Institute of Polar Studies
Report No. 19

Some Estimates About the Size and Variation of the Antarctic Pack Ice Belt

by

Eberhard Vowinckel
Institute of Polar Studies
and
McGill University

March 1966

The Ohio State University
Columbus, Ohio 43210

INSTITUTE OF POLAR STUDIES
125 SOUTH OVAL DRIVE
THE OHIO STATE UNIVERSITY
COLUMBUS 10, OHIO

INSTITUTE OF POLAR STUDIES

Report No. 19

SOME ESTIMATES ABOUT THE SIZE AND VARIATION OF THE ANTARCTIC PACK ICE BELT

by

Eberhard Vowinckel
Institute of Polar Studies
and
McGill University

The Ohio State University
Columbus, Ohio 43210

March 1966

CONTENTS

INTRODUCTION

The extent to which an ocean area is covered by ice is significant for the energy budget of the area, because (1) the existence of ice changes the albedo of the area, and therefore the absorbed solar energy, (2) its low thermal conductivity alters the energy expended by the ocean in the form of long wave radiation, sensible and latent heat, and finally, (3) freezing and melting frequently do not occur at the same place, so that the movement of ice may export or import energy into a given area.

The pack ice belt surrounding Antarctica is by far the largest sea ice area in the world. Although there is a paucity of data, it seems worthwhile to analyze the available information in order to obtain at least a tentative picture and to draw attention to the most critical observations which are required for a better understanding of the pack ice belt.

ICE DISTRIBUTION

During the summer months good observations of ice distribution are available from whaling ships. For the winter, however, observations are scanty and our knowledge is based essentially on the results from the "Discovery". The best summary about the ice limits, based on these results, is given by Mackintosh (1940). The uncertainties even in the best known area, the Falkland Island Dependencies, is shown by Heap (1964) who especially draws attention to the large variations from year to year. In addition, there are the ice atlases, Deutsches Hydrographisches Institut (1950), Morskoi Atlas (1950), and U. S. Hydrographic Service (1957-58). The difference between these atlases and the maps given by Mackintosh is not very great, and in the present investigation the maps of the U. S. Hydrographic Office were used because they have the added advantage of giving ice concentration in the pack ice belt.

The area covered by ice of any concentration was evaluated on a monthly basis for the pack ice belt as a whole and in the following six subdivisions:

A_1	60°W - 20°W	B_2	90°E - 160°E
A_2	20°W - 20°E	C_1	160°E - 130°W
B_1	20°E - 90°E	C_2	130°W - 60°W

The results are given in Table 1. The area affected by ice varies very much indeed, very nearly in the ratio 1:4 between the minimum in March and the maximum in September. There are significant regional differences. During all months the largest area per unit length of 1° longitude occurs in the western Weddell Sea. This is most pronounced in autumn, when the ice area there is ten times as large as in the next area to the east, whereas in spring the figures are much more even, as shown by the following values:

	A_1	A_2	B_1	B_2	C_1	C_2	
Area affected by ice, March	50	5	7	4	18	12	km^2/1°long.
Area affected by ice, Sept.	101	91	62	35	54	33	

This ice accumulation in the Weddell Sea is the result of the westward-moving ocean current along the Antarctic coast, which transports the ice into the Weddell Sea where it is blocked from further westward movement by the Antarctic Peninsula. However, this westward current is ice-covered during practically the whole year because the Antarctic divergence line (as given by the U. S. Hydrographic Office) remains south of the pack ice border, so that the differences in the relative amounts of ice in autumn and in spring may be due to the following causes:

1. The Antarctic coastal current has an annual variation in speed, with its maximum in autumn, or

2. The rate of melting in the Weddell Sea is less per unit than in other regions.

The lack of observations precludes an evaluation of these two possibilities, but it can be stated that the second is certainly significant. In summer, when ice production in the pack ice belt stops, ice is lost, by export, from areas other than the Weddell Sea. In these areas largely freed from ice, absorption of solar radiation, which at that time is at its maximum, is increased so that further melting is facilitated. The process, therefore, is self-strengthening. In the Weddell Sea, however, the melting which takes place is at least partly compensated by ice import from the east, with the result that the albedo is kept high; accordingly, the absorbed radiation is low and melting is retarded. In addition, the remaining ice will produce a stabilizing influence on the atmosphere; a surface inversion allows the moisture from the surface to be retained in the lowest air layer. The result is a large amount of clouds with stratiform layers. These arguments are strongly supported by the maps of cloud amount and type for summer (Vowinckel, 1957), which show maxima of cloud amount and of stratiform clouds over the ice-covered parts of the Weddell Sea. This cloud development decreases the amount of incoming solar radiation with the subsequent further decrease in melting. Whether these processes are sufficient to cause the excess of ice in the Weddell Sea in autumn or whether variations in the ice transported by the ocean current also contribute, can be decided only by more observations. It is, however, quite apparent that the Weddell Sea area has a fundamentally different pack ice regime from that of the rest of the Antarctic pack ice belt.

For further study, it is necessary to convert the areal extent of any ice cover, as given in Table 1, into areas of ice cover with the ice concentration 1.0 (i.e. to eliminate all open water areas within the pack ice). The U. S. Hydrographic Office atlas gives five coverage types, <0.1, 0.1-0.5, 0.5-0.8, 0.8-1.0, >1.0. These areas were evaluated separately for each month for which concentration data was given. In the winter months, for which no additional information is available, the coverage was assumed to be 0.9 and 1.0. The resulting areal extent of the pack ice with the concentration 1.0 is given in Table 2. These figures show essentially the same results as Table 1, except that the differences between spring and autumn are accentuated, as expected, since the concentration is least in autumn. The maximum amount of ice in all areas occurs in September, whereas the minimum occurs between February and March, so that the period of ice increase is slightly longer than the period of decrease. This is in accordance with the air temperature regime of polar regions, where the duration of temperature rise generally is significantly shorter than the temperature fall. However, the variation of pack ice through the winter shows no effect analogous to the "Kernlose" winter of the air temperature regime; ice amount increases until the returning sun increases the energy input into the sea surface. It may be noted here that the conditions in the northern hemisphere are quite different, the changes during the last months of winter being much smaller.

Figure 1 gives the annual variation of the ice cover for selected areas of the Antarctic, all values being expressed in percent of the September value. The difference between the Weddell Sea (A_1) and the rest of the area becomes apparent; in the Weddell Sea the ice amount changes much more smoothly throughout the year than it does elsewhere.

EVAPORATION WITHIN THE PACK ICE BELT

In the pack ice belts, most of the energy exchange with the atmosphere via sensible and latent heat takes place from the open water areas, the leads and polynyi. In the Antarctic these openings seem to be larger in winter than they are in Arctic pack ice (Wright and Priestley, 1922; Simpson, 1919-23). There are practically no winter observations available for calculations of turbulent transport (see the discussion of evaporation, Viebrock, 1962), but an approximation is possible from the general information about the temperature regime.

The main difficulty is in determining the position of the leads in relation to the ice border and the continent. According to the sources above, leads open during each intense storm, even in the far south. The U. S. Hydrographic Office maps give ice concentrations for October and November but not for the rest of the winter. Using the concentration along each 20° longitude and averaging, Figure 2 was constructed. The y-axis gives the percent distance from the coast to the pack ice border and the x-axis gives the accumulative open water area (found to the north) of the percent distance from the pack ice rim. For further calculation, it was assumed that the same relation is valid for the whole winter period; the most likely error is an underestimation of the open area near the coast. With strong south winds on the rear of a cyclone, the whole pack ice drifts northward with the formation of open water near the continent (Wright and Priestley, 1922). Moreover, during October and November some melting may have already taken place in the north, increasing the open water in the north from the winter values. Using isopleths of monthly temperatures in relation to the pack ice border (Vowinckel, 1957), mean monthly temperature was determined for each ten percent interval of the pack ice belt. Similarly, a mean scalar wind force was determined for those intervals from the map in Vowinckel (1957). Those figures are for January, but no other data is available, and the circulation does not change sharply from season to season, so the values may be regarded as representing the whole year. Separate calculations were made for relative humidity of 90 percent and 95 percent. The sea surface temperature was assumed to be -1.8°C in all open areas between the pack ice.

The calculations were done with the revised Sverdrup formula (Vowinckel and Taylor, 1964). Vowinckel (1965) notes that the values of evaporation and sensible heat flux obtained in this way are only approximate, because a proper evaluation requires daily calculations, which are not possible at present.

Figure 3 shows the mean daily energy transport by evaporation, Q_e, and sensible heat flux, Q_s, for June-August in relation to the distance from the pack ice rim. In winter, all over the pack ice, the sensible heat is the more significant, especially near the continent, where lower air temperatures reduce the water holding capacity and hence the evaporation.

Figure 3 shows that the energy loss depends on the latitude of the open water in the pack ice. For the same amount of open water the evaporation may vary by a factor of 2, depending on the location.

The evaporation and sensible heat fluxes from the average cm^2 of open water in the whole pack ice belt are given in Table 3. For comparison, the table also gives the values for the pack ice belt in the Norwegian Barents Sea between 65° and 70°N. The northern hemisphere winter figures are significantly higher than the southern ones, especially for sensible heat flux. The higher frequency of anticyclonic situations in the north, with the development of surface inversion and low temperatures, is responsible, while in the south the pack ice belt is in a cyclonic belt. The difference between the two hemispheres is smaller for latent heat, because the changes in water vapor pressure with decreasing temperature at low temperatures are small.

To obtain the flux contributed by the open water to the average cm^2 of the whole area, the percent frequency of open water in a particular month must be considered. The results of this calculation are given in Table 4, using relative humidities of 90 and 95 percent. In winter the loss is about 200 cal/cm^2 month and does not alter the general temperature more than about 1°C. However, a comparison with the values given by Vibrog (1962) shows the importance of these small areas in the overall evaporation and sensible heat transport of the area. Furthermore, Table 4 shows that during winter a chance in ice cover by one percent increases the energy loss from the ocean by 50-60 cal/cm^2 month. Expedition reports show that weather patterns are very variable throughout the pack ice belt and that ice concentrations can change by ten percent, resulting in large changes in energy transfer.

Drygalski (1903) and Wright and Priestley (1922) report very large deposits of hoar frost on the pack ice. This indicates that a significant portion of the latent energy of evaporation is converted into sensible heat directly at the surface and that the water vapor functions as an energy carrier for only a short distance. This should probably occur in all pack ice areas where the cold ice surface is intimately mixed with the warm water surface. However, the observations do not indicate similar amounts of hoar frost in the central Arctic Ocean. The winter evaporation figures there are less than half of the southern pack ice ones (Vowinckel and Taylor, 1964), but similar amounts of hoar frost should be observed in the pack ice of the Norwegian-Barents Sea.

ICE TRANSPORT

In the discussion so far, the ice could be regarded as stationary, exhibiting only melting and freezing, as revealed by the monthly distributions. Nazarov (1963), when discussing the ice distribution of the world oceans, uses only this information, which is certainly permissible for net mass changes but not in considering energy balance. Because of ice movement, freezing takes place in the south and melting in the north, that is, the consumption and release of energy occurs in different areas, and therefore, melting and freezing must be considered independently.

Movement of the ice is caused by wind drift and transport by ocean currents.

Wind Drift

The relation between ice drift and wind speed and direction in the central Arctic Ocean was evaluated by Zubov (1943). The north polar ice is generally thicker and more densely packed than that in the Antarctic seas, but in the north there is little difference in drift speed between summer and winter, with their quite different ice densities (Vowinckel and Orvig, 1962), so Zubov's formula should also be applicable to the south.

For the calculation of wind drift using Zubov's formula

$$V = 13000 \frac{dp}{dz}$$

where V = drift speed in km/day

and $\frac{dp}{dz}$ = pressure gradient in mb/km.

the pressure gradients along the ice rim were determined using the mean pressure distributions after Vowinckel (1955) and Vowinckel and van Zoon (1957). Probably, this formula underestimates the drift speed.

Considering the mean pressure distributions, for transport over the ice rim (which involves south-north transport), only the south-north average pressure gradient needs to be considered, because the north-south gradient cannot create any compensating import. On the other hand, the effectiveness of eddy wind transport (when daily synoptic maps are used) depends on the relative duration of the southerly and northerly winds and on the rate of melting which takes place before the pack ice field drifts back to the ice rim. Because the required data is lacking, the effect of eddy transport will not be considered in this report.

The effectiveness of wind drift also depends on the ice concentration at the edge of the pack ice belt. This was estimated as an average for each sector over the distance of south winds. The ice movement due to north-south wind transport are given in Table 5. The ice export is quite substantial, the total being nearly twice the total of wind and current export of the Arctic Ocean. The largest amount is contributed by the Weddell Sea sector. The table shows, moreover, a seasonal variation with the minimum in autumn and the maximum in spring. Twelve percent of this variation is due to the larger circumference of the pack ice at its maximum northward extension. As the pressure pattern does not change substantially, the other 88 percent is caused by the seasonal variation of the pack ice rim with respect to the pressure pattern.

Ocean Currents

The ice export by ocean currents is significantly higher than that by wind transport. Unfortunately, observations of both current direction and speed are inadequate. The two main sources of information for current direction are the U. S. Hydrographic Office atlas (1957) and the Morskoi atlas (1950). The U. S. atlas gives only one distribution for the year, whereas the Morskoi atlas gives summer and winter maps. The difference between the two seasonal maps, however, is small and has no significant influence on the calculations.

The current speed normal to the ice rim was determined for 500 km sections, separately for each month. The resulting transport values were again corrected to ice concentration 1.0. The comparison between the two calculations, using the U. S. Hydrographic Office atlas and the Morskoi atlas, is given in Table 6. The Morskoi atlas maps give values nearly 1.9 times those from the U. S. Hydrographic Office map. The differences are higher in the eastern Indian Ocean and Pacific sector than in the Atlantic and western Indian Ocean. Since the observations are much more numerous in the latter sector, this discrepancy is at least partially caused by insufficient data. The two maps, however, show a major difference in the circulation pattern: while the American source assumes a divergence line within the subantarctic trough with a sharp change in direction of the current and little meridional component on either side, the Russian source assumes larger cyclonic vortices and a corresponding wide belt with a high meridional component in the current. This is clearly evident from Figure 4, where the streamlines constructed from the two sources are superimposed.

Concerning current speed, the American source gives for all areas only the statement: less than 0.5 knots. The Russian authors give dynamic maps, permitting evaluation of the speed for all areas around Antarctica (Maximov, 1958; Kleipikov, 1963; Zverev, 1963; Zverev, 1963; Moroshkin, 1960; Ivanov, Smetanina, 1960; Tareyev and Fomichev, 1960). Furthermore, Tareyev and Fomichev (1963) have combined the geostrophic calculations with the calculation of wind stress in the ocean, using for the wind values typical daily synoptic maps for zonal circulation type of winter and summer. For the present calculations these latter values of total drift speed were used since they proved to be the most homogeneous material with a complete coverage of the area under discussion. For the Pacific sector these values were compared with the measurements as reported by Moroshkin (1960). The observed speed was reasonably near the calculated values of Tareyev and Fomichev, being slightly higher on the one cross section and slightly lower on the other. As the cross sections were 60° longitude apart, the Tareyev and Fomichev values seem to be of the right order of magnitude and seem to show the correct longitudinal variations. In the Davis Sea, comparisons were made with Zverev (1960a, b) although he distinguishes only between currents less than and greater than 1 knot. Here the comparison showed that the values of Tareyev and Fomichev are rather low.

Thus, the Tareyev and Fomichev values can be accepted at least as a first approximation. Table 7 gives the resulting transport values from the different authors. Although in the Atlantic-western Indian Ocean sector the difference between the two sets is small, in the eastern Indian Ocean-Pacific sector the Morskoi atlas values are much larger.

To consider freezing and melting within the pack ice area and to the north of it, the results of Tables 2, 5, and 7 must be combined. If the pack ice area is stationary, the ice exported and melting in the north is balanced by that forming in the south:

$M=E=F$, where

E = Export
M = Melting
F = Freezing

If the ice boundary receded by an amount larger than the export, no freezing takes place, $M = \Delta A$; if, however, the export is larger

$M = E$ and $F = E - \Delta A$, where ΔA is the change in ice area.

If the ice boundary expands by more than the export

$$F = \Delta A \quad M = 0$$

whereas with the export larger

$$F = E \quad M = E - \Delta A.$$

Because Table 2 gives the ice extent for the fifteenth of each month and the values in Tables 5 and 7 refer to the interval of the full month, the values of Table 2 were converted by interpolation to the ice extent for the first of each month. From these new values, the changes in ice cover taking place during a calendar month were calculated. The combination of these values with the export values gives the value of melting and freezing during a month (Table 8). The values given for the individual sectors have the shortcoming that the zonal transport from sector to sector could not be considered, either in the pack ice belt or farther north. The totals given in the last column, therefore, are obtained by summing up Tables 2, 5, and 8 before the calculation of freezing and melting. Thus, in these totals inter-zonal transport is ignored. The totals derived by summing up Table 8 are indicated by an asterisk. It is apparent that the real values must lie somewhere between these two extremes. The question arises whether splitting into smaller areas would have given a different result. Experiments with a few 10° longitude units showed differences that are small compared with the large uncertainties of the ocean currents.

The results in Table 8 derived from the American and Russian sources are even more contradictory than in the previous tables. Without further information it is not known which one is nearer reality. The Russian values certainly seem very high; the total of freezing and melting areas is higher than the maximum ice area, implying that the average life of the ice is under one year. The information from Wright and Priestley (1922) and Drygalski (1903) indicates that most of the Antarctic pack ice is only one year old, and that ice older than two years is rare. Furthermore, it is quite possible that the ice export in winter involves much very young ice which has recently formed near the ice rim. Therefore, the figures based on the streamlines of the Morskoi atlas may be correct. In the present investigation, Table 8a is regarded as more representative of the actual conditions. It is understood that this is a compromise, since U. S. Hydrographic Office streamlines are combined with the Russian speed results, so that the basic material is not homogeneous.

The amount of freezing in Table 8 is equal to the melting, so that it gives the turnover of ice (that is, seasonal variation plus export). The true export is given by Σ melting minus seasonal change, shown in Table 9 under Σ Export. It is apparent that the real export is only 15-20 percent of the total melting or freezing that takes place.

Ice Volume

To transfer the areal ice values given so far into volume, ice thicknesses are required. Apart from sporadic statements in expedition reports, no observations of this type are available. Nazarov (1963), when estimating the ice volume in the world oceans, relates the ice thickness in percent of its maximum thickness to ice extent in percent of its maximum, using results mainly from the Baltic Sea as a basis. To apply this method, the maximum ice thickness is required, but this is totally unknown for the melting and freezing part of the pack ice belt. Furthermore, the maximum and minimum thickness of the permanent pack ice belt are required. An order of magnitude calculation can be made, using Nazarov's relation and assuming that the average thickness of the pack ice belt varies between 2 m and 0.5 m, and that the freezing, to compensate for export, creates ice of the average thickness of the pack ice during the month when the export takes place. The results are given in Table 9. The values are very high indeed, representing large energy storage and release.

Nazarov (1963) gives only values for area and ice in temporarily ice-covered areas. His results of the total ice area are presented only in a graph from which no exact values can be interpreted. His volume values must be compared against $\Sigma-$ in Table 9, because he disregarded the export. His value is about one-third lower than the present result. As far as his graph permits a conclusion, the reason seems to be that the ice concentration he assumed in winter is significantly lower than the one used in this investigation. Both assumptions are purely arbitrary due to the lack of any observations. A careful investigation of satellite pictures might result in better substantiated assumptions of ice concentration.

It can be concluded from the above discussions that many more precise observations within the pack ice belt are required before reasonably well-founded qualitative statements can be made. However, with the present information, a qualitative picture can be obtained which shows the importance of the ice in energy budget considerations in the southern oceans.

ACKNOWLEDGMENTS

This study is part of a continuing interest the writer has in meteorology of the polar regions. This phase of the study was funded partly by The Ohio State University through the Mershon Fund and through the Office of Research. Report costs, including typing and drafting, were borne by the Institute of Polar Studies at The Ohio State University.

The writer is grateful to the Institute of Polar Studies for its encouragement to carry out this research. Special thanks are extended to Dr. Fritz Loewe and Dr. Colin Bull of the Institute for their critical comments and editing of this report.

REFERENCES

Deutsches Hydrographisches Institut (1950), Atlas der Eisverhältnisse des nordatlantischen Ozean und Übersichtskarten der Eisverhältnisse des Nord- und Sudpolargelieber: Hamburg.

Drygalski, E. (1903), Deutsche Südpolar Expedition, Gauss: Institut für Meereskunde, Berlin.

Heap, J. A. (1964), Pack Ice, in Antarctic Research: R. Priestley, R. J. Adie, G. de Q. Robin, Ed., London, p. 308-317.

Ivanov, J. A., Smetanina, N. S. (1960) Geostrophic currents in the Indian Sector of the Antarctic waters: Oceanological Researches No. 2, p. 100-103.

Kleipikov, V. V. (1963), Weddell Sea hydrology: Arct. and Antarct. Inst., Trudy of Soviet Antarct. Exped., v. 17, p. 45-93.

Mackintosh, N. A., Herdman, H.F.P. (1940), Distribution of the Pack Ice in the Southern Ocean: Discovery Reports, Cambridge University Press, Cambridge, England, vol. 19, p. 285-296.

Maximov, I. V. (1958), On the study of the west coastal Antarctic currents: Inf. Bull. Soviet Ant. Exped., No. 2, p. 31-36.

Moroshkin, V. V. (1960), Characteristics of the circumpolar current in the Pacific Ocean: Oceanological Researches, No. 2, p. 86-90.

Morskoi Atlas (1950-1958), USSR Ministerstvo Obrony: Moscow, 3 Vol.

Nazarov, V. S. (1963), Ice in the waters of the world oceans and the variation of its state (in Russian): Oceanology, V. 3, p. 243-249.

Simpson, G. C., British Antarctic Expedition 1910-1913: Vol. 1-3, Meteorology, Calcutta 1919-23.

Tareyev, B. A., Fomichev, A. V. (1960), Dynamic map of the Pacific sector of the Antarctic waters: Oceanological Researches, No. 2, p. 104-107.

Tareyev, B. A., Fomichev, A. V. (1963), On the surface currents of the Southern Ocean: Oceanological Researches, No. 8, p. 24-33.

U. S. Hydrographic Service 1957-58, Oceanographic Atlas of the Polar Seas: U. S. Navy Hydrographic Office, Washington, D. C. 1957-58.

Viebrock, H. (1962), The transfer of energy between the ocean and the atmosphere in Antarctic regions: J. of Geophys. Res., V. 67, p. 4293-4302.

Vowinckel, E. (1955), Southern Hemisphere Weather Map Analysis: 5 year mean pressures: Notos, V.4, p. 17-48.

Vowinckel, E., van Loon, H. (1957) Das Klima des Antarktischen Ozeans, Teil III: Archiv Met. Geophys. Bibl. Serie 3, p. 75-102, Vol. 8.

Vowinckel, E. (1957), Climate of the Antarctic Ocean, in Meteorology of the Antarctic: ed. van Rooy, Pretoria, S. Af., p. 91-110.

Vowinckel, E., Orvig, S. (1962), Water balance and heat flow of the Arctic Ocean: Archiv, V. 15, No. 3, p. 205-223.

Vowinckel, E., Taylor, B. (1964), Evaporation and sensible heat flux over the Arctic Ocean: Sci. Rep. No. 10, Contr. No. AF 19(604)-7415, Air Force Cambridge Res. Lab., 29 pp.

Vowinckel, E. (1965), Energy budget over the North Atlantic, January 1963: Arctic Met. Res. Group, McGill University, Publ. in Met. No. 78.

Wright, C. S., Priestley, R. E. (1922), British Antarctic Expedition 1910-13: Vol: Glaciology, London, England.

Zubov, U. N. (1943), Arctic Ice: Moscow.

Zverev, A. A. (1963a), Davis Sea Hydrology: Arct. and Antarct. Inst., Trudy of Soviet Antarct. Exped., V. 17, p. 94-143.

Zverev, A. A. (1963b), Currents of the Indian Sector of the Antarctic: Arct. and Antarct. Inst., Trudy of Soviet Antarct. Exped., V. 17, p. 144-155.

TABLE 1

Area covered by any ice

	J	F	M	A	M	J	J	A	S	O	N	D	
A_1	2697	2120	2109	2818	3091	3419	3809	3920	4041	3249	3495	3121	km^2x10^3
A_2	799	422	193	994	1641	2887	3331	3464	3612	3302	2530	2215	
B_1	808	775	524	842	1495	2905	3759	4033	4362	4104	3580	1464	
B_2	791	432	256	733	1076	1904	2212	2318	2466	2352	1942	1144	
C_1	1857	1073	1267	1658	1985	3276	3493	3618	3797	3725	3102	2813	
C_2	1160	1047	811	1091	1191	1665	1964	2116	2319	2205	1872	1283	
Total	8112	5869	5160	8136	10487	16056	18568	19469	20597	19437	16521	12040	

TABLE 2

Pack ice area of ice concentration 1.0

	J	F	M	A	M	J	J	A	S	O	N	D	
A_1	2299	1669	2002	2621	2937	3316	3695	3842	4036	3664	3308	2770	km^2x10^3
A_2	617	289	176	925	1559	2800	3231	3305	3597	3175	2210	1583	
B_1	598	430	451	783	1420	2818	3646	3952	4308	3720	2772	1110	
B_2	569	345	246	682	1024	1847	2146	2272	2425	2155	1636	905	
C_1	1069	613	1086	1542	1886	3178	3378	3546	3742	3491	2810	1976	
C_2	915	834	777	1015	1139	1615	1905	2074	2268	2010	1699	1122	
Total	6067	4180	4738	7568	9965	15574	18001	19081	20376	18215	14435	9466	

TABLE 3

Evaporation and sensible heat flux per cm^2 of open water in cal/cm^2 month
+ = lowered ocean

		J	F	M	A	M	J	J	A	S	O	N	D
Southern	Q_s	+ 608	- 67	-1287	-2838	-3723	- 4440	-5422	- 5506	- 9590	- 3026	- 795	+468
Pack Ice	Q_e	-73	-165	-1171	-1929	-2323	- 2602	-3000	- 2981	- 2602	- 2048	- 938	+183
		J	A	S	O	N	D	J	F	M	A	M	J
Norw.	Q_s	+1674	+2335	-1260	-6268	-9636	-10621	-9170	-12230	-12927	-10098	-2251	+666
Barents Sea 20-65°N	Q_e	+ 818	+ 781	-1440	-3157	-3924	- 3385	-4427	- 4553	- 5096	- 2196	- 670	+936

TABLE 4

a) Energy loss per cm^2 of open water, weighted according to latitudinal variations in the distribution of open water.
b) Energy loss originating from open water, expressed as loss of the average cm^2 of the whole pack ice belt.

(cal/cm^2 month)

a)	J	F	M	A	M	J	J	A	S	O	N	D
with 90% RH	+756	-241	-2155	-4321	-5061	-6077	-7136	-7015	-5581	-3279	-646	+625
with 95% RH	+989	+ 89	-1972	-4169	-5010	-4931	-6940	-6859	-5472	-2958	-387	-1069
b)												
with 90% RH	+189	- 70	- 194	- 302	- 253	- 182	- 214	- 140	- 112	- 197	- 84	+131
with 95% RH	+247	+ 26	- 177	- 252	- 251	- 148	- 208	- 137	- 109	- 177	- 50	+224

TABLE 5

Northward transport of ice by wind

	J	F	M	A	M	J	J	A	S	O	N	D	Σ	per 1° long.	
A_1	46.8	46.8	54.6	95.6	72.8	52.0	46.8	49.4	52.0	45.5	54.6	19.5	626.4	15.8	$km^2 x 10^3$
A_2	19.5			9.1	5.2	46.8	46.8	46.8	46.8	41.0	27.3	23.4	312.7	7.8	
B_1	66.3	66.3	50.1	41.0	98.8	36.4	26.0	33.8	41.6	18.2	31.9	62.4	572.8	8.2	
B_2	23.4	11.7		18.2	15.6	10.4	20.8	26.0	31.2	36.4	13.7	15.6	223.0	3.2	
C_1	3.9					5.2	5.2	7.8	10.4	9.1	9.1	3.9	54.6	0.8	
C_2	31.2	7.8	22.8	27.3	31.2	36.4	36.4	39.0	41.6	54.6	27.3	23.4	379.0	5.4	
Total	191.1	132.6	127.5	191.2	223.6	187.2	182.0	202.8	223.6	204.8	163.9	148.2	2178.5		

TABLE 6

See export by current with current speed of 1 km/day after
(a) U.S. Hydrographic Office and (b) Morskoi Atlas

		J	F	M	A	M	J	J	A	S	O	N	D	Σ	b in % of a
A_1	a	26	24	20	22	25	17	7	12	16	20	17	13	219	
	b	23	21	23	16	19	25	21	22	24	22	25	27	268	122
A_2	a	7				18	12	20	21	23	16	18	14	149	
	b	17	3	2	14	30	25	29	29	30	30	27	28	264	177
B_1	a		3			15	23	21	22	23	14	24	31	176	
	b	8	8	8	21	12	15	10	12	14	13	16	29	166	94
B_2	a	25	6	5	5	27	31	35	32	28	34	34	29	291	
	b	25	20	12	36	66	87	87	86	85	75	70	51	700	240
C_1	a	13	8	4	9	7	36	27	32	36	50	27	31	280	
	b	36	16	24	36	52	76	76	76	76	63	63	55	649	231
C_2	a	18	18	4	14	19	26	25	24	22	21	14	17	221	
	b	36	34	31	56	45	47	46	44	44	27	31	29	470	212
Total	a													1336	
	b													2517	188

TABLE 7

Ice transport by ocean current with consideration of speed
(a) after U.S. Hydrographic Office, (b) after Morskoi Atlas

units 10^3 km^2, reduced to ice concentration 1.0

		J	F	M	A	M	J	J	A	S	O	N	D	Σ	b in % of a
A_1	a	106	212	152	363	368	160	133	163	193	151	138	80	2219	
	b	169	174	253	276	295	392	259	268	286	166	186	212	2936	132
A_2	a	47				231	177	307	324	340	236	197	136	1995	
	b	55	7	6	73	356	389	387	416	444	305	276	208	2922	147
B_1	a		15			185	258	253	244	235	247	328	271	2036	
	b	66	223	58	295	179	186	146	174	205	226	192	346	2294	112
B_2	a	164	67	64	56	400	500	593	477	360	232	222	212	3347	
	b	216	192	121	480	932	1356	1437	1411	1405	490	432	379	8851	262
C_1	a	117	101	43	141	94	498	374	414	454	342	330	399	3307	
	b	170	197	229	522	790	1061	1057	1054	1051	557	710	625	8023	243
C_2	a	159	195	35	168	232	315	298	250	203	119	116	165	2215	
	b	306	349	286	738	561	559	519	501	482	186	347	270	5104	230
Total	a													15119	
	b													30130	200

TABLE 8

Freezing, melting and export of ice
(a) after U.S. Hydrographic Office, (b) after Morskoi Atlas
F = freezing, M = melting, units 10^3 km^2

	A_1		A_2		B_1		B_2		C_1		C_2		Total			
(a)	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M^*	F^*
J	551		647		340		280		682		180	36	2644		2680	36
F	259	111	220		81	8	161		92	101	163	94	683	21	976	314
M		476		318		176		168		464		90		1692		1692
A		467		691		485		389		400	14	195		2613	14	2627
M	94	441		938		1017		583		818		300		4003	94	4097
J		380		836		1113		558		746		383		4016		4016
J		263	57	354		567	399	614	195	379	104	334	384	2140	735	2511
A	42	212	188	371		331	363	503	240	422	108	289	868	2055	941	2128
S	245	156	387	277	277	161	391	332	464	437	245	213	2009	1576	2009	1576
O	364		693		768		394		466		284		2969		2969	
N	447		796		1305		625		758		444		4375		4375	
D	504		797		1087		534		870		392		4184		4184	
	2506		3785		3858		3147		3767		1934		18136		18997	
Exp.	403		522		169		1094		964		579		2869		3731	
(b)																
J	557		647		340		280		682		337	193	2644			
F	221	73	226		289	216	204	43	188	197	357	288	1275	613		
M		476		318		176		168		464	219	309		1692		
A		467		691		485	109	498	122	522	584	765		2613		
M	21	368		938		1017	365	948		818	292	592		4003		
J	64	444		836		1113	808	1366	320	1066	212	595		4130		
J	43	306	137	434		567	1243	1458	878	1062	325	535	2229	3985		
A	146	316	280	463		331	1297	1437	880	1062	359	540	2840	4027		
S	338	249	491	381	247	131	1436	1377	1061	1034	524	492	4097	3664		
O	364		693		768		526	137	566	100	284		2969			
N	447		796		1305		625		758		444		4375			
D	504		797		1087		534		870		392		4184			
	2699		4061		4036		7427		6325		4329		24747			
Exp.	596		798		347		5374		3522		2964		9480			

TABLE 9

Mass budget of the pack ice belt in km^3 ice

- = melting, + = freezing

	J	F	M	A	M	J	J	A	S	O	N	D	Σ+	Σ-
From all changes	-4628	-1902	+1154	+1788	+7852	+10811	+8972	+8705	+1514	-7452	-11842	-9748	40796	35572
From export		17					545	1510	3152					

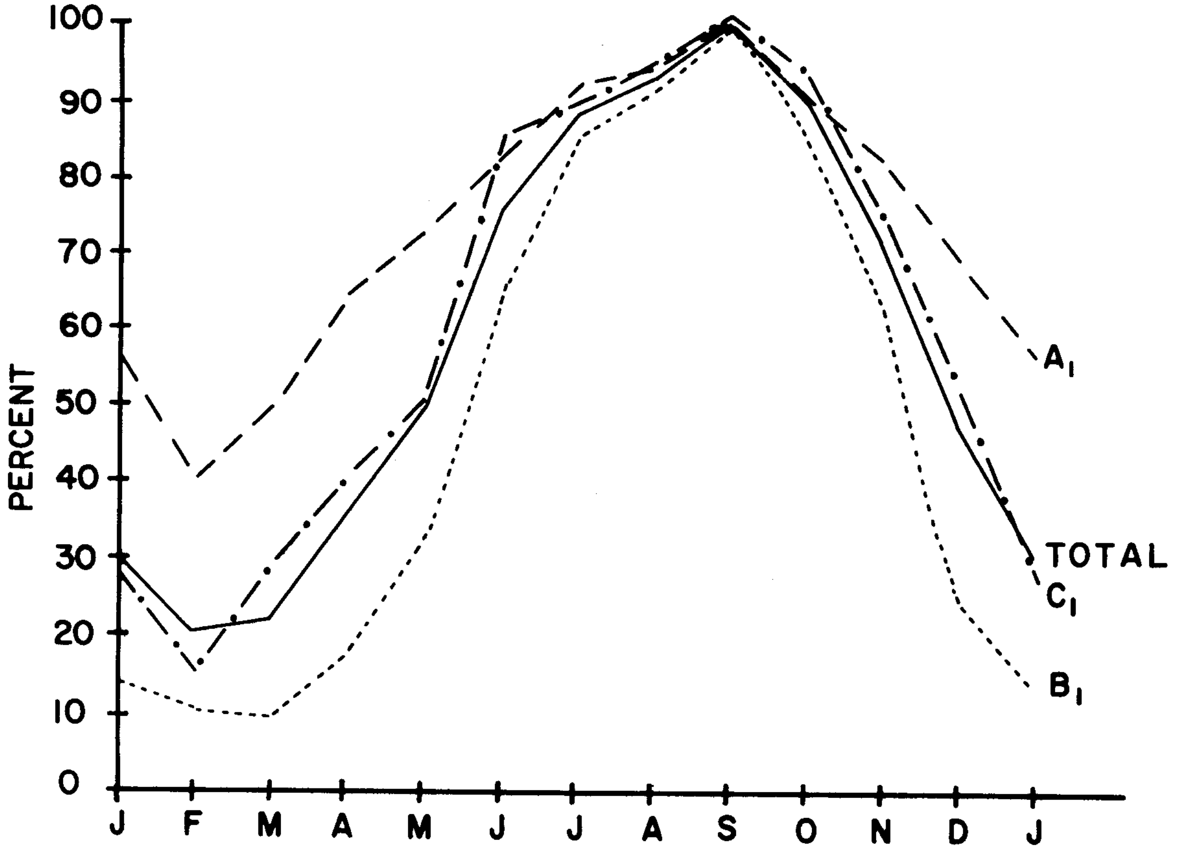

FIGURE I. SEASONAL ICE CHANGE (IN%) OF MAXIMUM ICE EXTENT

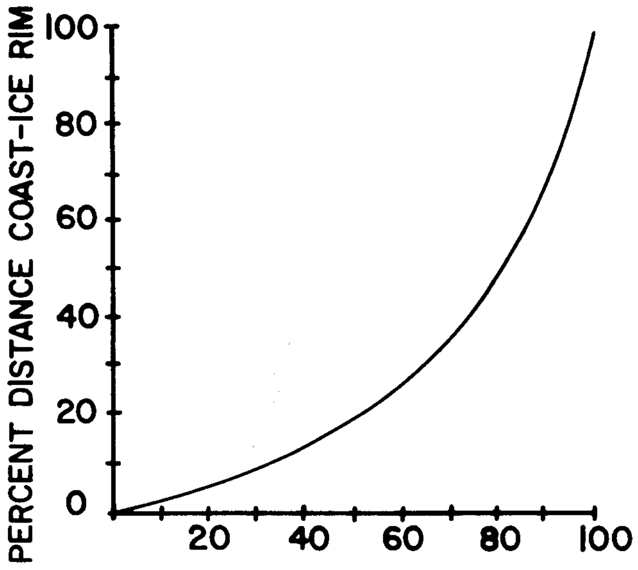

FIGURE 2. RELATION OF OPEN AREAS TO DISTANCE FROM ICE RIM

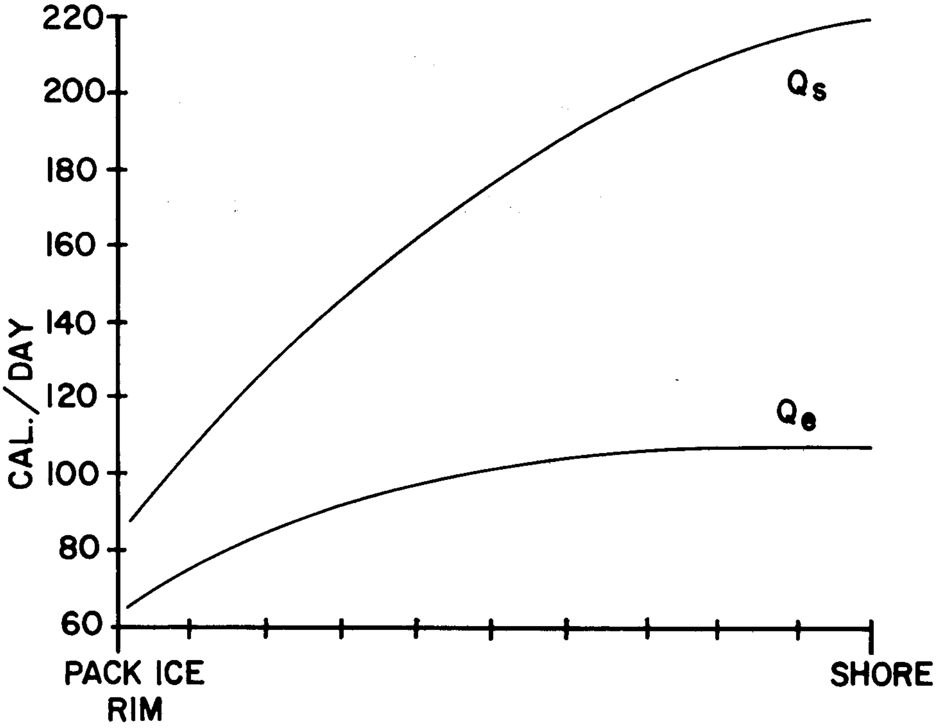

FIGURE 3. ENERGY LOSS WITH RELATION TO DISTANCE FROM SHORE

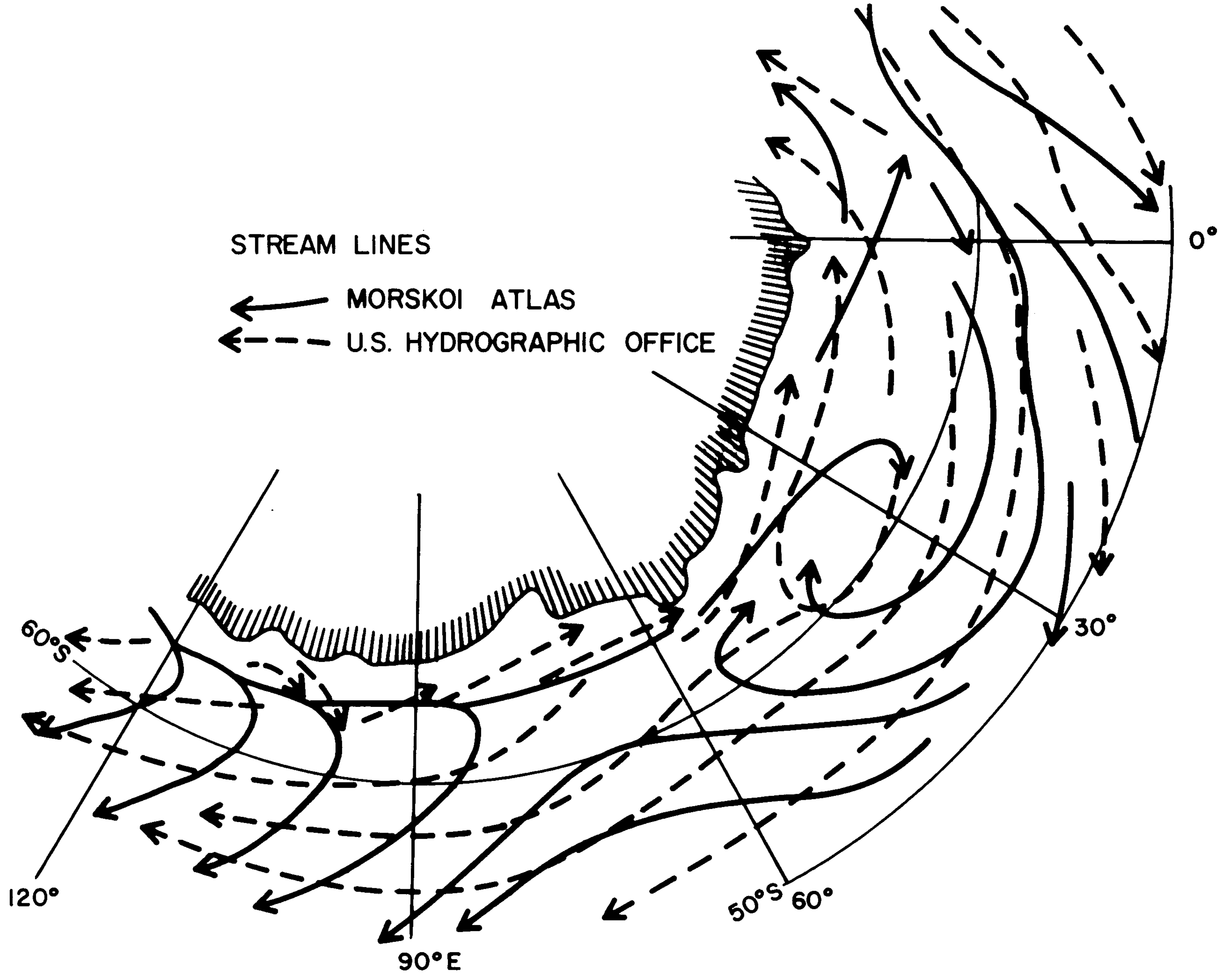

FIGURE 4. COMPARISON OF STREAM LINES OF OCEAN CURRENTS