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Observations on the Snow Algae of the South Orkney Islands

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Observations on the snow algae of the South Orkney Islands

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One of the most abundant algal species found in snow on the South Orkney Islands is a unicellular chrysophycean not hitherto reported from this region. Investigations both by direct counts and by *in situ* determinations of metabolic activity by a radiocarbon technique suggest that growth of snow algae is, in general, slow. Their primary productivity is estimated as being of the order of 10 mg carbon fixed m^{-2} snow surface day^{-1}. The sudden appearance of patches of these algae seems to be due to mechanical accumulation at the surface, as ablation of the snow proceeds, of cells previously distributed sparsely through its thickness. There appear to be no great differences either in species composition or in metabolic activity between green, yellow and red snow. The greater population densities and absence of red resting spores characteristic of green snow are perhaps attributable to greater availability of liquid water.

Introduction

Snow coloured red, yellow or green by algae is found where permanent snow fields are subject to extensive annual thawing. In Antarctica it is restricted to the coasts and is, on the whole, infrequent (Llano 1962). Thus, whereas Charcot (undated, p. 157) described extensive areas of green and red snow on Petermann Island, west Graham Land during a period of thaw, Nordenskjöld & Andersen (1905, p. 418), in about the same latitude but on the more frigid east coast, found red snow to be rare, and few other writers on Antarctica mention the phenomenon at all. Studies on the algae have been summarized by Hirano (1965). These investigations and those on snow algae from other parts of the world have been mainly of a floristic nature and little is known of the ecological and physiological aspects. Snow algae were much in evidence on Signy Island, South Orkney Islands, during my visit there in January and February 1966 and are the subject of the preliminary investigations described in this paper.

Identification

In identifying the algae the paper by Fritsch (1912), based on studies on preserved samples collected by Rudmose Brown in the region of Laurie Island, South Orkneys, during the '*Scotia*' Expedition of 1902–04, has been followed. There is, however, one major discrepancy that requires comment. In my samples one of the most abundant organisms was unicellular with spherical cells between 4·5 and 9·0 μm in diameter, each containing a single greenish yellow parietal curved plate chromatophore. Spectrophotometric determinations on a methanol extract of a nearly pure population gave the ratio of the optical densities at 440 and 662 nm as 5·57:1, confirming a predominance of carotenoids. No biliproteins could be detected in an aqueous extract of autolysing cells. No starch grains could be demonstrated, nor were any division stages found. Dr J. H. Belcher, who has kindly examined the material for me, reports the presence of chrysophycean-type cysts with short spouts. The organism thus appears to be a member of the Chrysophyceae. Since

no motile stages which could definitely be connected with these cysts were observed, identification cannot be carried further, but it may possibly be related to or identical with *Ochromonas smithii* reported by Fukushima (1963) from snow fields in Japan. It is therefore designated as *Ochromonas* (?) sp. in this paper. Fritsch (1912) did not report anything exactly corresponding to this form but it is possibly identical with his *Protoderma brownii*, described as a unicellular green alga, which, although said to be the most abundant component of the yellow snow flora, was not encountered by me. The size and cell morphology of the two forms correspond and the sheet-like aggregations of cells 'regularly arranged with reference to one another and separated by marked colourless intervals', on which Fritsch put emphasis as a character of *P. brownii*, is perhaps one that might be assumed by any dense mass of thick-walled spherical cells under the pressure of a coverglass. Fritsch reported that 'iodine generally showed the presence of a limited number of starch grains'; this, together with the idea that the chromatophore was green, may be put down as an error of a sort which is difficult to avoid when only preserved material of such minute organisms is available. Anything resembling *Ochromonas* (?) sp. does not appear to have been noted in the snow flora of Antarctica by other workers (see Hirano 1965).

The most abundant *Chlamydomonas* appeared to be *C. nivalis* (Sommerf.) Wille. (Kol (1944), however, considered that *C. antarctica* Wille is the predominating form in Antarctica.) Especially when counting it was found difficult to distinguish the spores of *Chlamydomonas* spp. from those of other forms such as *Chlorosphaera antarctica* Fritsch, consequently all red or orange pigmented spores were grouped as 'red spores' and only green cells were further identified. Culture studies such as those carried out by Fukushima (1963) with *C. nivalis* and *Chodatella brevispina* seem essential if the taxonomy of snow algae is to be put on a firm basis.

In what follows only the most abundant species are mentioned but most of those listed by Fritsch were encountered. In addition, there were lesser numbers of algae, apparently derived from freshwater or soil, which included species of *Achnanthes*, *Navicula*, *Amphora* and *Hantzschia*, a large unidentifiable *Cocconeis* and *Pinnularia borealis*. (I am grateful to Dr J. H. Belcher for these identifications.)

Distribution and composition of the flora

Patches of coloration on snow developed rapidly during thaws and were generally distributed over Signy Island and the adjacent coast of Coronation Island. Red coloration occurred on well-drained firn snow, especially at the margins of ice exposures where the snow had been reduced to a thin layer by ablation. Gelatinous aggregations of red snow algae were often encountered on bare ground from which the snow had recently disappeared. Distinct yellow coloration found where seepage ran on to snow was due to ferruginous deposits but paler yellow coloration by algae occurred in similar situations to those in which red snow was found. Green coloration, which was not so common as red but nevertheless frequent, occurred in waterlogged or flushed firn snow.

The abundance and composition of the snow flora were examined in some ninety snow samples, counts being made on samples, within 1 or 2 h of melting, by means of a haemacytometer. The selection of results given in table 17 is for surface samples showing obvious

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coloration. From these and the other results it appears that, with the exception that *Hormidium* was found only in green snow, there was no constant difference in floristic composition between the red, yellow and green communities. *Chlamydomonas nivalis* (either as green motile cells or spores), *Raphidonema nivale*, and *Ochromonas* (?) sp. were present in most samples and although one or other might greatly out-number the rest no species had an absolute association with a particular snow colour. Because of their intense colour, red spores often determine the colour of snow even though, as in sample no. 6, other species may be numerically far more abundant. *R. nivale* may be the most abundant alga in either green or yellow snow, the cells in the latter case being chlorotic presumably because of mineral deficiency. Many samples showing no obvious coloration were examined. When these came from the surface of firn snow they usually contained 1 or 2 cells/mm^3 of *Ochromonas* (?) sp., *Raphidonema nivlae* or red spores.

TABLE 17. COUNTS OF ALGAL SPECIES (CELL NO. mm^3) IN SURFACE SNOW FROM VARIOUS SITUATIONS IN THE SOUTH ORKNEY ISLANDS

Red spores include those of *Chlamydomonas nivalis* and *Chlorosphaera antarctica*, the numbers given separately under these names being for green cells only.

	green snow, 30. i. 66, Meier Point, Coronation Island	green snow, 13. ii. 66, Moraine Valley, Signy Island	yellow snow, 4. ii. 66, Factory Cove, Signy Island	yellow snow, 12. ii. 66, Moraine Valley, Signy Island	red snow, 14. ii. 66, Moraine Valley, Signy Island	red snow, 4. ii. 66, Factory Cove, Signy Island
Chlamydomonas nivalis	955	0	0	0	0	0
Chlorosphaera antarctica	15	0	0	1	3	0
red spores	0	0	0	0	40	45
Raphidonema nivale	115	4770	364	289	2	320
*Hormidium subtile**	768	0	0	0	0	0
Trochiscia antarctica	2	0	0	0	0	0
Chodatella brevispina	0	12	0	0	1	10
Scotiella antarctica	0	0	33	3	0	55
Ochromonas (?) sp.	32	12	2620	3	1	4170

**Ulothrix subtilis* Kütz of Fritsch.

Concentrations of cells high enough to give obvious colorations were generally found only within the top centimetre of firn snow, cell numbers at greater depths being low. However, distinctly green snow sometimes occurred at a depth of several centimetres and it is of particular interest that green, actively motile, cells of *Chlamydomonas nivalis* and green cells of *Chlorosphaera antarctica* in concentrations of the order of 1 cell/mm^3 were found down to depths of 25 cm below red snow patches.

The vertical distribution of the algae was studied in detail by counts on samples taken at different depths at intervals of a few days at a site near the bottom of a south-facing snow slope in Factory Cove. The top of a well defined crust, initially at 35 cm, was taken as a reference horizon. The horizontal distribution of cells at this site appeared to be reasonably uniform, four counts of *Ochromonas* (?) sp. in samples taken from 15 cm down at random within an area of approximately 1 m^2 giving a mean of 153·5 cells/mm^3 with a standard deviation of 27·7 (18%) for the individual count. The results for *Ochromonas* (?) sp. are given in figure 41. The counts of *Raphidonema nivale*, which was present in about the same numbers as *Ochromonas* (?) sp., gave a similar picture. When the observations were begun

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the top 14 cm were of settled snow, which had begun falling 3 days before, and contained no algae. Cell numbers were greatest, 129 cells/mm^3, at the surface of the advanced firn snow (nomenclature of Seligman 1936) but there was a secondary peak of 66 cells/mm^3 at 25 cm. Four days later the settled snow had decreased by ablation to a thickness of 6·5 cm and although rock fragments were visible on its surface no algae were detected in it. Cell numbers at the advanced firn snow surface had increased to 300/mm^3. Below this there was a general slight increase in numbers and a secondary peak was again encountered.

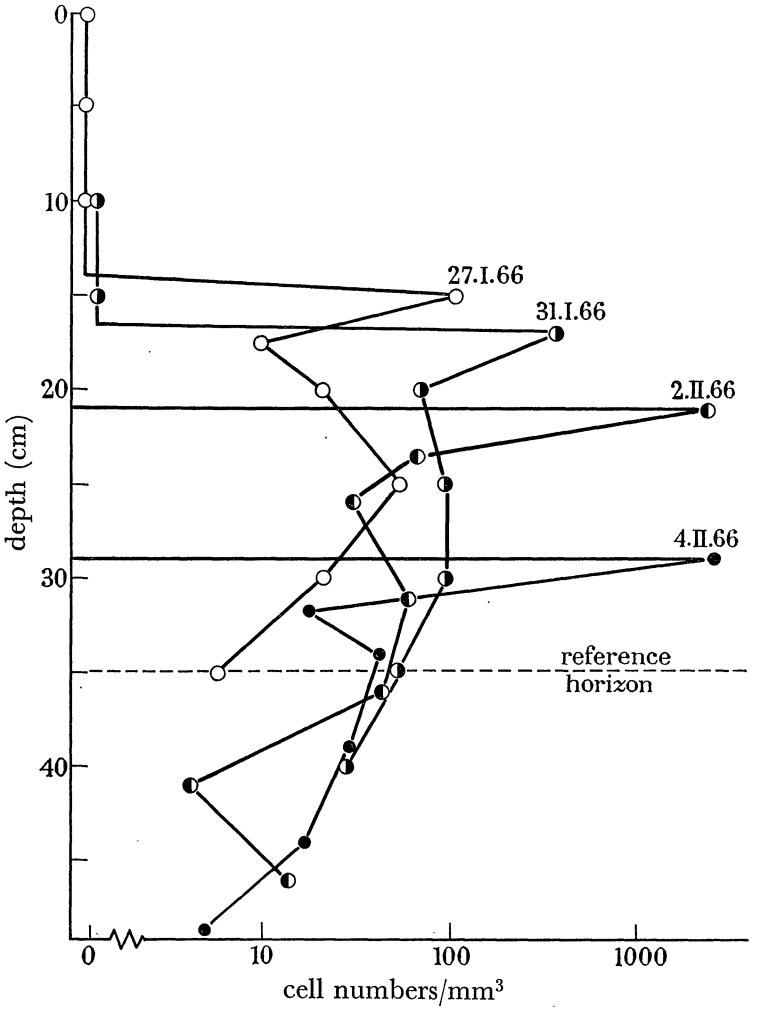

FIGURE 41. Change over a period of 8 days of depth distribution of *Ochromonas* (?) sp. in a south-facing snow slope, Factory Cove, Signy Island. Cell numbers/mm^3 plotted on a logarithmic scale.

The same features showed in the two subsequent sets of observations. By the 6th day the settled snow had completely ablated. Eight days after the observations were begun, cell numbers at the advanced firn snow surface had increased some 20-fold to 2620/mm^3, an increase which is clearly statistically significant. However, below this there was no appreciable increase in cell numbers over the period of the last three observations. The secondary peak persisted to the 8th day, shifting downwards as ablation occurred. The total numbers of *Ochromonas* (?) sp. cells in a snow column 1 cm^2 in cross-section extending from the surface down to the reference crust, as obtained by integration of direct plots of

numbers (corrected for a mean specific gravity for the firn snow of 0·635) against depth, were $4{\cdot}3 \times 10^5$ and $2{\cdot}2 \times 10^6$ at the beginning and end respectively of the period of observation. It thus seems that the great increase in cell numbers at the firn snow surface is more the result of concentration of cells there as a result of ablation than of cell multiplication.

Measurements of carbon dioxide fixation

Fixation of carbon dioxide as measured by the radiocarbon method seemed to be the most easily determined index of the metabolic activity of snow algae *in situ*. The apparatus used is depicted in figure 42.

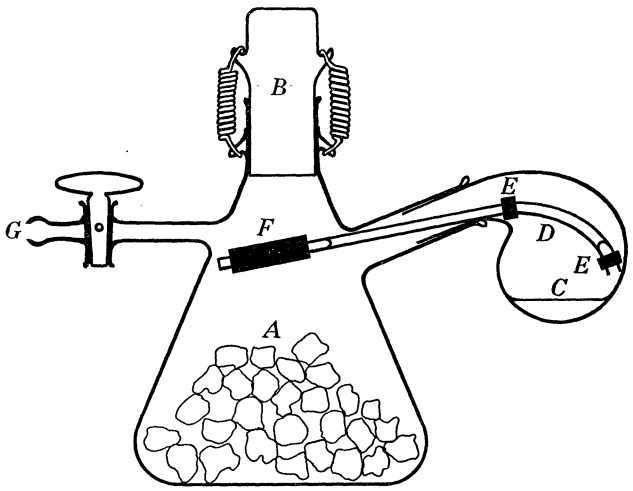

Figure 42. Apparatus for determination of carbon dioxide fixation by snow algae. *A*, 100 ml. conical flask; *B*, stopper, B.24 standard joint; *C*, side-arm, B.14 standard joint, containing ^{14}C-carbonate solution; *D*, tube containing sulphuric acid; *E*, rubber friction rings; *F*, glass rod and rubber tubing closing *D*; *G*, stopcock connecting with hand vacuum pump.

A snow sample of approximately known volume (between 15 and 30 ml.), was introduced into the 100 ml. conical flask *A*, which had previously been allowed to equilibrate to ambient temperature, with as little disturbance to its structure as possible. The flask was then closed with the stopper, *B*, and the side-arm, *C*. *C* contained 0·33 ml. N/10 sodium carbonate plus 1 ml. of $NaH^{14}CO_3$ solution with an activity of $6{\cdot}67 \times 10^6$ counts/min, calculated to give an eventual concentration of about 0·5% carbon dioxide in the system (total volume about 150 ml.). *C* also contained a bent glass tube, *D*, held in position by two rubber friction rings, *E*. *D* was closed at one end by rubber tubing and glass rod, *F*, and had been charged previously with about 0·4 ml. N/10 sulphuric acid. The carbon dioxide was liberated by evacuating with a hand pump via *G* whereupon the acid was ejected into the carbonate solution. A drop of indicator included in the latter enabled a check to be made that this has taken place properly. Immediately after evacuation the tap *G* was closed. After a few minutes, when liberation of carbon dioxide was complete, *G* was reopened momentarily to admit air to atmospheric pressure. When temperatures were below zero the solution in the side arm was kept from freezing during these operations by warmth from the hand. The apparatus was then embedded in snow up to the level of

the top of the sample and clamped in position. Determinations of dark fixation of carbon dioxide were made in a similar apparatus which was blacked out with insulating tape and exposed in a black plastic bag filled with snow. At the end of an appropriate period of exposure the side arms were removed from the flasks, which were then stoppered, placed in a dark container, and taken as quickly as possible to the laboratory with the samples still unmelted inside them. In the laboratory the samples were melted rapidly but with minimum rise in temperature, the volumes of melt water measured, then the radioactivity of algal cells and dissolved organic matter determined as described for plankton samples by Watt (1966). Volumes of algal material were calculated from numbers and mean dimensions of cells, assuming them to be simple geometrical shapes. In calculating rates of photosynthesis no correction has been made for dark fixation but an isotope discrimination factor of 1·05 has been assumed.

The results of the *in situ* determinations are summarized in table 18. In addition, a laboratory determination (table 19) was made of the effect of temperature on photosynthesis of green snow at limiting light intensity. Since this determination was made by adding ^{14}C-bicarbonate solution directly to the algal suspension it provides a means of checking that the *in situ* method gives reasonably reliable results. Taking the carbon dioxide content of Lake III water in March as 2·5 mg/l. (Heywood, personal communication) the rate of carbon fixation in the light at 0 °C was 0·000 069 mg (mm^3 algal material)$^{-1}$ h^{-1}, which, allowing for the lower light intensity in the laboratory experiment, corresponds well with those found in the *in situ* determinations.

Dark fixation of radiocarbon varied between 8 and 50 % of light fixation in approximately corresponding samples. It is noteworthy that low rates of light fixation were associated with relatively high rates of dark fixation—an indication that the algal cells in samples showing this were becoming moribund (Fogg 1956).

These results do not show any significant differences between species in capacity to fix carbon when this is expressed on a cell volume basis. It is particularly interesting that samples in which red spores predominated did not differ appreciably in photosynthetic activity from those in which green cells were most abundant. In the *in situ* series 1–4, in which air temperatures were above zero, the temperature of the surface snow was 0 °C. In series 5 the mean temperature was −4·65 °C and the rates observed were of the order of $\frac{1}{100}$th of those at freezing point. With light intensity limiting there was only a small increase (15 %) in carbon fixation when temperature was increased from 0 to 15 °C, as would be expected, but over the same temperature range dark fixation increased by 105 % (table 19).

In every case examined ^{14}C-labelled organic matter was found in the filtrate from the algal suspension, varying from less than 1 % to about 10 % of the total fixed. In this respect snow algae resemble marine and freshwater phytoplankton (Fogg, Nalewajko & Watt 1965). It is hoped to discuss the significance of this phenomenon in aquatic Antarctic environments in a later paper.

The rates of photosynthesis observed are low. From the data given by Sorokin (1959) the rate of photosynthesis by actively growing light saturated *Chlorella pyrenoidosa* (Emerson strain) at 25 °C is equivalent to 0·02 mg C mm^{-3} algal material h^{-1}. The highest rate found with the snow algae is only 0·043 of this. Assuming a mean dry weight of 0·5 mg/mm^3 algal material for snow algae, which seems reasonable from the data given for other

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Table 18. Fixation by snow algae of ^{14}C in *in situ* experiments on Signy Island

Each sample was exposed to 1·47 mg CO_2 with an activity of $6{\cdot}67 \times 10^6$ counts/min, giving a CO_2 concentration of about 0·5% in the atmosphere. Radioactivity of the algal cells is expressed as counts min^{-1} (10 ml. of melt water)$^{-1}$ and of extracellular products as counts min^{-1} (10 ml. filtrate)$^{-1}$.

date, duration and site	principal algae (numbers/mm³)				max. and min. air temp. (°C)	light conditions	L = light flasks D = dark flasks radioactivity of cells	radioactivity of extracellular products	fixation of C mg (mm³ of cell material)$^{-1}h^{-1}$
(1) 15.15 h, 20. i. 66 to 15.15 h, 21. i. 66, Factory Cove, south-facing slope	*Ochromonas* (?) sp.		311		3·8	bright intervals (3·9 h sun)	(*a*) L 33129 ± 1627	127 ± 14	0·000216
	Raphidonema nivale		42		−0·7*		(*b*) L 48863 ± 1958	106 ± 12	0·000245
							(*c*) D 3990 ± 108	50 ± 5	—
		a	*b*	*c*					
(2) 10.50 to 17.20 h, 28. i. 66, Factory Cove, south-facing slope	*Ochromonas* (?) sp.	147	100	148	3·0	overcast (0 h sun)	(*a*) L 19065 ± 822	183 ± 11	0·000522
	Raphidonema nivale	79	46	65	0·4		(*b*) L 9362 ± 411	115 ± 4	0·000396
							(*c*) D 1398 ± 34	42 ± 2	—
(3) 11.55 h to 16.55 h, 12. ii. 66, north-west end of Moraine Valley	(*a*) red spores		31		—	overcast (0 h sun), mean light intensity 16000 lux	(*a*) L 39361 ± 3387	1014 ± 53	0·000864
	Ochromonas (?) sp.		16		3·0		(*b*) L 13991 ± 1051	1394 ± 81	0·000428
	Raphidonema nivale		184		−0·5		(*c*) L 12540 ± 378	1381 ± 50	0·000260
	(*b*) *Ochromonas* (?) sp.		3		—				
	Raphidonema nivale		289		—				
	(*c*) *Ochromonas* (?) sp.		3		—				
	Raphidonema nivale		428		—				
(4) 10.45 to 16.45 h 14. ii. 66, north-west end of Moraine Valley	(*a*) *Raphidonema nivale*		5540		6·0*	overcast (0 h sun), mean light intensity 8000 lux	(*a*) L 102760 ± 497	1514 ± 71	0·000069
	(*b*) red spores		40		3·6		D 29619 ± 960	1811 ± 81	—
	Chlorosphaera antartica		3		—		(*b*) L 1455 ± 20	336 ± 9·5	0·000041
							D 472 ± 14	582 ± 28	—
(5) 16.25 h on 22. ii. 66 to 17.25 h on 24. ii. 66 (*a*) head of Moraine Valley (*b*) Factory Cove, south-facing slope		L	D						
	(*a*) red spores	52	18		−1·7	overcast (0 h sun)	(*a*) L 937 ± 15·8	—	0·00000212
	Ochromonas (?) sp.	21	27		−7·6		D 455 ± 8·4	—	—
	Chlorosphaera antarctica	6	1		—		(*b*) L 2330 ± 75·7	—	0·00000702
							D 458 ± 17·5	—	—
		L	D						
	(*b*) *Ochromonas* (?) sp.	249	531		—				
	Raphidonema nivale	6	473		—				
	red spores	1	2		—				

* By the end of these experiments the snow samples in the light flasks were largely melted.

algae by Lund (1964), and that 40% of this is carbon, then carbon fixation at the rate of 0·00025 mg mm^{-3} h^{-1} implies a doubling time of about 23 days, The results obtained in series 1 of the *in situ* determinations give a rate of fixation of 10 mg C day^{-1} m^{-2} of snow surface. This is a very low value for primary productivity; corresponding values for diatoms in sea-ice and plankton in the Bellinghausen Sea are 190 and 90 respectively (Burkholder & Mandelli 1965) and for extremely oligotrophic lakes in Swedish Lappland, 20 to 100 (Rodhe 1958). Furthermore, it must be remembered that the values for snow algae were obtained with an increased carbon dioxide concentration which may have increased the rate of photosynthesis somewhat above the normal.

TABLE 19. EFFECT OF TEMPERATURE ON PHOTOSYNTHESIS OF GREEN SNOW ALGAE

50 ml. of melted snow were mixed with 300 ml. Lake III water giving per mm^3—*Raphidonema nivale*, 562; *Ochromonas* (?) sp., 2·5; *Chlamydomonas nivalis* 7·5; *Chlorosphaera antarctica*, 6. 1 ml. of ^{14}C-bicarbonate ($6{\cdot}67 \times 10^6$ counts/min) was added to 50 ml. portions after bringing to temperature indicated. Light intensity 1300 lux. Exposure time 2·5 h. Radioactivity in counts min^{-1} $(10\ ml.)^{-1}$.

temp. (°C)		cells	extracellular	extracellular as % of total
0	light	40600 ± 1728	373 ± 21·0	0·91
	dark	1998 ± 69·5	118 ± 13·6	5·58
7·5	light	46600 + 7140	1651 ± 55·3	3·43
	dark	2385 ± 117	188 ± 15·4	7·31
15·0	light	46800 ± 635	1264 ± 117	2·62
	dark	4105 ± 46·8	211 ± 33·0	4·88

DISCUSSION

Low temperature does not of itself necessarily impose a restriction on the metabolic activity of algae—instances of active algal growth at freezing point are numerous and the assimilation numbers (mg C h^{-1} mg^{-1} chlorophyll) found by Burkholder & Mandelli (1965) for diatoms in sea-ice are about the same as those for algae in temperate waters. Nor is the snow on Signy Island deficient in nutrient elements. Mineral particles are frequently encountered during microscopical examination of the snow and analyses by Heywood (personal communication) have shown the presence of as much as 1·1 parts/10^6 Ca, 2·5 parts/10^6 Mg, 79·6 parts/10^6 Cl and 0·04 parts/10^6 NO_3^-. Nevertheless, both the direct counts and the determinations of carbon fixation indicate low rates of growth even at melting point and almost negligible activity at temperatures below this. Tentatively this low activity may be attributed to the desiccation to which the algae are normally exposed in the snow. The sudden appearance of patches of red or yellow snow algae during thaws seems to be due to mechanical accumulation of cells at the surface rather than to their multiplication. Just as mineral particles are, algal spores and resting stages are presumably carried by wind and disseminated through the settling snow. When thawing releases sufficient moisture these become active and multiply slowly. Ablation, which takes place partly by sublimation and partly by percolation of thaw water as films over the surface of the ice crystals (Seligman 1936), evidently does not result in the algal cells being carried downwards and their marked tendency to aggregate will further hinder this. This will result in their progressive accumulation at the snow surface as ablation takes place. Accumulations will presumably persist from year to year and exceptional thaws result in the

densest colorations of the snow surface. The location and accumulation of green snow algae seems more related to bulk flow of meltwater.

These investigations have shown little important difference either in species composition or metabolic activity between red, yellow and green snow. Green snow is characterized by higher population densities than the other forms and by the absence of red resting spores of *Chlamydomonas* and *Chlorosphaera*. Kol (1944) suggested that green snow is characteristic of calcareous snow fields and red of siliceous snow fields, but on Signy Island no association of particular colorations with adjacent rock types was noted, although both acidic schists and basic amphibolite and marble occur. Fukushima (1963), who also disagrees with Kol's suggestion, put forward the hypothesis that green snow is the shade form and red snow the sun form. There was, however, no obvious correlation on Signy Island of snow colour with the amount of sunlight received. Since the green coloration was always found by me in waterlogged firn snow, I am inclined to think that availability of liquid water is the determining factor but this needs to be confirmed by further investigations.

I am grateful to Sir Vivian Fuchs, Dr M. W. Holdgate and the British Antarctic Survey for making my visit to Signy Island possible, to Westfield College for the necessary leave of absence, and to the Royal Society for a travel grant. My thanks are also due to Mr D. J. Eagle for making the radiocarbon assays.

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