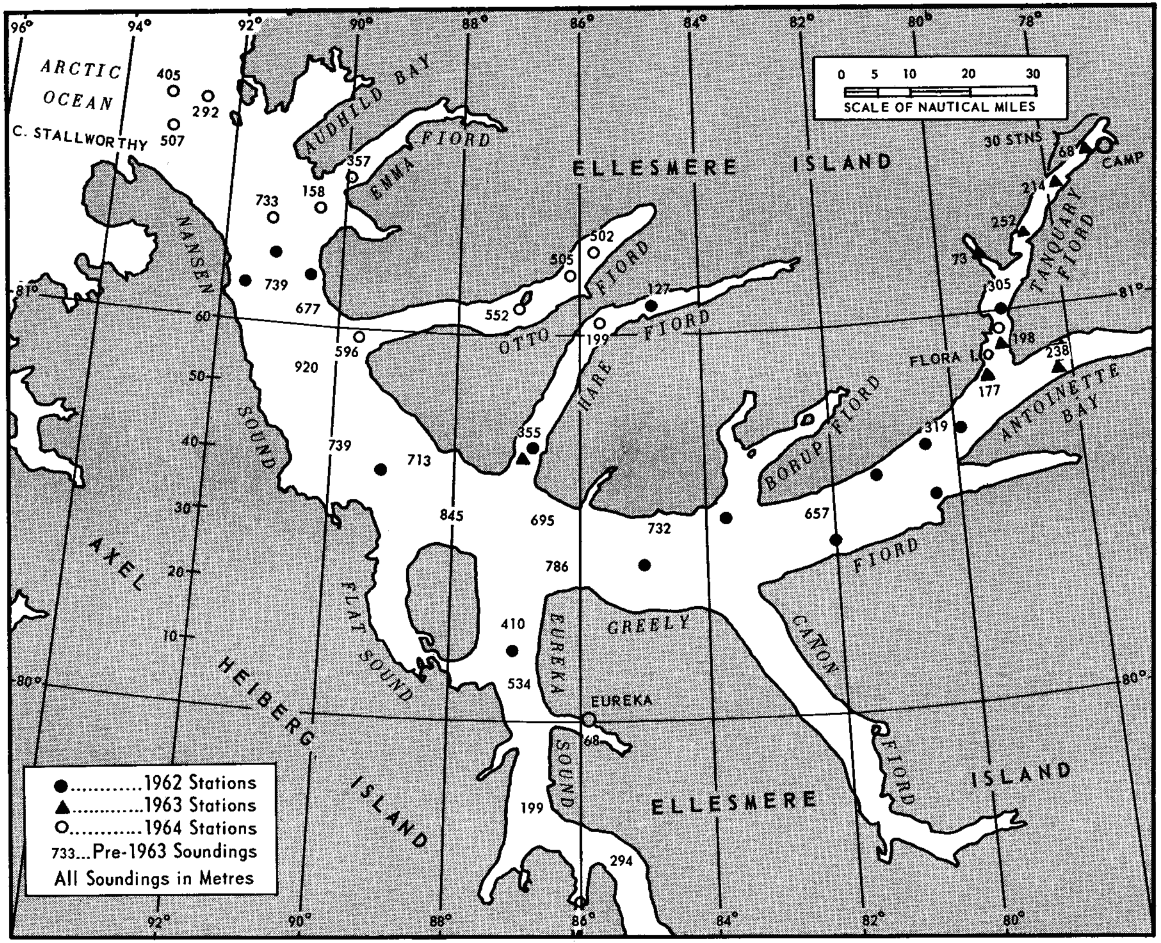

Fig. 1. Map of the Nansen Sound fiord system showing the location of oceanographic stations and representative soundings.

Papers

ON THE OCEANOGRAPHY OF THE NANSEN SOUND FIORD SYSTEM

Wm. L. Ford* and G. Hattersley-Smith†

Introduction

THE TERM Nansen Sound fiord system is used in this paper to describe that considerable body of water located for the most part above 80° N. latitude off northwest Ellesmere Island. The main stem stretching some 210 nautical miles from the Arctic Ocean is comprised of Nansen Sound, Greely Fiord and Tanquary Fiord from which nine major branches extend out from 20 to as much as 60 miles (Fig. 1). While the system may be looked upon as stemming mainly from the Arctic Ocean, it does have a second connection to the outside through the 160 mile length of Eureka Sound, the northern end of which joins Nansen Sound and Greely Fiord.

The first explorer to enter the region was J. B. Lockwood of the Lady Franklin Bay expedition (under A. W. Greely) who, in 1883, reached as far as the head of Greely Fiord from Archer Fiord on the eastern coast of Ellesmere Island. In 1901-02 the Second Norwegian expedition in the *Fram,* under Otto Sverdrup, explored much of the system from the Arctic Ocean up to and including Canon Fiord. Important work was done by W. E. Ekblaw of the MacMillan Crocker Land expedition in 1915 when he surveyed the upper reaches of Greely and discovered Borup and Tanquary fiords. The Danish Thule and Ellesmere Land expedition in 1939-40 travelled extensively in the area adding more detailed knowledge. Before World War II four other parties traversed parts of the area, but it was not until the establishment in 1947 of the joint US-Canadian weather station at Eureka, which serves as a base of operations, that the modern phase of scientific studies got under way. For a more detailed description of the area and of its history, the reader is referred to Dunbar and Greenaway (1956).

Oceanographically the region remained completely unexplored until 1952 when the icebreaker *USS Edisto,* having completed a resupply operation of the weather station at Eureka, made a penetration into Nansen Sound reaching to about 81° 10′ N. Observations were limited to soundings which indicated depths as great as 925 m. In the summer of 1962, which was an exceptionally open ice season, the *CCGS John A. Macdonald* made a reconnaissance oceanographic survey along the length of the main stem of the system from near the mouth of Nansen Sound to the head of Tanquary Fiord.

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Aside from two lines of soundings, 7 oceanographic stations (temperature and salinity) and 14 bathythermograph observations were obtained. (Oxygen determinations were made and bottom and plankton samples were taken, but are not reported in this paper.) The *Macdonald* also laid down, at the head of Tanquary Fiord, a cache of requirements for a new field station for geophysical research sponsored by the Defence Research Board. From this station a further series of oceanographic stations, 23 in 1963 and 28 in 1964, were occupied, mostly through the ice in May, June and July. Station locations are shown in Fig. 1. A data record covering all of these stations may be obtained from the Canadian Oceanographic Data Centre, Department of Mines and Technical Surveys, Ottawa.

Also during the summer of 1962 a marine biological collecting program was carried out by Black and Olson (1963), during which a station in Slidre fiord near Eureka was occupied 14 times between 2 July and 16 August. Two other stations were occupied, one in northern Nansen Sound and the other in Strand fiord, west Axel Heiberg Island, on 11 and 18 July respectively. The maximum depth of sampling was 50 m.

An account of the logistics, vehicles, oceanographic equipment and operating techniques used in the 1963 and 1964 operations is given by Hattersley-Smith and Serson (1965).

Observations and discussion

The oceanographic features of the Nansen Sound system might be expected to reflect those to be found along the Arctic Ocean coast subject to modifications resulting from sills, if any, and in the near surface layers from the considerable fresh water run-off during the melt period. The semi-continental nature of the inner regions of the system and the associated relatively high summer temperatures, as compared with the western parts of the Queen Elizabeth Islands, correlate with the more open water conditions observed and may lead to considerable surface warming in ice-free years.

The nearest oceanographic observations (Collin, 1962) typical of the outer Arctic coast extend across the mouths of Prince Gustaf Adolf Sea, Peary Channel and Sverdrup Channel, the last-mentioned, being about 100 miles southwest of Nansen Sound, is the closest to it. These stations taken in April and May 1960 reveal little variation from one to another and for the present purpose the temperature and salinity distribution with depth are well represented by the curves marked A in Fig. 2. Curves B of this figure represent the means of six stations in Nansen Sound and Greely Fiord taken in August 1962.

The curves show that below about 200 m. Nansen Sound like the outer coast is flooded with a relatively warm and saline water mass, the origin of which must be the Atlantic water intermediate layer in the Arctic Ocean (Collin, 1962; Worthington, 1959). It is not known whether there is any significance in the differences of temperature and salinity that appear in the main thermocline. Particular interest is attached to an unexpected positive

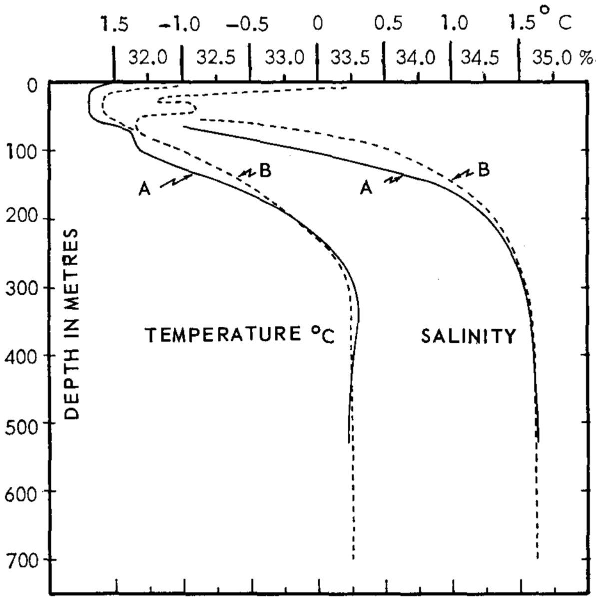


Fig. 2. Representative curves of the distribution of temperature and salinity with depth: A — along the open Arctic Ocean coast, April and May 1960; B — Nansen Sound and Greely Fiord, August 1962.

temperature inversion first observed in 1962, which is schematically indicated in Curve B at a depth of about 40 m. It was most pronounced in Tanquary Fiord, diminishing seaward to disappear in Nansen Sound (Fig. 3). The field work of 1963 and 1964 provided valuable data on the history of this unusual feature, as well as adding significantly to the meagre knowledge of the system generally.

While the maximum depth so far observed in Nansen Sound is about 925 m., there is evidence that it shoals at the mouth probably to the depth of the continental shelf. The virtually isothermal and isohaline structure (see Fig. 2) below about 300 m. is indicative of a sill at or below this depth. This is supported by a sounding of 507 m. obtained about 6 miles northwest of Cape Stallworthy by the Defence Research Board party in 1964. Collin (1962) reports depths of 400 to 600 m. for the polar continental shelf to the southwest of Nansen Sound. In 1955 Ice Island T3 drifted over and along the shelf some 60 to 70 miles north of the mouth of Nansen Sound. Here Crary and Goldstein (1957) noted depths varying between 430 and 500 m. Although it remains to be determined whether or not there is a submarine valley representing an extension of Nansen Sound across the shelf, the oceanographic features of the deep waters of the sound do not indicate that such a valley, if it exists, is comparable in size to the sound itself. If this were the case one might expect to see reflected within the sound in some degree the characteristic structure of the Arctic Ocean at the edge of the shelf (Collin 1962; Worthington 1959), with its pronounced Atlantic warm layer (temperature >0.4°C at 400 to 500 m. and negative temperature gradient below). This structure was not observed.

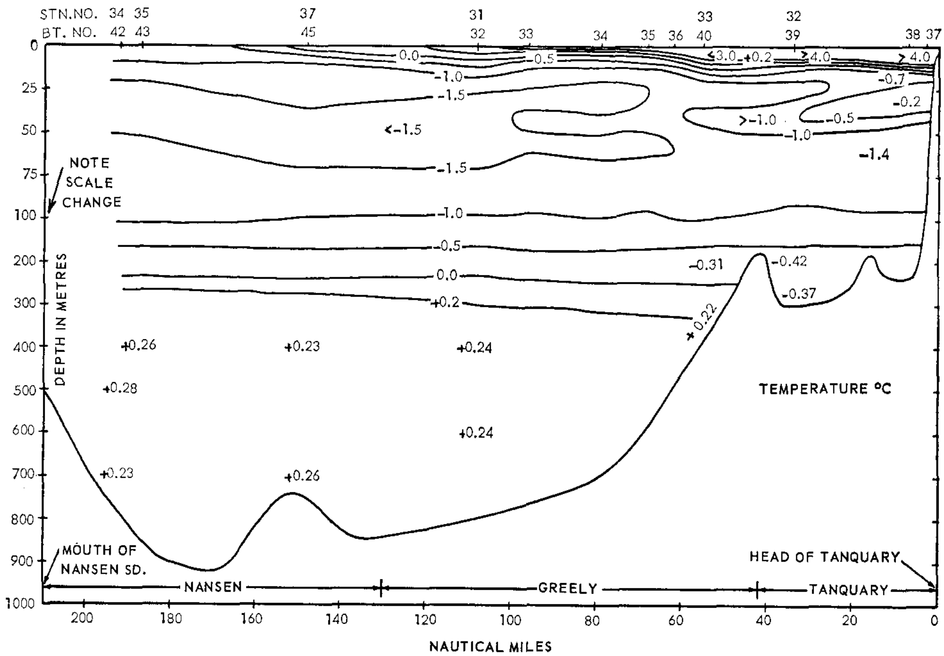


Fig. 3. Profile of the temperature distribution from the mouth of Nansen Sound to the head of Tanquary Fiord, August 1962.

Some other features of the bathymetry of the system are schematically represented in Fig. 3, based upon the limited soundings taken in 1962. Inward from the deep basin in Nansen Sound the available soundings suggest at least one deep basin of 845 m. and a steep rise to 175 m. at the sill of Tanquary Fiord. Within this fiord, which was surveyed in somewhat more detail, the depth increases again to a maximum of about 300 m. and the bathymetry takes on a more complex appearance as the water shoals towards the head. The sill depth of 175 m. is deduced from the fact that the temperature of the water in the fiord below this depth was observed to be isothermal at −0.4°C, and isohaline at 34.35‰. The maximum sill depth observed by the ship was 128 m. but only two passes were made over the sill. The bathymetry of the system is reported not only in more detail but also in terms of the geology and glaciology of the region by Hattersley-Smith and Serson (1965).

Returning to a closer look at the oceanographic features of the system as observed in August 1962 (see Fig. 3 and 4) special note is made of the unusually open conditions. Indeed Greely and Tanquary fiords were virtually ice free throughout. The estuarine features fed by rivers in Tanquary Fiord were well developed with a low salinity, warm surface layer (>2°C.) extending at least 80 miles seaward from the head of the fiord. On the other hand the deeper waters of the fiord, between about 75 m. and the sill depth of 175 m. reflected quite precisely both the temperature and salinity structures in the corresponding depths to seaward. The outstanding and unexpected feature was the layer of relatively warm water lying between depths of 25 and 50 m. The core of the layer which had a maximum temperature of —0.2°C. at the head of the fiord was traced for about 100 miles downstream where the positive temperature inversion disappeared. It is of particular interest to note first that the warm layer was within the salinity range 30.8 to 32.5‰ (Fig. 6), that is, within the characteristic strong halocline of polar waters; second that it was remarkably persistent having survived, if in reduced strength, over at least two years (compare Figs. 3 and 5, also curves A, B and C in Fig. 6). Since the temperature coefficient of density of sea water is almost zero in the temperature range involved, the inversion would have no significant effect on the considerable stability of the halocline, and because of this stability it would tend to be relatively unaffected by mixing activity from above or below. The distributions of temperature and salinity in Figs. 3 and 4 respectively are indicative of a degree of isolation of the warm layer from the advective processes of the near surface waters. The surface layer with temperatures in excess of 4°C. and salinities less than 15‰ near the head of the fiord, fed by rivers, must flow seaward. As in all such estuaries there must also be a return flow of more saline water. The return flow does not appear to involve the warm inversion layer to any great extent because first the increase in temperature in the latter from seaward towards the head of the fiord is inconsistent with an inward flow at that depth; second, the inward pointing cold tongue at about 20 m. suggests that this is the location of the return flow. Quite independent evidence of the degree of isolation of the warm layer from mixing is its remarkable persistence mentioned above.

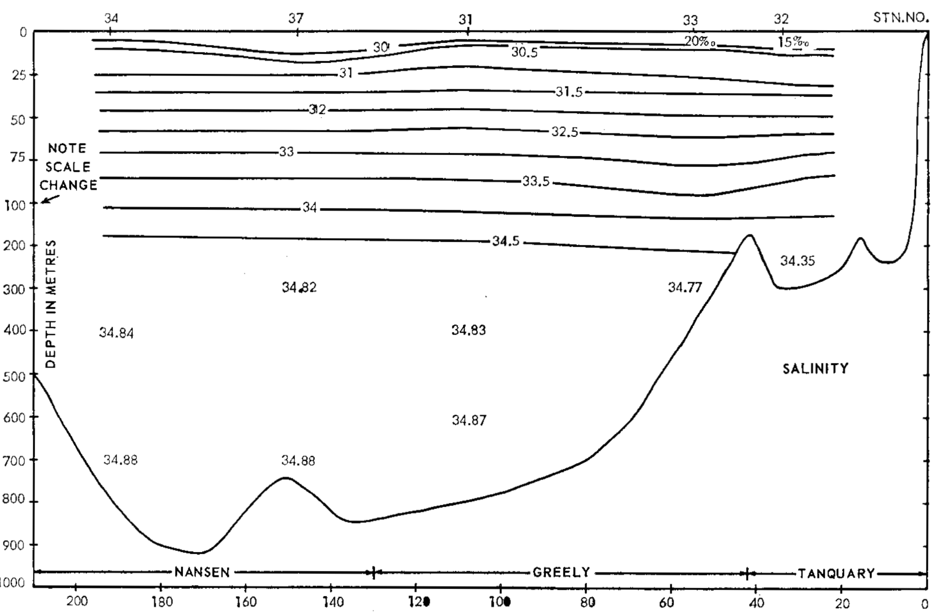


Fig. 4. Profile of the salinity distribution from the mouth of Nansen Sound to the head of Tanquary Fiord, August 1962.

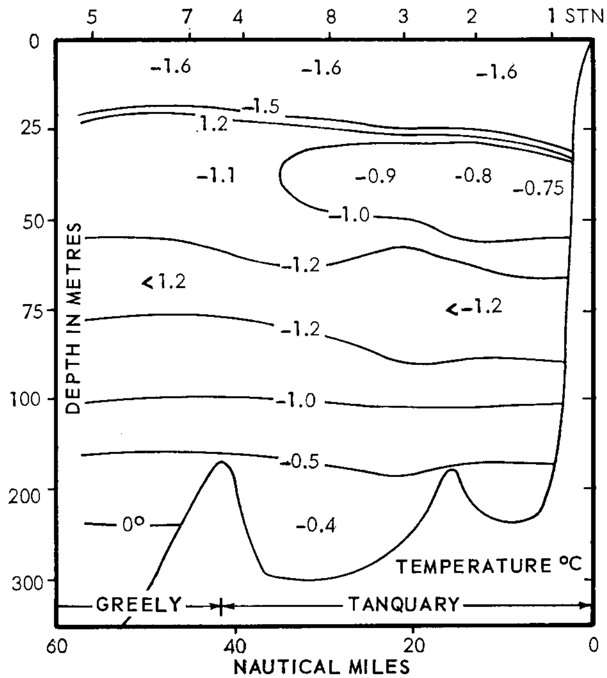


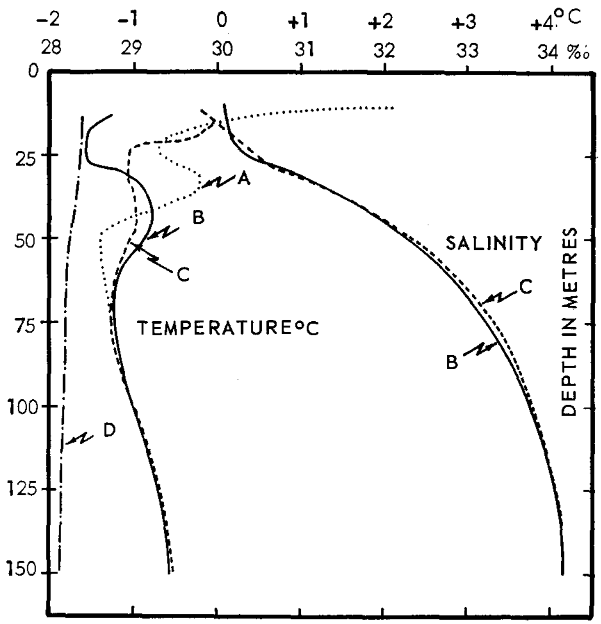
Fig. 5. Profile of the temperature distribution in Tanquary Fiord, 26 May to 9 June 1963.

From Fig. 6 it is also seen that throughout nearly all the periods of the observations, the waters of Tanquary Fiord were substantially above the freezing point, represented by Curve D. The exception occurs in the top 25 or 30 m. where a mixed layer at or near the freezing point was observed early in the 1963 season (Fig. 5); the remnants of this effect are reflected in Curve B of Fig. 6. Below 75 m. the positive temperature gradient closely follows the pattern observed in the Arctic Ocean, (see Curve A, Fig. 2) which is attributed to the presence of the Atlantic layer. Indeed the depths of the Nansen Sound system are filled with relatively warm water at +0.25°C. as is illustrated in Fig. 3. In other words below about 75 m. the reserve of heat has its origin in the Atlantic Ocean. On the other hand the reserve of heat in the upper 75 m. of Tanquary Fiord is in marked contrast with the corresponding zone in the lower reaches of Nansen Sound or in the open polar ocean which are characterized by a permanent frigid layer at or near the freezing point. This latter layer is represented in Curve A of Fig. 2 and in Fig. 3 by temperatures of <—1.5°C. Thus the heat trapped in the upper zone is considered to be a local effect. It is reasonable to apply the same conclusion to the heat trapping observed in two other fiords, Hare and Strand (see Figs. 7 and 8).

The upper end of Tanquary Fiord is the area of the system which has been most intensively observed and the results of three seasons work therein, summarized in Fig. 6, permit an assessment of the temporal changes from one year to the next. The temperature distribution below 75 m. remained remarkably unchanged over the 3 years as did that of the salinity below 25 m. (2 years' data). In fact the salinity distribution below 25 m. observed in 1962 near the mouth of the fiord is virtually identical to that given in Fig. 6 for 1963 and 1964 for the head of the fiord.

The change in the temperature distribution in the zone of the positive inversion, 25 to 75 m., suggests that the warm layer, having developed prior to the first observation of it in August 1962 underwent a slow decay by mixing with more active layers above and below in such a manner as to leave the salinity distribution unchanged. Observing that in the summer of 1962 the region was virtually free of ice, while in 1963 and 1964 the ice cover retreated only briefly from the upper reaches of the fiord, it might appear that the warm layer originated in the open season of 1962 and received no replenishment in the following 2 years. However, later in the paper the origin of the heat trapping represented by the layer is discussed in terms of the penetration of solar radiation from which it is seen that there is some possibility of replenishment in the presence of an ice cover. Accordingly no attempt is made to estimate the rate of diffusion in the layer on the basis of the temperature anomaly.

Another interesting feature of the data represented in Fig. 6 is the trend from 1963 to 1964 towards increased stability in the water column



Curve A: 23 August 1962, comprises 2 BT stations in good agreement with one another; Curves B: the means of data from 15 stations occupied between 27 June and 18 August 1963; Curves C: the means of data from 13 stations occupied between 29 June and 18 August 1964 (in each year the salinity curve is representative of the data within 0.1‰ and the temperature curve below 20 m. within 0.1°C.); Curve D: freezing point of water of corresponding salinity.

Fig. 6. Comparison over 3 years of the temperature distribution with depth and over 2 years of the salinity in the upper 8 miles of Tanquary Fiord. (Omitted from this figure are data for depths shallower than 10 m. since they exhibit wide fluctuations both in the time and place.)

above 25 m. as evidenced by the change in the salinity gradient (compare Curves B and C). While not fully shown in Curve B the salinity gradient in 1963 tended to be isohaline from the near surface to about 25 m., while in 1964 the isohaline feature was absent. This suggests that superimposed on the annual cycle of events there are significant changes in stability of the near surface water column involving a time cycle of more than 2 years, which may be related to the persistence or otherwise of the ice cover. These observations are a further indication of the need for long term time-series studies in the seasonally active zone which are notably few in the literature of arctic oceanography.

By what mechanism could heat be trapped and held in a layer lying 30 to 50 m. below the surface? As previously implied there is no evidence that it could have come from seaward of Tanquary Fiord by advective flow. Nor does downward mixing of a warm surface layer offer an acceptable hypothesis. Such a surface layer existed in the fiord in 1962 and 1963 with temperatures as high as 4°C, but with salinities between 1.5 and 15‰. The resulting very strong density gradient is not conducive to mixing and, if mixing did take place, the salinity range of the warm layer should have been markedly lower than was observed. The latter was not significantly different from that found at similar depths throughout the Nansen Sound system (see Fig. 4). Nutt (1963) reports on the presence in late winter of a small warm wedge at a depth of 4 to 5 m. through the main body of Lake Melville in the Hamilton Inlet-Lake Melville estuary. His data show that it was a remnant of the strong seasonal thermocline developed in the preceding summer and that it was preserved by the stratification due to the strong halocline which persists throughout the year and inhibits vertical mixing. While the two examples of heat trapping both owe their survival to the presence of a strong halocline, they must differ in origin since, as has been shown, the Tanquary Fiord layer could not be a remnant of a seasonal thermocline.

Direct *in situ* heating by solar radiation may be the explanation if what appear to be unlikely values of two parameters are in fact valid. The parameters in question are the radiation absorption coefficient of the sea water and the fraction of the radiation incident on the ice surface which reaches the water. The amount of energy reaching any depth is sensitively dependent upon the values of these factors in accordance with Beer's Law $\frac{Qz}{Qo} = \alpha z$ where Qo is the radiation penetrating the surface, Qz is that reaching the depth z and α is the absorption coefficient.

Consider first an ice free situation in mid-summer during which an average of 600 ly/day is a reasonable estimate of the incident radiation in Tanquary Fiord (Barry 1964). It is assumed that one-half of this penetrates the surface to give a Qo=300 ly/day. In Table 1A the heat input at the 30 and 40 m. levels and the resulting average temperature increase for this layer are given for three values of α. α=0.2 is the coastal seas minimum from Sverdrup (1942), α=0.12 is the value observed by Shirtcliffe and Benseman (1964) for the highly saline Lake Bonney in Antarctica and α=0.07 the value observed by Wilson and Wellman (1962) for the saline

Table 1A. Theoretical radiation heating in the 30-40 metre layer. Ice free, Qo=300 ly/day.

α	Q_{30}	Q_{40}	ΔT* °C/day	No. of days for $\Delta T = +0.5°$
0.2	0.74	0.10	0.0006	800
0.12	8.2	2.5	0.0057	90
0.07	37.0	18.4	0.0186	27

Table 1B. Theoretical radiation heating in the 30-40 m. layer. 2 m. ice cover, Qi=400 ly/day.

α	Percent Qi to reach water	Q_{30} ly/day	Q_{40} ly/day	ΔT* °C day	No. of days for $\Delta T = +0.5°$
0.12	15	1.6	0.5	0.0011	450
0.12	1.5	0.16	0.05	0.0001	5000
0.07	15	7.3	3.7	0.0036	140
0.07	6	2.9	1.5	0.0014	360

Table 1C. Theoretical radiation heating in the 5-10 metre layer. 2 metre ice cover, Qi=400 ly/day.

α	Percent Qi to reach water	Q_5 ly/day	Q_{10} ly/day	ΔT* C/day	No. of days for $\Delta T = +1.5C$
0.30	15	13	3	0.020	75
0.20	15	22	8	0.028	54
0.16	15	27	12	0.030	50
0.12	15	33	19	0.028	54
0.12	1.5	3.3	1.9	0.0028	540
0.07	15	42	30	0.024	63
0.07	6	17	12	0.010	150

*ΔT is the average temperature rise per day due to the absorption of radiation as heat in the layer assuming no heat loss. This assumption is reasonable if there is no advection or mixing since heat loss by conduction or re-radiation is negligible for the time scales being considered.

Lake Vanda, also in Antarctica. (Incidentally, while these two lakes provide striking examples of solar heat trapping under polar climatic conditions, the aforementioned authors' elegant analytical explanation of the observed temperature distribution is not considered applicable to Tanquary Fiord. The stability of the water column is certainly not high enough to limit heat transfer to the thermal conduction mode as in these lakes). The range of values of the absorption coefficient used herein corresponds with that reported for the Beaufort Sea and adjacent waters in summer. There Secchi disc readings varied from 5 to 21 m. which, using the conversion factor $\alpha = \frac{1.7}{D}$, give values of α from 0.3 to 0.08. Given α=0.07, that is a clarity equivalent to the clearest of open ocean waters, and assuming that the layer of interest is not subject to any appreciable advection or mixing, it would appear that the positive temperature inversion observed in Tanquary Fiord in 1962 could have been produced by the direct absorption of solar radiation in about one month in the absence of an ice cover. However, the absence of ice strongly suggests rather warm weather and hence a considerable sediment laden run-off in the local glacially-fed rivers. Silt laden water has been repeatedly observed off the mouth of the river at the head of the fiord. Under these circumstances values of the absorption coefficient α as low as 0.07 or even 0.12 seem unlikely.

Estimates are given in Table 1B of the theoretical radiation heating in the 30 to 40 m. layer under an ice cover. In this case an average value of 400 ly/day for the radiation incident on the surface is taken as representative of the period April through September. In the absence of any direct measurements, the amount of this energy to penetrate the ice cover is variously taken at 1.5, 6 and 15 per cent. The first two values are from Shirtcliffe (1964) and Wilson (1962) respectively, whose observations were made under about 3.5 m. of old rough ice. The 15 per cent estimate may not be unreasonable for the 2 m. of winter ice found in Tanquary Fiord. Using this value and the very low absorption coefficient of 0.07, it would take about 5 months for enough heat to be trapped in the 30 to 40 m. layer to account for the observed warming.

If strongly stratified conditions, free from advection, occur in shallower depths of the water column, the rate of temperature rise therein could be markedly greater since more of the available radiant energy would be absorbed in the near surface layers. Evidence for this was found at the two stations occupied in Hare Fiord in 1964, where a positive temperature anomaly of 1.5°C. and a pronounced salinity gradient were observed in the 5 to 10 m. zone under a 1.4 to 2.0 m. ice cover (Fig. 7). The estimates given in Table 1C indicate that this temperature anomaly could have been produced

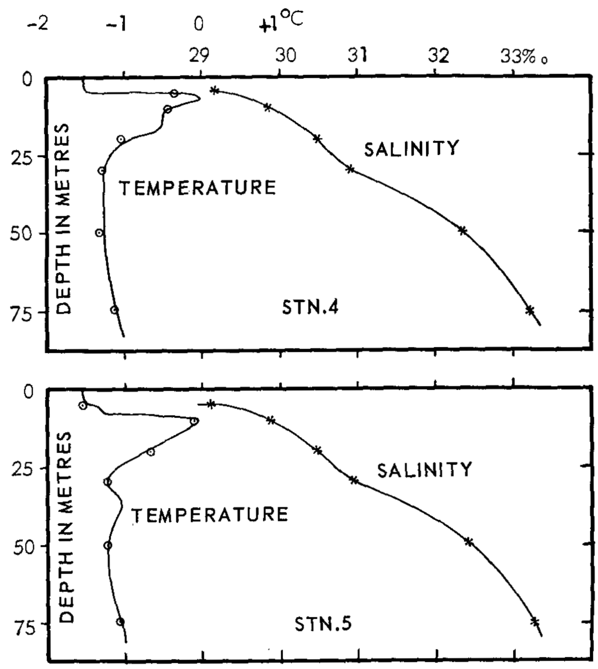


Fig. 7. Temperature and salinity distribution with depth at two stations in the middle part of Hare Fiord, 21 May 1964. Circled points, temperatures from reversing thermometers; continuous temperature trace from bathythermograms. Ice thickness 2.0 m. at station 4, 1.4 m. at station 5.

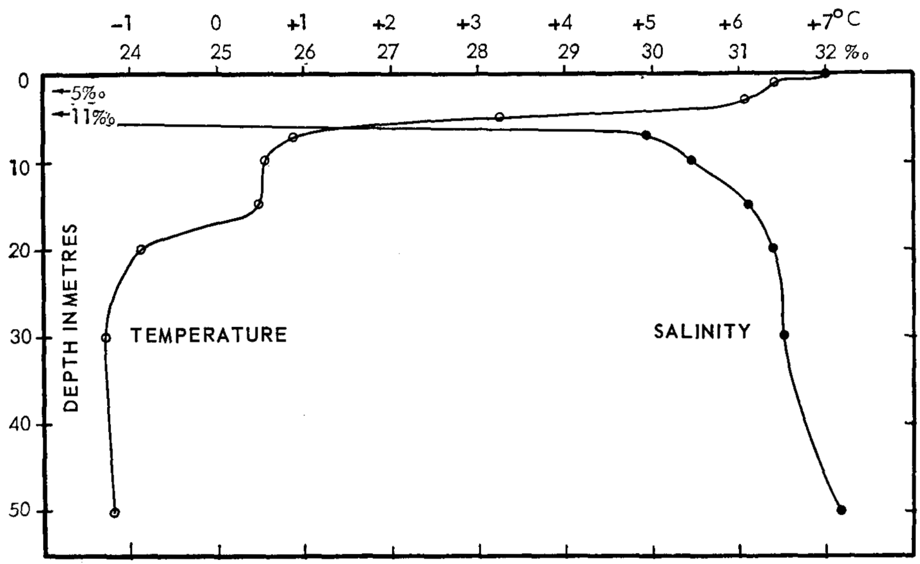


Fig. 8. Temperature and salinity distribution with depth at a station in Strand Fiord, west coast of Alex Heiberg Island, lat. 79° 10′N., long. 92° 00′W., 18 July 1962.

in a period of one to two months, provided that about 15 per cent of the incident radiation penetrated the ice cover and the other conditions specified existed. Incidentally, a wider range of values of the absorption coefficient, α, is used in this table to bring out the point that the radiation heating is much less sensitive to these values than is the case in deeper layers.

It is interesting to note that at the 3 stations occupied in Otto Fiord the water column was nearly isothermal at -1.5°C. to a depth of 100 m. in marked contrast to structure observed at the same time in Hare Fiord (Fig. 7). On the other hand the salinity structures of the two fiords were essentially the same. It may be significant in this context that Otto Fiord contains the only known large floating ice tongue in the system which it is estimated may draw 200 to 300 m. of water.

The temperature and salinity distribution with depth observed by Black and Olsen (1963) in Strand Fiord in July 1962 (Fig. 8) strongly suggests that this is another example of solar heat trapping. The 10 to 15 m. layer with its temperature of $+0.5°$ accompanied by a salinity of about 31‰ is some 1.5° to 2° warmer than would be expected in polar waters, as for example in the nearby Arctic Ocean. It is evident from the extreme density gradient in the water column that the heat in this layer could not be derived by downward mixing from the unusually warm surface layer. On the other hand it is reasonable that conditions for exceptionally effective solar heating that prevailed in 1962 not only would account for the extraordinary surface temperature of 7°C, but also for the warming at 10 to 15 m.

It is evident that in order to determine with certainty the role of solar radiation in the occurrence of the near surface warm layers, future studies must include *in situ* measurements of the penetration of radiant energy.

Summary

The deeper waters of the Nansen Sound system, below about 75 m. exhibit a temperature and salinity profile closely reflecting their polar ocean source modified only by the effects imposed by sills. Towards the head of the system in Tanquary Fiord the polar layer within the upper 75 m. zone is seen to be modified by progressive warming but without any significant change in its characteristic salinity gradient. A similar pattern is to be expected in other branches of the system unless some perturbing factor such as an actively calving glacier is present.

Theoretical evidence has been presented which indicates that the heat trapping observed may be explained by the direct absorption of solar radiation in the layers concerned if certain rather stringent conditions governing heat loss and gain are met. They are as follows:

(a) a very stable water column, i.e., virtually no vertical mixing;
(b) very little advection, i.e., almost no horizontal transport;
(c) values of the radiation absorption coefficients of the ice cover and the water which are low enough to bring the heating time within reasonable bounds.

The resulting temperature distribution is largely determined by the balance between the heat loss factors represented by (a) and (b) and the heat gain factors involved in (c).

The stable, static conditions necessary for heat trapping may reasonably be expected to occur in fiords remote from the mass transport effects of the open ocean or connecting passages. Evidence has been presented that suggests the estuarine circulation developed by the summer run-off of melt water is confined in near surface layers and is well isolated from the zone of heat trapping below by a strong density gradient which effectively inhibits vertical mixing.

Future field studies of the heat trapping phenomenon require *in situ* measurements of the penetration of radiant energy if quantitive and predictive assessments are to be made. Also required are long time-series observations on factors affecting the stability of the water column in the active zone, principally within the top 30 m. The evidence to date suggests that superimposed on the annual cycle of events there are significant changes in stability, involving a time cycle of perhaps several years, which may be related to the persistence or otherwise of the ice cover.

Acknowledgements

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