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Arctic Outflow and the Oceanographic Conditions of the Northwest Atlantic

by

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Abstract

The waters over the continental shelves of Greenland and eastern Canada are dominated by the cold, low salinity Arctic outflows. The largest portion of these outflows originates in Fram Strait, so the entire system can respond to interannual changes occurring in the Arctic. Such an event occurred in the late 60's and early 70's when excess fresh water was first detected in Icelandic surface waters, then moved cyclonicly around the sub-polar gyre of the North Atlantic descending to denser levels as it moved. The timing of the appearance of this water at various locations has provided us with valuable information concerning the strength of the gyre circulation.

Events such as the low salinity anomaly are detected chiefly from hydrographic stations occupied on somewhat regular basis by various organizations. Modern technology also allows one to obtain moored measurements of temperature and velocity over periods of a year. Year long moored measurements in Baffin Bay and on the Labrador shelf are discussed in terms of the time scales of their variability. From these analyses, we can see how susceptible hydrographic sections occupied annually, seasonally or even monthly are to aliasing by high frequency variability.

SPECIAL SESSION ON DEEPWATER FISHES

Introduction

The waters over the continental shelves and slopes of Greenland and eastern North America are considerably colder and less saline than the waters found further offshore and this has considerable influence on the marine life found in these regions. The temperature and the salinity of these waters also changes, both with the season and on a longer interannual time scale. The water properties, both in the mean and in their variability, largely arise from the effect of the Arctic Ocean outflows. In this paper, we shall describe the current structure arising from these Arctic outflows; give evidence showing that all these waters respond to changes in the Arctic outflows in a fashion consistent with it being a continuous current system; and, finally show how difficult it is to describe interannual variability with the existing data sets in the face of strong seasonal and monthly changes.

The Arctic Outflows

The Arctic Ocean has its major exchange with the rest of the world's ocean through Fram Strait, between Greenland and Svalbard as well as over shallow Barents Sea between Svalbard and northern Norway. Warm saline Atlantic water enters the Arctic Ocean over the Barents Sea shelf and to the west of Svalbard and sinks below the cold low salinity Arctic surface layers. The Arctic outflow that is the concern of this paper consists of cold low salinity upper waters and takes place over the east Greenland continental shelf as the East Greenland Current as shown schematically in figure 1. Additional outflow of Arctic Surface Water also occurs through the Canadian Arctic Archipelago, mostly through passages entering into Baffin Bay (Aagaard and Greisman, 1975).

The low salinity of the Arctic surface layers is maintained by the extensive river runoff from northern Asia and North America as well as by sea ice meltwater in the summer months. The outflow through Fram Strait consists of $10^5\ m^3s^{-1}$ of ice, $1.8 \times 10^6\ m^3s^{-1}$ of Polar Water and $5.3 \times 10^6\ m^3s^{-1}$ of modified Atlantic Water (Aagaard and Greisman, 1975). The additional outflow through the Canadian Arctic consists of $2.1 \times 10^6\ m^3s^{-1}$ of Polar Water that is somewhat warmer and saltier than that exiting Fram Strait according to Aagaard and Greisman (1975). This latter estimate is somewhat higher than previous estimates of this exchange and its higher temperature and salt may be due to the fact that the estimate is based on summer data.

The Arctic outflow, after exiting Fram Strait, flows southward along the edge of the east Greenland continental shelf as the East Greenland Current. At Cape Farewell, the waters of the East Greenland Current are joined with those of the Irminger Current and this mixture which is warmer and saltier flows northward again along the shelf break as the West Greenland Current. While the East Greenland Current is ice covered over its entire length during much of the year, the West Greenland Current off southwestern Greenland is almost always ice free. In winter, the sea ice generally forms a front to the south of Cape Farewell; suggesting that the mixing regime is very narrow and intense. The intensity of the front may be due to the predominantly northerly winds that will inhibit ice and surface waters rounding the cape from flowing northward.

The waters of the West Greenland Current partially enter Baffin Bay and partially move westward across Davis Strait. Along the western side of Baffin Bay is found the southward flowing Baffin Current, an intense low salinity cold water flow made up of the outflows through the various principal channels of the Arctic Archipelago as well as recirculation within Baffin Bay. South of Davis Strait, this flow partially enters Hudson Strait and its water characteristics change significantly at this point (Lazier, 1982). This change is likely to be due to some combination of the addition of low salinity outflow from Hudson Bay and Foxe Basin and strong mixing of the water column due to intense tides at the mouth of Hudson Strait.

On leaving Hudson Strait, the waters continue to flow southward along the edge of the Labrador shelf as the Labrador Current. This current continues southward onto the Newfoundland shelf and southward along the western side of Flemish Pass. South of Flemish Pass, branches of the Labrador Current are believed to turn offshore with the greatest part of the flow retroflecting at the Tail of the Banks. Some portion of the flow does, however, continue to flow westward at this point and the cold low salinity core marking the Arctic outflows can be seen as far west as the entrance to the Laurentian Channel.

This description of the current patterns and the movement of water masses around the periphery of the N.W.Atlantic has been the oceanographers working hypothesis for many years yet many aspects of this circulation are still uncertain. It is clear from the offshore salinity distribution that, along the whole length of passage, there is considerable exchange of water between the offshore regions and these currents trapped on the continental slopes. There is little evidence that the currents remain completely intact along this entire length. In fact, it is likely that there is substantial breakdown of the currents and exchange of low salinity water offshore at the latitude of Jan Mayen, off Cape Farewell, at Davis Strait, off Hamilton Bank and finally at Flemish Cap. It is quite possible that the exchange of water at these locations is highly variable in time and has large implications for the water characteristics in the downstream direction.

<u>Variability in these waters</u>

The waters over the continental shelves of Greenland and northeastern North America undergo a strong seasonal variation of temperature as would be expected considering the strong seasonality in the solar heating at these latitudes. In addition there is a strong variation in salinity, as large amounts of fresh water are released each spring from melting sea ice and river runoff. Both solar heating and meltwater runoff cause the upper waters to be very much less dense in summer than in winter and this tends to increase the transports of the density driven currents such as the East Greenland and Labrador currents at this time. On the other hand, these currents also have a wind driven component and this component is strongest during the winter months so that it is difficult to say whether the transports should have a pronounced seasonality or not.

The annual variation of temperature and salinity can be best seen from the monthly averaged data from Station 27 in the Avalon

Channel just offshore from St. John's, Newfoundland (Keeley, 1981). Here, (figure 3) we see the low salinity pulse arising from earlier freshwater input further to the north and in Hudson Bay arriving off St. John's in September / October (Figure 2). The amplitude of the annual cycle of salinity in the surface waters is nearly a one. If the salinity over the entire water column is converted into fresh water equivalents, the low salinity pulse is equivalent to the addition of 2.67 m of fresh water. Similar cycles in temperature and salinity can be seen further north on the Labrador shelf (Lazier, 1982). Here the low salinity pulse arrives earlier, in July / August, and has an amplitude at the surface of more than 2. On the Labrador Shelf, the change from the winter salinity maximum to the late summer salinity minimum is equivilent to the addition of 4.7 m. of fresh water to the water column.

It is important to note that these two annual cycles were constructed using mean monthly data; hence their temporal resolution can be no better than a month. Even at this resolution, the change in salinity at the onset of winter appears quite abrupt. Since this picture is obtained by averaging over large areas and many years of data, it is likely that at a given section and in a given year, the change may take place over a few weeks. If, therefore, one is trying to interpret hydrographic data that are obtained only once each year at some location, there is a danger of interpreting changes due to changes in the timing of an event with interannual changes in the strength of that event. An earlier discussion of the problems of interpreting infrequently sampled environmental data can be found in Mann and Needler (1967).

The 1970's Anomaly

In spite of these difficulties with the interpretation of hydrographic data collected on standard sections; much of what oceanographers know about the interannual variability arises from such observations; usually collected in support of various fisheries. The most recent and perhaps the most widely observed anomoly occurred throughout the entire Northwest Atlantic during the 1970's and has come to be called in the ICES community as the great 1970's anomaly. This anomaly was detected by a number of different investigators at different times and at different depths and it was only in retrospect that a picture of a large scale anomaly pattern moving first westward from the Nordic Seas to the Grand Banks following the Arctic outflow and then eastward again following the North Atlantic current was developed.

The 70's anomaly consists of the appearance of water with abnormally low salinity and temperature for a period of several years within the sub-polar gyre of the North Atlantic. Lazier (1980), in his analysis of the oceanographic data collected at OWS Bravo, noted the appearance of a cold low salinity layer in the early 1970's that suppressed convection and turned off the processes of the renewal of Labrador Sea Water. He linked the appearance of this water with an increased southerly flow of ice in the Greenland and Iceland Seas in the late 1960's in response to increased winter northerly winds in the same area over the same period (Dickson *et al.*,1975; Malmberg, 1969). During this period, northern Icelandic waters suffered extreme ice conditions and the ratio of cold fresh polar water to warm salty Atlantic water in this region increased markedly.

Clarke and Gascard (1983) reported that Labrador Sea Water observed forming through deep convection during March 1976 was very much colder and less saline than had previously been reported. Clarke (1984) also showed from these observations and further observations obtained in April, 1978 that the waters entering the Labrador Sea from the Irminger Sea were also colder and fresher, indicating that this pattern was wide spread. He demonstrated that the low salinity anomaly could also be seen in the integrated fresh water content at Station 27 off St. John's.

Dickson and Blindheim (1984) reported the appearance of low salinity water entering the Nordic Seas in the Atlantic inflows through the Faroe-Shetland channel in 1976 and then in the inflow to the Barents Sea in 1979. The remarkable feature of these observations is the sharpness in time of the anomaly signal, that is it appears and disappears over a period of 3 to 4 years and appears to have the ability to propagate over large distances and times without broadening significantly.

Finally, Brewer *et al.* (1983) reporting that the North Atlantic Deep Water overflowing the sill in Denmark Strait and flowing equatorward along the continental slope of Greenland and North America was much colder and fresher in the summer of 1981 than had been previously observed. Continuing observations of this water off the Labrador coast by Lazier (per.com.) indicate that these abnormal conditions did in fact begin in 1981 and persisted until 1985. Conditions had returned to a more normal by the summer of 1986.

These various pieces of information were brought together and discussed at various meetings of the ICES working group of Oceanic Hydrography and the in the course of those discussions the preceding conceptual framework on how water moves around the sub-polar gyre of the North Atlantic was developed. This picture should some day appear in a publication that is being prepared by Dickson (per.Com).

<u>Monitoring Environmental Change</u>

This problem is very important in these regions because ice cover generally restricts hydrographic measurements to the summer months when the changes are most rapid. Moored current meters will give a continuous picture of the temperature and current fields (and also in some cases salinity) but these cannot be located in the surface layers where the changes are the largest.

BIO has had current meter moorings both under the Labrador Current at Hamilton Bank and in Baffin Bay for a number of years. Since John Lazier will speak on the Labrador shelf and Labrador current, we will concentrate on the Baffin Bay observations. A number of year long current meter moorings have been successfully deployed in the locations given in figure 4. Most of these moorings had their shallowest meter at 200m to avoid damage from icebergs.

The data from these instruments were broken into 15 day segments and the means and standard deviations were computed. As a second step the standard deviations of the year long series of 15 day means was also computed and these are given in table I. From these data, we see that the standard deviations of the low frequency variations (15 days and longer) range from 0.05°C to 0.42°C and that for the variations with periods of a few hours to 15 days (average of the standard deviations over each 15 day block) have a similar range. The ratio of the higher to lower frequency standard deviations is generally greater than 0.5 averaged over the entire year. There was little evidence of any annual cycle in temperature at the observed depths and positions. However, the annual surface heating does not usually penetrate below 100 metres in this area.

Correlations were computed for all the 15 day mean temperature time series observed at the 700 series moorings during 1985/86. The correlation coefficients are given in Table II. Correlations based on mean monthly temperatures are given for mooring data from the two previous years in Tables III and IV. Because of the low frequency character of the temperature signal, it is not clear what value of correlation coefficient represents a significant correlation. It is likely that such a value lies considerably higher than 0.5. There is a surprising difference between the three different years of data. Mooring 700 and to a lessor degree 701 exhibit a fair degree of correlation between levels on the same mooring with little correlation between moorings in spite of the fact that the mean temperatures from each instrument show considerable vertical temperature structure. On the other hand the 500 and 600 series moorings show much higher correlations between moorings than between levels on the same moorings. The mean temperatures suggest that these higher correlations are often within definable temperature ranges suggesting that changes in the characteristics of some layer of water might be the cause; although this simple picture does not apply in every case.

To summarize this evidence from the moorings, we would suggest that it shows little evidence of an annual signal, that its variability over a few days to a few weeks is of the same order as its variability over a few months to a year and the horizontal and vertical scales of this variability can be quite short (10's of km horizontally, 100 m vertically). This suggests that the monitoring of interannual changes that are applicable over large areas is a difficult undertaking. There is some cause, however, for optimism in that their is some evidence that changes within distinct layers of water show greater correlations over greater distances. Salinity is often a key parameter to determine the density and hence the boundaries between layers in these high latitude waters. Unfortunately, monitoring salinity changes using moored or drifting instrumentation is at present a difficult and not particularly reliable undertaking.

Because of the importance of looking at the water structure of the entire area in order to detect changes from year to year, it is important to collect temperature and salinity data along sections crossing the major oceanic fronts and currents as often as possible and to exchange all such data as quickly as possible. This latter is particularly important. At present the IODE mechanism takes the order of 5 years before data is in the international archives and available for exchange. Much data never reaches the IODE data centres. An alternative mechanism is the IGOSS system which requires data to be submitted within a few months. This data is transferred via the meteorologist's Global Telecommunication System (GTS) and is pulled of and stored on data bases in a number of countries including Canada. Very little salinity data is presently being exchanged via this mechanism; however, with the use of CTD's and increasingly cheap computing power at sea there is no really good reason why IGOSS messages summarizing every CTD station can not be produced automatically and quickly exchanged.

Regular occupation of standard oceanographic sections as established by ICES and ICNAF remain the basic source of data available for studies of interannual change. Only a few of these sections have been run often enough (or have exchanged their data) to allow some sort of analysis of their variability. In interpreting these sections, the presence of a few more frequently sampled locations such as Station 27, OWS Bravo, and our Hamilton Bank moorings provide the control to allow some estimates of the effects of aliasing by shorter term fluctuations. There may be other well sampled sections along the Greenland and Iceland coasts that could serve as a similar control in these regions.

Conclusions

The Arctic outflows through Fram Strait and Hudson Bay effect the oceanographic conditions over much of the northern North Atlantic. Very strong variations in this source have in the past changed conditions all around the sub-polar gyre in a fashion consistent with our understanding of the circulation patterns and the thermodynamical processes of this region.

Temperature data from current meters moored below the depth of direct solar influence show little evidence of a seasonal signal and have as much variance from their short period variations (less than 15 days) as from the longer periods. Temperature signals are poorly correlated both vertically and horizontally although there is some evidence that there is some correlation within water layers or water masses. This suggests that temperature measurements from moorings are a poor monitor of longer term temperature changes over large areas of the ocean.

To monitor such longer term changes, one needs salinity as well as temperature information with reasonable spacing both vertically and horizontally. Continued observations of standard hydrographic sections and rapid exchange of the data seem to be the principal tool presently available for this monitoring. It is believed by the senior author that the calibration and exchange of data that is routinely collected on these sections is more important at this time than to attempt to increase the amount of data being collected.

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Table I: Temperature statistics from year long temperature records collected in Baffin Bay

Mooring No.	Depth (m)	No. of days	Mean	stnd. dev.	high freq stnd.dev.	Ratio high to low
700	213	318	- .34	.42	.11	.3
	363		1.27	.29	.08	.3
	513		1.83	.15	.04	.3
701	218	317	.25	.31	.15	.5
	368		1.04	.35	.43	1.2
	518		.46	.35	.31	.9
702	229	318	- .60	.31	.26	.8
	292		- .21	.18	.08	.4
703	174	319	- .40	.32	.19	.6
	324		.13	.26	.19	.7
	531		- .18	.18	.06	.3
579	95	424	-1.49	.17	.11	.6
	195	285	-1.40	.07	.02	.3
581	116	387	-1.54	.10	.06	.6
	216		-1.45	.08	.05	.6
	516		.54	.08	.06	.7
582	116	420	.26	.39	.41	1.1
	485		- .18	.17		
615	160	367	-1.48	.08		
	260		- .91	.17		
	360		- .90	.13		
616	235	366	-1.53	.09		
	335		- .34	.31		
	535		.90	.12		
617	257	367	-1.11	.21		
	357		.04	.17		
	557		.90	.13		
618	325	367	- .39	.37		
	525		1.08	.08		
E13	35	307	-1.71	.16	.07	.4
	250		-1.28	.15	.10	.6
	500		.81	.07	.05	.7
	750		1.18	.05	.03	.7

Table II: Correlations between series of 15 day mean temperatures from Baffin Bay - 1985/86 moorings.

Mooring	Depth	700 213	700 363	700 513	701 218	701 368	701 518	702 229	702 292	703 174	703 324
700	363	.83									
	513	.71	.70								
701	218	.25	.23	.74							
	368	.26	.32	.55	.72						
	518	.55	.49	.43	.31	.39					
702	229	-.05	-.10	-.50	-.66	-.51	-.12				
	292	.58	.43	.33	.12	.23	.35	.26			
703	174	.17	.25	.42	.53	.64	.00	-.41	.20		
	324	.50	.54	.69	.57	.58	.52	-.22	.46	.60	
	531	.45	.43	.84	.79	.52	.41	-.56	.20	.24	.50

Table III: Correlations between mean monthly temperatures from Baffin Bay - 1983/84 moorings.

Mooring	Depth	579 95	581 116	581 216	581 516	582 285
581	116	.93				
	216	.76	.65			
	516	.08	-.04	.09		
582	285	.51	.40	.72	.00	
	485	.22	.29	.31	-.70	.34

Table IV: Correlations between mean monthly temperatures from Baffin Bay - 1984/85 moorings.

Mooring	Depth	615 160	615 260	615 360	616 235	616 335	616 535	617 257	617 357	617 557	618 325
615	260	-.02									
	360	-.41	.74								
616	235	.48	.23	-.21							
	335	.25	.60	.15	.64						
	535	-.49	-.25	.24	-.39	-.49					
617	257	.13	.73	.45	.40	.62	-.55				
	357	-.45	.70	.93	-.21	.17	.18	.57			
	557	-.50	-.05	.38	-.31	-.33	.94	-.50	.27		
618	325	-.40	.68	.65	-.08	.19	.14	.47	.70	.19	
	525	.40	.67	.48	.23	.42	-.69	.68	.42	-.57	.23

ARCTIC OUTFLOWS

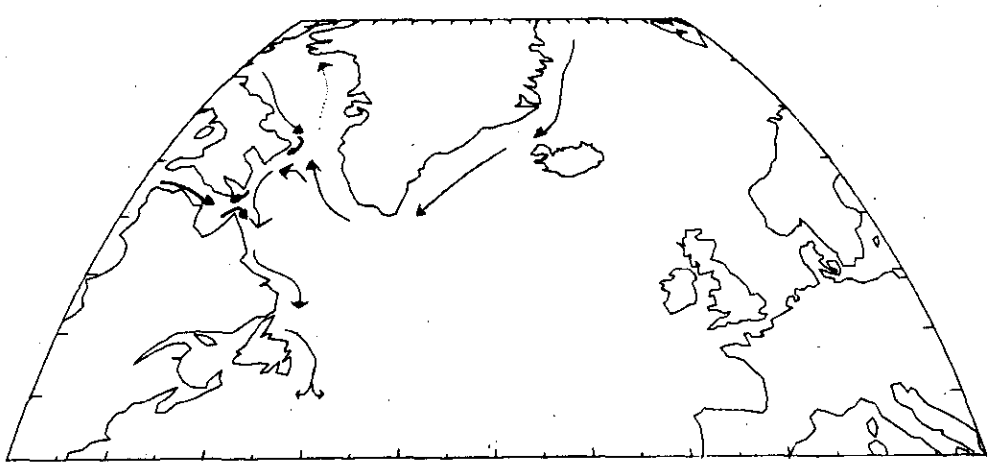

Figure 1: Arctic outflow and associated density driven upper ocean current field in the north-western Atlantic.

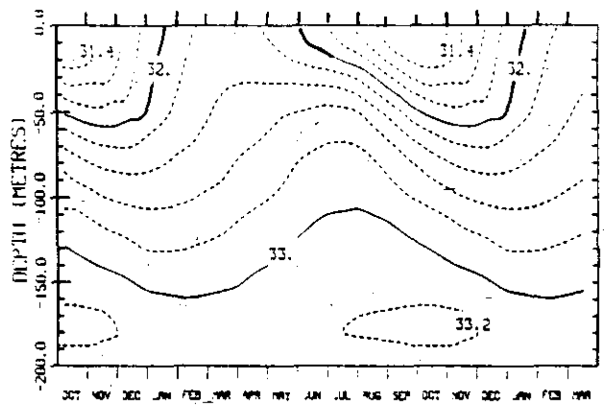

Figure 2: Mean annual salinity cycle (1948-1976) at Station 27 off St. John's, Newfoundland (after Keeley, 1981).

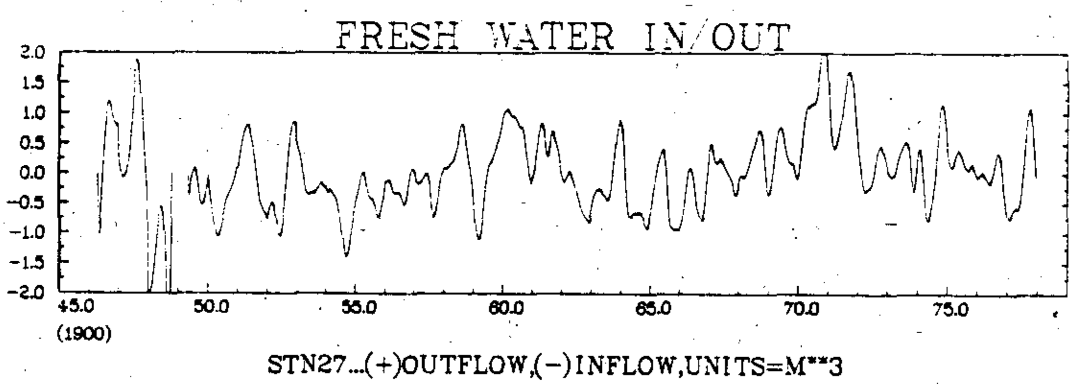

Figure 3: Fresh water anomaly integrated over the entire water column at Station 27.

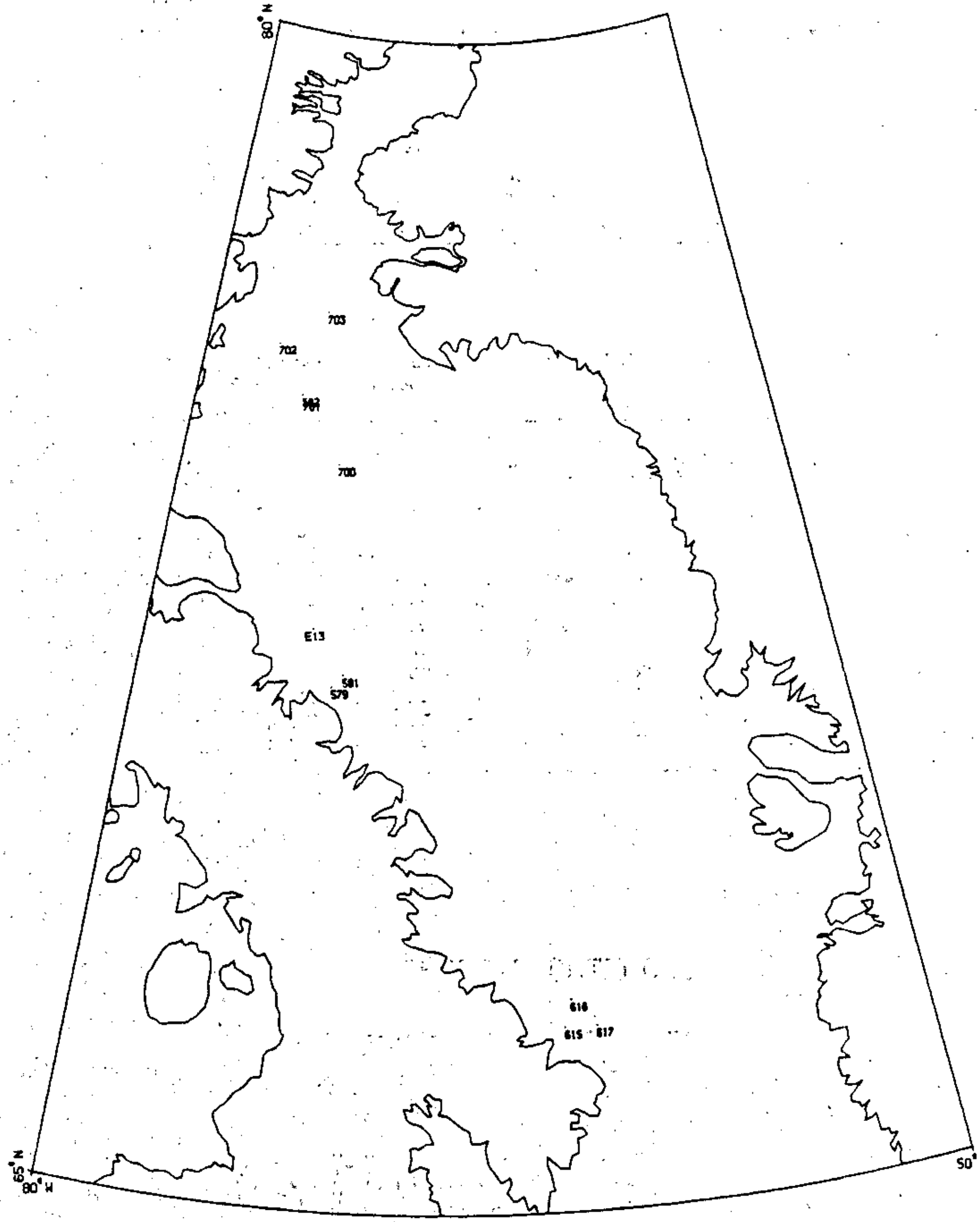

Figure 4: Location of year long current meter moorings in Baffin Bay.