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Seasonal Variations in Currents and Water Properties in Northwestern Baffin Bay, 1978-1979

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ABSTRACT. Year-long records of current speed and direction, temperature and conductivity were obtained from five current meter moorings in northwestern Baffin Bay. Significant seasonal changes in all these parameters were found, which closely followed the seasonal cycle of sea-ice cover. A general winter weakening of the near-surface currents (by a factor of 2 or more) was observed. Deeper currents exhibited a smaller decrease, resulting in a general decrease in baroclinicity during the winter. An exceptional case was observed off the north coast of Bylot Island, where the deep currents reversed.

An increase in salinity combined with freezing temperatures was observed in the upper part of the water column during the winter. At some sites this uniform layer appeared to deepen at a steady rate of approximately 40-50 m per month, to a maximum depth between 200 and 250 m. It was not possible, however, to distinguish between the effects of local convection and horizontal advection in deepening the layer.

Key words: current, seasonal variation, temperature, salinity, Arctic, Lancaster Sound, Baffin Bay

RÉSUMÉ. Cinq compteurs de courants, mouillés au nord-ouest de la baie de Baffin, ont permis d'obtenir à l'année longue des relevés de la vitesse et la direction des courants ainsi que de la température et de la conductivité. Des variations saisonnières significatives, étroitement reliées aux cycles saisonniers du couvert de la glace marine, ont été observées pour chacune de ces variables. En hiver, un ralentissement (par un facteur de 2 ou plus) de la vitesse des courants fut observé. Les courants plus profonds ont montré une baisse moins accentuée, entraînant tout de même une baisse générale de la baroclinicité durant l'hiver. Un cas exceptionnel a été observé au large de l'île Bylot, où les courants firent une renverse.

Durant l'hiver, nous avons observé une augmentation de la salinité, ainsi que des températures sous le point de congélation dans la partie supérieure des échantillons d'eau. A certains endroits, cette couche uniforme semble descendre jusqu'à une profondeur maximum de 200 à 250 m, et ce à un taux régulier d'environ 40-50 m par mois. Il a par contre été impossible de distinguer les effets de la convection locale et de l'advection horizontale dans l'approfondissement de la couche.

Traduit par Pierre Bibeau, Arkéos Inc., Montréal.

INTRODUCTION

In 1978 and 1979 a major physical oceanographic study of western Baffin Bay and Lancaster Sound was undertaken as part of the Eastern Arctic Marine Environmental Studies (EAMES) project (Fissel *et al.*, 1982). During the course of the project, subsurface current meter moorings were maintained at four locations for one year, and at a fifth location for 10 months.

Winter measurements of any sort, and particularly direct current measurements, have been rare in the Arctic Archipelago and Baffin Bay. As Muench (1971) pointed out, knowledge of the seasonal variations in the circulation of the area is vital to a proper understanding of its oceanography. Without winter measurements such an understanding is not possible. Although they by no means constituted a comprehensive experiment, the data from our winter moorings provided the first direct simultaneous measurements of winter currents and water properties in Lancaster Sound. As such, they provide an initial estimate of the seasonal changes in the circulation of the region.

METHODS

The locations of the moorings are shown in Figure 1. The sites (as well as two others from which the instruments were not recovered) were chosen to monitor the evolution of the major summer circulation features (described by Fissel *et al.*, 1982). Stations 1 and 2 (Fig. 1) were both located to the east of Devon Island in the Baffin Current, prior to its entering eastern Lancaster Sound. Station 8a was located within the current flowing out of eastern Lancaster Sound, which arises from a combination of the intruding Baffin Current and outflows from western Lancaster Sound. Station 10 was located in an area of generally weak westerly flows beyond the eastern edge of the current where it enters Lancaster Sound. Station 13 was placed in the Baffin Current, further south along the Baffin Island coast. Because of the high risk of operating current meter moorings throughout the extended arctic winter, the number of measurement sites was necessarily limited. As a result the spatial resolution of the winter data was reduced in comparison with the data obtained in the summer programs.

The moorings carried three or four Aanderaa RCM-4 current meters each, with each meter recording hourly values of temperature, conductivity, pressure, current speed and direction. Complete data sets were not recovered from all the meters, however. Table 1 lists the data recovered from each depth at each mooring.

Manufacturer's specifications for the RCM-4 gave the temperature accuracy as ±0.15°C. The accuracy of the conductivity cell was not provided. A comparison of laboratory calibration data obtained before and after the sum-

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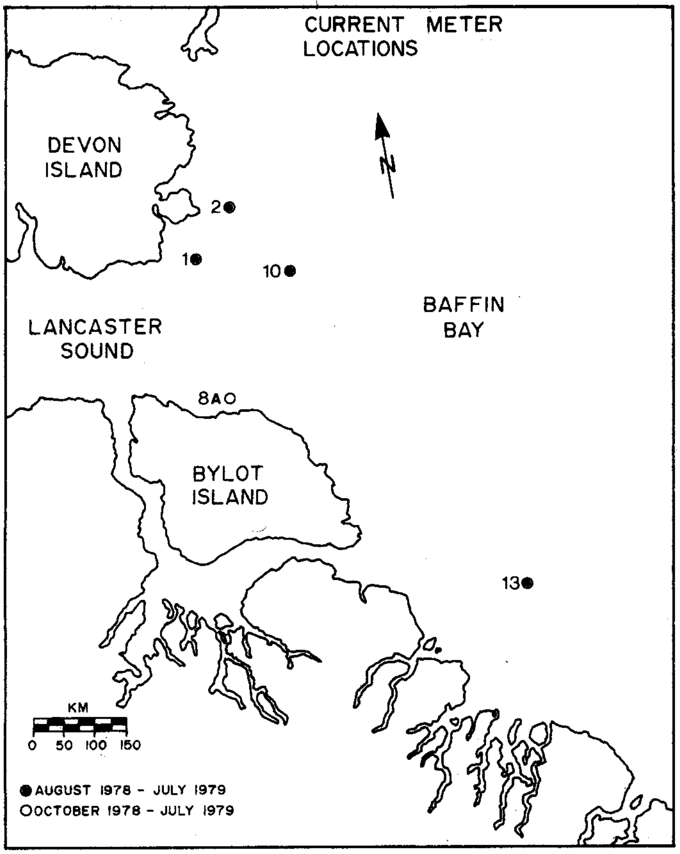


FIG. 1. Location of 1978-1979 current meter moorings.

mer 1978 field program suggested that the conductivity measurements were reliable to 0.11 mmho/cm or better in 14 out of 15 cases (Fissel and Wilton, 1980). Using these figures, the combined uncertainty in single salinity measurements amounts to 0.2‰.

When average readings are considered, the accuracy may be estimated by σ_M, the standard error in the mean of N readings, which is given by

$$\sigma_M = \sigma/\sqrt{N}$$

where σ is the error in a single measurement. In the case of monthly averages, $N = 730$; therefore the standard error in the monthly mean for salinity is 0.01‰ and for temperature is 0.01°C. Barring any systematic drifts in the conductivity sensors, changes in the monthly means of 0.02‰ and 0.01°C or greater are statistically significant at the 1% level. (It has been assumed that the means are normally distributed, and the standard form of hypothesis test has been used (Meyer, 1965).)

RESULTS

Seasonal Current Variations

The time series from each meter were divided into monthly intervals for which the vector-averaged mean currents were computed (Fig. 2). Seasonal variations are evident in the monthly mean currents at every mooring location at some or all depths. Maximum current values were measured from August to October, inclusive, while minimum currents generally occurred from February to May, inclusive. These seasonal changes in circulation appear to reflect changes in ice cover with the maximum mean current coinciding with minimum ice cover (August to October) and the minimum mean current occurring prior to local ice breakup. At stations 1, 2, 8a and 10, considerable amounts of open water appeared in June and July, 1979, and the mean current velocity increased. At station 13, the ice cover persisted until the end of July and a corresponding extension in the duration of the minimal monthly current occurred (February to July, inclusive).

TABLE 1. Data recovered from subsurface current meter moorings

Summer 1978

Station	Nominal Depth (m)	Periods of Missing or Erroneous Data
1	35	
	250	
	400	
2	35	No speed data for 2-3 Sept. & after 9 Sept.
	125	
	250	
10	35	No speed data for 23-25 Sept.
	250	
	500	
13	35	
	250	
	500	
	750	No speed data.

Winter 1978-1979

Station	Nominal Depth (m)	Periods of Missing or Erroneous Data
1	35	No speed data from 27 Sept.
	250	
	400	
2	35	Timing off - 3 records gained.
	125	
	250	
8a	35	Timing off - 2 records gained.
	250	
	500	
10	35	Less than 3 days of data; timing may be completely off.
	250	
	500	No speed data from 6-12 Oct., inclusive.
13	35	Timing off - gained 2 records.
	250	
	500	No speed data from 23-27 Oct., inclusive; pressure sensor not used.
	750	No speed data for first 11 hourly readings.

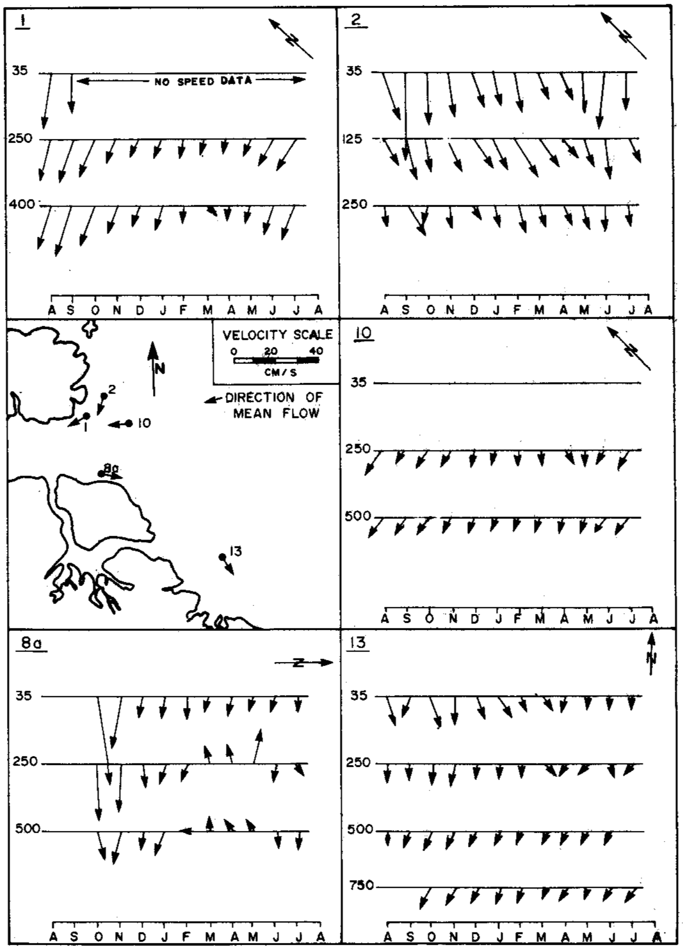


FIG. 2. Monthly vector-averaged current velocities from August 1978 to July 1979. The orientation of the vectors is indicated by the true north arrow in each plot. Depths at left of each line are in meters.

Despite the decreased amplitude of the currents in the winter months, the overall circulation pattern apparently remained much the same as for the summer months. The southerly to southwesterly flow along Devon Island at stations 1 and 2, the westerly flow at station 10, and the southerly flow off Baffin Island at station 13 were evident in both seasons. Only in the deeper current data at station 8a was a marked change in the pattern observed; here the currents at 250 m and 500 m reversed to westerly in the months of March, April and May, while at 35 m they remained generally easterly with reduced strength.

Pronounced seasonal variations were apparent in all current meter time series data obtained at nominal depths of 35 m (three stations). At greater nominal depths of 250 m and 400-500 m, the presence of seasonal variations in the circulation varied according to location. At stations 1 and 8a, very marked seasonal variations occurred in the currents at depths of 250 m and 400 m (station 1) or 500 m (station 8a). Mean monthly velocities at station 1 declined during the months from February to May to less than one-third of their summer magnitudes. The mean monthly velocities at station 8a reversed during the months of March to May with respect to the net flow in the summer months. The seasonal variations in the deeper currents at stations 10 and 13 were less pronounced, although the generally weaker currents as measured in summer were further reduced in winter to approximately one-half of their summer levels. No significant seasonal variations were apparent at 250 m depth at station 2, even though they were apparent both at 35 m and, with a reduced amplitude, at 125 m. While variations in the monthly mean velocities did occur at 250 m at station 2, they appeared to have periods shorter than one year. The causes of these differences in the amplitude of seasonal variations among the various mooring locations are not fully understood. They may be related to differences in the local circulation patterns or the degree of vertical stratification present at each site as discussed below.

With the exception of station 8a (and station 1, which lacks 35 m data) the averaged vertical shear present in the records decreased in the winter. This effect was particularly noticeable at stations 2 and 13 where the flow became more nearly uniform with depth in the winter.

Along with the decrease in the monthly mean velocities during periods of extensive ice cover, the level of variability at synoptic frequencies appeared to decrease as well. As an example, the low-passed currents at station 2 are presented in Figure 3. (The tidal-elimination filter $A_{24}A_{24}A_{25}$ (Godin, 1972), which passes half the amplitude at a period of three days, was used.) At all depths the synoptic variations in amplitude and direction were somewhat lower in winter than in summer. However, while they were reduced, synoptic variations did persist through periods of seasonal ice cover.

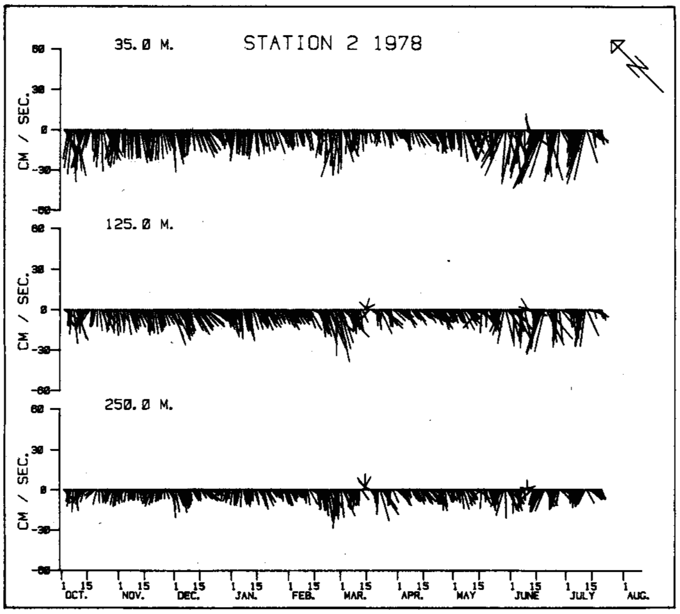


FIG. 3. Current at station 2 after low-pass filtering to remove 2-day and shorter period variations.

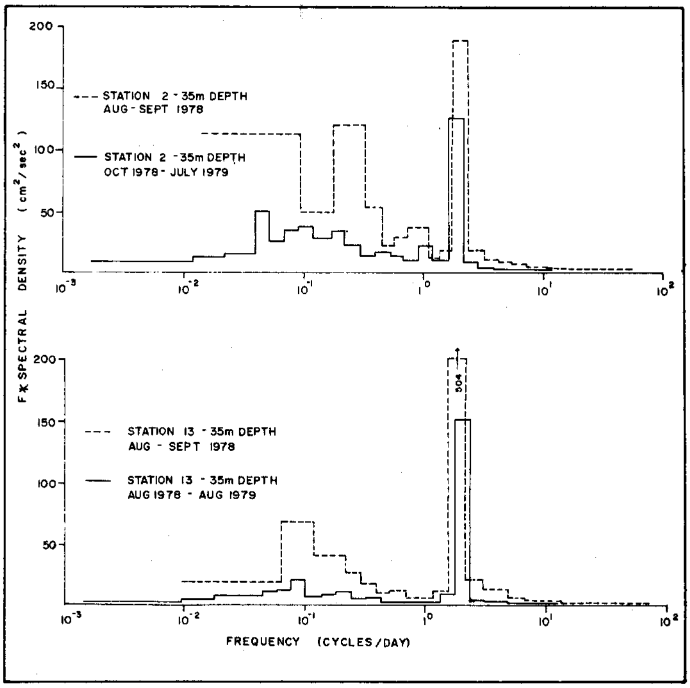


FIG. 4. Kinetic energy spectra of currents at:
(a) Station 2, 35 m depth*
(b) Station 13, 35 m depth
* missing data (See Table 1) precludes use of full-year record.

The change in the level of synoptic variations may be seen more clearly in the auto-spectra of the currents for the summer and winter periods. Figure 4 shows the spectra of the 35 m currents at stations 2 and 13. The spectral values are band-averaged, kinetic energy spectral densities, presented as the sum of the spectral density of each current component. The degree of band-averaging is variable, increasing from a minimum of three at the lower frequency extreme (standard error of 58%) to in excess of one hundred (standard error of 10% or less) at the higher frequencies. The spectra are plotted with frequency-times-spectral density as the ordinate and the logarithm of the frequency as the abscissa.

Significant changes in the spectral levels appeared to occur with the seasons, possibly related to the seasonal variations in ice cover. The spectral levels were higher in the generally open-water period (August to September) than in the largely ice-covered period (October to July) for the same measurement sites. These seasonal changes were observed in both the synoptic band and the semi-diurnal band. The seasonal change in the latter can be largely attributed to the reduction of wind-generated inertial oscillations during periods of ice cover (Fissel, 1982).

Temperature and Salinity Variations

Figure 5 shows the monthly average temperature records from each current meter. A strong seasonal signal is visible in the nominal 35 m temperature records. At all four locations from which 35 m temperatures were obtained (stations 1, 2, 8a and 13), the monthly mean temperatures declined from peak summer values of 0.4 to −1.0°C to temperatures near the freezing point of seawater (−1.8°C) from October through May. The corresponding plots of monthly average salinities are shown in Figure 6. Large variations of a seasonal character are apparent at 35 m depths here as well.

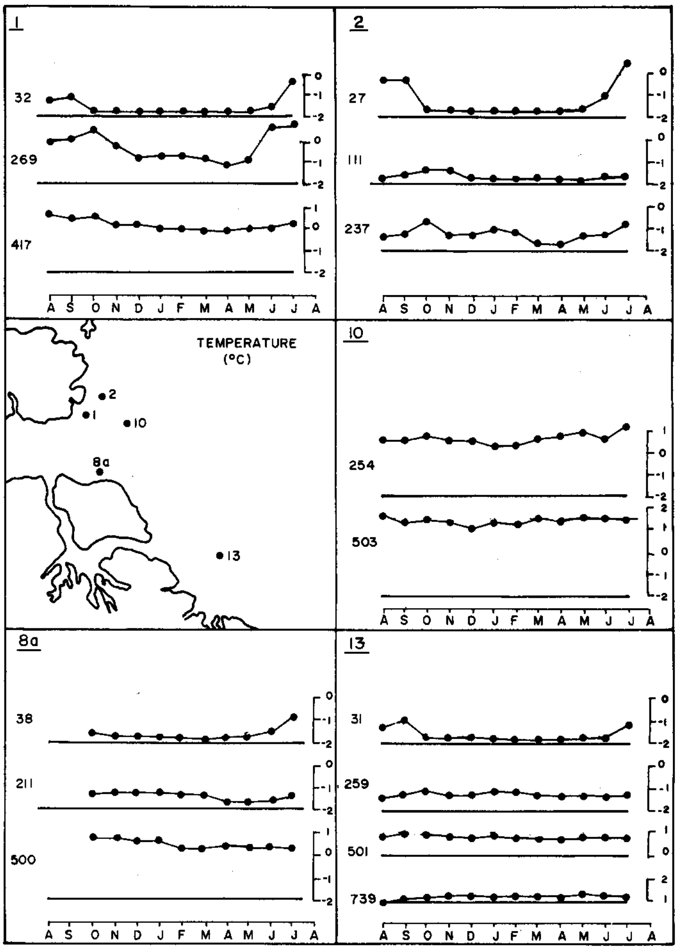


FIG. 5. Monthly mean temperatures from current meter data, August 1978 to July 1979. The numbers beside each time series indicate the actual mean depth of the current meter.

The appearance of the low temperatures was accompanied (at 35 m depth) by a sharp decrease in the level of temperature fluctuations. Figure 7 shows an example of the fall cessation and spring reappearance of fluctuations in temperature at station 1. Plots of the RMS fluctuations in temperature computed over monthly intervals for all moorings are shown in Figure 8. In all cases, the level of fluctuations at 35 m declined sharply in the winter, in conjunction with the mean temperature.

Monthly plots of RMS variations in salinity are shown in Figure 9. With the exception of mooring 8a, all mooring sites showed a winter decrease in the level of salinity fluctuations. The mean 35 m salinities (Fig. 6) showed a steady increase over the winter, followed by a decrease in spring. As inspection of Figure 6 shows, this also resulted in a seasonal variation in the stratification of the Arctic

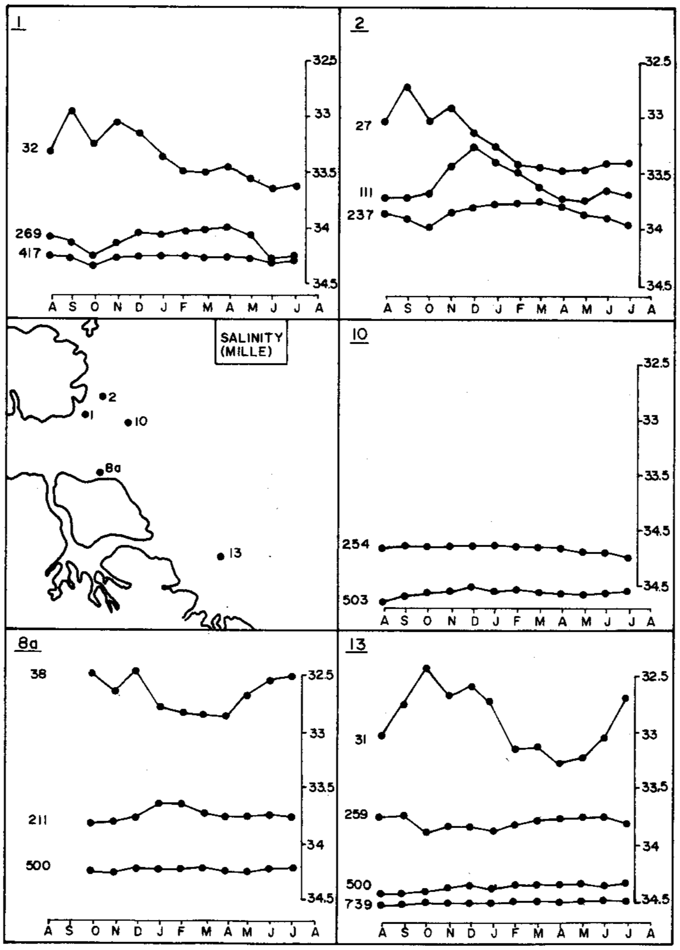
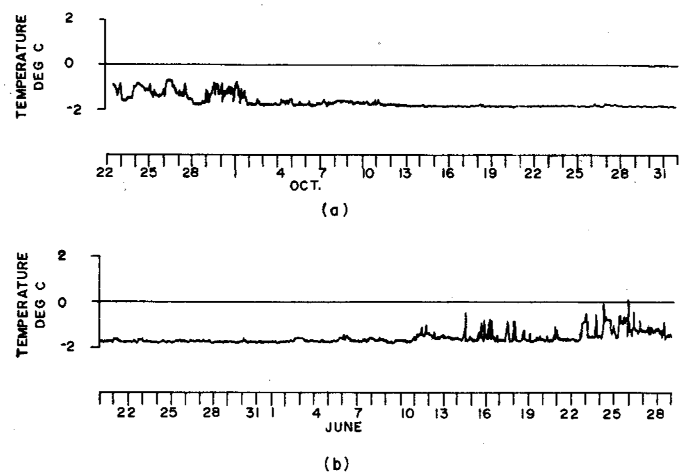


FIG. 6. Monthly mean salinities from current meter data, August 1978 to July 1979. The numbers beside each time series indicate the actual mean depth of the current meter. Note salinity decreases upward in each diagram.

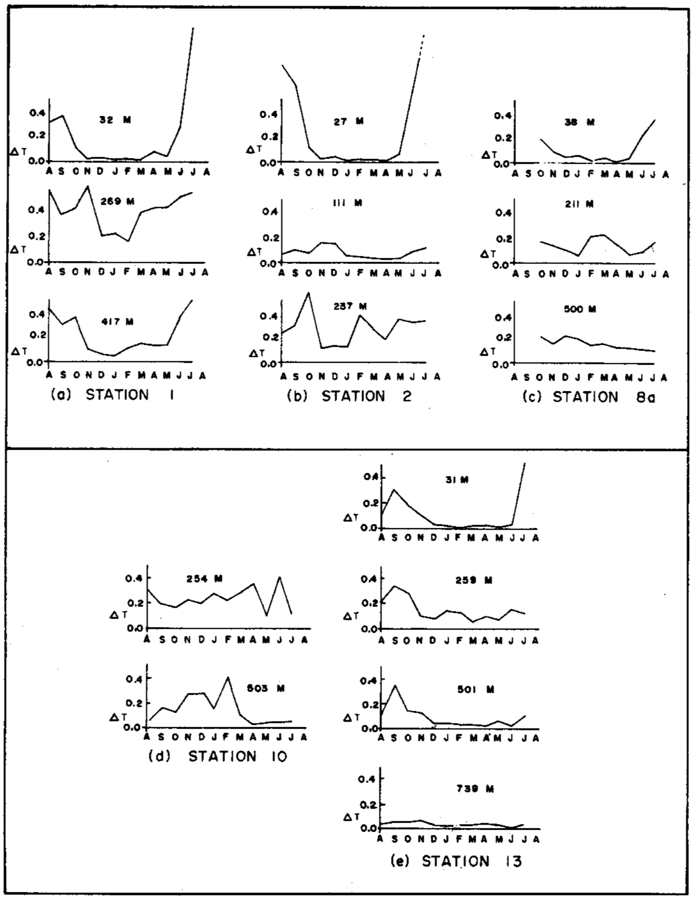


(a)

(b)

FIG. 7. Cessation (a) and onset (b) of temperature fluctuations at station 1, 35 m.

Water layer. In late summer, the stratification reached a maximum value and was subsequently reduced. In February and March, the net vertical density difference between 27 m and 237 m at station 2 was only one-half of the summer value.



(a) STATION 1

(b) STATION 2

(c) STATION 8a

(d) STATION 10

(e) STATION 13

FIG. 8. Monthly values of RMS fluctuations in temperature (°C), 1978-1979.

At both moorings 1 and 2 there was a decrease in the mean salinity at depths greater than 35 m in the early part of the winter. The decrease was most pronounced at 111 m at station 2, where the mean salinity decreased by 0.44 ‰ from October to December. From January onward, it increased once again, presumably in response to advection or to convection driven by ice formation.

At stations 1, 2 and 8a, at nominal depths of 250 m, there was a decrease in the mean salinities of approximately 0.2 ‰ in the early winter, which was maintained until the spring. As was pointed out in the section on Methods, changes of 0.02 ‰ or greater in the monthly mean salinities are statistically significant at the 1% level. Note that 0.02 ‰ is in the order of the RMS variations in salinity at the deeper current meters during the winter months. It may be concluded, then, that the winter salinity decreases at stations 1, 2 and 8a are of significant magnitude.

DISCUSSION

The diminished circulation measured at all five of the mooring stations during the months of ice cover strongly suggests that the cyclonic circulation of northwestern Baffin Bay is generally reduced during this period. This reduction is apparently at variance with the only other set of

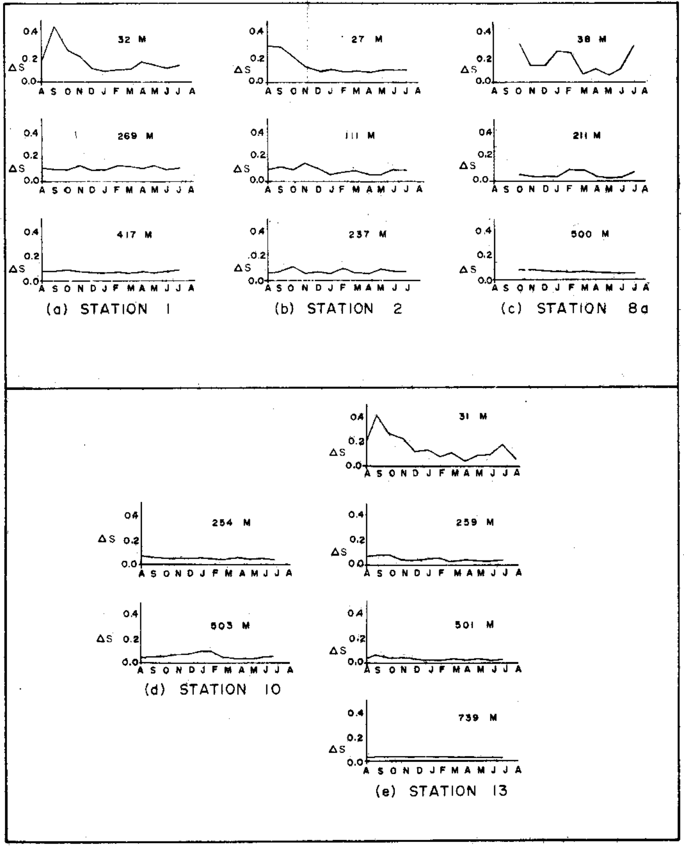


FIG. 9. Monthly values of RMS fluctuations in salinity (‰), 1978-1979.

direct winter current measurements in the archipelago. Contrary to the reduced winter flows reported here, Greisman and Lake (1978) found that current speeds measured in Crozier Strait in 1977-78 were enhanced during the winter. Because of the relatively sparse nature of the Baffin Current measurements, it is not possible to state whether or not changes in the pattern of the Baffin Current occurred which may have maintained its transport despite the decreased velocities. The pattern of moorings was not sufficiently dense to reveal whether the slowing of the current coincided with, for example, a broadening of the flow or if a change in the transport of the current did in fact occur. Further measurements are necessary to determine which, if either, of these patterns is typical of winter conditions in the archipelago.

At all but one station (8a), the average vertical shear in the current decreased during the winter. Aagaard and Coachman (1968) noted that observations in the East Greenland Current showed little variation of current with depth in winter, but that computed shears in summer were significant. They suggested that the most probable cause was a seasonal variation in the baroclinic contribution to the pressure gradient. The absence of freshwater runoff, and possible reduction in the transmission of wind stress because of the presence of pack ice, could account for such a variation. Muench (1971) has suggested the same possibility for the West Greenland Current.

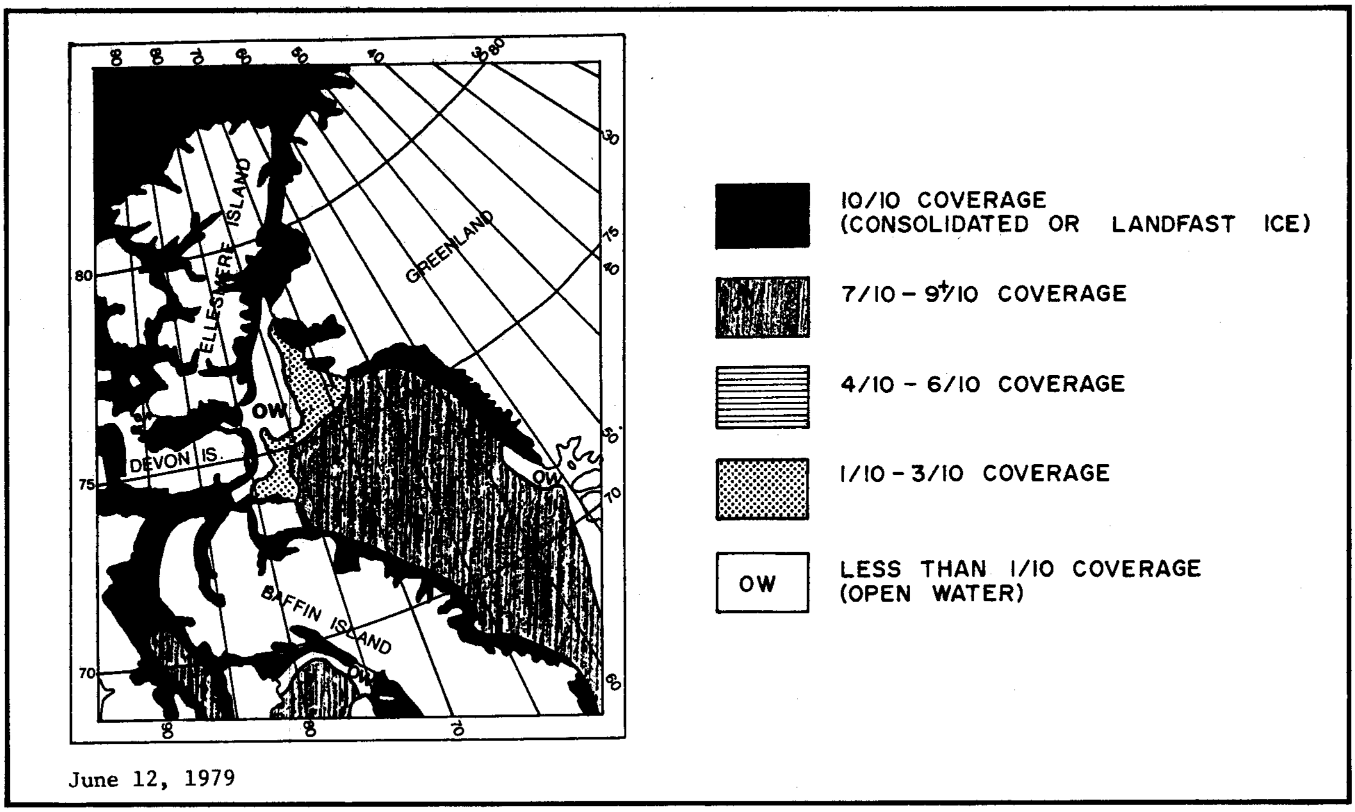


FIG. 10. Ice cover in Baffin Bay, 12 June 1979.

The seasonal changes in the level of the synoptic variations are not well understood. They could result from the locally reduced coupling between the wind and near-surface water motions, due to the presence of winter ice cover, or they may be indicative of seasonal changes in the larger-scale outflow of Arctic Ocean water into and through Baffin Bay.

The seasonal changes in the properties of the upper part of the water column (near-freezing temperatures and an increase in salinity during the winter months) clearly must be related to the seasonal changes in sea-ice coverage. Marko (1981) has described the ice cover in northwestern Baffin Bay during the winter of 1978-1979. Significant new ice (>0.5 of the sea surface ice-covered) had appeared over all the mooring sites by 10 October, with essentially solid cover achieved by late November. Clearing had begun over the more northerly mooring sites by early June, with open water beginning to expand southward from Smith Sound along the east coast of Devon Island (Fig. 10). Ice persisted over the southern site (mooring 13), however, until late July.

Formation of ice at the sea surface is accompanied by salt rejection and the extrusion of brine at freezing temperatures. (Very rapid freezing may lead to the production of supercooled water [Coachman, 1966].) Because the density of sea water at near-freezing temperatures is controlled by its salinity, the production of cold brine during the freezing of sea ice will lead to a convective circulation in the upper part of the water column. Examination of the monthly mean temperatures in Figure 5 shows that at all moorings with records from 35 m, near-freezing temperatures (−1.7°C) at that depth were present from October through May (June in the case of mooring 13). The appearance of such low water temperatures at a given depth could be an indication that convection of cold, salty water produced by ice formation at the surface had penetrated to that depth, although advection of cooled water produced elsewhere cannot be completely ruled out.

While the seasonal decline in both the mean temperature and the level of RMS temperature fluctuations at 35 m most likely results from the production of a uniformly cold water column by convective mixing under the growing ice, changes in the RMS value of the fluctuations at other depths are not so easily interpreted. Muench (1971) has calculated that brine released during the annual formation of 2 m of ice in Baffin Bay would be sufficient to cause convection to approximately 150 m depth, forming a uniform layer with a temperature of −1.83°C and a salinity of about 33.7 ‰. Both the mean temperatures and the level of fluctuations at 111 m at mooring 2 indicate that the effects of convective mixing (not necessarily of local origin) appeared at that depth three months after mixing passed the 32 m instrument. At mooring 13 (in the Baffin Current south of Bylot Island) there is a consistent winter decrease in RMS temperature fluctuations. The same is true at mooring 1, although at 269 m the duration of the decrease is relatively short. Moorings 8a and 10 show an increase in the level of fluctuations during the winter at 211 and 503 m, respectively.

At a depth of 237 m at mooring 2, the RMS temperature fluctuations were low in the early part of the winter, but then rose sharply in February only to decline again until the end of April. The monthly mean temperatures dropped by approximately 0.5°C to −1.8°C at the same time. Examination of the detailed record of temperature for this meter (Fig. 11) shows that from November to mid-February, the temperature had risen smoothly from −1.3°C to −0.8°C. In mid-February, a three-week series of intrusions of very cold (−1.8°C) water started, followed by stabilization of the temperature at −1.8°C through March and part of April. These cold-water intrusions were significantly fresher than the alternating periods of warmer water, suggesting that the variations resulted from horizontally propagating motion.

Both local convection and advection of cooled water appear to be responsible for the seasonal changes in water properties observed in Baffin Bay. In the upper part of the water column, the appearance over winter of essentially constant, near-freezing temperatures, in conjunction with an increase in salinity and a decrease in the levels of RMS fluctuations in both temperature and salinity, clearly indicate the influence of convection caused by growing ice. That these changes should occur at 35 m depth coincidentally with the appearance of ice is not surprising. However, other changes are apparent in the water column at this time, certainly as deep as 250 m, and perhaps down to 400 m. At three of the moorings (1, 2 and 8a) the upper level (35 m) increase in salinity is accompanied by a significant, simultaneous decrease in salinity at 250 and (perhaps) 400 m. This would seem to indicate either that the effects of freezing-induced convection are almost immediately felt down to at least 250 m, or that advective processes were simultaneously causing changes at this depth. Coachman and Aagaard (1974) have stated that freezing-induced convection under a continuous sheet of growing

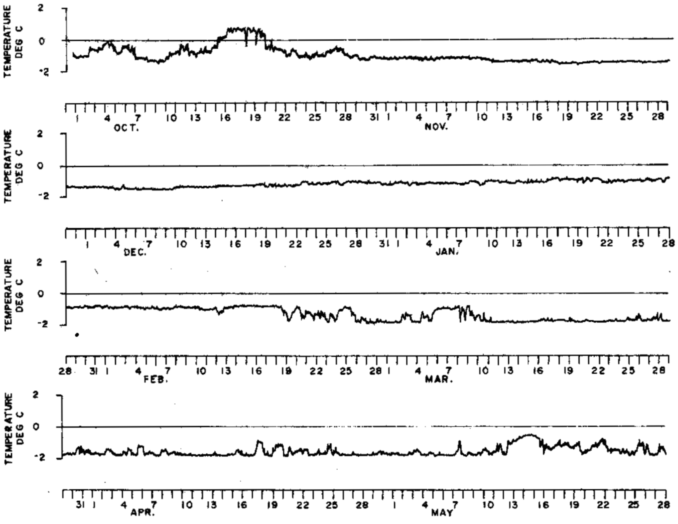


FIG. 11. The temperature record from mooring 10, 237 m.

ice is unlikely to penetrate to great depths through a pycnocline, but that rapid freezing of surface water in leads in the ice cover may drive significant vertical convection (Coachman, 1966). If advective processes are not responsible for the changes at 250 m and 400 m observed at the onset of ice formation, then perhaps a convective process such as the above may be responsible. In all probability, a combination of the two processes is responsible, but further detailed measurements are necessary to resolve this question.

If the appearance of increasing salinity, temperatures of approximately −1.8°C, and an absence of temperature fluctuations are taken as indications that a convectively-mixed layer generated under the ice has reached an instrument at a given depth, then the data from mooring 2 may be used to estimate the rate of deepening of that layer. The signs of convective penetration appeared at mooring 2 at 27 m in October, 111 m in December, and (if one assumes convective and not advective processes are responsible for the March-April uniform low temperatures at 237 m) at 237 m in March. The layer appears to have deepened at an essentially uniform rate of 40 to 50 m per month. Data from moorings 1 and 8a appear to be consistent with that rate; however, the lack of 125 m measurements at these sites makes interpretation of the results much more difficult.

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