sistance in the field of Mr. J. S. J. Haight. This note is published by permission of the Chairman, Defence Research Board.

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ICE TRANSPORT IN THE EAST GREENLAND CURRENT AND ITS CAUSES*

Introduction

When water freezes, about 80 cal./gm. are liberated and the same amount is taken up when the ice melts. As long as these processes happen at the same place, heat gains and losses cancel in the course of a year and can therefore be disregarded. However, if freezing takes place in one area and melting of the ice in another, then the area of freezing will represent a heat source and the melting area a heat sink.

Large quantities of ice are exported from the Arctic Ocean, mostly between Greenland and Spitsbergen. An energy budget for the Arctic Ocean cannot disregard this energy source, as has been shown by Mosby[1], and Vowinckel and Orvig[2]. In the area of melting, the Greenland Sea and directly south of it, a corresponding amount must be found on the negative side of the energy balance.

The available estimates of the ice export all go back, directly or indirectly, to Russian investigations. The best value seems to be the one by Gordienko and Karelin[3] of 1,036,000 km.^{2} as an annual average for the period 1933-1944. No details are given about the method by which this value was obtained, and such information is not available to the present author. However, as the period used by Gordienko and Karelin lies before and during World War II, the data available for this estimate cannot have been especially plentiful. It therefore seems appropriate to re-examine the ice export and, if possible, to obtain some estimates about its variations.

Ice transport in the ocean is effected in two ways:

(a) Ice is carried along by the ocean current on which it floats, the transport being directly proportional to the current speed.

(b) Ice is moved, independently of the current, by the wind.

The relation between wind and ice drift was evaluated by Zubov and Somov[4]. Their results were confirmed by Zubov[5], Gordienko[6], and Crary[7]. The ice movement was found to be parallel to the surface isobars, the speed given by the empirical formula:

$$V = 13{,}000\ p$$

where V: ice movement (km./month)
and p: pressure gradient (mb./km.)

Daily synoptic weather maps for the area under consideration covering a long period are available from different sources. There is, therefore, no difficulty in determining the wind component of the ice export by this formula.

For the East Greenland Current, however, estimates of flow are not satisfactory. Oceanographic soundings are only few in number for the summer and there are none for the winter. Therefore, indirect methods have to be used to obtain the ice export by currents.

The only sets of observations for such an indirect approach are the ice charts published each year (for the months April to August) by the Danish Meteorological Service[8] and the monthly mean ice charts by the U.S. Hydrographic Office[9] and the German Seewetteramt[10]. The Danish charts are based on all ice information available for a particular month. The amount of information varies greatly, with the result that the reliability of the charts is quite different from year to year. However, the analysis is carried out by assuming that the ice limit is near its

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average position unless observations indicate otherwise. This has the result that the variations found from a study of these charts will be an underestimate rather than an overestimate.

The above sources for data were used to determine the total ice export. The ice export by current can then be obtained from the total by subtracting the ice export by wind.

Ice export by wind

In the present investigation, only the ice movement to and from the Arctic Ocean is of interest. The only element necessary for the determination of the motion is the zonal west-east pressure gradient in the critical area.

The monthly mean zonal west-east pressure gradients were determined along 80°N. between 20°W. and 0° and along 65°N. between 40° and 30°W. Monthly mean surface pressure maps published by Deutscher Wetterdienst (1949 onwards)[11] could be used for the period 1949 to 1956. For the periods 1921 to 1939 and 1946 to 1948, grid point values were tabulated from the Historical Weather Map Series published by the U.S. Weather Bureau[12].

The ice drift was then calculated for each month in the 30-year period, according to the formula given above. To obtain the actual ice export, ice concentration and width of the drift had to be known.

Information about ice concentration is insufficient for an evaluation of specific values for each month of each year. Therefore, the average concentrations, as given by the U.S. Hydrographic Office (ref. 9), had to be used throughout the period.

The width of the pack-ice at 65°N. could be taken from the Danish ice charts. Matters are more complicated at 80°N. The East Greenland Current flows southward and the West Spitsbergen Current northward next to it and both have significant speeds. The predominantly northerly winds of this area will certainly increase the ice export in the region of the East Greenland Current. Over the West Spitsbergen Current, however, the wind should merely cause a decrease in ice import, if this import takes place at all. The considerable extent of open water west of Spitsbergen, even in winter, seems to indicate that such an import cannot be very significant. A further restriction in the northward transport of ice must be caused by the fact that the Arctic Ocean contains pack ice of considerable concentration. This will cause resistance to ice import. If, for these reasons, wind-driven ice import over the West Spitsbergen Current is disregarded, no export can be assumed either. This is so, because the current must certainly be strong enough to counter-balance any wind-induced southward movement of ice.

However, there must be a certain area, between the two currents, with a variable direction of flow due to the formation of eddies. It seems likely that wind-caused ice export must take place over this area, although it is a region low in efficient transport by currents. The west-east extent of the area of ice export resulting from wind will therefore be rather wider than the actual extent of the East Greenland Current.

The most likely width of the East Greenland Current seems to be 200 km. (ref. 2). The distance between Greenland and Spitsbergen is about 600 km. If the width of the West Spitsbergen Current is assumed to be also 200 km., there would remain an area 200-km. wide, with varying currents. The closer one approaches the West Spitsbergen Current, the more predominant the northward component will be, hence the less favourable the area will be for wind-driven ice export. It is assumed that one-half of the width will have as effective a wind-caused ice export as the area of the East Greenland Current, whereas the other half will show no wind effect. Accordingly a total width of 300 km. has been assumed. Since the pack ice always extends over this distance, it was taken to be constant for the whole year. It seems unlikely that the assumption of 300 km. is too high, and the wind influence on ice export will be an underestimate rather than an overestimate.

With information on wind, ice concentration, and width of the drift, the wind-caused ice export was calculated for each month of the 30-year period, for 80°N. and 65°N. The average values are given in Table 1. Generally, the wind-caused ice export is considerably higher at 80°N. than at 65°N. The reason lies, not in the weaker winds at 65°N., but rather in the fact that northerly and southerly wind components are more equal in frequency there, and compensate each other on the average. The large values in the north are caused by the semipermanent high, or ridge, over northern Greenland, and the tendency for low pressure over the open water to the east. This pressure distribution is especially stable in winter, resulting in very high export values.

Table 1. Ice export by wind (southward) (in km.^{2} — ice concentration 1.0).

	Jan.	*Feb.*	*March*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
80°N.	26,570	28,930	30,500	29,230	15,450	9,280	1,550	4,010	14,400	22,440	27,190	27,810	237,360
65°N.	7,940	940	1,050	10,030	900	0	2,430	1,220	1,770	4,050	5,770	8,760	44,860

The high values of wind-caused ice export at 80°N. raise the question whether Zubov's formula is still applicable. The formula was developed empirically for conditions in the Arctic Ocean, where, with the passage of weather systems, the direction of movement will change frequently. Under these conditions heavy accumulation of ice will be at a minimum. Between Greenland and Spitsbergen, however, the high wind speed is semi-permanently from one direction and extends only over a relatively short distance. The result might well be accumulation of ice and a retardation of the wind influence. This effect will be insignificant in summer as there is then always sufficient open water. In winter, however, the concentration of ice is great. One could expect a wind-caused transport eastward farther south, but this is not so, especially in winter, as the following figures show. They give the pressure difference (mb.) between 80° and 70°N. along 0° (average for the period 1949-56, the minus sign indicates that the pressure at 70°N. is lower).

Jan.	Feb.	March	Apr.	May	June
−7.1	−6.6	−6.5	−8.9	−2.8	−0.4
July	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
+0.4	−0.8	−5.9	−4.6	−7.8	−10.2

These considerations indicate that a certain amount of accumulation is possible. Its influence on wind-caused ice export is not known. Its magnitude is not likely to be very high, as the East Greenland Current will constantly carry any accumulation to the south, so that the effect will probably be temporary only, after spells of abnormally strong wind. If the accumulation has any influence at all, it will certainly be in the direction of retarding export. Therefore, the figures in Table 1 represent an upper limit in this regard. Since the width of the export area is probably underestimated as mentioned above, the two sources of error will work in opposite directions.

Total ice export and ice export by current in winter

The amount of ice south of 80°N. is determined by the following factors:

1. Amount of ice exported from the Arctic Ocean.
2. Amount of freezing south of 80°N.
3. Amount of melting south of 80°N.

During summer the melting must play the most important role. The process of melting is rather complicated (ref. 13) and the relevant factors are not known in sufficient detail at present for the Greenland Sea to permit a calculation of the amount of melting. Therefore, summer does not lend itself to further analysis.

During winter, i.e., September to April, melting can be disregarded in a first approximation. Freezing may be of importance during this season. Nusser[14], when discussing the ice types found in the East Greenland Current, regards ice formation south of 80°N. as of minor importance. Assuming a complete absence of ice formation in this region does, however, seem unrealistic. According to the U.S. Hydrographic Office (ref. 9) the ice concentration of the pack ice at the end of summer is low, around 0.6. The changeover to winter concentrations of 0.8 to 1.0 is rather rapid over a wide latitudinal belt. From the second half of September to the second half of October the concentration line of 0.8 to 1.0 progresses southward with an average speed of 19-20 km. per day, while during the next 23 days the speed is reduced to under 10 km./day. Such variations in the average speed of the ice movement seem extremely unlikely. A more probable explanation seems to be a local freezing of the open areas in the pack ice *when winter sets in*. However, the areal extent of this freezing within the pack ice is of small importance in the determination of winter ice export.

On the other hand, it is of great significance if any freezing takes place at the outer edge of the pack ice in the Greenland Sea. Observations indicate that this outer rim is generally composed of polar ice proper. Furthermore, this edge is relatively near the warm water of the Atlantic, which is constantly renewed by the northward current. Although the air coming from Greenland and the Arctic Ocean is very cold in winter, its heat capacity is small compared to that of the constantly renewed water and, in addition, the flow of air is intermittent, being replaced for long periods by onshore winds with respect to the ice edge. These facts, as well as the observations of the composition of the ice edge, indicate that freezing at the ice edge is probably negligible.

From these considerations it follows that the total ice export between September and April will correspond, in the first approximation, to the areal increase of the pack ice south of 80°N. during the same period.

The total ice cover for April was determined from the Danish ice charts for belts of 1° latitude from 80°N. southward. The 30-year period 1921 to 1939 and 1946 to 1956 was used. Unfortunately, these ice charts are available only until August and not for September, the month with the smallest ice cover. Approximate values for September for the same 30-year period were obtained as follows: From the U.S. Hydrographic Office (ref. 9) mean charts the average ice cover was determined for August and September. The relation of the two areas was then used to reduce the August value determined for the 30-year period from the Danish charts to a comparable September value. As most of the melting takes place before August, the possible error introduced by this approximation will be small.

Subtracting the September value from the April value gives the export during winter. The result, however, is the area of ice carried southward of a certain concentration. The real areal extent of the ice export was obtained by multiplying by the mean ice concentration at 80°N. for this period, which was again obtained from the U.S. Hydrographic Office publication (ref. 9).

The results obtained in this way can only be a first approximation, because the pack ice area during winter moves southward into latitudes where the assumption of no melting in winter becomes questionable.

To determine the possible amount of melting it has been estimated how far south the calculated winter ice export would cover the observed pack-ice area of April. The southern boundary was found to be 71.5°N. A graph of the pack-ice area was constructed in which the western edge was taken as a straight line and its width always perpendicular to the direction of the current. This graph is shown in Fig. 1. Disregarding irregular fluctuations in width caused by the coastline of Greenland, the curve for September is rather smooth, probably because of a gradual decrease of melting towards the north during the summer. The curve for April, however, shows a very pronounced break around 72°N. The marked decrease south of 72°N. is prob-

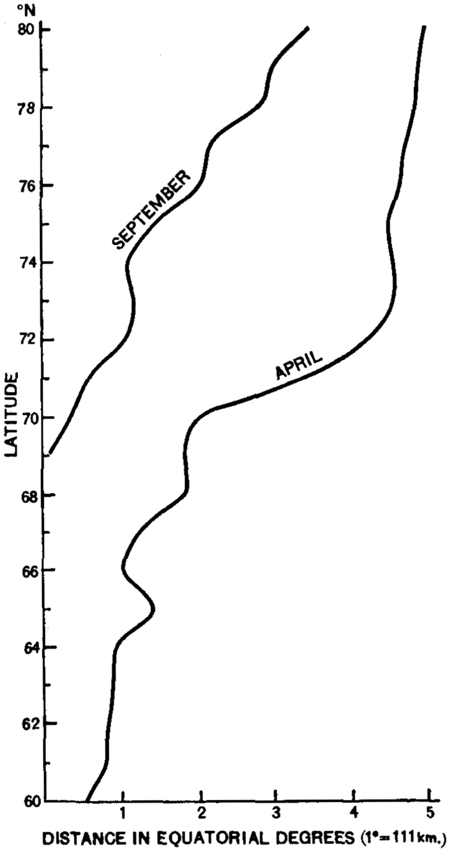

Fig. 1. Width of pack-ice in April and September.

ably the effect of melting, which seems to increase sharply south of this latitude. Neither radiation nor atmospheric circulation can account for this abrupt decrease in width. A possible explanation may be the branching off of the Jan Mayen-East Iceland Current in this area. It is possible that a branch of the warm current moves northward into the area between the East Greenland Current and its branch to the east and causes this rapid melting of the pack-ice. As the width of the ice decreases much more slowly with latitude farther south, indicating a new equilibrium between ice transport from the north and the rate of melting, this oceanographic explanation would seem to be satisfactory.

As the transport of ice during the winter fills the pack-ice area down to 71.5°N., the ice found north of this latitude in September must have been transported southward across 71.5°N. Therefore, the total ice area south of 80°N. in September must correspond to the total ice area south of 71.5°N. in April — if no melting takes place. It is found that the actual area is smaller than the postulated one. Therefore, the "missing" ice must have melted between September and April.

If no melting took place, the ice area actually reported in April would be larger. Accordingly, this melted area must be added to the overall transport value. This will bring slight adjustments to the area of freshly imported ice. The final southern limit of newly imported ice will be near 71°N. and the amount of melting will be 50,740 km.^{2}.

Table 2. Total ice export southward in winter (September 15 to April 15) across different latitudes (in km.^{2}).

	80°	*75°*	*70°*	*65°N.*
Ice area observed, April	908,840	617,210	363,010	142,900
Ice area observed, September	280,900	104,400	16,300	0
Areal transport	678,680	563,550	397,450	146,960
Mean ice concentration	0.857	0.857	0.814	0.771
Ice transport	581,630	482,960	323,520	113,310

From these results, areal and actual ice export can be calculated for the period September 15 to April 15. The results are given in Table 2. Using the wind-caused ice export given in Table 1, the ice export by current can be obtained. For 80°N. the result is 396,375 km.^{2} ice and for 65°N., 78,900 km.^{2}. The comparison of these values with those given in Table 1 shows the relatively high importance of the wind-caused ice export during winter. The wind export is about one-half of the current export and one-third of the total export. This

Table 3. Monthly flux values for different ocean currents as percentage of total annual flux. (smoothed by: ¼ (month$_1$ + 2 month$_2$ + month$_3$)).

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*	*Ratio of min. to max.*
Bering Strait	6.1	4.8	3.7	4.3	5.6	8.4	11.9	14.3	13.5	10.7	9.0	7.6	1:3.8
Faeroe-Shetland	12.0	13.5	9.5	5.9	7.0	7.8	6.9	5.3	5.4	7.7	9.2	9.9	1:2.6
Bear Island	13.4	10.3	7.9	5.4	5.0	6.3	5.7	5.0	6.8	8.5	11.2	14.6	1:2.9

Surplus or deficit, mid-September to mid-April (actual winter flow compared to hypothetical uniform flow throughout the year):

Bering Strait	− 7.5 per cent
Faeroe-Shetland	+ 9.2 per cent
Bear Island	+13.7 per cent

shows clearly that the wind component must certainly not be neglected, and transport estimates based solely on considerations of current cannot lead to realistic values.

It is of interest to compare the mean speed given by Koch[15] with the mean speed that would result from the values given in Tables 1 and 2. Koch's values refer to the area of the East Greenland Current proper, whereas the export values at 80°N. refer to a width of 300 km. The ice export figures must therefore be reduced by the wind-caused export in the region to the east of the East Greenland Current, i.e., by one-third of the wind-caused export. The areal export for the East Greenland Current region would then be 606,630 km.^{2}. With a width of the current of 200 km. this would give a mean drift speed of 14.3 km./day, a value that compares fairly well with the average of 15 to 17 km./day given by Koch.

Annual ice export — total and by current

Although the wind export has now been estimated for each month, the export by current is known only as a total for 7 months. Therefore, to arrive at an annual transport, the variations in the current speed during the year have to be considered.

Significant variations in the current speed in the course of the year are to be expected. Table 3 gives the relative flux values for the better-known currents of the Arctic after Timofeyev[16], Tait[17], and Lee[18]. The table shows that all currents vary significantly and even if the winter period of 7 months is compared with the rest of the year, the variation between the seasons is still considerable. The Atlantic currents have their maximum in winter but the Bering Strait maximum is found in late summer. As the volume of water transported by the Atlantic currents is far larger than the import through the Bering Strait, and as the Atlantic current is much nearer to the region under investigation, it seems more likely that the East Greenland Current is in phase with the Atlantic currents rather than with the Bering Strait current.

Other observations indicate the opposite: Koch[15], when investigating the speed of the East Greenland Current from drift observations, did not mention any seasonal variation in the drift speed. Vowinckel and Orvig[2] found no variation in the drift speed in the Arctic Ocean. As the wind-caused drift is known, and found to be significantly smaller in summer than in winter, this would mean a substantial increase in current speed in summer, contrary to the observations of the Atlantic current.

Therefore, the time of occurrence of maximum speed and the variation in speed remain uncertain for the East Greenland Current. However, some calculations can determine at least the magnitude of the resulting uncertainty in the ice export.

For this purpose the wind transport was eliminated at 80°N., for the period September 15 to April 15. The result is an areal export by current of 462,500 km.^{2} or, with a width of the current of 200 km., 10.2 km./day. This result is in good agreement with Mosby's[1] estimate of 8.6 to 12.9 km./day.

The ratio of minimum to maximum speed was assumed from the results of Table 3 to be 1:3. The annual variation was considered to follow a sine curve. This is not strictly correct, but the differences in the results will be slight for different shapes of the annual curve.

It was further assumed that the monthly values have to fulfil the requirement that the total areal transport from September 15 to April 15 is 462,500 km.^{2}.

The calculations were carried out for one medium and two extreme possibilities of the annual variation in export:

1. Maximum current in December.
2. Maximum current in June.
3. No annual variation.

The results obtained for the three alternatives show that the difference between the extremes is quite large. The pencentage difference, however, will be less for the total ice export, since the wind-caused export remains constant. But even so, the maximum value is still 150 per cent of the minimum.

It must be considered that the current speed has to satisfy also the requirements of water export from the Arctic Ocean. With the three assumptions the following mean speeds would result for a width of 200 km.:

(1) 9.16 km./day
(2) 14.71 km./day
(3) 10.75 km./day

Mosby[1] uses a width of the East Greenland Current of 200 km. and a depth of 100 m. Considering the temperature profiles given by Chaplygin[19], this depth seems to be rather shallow. Using a depth of 150 m. a mean between Chaplygin's and Mosby's estimates, and using Timofeyev's two estimates for the flux, 93,500 and 117,500 km.^{3}/year, the required average speed would be 8.5 or 10.7 km./day. Considering that the speed probably decreases with depth, it seems likely that the surface speed of the current lies between assumptions (1) and (2), but nearer to (2) than to (1). The resulting ice export should lie between 950,000 and 1,000,000 km.^{2}. Comparing this figure with Gordienko and Karelin's[3] estimate of 1,036,000 km.^{2} it will be seen that quite independent estimates give nearly the same result. That the Russian estimate is about 5 percent higher may well be caused by the different observational period used.

Variations in annual ice export

The available results permit estimates of the variability of the ice export. For the wind-caused export there are no further difficulties. For the total ice export, however, melting and freezing must again be considered. This is so because the annual variations in total export can only be determined from the variations in ice extent in a particular month from one year to the next, and both melting and freezing take place in the course of one year.

The relation between ice extent and amount of freezing and melting was examined. It became apparent that the greater the ice cover in April, the greater the likely decrease (melting effect) towards August, and the reverse holds for the period August to April of the next year. This means that freezing and melting have, on the average, the tendency to dampen the variations resulting from ice import.

It can be concluded that:

1. The variations in ice extent over a year are on the average the result of fluctuations in ice import.

2. The variations of ice cover from year to year are smaller than the variations in import, as freezing and melting have the tendency to counterbalance the extremes in ice cover.

The calculated variations in total ice export from areal extent figures will therefore be rather smaller than the real values.

For all further calculations the areal ice extent figures were converted to an ice concentration of 1.0. The differences between individual years were determined by using the extent of ice at the end of March. The average ice concentration for April was estimated, after U.S. Hydrographic Office (ref. 9), to be 0.9.

1. *Variations in wind-caused ice export.* The frequency distribution of the deviation from the mean of monthly

and annual wind-caused ice export, as well as their averages for 80°N. and 65°N., show that the mean deviations are extraordinarily high, especially for 65°N. Results from individual months have in fact little meaning in both latitudes. This sheds some doubt on the significance of Koch's[15] mean speed values, derived from a few drift observations. Part of this high variability is cancelled if full years are considered.

The deviations along 65°N. are quite independent of those at 80°N., as might be expected.

2. *Variations in current — and total export.* The values for 1921-56 (excluding 1940-45) show that, whereas the mean deviation of the wind-caused ice export at 80°N. amounted to 16.0 per cent of the mean value, the same figure for the current export is 15.6 per cent, or practically identical. The current therefore seems to be no more stable than the wind. These variations in the current speed are not caused by the local wind. The correlation coefficient between the yearly deviations of the long-term mean wind- and the current-caused exports is −0.59. It is not clear why the correlation is negative. As no information is available on the reasons for the variation in current speed, speculation about the causes for this negative correlation seems futile at present.

Since the ocean current is as variable as the wind rather extended oceanographic observations are necessary to obtain reliable transport values for this current. This makes understandable the discrepancies that are found in the estimates of different authors of the water transport by the East Greenland and West Spitsbergen currents (discussed by Vowinckel and Orvig[2]). Therefore, indirect methods for the determination of these two currents, as used by Mosby[1], should certainly be followed up.

Table 4 gives the ice transport by current, calculated for the three possibilities of seasonal variation in current speed. If such variations in the surface speed of the East Greenland Current exist, it can be assumed that the transported water masses fluctuate proportionally. This must be considered when the overall fluctuations in heat gain for the Arctic Ocean are estimated. The results of considering these fluctuations in water transport (without postulating fluctuations in temperature) is a mean deviation of $24{,}776 \times 10^{15}$ cal./year. The heat content of the exported ice and of the water masses was taken from the results given by Vowinckel and Orvig[2]. This mean deviation must be compared with the overall average heat gain by ocean currents and ice export, which is after Mosby[1] and Vowinckel and Orvig[2] around $530{,}000 \times 10^{15}$ cal./year. The mean deviation would therefore be 4.7 per cent of the total heat gain and the deviation of the highest quartile, 8.3 per cent.

These variations are not the only ones that can be expected in the Arctic Ocean. It seems probable that a decrease or increase in the major water export would require similar variations in the import, i.e., mainly in the Atlantic inflow. This could very easily increase the mean deviation to 10 per cent.

A difference from the long-term mean, for a particular year, of 15 to 20 per cent in the heat gain from ice and currents is quite likely for the Arctic Ocean.

However, these fluctuations are mainly rather short-term occurrences.

Table 4. Ice transport by current, calculated under different assumptions for variation in East Greenland Current speed (in km.^{2} at 80°N.).

Assumptions: (1) maximum export in December; (2) maximum export in June; (3) no annual variation

	Jan.	*Feb.*	*March*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
(1)	66,900	57,980	46,280	34,570	26,200	20,810	23,290	26,890	35,990	51,540	66,900	69,690	527,040
(2)	45,460	60,150	80,280	100,590	116,060	107,460	103,170	78,230	62,440	53,300	45,460	40,620	893,220
(3)	58,860	58,860	58,860	58,860	58,860	52,320	52,320	45,780	45,780	52,320	58,860	58,860	660,540

If 5-year running means are used, instead of individual years, the mean deviation drops from 91,980 to 32,690 km.^{2}, and the highest quartile from 171,580 to 62,240 km.^{2}, in other words, to something rather more than one-third.

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PRELIMINARY GEOMORPHOLOGICAL STUDY OF A NEWLY DISCOVERED DORSET CULTURE SITE ON MELVILLE ISLAND, N.W.T.

During the summer of 1962 a Geographical Branch field party carried out geomorphological investigations on Melville Island, in co-operation with the Polar Continental Shelf Project, Department of Mines and Technical Surveys, Ottawa. The party consisted of W. E. S. Henoch of the Geographical Branch, his student assistant J. Chalk (University of British Columbia), and the pilot of the Super Piper Cub, B. Warnock. The main objective of the field work was the study of emerged shore features.

In this paper I list the prehistoric sites on Melville Island recorded by other explorers, describe the newly discovered prehistoric site in McCormick Inlet, give the account of the investigations that were carried out, and summarize their results.

Reported campsites on Melville Island

There were no Eskimos living on Melville Island when it was discovered by Parry in 1819 and as far as is known