# Notes on the Oceanography of d'Iberville Fiord

R. A. LAKE and E. R. WALKER[1]

ABSTRACT. The oceanography of a small arctic fiord has been studied over a period of three years. The shallow water structure is determined by convection in the fiord, as is shown by temperature-time series and budget studies. The fiord contains temperature inversions at shallow depths which have been present in observations over several years. The deeper water structure is determined by the sill across the fiord mouth and similar sills in Nansen Sound which restrict free access at depth of water layers from the Arctic Ocean.

RÉSUMÉ. *Notes sur l'océanographie du fjord d'Iberville.* Les auteurs ont étudié l'océanographie d'un petit fjord arctique pendant trois ans. Comme le montrent les séries température-temps et les études de bilan, la structure de l'eau peu profonde est déterminée par la convection à l'intérieur du fjord. Celui-ci montre des inversions de température à faible profondeur qui sont présentes dans les observations portant sur plusieurs années. La structure de l'eau en profondeur est déterminée par le seuil à travers l'entrée du fjord et par les seuils semblables dans le détroit de Nansen, qui réduisent le libre accès des couches d'eau profondes de l'océan Arctique.

РЕЗЮМЕ. *Заметки об океанографии фиорда д'Ибервиль.* В течение трёх лет проводилось исследование океанографии маленького арктического фиорда. Согласно температурно-временным измерениям и исследованию водного баланса, структура мелководья определяется конвекцией в фиорде. Наблюдения нескольких лет показывают, что на малых глубинах в этом фиорде *имеются* температурные инверсии. Структура более глубоких вод определяется порогом, пересекающим вход в фиорд, и аналогичными порогами в проливе Нансена, которые на глубине преграждают свободный доступ в фиорд водным слоям из Арктического океана.

## INTRODUCTION

A number of papers have been written on the overall oceanographic features of the Canadian Archipelago (Collin 1963; Collin and Dunbar 1964; Pelletier 1966), whereas others have dealt in more detail with particular regions (Barber 1968, Ford and Hattersley-Smith 1965; Keys *et al.* 1969). This paper is in the latter category, describing oceanographic features of d'Iberville Fiord (Fig. 1). D'Iberville Fiord, an appendage to the Nansen Sound — Greely Fiord system, is approximately 35 km. in length and 6 km. in width, having an area of 213 km.$^2$ Soundings show that the fiord has a sill extending across its mouth with a maximum depth of 330 m. while the maximum depth in the fiord is 560 m. The fiord was probably subject to glacial over-deepening during the Pleistocene period as described by Pelletier (1962).

One tongue of the large glacier capping the Victoria and Albert Mountains terminates at the head of the fiord. During the summer icebergs calving from this glacier make their way down d'Iberville Fiord provided that the sea-ice cover is

---

[1] Frozen Sea Research Group, Marine Sciences Directorate, Pacific Region, Department of the Environment, Canada.

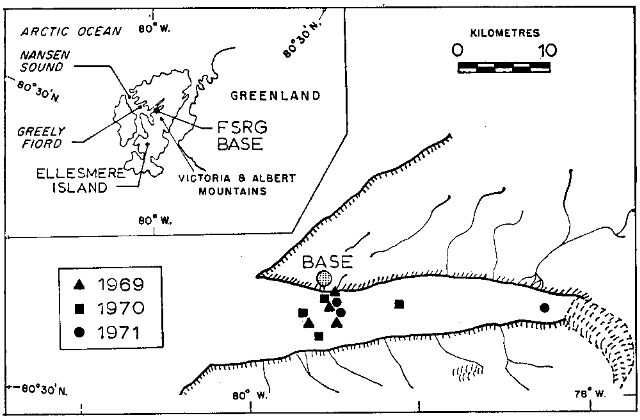

FIG. 1. D'Iberville Fiord, Ellesmere Island, N.W.T. Experimental sites spring 1969, 1970, 1971 and summer 1969, 1970. Summer sites are the two closest to the north shore.

sufficiently removed. In 1969 and 1971 the fiord was ice free, except for many icebergs, during the entire month of August. In the summer of 1970 the fiord remained covered with sea ice and the icebergs were retained at the head of the fiord. The depth of fresh water laid down on the fiord from summer runoff in a year of average precipitation is about 1.0 m. This amount is estimated from the average precipitation over the fiord drainage area with allowance for evaporation. We estimate that as much as one third of this fresh water input can be derived from icebergs melting in the fiord, in a quantity varying from year to year.

Oceanographic observation periods included March and April in 1969, 1970, and 1971, and August and September in 1969 and 1970. Most of the spring and all of the summer data were collected within 3 km. of the base. During the spring trips additional information was collected at various points along the length of the fiord.

Observations were made of the salinity and temperature of the water, sea ice thickness and growth rates, currents, tides and meteorology. In spring seasons a Guildline C.T.D. *in situ* instrument provided conductivity, temperature and pressure information from which salinity, density and depth were derived. The calibration of this instrument was checked periodically with water sample bottles and thermistors. Observations were taken at depth intervals of 1 m. in 1969; in 1970 and 1971 this interval was decreased to 0.25 m. above 30 m. Accuracy varied from operation to operation but in all, absolute accuracy in salinity and temperature lies within manufacturer's specifications of ± .04‰ and ± 0.02°C. respectively. Pressure readings agreed closely with metered cable lengths. In summer field seasons bottle samples provided salinity data and were taken in shallow depths close to shore. In both 1969 periods and in spring 1970 temperature data over a period of time were taken from an array of thermistors suspended from the ice or, in the case of August 1969, suspended from a buoy just below the water surface. The details of the methods used in obtaining the thermistor data have been reported by Lewis and Walker (1970). The thermistor data from the arrays have an absolute accuracy of the order of 0.01°C.

It was determined that currents to a 2-m. depth were below the 5-cm. sec.$^{-1}$ threshold of the instrument available. Currents were estimated from dye plumes but were limited to the first 2 m. beneath the ice sheet. Velocities in this region

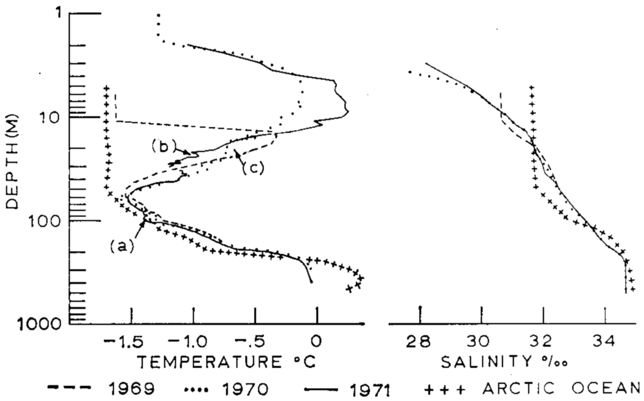

FIG. 2. Temperature, salinity curves to 300 and 500 m., d'Iberville Fiord. April 1969, March 1970, March 1971 and Arctic Ocean (Worthington 1959).

ranged from 0 to 3.5 cm. sec.$^{-1}$. The scatter of velocities was too great to permit measurement of velocity profiles. From the summer of 1969 onward tide measurements were made by diaphragm-operated Ottboro recorders off the beach adjacent to the base camp. Measurements of ice thickness and growth rates were made during spring field trips. Weather observations were routinely made at the base.

## WATER STRUCTURE

Temperature and salinity samplings during each spring season in d'Iberville Fiord are shown in Fig. 2 with a representative sounding from the Arctic Ocean (after Worthington 1959). The overall water structure is much the same from year to year. The temperature and salinity profiles in Fig. 2 agree closely with the only other oceanographic stations in d'Iberville Fiord. These stations, at the head and mouth of the fiord were taken in May 1965 by Keys and Seibert (1969). Small scale details, not visible in Fig. 2, having a vertical extent of only a few metres, give an impression of extensive horizontal layering. No regular step-like formations of temperature or salinity such as those observed by Neshyba *et al.* (1971) were found. As expected (Ford and Hattersley-Smith 1965, Hattersley-Smith and Serson 1966), the warm layer between 400 and 500 m. which exists in the Arctic Ocean off the western Archipelago (Collin 1963) is absent. Typical water of Atlantic origin found in the Arctic Ocean from below the surface layer to a depth of 900 m. has temperature and salinity values above 0°C. and 34.92‰ (Ostenso 1966). The water below about 250 m. in d'Iberville Fiord approaches a temperature value of 0°C. and a salinity value of 34.7‰. This difference in water structure below 300 m. is almost certainly due to the shallowness of the shelf at the mouth of Nansen Sound (Crary and Goldstein 1957; Ford and Hattersley-Smith 1965).

Above a depth of 250 m. the salinity decreases towards the surface (Fig. 2). The density is determined almost exclusively by the salinity so it is evident that on the large scale the static stability increases upward to the isopycnic layer just below the ice. Small scale variations can occur in the static stability of the water mass. In the temperature plots the most outstanding feature is the warm layer which occurs in d'Iberville Fiord at all times above 50 m.

A number of features which are not prominent on the temperature plots in Fig. 2 proved to extend over wide areas of Greely Fiord and to be more prominent there. These include the small feature, marked (a), appearing at a depth of 100 m. on the temperature curves. Some of the small features appearing on the 1970 and 1971 temperature traces between 25 m. and 50 m., (b) and (c) for example, may be quite extensive. In a long trip down Greely Fiord in 1970 the feature (c), Fig. 2, hardly discernible in d'Iberville Fiord was continuous westward and very much stronger in Greely Fiord. This appears to be the same structure that attracted the attention of Ford and Hattersley-Smith (1965) in August 1962. At that time the warm layer extended some 100 miles from the head of Tanquary Fiord. Work during 1963 and 1964, described by Hattersley-Smith and Serson (1966), confirmed that this layer also existed during the spring of those years. Evidently this feature has been present in observations over nine years. The stability of the water structure, depending overridingly on salinity, prevents convective dispersion of the warm layer. Molecular diffusion and a small degree of turbulence should however be sufficient to disperse this layer in a fraction of a period of nine years. We must conclude that the heat in the 25- to 50-m. layer is renewed from time to time, probably annually. Ford and Hattersley-Smith (1965) suggest radiative heating as a possibility.

In the spring of 1969 the isopycnic layer under the ice extended to a depth of 10 m. In 1970 and 1971 this layer extended down only to 1 to 2 m. The causes of these differences in the thickness of the isopycnic layer are complex. Causative factors include differing amounts of ice cover in summer, wind effects in summer, variations in fresh water input and consequent variations of the estuarial circulation in the fiord. We are at present investigating the problem in detail.

## TEMPERATURE-TIME RECORDS

Temperature-time records were obtained from strings of thermistors which were deployed in April and August 1969 and March to April 1970 at locations fairly close to shore. Intensive recording at sampling intervals varying from 10 seconds to 1 hour were conducted over a few days to a week of each field trip. Thermistor time constants permitted sampling that was effectively instantaneous. The thermistor strings reached from near the ice bottom to depths of 46 m. in April 1969 and to 15 m. in April 1970. The magnitude of temperature changes observed depends upon the mean temperature gradient at the appropriate level insofar as temperature changes are the result of vertical water motion.

In Fig. 3 are shown brief portions of the temperature-time traces with sampling at 1-minute intervals. They are in three groups. In the upper group the traces made in April 1969 and April 1970 are from thermistors in the isothermal, isopycnic layer just below the ice. The trace made in August 1969 is from a thermistor in a fresh warm stable layer with the temperature decreasing downwards. In August 1969 open water caused very irregular temperature traces. In April 1969 small temperature variations were noted with periods of about 24 hours, 8 hours, and 10 minutes. In April 1970 very little temperature variation was noted at 2.0 m.

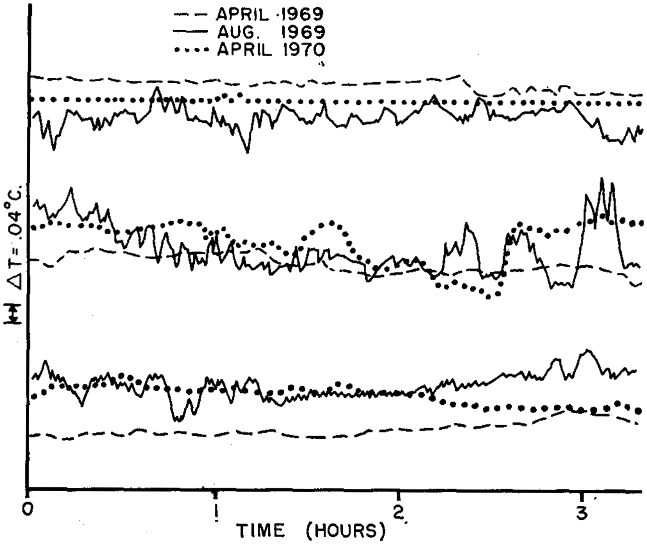

FIG. 3. Temperature-time records, d'Iberville Fiord for April 1969; 4, 10, 31 m., August 1969; 3, 9, 21 m., April 1970; 2, 4, 10 m. See text for water structure description.

In the middle group all thermistors were at depths where salinity, density and temperature were increasing rapidly downward. In April 1969 temperature variations at near-tidal periods were evident. In August 1969 temperature oscillations were present at a wide range of frequencies some so high as to be unresolved by the fastest sampling rate of one reading per minute. In April 1970 irregular oscillations were marked.

In the lower group all thermistors were at depths just below the temperature maximum with the temperatures decreasing downwards while salinity and density increased downwards. During April 1969 temperature variations of tidal periods were present. During August 1969 temperature variations were irregular. In April 1970 temperature oscillations at periods of 5 to 10 minutes were present.

Consideration was given to correlating variations of temperature with tidal cycles. The only period in which variations of near-tidal frequency were evident in temperature records was in April 1969, but actual tidal records were not available for this period. In August 1969 the large variations in temperature, particularly the cooling which began during the experimental period, obscured any easily identifiable correlation between tides and temperatures. In March to April 1970 no correlation was evident. Perhaps this is not too surprising as the temperature records were made fairly close to shore where the actual water movement may be irregular. A more subtle analysis with longer records will be undertaken in future.

In the layer just above the temperature maximum in March 1970 the temperature at 3.25 m. decreased to form a marked temperature inversion, which lasted for several hours until the former uniform gradient was re-established. The explanation for this record seems to be interleaving of cold and warm layers. A similar event occurred in April 1969. Temperatures at 7.0 m. went from temperatures typical of the isothermal layer (−1.6°C.) to something in excess of −1.0°C., then returned after 30 hours to the former cold temperatures. The small vertical extent and rather lengthy existence of these phenomena suggest the presence of rather extensive horizontal, vertically thin patches. It may be that exchange of heat and salt with the under-ice layer is accomplished by mixing of such patches.

To sum up, the temperature-time records differ from year to year. In April 1969 variations with tide periods were evident in the temperature records particularly in the upper layers, but were not in March to April 1970. The temperature variability below ice during winter was of course very much less than in the open water of August 1969. The records have a completely different character in winter from those in Cambridge Bay (Lewis and Walker 1970). The temperature and salinity-density structure is similar in upper layers in both locations, although the under-ice isopycnic layer is much deeper in Cambridge Bay, extending on occasion to a depth of 40 m. The temperature-time records at Cambridge Bay have marked variability at frequencies of 1 to 10 cycles per hour lacking in d'Iberville Fiord.

TABLE 1. Salt changes and rates of change, and sensible heat changes and rates of change, from 11 April 1969 to 13 August 1970 in a water column from depths of 1.5 m. to 35.0 m. in d'Iberville Fiord.

| | Salt Gain (+) or Loss (−) gm. cm.$^{-2}$ | Rate of Salt Gain (+) Loss (−)$10^{-6}$ gm. cm.$^{-2}$ sec.$^{-1}$ | Heat Gain (+) or Loss (−) (cal. cm.$^{-2}$) | Rate of Heat Gain (+) or Loss ($10^{-3}$ cal. cm$^{-2}$ sec.$^{-1}$) |
|---|---|---|---|---|
| *11 April 1969 to 23 August 1969* | −13.8 | −13.0 | +4324 | +4.0 |
| *23 August 1969 to 5 September 1969* | +5.5 | +49.1 | −202 | −1.8 |
| *5 September 1969 to 12 March 1970* | +5.4 | +3.3 | −2649 | −1.5 |
| *12 March 1970 to 13 August 1970* | −2.1 | −2.3 | +2411 | +2.6 |

## SALT AND HEAT BUDGETS

In Table 1 are salt and heat budgets for surface waters for the period April 1969 through August 1970. These are incomplete in that only levels from 1.5 m. to 35 m. are available. The locations of observations differed. With these reservations the heat gain from April 1969 to August 1969 when the fiord was open with very warm fresh surface water, is very large, compared to the heat gain from spring to summer 1970. The decrease in salt in the column spring to summer 1969 is large. The rate of salt gain, 23 August 1969 to 5 September 1969 must be due to horizontal advection as ice did not form until 8 September 1969. The salt gain from autumn 1969 to spring 1970 is double that released by growing sea ice. A budget calculation from 5 September 1969 to 13 March 1970 indicated 800 cal. cm.$^{-2}$ released from cooling of sea ice, 8,200 cal. cm.$^{-2}$ from ice formation and 2,600 cal. cm.$^{-2}$ from cooling of the water column from 1.5 to 35.0 m. The water column heat loss would thus be over 30 per cent of the heat released by ice formation or double the percentage found in Cambridge Bay (Lewis and Walker 1970). Again horizontal advection is indicated.

To complement heat budgets of the water columns, heat flows through the ice were calculated using records from thermistors implanted in the ice and in the snow on top of the ice. The heat flux calculations used the measured temperature gradients multiplied by values of thermal conductivity appropriate for ice conditions (after Lewis 1967, Schwerdtfeger 1963) and for the measured snow densities (Abels' formula, Mellor 1964).

In both April 1969 and April 1970 the calculations indicated near balance of the heat flows through ice and snow, and the heat released by ice forming at the rate we observed. While the errors may be sizable the calculations clearly indicate that large water column heat losses are not present towards the end of the winter season.

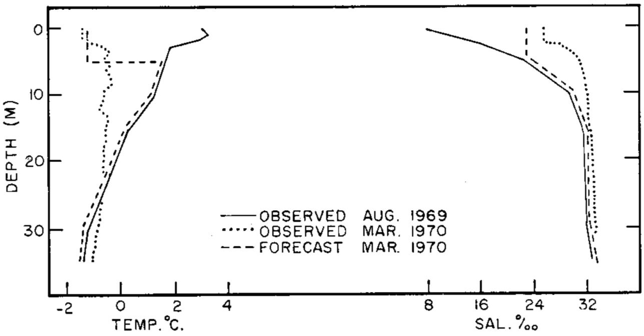

FIG. 4. Temperature and salinity curves, to 35 m. d'Iberville Fiord; observed 23 August, 1969; observed 15 March, 1970; and structure on 15 March, 1970 forecast from water column on 23 August, 1969, with one-dimensional heat loss, salt gain (after Zubov 1943).

The seasonal change in a water column used in budget calculations is shown in Fig. 4. In comparison an energy balance calculation (Zubov 1943) using a climatic heat loss of 16,000 cal. cm.$^{-2}$ (Leahey 1966) is shown. The total heat from ice cooling, ice formation, and water column heat loss over the period was about 12,000 cal. cm.$^{-2}$. If this heat loss is accepted instead of the climatic loss, the calculated ice thicknesses and parameters of the under-ice layer still fail to agree with those observed.

From these calculations it is evident however that the budget of a water column is determined by the estuarial circulation as well as the upper boundary condition of ice formation. The large autumnal salt changes in 1969, and the late winter balance of heat from ice formation and heat flux upward suggest the estuarial circulation has an annual variation, being larger in the autumn than in late winter. The isothermal, isohaline layer just below the ice bottom is undoubtedly a manifestation of the efficient transfer mechanism driven by salt release from growing ice. The reason for the difference in thickness of this layer, say between spring 1969 and spring 1970 is, as noted earlier, complex.

## REFERENCES

BARBER, F. G. 1968. On the water of Tuktoyaktuk Harbour. *Canada Department of Energy, Mines and Resources, Ottawa. Marine Sciences Branch. Manuscript Report Series, 9.* 32 pp.

COLLIN, A. E. 1963. The waters of the Canadian Arctic Archipelago. *Proceedings, Arctic Basin Symposium, October 1962.* pp. 120-28.

COLLIN, A. E. and M. J. DUNBAR. 1964. *Physical oceanography in Arctic Canada. Oceanography and Marine Biology, Annual Review,* 6. London: Allen and Unwin. pp. 11-46.

CRARY, A. P. and M. GOLDSTEIN. 1957. Geophysical studies in the Arctic Ocean. *Deep Sea Research,* 4: 185-201.

FORD, W. L. and G. HATTERSLEY-SMITH. 1965. On the oceanography of the Nansen Sound Fiord System. *Arctic,* 18: 158-71.

HATTERSLEY-SMTH, G. and H. SERSON. 1966. Reconnaissance oceanography over the ice of the Nansen Sound Fiord System. *Defence Research Board of Canada, Ottawa, Directorate of Physical Research, Geophysics. Hazen,* 28. 13 pp.

KEYS, J. E. and G. H. SEIBERT. 1969. Operation Tanquary, Ellesmere Island, N.W.T. 1963-1966. *Canadian Oceanographic Data Centre, 1969 Data Record Series* No. 13, 1969. pp. 99-100.

KEYS, J., O. M. JOHANNESSON and A. LONG. 1969. The oceanography of Disraeli Fiord, northern Ellesmere Island. *Defence Research Board of Canada, Ottawa. Defence Research Telecommunications Establishment, Geophysics. Hazen,* 34. 7 pp.

LEAHEY, D. M. 1966. Heat exchange and sea ice growth in Arctic Canada. *Arctic Meteorology Research Group, Dept. of Meteorology, McGill University, Montreal. Meteorology,* 82. 48 pp.

LEWIS, E. L. 1967. Heat flow through winter ice. Physics of snow and ice. *Proceedings of the International Conference on Low Temperature Sciences, 1966.* Part 1. pp. 611-31.

LEWIS, E. L. and E. R. WALKER. 1970. The water structure under a growing sea ice sheet. *Journal of Geophysical Research,* 75: 6836-45.

MELLOR, M. 1964. Properties of snow. *CRREL Research Report 169, Hanover, New Hampshire,* 105 pp.

NESHYBA, S., V. T. NEAL and W. DENNER. 1971. Temperature and conductivity measurements under Ice Island T-3. *Journal of Geophysical Research,* 76 (33): 8107-20.

OSTENSO, N. A. 1966. Arctic Ocean. In: R. W. Fairbridge, Editor, *The Encyclopedia of Oceanography.* New York: Van Nostrand Reinhold. pp. 49-55.

PELLETIER, B. R. 1962. Submarine geology program, polar continental shelf project, Isachen, District of Franklin. *Canadian Geological Survey Paper No.* 61-21, 10 pp.

————. 1966. Canadian Arctic Archipelago and Baffin Bay. In: R. W. Fairbridge, Editor, *The Encyclopedia of Oceanography.* New York: Van Nostrand Reinhold, pp. 157-68.

SCHWERDTFEGER, P. 1963. The thermal properties of sea ice. *Journal of Glaciology,* 4: 789-807.

WORTHINGTON, L. V. 1959. Oceanographic observations in scientific studies at Fletcher's Ice Island T-3, (1952, 1955). *Geophysical Research Papers, Air Force Cambridge Research Center,* 1. pp. 31-35.

ZUBOV, N. N. 1943. *Arctic Ice.* Translated from the Russian by the U.S. Navy Oceanographic Office and the American Meteorological Society. Published by the U.S. Navy Electronics Laboratory, San Diego. 491 pp.