	n.d.	n.d.
21 March	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	14·0	n.d.	n.d.	n.d.
25 April	64·3	15·0	0·45	n.d.	n.d.	n.d.	12·6	2·5	0·1575	6·7
24 May	56·6	11·2	1·06	0·064	n.d.	n.d.	9·1	5·4	0·1764	6·4
6 July	64·0	16·0	1·95	n.d.	6·7	5·7	5·5	10·0	0·1807	6·2
27 July	65·2	13·3	1·77	n.d.	6·4	6·3	5·1	7·9	0·1867	6·2
20 August	70·0	14·7	2·37	n.d.	7·5	6·2	4·3	9·0	0·1773	6·1
1 October	72·8	15·4	1·78	0·117	7·3	6·7	3·2	11·6	0·1961	6·3
23 October	72·7	14·8	n.d.	n.d.	7·0	6·6	n.d.	n.d.	n.d.	n.d.
2 November	72·0	14·2	n.d.	n.d.	6·7	6·7	2·9	14·5	0·1985	6·2
19 November	85·0	12·4	n.d.	n.d.	6·3	7·2	7·7	11·4	0·1976	6·3
1964										
5 January	45·6	6·3	0·25	0·016	3·2	3·7	13·9	1·6	0·1269	6·8
28 January	44·0	6·1	0·07	0·013	3·7	3·1	n.d.	1·9	0·1379	6·9
20 March	n.d.	n.d.	0·21	0·010	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. Not determined.

been derived from precipitation of the previous winter, when the surrounding sea was frozen and the amount of contamination by sea spray was very low (the substrate remains permanently waterlogged and most of the summer precipitation enters the lakes as surface run-off water).

TABLE XI. SEASONAL VARIATION IN THE TOTAL AMOUNTS (kg.) OF CERTAIN RADICALS AND GASES IN LAKE 2

Date	Cl'	SO_4''	NO_3'	PO_4'''	Ca^{++}	Mg^{++}	O_2	CO_2
1963								
7 January	3780	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
30 January	3560	525	28	n.d.	n.d.	n.d.	1084	n.d.
17 February	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1118	n.d.
21 March	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1200	n.d.
25 April	5270	1230	37	n.d.	n.d.	n.d.	1033	205
24 May	4415	874	83	5·0	n.d.	n.d.	710	420
6 July	4415	1120	137	n.d.	470	400	385	700
27 July	4415	891	119	n.d.	430	420	340	530
20 August	4415	941	152	n.d.	480	395	275	575
1 October	4415	909	105	6·9	430	395	190	685
23 October	4415	873	n.d.	n.d.	415	390	n.d.	n.d.
2 November	4415	880	n.d.	n.d.	415	415	180	900
19 November	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
1964								
5 January	3950	542	22	1·4	275	318	1195	138
28 January	3770	525	6	1·1	320	267	n.d.	163
20 March	n.d.	n.d.	18	0·9	n.d.	n.d.	n.d.	n.d.

n.d. Not determined.

After this early winter period, the total chloride content of the lake should remain constant until melt water gains access to the lake in the spring. Any change in concentration of the chloride ion must be caused by the removal of water molecules in the formation of the ice cover (less than 1 per cent of salts were trapped within the ice samples analysed). The volumes of ice and water in the lake at any given time can be calculated from the known dimensions of the lake (Heywood, 1967*b*) and the mean ice thicknesses measured at the three sampling stations. These volumes were calculated for five occasions* (Table XII) and the water volumes were used, with the recorded chloride concentrations, to determine the chloride content of the lake. After 24 May the chloride-content figures varied by less than 3 per cent; this is good evidence for the accuracy of the 24 May chloride values and for the hydrographic survey. Variations in ice thickness over the different parts of the lake will be least nearest to the time of freeze-up and, consequently, the 24 May figure has been taken as the constant chloride content of the lake for the 1963 winter.

* Using a National-Elliot 803 computer and a standard library programme based on the estimation of volumes by the trapezium rule.

TABLE XII. ESTIMATED VOLUMES OF WATER IN LAKE 2 DURING 1963–64

Date	*Volume* ($\times 10^6$ l.) A	B
1963		
7 January	86	
30 January	86	
25 April	82	
24 May	78	
6 July	n.d.	70
27 July	67	
20 August	n.d.	64
1 October	59	
23 October	59	
2 November	n.d.	62
1964		
5 January	86	
28 January	86	
20 March	86	

n.d. Not determined.

A. Calculated from morphometric parameters and mean ice thickness.
B. Calculated from assumed constant chloride content and chloride concentration.

In 1963, melt water first gained access to the lake after mid-November. Measurements of ice thickness at this time indicated that the ice was also melting and supplying more water for the dilution of the salt content. The results of chloride analyses on 19 November samples suggested, however, that either a notable increase in ice thickness had occurred or that the chloride content of the lake had increased. Neither phenomenon is likely and, as a parallel increase was not noted for any other ion, no explanation for this can be offered at present. Melt water produced by minor thaws (p. 28) often flowed into sampling holes cut at station E after August. This caused dilution of the upper metre of water but the effect is thought to have been very localized.

Analyses for the chloride ion have shown that it is essential to study variation in total ionic content and not in ionic concentration to determine the amount of chemical and biochemical activity taking place during the winter. Where the water volume of the lake is not already known, the figure can be calculated from the constant chloride content and the change in the chloride concentration (Tables X and XI). The relative effects of physical and chemical/biochemical agencies on the various ions and gases is indicated in Fig. 16. The figures calculated for this diagram were based on the 24 May values because of the early winter dilution, and consequently some error has been introduced from the assumption that any increase in a particular ion between dilution and this date is entirely due to the formation of ice.

Sulphate. Although some of the gain in sulphates during the 1963 summer was clearly from precipitation and sea spray, the changing ratio of sulphate to chloride indicated that there were other sources of this ion (Table XIII). These were most likely to have been the oxidation of hydrogen sulphide produced in the lake during the winter, and the oxidation of organically precipitated ferrous sulphide washed out of peat lying under surrounding moss stands.

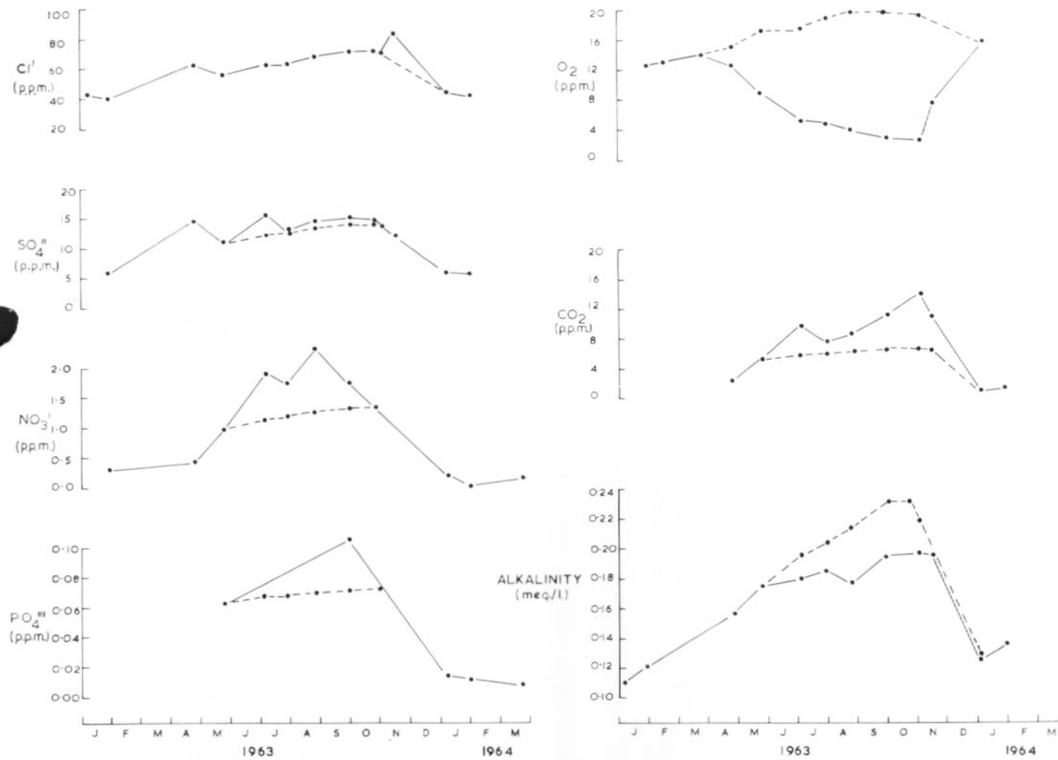

Fig. 16. The unbroken lines connect values recorded for the mean concentrations of certain salts and gases in lake 2. The estimated effect of the removal of water in the formation of ice on each chemical is indicated by the broken line.

There was some circumstantial evidence in support of these suggestions. First, hydrogen sulphide was produced in the lake and the odour was readily detected from dredge samples. The gas will have been produced from the reduction of sulphates under anaerobic conditions and from the heterotrophic break-down of proteins. Secondly, the ratio of sulphate to chloride was lowest in those lakes which did not receive, as their main supply, water which flowed through or under moss (lakes 3, 6 and 7).

There appears to have been a gain in sulphates immediately after the early winter dilution which may have resulted from the oxidation of ferrous sulphide carried in by the seepage water. As the oxygen content of the water fell, this initial gain of sulphate was lost. Oxidation of sulphur compounds may still have occurred in the free water but reduction to hydrogen sulphide must certainly have been occurring at the now anaerobic mud surface in the troughs. Most of this gas was probably converted to ferrous sulphide which precipitated out into the sediments. The eventual loss of sulphates through reduction seems small.

Some loss of all sulphur compounds, except precipitated ferrous sulphide, must have occurred in the spring when the lake was flushed out with melt water. It is presumed that the ferrous sulphide was converted to hydrogen sulphide and finally sulphates during the summer.

This work on sulphates (and on phosphates; see below) suggests that availability of iron may be an important factor in the lakes of Signy Island.

TABLE XIII. RATIOS OF CERTAIN RADICALS TO CHLORIDE IN LAKE 2

Date	SO_4''	NO_3'	PO_4'''	Ca^{++}	Mg^{++}
1963					
7 January	n.d.	n.d.	n.d.	n.d.	n.d.
30 January	0·1470	0·0077	n.d.	n.d.	n.d.
25 April	0·2340	0·0070	n.d.	n.d.	n.d.
24 May	0·1970	0·0187	0·0011	n.d.	n.d.
6 July	0·2490	0·0307	n.d.	0·1054	0·0897
27 July	0·2040	0·0274	n.d.	0·0992	0·0977
20 August	0·2100	0·0341	n.d.	0·1078	0·0887
1 October	0·2120	0·0246	0·0016	0·1008	0·0926
23 October	0·2030	n.d.	n.d.	0·0967	0·0913
2 November	0·1980	n.d.	n.d.	0·0941	0·0941
19 November	n.d.	n.d.	n.d.	n.d.	n.d.
1964					
5 January	0·1370	0·0054	0·0004	0·0696	0·0805
28 January	0·1393	0·0013	0·0002	0·0843	0·0700

n.d. Not determined.

Nitrate and phosphate. Nitrates, phosphates and presumably ammonium compounds were gained throughout the summer from surface run-off and from the decomposition of debris within the lake. The ammonium compounds were presumably nitrified both in free water and at the oxygenated surface of the sediments. But, while the nitrate content of the lake increased, the soluble phosphate content fell. The phosphate was probably lost by adsorption on to ferric hydroxide which subsequently precipitated (personal communication from F. J. A. Mackereth). Both nitrates and phosphates were presumably utilized by the lake flora during this period.

The lake continued to gain nitrates during most of the winter (Table XI) but the increase in rate is thought to have been more apparent than real. Biological demand was presumably reduced at this time as most of the flora was encased in ice and there was no loss through an outflowing stream. The actual rate of nitrification could have been very low under the almost anaerobic conditions that eventually prevailed in the lake. Phosphate is thought to have been liberated at an increasing rate, however, as the ferric hydroxide on to which it was originally adsorbed was reduced to ferrous sulphide and ferrous bicarbonate. A considerable loss of both nutrient salts towards the end of the winter in a probable phytoplankton bloom (Heywood, 1967*a*) may have been obscured by the lack of analyses at this time.

Calcium and magnesium. Lack of results for the 1963 summer make comment on the calcium and magnesium content of the lake particularly difficult. The calcium to chloride and the magnesium to chloride ratios (Table XIII) indicate that both cations were gained by leaching as well as from precipitation/sea spray during the summer months, and there appears to have been a considerable gain of these cations before the lake surface froze. Values obtained during the winter fluctuate only within the range of experimental error expected with the methods used. It is concluded that, after the early winter dilution, the calcium and magnesium contents remained more or less constant until melt water gained access to the lake.

Oxygen. The oxygen content of the lake increased as the solubility of the gas rose with falling water temperatures during the summer.

Immediately after the lake surface had frozen over the oxygen content fell rapidly. This was due to biological activity and, perhaps, to the inflow of oxygen-depleted seepage water during the early winter dilution. The decrease in the rate of oxygen loss coincided with the death of the anostracan population and the reduced winter numbers of other crustacean populations. There is evidence that the rate of oxidation of chemical components by bacteria is also low at this time.

There was no marked fall in the oxygen content to coincide with the observed pre-spring zooplankton bloom (Heywood, 1967*a*). A loss may have been offset by the photosynthetic production of oxygen by phytoplankton and by blue-green algae on areas of shelf now unfrozen beneath the ice layer. The oxygen content of the lake quickly regained its early summer level with the entry of melt water to the lake.

Carbon dioxide. Fluctuations in carbon dioxide concentration were roughly inverse of the oxygen changes, as expected. This relationship could not be established quantitatively because only the "free" carbon dioxide was measured. The values for "free" carbon dioxide are of uncertain accuracy because of certain errors inherent in the technique used (p. 15). Variation in concentration with depth (Table XXII) indicated that considerable amounts of the gas escaped during the period between the cutting and re-freezing of the sampling holes, particularly towards the end of the winter when an insulating layer of fresh snow could prevent the holes from freezing altogether.

pH. The pH determinations were also of uncertain accuracy and the only conclusion that can be drawn is that the acidity of the lake did increase during the winter, presumably because of the increase in carbon dioxide concentration.

Alkalinity. There appears to be a semi-quantitative relationship between the carbon dioxide and the alkalinity figures but the gain in alkalinity through chemical/biochemical agencies may lie well within the limits of experimental error. As one is uncertain as to what is actually represented by the alkalinity figures for these lakes, further comment must await a more detailed investigation.

Only a few points concerning the other lakes are worthy of note; most of the seasonal changes of the biologically active chemicals may be readily explained in terms of apparent fauna densities, and the density of transported debris in the lake water. In lake 10 conditions became very toxic during the winter and the fauna appeared to overwinter in the egg or other resting stages. The very low oxygen concentration is thought to be due to the chemical and biochemical break-down of the very large amounts of dissolved and particulate organic matter which this lake contained. The low mid-winter oxygen concentration in lake 7 is puzzling (the oxygen probe was examined and re-calibrated on return to the station laboratory, and it was found to be working correctly). The visit to lake 7 coincided with a zooplankton bloom and it must be concluded that the low oxygen concentration was the result of biological demand. However, the concentration is surprisingly low.

December samples taken from lakes 3 and 6 showed a large increase in the concentration of certain ions in the lower depths of the trough. This probably resulted from the sediments being disturbed by inflowing melt water and it was probably an event common to all the lakes.

Conclusion

The present study of physical and chemical factors suggests that formation and duration of ice cover (with attendant snow cover) have the greatest effect on the biota of the Signy Island lakes.

The climate of Signy Island, which is strongly influenced by the cold air mass over the ice-bound Weddell Sea, is probably as rigorous as the climate of most other coastal areas of the Antarctic Peninsula as far south as the Antarctic Circle (Pepper, 1954). The lake system of Signy Island, with its wide range of physical and chemical properties, may therefore contain representatives of all lake types to be found in this area of the Antarctic. The only known exception is a volcanically warmed lake on Deception Island (Kroner Lake).

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APPENDIX

TABLE XIV. TEMPERATURE OF LAKE 2 (°C)

Date	Station A							Station C		Station E				
	Depth S	1 m.	2 m.	3 m.	4 m.	5 m.	B	Depth S	B	Depth S	1 m.	2 m.	3 m.	B
1962														
20 March	2·2	2·3	2·3	2·3	2·3	2·3	2·3	n.d.	2·2	2·1	2·2	2·2	n.d.	n.d.
2 April	0·6	n.d.	0·6	n.d.	0·6	0·6	n.d.	n.d.	0·3	0·5	0·4	0·5	0·5	n.d.
21 April	0·9	n.d.	0·9	n.d.	n.d.	0·9	0·9	n.d.	0·9	1·0	1·0	1·0	1·0	n.d.
3 June	n.d.	0·3	n.d.	n.d.	0·3	n.d.	0·6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
12 June	n.d.	0·2	0·3	n.d.	n.d.	n.d.	0·5	n.d.	0·0	n.d.	n.d.	0·3	n.d.	0·5
19 July	n.d.	0·2	0·3	n.d.	0·5	n.d.	0·5	n.d.	0·0	n.d.	0·3	0·4	n.d.	0·5
24 August	n.d.	0·4	n.d.	0·6	n.d.	0·7	0·9	n.d.	0·1	ice	0·5	0·6	n.d.	0·6
26 September	n.d.	0·5	n.d.	0·8	n.d.	0·8	0·9	n.d.	n.d.	ice	0·5	0·7	n.d.	0·8
2 November	n.d.	0·6	n.d.	0·7	n.d.	0·7	0·9	n.d.	0·2	n.d.	0·6	n.d.	n.d.	0·8
1963														
30 January	4·75	4·68	4·68	4·68	4·72	4·68	4·68	n.d.	5·48	5·08	5·08	5·10	5·08	n.d.
17 February	3·83	3·88	3·85	3·85	3·85	3·85	3·85	4·06	4·08	4·12	4·12	4·19	4·19	n.d.
21 March	1·30	1·33	1·33	1·38	1·40	1·43	1·43	1·75	1·75	1·55	1·62	1·58	1·62	n.d.
25 April	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0·15	0·30	0·45	0·55	0·62	n.d.
28 April	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0·17	0·33	0·44	0·65	n.d.
23/27 May	0·20	0·38	0·60	0·70	0·83	1·00	1·02	n.d.	0·10	0·08	0·35	0·55	0·68	n.d.
6/8 July	0·08	0·14	0·41	0·55	0·70	0·86	0·93	ice	0·00	0·03	0·13	0·43	0·64	n.d.
29 July	0·01	0·08	0·41	0·55	0·66	0·88	0·88	ice	ice	0·08	0·20	0·50	0·66	0·69
20/23 August	0·08	0·10	0·43	0·62	0·66	0·83	0·88	ice	ice	ice	0·08	0·50	0·59	n.d.
3 October	0·03	0·03	0·48	0·53	0·65	0·83	0·90	ice	ice	ice	0·13	0·58	0·70	0·75
23 October	0·18	0·23	0·60	0·70	0·90	1·03	1·10	ice	ice	ice	0·38	0·85	0·95	1·00
17 November	0·03	0·20	0·93	0·93	0·95	0·98	1·03	ice	ice	n.d.	0·00	0·95	0·98	0·85
1964														
5 January	2·68	2·68	2·68	2·68	2·68	2·68	2·68	3·52	3·45	3·75	3·75	3·83	3·83	3·64
28 January	4·33	4·33	4·23	4·13	4·06	4·05	n.d.	n.d.	5·58	n.d.	n.d.	n.d.	n.d.	n.d.

S 5 cm. depth or ice–water interface if at less than 1 m. depth.
B Bottom.
n.d. Not determined.

TABLE XV. TEMPERATURE OF LAKE 3 (°C)

Date	Station A						
	Depth						
	S	1 m.	2 m.	3 m.	4 m.	5 m.	B
1962							
11 July	n.d.	0·0	0·0	0·0	0·0	0·0	n.d.
13 August	ice	ice	0·1	n.d.	n.d.	0·1	n.d.
17 October	ice	0·4	n.d.	n.d.	n.d.	0·6	n.d.
20 November	ice	0·2	0·3	0·3	0·3	0·3	n.d.
1963							
28 February	0·85	0·85	0·85	0·84	0·90	0·93	n.d.
13 June	ice	0·05	0·13	0·13	0·15	0·36	0·57
13 September	ice	ice	0·05	0·03	0·08	0·20	n.d.
14 December	0·13	0·23	0·40	0·40	0·30	0·50	n.d.

S 5 cm. depth or ice–water interface if at less than 1 m. depth.
B Bottom.
n.d. Not determined.

TABLE XVI. TEMPERATURE OF LAKE 6 (°C)

Date	Station A				Station C	
	Depth				Depth	
	S	1 m.	2 m.	B	S	B
1962						
30 January	3·3	n.d.	3·6	3·6	n.d.	4·5
13 February	3·4	3·7	3·7	n.d.	n.d.	3·8
8 August	n.d.	0·5	0·8	0·8	n.d.	0·0
3 October	n.d.	1·0	1·8	1·8	n.d.	0·5
1963						
20 January	4·05	4·08	4·08	n.d.	4·73	4·75
15 March	3·35	3·35	3·43	3·50	3·33	3·33
9 June	0·01	0·42	0·98	1·08	n.d.	0·01
17/18 July	0·18	0·15	1·01	1·15	n.d.	0·10
11 September	0·21	0·30	1·00	1·25	n.d.	0·45
15 December	0·23	3·08	3·64	4·33	0·26	2·30
1964						
28 January	5·50	5·60	5·63	5·55	n.d.	n.d.

S 5 cm. depth or ice–water interface if at less than 1 m. depth.
B Bottom.
n.d. Not determined.

TABLE XVII. TEMPERATURE OF LAKE 7 (°C)

Date	Station A Depth S	1 m.	1·5 m.	2 m.	3 m.	4 m.
1963						
5 September	0·00	0·00	0·01	0·50	n.d.	n.d.
1964						
27 February	2·93	2·93	n.d.	2·92	2·88	2·93

S 5 cm. depth or ice–water interface if at less than 1 cm. depth.
n.d. Not determined.

TABLE XVIII. TEMPERATURE OF LAKE 10 (°C)

Date	Station A Depth S	1 m.	2 m.	3 m.	B
1963					
4 September	0·10	0·08	0·13	0·30	0·43
1964					
28 February	3·85	3·83	3·79	3·80	3·80

S 5 cm. depth or ice–water interface if at less than 1 m. depth.
B Bottom.

TABLE XIX. TEMPERATURE OF LAKE 12 (°C)

Date	Station A Depth S	1 m.	3 m.	5 m.	10 m.	15 m.
1963						
7 September	0·01	0·05	0·33	0·36	0·55	0·90

S Ice–water interface.

TABLE XX. TEMPERATURE OF LAKE 14 (°C)

Date	Station A Depth S	 1 m.	 2 m.	 3 m.
1963				
8 September	0·08	1·10	1·68	2·10

S Ice–water interface.

TABLE XXI. TEMPERATURES OF INFLOWING WATER (°C)

Date	*Lake*	*Particulars*	*Temperature*
1963			
17 February	2	Stream connecting lakes 2 and 5, near lake 2 shore	5·15
15 March	6	Surface water draining into lake from ice face, near lake shoreline	5·15
21 March	2	Stream connecting lakes 2 and 5, near lake 2 shore	0·33
17 November	2	Stream connecting lakes 2 and 5, near lake 2 shore	−0·40
	2	Surface water flowing into north basin, near lake 2 shore	−0·13
15 December	6	Surface water draining into lake from ice face, near ice face	0·26
	6	Surface water draining into lake from ice face, near lake shoreline	12·45
1964			
5 January	2	Stream connecting lakes 2 and 5, near lake 2 shore	3·73
28 January	2	Stream connecting lakes 2 and 5, near lake 2 shore	7·75
	2	Surface water flowing into north basin, near lake 2 shore	4·07
28 January	6	Surface water draining into lake from ice face, near lake shoreline	4·90
27 February	7	Surface water flowing into east side of lake, near lake shore	1·20
	7	On sub-lacustrine shelf under snow bank, north shore of lake	2·68
28 February	10	Stream flowing from subsidiary pool into lake, near lake shore	4·10

TABLE XXII. CERTAIN DISSOLVED GASES AND RADICALS IN LAKE 2

Date	*Station*	Depth (m.)	O_2 (per cent saturated)	CO_2 (p.p.m.)	pH	Alkalinity (meq./l.)	Ca^{++} (p.p.m.)	Mg^{++} (p.p.m.)	Cl′ (p.p.m.)	$SO_4''+NO_3'$ (meq./l.)	SO_4'' (p.p.m.)	NO_3' (p.p.m.)	PO_4''' (p.p.m.)
1963													
7 January	A	0·3	n.d.	n.d.	n.d.	0·110	n.d.	n.d.	47·3	0·150	n.d.	n.d.	n.d.
		2·0	n.d.	n.d.	n.d.	0·100	n.d.	n.d.	45·1	0·129	n.d.	n.d.	n.d.
		3·5	n.d.	n.d.	n.d.	0·112	n.d.	n.d.	44·0	0·132	n.d.	n.d.	n.d.
		5·0	n.d.	n.d.	n.d.	0·112	n.d.	n.d.	44·3	0·127	n.d.	n.d.	n.d.
	C	0·3	n.d.	n.d.	n.d.	0·111	n.d.	n.d.	42·5	0·127	n.d.	n.d.	n.d.
	E	0·3	n.d.	n.d.	n.d.	0·112	n.d.	n.d.	42·4	0·130	n.d.	n.d.	n.d.
		1·5	n.d.	n.d.	n.d.	0·110	n.d.	n.d.	42·1	0·138	n.d.	n.d.	n.d.
		3·0	n.d.	n.d.	n.d.	0·112	n.d.	n.d.	42·1	0·138	n.d.	n.d.	n.d.
30 January	A	0·3	105·0	n.d.	6·7	0·121	n.d.	n.d.	41·3	0·132	6·1	0·31	n.d.
		2·0	104·4	n.d.	6·5	0·120	n.d.	n.d.	41·5	0·116	5·3	0·31	n.d.
		3·5	104·3	n.d.	n.d.	0·120	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		5·0	103·7	n.d.	6·8	0·124	n.d.	n.d.	41·0	0·147	6·7	0·45	n.d.
	C	0·3	99·6	n.d.	6·7	0·120	n.d.	n.d.	41·4	0·147	6·8	0·33	n.d.
	E	0·3	100·5	n.d.	6·7	0·125	n.d.	n.d.	41·5	0·133	6·0	0·45	n.d.
		1·5	101·0	n.d.	6·6	0·123	n.d.	n.d.	42·1	0·125	5·7	0·40	n.d.
		3·0	100·9	n.d.	6·9	0·121	n.d.	n.d.	41·0	0·142	6·6	0·32	n.d.
25 April	A	0·3	n.d.	2·4	6·8	0·153	n.d.	n.d.	66·1	0·329	15·3	0·66	n.d.
		2·0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		3·5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		5·0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	C	0·3	68·6	5·2	6·4	0·138	n.d.	n.d.	54·3	0·266	12·3	0·52	n.d.
	E	0·3	98·5	2·8	6·8	0·166	n.d.	n.d.	63·9	0·303	14·3	0·35	n.d.
		1·5	98·0	2·2	6·9	0·159	n.d.	n.d.	63·4	0·320	15·2	0·27	n.d.
		3·0	97·1	2·6	6·8	0·160	n.d.	n.d.	63·6	0·318	14·9	0·52	n.d.
24 May	A	0·6	87·0	5·0	6·5	0·170	n.d.	n.d.	57·4	0·250	10·9	1·48	n.d.
		2·0	62·4	5·6	6·4	0·163	n.d.	n.d.	57·2	0·250	11·1	1·22	0·096
		3·5	51·8	7·4	6·3	0·157	n.d.	n.d.	56·7	0·263	11·6	1·35	n.d.
		5·0	18·0	7·9	6·2	0·154	n.d.	n.d.	56·5	0·274	12·2	1·17	n.d.
	C	0·6	55·5	8·0	6·3	0·182	n.d.	n.d.	60·5	0·263	11·8	1·11	0·102
	E	0·6	88·8	3·2	6·8	0·211	n.d.	n.d.	[illegible]	0·230	10·7	0·41	n.d.
		1·5	85·6	4·2	6·7	0·196	n.d.	n.d.	[illegible]	0·250	11·7	0·44	0·032
		3·0	37·0	4·4	6·6	0·168	n.d.	n.d.	55·5	0·242	10·6	1·35	n.d.
6 July	A	1·0	55·2	9·6	6·2	0·183	6·8	5·4	63·9	0·315	13·3	2·37	n.d.
		2·0	49·2	8·0	6·1	0·109	6·8	5·3	62·7	0·295	n.d.	n.d.	n.d.
		3·5	27·8	11·6	6·1	0·175	6·8	5·7	64·9	0·306	12·7	2·52	n.d.
		5·0	4·1	12·4	6·1	0·183	6·6	5·8	[illegible]	0·371	16·2	2·08	n.d.
	C	0·6	40·5	15·6	6·1	0·251	9·2	6·9	77·6	0·565	25·3	2·30	n.d.
	E	1·0	66·9	9·4	6·3	0·195	6·4	5·9	57·0	0·563	25·8	1·59	n.d.
		1·5	63·3	8·6	6·2	0·202	7·0	5·8	69·5	0·328	14·5	1·55	n.d.
		3·0	7·0	10·0	6·3	0·198	6·6	5·8	65·4	0·302	13·3	1·55	n.d.
27 July	A	1·0	49·1	7·4	6·2	0·189	4·7	7·3	65·8	0·330	14·2	2·17	n.d.
		2·0	41·2	8·1	6·2	0·180	7·1	5·9	66·5	0·315	13·5	2·13	n.d.
		3·5	27·8	8·9	6·2	0·177	6·2	6·4	65·1	0·313	13·8	1·55	n.d.
		5·0	5·6	9·2	6·2	0·182	7·0	6·0	66·8	0·318	13·8	1·90	n.d.
	C		FROZEN SOLID										
	E	1·0	63·9	6·7	6·3	0·192	6·6	6·1	64·5	0·284	12·4	1·62	n.d.
		1·5	60·9	5·8	6·3	0·192	6·3	6·2	63·9	0·288	12·8	1·31	n.d.
		3·0	4·7	6·2	6·3	0·190	6·9	6·0	64·0	0·288	12·5	1·68	n.d.
20 August	A	1·3	42·9	7·3	6·0	0·105	7·7	5·8	67·9	0·356	15·1	2·55	n.d.
		2·0	37·8	8·8	6·2	0·187	7·8	5·7	68·0	0·343	14·5	2·53	n.d.
		3·5	23·6	11·1	6·1	0·198	6·9	6·3	72·4	0·360	15·3	2·55	n.d.
		5·0	6·0	11·1	6·0	0·203	7·9	7·1	77·4	0·411	17·8	2·57	n.d.
	C		FROZEN SOLID										
	E	1·3	47·6	8·0	6·3	0·192	7·7	5·8	67·8	0·314	13·7	1·77	n.d.
		1·5	46·4	7·5	6·3	0·152	7·8	5·6	67·1	0·310	13·1	2·30	n.d.
		3·0	27·5	8·4	6·2	0·201	6·7	6·9	69·7	0·322	13·7	2·35	n.d.
1 October	A	1·3	33·7	10·9	6·3	0·198	7·4	6·7	74·2	0·367	16·5	1·42	n.d.
		2·0	28·2	11·4	6·2	0·200	6·8	7·0	73·8	0·349	15·0	2·21	0·123
		3·5	25·1	11·9	6·2	0·196	7·3	7·2	75·1	0·344	n.d.	n.d.	n.d.
		5·0	4·1	12·1	6·2	0·197	7·4	7·0	75·4	0·380	16·2	2·61	n.d.
	C		FROZEN SOLID										
	E	1·3	33·4	6·9	6·4	0·155	6·9	6·1	51·0	0·194	8·4	1·20	n.d.
		1·5	33·0	7·2	6·5	0·229	7·7	6·1	70·0	0·322	14·3	1·56	0·110
		3·0	4·6	8·5	6·4	0·200	7·1	6·2	68·5	0·340	15·0	1·68	n.d.
			Sampling hole at E had not re-frozen during the previous month and was filled with slush										
23 October	A	1·3	44·0	n.d.	n.d.	n.d.	7·3	6·7	74·7	0·359	n.d.	n.d.	n.d.
		2·0	33·5	n.d.	n.d.	n.d.	6·9	6·7	73·7	0·343	14·8*	n.d.	n.d.
		3·5	22·4	n.d.	n.d.	n.d.	7·3	7·0	75·8	0·350	n.d.	n.d.	n.d.
		5·0	5·0	n.d.	n.d.	n.d.	6·6	6·3	67·0	0·310	n.d.	n.d.	n.d.
	C		FROZEN SOLID										
	E	1·3	15·0	n.d.	n.d.	n.d.	3·3	3·3	34·0	0·142	n.d.	n.d.	n.d.
		1·5	17·5	n.d.	n.d.	n.d.	7·2	6·4	72·2	0·319	14·8*	n.d.	n.d.
		3·0	3·2	n.d.	n.d.	n.d.	6·8	6·4	72·7	0·310	n.d.	n.d.	n.d.
2 November	A	1·3	n.d.	12·1	6·3	0·208	7·3	7·2	77·1	0·337	n.d.	n.d.	n.d.
		2·0	n.d.	13·2	6·3	0·206	7·0	7·2	77·2	0·323	14·2*	n.d.	n.d.
		3·5	n.d.	15·7	6·3	0·206	7·1	7·0	75·4	0·339	n.d.	n.d.	n.d.
		5·0	n.d.	16·6	6·2	0·210	7·0	6·9	75·6	0·343	n.d.	n.d.	n.d.
	C		FROZEN SOLID										
	E	1·3	n.d.	15·2	6·3	0·193	6·2	6·2	67·3	0·279	n.d.	n.d.	n.d.
		1·5	n.d.	11·6	6·2	0·168	5·4	5·8	60·2	0·244	14·2*	n.d.	n.d.
		3·0	n.d.	17·3	6·2	0·208	6·8	6·5	72·2	0·328	n.d.	n.d.	n.d.
17 November	A	1·3	60·0	10·2	6·2	0·169	5·9	7·7	87·7	0·324	n.d.	n.d.	n.d.
		2·0	55·5	11·5	6·2	0·188	6·5	7·2	83·9	0·319	12·4*	n.d.	n.d.
		3·5	55·0	12·1	6·2	0·185	6·6	7·3	83·9	0·333	n.d.	n.d.	n.d.
		5·0	36·0	11·7	6·3	0·188	6·8	7·4	85·4	0·324	n.d.	n.d.	n.d.
	C		FROZEN SOLID										
	E	1·3	72·9	6·6	6·4	0·215	6·0	6·3	85·0	0·276	n.d.	n.d.	n.d.
		1·5	55·4	8·6	6·3	0·216	6·0	6·3	85·0	0·279	12·4*	n.d.	n.d.
		3·0	29·7	11·7	6·2	0·210	6·5	8·1	83·6	0·315	n.d.	n.d.	n.d.
1964													
5 January	A	0·3	110·4	1·5	6·8	0·126	3·6	3·8	46·6	0·134	6·3	0·20	n.d.
		2·0	111·4	1·6	6·9	0·123	3·4	3·7	46·6	0·129	6·0	0·22	0·012
		3·5	108·8	1·6	6·9	0·130	3·0	4·0	46·4	0·134	6·2	0·23	n.d.
		5·0	109·0	1·6	6·9	0·124	3·1	3·6	46·0	0·160	7·5	0·21	n.d.
	C	0·3	106·8	1·5	6·7	0·125	3·4	3·6	42·3	0·103	4·8	0·19	0·012
	E	0·3	103·0	1·6	6·8	0·124	3·1	3·5	44·1	0·120	5·6	0·20	n.d.
		1·5	106·5	1·7	6·8	0·124	3·0	3·5	44·2	0·134	6·2	0·31	0·012
		3·0	105·0	1·9	6·7	0·136	3·1	3·5	44·6	0·134	6·2	0·35	n.d.

* Estimated from $SO_4''+NO_3'$ values.
n.d. Not determined.

TABLE XXIII. CERTAIN DISSOLVED GASES AND RADICALS IN LAKE 3

Date	*Station*	*Depth* (m.)	O_2 (per cent saturated)	CO_2 (p.p.m.)	pH	Alkalinity (meq./l.)	Ca^{++} (p.p.m.)	Mg^{++} (p.p.m.)	Cl' (p.p.m.)	$SO_4''+NO_3'$ (meq./l.)	SO_4'' (p.p.m.)	NO_3' (p.p.m.)	PO_4''' (p.p.m.)
1963													
13 June	A	1·3	104·0	0·6	7·3	0·157	3·7	2·6	32·5	0·121	n.d.	n.d.	n.d.
		2·0	98·8	0·6	7·4	0·160	3·7	2·6	32·1	0·130	n.d.	n.d.	0·007
		3·5	87·9	1·0	6·9	0·111	3·9	3·1	40·8	0·147	n.d.	n.d.	n.d.
		5·0	68·0	1·6	6·9	0·146	4·1	[illegible]	49·9	0·216	n.d.	n.d.	n.d.
13 September	A	1·3	110·0	4·0	6·7	0·211	5·4	3·7	40·4	0·133	n.d.	n.d.	n.d.
		2·0	83·0	4·0	6·7	0·216	5·3	4·0	42·8	0·129	6·0	0·18	0·002
		3·5	83·0	5·1	6·5	0·200	5·1	4·2	49·3	0·172	n.d.	n.d.	n.d.
		5·0	46·7	7·7	6·3	0·198	5·4	4·6	53·9	0·214	n.d.	n.d.	n.d.
14 December	A	1·3	100·0	1·4	6·6	0·008	2·3	2·8	32·2	0·081	3·8	0·09	n.d.
		2·0	107·0	2·0	6·7	0·095	2·8	3·1	36·9	0·103	4·9	0·08	tr
		3·5	100·0	2·6	6·5	0·100	3·6	5·2	72·1	0·215	10·2	0·19	n.d.
		5·0	88·0	3·2	6·4	0·103	5·8	10·7	125·9	0·377	18·0	0·11	n.d.

n.d. Not determined.
tr Trace.

TABLE XXIV. CERTAIN DISSOLVED GASES AND RADICALS IN LAKE 6

Date	*Station*	*Depth* (m.)	O_2 (per cent saturated)	CO_2 (p.p.m.)	pH	Alkalinity (meq./l.)	Ca^{++} (p.p.m.)	Mg^{++} (p.p.m.)	Cl' (p.p.m.)	$SO_4''+NO_3'$ (meq./l.)	SO_4'' (p.p.m.)	NO_3' (p.p.m.)	PO_4''' (p.p.m.)
1963													
9 June	A	1·0	75·6	1·8	7·0	0·211	5·5	3·1	36·7	0·134	n.d.	n.d.	0·012
		2·0	32·1	4·3	6·6	0·205	4·8	3·3	37·5	0·130	n.d.	n.d.	n.d.
	C	0·7	75·5	3·2	6·9	0·251	6·9	3·3	41·0	0·151	n.d.	n.d.	0·009
17 July	A	1·0	58·6	8·0	6·2	0·238	6·3	3·2	40·6	0·149	7·0	0·186	n.d.
		1·5	50·4	7·0	6·1	0·150	5·8	3·3	24·9	0·078	3·6	0·173	n.d.
		2·0	17·8	11·4	6·1	0·267	5·5	3·8	40·3	0·136	6·4	0·128	n.d.
	C	0·7	42·2	11·3	6·2	0·267	6·6	3·7	43·3	0·169	8·0	0·144	n.d.
11 September	A	1·0	17·9	15·4	6·2	0·308	7·2	4·5	47·4	0·172	8·0	0·29	n.d.
		1·5	10·8	16·8	6·3	0·308	7·3	4·4	46·7	0·172	8·0	0·27	0·012
		2·0	2·7	16·9	6·2	0·314	7·4	4·6	47·0	0·154	7·2	0·22	n.d.
	C	0·7	21·0	15·1	6·3	0·356	7·9	4·7	52·4	0·176	8·2	0·27	0·007
15 December	A	0·7	98·2	2·1	6·4	0·092	2·1	3·0	46·0	0·126	6·0	0·05	n.d.
		1·5	90·1	3·9	6·5	0·138	4·4	4·8	60·9	0·184	8·8	0·06	0·001
		2·0	107·1	4·8	6·5	0·183	7·3	5·9	74·5	0·274	13·1	0·07	n.d.
	C	0·7	86·4	1·9	6·7	0·105	1·4	1·1	15·6	0·027	1·2	0·06	tr

n.d. Not determined.
tr Trace.