

# Over-Winter Oceanographic Profiles in Jones Sound, Canadian Arctic Archipelago, November 1961 – June 1962: Temperature, Salinity, Oxygen, and Nutrients

SPENCER APOLLONIO<sup>1</sup> and DAVID W. TOWNSEND<sup>2</sup>

*(Received 11 October 2010; accepted in revised form 18 March 2011)*

**ABSTRACT.** Vertical profiles of temperature, salinity, dissolved oxygen, and inorganic nutrients (nitrate, phosphate, and silicate) were measured at five depths (2, 10, 25, 50, and 80 m) beneath the ice off the southern shore of Jones Sound, north of Devon Island, through the winter of 1961–62. Additional data were collected from the north side of the sound off Grise Fiord, Ellesmere Island, on 13 May 1962 and 12 May 1969. The over-winter data set is used here to characterize the transition of Arctic waters from autumn to late-spring–early summer. Minimum temperatures ( $< -1.8^{\circ}\text{C}$ ) and maximum salinities ( $> 33.2$ ) were reached in late winter and early spring. Oxygen levels declined over the same fall-to-late-spring period and increased markedly in June. Nitrate, phosphate, and silicate concentrations all increased from their lowest values in fall to overall highest values in late spring, after which each nutrient showed evidence of biological uptake. A deep pycnocline, between 50 and 80 m, persisted from November to February, isolating a bottom-water layer that showed evidence of microbially mediated silicate regeneration (silicate concentrations increased, phosphate decreased, and nitrate concentrations were variable). In early spring (19 March to 1 May), nitrate concentrations dropped abruptly at all depths from more than  $10\ \mu\text{M}$  to less than  $7\ \mu\text{M}$ , apparently in response to the growth of ice algae. Temperature-salinity (T-S) analyses found little evidence of significant water-mass replacements during the study period, but interpretations of coherent variations in nutrient concentrations, as well as observed salinities slightly different from those expected on the basis of ice formation, suggest otherwise. Comparison of results from north of Devon Island with those from sampling off Grise Fiord in May 1962 indicate both higher salinities and lower nutrient concentrations at the latter site; however, data collected at the same site off Grise Fiord in May 1969 showed lower salinities and more variable nutrient concentrations than in 1962.

**Key words:** salinity, temperature, oxygen, nutrients, circulation, nutrient ratios, interannual variability, bacteria and nutrients, ice algae and nutrients

**RÉSUMÉ.** Les profils verticaux de la température, de la salinité, de l'oxygène dissous et des éléments nutritifs inorganiques (nitrate, phosphate et silicate) ont été mesurés à cinq profondeurs (2, 10, 25, 50 et 80 m) en-dessous de la glace, sur la rive sud du détroit de Jones, au nord de l'île Devon, au cours de l'hiver 1961-1962. Des données supplémentaires ont été recueillies à partir du côté nord du détroit à la hauteur du fjord Grise, à l'île d'Ellesmere, le 13 mai 1962 et le 12 mai 1969. L'ensemble de données prélevées l'hiver sert à caractériser ici la transition des eaux de l'Arctique de l'automne à la fin du printemps et au début de l'été. Les températures minimales ( $< -1,8^{\circ}\text{C}$ ) et les salinités maximales ( $> 33,2$ ) ont été atteintes à la fin de l'hiver et au début du printemps. Au cours de cette même période de l'automne à la fin du printemps, les taux d'oxygène ont baissé, puis ont connu une hausse considérable en juin. Les concentrations de nitrate, de phosphate et de silicate ont toutes connu une augmentation par rapport à leurs valeurs les plus basses de l'automne jusqu'à leurs valeurs générales les plus élevées à la fin du printemps, après quoi chaque élément nutritif a montré des signes d'implantation biologique. Une pycnocline profonde, soit entre 50 et 80 m, a persisté de novembre à février, ce qui a eu pour effet d'isoler une couche d'eau de fond laissant voir des signes de régénération du silicate assistée par les microbes (les concentrations de silicate se sont accrues, celles de phosphate ont baissé et les concentrations de nitrate étaient variables). Au début du printemps (du 19 mars au 1<sup>er</sup> mai), les concentrations de nitrate ont chuté considérablement à toutes les profondeurs de plus de  $10\ \mu\text{M}$  à moins de  $7\ \mu\text{M}$ , apparemment en réaction à la croissance des algues des glaces. Les analyses de température et de salinité (T-S) ont permis de déceler peu de signes d'importantes substitutions de la masse d'eau au cours de la période visée par l'étude, mais l'interprétation des variantes cohérentes caractérisant les concentrations d'éléments nutritifs, de même que les salinités observées qui différaient légèrement de celles escomptées en fonction de la formation des glaces, laissent entendre autrement. La comparaison des résultats du nord de l'île Devon avec les résultats de l'échantillonnage prélevé au fjord Grise en mai 1962 indique dans les deux cas des concentrations de salinité supérieures et des concentrations d'éléments nutritifs inférieures au dernier emplacement. Toutefois, les données recueillies au même emplacement du fjord Grise en mai 1969 ont montré des salinités moins élevées et des concentrations d'éléments nutritifs plus variables qu'en 1962.

---

<sup>1</sup> Arctic Institute of North America; present address: 43 Eastern Avenue, Boothbay Harbor, Maine 04538, USA; asapollonio@myfairpoint.net

<sup>2</sup> School of Marine Sciences, University of Maine, Orono, Maine 04469, USA; davidt@maine.edu

Mots clés : salinité, température, oxygène, éléments nutritifs, circulation, rapports d'éléments nutritifs, variabilité interannuelle, bactéries et éléments nutritifs, algues des glaces et éléments nutritifs

Traduit pour la revue *Arctic* par Nicole Giguère.

## INTRODUCTION

This paper records a previously unreported oceanographic study conducted from Jones Sound in the Canadian Arctic Archipelago in the winter of 1961–62 as part of an Arctic Institute of North America research program (Apollonio, 1963). The data are of interest with regard to the sources, circulation, and interannual variations of water in the sound. They show interesting variations between phosphate and silicate, apparently associated with the sea bottom, for which a possible explanation is offered. They also show nutrient reductions in the water column, apparently associated with the development of spring ice algae.

The main sampling site was approximately 75°44' N, 84°40' W, about 3.6 km off the shore of Devon Island (Fig. 1). The depth of water at the site was just over 80 m. Sampling by the first author began in mid November 1961, when ice formation permitted setting up a small sampling hut, and continued at approximately two-week intervals until the end of June 1962. Sea ice generally covers the southern half of Jones Sound by mid November and most of the sound by early January. In 1962, the ice attained a

thickness of about 1.9–2.0 m at the sampling site, with a maximum snow cover of 10–12 cm. The ice was snow-free by 12 June and broke up on 5 July. By comparison, ice break-up occurred on August 1 in 1961 and August 10 in 1963. The sun is continuously below the horizon from 23 October until 8 February and continuously above the horizon from 20 April until early September. The mean air temperature in February was about -34°C. In addition to the time series, data from single stations at the entrance of Grise Fiord, Ellesmere Island (approximately 76°24' N, 82° 58' W), on the north side of Jones Sound, sampled on 13 May 1962 and 12 May 1969 (Apollonio, 1973), are included for comparison.

## METHODS

At the main sampling site, five depths were successively sampled on each date through the winter using a single Nansen bottle with a reversing thermometer (Kahl SICO). In Grise Fiord, three depths per cast were sampled. Salinity was analyzed at the Woods Hole Oceanographic Institution,

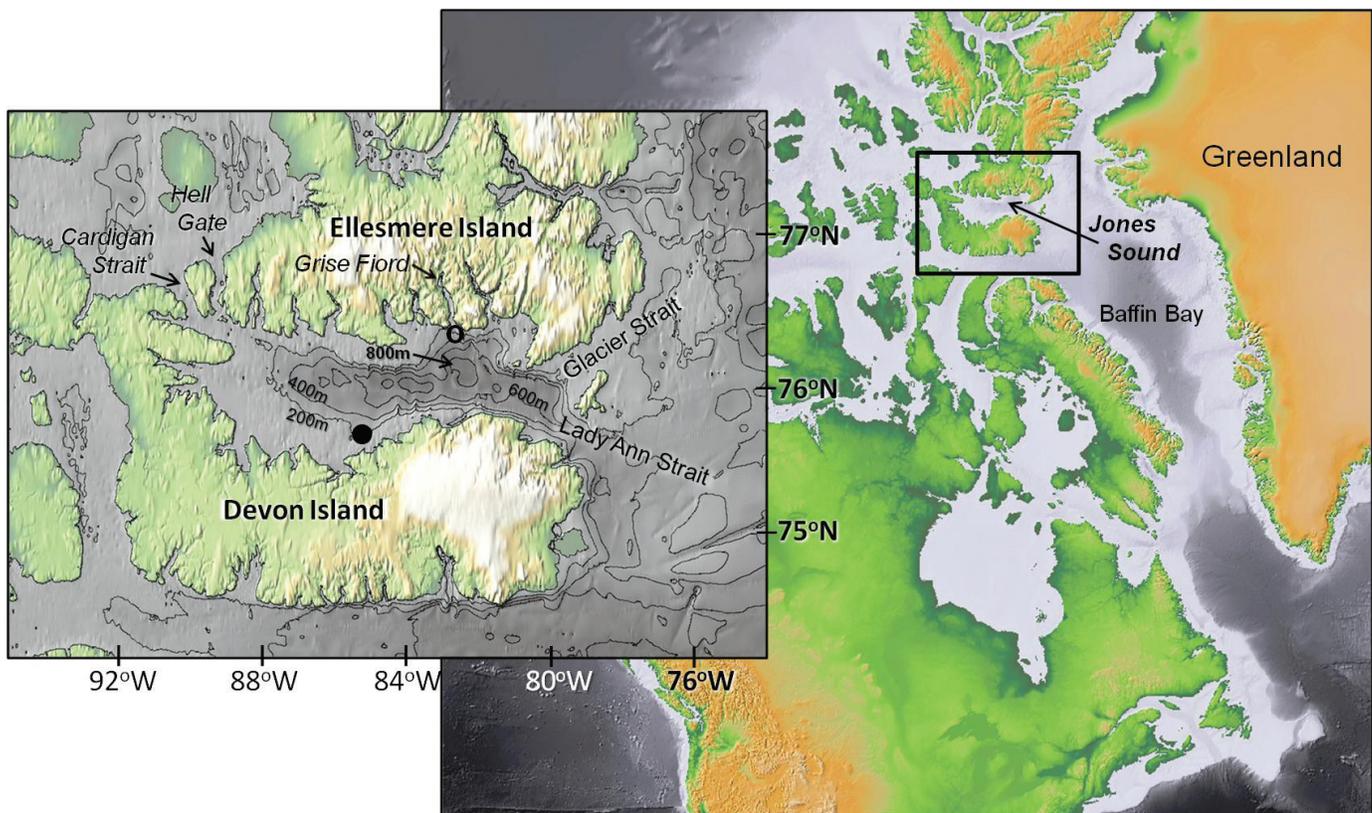


FIG. 1. Jones Sound in the Canadian Arctic Archipelago, showing the locations of the principal study site north of Devon Island (●) and two stations off Grise Fiord, Ellesmere Island (○).

and other parameters in the 1961–62 data were measured at the research station on Devon Island. Nutrient samples taken from Grise Fiord in 1962 were frozen until returned to the Devon Island laboratory; those from 1969 were returned frozen to the Maine Department of Marine Resources laboratory for analyses. All analyses used the standard methods of the time. Oxygen was measured by the Winkler method (Strickland, 1960); however, it was not possible to measure oxygen at the Grise Fiord stations. Nutrients were measured on a Klett-Summerson photoelectrical colorimeter using appropriate filters; nitrate, by the method of Mullin and Riley (1955a); phosphate, by the ammonium molybdate method (Harvey, 1955) as modified by the Woods Hole Oceanographic Institute; and silicate, by the method of Mullin and Riley (1955b). Appropriate salt factors were applied. The oxygen and nutrient data presented here are the averages of two analyses for each sample. Analytical errors are as follows: temperature (reversing thermometer):  $\pm 0.02^\circ\text{C}$ ; salinity (bench salinometer):  $\pm 0.001$  psu; dissolved oxygen (Winkler): mean of  $n$  determinations,  $\pm (0.003 \text{ mg-at O}_2\cdot\text{l}^{-1})/\sqrt{n}$ , which converts to  $\pm 0.023 \text{ ml O}_2\cdot\text{l}^{-1}$ ; dissolved inorganic nutrients: mean of  $n$  determinations,  $\pm 0.03 \mu\text{M}/\sqrt{n}$ , or  $\pm 0.021 \mu\text{M}$ . Sampling errors associated with single samples collected are unknown; however, the general coherence of all data supports the probability of data validity.

## RESULTS

The data from off the north shore of Devon Island are shown in Table 1 and Figure 2. They show gradually cooling temperatures with increasing salinities, decreasing oxygen, and generally increasing nutrient concentrations through the winter. Temperatures reached their winter minima in mid March, and salinities their winter maxima in mid April. Temperatures at 80 m remained relatively warm ( $-1.0^\circ$  to  $-1.6^\circ\text{C}$ ) until early February, after which the water column was essentially isothermal at about  $-1.8^\circ\text{C}$ . Slight warming is apparent in early May, with definite warming in mid June. Salinities increased steadily from about 32.4 in November to about 33.2 early in April. Surface salinities just under the ice show evidence of enrichment from February to early May as salt was extruded from growing sea ice, and the same pattern is seen in the data from Grise Fiord (Tables 2 and 3). Some decrease in salinity occurred after early May, notably in early June.

Oxygen at 80 m varied irregularly between 6.7 and 7.2  $\text{ml l}^{-1}$  until late May, but oxygen at shallower depths declined from about 7.8 to about 6.6  $\text{ml l}^{-1}$ . Increases in oxygen at all depths are apparent in June.

Nutrients appear to have reached their maximum annual values in late May and early June. Nitrate concentrations were most variable, ranging from 4.13 to 11.9  $\mu\text{M}$ , and were quite irregular in their increase. For nitrate, as for salinity, there is a suggestion of slight enrichment in the shallowest layer (2 m) just under the ice from January to May.

Phosphate concentrations increased rather steadily from 0.9 to about 1.4  $\mu\text{M}$ , and silicate generally increased from 10.6 to about 30.2  $\mu\text{M}$  by the end of May. Both phosphate and silicate showed declines in early May followed by maximum annual values in late May. All nutrients declined in late June 1962.

Table 2 shows the data for mid May 1962 from a station off Grise Fiord, where the bottom depth was 262 m. It appears that this station was somewhat warmer and definitely more saline in the shallower depths than the station off Devon Island on the south side of Jones Sound. This sample also shows lower levels of nitrate, phosphate, and silicate than the sample from the south side of Jones Sound taken at about the same time.

Table 3 shows data collected on 12 May 1969 from Station 8 off Grise Fiord, which were typical for the three stations sampled at that time and location (Apollonio, 1973). The depth of the bottom at Station 8 was about 230 m. Temperatures at depths from 3 to 75 m were colder than those at depths from 100 to 225 m. Salinities increased markedly between 100 and 225 m. Nitrate increased uniformly from 3 to 225 m, while phosphate was nearly uniform from 3 to 125 m and notably less from 150 to 225 m. Silicate showed no clear pattern of increase or decrease with depth, but these results are subject to the uncertainty noted elsewhere (Apollonio, 1973) regarding analysis of previously frozen silicate samples.

## DISCUSSION

The differences in all parameters of the 1961–62 samples taken from the north and south sides of Jones Sound, under intact snow cover and sea ice and unaffected (except for the June data) by the dilution of snow and sea ice melt, are consistent with concepts of water-mass origins and circulation in Jones Sound (Barber and Huyer, 1977). The conditions observed throughout the winter off Devon Island may be explained by movements of water masses entering Jones Sound and by diffusion of nutrients within the water column. Water with lower salinities and higher nutrient levels, considered to be derived from Pacific water in the Canada Basin of the Arctic Ocean (Jones and Coote, 1980), flows through Hell Gate and Cardigan Strait at the western end of Jones Sound and along the southern half of the sound. Water with higher salinities and lower nutrient levels flows from the east through Glacier Strait and is found in the northern part of the sound. In addition, the ratio of nitrate to phosphate for all data appears to be lower on the south side of Jones Sound (7.89, compared to 10.24 off Grise Fiord). The ratios for nitrate to silicate are 0.33 for the south shore and 0.43 for Grise Fiord. The lower ratios are indicative of Pacific water, which has higher silicate levels, and the higher ratios are indicative of water with a component of Atlantic water (Jones et al., 2003; Michel et al., 2006). These winter data indicate that winter circulation may be similar to summer circulation (Jones and Coote, 1980). It

TABLE 1. Oceanographic data from Jones Sound off the north shore of Devon Island.

| Depth (m)               | Temperature (°C) | Salinity | Oxygen ml l <sup>-1</sup> | Nitrate (µM) | Phosphate (µM) | Silicate (µM) |
|-------------------------|------------------|----------|---------------------------|--------------|----------------|---------------|
| <b>13 November 1961</b> |                  |          |                           |              |                |               |
| 1                       | -1.75            | 32.439   | 7.82                      | —            | 0.89           | 10.6          |
| 10                      | -1.73            | 32.465   | 7.78                      | —            | 0.93           | 11.9          |
| 25                      | -1.74            | 32.484   | 7.75                      | —            | 0.93           | 11.8          |
| 50                      | -1.74            | 32.621   | 7.30                      | —            | 1.01           | 14.3          |
| 80                      | -1.00            | 32.955   | 6.88                      | —            | 1.20           | 18.4          |
| <b>27 November 1961</b> |                  |          |                           |              |                |               |
| 1                       | —                | 32.613   | 7.34                      | —            | 0.95           | 16.5          |
| 10                      | —                | 32.642   | 7.31                      | —            | 1.01           | 15.7          |
| 25                      | —                | 32.652   | 7.29                      | —            | 0.95           | 17.6          |
| 50                      | —                | 32.681   | 7.19                      | —            | 1.03           | 17.0          |
| 78                      | —                | 33.003   | 6.68                      | —            | 1.15           | 26.9          |
| <b>24 December 1961</b> |                  |          |                           |              |                |               |
| 1                       | —                | 32.850   | 7.40                      | 4.13         | 0.93           | 17.4          |
| 10                      | -1.76            | 32.833   | 7.38                      | 4.94         | 0.95           | 17.4          |
| 25                      | -1.75            | 32.851   | 7.35                      | 4.25         | 0.93           | 17.4          |
| 50                      | -1.46            | 32.924   | 7.12                      | 5.50         | 1.00           | 20.9          |
| 78                      | -1.05            | 33.093   | 6.71                      | 9.65         | 0.93           | 28.4          |
| <b>9 January 1962</b>   |                  |          |                           |              |                |               |
| 2                       | -1.75            | 32.897   | 7.22                      | 6.38         | 0.84           | 22.0          |
| 10                      | -1.75            | 32.908   | —                         | 6.82         | 0.84           | 24.7          |
| 25                      | -1.76            | 32.925   | 7.20                      | 7.62         | 0.91           | 24.7          |
| 50                      | -1.74            | 32.923   | 7.12                      | 6.25         | 0.98           | 23.8          |
| 80                      | -1.36            | 33.052   | 6.79                      | 11.48        | 1.02           | 24.7          |
| <b>21 January 1962</b>  |                  |          |                           |              |                |               |
| 2                       | -1.74            | 32.953   | 7.18                      | 8.00         | 1.00           | 27.9          |
| 10                      | -1.74            | 32.981   | 7.21                      | 7.30         | 1.12           | 20.9          |
| 25                      | -1.76            | 32.988   | 7.20                      | 9.90         | 0.87           | 28.4          |
| 50                      | —                | 33.011   | 7.10                      | 8.39         | 0.95           | 27.5          |
| 80                      | -1.62            | 33.040   | 7.10                      | 10.01        | 0.74           | 36.2          |
| <b>3 February 1962</b>  |                  |          |                           |              |                |               |
| 2                       | —                | 33.054   | 7.13                      | 7.28         | 1.02           | 24.1          |
| 10                      | -1.79            | 33.053   | 7.12                      | 6.82         | 1.09           | 22.9          |
| 25                      | -1.74            | 33.079   | —                         | 8.77         | 1.09           | 22.4          |
| 50                      | -1.71            | 33.144   | 6.80                      | 8.00         | 1.14           | 27.9          |
| 80                      | -1.60            | 33.185   | 6.71                      | 10.85        | 1.19           | 29.4          |
| <b>18 February 1962</b> |                  |          |                           |              |                |               |
| 2                       | -1.78            | —        | 7.24                      | 11.22        | 1.14           | 25.8          |
| 10                      | -1.81            | 33.139   | 7.28                      | 10.45        | 1.19           | 25.8          |
| 25                      | -1.78            | —        | 7.26                      | 8.98         | 1.19           | 24.9          |
| 50                      | -1.79            | 33.215   | 7.18                      | 8.85         | 1.24           | 24.9          |
| 80                      | -1.79            | —        | 7.18                      | 10.00        | 1.21           | 24.9          |
| <b>5 March 1962</b>     |                  |          |                           |              |                |               |
| 2                       | -1.80            | 33.171   | 7.00                      | 9.42         | 1.12           | 25.3          |
| 10                      | -1.81            | 33.168   | 6.95                      | 10.85        | 1.19           | 25.8          |
| 25                      | -1.77            | 33.158   | 6.88                      | 9.19         | 1.14           | 26.4          |
| 50                      | -1.81            | 33.190   | 6.86                      | 10.60        | 1.19           | 26.9          |
| 80                      | -1.82            | 33.225   | 6.83                      | 9.45         | 1.19           | 26.9          |
| <b>19 March 1962</b>    |                  |          |                           |              |                |               |
| 2                       | -1.82            | 33.173   | 7.03                      | 11.22        | 1.12           | 28.8          |
| 10                      | -1.81            | 33.186   | 7.01                      | 10.75        | 1.21           | 29.4          |
| 25                      | -1.82            | 33.191   | 7.00                      | 10.10        | 1.25           | 29.4          |
| 50                      | -1.80            | 33.199   | 6.95                      | 11.75        | 1.19           | 31.7          |
| 80                      | -1.76            | 33.208   | 6.92                      | 11.90        | 1.24           | 31.7          |
| <b>2 April 1962</b>     |                  |          |                           |              |                |               |
| 2                       | -1.81            | 33.218   | 6.98                      | 9.79         | 1.14           | 29.9          |
| 10                      | -1.82            | 33.194   | 7.00                      | 9.45         | 1.25           | 29.4          |
| 25                      | -1.73            | 33.196   | 6.88                      | 9.32         | 1.24           | 29.4          |
| 50                      | -1.80            | 33.208   | 6.86                      | 9.45         | 1.25           | 30.8          |
| 80                      | -1.79            | 33.218   | 6.79                      | 7.88         | 1.19           | 30.8          |
| <b>16 April 1962</b>    |                  |          |                           |              |                |               |
| 2                       | -1.79            | 33.198   | 6.94                      | 7.20         | 1.25           | 30.2          |
| 10                      | -1.79            | 33.196   | 6.95                      | 7.75         | 1.26           | 30.2          |
| 25                      | -1.79            | 33.197   | 6.84                      | 7.19         | 1.26           | 30.2          |
| 50                      | -1.79            | 33.208   | 6.88                      | 7.08         | 1.26           | 30.2          |
| 80                      | -1.79            | 33.224   | 6.81                      | 7.08         | 1.26           | 32.2          |
| <b>1 May 1962</b>       |                  |          |                           |              |                |               |
| 2                       | -1.75            | 33.169   | 6.90                      | 7.40         | 1.00           | 27.9          |
| 10                      | -1.71            | 33.143   | 6.87                      | 6.70         | 1.14           | 27.9          |
| 25                      | -1.73            | 33.172   | 6.72                      | 7.39         | 1.14           | 28.4          |
| 50                      | -1.69            | 33.212   | 6.60                      | 6.81         | 1.19           | 29.4          |
| 80                      | -1.66            | 33.220   | 6.57                      | 7.40         | 1.21           | 30.1          |

TABLE 1. Oceanographic data from Jones Sound off the north shore of Devon Island – continued:

| Depth (m)           | Temperature (°C) | Salinity | Oxygen ml l <sup>-1</sup> | Nitrate (μM) | Phosphate (μM) | Silicate (μM) |
|---------------------|------------------|----------|---------------------------|--------------|----------------|---------------|
| <b>26 May 1962</b>  |                  |          |                           |              |                |               |
| 2                   | -1.73            | 33.073   | 7.06                      | 11.85        | 1.41           | 30.2          |
| 10                  | -1.76            | 33.129   | 6.95                      | 10.38        | 1.35           | 30.2          |
| 25                  | -1.82            | 33.159   | 6.79                      | 11.10        | 1.35           | 30.0          |
| 50                  | -1.68            | 33.187   | 6.70                      | 11.10        | 1.35           | 30.0          |
| 80                  | -1.63            | 33.228   | 6.68                      | 11.84        | 1.54           | 34.1          |
| <b>12 June 1962</b> |                  |          |                           |              |                |               |
| 2                   | -1.57            | 32.910   | 7.80                      | 9.45         | 1.33           | 27.8          |
| 10                  | -1.49            | 33.062   | 7.25                      | 11.48        | 1.39           | 28.8          |
| 25                  | -1.58            | 33.121   | 6.98                      | 11.72        | 1.36           | 28.8          |
| 50                  | -1.58            | 33.148   | 6.90                      | 12.05        | 1.38           | 30.7          |
| 80                  | -1.50            | 33.149   | 6.99                      | 11.60        | 1.38           | 31.6          |
| <b>29 June 1962</b> |                  |          |                           |              |                |               |
| 2                   | -0.95            | 30.465   | 9.77                      | –            | 0.84           | 18.1          |
| 10                  | -1.18            | 32.783   | 8.67                      | –            | 1.09           | 22.4          |
| 25                  | -1.27            | 32.933   | 8.05                      | –            | 1.22           | 25.3          |
| 50                  | -1.30            | 33.017   | 7.64                      | –            | 1.31           | 28.4          |
| 80                  | -1.43            | 33.062   | 7.30                      | –            | 1.39           | 32.3          |

is of interest, however, that the water samples taken from three stations off Grise Fiord in May 1969 were all noticeably fresher than those from 1962; the 1969 samples had an intermediate N/P ratio of 9.52, primarily because of higher phosphate than in 1962. Average near-surface (2–75 m) salinity data for the three sets of samples are 33.20 (Devon), 33.45 (Grise Fiord, 1962), and 33.12 (Grise Fiord, 1969). These data suggest interannual variability.

In addition to nutrient variations reported here that may be attributed to horizontal water-mass movements and vertical diffusions, two other kinds of variations are apparent in Table 1 and Figures 2 and 3. The first concerns variations of phosphate and silicate values at 80 m that were inversely correlated until 5 March 1962, after which they were directly correlated. Figure 3 shows how silicate co-varies with phosphate over the first seven sample periods through 18 February. The negative correlation ( $r^2 = 0.81$ ) for those dates is shown in Figure 4. The positive correlation is less clear for the two remaining data clusters, 18 February to 25 May and 12 to 29 June. After 18 February, the two nutrients track one another, with each nutrient clearly increasing to maximum concentrations in late May. During the fall, the concentrations of silicate were highest in the 80 m depth sample, and they generally increased by some 20 μM between 13 November and 21 January (Fig. 2). The dense bottom layer (80 m) was effectively isolated from water layers above, and we suspect that the deep layer was accumulating regenerated silicate from diatom frustules. The data from 50 m suggest similar variations, but less clearly than those from 80 m. Similar variation between nitrate and silicate values was seen at 80 m, though it is less clearly marked. These data suggest that the phenomenon is associated with the bottom.

Arctic ice algae and phytoplankton often sink rapidly from the euphotic zone. In Jones Sound, Longhurst and Head (1989) found that large zooplankton consumed less than 1% of the phytoplankton standing stock daily and concluded that large proportions of the phytoplankton that are not consumed sink out of the surface layers and may

accumulate on the bottom, where regeneration of their nutrients may occur. The decrease in deep-water phosphate over that same time interval suggests microbial activity, as the removal by microbes of the organic film coating on diatom frustules is required before the biogenic silica can dissolve (Hecky et al., 1973). The present data from 80 m suggest that reduced phosphate indicates microbial action, which may result in dissolution of silicon shells and concomitant increases of silicate in bottom waters. Presumably this process was completed by early March, after which time both phosphate and silicate were regenerated concurrently. Unfortunately, nitrate data for the first two sample dates are not available, but nitrate concentrations were also highest in the deep layer from 24 December to 23 January, which might reflect nitrification in the deep layer.

The second kind of nutrient variation of interest is apparent most clearly in nitrate reductions in April and early May (Fig. 2). The abrupt decrease in nitrate at all sample depths after 19 March was accompanied by a general leveling off in silicate concentrations, which had been increasing immediately prior to that date, and a leveling off or a decline in concentrations of phosphate (Fig. 2). The depth-averaged nitrate concentration was about 11.2 μM on 19 March and dropped to about 7.2 μM on 1 May, which would correspond to an apparent biological uptake of approximately 4 μM. Phosphate decreased by only 0.05 μM over the same period. If we assume, however, that both nitrate and phosphate were continuing to increase in concentration, reflecting regenerative processes for the period from before the abrupt nitrate decline to the time of the highest concentrations of each nutrient in late May and early June, then the apparent uptake of nitrate would be just over 4 μM and that of phosphate about 0.25 μM. This assumption is consistent with a biological uptake of nitrate and phosphate corresponding to the Redfield Ratio of 16 N:1P, which would lead us to surmise that the period between 19 March and late May–early June is one of a growing ice algae population (Apollonio, 1965). Similar declines of nitrate and silicate to 100 m between April and June in Barrow Strait, Lancaster

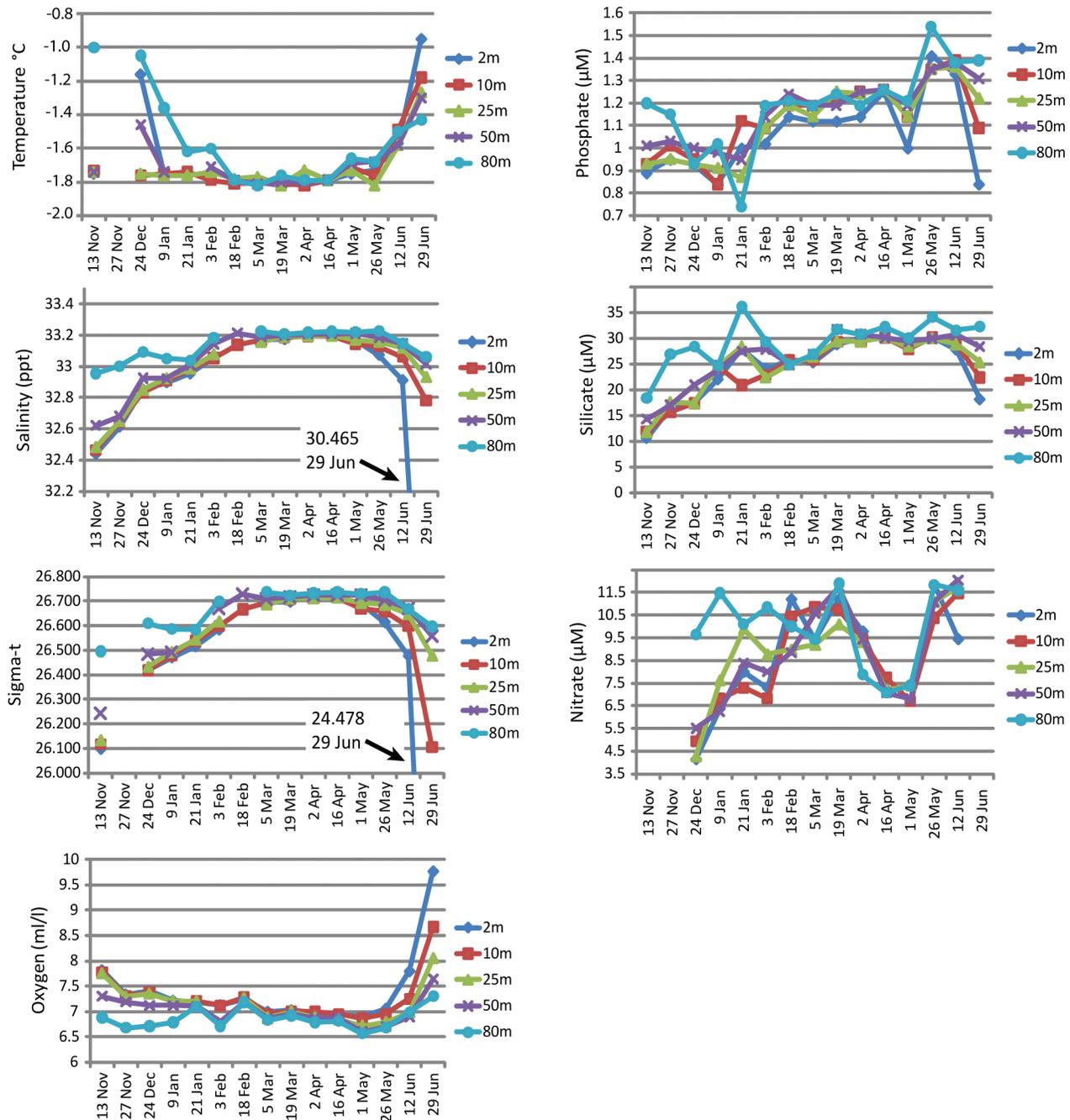


FIG. 2. Changes in temperature, salinity, sigma-t, oxygen, nitrate, phosphate, and silicate at the principal study site in Jones Sound north of Devon Island, throughout the study period (13 November 1961 to 29 June 1962). Data are plotted for five sampling depths: 2, 10, 25, 50, and 80 m. No line is plotted to connect points across missing data.

Sound, were reported by Welch and Bergmann (1989) and by Cota et al. (1990). Harrison and Cota (1991) suggested that those declines were related to the growth of ice algae. In each of these three data sets, nutrients increased near the expected end of the growing season for ice algae, but declined again with the onset of phytoplankton production. By 26 May in Jones Sound, nitrate, phosphate, and silicate were all replenished to their highest levels, most likely as a result of a water-mass replacement, although there was no evidence of such in our temperature-salinity analyses.

Temperature and salinity data pairs were plotted (as T-S diagrams) for the overwinter time series, color-coded by sample dates (Fig. 5). As revealed by the contour lines of constant density on the T-S diagram (density anomaly, or sigma-t, in  $\text{g kg}^{-1}$ ), changes in density are controlled principally by changes in salinity, even slight changes. Temperature has only a minor influence, even on 13 November, the first sample date, when the broadest range in temperatures was observed. The densest water on that date is at the bottom (sample depth 80 m). This pattern of the bottom water

TABLE 2. Oceanographic data from Grise Fiord, Ellesmere Island, 13 May 1962. Nitrate, phosphate, and silicate amounts are in  $\mu\text{M}$ .

| Depth (m) | Temperature ( $^{\circ}\text{C}$ ) | Salinity | Nitrate | Phosphate | Silicate |
|-----------|------------------------------------|----------|---------|-----------|----------|
| 2         | -1.83                              | 33.399   | 9.31    | 1.03      | 27.5     |
| 10        | -1.78                              | 33.240   | 9.20    | 1.00      | 25.9     |
| 25        | -1.76                              | 33.370   | 8.26    | 0.88      | 26.4     |
| 50        | -1.24                              | 33.577   | 12.30   | 1.01      | 26.4     |
| 75        | -1.31                              | 33.664   | 9.59    | 1.04      | 22.8     |
| 100       | -1.22                              | 33.693   | 11.38   | 1.06      | 26.4     |
| 125       | -1.33                              | 33.768   | 12.40   | 1.12      | 25.9     |
| 150       | -1.25                              | 33.804   | 11.60   | 1.23      | 24.8     |
| 175       | -1.21                              | 33.833   | 13.63   | 1.36      | 24.8     |
| 200       | -                                  | -        | 9.92    | 1.37      | 28.4     |
| 250       | -1.08                              | 33.958   | 14.14   | 0.87      | 25.9     |

TABLE 3. Oceanographic data from Station 8 off Grise Fiord, 12 May 1969. Nitrate, phosphate, and silicate amounts are in  $\mu\text{M}$ .

| Depth (m) | Temperature ( $^{\circ}\text{C}$ ) | Salinity | Nitrate | Phosphate | Silicate |
|-----------|------------------------------------|----------|---------|-----------|----------|
| 3         | -1.74                              | 33.084   | 9.6     | 1.19      | 18.9     |
| 6         | -1.68                              | 33.061   | 9.9     | 1.24      | 15.3     |
| 11        | -1.69                              | 33.058   | 10.1    | 1.20      | 17.6     |
| 25        | -1.67                              | 33.054   | 9.9     | 1.23      | 15.4     |
| 50        | -1.49                              | 33.115   | 10.2    | 1.22      | 16.3     |
| 75        | -1.31                              | 33.280   | 10.7    | 1.23      | 16.0     |
| 100       | -0.99                              | 33.455   | 12.0    | 1.24      | 14.0     |
| 125       | -0.89                              | 33.599   | 12.2    | 1.20      | 23.9     |
| 150       | -0.91                              | 33.726   | 11.9    | 1.10      | 29.7     |
| 175       | -0.76                              | 33.756   | 12.2    | 1.19      | 16.1     |
| 200       | -0.55                              | 33.879   | 12.9    | 1.08      | 14.8     |
| 225       | -0.47                              | 33.932   | 13.2    | 1.10      | 17.8     |

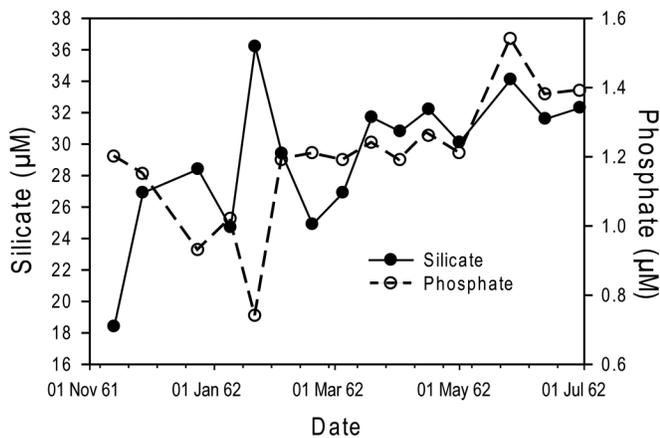


FIG. 3. Variations in phosphate and silicate ( $\mu\text{M}$ ) at the bottom sampling depth (80 m) in Jones Sound throughout the sampling period.

being the saltiest, warmest, and densest continues through late winter and early spring, with each successive sample period reflecting steadily increasing salinities at all depths, caused partly by the exclusion of salt as the surface ice thickens, and perhaps partly by advection. The T-S pairs for the sample dates 3 February to 26 May cluster together in a fairly tight envelope, which would indicate that this is a period of only slight changes of ice cover, while in fact, it is more likely that the ice continued to thicken until about 16 April. The last two sample dates, 12 and 29 June, reveal decreasing salinities and warming temperatures, thus marking a period of significant ice melt.

The temporal progression of these T-S properties does not reveal obvious intrusions of water masses with markedly different T-S properties, but the total changes in salinities suggest otherwise. Depth-averaged salinities increased from 32.61 on 13 November to about 33.21 for the period 5 March to April 16, an increase of 0.60. Assuming that 90% of the salt is extruded from first-year sea ice (Grainger, 1977) and that the ice grew about 1.7 m (from about 0.3 m on 13 November to 2 m), the salinity should have increased to about 33.24. This slight difference, if significant, would suggest a dilution of waters at the study site by an influx

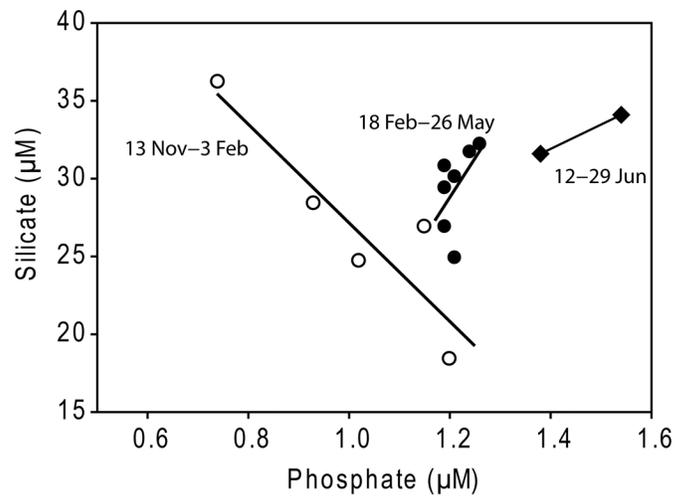


FIG. 4. Silicate concentrations in relation to phosphate ( $\mu\text{M}$ ) for the bottom sampling depth (80 m) in Jones Sound throughout the sampling period. Data are separated into three periods: 13 November to 3 February ( $\circ$ ), 18 February to 26 May ( $\bullet$ ) and 12 to 29 June ( $\blacklozenge$ ). Linear regressions are given for the first two sub-periods: for 13 November to 3 February,  $\text{Si}(\text{OH})_4 = 58.77 \times -31.59 (\text{PO}_4)$ ;  $r^2 = 0.81$ , and for 18 February to 26 May,  $\text{Si}(\text{OH})_4 = -32.09 \times 50.72 (\text{PO}_4)$ ;  $r^2 = 0.28$ .

of lower-salinity waters throughout the fall and winter. One possibility for such an influx is a cross-isobath exchange between the relatively shallow waters in the immediate vicinity of the study site and the deeper waters of the Sound. All else being equal, those deeper waters would remain fresher throughout the winter, experiencing proportionately less salinity increase than shallower waters as a result of ice formation. It is also possible that some of the fresher waters resulted from an influx of lower-salinity Pacific waters into Jones Sound.

While we expect that advective processes are important throughout the winter in Jones Sound, the horizontal length scales of water properties are sufficiently great that the continuous exchange of waters beneath our sampling station was not reflected in the T-S properties, but only in changes in depth-averaged salinity as compared with changes in ice thickness. Dissolved inorganic nutrient fields are less conservative, however, and are constantly changing throughout

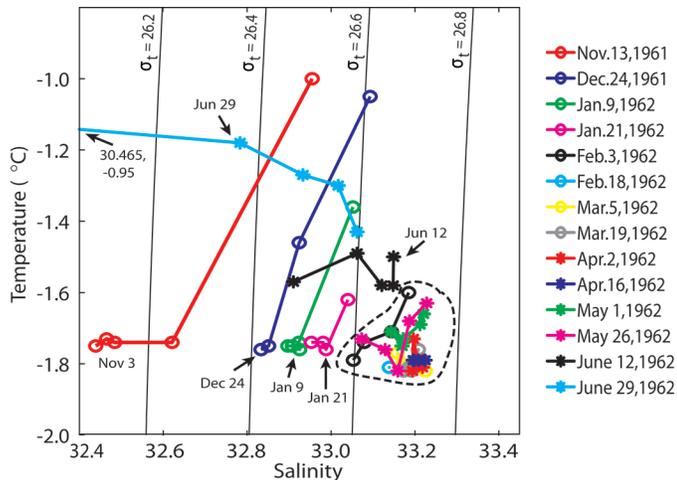


FIG. 5. Temperature-salinity diagram for each sampling date from 13 November to June 29 in Jones Sound. The cluster of data for the sampling period 3 February to 26 May is enclosed in a dashed envelope. Density contours are given in sigma-t units (density anomaly in grams per kilogram).

the time series as nutrients (nitrate, phosphate, and silicate) are regenerated, lost by way of possible sediment denitrification (nitrate loss), and taken up by benthic microbes and ice algae. Such appears to be the case for the sudden uptake of nitrate between 19 March and 1 May, as well as its replenishment by 26 May (Fig. 2), which we suspect is the result of a water-mass exchange.

## CONCLUSIONS

This report presents a record of hydrographic, oxygen, and nutrient data taken in Jones Sound at roughly two-week intervals from mid November 1961 until early June 1962. The data show three patterns of particular interest: 1) the changes in physical properties and nutrient concentrations that would be expected from circulation and water-mass exchanges in Jones Sound; 2) an inverse relation between phosphate and silicate concentrations close to the bottom (80 m until 5 March), perhaps because of microbial activity and regeneration of silica from diatom frustules; and 3) a spring reduction of nutrients because of the growth of ice algae, followed by an increase in nutrients near the end of algal growth. Nutrient loads are continuously recharged during the transition from ice formation to ice-out. This recharge of nutrients first reflects regenerative processes in the water column and near the bottom, and later, spring uptake. It is likely that nutrient distributions are patchy both within and outside of the sampling site.

## REFERENCES

- Apollonio, S. 1963. The Devon Island Expedition 1960–64: Oceanography, winter 1961–62. *Arctic* 16(1):63–66.
- . 1965. Chlorophyll in Arctic sea ice. *Arctic* 18(2):118–122.
- . 1973. Glaciers and nutrients in Arctic seas. *Science* 180: 491–493.
- Barber, F.G., and Huyer, A. 1977. On the oceanography of Jones Sound, NWT. Manuscript Report Series 40. Ottawa: Marine Sciences Directorate, Department of Fisheries and the Environment.
- Cota, G.F., Anning, J.L., Harris, L.R., Harrison, W.G., and Smith, R.E.H. 1990. Impact of ice algae on inorganic nutrients in seawater and sea ice in Barrow Strait, NWT, Canada, during spring. *Canadian Journal of Fisheries and Aquatic Sciences* 47:1402–1415.
- Grainger, E.H. 1977. The annual nutrient cycle in sea ice. In: Dunbar, M.J., ed. *Polar oceans*. Calgary, Alberta: Arctic Institute of North America. 285–299.
- Harrison, W.G., and Cota, G.F. 1991. Primary production in polar waters: Relation to nutrient availability. *Polar Research* 10: 87–104.
- Harvey, H.W. 1955. *The chemistry and fertility of sea waters*. Cambridge: Cambridge University Press.
- Hecky, R.E., Mopper, K., Kilham, P., and Degens, E.T. 1973. The amino acid and sugar composition of diatom cell-walls. *Marine Biology* 19:323–331.
- Jones, E.P., and Coote, A.R. 1980. Nutrient distributions in the Canadian Archipelago: Indicators of summer water mass and flow characteristics. *Canadian Journal of Fisheries and Aquatic Sciences* 37:589–599.
- Jones, E.P., Swift, J.H., Anderson, L.G., Lipizer, M., Civitarese, G., Falkner, K.K., Kattner, G., and McLaughlin, F. 2003. Tracing Pacific water in the North Atlantic Ocean. *Journal of Geophysical Research* 108, C4, 3116, doi:10.1029/2001JC001141.
- Longhurst, A., and Head, E. 1989. Algal production and variable herbivore demand in Jones Sound, Canadian High Arctic. *Polar Biology* 9:281–286.
- Michel, C., Ingram, R.G., and Harris, L.R. 2006. Variability in oceanographic and ecological processes in the Canadian Arctic Archipelago. *Progress in Oceanography* 71:379–401.
- Mullin, J.B., and Riley, J.P. 1955a. The spectrophotometric determination of nitrate in natural waters, with particular reference to sea-water. *Analytica Chimica Acta* 12:464–480.
- . 1955b. The colorimetric determination of silicate with special reference to sea and natural waters. *Analytica Chimica Acta* 12:162–176.
- Strickland, J.D.H. 1960. Measuring the production of marine phytoplankton. *Bulletin of the Fisheries Research Board of Canada* 122. 172 p.
- Welch, H.E., and Bergmann, M.A. 1989. Seasonal development of ice algae and its prediction from environmental factors near Resolute, N.W.T., Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 46:1793–1804.