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ICE COVER AND SURFACE HEAT FLUXES IN BAFFIN BAY

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by

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ABSTRACT

Latent and sensible heat fluxes at the surface of Baffin Bay are calculated throughout the year using, in addition to the essential meteorological data and surface temperatures, values of the ice cover corresponding to three different periods of years, ranging from 1919 to 1965. A discussion of the variation of the fluxes in time and space and with varying ice conditions is given and mean values for the Bay are presented at intervals during the year. Finally, an attempt is made to balance the atmospheric fluxes of radiation, latent heat, and sensible heat with estimates of the oceanic fluxes in order to obtain an impression of the surface energy budget of the Bay.

ACKNOWLEDGEMENTS

I wish to express my gratitude to my research supervisor, Professor S. Orvig, for his encouragement and guidance; to Dr. E. Vowinckel for several extremely helpful discussions; and to Professor B.E. O'Reilly for computer programming assistance. I would also like to thank Miss S. Hoblyn who did the typing and Mr. S. Lapczak who drew most of the diagrams. I am indebted to the Arctic Institute of North America for the use of its excellent library (and particularly to Miss N. Corley, the Institute Librarian, for her assistance); to the staff of the McGill Computing Centre for the use of the facilities; to the Meteorological Branch, Department of Transport for financial support; and to the staff and students of the Meteorology Department for several useful suggestions. Finally, I would like to thank my family for encouragement during the writing of this thesis.

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INTRODUCTION

1.1 General Description of Area

Baffin Bay, a north-west extension of the Atlantic Ocean, lies between Greenland and Baffin Island and stretches for a distance of about 800 mi from Davis Strait (67N) to Smith Sound (78N). Its average width is about 350 mi, but it narrows to about 220 mi at Davis Strait. The area of the Bay is very nearly 750,000 km^2 (almost 300,000 mi^2).

The West Greenland Current enters Baffin Bay with a surface speed of about 0.1 kt and continues on, keeping to the coast, to the northernmost regions of the Bay. The water in this current is relatively warm and fairly saline and, as a result, ice concentration tends to be low even as far north as Upernavik in winter. Just south of Davis Strait branches of the West Greenland Current swing westward to join the outflowing Canadian Current which, farther south, becomes the Labrador Current. This water is cold (very nearly at the freezing point) and less saline, having come mainly from the Arctic Ocean via Smith, Jones, and Lancaster Sounds. Surface speeds in the Canadian Current range from about 0.1 to 0.4 kt (see Fig. 1-2).

Except for a small area off the Greenland coast, south of Jakobshavn, ice is normally found everywhere in the Bay in winter; although about 10 per cent of the area is usually a water surface even

FIG. 1-1. Location Map (see next page).

Weather Stations in the Baffin Bay region

GREENLAND		CANADA	
202	Thule Air Base	918	Arctic Bay
210	Upernavik	090	Clyde
212	Umanak	093	Cape Hooper
216	Jakobshavn	094	Cape Dyer
230	Holsteinsborg		
250	Godthaab		

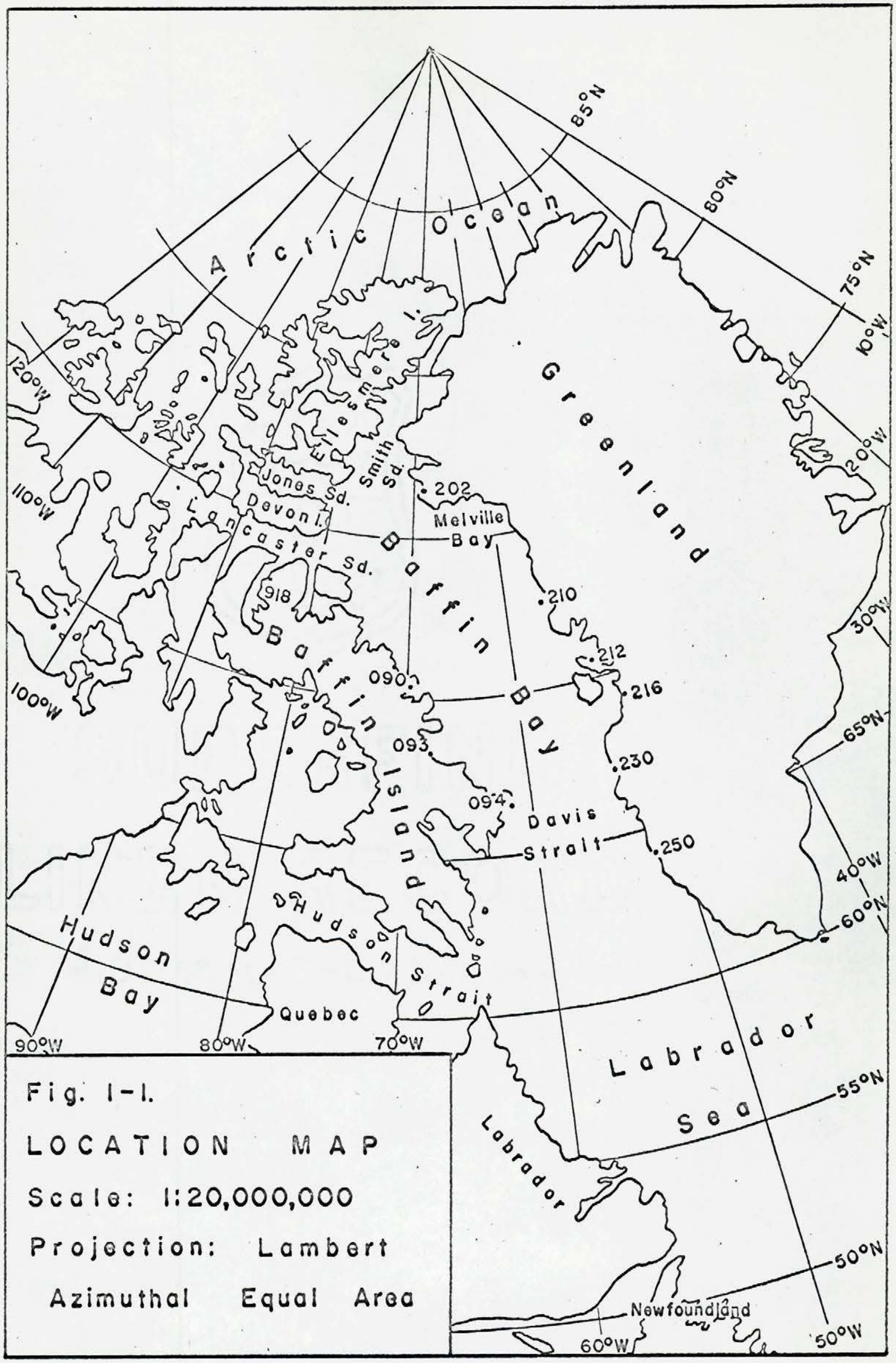

Fig. 1-1.

LOCATION MAP

Scale: 1:20,000,000

Projection: Lambert Azimuthal Equal Area

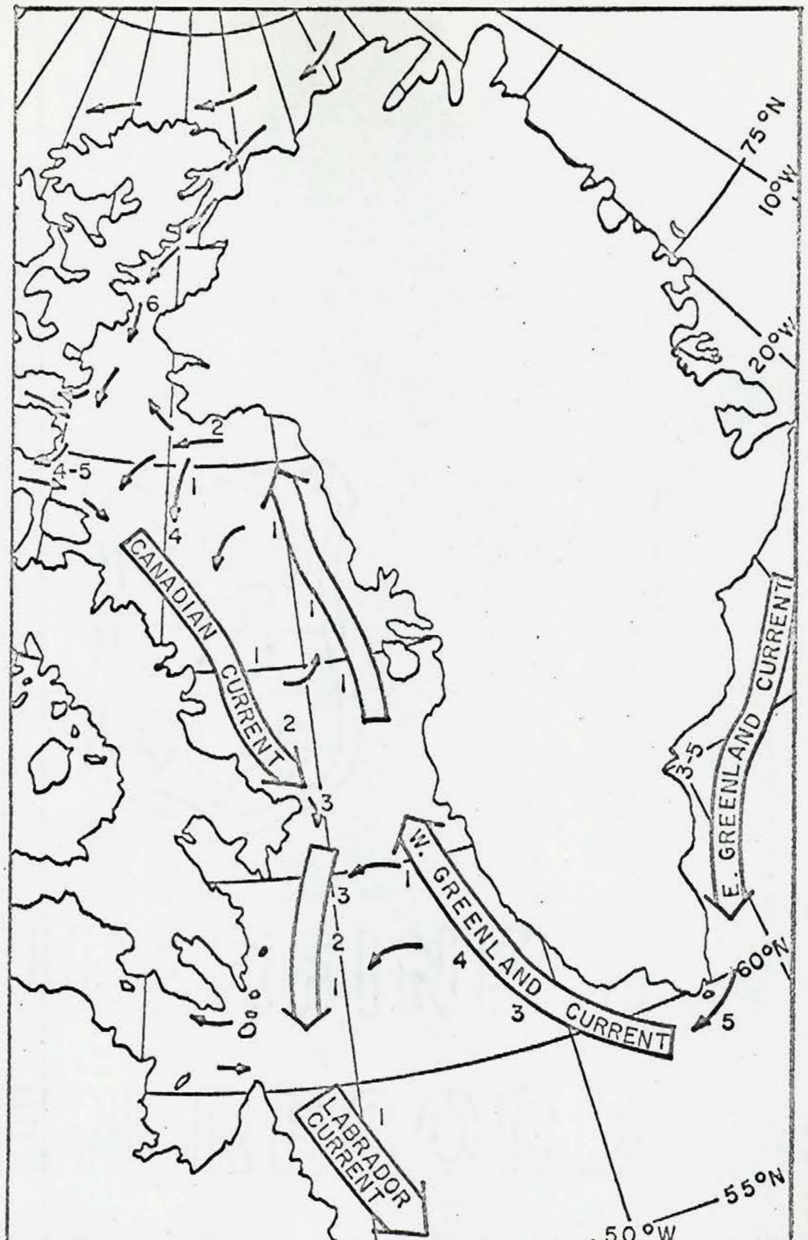

Fig. 1-2.
GENERAL OCEAN SURFACE CIRCULATION
Source: U.S.H.O., 1958 (tenths of knots)

in February, March, and April, the severest months. In summer, on the other hand, (i.e., late August and September) the ice cover reaches a minimum of less than 10 per cent of the total area. This ice is generally found in the Smith Sound region; but occasionally some ice off the Baffin Island coast survives the summer. An interesting feature of the sea ice distribution in Baffin Bay is the "North Open Water", an area south of Smith Sound which generally has a lower ice concentration than the surrounding regions.

> The contrast in climate between the two sides of Davis Strait and Baffin Bay is well known, as it persists throughout the year, and makes the Greenland coast much more accessible and attractive for settlement than the Baffin Coast. (Hare, 1950).

This contrast is quite evident, particularly in winter, in the monthly maps of mean air temperature shown in Fig. 3-1. One can also see from these maps that the "nose" of warm air which protrudes northward along the Greenland coast corresponds roughly with the position of the known area of open water (e.g., for 1955, see Fig. 2-1). In summer, when the largest areas of open water occur, the east-west air temperature gradient is quite weak. In winter, on the other hand, the Baffin Island coast experiences the same intense cold as the rest of the Canadian Arctic; whereas the air over the West Greenland coast has been modified a great deal mainly by the warm open offshore water. (Hare, 1950).

1.2 Outline of Objectives

Baffin Bay is one of the most interesting bodies of Arctic water due to the widely variable ice conditions encountered there during a twelve month period. While the Bering, Norwegian, and Barents Seas remain largely open and the Arctic Ocean experiences very heavy ice conditions throughout the year (D.H.I., 1950 and U.S.H.O., 1958), the Baffin Bay ice cover ranges from a minimum of less than 10 per cent in late August and September to a maximum of about 90 per cent in winter (see Fig. 2-2).

Although it borders on the Arctic Ocean where much work has been done, Baffin Bay itself seems to have been relatively little studied. Of the vast regions investigated by Vowinckel and Taylor (1965), for example, almost the only ocean areas north of 65N not considered are those nearest to Canada: Baffin Bay and the waters of the Canadian Arctic Archipelago. As one of the objects of the present study is to calculate latent and sensible heat fluxes in Baffin Bay throughout the year, hopefully the results will complement those of Vowinckel and Taylor and help to fill this large gap.

It is intended to discuss not only the mean values of evaporation and sensible heat, but also the variation of these fluxes from season to season and from region to region within Baffin Bay. The corresponding variations in ice cover, which have a great effect on the fluxes, will be included in the discussions.

Finally, an attempt will be made to balance the atmospheric fluxes of radiation, evaporation, and sensible heat with estimates of the oceanic fluxes in order to verify the calculations made in this study and to obtain an impression of the energy budget of Baffin Bay.

1.3 Heat Balance Equation

The equation of the surface heat balance may be written as follows:

$$Q_N + Q_E + Q_H = Q_S \quad , \qquad (1.1)$$

where Q_N is the net radiation, or the total radiation balance*,

Q_E is the latent heat flux between the surface and the atmosphere,

Q_H is the sensible heat flux between the surface and the atmosphere, and

Q_S is the net heat exchange with the ocean, or the "storage change".

The units of all Q terms in this study will be "calories per square centimeter per day" (cal cm^{-2} day^{-1}) or, equivalently, "langleys per

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* Budyko (1956) points out "the application of the expression 'radiation balance' is especially inconvenient to use in the study of heat balance, since these similar terms have an entirely different physical meaning (for instance, the radiation balance usually is not equal to zero, whereas the sum of the components of heat balance always equals zero, etc.); however, at the present time, it would be very difficult to discard this term since it has been so largely used in all hydrometeorological studies".

day" (ly day^{-1}). The sign convention to be used in discussions is shown in Fig. 1-3, where all arrows are directed positively.

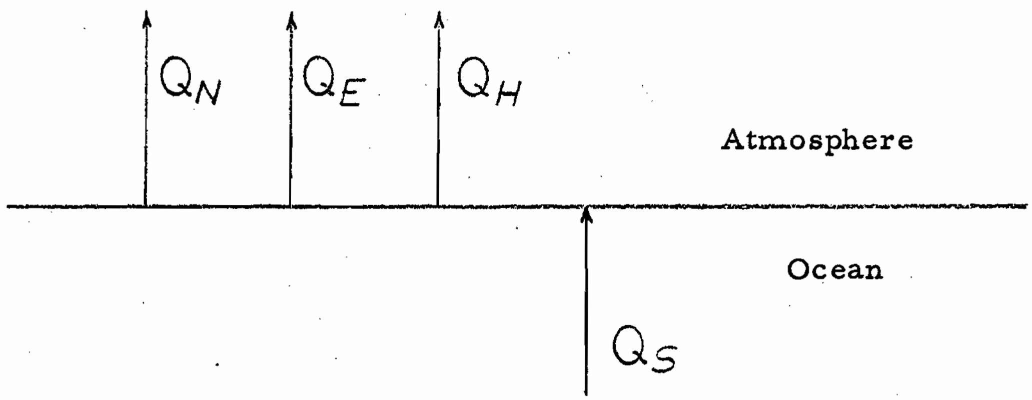


FIG. 1-3. Positively directed Terms of the Surface Heat Balance Equation.

A more detailed description of the terms in Eq. (1.1) is contained in the following paragraphs of this Section.

(a) Q_N , the radiative term

$$Q_N = L\uparrow - L\downarrow - Q_{S_a} \quad , \quad (1.2)$$

where $L\uparrow$ is the (upward) terrestrial radiation,

$L\downarrow$ is the (downward) atmospheric back radiation, and

Q_{S_a} is the absorbed global (solar) radiation.

In the present study Q_N was obtained from published maps (Vowinckel and Orvig, 1964b).

(b) Q_E , the evaporative term

$$Q_E = 0.1 \rho K L (e_s - e_a) V \qquad , (1.3)$$

where ρ is the density of water,

K is a coefficient,

L is the latent heat of vaporization or sublimation,

e_s is the saturation vapour pressure at the surface,

e_a is the vapour pressure in the air, and

V is the wind speed.

(c) Q_H , the sensible heat term

The formula most often used is the following:

$$Q_H = K' (T_s - T_a) V \qquad , (1.4)$$

where K' is a coefficient,

T_s is the surface temperature,

T_a is the air temperature, and

V is the wind speed.

(d) Q_S , the heat exchange with the ocean.

This term may be considered to have four components:

(i) Q_T , the heat transported by ocean currents through Davis Strait, and Smith, Jones, and Lancaster Sounds;

(ii) Q_W , the heat due to the cooling or warming of water in the upper layers of the ocean;

(iii) Q_F, the heat due to the freezing or melting of ice; and

(iv) Q_I, the heat due to the cooling or warming of ice.

The terms Q_T and Q_W are related in that both depend on the average temperature in the upper layers of the ocean. Theoretically, Q_W will be zero over the period of a year, whereas it will be seen in Table 5-1 that Q_T is positive (i.e., heat is transported into the region) in all months. The terms Q_F and Q_I may be further divided into terms referring to ice which forms and remains in the Bay and that which is transported out by the surface currents and the wind. In the former case, any heat which is released in the formation or cooling of ice during the winter is taken up again in warming and melting during the summer. Ice which is exported, however, leaves behind the heat which was released at formation and during cooling. This heat, therefore, becomes a factor in the annual energy budget of the region (see Table 5-1).

It is useful to imagine, in the surface layer of the ocean, a "storage volume" through which all heat fluxes must pass such that there is neither accumulation nor deficit of energy at any time. Eq. (1.1), therefore, will apply to this theoretical volume. This concept is shown in Fig. 1-4 for both winter and summer situations. The lengths of the solid arrows are indicative of the relative magnitudes of the terms in typical cases. The dotted arrows, which indicate sources and sinks of energy in the ocean, are the four components of Q_S.

The heat exchange, Q_S, could not be calculated properly

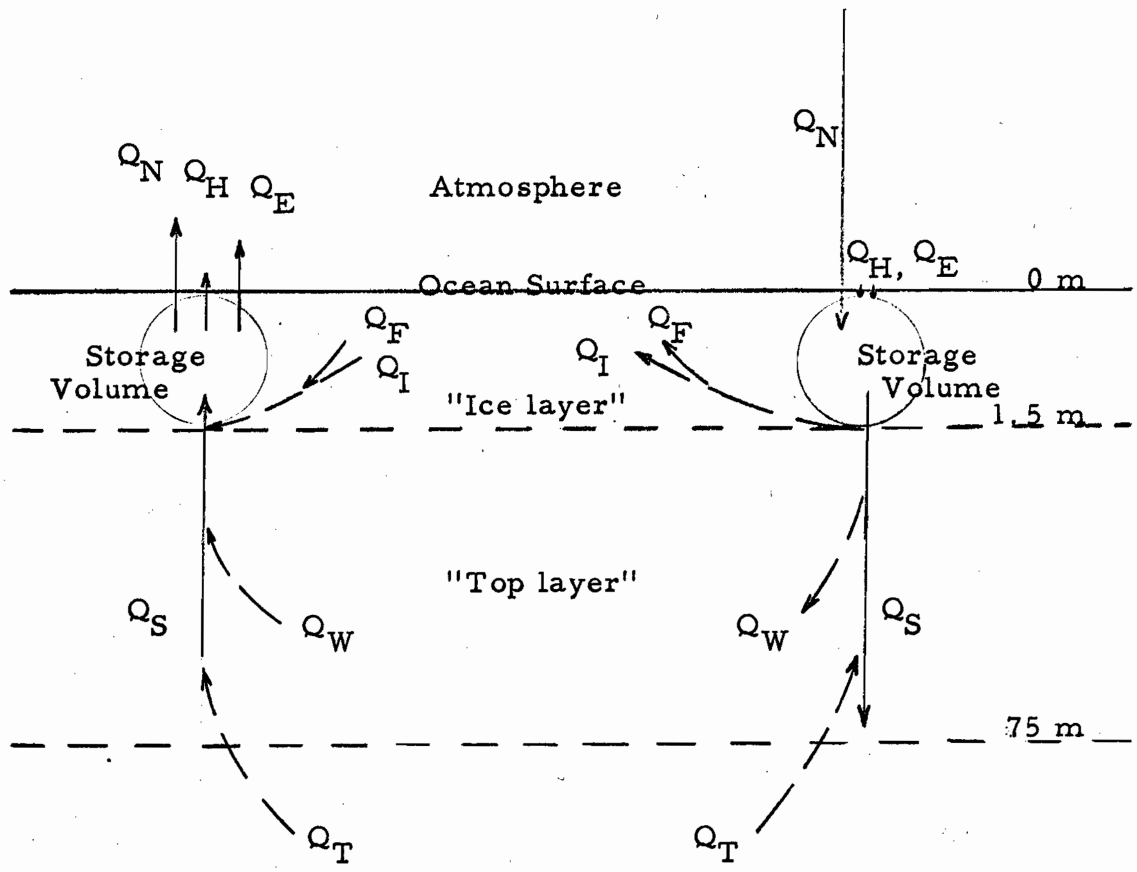


FIG. 1-4. Typical Heat Exchanges in Baffin Bay.

because of a lack of sufficient data. Table 1-1 indicates the information required in order to obtain Q_T, Q_W, Q_F, and Q_I. Except for the surface area of Baffin Bay and the ice concentration, these required data must be estimated or, at best, determined approximately from a very small number of observations. It was found desirable, however, to obtain rough estimates of the four terms during the year in order to attempt to verify the heat balance equation, (1.1), and so lend credence to the Q_E and Q_H calculations. These estimates and their implications are discussed in Chapter 5.

TABLE 1-1. Components of the Q_S term and the information necessary for their calculation.

Term	Required Information
Q_T	(i) Rate of inflow and outflow of water through Davis Strait and the three northern Sounds. (ii) Average temperature of each of the currents. (iii) Average temperature in the top layer* of the ocean in Baffin Bay. (iv) Surface area of Baffin Bay.
Q_W	(i) Rate of change of average temperature in the top layer of the ocean in Baffin Bay. (ii) Depth of the top layer. (iii) Ice concentration.
Q_F	ICE NOT EXPORTED (i) Ice thickness and its rate of change. (ii) Ice concentration and its rate of change. — — — — — — — — — — — ICE EXPORTED (i) Width of ice (100 per cent concentrated) at Davis Strait. (ii) Ice thickness at Davis Strait. (iii) Surface current speed (Canadian Current). (iv) Average wind velocity at Davis Strait. (v) Surface area of Baffin Bay.
Q_I	(i) Rate of change of average temperature in the ice. (ii) Thickness of ice. (iii) Ice concentration.

*The "top layer" is the layer heated by solar radiation in summer. It extends down to a depth of about 50 or 75 m (Defant, 1961, p. 135).

Chapter 2
ICE CONDITIONS

It was essential to know the location and relative amounts of ice and water throughout the year on the surface of Baffin Bay before a study of the energy balance could be satisfactorily completed. The presence of ice will naturally affect both the sensible and latent heat loss to the atmosphere - major items in the heat balance equation. It is therefore necessary to discuss the ice distribution and concentration.

2.1 Sources of Information

The U.S. Hydrographic Office ice atlas (1958) contains a series of maps showing ice distribution and concentration averaged over the years 1952 to 1956, inclusive. From November to April the maps each cover a period of one month. During the remainder of the year (May to October) they appear at half-monthly intervals.

Monthly mean maps of "Probability of occurrence of ice" are available for the period 1919 to 1942 in the German Hydrographic Institute atlas (Deutsches Hydrographisches Institut, 1950). This method of describing the ice conditions did not at first appear to be completely satisfactory for the present study, since the ice concentration, rather than the frequency of occurrence, was required. From one point of view, however, the two terms (concentration and frequency) are the same. For, although the ice concentration of a particular area at a given moment is simply the area of ice cover divided by the total area, the mean concentration of the same area during a given month averaged over a period of years may be computed quite differently. For example:

$$\text{Mean concentration} = \sum_{i=1}^{N} \frac{N_i}{N \mathrm{N}} , \qquad (2.1)$$

where

N_i is the total number of years that ice was observed during the month at the i th. point,

the i th. "point" is actually an area of, say, 1 m^2 within the larger area under discussion,

N is the number of such points (i. e., the total area is N square meters), and

N is the number of years of observations.

Thus, Mean Concentration = Mean Frequency.

From another point of view, the concentration and frequency may be quite different. Suppose, for example, that ice of 10 per cent concentration is observed at a particular location (where "location" here means an area corresponding to the field of view from a land station or a ship's bridge, rather than an area of 1 m^2) during a particular month in twenty years out of twenty. Thus the frequency of occurrence of ice is 100 per cent, whereas the average concentration is 10 per cent. It is unlikely, however, that frequency of occurrence would actually be calculated in this manner; for, if so, the resulting maps would have to show 100 per cent frequency over most of Baffin Bay for all but a very few months of the year (e.g., August and September). The German maps do not show such a high frequency of occurrence of ice. In fact the well-known "North Open Water" (Dunbar, 1951) in Smith Sound is quite evident in the German maps for May and June. Since the frequency is not 100 per cent in this region (about 76N) at a time of year which is still late spring (or, at best, very early summer) as far as ice is concerned, it may be implied by the above method of calculation that, at least in some years, the Sound is ice-free. This is in contradiction to other sources (U.S.N.O.O. Reports for 1960, 1961, 1962, 1963; Hill, Cooper, and Markham, 1965) which depict the "North Open Water" as an area of lesser ice concentration; but not an ice-free area in May and June by any means.

Thus a "probability" of 50 per cent, for example, on the German maps cannot be taken to mean that there will be some ice in the area five years out of ten and that the remaining five years will be free of ice. Rather it must be interpreted to imply that a ship travelling in this region during any year will likely be in ice 50 per cent of the time; or, in other words, that the mean concentration is 50 per cent.

The difficulty lies partly in the translation of the map keys. The English "ice concentration" might be translated directly into German as "eiskonzentration", a term which, to a German, would mean very nearly what "ice density" means to an Englishman. (Dr. Vowinckel, personal communication). Thus, "konzentration" is not mentioned in this connection in the map keys. Instead "wahrscheinlichkeit", which is translated "probability" (Cassell's German and English Dictionary, 1963) must be used for lack of a better alternative. It should be noted, however, that "wahrscheinlichkeit" does not imply the rigid mathematical definition of probability. (Dr. Vowinckel, personal communication). Hence the confusion between the two terms, "wahrscheinlichkeit" and "concentration", which likely call to mind the same concept to German and Englishman, respectively.

The above-mentioned atlases produced by the German Hydrographic Institute and the United States Hydrographic Office contain the only published maps of mean ice concentration consulted in this study. Another atlas (Swithinbank, 1960) displays the ice conditions in two different ways. The periods of the year that are discussed are as follows:

March	
April	(semi-monthly)
May	(weekly)
June	(weekly)
July	(weekly)
August	(weekly)
September	(weekly)
October	(weekly)
November	(semi-monthly)

In the preparation of this atlas a great number of reference stations were chosen throughout the waters of the Canadian arctic. The ice concentration, when known, was then entered on a chart for the period in question. Each chart included a column for each of the reference stations and a row for each of the years 1900 to 1958. From these charts maps were drawn for each of the periods showing frequency of occurrence of ice of various concentrations at all the reference points.

Fortunately the charts as well as the maps are presented in this fine atlas. The charts show that the great majority of the observations were made in the 1950's. Large blank spaces in the years before this make it virtually impossible to conclude anything about the ice concentration. However, the years 1919 to 1956 are quite adequately covered (except for 1943-1951) by the two sources already mentioned. Thus, the Swithinbank atlas was only used for 1957 and for a small number of observations in 1958. The reported concentration in 1957 at each of the reference stations in Baffin Bay was plotted on maps covering the following sixteen periods:

March 1-31
April 1-15
April 16-30
May 1-15
May 16-31
June 1-15
June 16-30
July 1-15
July 16-31
August 1-15
August 16-31
September 1-15
September 16-30
October 1-15
October 16-31
November 1-30

In many cases this meant combining data from two of the periods used in the atlas (e.g., June 1-7 and June 8-15 were combined for June 1-15). The maps were then analyzed and the concentrations at seventy-two reference points ranging from 65N to 78N were determined.

Several other sources were used to obtain values of ice concentration at the same seventy-two reference points in the years 1959 to 1965, inclusive. Basically the same periods, listed above, were used except that it was found necessary to combine February and March due to the scarcity of data. Also one more period, December-January, was added to make a total of seventeen. The sources consulted for the compilation of these data are as follows:

(i) United States Navy Oceanographic Office, Report of the Ice Observing and Forecast Team, for 1957, 1959, 1960, 1961, 1962, 1963.

(ii) United States Navy Oceanographic Office, Ice Outlook, Eastern Arctic, for 1962, 1964, 1965. (Only observed conditions were used.)

(iii) Hill, Cooper, and Markham, (1965), for 1963.

(iv) Canadian Meteorological Branch, Department of Transport, Aerial Ice Observing and Reconnaissance for 1962, 1963.

(v) Canadian Meteorological Branch weather facsimile charts (unpublished) for 1964, 1965.

One other source was investigated but not used. This is the series of annual ice maps for the months April to August published in Denmark for the years 1900 to 1939 and 1946 to 1956 under the title Isforholdene i de Arktiske Have or State of the Ice in the Arctic Seas, an appendix to the Nautical-Meteorological Annual.* Both Danish and English are used to an equal extent throughout. The ice concentration is shown qualitatively for the most part, except for the years 1954, 1955, and 1956 when the terminology was altered slightly to conform with the World Meteorological Organization (which specifies concentration in some of its definitions). All too often, except near the Greenland coast, the words "State of ice unknown" or "Ice supposed but no information at hand" appear, making this source not particularly useful for Baffin Bay. But all of the years from 1919 onwards except for 1943 to 1951 are covered elsewhere, so that Isforholdene. . . .

* This series was resumed,under a new title, in 1964 with the publication of ice cover maps for 1960.

can only contribute a few data for 1946 to 1951. It was decided not to use this information as a false impression of its accuracy and completeness might result if, for example, it were to be combined with the Hydrographic Office data for 1952-56. Such a combination would enable one to say the concentrations were based on data for 1946-56 when, in fact, the insufficiency of the Danish maps would mean that the averages were heavily weighted in favour of the latter five years.

2.2 Ice Distribution and Concentration

Maps can describe much better than words the ice conditions that generally prevail. The year 1955 was chosen rather arbitrarily for this purpose, and eight maps from the Report of the Ice Observing and Forecasting Program, 1955 (U.S.H.O., 1956) are shown in Fig. 2-1. No maps for December, January, and February were included in the report. There is little change, however, in the conditions between December and March, except for an increase in ice thickness.

In March 1955 the Bay north of 65N was almost completely covered by ice. Some open water was found south of Disko Bay near the Greenland coast. Just south of Smith Sound the "North Open Water" was observed. By June the area of open water in Smith Sound increased greatly and the surface was less than 10 per cent covered with ice in Melville Bay. This region of light ice concentration

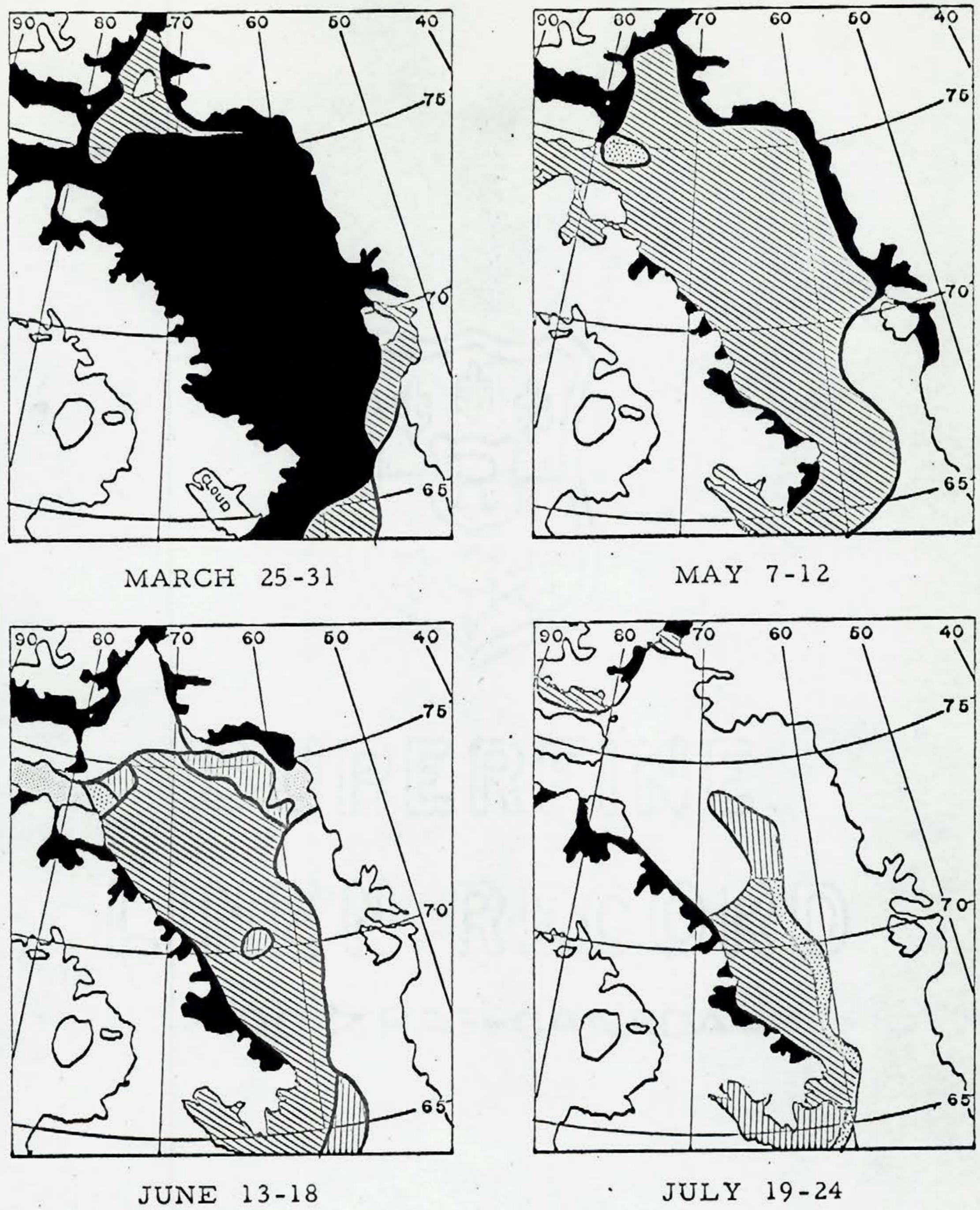
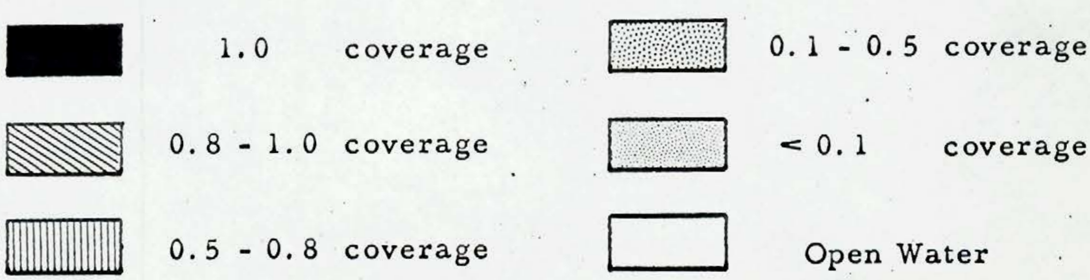


FIG. 2-1. Ice Cover Maps for 1955.
(Source: U.S.H.O., 1956)



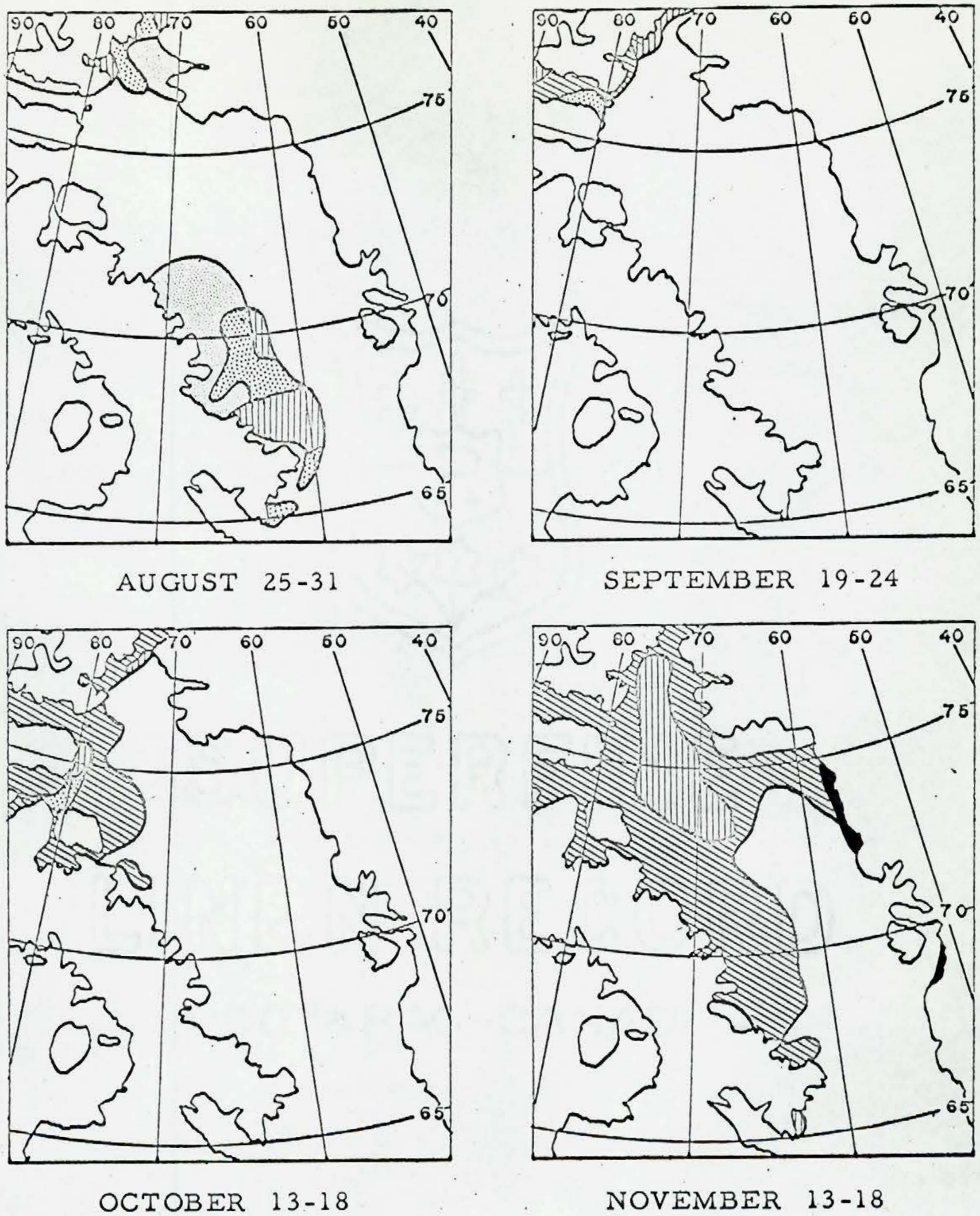


FIG. 2-1. Ice Cover Maps for 1955.
(cont'd)

connected with the open water off Greenland which extended as far north as Upernavik. Presumably, then, ships would have been able to reach Thule by mid-June 1955. By mid-September almost all the ice in Baffin Bay had melted or drifted out to melt in warmer waters. Only a small area of ice near Ellesmere Island remained. But the "summer" was, as usual, very short-lived. By mid-October ice had begun to form again in the north, and by mid-November young ice covered about half of the area.

As mentioned in Section 2.1 actual values of ice concentration were determined from maps such as are shown (for 1955) in Fig. 2-1. Seventy-two reference points (one degree of latitude apart, and ranging from five degrees of longitude apart in the north to two degrees in the south) were chosen in the Bay between 65N and 78N. For each year from 1957 to 1965, inclusive, ice conditions were estimated for as many of these points as possible by assuming the middle value of the range of concentrations within which the points lay. As an example, the concentration was taken to be 0.65 at a point which fell inside the area of 0.50 - 0.80.

The average concentration for the period 1957-1965 at latitude I, longitude J was calculated on the McGill IBM 7040/7044 Computer as follows:

$$\text{CONC (I, J)} = \frac{1}{N} \sum_{K=1957}^{1965} \left[\text{CONC (I, J, K)} \right] \quad , \quad (2.2)$$

where CONC (I, J, K) = 0 when no data is available

= 0.01 when no ice is observed, and

N is the number of years that CONC (I, J, K) $\neq 0$.

Since blanks on the data cards represented years with no data and since the Computer could not distinguish between zeros and blanks in this program, it was necessary to represent periods in which no ice was observed by the minimum possible non-zero ice concentration (i.e., 0.01). This introduced a small error but enabled quite a simple calculation of the average concentration. As shown in Eq. (2.2), the machine simply added nine values of CONC, including zero values, and divided by N, the number of years that CONC was non-zero.

Table 2-1 shows the data available for the computations. In some cases where ice conditions were given for the 13 th. to the 18 th. of a particular month, for example, these conditions were used for both the first and last half of the month if no other data were available. Thus the figures in Table 2-1 slightly overestimate the number of observations.

The small number of observations in winter (e.g., an average of 66 per month for December-January, compared with 979 for June) reflects the severity of the ice conditions. Except for a small area off south-west Greenland, ships are unable to enter Baffin Bay in winter.

TABLE 2-1. Number of Reference Points at which Ice Observations were available for the indicated number of years of the period 1957 - 1965.

Period of Observation	Number of Reference Points									Total no. of Points	Total no. of Obs.	No. Obs. per Mo.
Yrs.	1	2	3	4	5	6	7	8	9			
Dec-Jan	33	22	13	4	0	0	0	0	0	72	132	66
Feb-Mar	0	0	6	18	15	22	11	0	0	72	374	187
Apr 1-15	0	0	5	13	15	23	7	9	0	72	401	650
Apr 16-30	9	10	12	23	16	2	0	0	0	72	249	
May 1-15	10	10	16	17	9	4	0	0	0	72	221	582
May 16-31	0	0	3	25	18	20	6	0	0	72	361	
June 1-15	0	0	4	2	7	12	22	24	1	72	554	979
June 16-30	0	0	0	9	14	24	25	0	0	72	425	
July 1-15	0	0	0	5	12	19	36	0	0	72	446	895
July 16-31	0	0	0	2	15	19	36	0	0	72	449	
Aug 1-15	0	0	2	8	14	16	32	0	0	72	428	873
Aug 16-31	0	0	0	8	7	21	36	0	0	72	445	
Sept 1-15	0	0	0	30	4	10	28	0	0	72	396	790
Sept 16-30	0	0	0	29	7	9	27	0	0	72	394	
Oct 1-15	0	0	0	17	30	19	6	0	0	72	374	767
Oct 16-31	0	0	0	19	18	23	7	5	0	72	393	
Nov	0	7	23	14	18	8	2	0	0	72	291	291
											6080	6080

This has the two-fold effect of very few ship reports and little necessity for aerial observations of ice as an aid to navigation. As a result of the great scarcity of winter observations it was necessary to have longer periods (i.e., one month or more) from November to March.

One would expect that the greatest number of observations would be available for September, when navigation is most favourable. This, however, is not the case. Table 2-1 shows only 790 observations in September compared with 979 in June. The relatively few observations in the former month are probably due to two factors: (i) ships would tend to neglect to report open water conditions as ice-free navigation is to be expected at that time of year, and (ii) there is normally not enough ice to warrant aerial reconnaissance in Baffin Bay at that time.

One further comment should be made regarding Table 2-1. The figures represent the actual number of data used in the calculations. Observations for the summer of 1959 became available only after averages had already been computed for the summer months. For 1958 only a very few data were discovered (Swithinbank, 1960). This accounts for the very small number of points at which eight or nine years of data were used.

2.3 Seasonal and Long-term Variations in Ice Cover

The ice coverage throughout the year in Baffin Bay was calculated for 1919-42, 1952-56, and 1957-65 and the results have been plotted on a graph (Fig. 2-2) of ice coverage in per cent versus time (January to December). Generally speaking, the three curves correspond quite well. The earliest period seems to have had the heaviest ice conditions during most of the year. The latter two periods are quite similar, although differences do occur at certain times of the year. It should be noted, however, that the 1952-56 curve is based on eighteen periods, compared with only twelve for that of 1919-42 which, therefore, may appear less smooth. The plotted

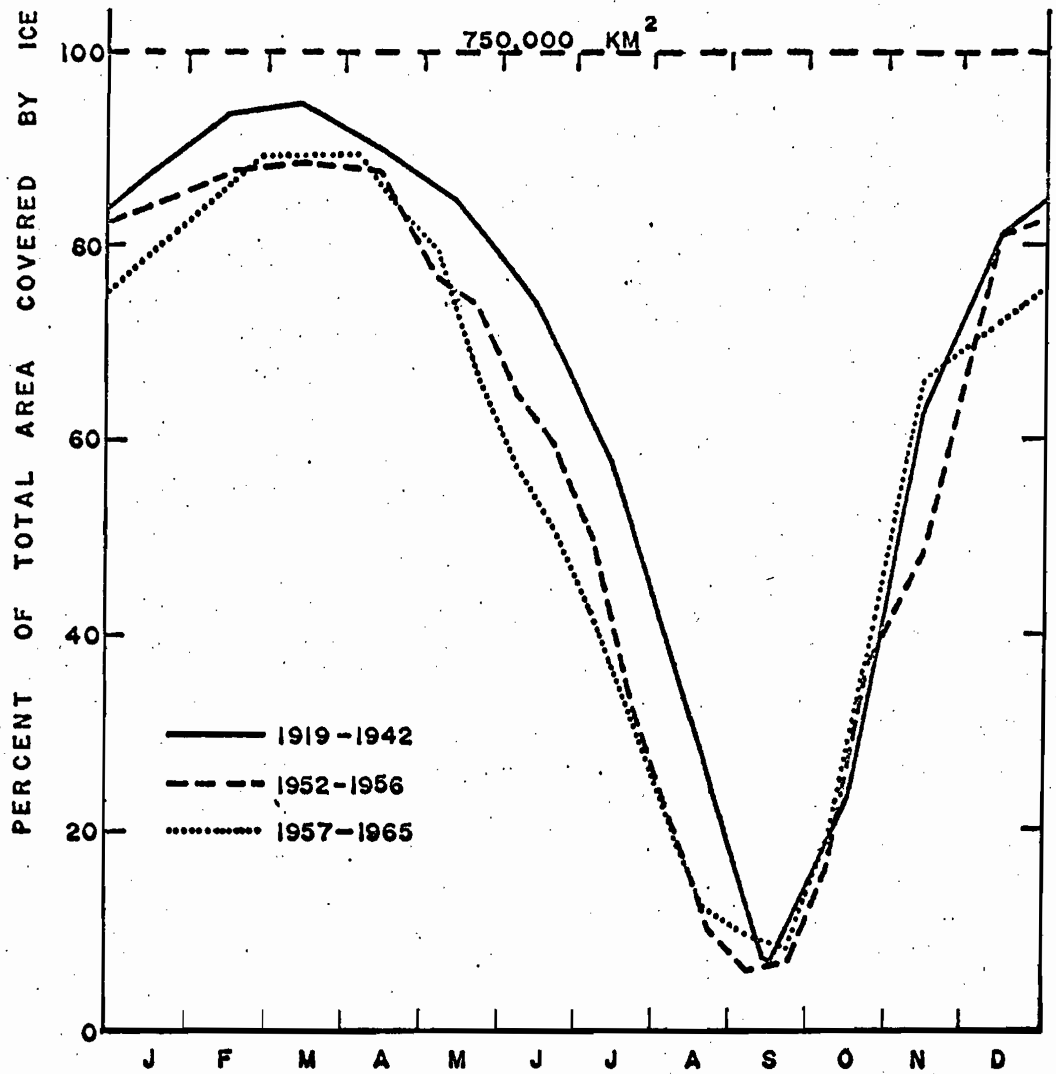


FIG. 2-2. Variation in Mean Ice Cover during the Year in Baffin Bay.

values for both of these curves were obtained by planimetering the published maps, redrawn on a Lambert Azimuthal Equal Area projection of scale 1:20,000,000 (see Fig. 1-1). The curve for 1957-65 was computed by taking the area weighted mean of the average ice concentration obtained from Eq. (2.2). With such a heavy density of points, however, the weighted mean is little different from the unweighted mean.

Regarding seasonal variations in ice cover, it is apparent that, on the average, the annual maximum occurs about March or April. In May, June, and July the ice disappears rapidly, probably due to the combined effects of melting and export. Practically ice-free conditions exist throughout the area for a few weeks in late August and September. In October the water in the northern parts of the Bay begins to freeze over; the ice cover increases rapidly during October and November until, by January, it is approaching the maximum once again. It is perhaps of interest to compare Fig. 2-2, which shows the ice cover averaged over the entire area and over a number of years, with Fig. 2-1, which shows the ice cover distributed throughout the Bay in a particular year.

During the earliest period, 1919-42, this region of the Arctic experienced warming significant enough to cause a northward migration of seals and an invasion of Iceland cod into waters where few had been found before. The warming period appears to have reached a peak in the 1940's, but temperatures in recent years still have been warmer than they were in the early years of the century (Rosendahl, 1961). This warming should be reflected in the ice cover. It has been mentioned that the period 1919-42 had the most severe ice conditions of the three periods through most of the year. This is to be expected, since this long period of more than twenty years would surely have an average temperature less than those recorded during the years of maximum warming. The two later periods, however, are of quite short duration and will likely have temperatures nearly at the maximum. One must bear in mind, however, that the three curves

TABLE 2-2. Average Ice Concentration in Baffin Bay for the period 1957-1965.

	%
December-January	75
February-March	89
April 1 - 15	89
April 16 - 30	84
May 1 - 15	79
May 16 - 31	67
June 1 - 15	58
June 16 - 30	51
July 1 - 15	42
July 16 - 31	31
August 1 - 15	20
August 16 - 31	12
September 1 - 15	9
September 16 - 30	8
October 1 - 15	18
October 16 - 31	37
November	66

were obtained from different sources by different methods of computation. Thus the evidence of the twentieth century climatic fluctuation in the Baffin Bay area which Fig. 2-2 apparently confirms should be accepted with caution.

To the author's knowledge, an atlas of ice cover for the very recent years has not been published. Although, from the data available, it would be possible to display a map of mean ice concentration for each of the seventeen periods of 1957-65, the task would be rather time consuming. Besides, the average ice data are only a by-product, not the main purpose, of this study. It was thought, however, that some use might be made of the areal averaged values; so these are given in Table 2-2 as well as in Figure 2-2.

Chapter 3

HYDROMETEOROLOGICAL DATA OTHER THAN ICE COVER

In addition to the ice concentration which has already been considered in the previous chapter, the following information is essential for calculation of the energy fluxes: temperature of the surface, temperature and humidity of the air above the surface, and wind speed. The following sections deal individually with each of the required parameters.

3.1 Water Surface Temperature

The Hydrographic Office atlas (U.S.H.O., 1958) contains four maps of sea surface temperature for the months of February, May, August, and November. Unfortunately only the August map gives a significant amount of useful information in the area of interest. Another Hydrographic Office publication (U.S.H.O., 1944) was of no use since detail north of 65N was lacking. Dunbar (1951) includes a map of sea surface temperature for September from which data were obtained for the present study for that month. For the remaining months, except for February, May, and November, in the extreme southern areas of the Bay where the Hydrographic Office atlas was used, sea surface temperature data are lacking. This is particularly serious in areas of light ice cover (say, less than 50 per cent concentration) where the water temperature will likely be above freezing. For some points in Baffin Bay, therefore, particularly in July and October, estimates of sea surface temperature were made by interpolating between August or September temperatures (when the water is warmest, but even then only barely reaches about 5C) and the freezing point (say, about -1C or -2C for salt water). Fortunately the range over which the temperature must be interpolated is not great and the errors, therefore, may not be serious.

It was assumed that the water temperature was at the freezing point whenever and wherever ice covered 50 per cent or more of the surface. If the salinity is known, the freezing point may be calculated from a formula given by Pounder (1962):

$$T_f = (-0.0543)\ S\ , \qquad (3.1)$$

where T_f is the freezing point in degrees Celsius, and

S is the salinity in parts per thousand.

Salinity data appear to be almost as scarce as surface temperature data. Dunbar (1951) gives a map of salinity in Baffin Bay for August-September; but, since the temperature data are available for these months anyway, the salinity is not required. Salinities are also shown in four seasonal maps (U.S.H.O., 1958). The "Summer" map was used as a source of data for June and July. The other three maps give salinity as an upper estimate only. Thus the calculated freezing points for the months October to May will be lower estimates which will have a tendency to decrease upward (or increase downward) fluxes of latent and sensible heat.

3.2 Ice Surface Temperature

In winter the ice surface temperature will be colder than the overlying air due to radiational cooling. In summer, on the other hand, there would be a tendency for the ice surface temperature to exceed the air temperature except for the fact that, when positive Celsius air temperatures occur, the heat absorbed by the ice is used for melting. Thus, as a first estimate, one could say that under such conditions the surface temperature would remain constant at 0C.

Vowinckel and Orvig (1964b) used correction values (obtained from observations on an Arctic ice floe) which, when added to the air temperature, give estimates of ice surface temperature. (See Table 3-1). Winter ice surface temperatures would tend to be slightly warmer than these estimates due to upward fluxes of heat from the water through open cracks and leads (as well as through the ice itself) which would not occur on the ice floe. Nevertheless "the error will probably not exceed 1-2C, which is equivalent to 5-10 cal/cm^2/day."

In a later paper in the same series, Vowinckel and Taylor (1965) use the corrections in Table 3-1 in evaporation and sensible heat calculations not only for the Arctic Ocean, but also for the Norwegian and Greenland Seas. However, one interesting further assumption is proposed: "The temperature of the surface layers of the puddles on the pack ice in summer can rise to +1C." The basis for this modification is the fact that solar radiation will cause heating of the surface layer of the water pools. The water will thus become thermally stratified, remaining at 0C in the bottom layers which are

TABLE 3-1 Corrections to Air Temperature used for Estimating Ice Surface Temperature (after Vowinckel and Orvig, 1964b).

Month	J	F	M	A	M	J	J	A	S	O	N	D
Deg C.	-2	-1	-1	+1	+1	+1	+1	+1	+1	0	-1	-1

in contact with the melting ice. This stratification "is likely to persist over considerable periods with generally light winds". It was found that during the main melting season (June to September, inclusive) the mean surface wind speeds were twelve knots or less at all points. Thus there is some argument for assuming ice surface temperatures can rise to +1C.

Both the correction values in Table 3-1 and the above modification for the melting season seem reasonable, qualitatively at least; and so they have been used in the present study to obtain ice surface temperature data used in the heat flux calculations.

3.3 Air Temperature

Monthly maps of mean air temperature at the surface are contained in Volume VI of the Marine Climatic Atlas of the World (U.S. Navy, 1963). The isotherms "are based on all pertinent ships' observations. . . as well as upon the [coastal] stations and [ocean] areas for which graphs are shown." In this atlas the term "ocean area" denotes a small region of data concentration in the ocean. There are two such areas in Baffin Bay. One is in Melville Bay, centred at

75N, 65W; the other is near Disko Island, centred at 70N, 56W. Their areas are about 34,000 km^2 and 27,000 km^2, respectively. The graphs (which, in the case of the maps of mean air temperature, show the "distribution of temperature observed with each wind direction") were omitted for the months November to May, inclusive, in both ocean areas and, in addition, for June in the Melville Bay area. The omission is due to too few observations and therefore excessive sampling error. Table 3-2 shows the number of observations which were available for the months with graphs.

The only coastal station in the area of interest is Thule Air Base (76.5N, 68.8W) for which the period of observation was September 1951 to April 1961. More than 2000 observations were available for each month.

The isothermal analyses obtained from this source (U.S. Navy, 1963) have been redrawn in Fig. 3-1 (see Section 3.4). Two comments should be made regarding these maps:

(i) For all months, except July and August, the analyses clearly show that the maximum temperature at any latitude occurs just off the Greenland coast, corresponding in position with the warm West Greenland Current (Fig. 1-2). The minimum occurs over the cold Canadian Current off the Baffin Island coast.

(ii) Very weak temperature gradients occur in May, June, July and August. In particular, in July only one isotherm (40F) appears on the map. This means that the mean air temperature throughout the Bay only ranges at most from 37F to 43F. In contrast, quite strong gradients occur in winter. In December, for example, the mean temperature ranges from -20F in Smith Sound to +20F off Greenland at 65N.

TABLE 3-2 Number of Observations of Temperature in two Baffin Bay Ocean Areas from which graphs were drawn (U.S. Navy, 1963).

Month	Disko Island	Melville Bay
June	269	-
July	553	509
Aug	404	440
Sept	203	128
Oct	52	38

3.4 Humidity

The acquisition of adequate humidity data presented one of the most difficult problems in this study. As shown in Eq. (4.4), in order to perform evaporation calculations the vapour pressure at an elevation of about eight meters is required. This may be determined from the dew point using the Clausius-Clapeyron Equation, (4.1). If it is not already known, the dew point may be calculated from the air temperature and relative humidity as follows:

$$T_d = \frac{L_v T_a}{L_v - \left[\frac{R^*}{0.622 M_d}\right] T_a \ln(r)} , \qquad (3.2)$$

where T_d is the dew point (deg K),

T_a is the air temperature (deg K),

r is the relative humidity,

L_v is the latent heat of vaporization (cal gm^{-1}),

R^* is the universal gas constant (erg $mole^{-1}$ deg K^{-1}),

M_d is the molecular weight of dry air (gm $mole^{-1}$), and

1 cal = 4.186×10^7 erg.

It proved impossible to locate sufficient reports of dew point from ships to determine reliable mean values for any region within Baffin Bay. Neither were any mean monthly maps of dew point or relative humidity available. Some data were obtained from coastal stations, however, and so the only choice was to make use of these in a manner to be discussed shortly. Table 3-3 gives an indication of the reliability of the data used.

It would be possible, of course, to simply compute an average dew point over the Bay for each month from all the data from coastal stations. But this method does not seem advisable since the dew point varies considerably from station to station and hence, presumably, from one region of the Bay to another. Furthermore, the dew point would exceed the air temperature in many locations were this procedure to be followed.

Neither would it be wise to simply make a linear interpolation of dew point between the east and west shores of Baffin Bay since neither

TABLE 3-3. Number of Years of Observations of Humidity at Coastal Stations in Baffin Bay.

Station	MSL ht. (feet)	RH or T_d	J	F	M	A	M	J	J	A	S	O	N	D	Source of Data
Thule	121	RH	---	---	---	---	---	3	---	---	---	---	---	---	1
Upernavik	59	RH	---	---	---	---	---	31	---	---	---	---	---	---	1
Umanak	26	RH	---	---	---	---	---	10	---	---	---	---	---	---	1
Jakobshavn	102	RH	---	---	---	---	---	30	---	---	---	---	---	---	1
Godthaab	66	RH	---	---	---	---	---	25	---	---	---	---	---	---	1
Padloping I.	130	T_d	4	3	4	4	4	4	4	4	4	3	3	3	2
C. Hooper	65	T_d	3	5	5	4	3	3	2	3	3	3	2	2	2
Clyde	10	T_d	11	11	13	13	13	14	13	12	12	12	13	12	2, 3
Arctic Bay	36	RH	---	---	---	---	---	4	---	---	---	---	---	---	4
Craig Harb.	-	RH	---	---	---	---	---	2 - 5	---	---	---	---	---	---	4

Source 1 . . . U.K. Air Ministry, Meteorological Office, 1958.

2 . . . Canada, Department of Transport, Meteorological Branch, Arctic Summary (various years).

3 . . . Canada, Department of Transport, Meteorological Branch, Monthly Record (various years).

4 . . . Petterssen, Jacobs, and Haynes, 1956.

the air temperature nor the water surface temperature showssuch an inclination. Moreover, strong gradients of dew point will almost certainly occur near the ice edge.

As no better alternative was discovered, it was decided to plot the available coastal dew point data for a particular month on a sheet of tracing paper placed over the map (U.S. Navy, 1963) of mean isotherms for that month. Then an isodrosotherm (i.e., "dew point isotherm") analysis was carried out making use of the plotted values as much as possible and bearing in mind the fact that the dew point must not exceed the temperature at any point. The isotherms were thus used as general guide lines for the isodrosotherms which were drawn with roughly the same pattern (see Fig. 3-1).

The validity of this procedure is not completely justifiable; although the isotherms do provide a gross control over the isodrosotherms, especially when the relative humidity is high. (They coincide, in fact, at 100 per cent relative humidity). It would appear that the method of obtaining dew point data described above is more open to question than the methods used to obtain values for any of the other parameters. Water surface temperature, air temperature, and wind data were acquired either from observations or from analyzed maps. Ice surface temperature data were derived from the data of air temperature, with the correction factors based on observations in the Arctic Ocean. But no humidity observations over the ocean were used and mainly only an "upper limit" control was provided by the air temperature. For this reason it is felt that the dew point values thus obtained may be too high. This would contribute to a decrease in the evaporation or an increase in the condensation results.

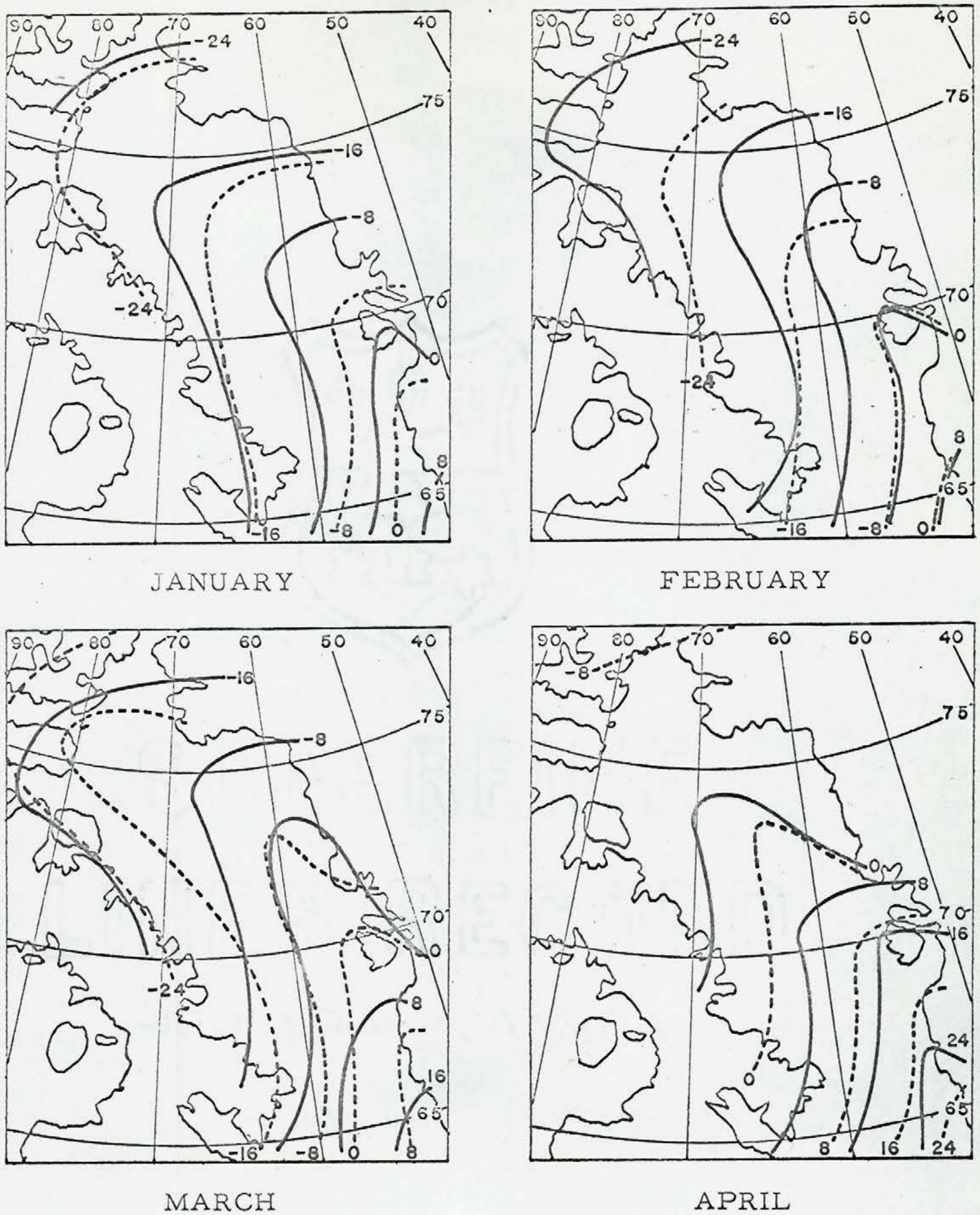
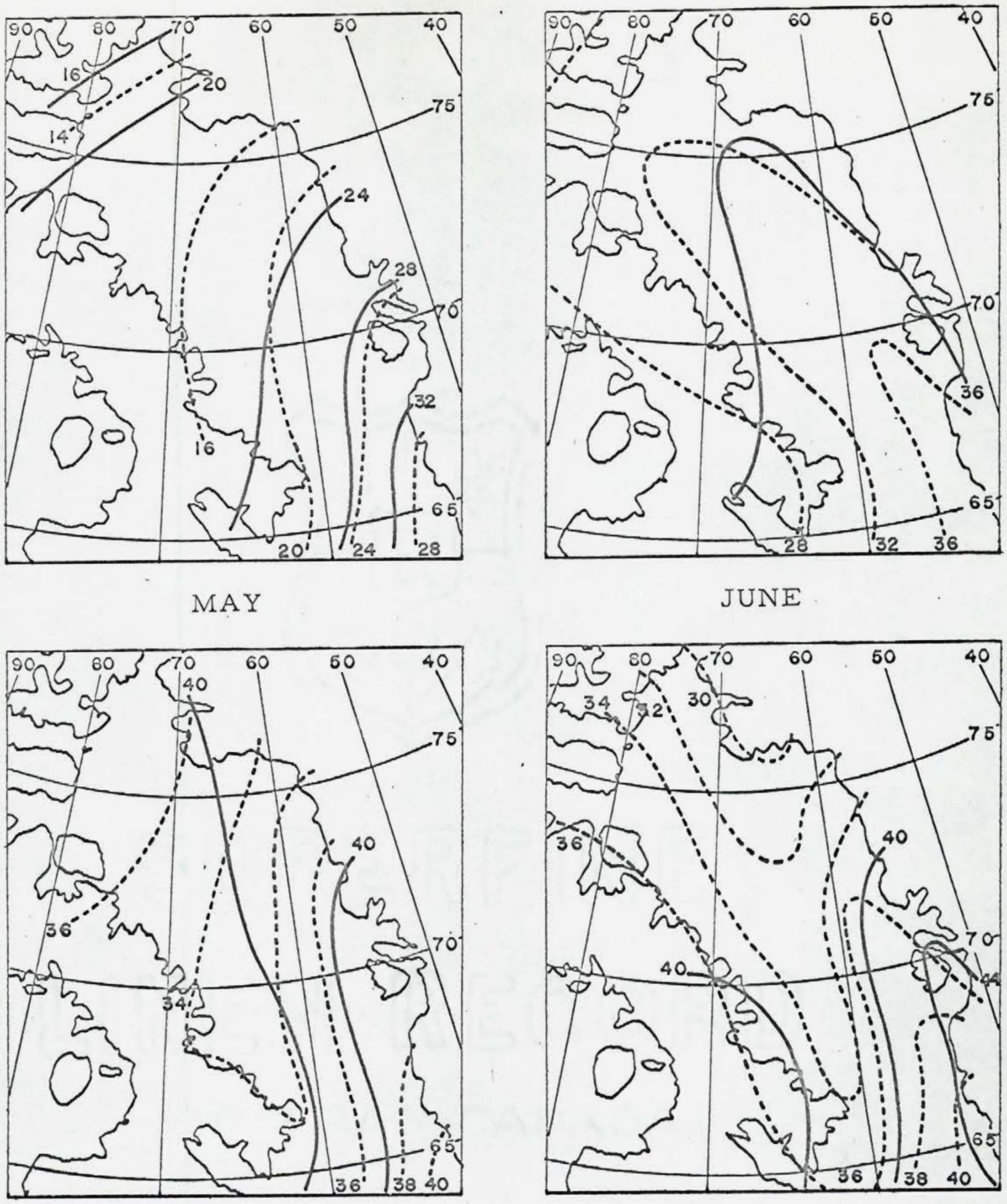


FIG. 3-1. Mean Air Temperature (from U.S. Navy, 1963) and estimated Mean Dew Point in Baffin Bay.

Isopleth Interval . . . 8F

Isotherms ————————

Isodrosotherms --------



MAY JUNE

JULY AUGUST

FIG. 3-1. (cont'd) Mean Air Temperature (from U.S. Navy, 1963) and estimated Mean Dew Point in Baffin Bay.

Isopleth Interval . . . 4F (with some intermediate isodrosotherms)

Isotherms ————————

Isodrosotherms - - - - - - - -

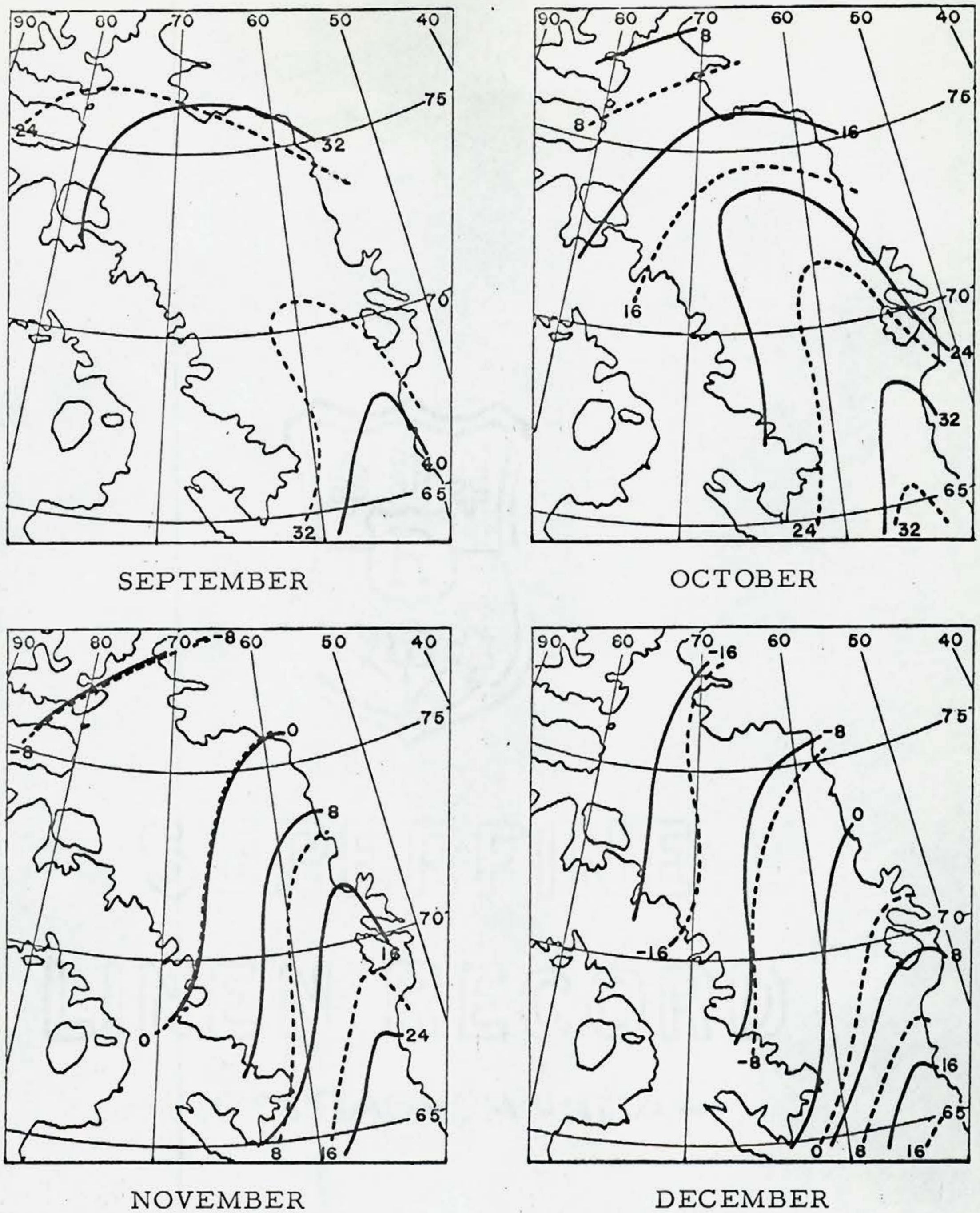


FIG. 3-1. (cont'd) Mean Air Temperature (from U.S. Navy, 1963) and estimated Mean Dew Point in Baffin Bay.

Isopleth Interval . . . 8F

Isotherms ————————

Isodrosotherms --------

3.5 Wind Speed

The average wind speed (in knots) for a given month may be defined as the "run of wind" for the month (in nautical miles) divided by the number of hours in the month. The run of wind may be determined, for example, from the number of revolutions of a cup anemometer. Mathematically, the average wind speed may be expressed as follows:

$$\overline{V}^{t} = \frac{\int_t V\,dt}{\int_t dt} \quad , \quad (3.3)$$

where $\overline{V}^{t}$ is the time averaged wind speed and

V is the wind speed at time, t .

Integration over time is carried out from the beginning to the end of the month. Several such calculations should be made for the same month in different years in order to obtain a mean value which will be valid over a reasonably long interval of time.

Often the run of wind is not available, however, and a series of observations must be used to calculate an average. If N such observations are made, then:

$$\overline{V}^{t} \approx \frac{1}{N} \sum_{i=1}^{N} V_i \quad , \quad (3.4)$$

where V_i is the wind speed measured at the time of the i th. observation.

If the wind speed is recorded as a Beaufort Force instead of in knots, then a less accurate mean value is obtainable as follows:

$$\overline{V}^t \approx \frac{1}{N} \sum_{j=0}^{12} N_j \overline{V}_j \quad , \quad (3.5)$$

where N is again the total number of observations,

N_j is the number of occurrences of Beaufort Force j, and

$\overline{V}_j$ is the average wind speed of Beaufort Force j.

The Beaufort Scale is given in Table 3-4.

If, instead of number of occurrences, frequency of occurrence is given, then Eq. (3.5) becomes:

$$\overline{V}^t \approx \frac{\sum_{j=0}^{12} F_j \overline{V}_j}{\sum_{j=0}^{12} F_j} = \frac{1}{100} \sum_{j=0}^{12} F_j \overline{V}_j \quad , \quad (3.6)$$

where F_j is the percentage frequency of occurrence of Beaufort Force j.

Graphs of frequency of occurrence of wind speed are available (U.S. Navy, 1963) for two areas in Baffin Bay for each of the months July to October, inclusive. The areas are in Melville Bay and near Disko Island and are the same as those discussed in Section 3.3. Table 3-5 shows the number of ship observations upon which the graphs are based.

TABLE 3-4. The Beaufort Scale of Wind Force.

Beaufort Force	Range of Speeds (knots)	Average Speed (knots)
j	-	$\overline{V_j}$
0	0	0
1	1 - 3	2.0
2	4 - 6	5.0
3	7 - 10	8.5
4	11 - 16	13.5
5	17 - 21	19.0
6	22 - 27	24.5
7	28 - 33	30.5
8	34 - 40	37.0
9	41 - 47	44.0
10	48 - 55	51.5
11	56 - 63	59.5
12	$\geqq$ 64	-

TABLE 3-5. Number of Observations of Wind used for Wind Speed Frequency Charts (U.S. Navy, 1963).

Month	Number of Observations	
	Disko Island	Melville Bay
JULY	584	509
AUG	423	451
SEPT	210	128
OCT	52	38

The wind speeds are classified into nine categories by Beaufort Forces (see Table 3-4). Forces 0 and 1 have been combined to form the first category. An average speed of 1.5 kt has been assumed in this case. Forces 9, 10, 11 and 12 have been grouped together into the ninth category, "Greater than 8". Here an average speed of 44 kt, the same as for Force 9, has been assumed. This assumption is justified by the fact that even the occurrence of Force 8 is very rare in the Bay. Thus an occurrence of "Greater than 8" is not likely to mean a Force in excess of 9. The remaining seven categories are Forces 2 to 8, inclusive. Because of this method of classification, Eq. (3.6) must be modified, in this study, so that the summation is carried out over the nine categories rather than the thirteen Beaufort Forces.

The mean wind speeds, in the Melville Bay and Disko Island areas, which result from the calculations, are assumed to represent the actual mean wind speeds in the northern and southern regions of Baffin Bay, respectively. Frequency charts are also given for the Disko Island area in June and the Melville Bay area in November. But, instead, it was decided to use the technique described in the following paragraphs to obtain average wind speeds for these two months.

Published frequency charts form the basis for calculating wind speeds for July, August, September and October. A different technique, however, must be used for the remaining eight months of the year. Observations over the ocean in the region of interest are not sufficient to calculate mean wind speeds satisfactorily. Winds are reported regularly at several coastal stations; but it was felt that these measurements are not representative of conditions over the surface of Baffin Bay.

Analyzed pressure maps, however, are available. Although isobars over the ocean must have been drawn mainly on the basis of observed pressures at coastal stations, the errors due to interpolation of mean sea level pressure are not likely to be as great as those due to interpolation of wind speed, since the former is largely unaffected by topography.

Geostrophic winds, from which actual winds may be estimated, can be obtained from the pressure charts either by computations based on grid point pressure values or by direct reading from a nomogram overlay. For reasons of greater simplicity and because much less time is involved, the latter method was chosen for use in the present study.

Since the Geostrophic Wind Equation (see Appendix I) is linear with respect to both the isobar interval and the map scale, any nomogram, regardless of the indicated interval and scale, which is constructed for the correct map projection, may be used to measure the geostrophic wind. Because of the small scale of the maps involved, however, it was not possible to find a nomogram already constructed which contained enough lines for satisfactory use. For this reason a wind scale was made according to directions given in Petterssen (1956) with a minor modification in his geostrophic wind equation since isobars and not height contours appear on the maps. This alteration necessitates substituting the variable α , the specific volume of air, for the quasi-constant, g , the gravitational acceleration. To simplify the nomogram, rough estimates of average annual pressure and temperature in the region were used to compute an approximate mean value of α . Further details of the construction of this nomogram, the "Sea-Level Geostrophic Wind Scale", are given in Appendix I.

One might at first think that it would be sufficient to determine the geostrophic wind from a mean surface pressure map for the month in question. Unfortunately the problem is not so simple; for the mean pressure map will give a mean vector wind (i. e., mean velocity) and not a mean wind speed which is required for heat flux calculations.

The ratio of the magnitude of the mean wind velocity to the mean wind speed is known as the "constancy of wind". This ratio ranges from 0 to 1 with low values indicating extremely variable wind directions and high values a nearly constant direction. Thus a mean pressure map will give an accurate value of mean wind speed only if the wind blows constantly from one direction throughout the month. This is very unlikely due to the occurrence of migrating cyclones, especially in the southern part of the Bay (see "Storm Tracks" maps, U.S. Navy, 1963). Thus one has no alternative but to make measurements of the wind using the geostrophic wind scale on daily (0000 GMT) maps. The German Weather Service (Deutscher Wetterdienst) daily map series, Täglicher Wetterbericht, was used for this purpose.

For the following two reasons inaccuracies in the analysis of pressure are not likely to cause serious errors:

(i) Only the pressure gradient is critical since the wind direction is not required. Thus the results will be affected only by the spacing of the isobars and not by their alignment.

(ii) The daily results are averaged over the month. This has the effect of smoothing out the errors.

It would be very laborious to carry out these measurements for 239 days (i.e., November to June) of every year. A better solution would be to find years in which each of the eight months may be considered typical. The German Weather Service also publishes a series of monthly maps, Die Grosswetterlagen Mitteleuropas, which show deviations of mean sea level pressure from the long-term (1899-1939) average. The following months had mean pressures within five millibars of the long-term values for all areas of Baffin Bay:

January	1954
February	1953
March	1954
April	1959
May	1961
June	1961
November	1960
December	1957

Three measurements of geostrophic wind in Baffin Bay were made for each day of the above eight months. The three values were determined at about 67.5N, 72.5N, and 76.5N, and were used for all points on latitudes 65-70N, 71-74N, and 75-78N, respectively. In addition, one measurement was made over Weather Ship "B" (56.5N, 51W) each day. The observed wind speed at "B" was also recorded in order to obtain an estimate of the ratio of the actual wind speed to the geostrophic wind speed. Whenever possible the observed speed at "B" was obtained from the synoptic hour report since winds are given to the nearest knot there, whereas they are only plotted to the nearest five knots on the map. Average ratios for Ship "B" are given in Table 3-6.

An attempt was made to determine a relation between V/V_g and V_g at "B" by plotting these values every day for eight months.

TABLE 3-6. Mean Ratio of Observed Surface Wind Speed to Geostrophic Wind Speed at Ship "B" (56.5N, 51W).

Month	Year	$\overline{V/V_g}$ %
JAN	1954	83.8
FEB	1953	82.5
MAR	1954	93.9
APR	1959	97.3
MAY	1961	91.3
JUN	1961	88.5
NOV	1960	106.5
DEC	1957	88.1
Average		91.5

No satisfactory conclusion could be drawn, however, regarding the relationship of the two quantities. So it was assumed the mean ratio determined at "B" each month was also applicable to Baffin Bay. Mean geostrophic wind speeds in the Bay were therefore multiplied by the ratio $\left(\overline{V/V_g}\right)$ at Ship "B" for that month.

By way of comparison, the average value given in Table 3-6 (91.5 per cent) agrees quite well with the value quoted by Sheppard (1952) for the mean ratio of the surface wind speed to the geostrophic wind speed. For cases where the geostrophic wind is determined from synoptic maps (as in the present study) Sheppard gives a ratio of 88 per cent.

Table 3-7 summarizes the techniques used to obtain wind speed data for the purpose of calculating energy fluxes. Figure 3-2 shows the time variation of the calculated mean wind speed in the northern and southern parts of Baffin Bay. Both areas show a summer minimum of about 6 or 7 kt, well below the 12 kt limit separating rough and smooth flow (see Section 4.1).

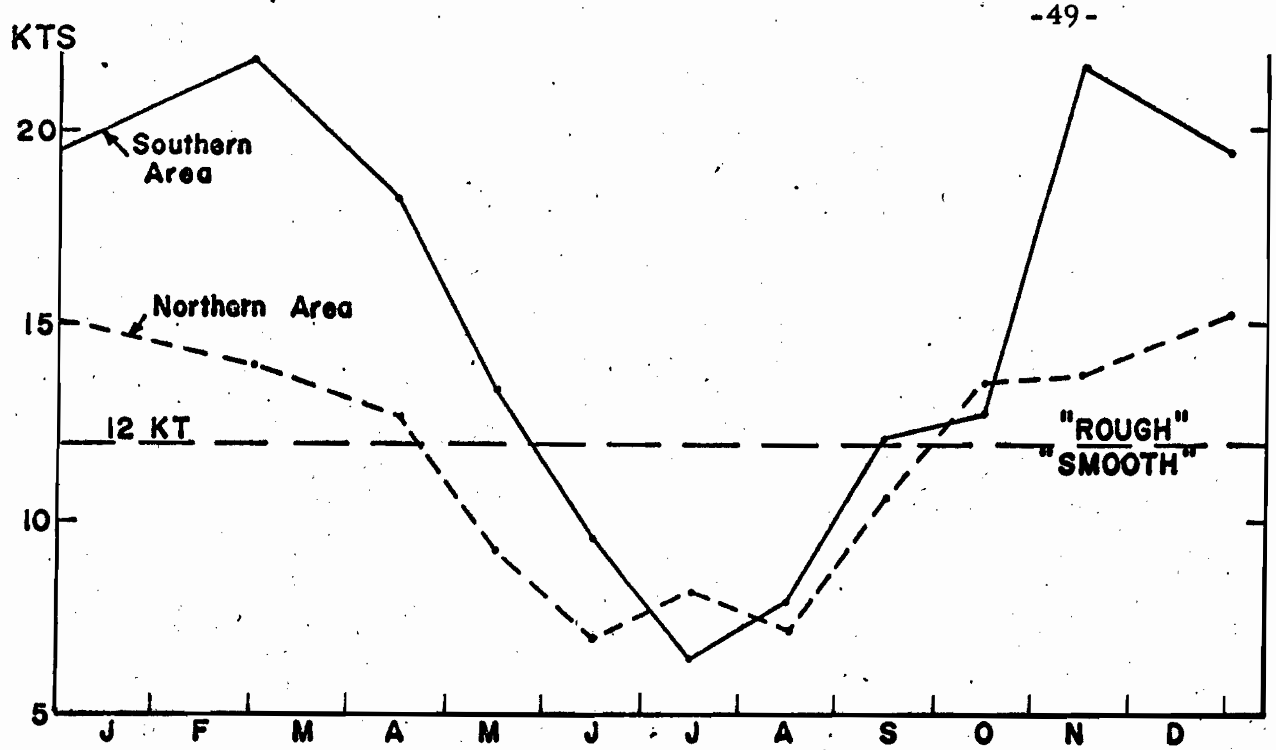


FIG. 3-2. Mean Wind Speed (knots) throughout the Year in Baffin Bay.

TABLE 3-7. Summary of Techniques used to Calculate Mean Wind Speeds.

Months	Source of Data	Format of Data	Processing of Data
NOV-JUNE	Täglicher Wetterbericht	M.S.L. Pressure Charts	(i) Measurement of Geostrophic Wind Speed. (ii) Multiplication by Ratio, $(\overline{V}/V_g)$
JULY-OCT	U.S. Navy, 1963	Charts showing Frequency of Occurrence of Wind Speeds by Beaufort Force.	$\frac{1}{100}\sum_{j=1}^{9} F_j \overline{V}_j$

Chapter 4

SURFACE HEAT FLUXES

4.1 Formulae

(a) Vapour Pressure

Following Hess (1959), the Clausius-Clapeyron Equation may be written in the form:

$$\ln\left(\frac{e}{6.11}\right) = \frac{M_v L}{R^*}\left(\frac{1}{273} - \frac{1}{T}\right) ,$$

where e is a vapour pressure in millibars, and
T is a temperature or dew point in degrees Kelvin.

Operating with the exponential function, EXP , we obtain:

$$e = (6.11) EXP\left\{\frac{M_v L}{R^*}\left(\frac{1}{273} - \frac{1}{T}\right)\right\} . \quad (4.1)$$

An explanation of the terms e , T , and L , in four different situations, is given below:

(i) For the vapour pressure at eight meters above the surface,
$e = e_a$,
$T = T_d$, the dew point, and
$L = L_v$, the latent heat of vaporization.

(ii) For the saturated vapour pressure just above a water surface,
$e = e_w$
$T = T_w$, the water surface temperature, and
$L = L_v$.

(iii) For the saturated vapour pressure just above an ice surface,

$e = e_i$,

$T = T_i$, the ice surface temperature, and

$L = L_s$, the latent heat of sublimation.

(iv) For the saturated vapour pressure just above a melt-water surface,

$e = e_i$,

$T = T_i$, the surface temperature (assumed $\leqq$ 1.0C), and

$L = L_v$.

From Hess (1959):

L_v = 597.3 cal gm^{-1}, and

L_s = 677.0 cal gm^{-1}, (at 0C). The variation of these terms with temperature is fairly small and will be neglected.

The remaining terms in Eq. (4.1) still to be explained are M_v and R^*. This is easily done as follows:

$$M_v = 0.622 \; M_d$$

$$\frac{R^*}{M_d} = 2.870 \times 10^6 \text{ erg gm}^{-1} (\text{deg K})^{-1}$$

$$1 \text{ cal} = 4.187 \times 10^7 \text{ erg}$$

$$\therefore \frac{M_v}{R^*} = 9.08 \text{ cal}^{-1} \text{ gm (deg K)}$$

where M_d is the molecular weight of dry air,

M_v is the molecular weight of water vapour,

R^* is the universal gas constant, and

$\frac{R^*}{M_d}$ is the gas constant for dry air.

(b) Latent Heat Fluxes

Given the "evaporation" term, E, the corresponding flux of latent heat is determined from:

$$Q = (0.1)\,\rho L E \qquad (4.2)$$

where Q is in langleys day^{-1} (i.e., cal cm^{-2} day^{-1}),

ρ is the density of water in gm cm^{-3},

L is in cal gm^{-1}, and

E is in millimeters of water per day.

The factor 0.1 must be included to convert E from mm day^{-1} to cm day^{-1} and so make (4.2) dimensionally correct.

It should be mentioned at this point that the term "evaporation" is taken to include condensation and sublimation as well as true evaporation. Condensation may simply be interpreted as negative evaporation. Sublimation may be considered (from the energy point of view, at least) the same as melting followed by evaporation, in the case of an upward flux of energy; or condensation followed by freezing, in the case of a downward flux. The terms Q and L in Eq. (4.2) may now be defined in more detail for two particular cases:

(i) For evaporation from an open ocean surface,

$Q = Q_{E_w}$ and

$L = L_v$.

(ii) For "evaporation" from ice or melt-water surfaces,

$Q = Q_{E_i}$ and

$L = L_s$.

It may not seem quite correct to use the latent heat of sublimation for evaporation from a melt-water pool. It may be assumed, however, that the energy required to melt the surface layers of ice and to form pools comes from the atmosphere. This assumption does not ignore or contradict the fact that heat from the ocean plays an important role in melting ice, too; but only that ice which is not exposed to the atmosphere. Thus the total energy necessary to turn one gram of ice into vapour is:

$$(L_f + L_v) (1 \text{ gm}),$$

where L_f = 79.7 cal gm^{-1} is the latent heat of fusion,

L_v = 597.3 cal gm^{-1} is the latent heat of vaporization, and

$L_s = L_f + L_v$ = 677.0 cal gm^{-1} is the latent heat of sublimation.

For evaporation from a surface which is partly ice covered:

$$Q_E = Q_{E_i}(\text{CONC}) + Q_{E_w}(1 - \text{CONC}), \quad (4.3)$$

where CONC is the ice concentration.

(c) Evaporation over an ice-free ocean

The formula most widely accepted for use in a climatic study of evaporation is Sverdrup's:

$$E = K \left| e_w - e_a \right| V ,$$

where K = coefficient,
V = wind speed (m sec^{-1}),
e_w, e_a = water vapour pressure at the surface and in the air (mb).

There are other equally good formulae but the main advantage of Sverdrup's is that it has been used in evaporation calculations by various authors . . . between 60N and 50S. Furthermore, in a recent summary of the available evaporation formulae, Swinbank (1959) concludes that no fundamental improvement in the Sverdrup formula is possible at present. (Vowinckel and Taylor, 1965).

This much being decided, the only difficulty remaining is the determination of a sufficiently good value of the coefficient, K. For evaporation from a salt water surface in units of millimeters per day, Jacobs (1951) gives a value of K = 0.142 which is an average for different areas determined from the energy balance equation.

Sverdrup (1951), however, showed that K varies with the wind speed. Provided that the wind speed is greater than 12 kt (about 6.2 m sec^{-1}) and average monthly values of wind and vapour pressure are used (as in the case in the present study) then:

$$E = 0.003 \left| e_w - e_a \right| V \quad , \qquad (4.4)$$

where E is the evaporation from an ocean surface in inches day^{-1},

e_a, V are measured at a height of about 20 to 30 ft,

V is in knots, and

e_w, e_a are in millibars.

Converting to units of m sec^{-1} and mm day^{-1} for V and E respectively, a value, $K = 0.145$, which shows excellent agreement with Jacobs' value of 0.142, was obtained for the case of "rough" flow (i.e. $V > 6.2$ m sec^{-1}). In the case of "smooth" flow ($V \leq 6.2$ m sec^{-1}) it is apparent from a graph of Sverdrup's (1951) that $K = 0.090$ is a reasonable average value.

(d) "Evaporation" over sea ice

The use of the Sverdrup formula for ice surfaces may be justified as follows:

> First, in summer . . . the surface is generally slush and melting ice which can be considered open water. Second, the frozen ice surface itself can be regarded as similar to water for evaporation purposes, provided that the saturation pressure over ice is used. (Vowinckel and Taylor, 1965).

The values of the coefficient, K, which are given above are for evaporation over an open ocean. They were used for the case of an ice surface as well. Although the critical wind speed which separates "rough" flow from "smooth" is taken to be 12 kt over water, this figure may not be correct over ice. Furthermore, the values of K_i may be different, even though the use of the Sverdrup formula itself is assumed to be permissible. Vowinckel and Taylor (1965) do not discuss this question and it is assumed, therefore, that the same coefficients were used both over water and over ice in that study. For this reason and for lack of information to the contrary, it was decided to use the following evaporation coefficients for both water and ice surfaces:

$$K = \begin{cases} 0.145, V > 6.2 \text{ m sec}^{-1} \\ 0.090, V \leq 6.2 \text{ m sec}^{-1} \end{cases}$$

These values are for saline water. When ice or melt-water surfaces are involved the vapour pressures are about 2 per cent larger. Hence the term ($e_i - e_a$) is altered to 1.02 ($e_i - e_a$), where e_i is the vapour pressure at the ice or melt-water surface.

(e) Sensible Heat

One method of calculating the sensible heat, Q_H , is by using the Bowen Ratio (Vowinckel and Taylor, 1965). The usual method in this case is to derive Q_H from the evaporation, Q_E . But, by making the calculation of sensible heat dependent on evaporation, any errors in Q_E will be reflected in the value of Q_H which results. This effect will likely be greatest when the evaporation is small to begin with. The evaporation in Baffin Bay (see Section 4.2) is less than about 120 ly day^{-1} at all times of year. In summer, in particular, the latent heat flux is practically zero. Thus the Bowen

Ratio method, as normally used, is not a good means of obtaining sensible heat fluxes in this area.

A number of authors have proposed the following formula which enables a calculation of Q_H , independently of Q_E :

$$Q_H = K'(T_s - T_a) V \quad , \quad (4.5)$$

where Q_H is the sensible heat flux (ly day^{-1}),
K' is a coefficient,
T_s is the surface temperature (deg C),
T_a is the air temperature at 8 m (deg C), and
V is the wind speed at 8 m (m sec^{-1}).

Even the Bowen Ratio formula may be reduced to the form of Eq. (4.5) by assuming a pressure of 1000 mb and by substituting for Q_E and E using (4.2) and the Sverdrup Equation (Section 4.1 (c)), respectively. Table 4-1 gives the value of the coefficient, K' , as determined after conversion to the above mentioned units from values given in several sources.

The four different coefficients in Table 4-1 which result from the Bowen Ratio formula are due to:

(i) the two different values of the evaporation coefficient in the Sverdrup Equation, depending on whether the wind speed is greater or less than 12 kt, and

(ii) the two different values of L in Eq. (4.2), depending on whether the surface is water or ice covered.

TABLE 4-1. Coefficients for the Sensible Heat Flux Equation, (4.5).

Source	K'	Remarks
Budyko, 1956	4.98	-
Batalin, 1960	3.46	Over water
Jarvis, 1964	6.75	Moderate or strong winds over water; upward fluxes
Vowinckel and Taylor, 1965 (BOWEN RATIO)	5.72	Rough flow — Over water
	3.55	Smooth flow — Over water
	6.48	Rough flow — Over ice
	4.02	Smooth flow — Over ice
Shuleikin, 1953	0.42	Downward fluxes
	30.24/V	Upward fluxes*

* If V_{max} = 22 kt and V_{min} = 7 kt, then K'_{min} = 2.67 and K'_{max} = 8.38.

TABLE 4-2. Comparison of the Shuleikin and Bowen Ratio Sensible Heat Flux Results.

Month	Percentage Deviation of Shuleikin Results from Shuleikin - Bowen Mean Value.	
	Norwegian-Barents Sea (Vowinckel and Taylor, 1965)	Baffin Bay (1919-42 Average Ice Cover).
JAN	8.9	3.1
FEB	2.8	56.4
MAR	-4.6	56.4
APR	1.3	-24.3
MAY	24.1	2.9
JUNE	168.	80.3
JULY	229.	80.1
AUG	1560.	96.9
SEPT	15.6	34.2
OCT	23.0	-12.3
NOV	12.3	-14.1
DEC	8.8	3.1

For this study it was decided to use the Shuleikin (1953) formula. This is given below:

$$Q_H' = \begin{cases} 30.24\,(T_s - T_a) & , T_s \geqq T_a \\ 0.42\,(T_s - T_a)V & , T_s < T_a \end{cases} \quad , \quad (4.6)$$

For upward fluxes, it may be seen, Shuleikin uses a very large coefficient but drops the wind speed from the formula as given in Eq. (4.5). Since the mean wind speed in Baffin Bay ranges between about 7 and 22 kt (see Fig. 3-2), this means that K' spans the range of values given in Table 4-1. For downward fluxes, on the other hand, the Shuleikin coefficient is very small. Due to the fact that downward fluxes occur only when a temperature inversion is present and the lower atmosphere is very stable, it would seem logical that the sensible heat fluxes would be small under these conditions. Proceeding further with this argument, however, leads to a contradiction; for quite stable conditions can exist even with a decrease of temperature with height. Yet, the Shuleikin formula gives a large increase to the sensible heat flux when the sign becomes positive, rather than when the atmosphere becomes unstable in the lower layers. Apart from this difficulty, which was not taken into consideration in the calculations, the Shuleikin formula seems reasonable. The actual values of his coefficients may well be disputed, but their orders of magnitude are likely correct.

Vowinckel and Taylor (1965) used both the Shuleikin formula and the Bowen Ratio for calculations in the Norwegian-Barents Sea.

This was also done in the present study, although it was decided to use the Shuleikin results. Table 4-2 gives a comparison of these two methods of calculating Q_H for the Norwegian-Barents Sea as well as Baffin Bay. It will be seen that large differences occur, particularly during the summer months when the fluxes are small and the Bowen Ratio results are least likely to be correct.

4.2 Results

The hydrometeorological data were punched onto computer punch cards and were read in by the McGill IBM 7040/7044 Computer which performed the calculations as outlined in the Fortran programme in Appendix II. Another part of the programme, not indicated in the Appendix, provided for results for each reference point to be printed at the proper location on a large map (15 in by 10 in) of Baffin Bay. The above calculations involved about sixteen minutes of computing time.

Fig. 4-1 shows the results obtained using the 1919-42 ice concentration compared with the Bering Sea results of Batalin (1960). The 1919-42 ice concentration for the two bodies of water is also shown. The Bering Sea has the greater radiation budget (see Fig. 5-1) and the lesser ice concentration of the two areas. This is especially true in the months October to June when, therefore, the Bering Sea sensible and latent heat fluxes may be expected to exceed those in Baffin Bay. From October to April the evaporation in the former area is considerably greater than in the latter; whereas the sensible heat flux is somewhat

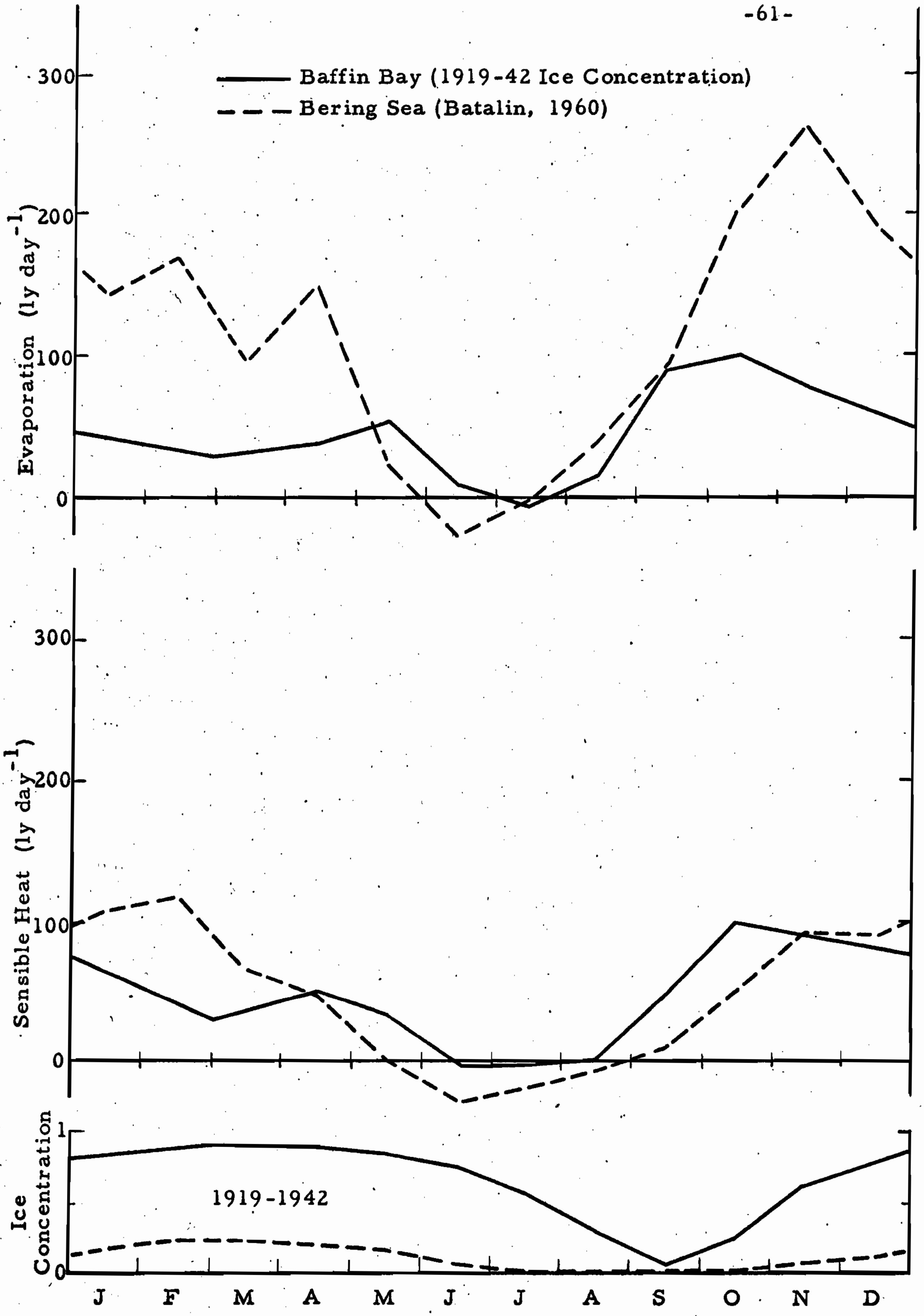


FIG. 4-1. Surface Heat Fluxes and Ice Concentration in Baffin Bay and the Bering Sea.

greater in the Bering Sea from December to March. The differences in the fluxes in winter, when differences are most probable, and their fairly close correspondence throughout the summer, when radiation and ice conditions are most nearly alike in the two areas, indicate that the results of the present study are reasonable.

The evaporation and sensible heat flux results of Vowinckel and Taylor (1965) for the Norwegian-Barents Sea show maxima (upward) in autumn and spring and minima (slightly downward) in summer. This is also true of the Bering Sea results. The results of the present study indicate that the seasonal variations in Baffin Bay follow the same pattern. Although this gives further support to the accuracy of the calculations, because of the methods used to obtain data (see Chapter 3), it is unlikely that the results are better than a reasonable approximation of the actual fluxes.

From Fig. 4-1 it may be seen that the maximum fluxes in Baffin Bay occur in October. There are three factors which cause this maximum:

(i) Strong winds over most of the area contribute to larger evaporation values.

(ii) Fairly low ice concentration reduces the significance of the small fluxes over ice.

(iii) Fairly large upward temperature and vapour pressure gradients* occur as the air cools with the approach of

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* In general, the direction of the "gradient" is from low to high values. Here, as elsewhere in meteorology, it is convenient to take the opposite direction in order that gradients and the corresponding fluxes may have the same direction.

winter and the water temperature is relatively little changed.

The minimum fluxes in June, July and August may also be explained by an examination of the data used in the calculations. Several factors appear:

(i) Downward temperature gradients as the air becomes warmer in summer necessitate the use of the smaller sensible heat coefficient in Eq. (4. 6).

(ii) Low wind speeds cannot compensate for the smaller sensible heat coefficient.

(iii) Low wind speeds reduce the evaporation directly, as well as reducing the evaporation coefficient from 0.145 to 0.090.

(iv) Small temperature and vapour pressure gradients occur over both water and ice.

These four factors clearly explain why the negative fluxes are never very large. Furthermore, small as they are, the downward latent heat fluxes may be overestimates since, according to Vowinckel and Taylor (1965) it seems likely "that a part of this energy gain [for the surface by condensation] is lost directly into the air". In view of the very small values involved, however, the fact that this possibility was ignored does not cause serious errors in the results obtained.

Mention has been made of the "North Open Water", a feature of the sea ice distribution which is evident in the mean ice maps (D.H.I., 1950 and U.S.H.O., 1958). It was decided to compare the fluxes in this area with those in neighbouring regions. Average values were calculated from the results at five reference points centred near 76N, 72.5W. Another five points, roughly surrounding the first five, were chosen in order to compute averages for the purpose of comparison. Such an investigation was attempted using the results of the 1957-65 mean ice cover. Little differences are evident, however, in the ice concentration during this period. Naturally, therefore, the fluxes are also quite similar in the two areas.

Despite the inconclusive results of the 1957-65 computation, the comparison was attempted a second time using the 1919-42 ice period. The results this time are more interesting and are shown in Fig. 4-2, where the five surrounding points have been identified as "North Ice". As should be expected, most of the year the fluxes are considerably greater in the "North Open Water" area. The small differences in September may be explained by the fact that the ice concentration is low in both areas. In July and August the differences are again small due to the fact that the fluxes are negative and, as shown above, can never be very large. In June the sensible heat fluxes are nearly identical, whereas the evaporation is greater in the "North Ice" area. It is possible to explain this apparent anomaly by an examination of the data which were used to calculate the evaporation. Water temperatures were at the freezing point (which, for a salinity of 3.2 per cent, would be -1.7C). Air temperatures were a few degrees Farenheit above freezing, so that ice surface temperatures were +1C. Thus the term $(e_i - e_a)$ was greater than $(e_w - e_a)$. In addition, as discussed in Section 4.1(d), the former term must be multiplied by 1.02; and, furthermore, Q_{E_i} is increased by 1.13 relative to Q_{E_w}

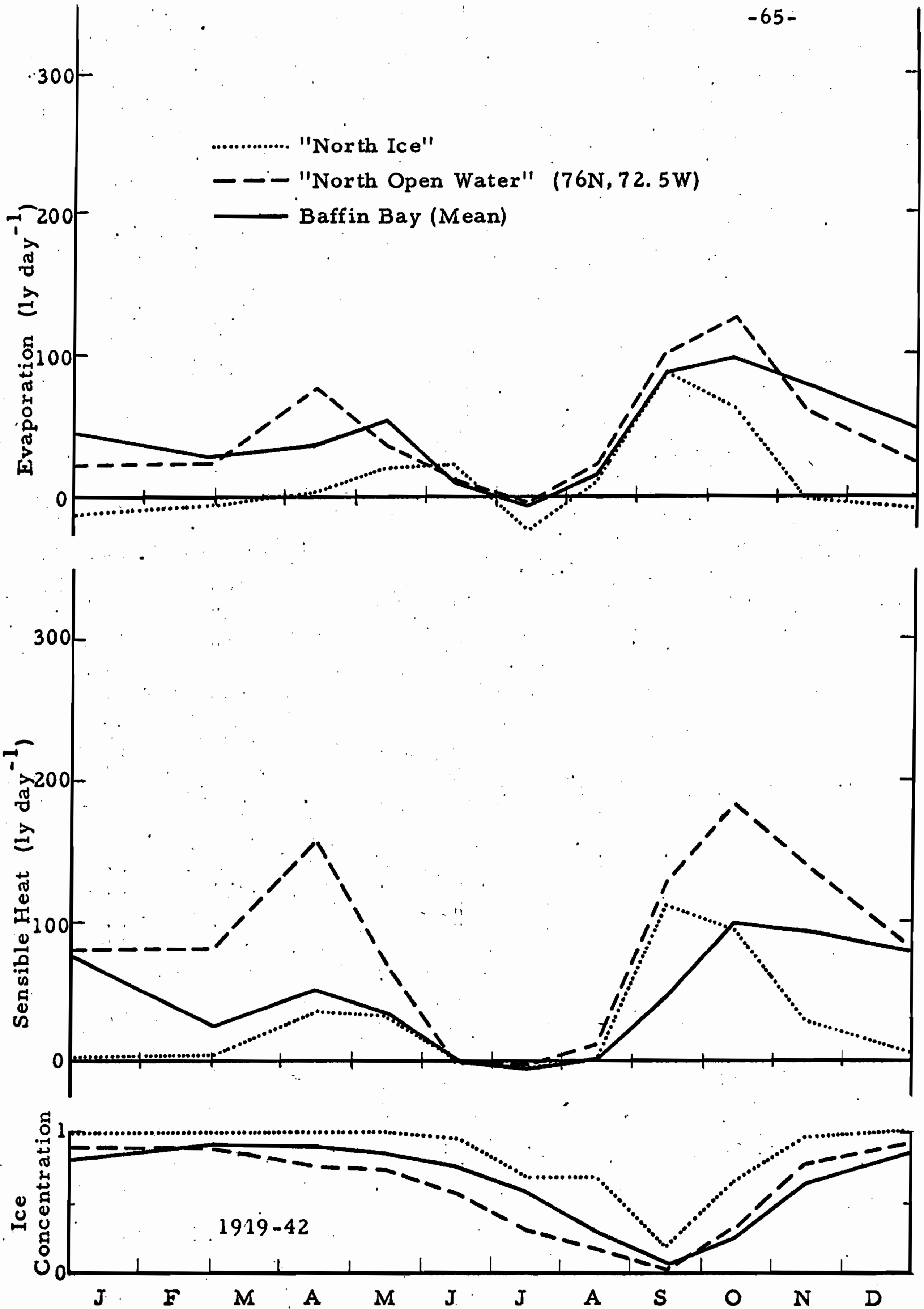

FIG. 4-2. The effect of the "North Open Water" on the Surface Heat Fluxes in northern Baffin Bay.

as a result of using L_s rather than L_v in Eq. (4. 2).

Calculations of the latent and sensible heat fluxes were performed at two additional locations within Baffin Bay. One of these areas, close to the geographical centre of the Bay, has fairly heavy ice conditions for nine months of the year. It has been called "Central Ice" for the purpose of identification. The other area, which experiences almost ice-free conditions for nine months, stretches for about 200 mi along the Greenland coast, near Holsteinsborg. Values of the fluxes in each region were determined by averaging the results at five reference points. The comparison of the "Central Ice and "Holsteinsborg" areas is presented in Fig. 4-3. In the latter area maximum fluxes in excess of 300 ly day^{-1} were found to occur in December-January. Even in November and February-March the latent heat fluxes were discovered to be greater than 200 ly day^{-1}. Generally, these values are more than twice as large as the net radiation (Vowinckel and Orvig, 1964b) but less than half as large as the terrestrial radiation component of Q_N in that corner of the Bay.

Maximum fluxes during the year for various Arctic areas from two other studies are presented in comparison with the results for the "Holsteinsborg" area in Table 4-3. The figures show that fluxes as large as 300 ly day^{-1}, though perhaps not extremely common, are very likely possible.

The secondary minimum in the fluxes in the "Holsteinsborg" area in October is mainly caused by smaller temperature and vapour pressure gradients in that month than in September. Since this is somewhat questionable, the irregularity in the curves may not be real.

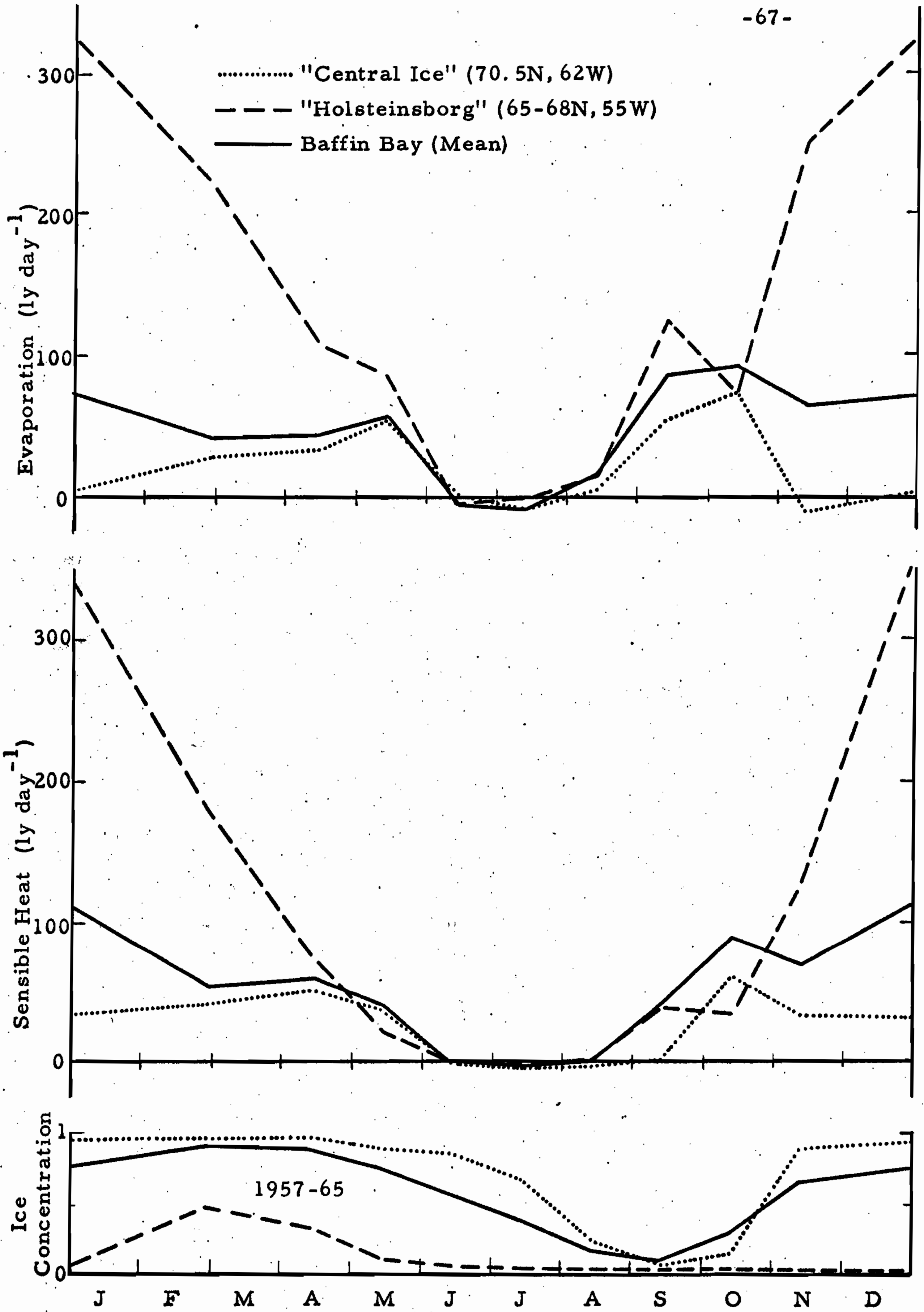

FIG. 4-3. Surface Heat Fluxes and Ice Concentration in central Baffin Bay and near Holsteinsborg, Greenland.

TABLE 4-3. Maximum Surface Heat Fluxes (ly day^{-1}) over Open Water in the Arctic.

Region	Month	Q_E	Q_H	Author(s)
Baffin Bay	Dec-Jan	325	345	Walmsley, 1966
Norwegian-Barents Sea	Mar	191	412	Vowinckel and Taylor, 1964*
Central Polar Ocean	Jan, Mar	143	850	
Kara-Laptev Sea	Jan	188	705	
East Siberian Sea	Jan	157	757	
Beaufort Sea	Jan, Feb	140	1083	
Bering Sea	Jan, Nov	406	273	Batalin, 1960

* A slightly more detailed version of Vowinckel and Taylor, 1965

Maximum fluxes of 50-75 ly day^{-1} in the "Central Ice" area occur in spring (April or May) and fall (October). They are caused by relatively strong winds, large gradients over water, and (in October) low ice concentration.

Small downward fluxes in summer in both regions are caused by the same factors listed earlier in this Section in the discussion of Fig. 4-1.

Average values of the latent and sensible heat fluxes are presented, for the three ice periods, in Table 4-4. At any given time of year the differences between values for the different ice periods are due entirely to the differences in ice concentration (see Fig. 2-2). The 1919-42 results throughout the months December to August are generally smaller than those for the other two periods. This is caused by a greater ice concentration in those months in the earliest period. Exceptions occur, however, and an explanation of this apparent irregularity has been given earlier in this Section for the case of latent heat fluxes.

TABLE 4-4. Evaporation and Sensible Heat Flux in Baffin Bay.

(langleys day^{-1})

	Ice Conc.	Dec. - Jan.	Feb. - Mar.	April		May		June		July		August		September		October		Nov.
		-	-	1-15	16-30	1-15	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-31	-
Q_E	1919-42	48.5	29.6	38.3		55.1		10.3		-7.0		15.2		88.9		101.		78.8
	1952-56	56.4	45.8	47.8		56.6	57.2	7.4	5.3	-5.8	-8.3	16.8	18.1	87.6	87.3	109.	85.4	120.
	1957-65	72.8	41.3	39.7	48.1	56.2	58.5	6.1	4.2	-7.5	-9.1	17.0	18.0	87.2	87.4	106.	82.2	66.4
Q_H	1919-42	75.7	30.9	50.7		33.5		-2.6		-5.2		-0.3		45.6		98.9		90.7
	1952-56	97.1	64.2	67.7		38.2	40.4	-3.0	-3.4	-5.1	-5.5	1.1	1.4	45.5	44.6	109.	76.4	152.
	1957-65	111.	51.7	52.3	64.4	36.4	44.1	-3.2	-3.5	-5.4	-5.6	0.9	1.2	44.2	44.0	106.	72.8	70.1

The 1919-42 results are shown again in the second and third rows of Table 5-1 (with the dimensions changed to langleys) in order to obtain an estimate of the energy budget of Baffin Bay.

Chapter 5

ENERGY BALANCE OF BAFFIN BAY

5.1 Net Radiative Balance at the Surface

The net downward radiation, $-Q_N$, was not calculated in this study. Instead, values were determined for each month from published maps (Vowinckel and Orvig, 1964b) at twelve points in Baffin Bay. Each of the seventy-two reference points (see Section 2.2) was then given the same value as the nearest of these twelve points. An area weighted average was computed and the results are shown in Fig. 5-1 in comparison with those (Batalin, 1960) for the Bering Sea, another body of water bordering on the Arctic Ocean. The maps of Vowinckel and Orvig (1964b) show that most of the year the surface of the Bering Sea benefits from radiation more than the Baffin Bay surface, thus confirming what is indicated in Fig. 5-1.

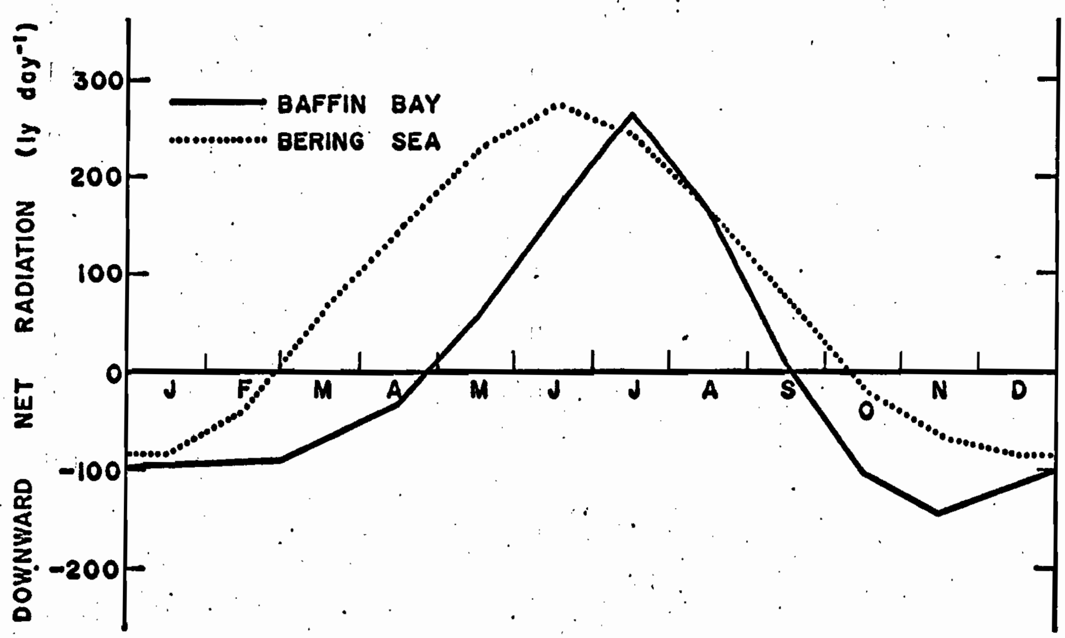

FIG. 5-1. Net Radiation at the Surface in Baffin Bay and the Bering Sea.

5.2 Oceanic Energy Fluxes

It can be seen from the latent and sensible heat flux results (Table 4-4) and from the radiation budget (Fig. 5-1) that during the year there is a net transfer of heat from the ocean surface to the atmosphere. The question of how to account for this transfer now arises. Obviously, the heat must be supplied from the ocean itself in the form of what may be called a "storage change". This term, Q_S in Eq. (1.1), has four components: Q_T, Q_W, Q_F, and Q_I, as mentioned in Section 1.3 (d). The latter two terms have contributions from two sources: ice which forms and remains in the Bay, and that which is exported. It was decided to make an estimate of Q_S during the year in order to try to account for the heat transferred to the atmosphere by the Q_N, Q_E, and Q_H terms. Reference is made to Table 1-1 which outlines the information required for the calculation of the oceanic heat flux terms. Under each Sub-Section below is listed the steps which were followed in the calculations.

(a) Q_T, the heat transported by ocean currents

(i) The West Greenland Current inflow of 75 $km^3\ day^{-1}$ was obtained as an average of results for Sections 1, 2, 3, and 5, p. 71, Smith, Soule, and Mosby (1937).

(ii) The Canadian (or Baffin Land) Current outflow of 190 $km^3 day^{-1}$ was obtained as an average of results for Sections 1 and 2, p.71, Smith <u>et al.</u> (1937).

(iii) A compensating inflow of 115 $km^3 day^{-1}$ through Smith, Jones and Lancaster Sounds was assumed.

(iv) An average temperature of 2.7C in the West Greenland Current was assumed. This was a mean of two results: 1.20C from Section 2 (September, 1928) and 4.08C from Section 1 (August, 1924) in Smith et al. (1937).

(v) An average temperature of -0.6C in the Canadian Current was obtained from Section 2, Smith et al. (1937).

(vi) The average temperature of the northern inflow currents was taken, as a first approximation, to be the same as the temperature in the top layer in Baffin Bay. This is likely a good approximation in times of heavy ice conditions in the Bay.

(vii) The average temperature in the top layer of the ocean in Baffin Bay was taken to be the unweighted average of the surface temperature and the temperature at the bottom of the layer, which was assumed to be 30F (-1.1C).

(viii) The average surface temperature in Baffin Bay was assumed to range from a maximum of 3.5C in August to a minimum of -1.5C in May. The most rapid decrease in temperature was assumed to coincide with the rapid increase in ice cover in the autumn and the surface temperature at the end of November was taken to be -1C. Conversely, the most rapid rise in surface temperature was presumed to occur in June, July, and August.

(ix) The surface area of Baffin Bay was determined to be 750,000 km^2 from a planimeter measurement of an equal area map (Fig. 1-1).

(x) Twelve monthly calculations were performed using the formula:

$$Q_T = \left[\left(T_G - T_B \right) V_G - \left(T_C - T_B \right) V_C \right] N / A$$

$$= \left[\left(2.7 - T_B \right) 75 - \left(-0.6 - T_B \right) 190 \right] N / 7.5 \quad , \quad (5.1)$$

where Q_T is in langleys,

T_G is the average temperature of the West Greenland Current (deg C),

T_C is the average temperature of the Canadian Current (deg C),

V_G, V_C are the corresponding rates of flow ($km^3 day^{-1}$),

T_B is the average temperature in the top layer of Baffin Bay (deg C),

N is the number of days in the month, and

A is the surface area of Baffin Bay (km^2).

(b) Q_W, the heat due to the cooling or warming of water in the top layer of Baffin Bay

(i) The average temperature in the top layer was obtained each month as described above.

(ii) The change in average temperature from month to month was then determined.

(iii) The depth of the top layer was assumed to be 75 m from an investigation of Defant (1961) and Sverdrup, Johnson and Fleming (1942).

(iv) The ice concentration was obtained from the published maps (see Fig. 2-2).

(v) Twelve monthly calculations were performed using the formula:

$$Q_W = -\Delta T_B \left(1 - CONC \right) Z \qquad , \quad (5.2)$$

where Q_W is in langleys,

ΔT_B is the change in the average temperature of the top layer since the previous month (deg C),

$CONC$ is the ice concentration, and

Z = 7500 cm is the depth of the top layer.

(c) Q_F , the heat due to the freezing or melting of non-exported ice.

(i) New ice was assumed to begin forming (in some areas of the Bay) in September and to grow rapidly to a thickness of 50 cm by the end of November and then, less rapidly, to a maximum of 150 cm at the end of April. These estimations were based on five years of ice thickness data for Clyde (Canadian Meteorological Branch, Department of Transport, 1961, 1962, 1963, and 1964c). It was assumed further that the thickness remains constant during the melting season.

(ii) The ice concentration was obtained as described above.

(iii) The formula used for each month's calculations is:

$$\begin{aligned} Q_F &= \rho L_f \left[H_1 \left(CONC_0 - CONC_{-1} \right) + \left(H_0 - H_{-1} \right) CONC_0 \right] \\ &= 73.6 \left[H_1 \left(\Delta CONC \right) + \left(\Delta H \right) CONC_0 \right] \qquad , \quad (5.3) \end{aligned}$$

where Q_F is in langleys,

H is the ice thickness (cm),

ρ = 0.92 gm cm^{-3} is the ice density,

L_f is the latent heat of fusion, and

the subscripts 0 and -1 refer to the present and the previous month, respectively.

(d) $Q_F(X)$, the heat due to the freezing of ice which is later exported.

(i) The width of the ice at Davis Strait was calculated each month from the published maps (D.H.I., 1950). Ice in the 0-20 per cent concentration range was neglected. Furthermore, the export was assumed to take place mainly in the western half of the Strait. Thus the surface area of the exported ice may be slightly underestimated. The widths of each concentration range were measured along 65N and the results were multiplied by the average concentration in that range. The sum of the resulting figures gave the total width of the 100 per cent concentrated ice for the month in question.

(ii) Ice thicknesses were obtained as outlined above.

(iii) The surface current speed was taken to be 0.3 kt (or 13.3 km day^{-1}) as shown in Fig. 1-2.

(iv) The effect of the wind on the ice export was ignored.

(v) The determination of the surface area has been described above.

(vi) The formula used for the calculation of heat gain due to ice export is:

$$Q_F(X) = \left(v\, W_{100}\, H\, \rho\, L_f \right) / A$$

$$= 0.00130 \ W_{100} \ H \qquad , \quad (5.4)$$

where $Q_F(X)$ is in langleys,

V = 13.3 km day^{-1} is the surface current speed, and

W_{100} is the width of 100 per cent concentrated ice (km).

(e) Q_I, the heat due to the cooling or warming of ice.

(i) The average surface temperature each month was obtained from the air temperature and Table 3-1.

(ii) The temperature of the lower surface of the ice was assumed to be at the freezing point (-1.7C for water of 3.2 per cent salinity).

(iii) A linear gradient of temperature with depth in the ice was assumed (see Vowinckel, 1964). Thus the average temperature in the ice is simply the mean of the surface temperature and -1.7C.

(iv) The thickness and concentration of the ice were obtained as described above.

(v) The formula for the heat released in the cooling of ice is:

$$Q_I = H \ \Delta T_I \ CONC \ \rho \ S_I$$

$$= 0.46 \ H \ \Delta T_I \ CONC \qquad , \quad (5.5)$$

where Q_I is in langleys,

ΔT_I is the change of the average temperature in the ice since the previous month (deg C), and

S_I =0.5 cal gm^{-1} $(deg\ C)^{-1}$ is the specific heat of ice. This will vary slightly with the temperature and the salinity of the ice (Untersteiner, 1961).

The calculations revealed that a total of about 700 ly was released due to the cooling of ice from November to April, inclusive. Since the exported ice during these months averaged about 14 per cent of the total ice frozen, it was assumed that 100 ly were exported and the remaining 600 ly were used to warm the ice in June, July and August, prior to melting.

5.3 Surface Energy Budget

The complete surface energy budget of Baffin Bay is given in Table 5-1. It was decided to use data mainly from the earliest (and longest) ice period. This was possible except for the radiation data, the speed of the ice-exporting surface current, the ice thickness data, and some of the meteorological data which was obtained by various means as described in Chapter 3. The budget year was begun in September at the time of minimum ice cover.

The figures for Q_N are simply those plotted in Fig. 5-1, except that the dimensions have been changed to langleys by multiplication by the number of days in the month. Similarly, the dimensions of the Q_E and Q_H values given in Table 4-4 have been changed in order to deduce the second and third rows of figures in Table 5-1. The atmospheric fluxes,which are assumed accurate to the nearest 10 ly, have been added to give the total surface-atmosphere exchange.

As only rough estimates of the oceanic fluxes were made (see Section 5. 2), it was decided to record them only to the nearest 100 ly. The sum of these terms gives Q_S , the total surface-ocean energy influx. In theory, according to Eq. (1. 1) and Fig. 1-4, Q_S should be equal to the total energy efflux in both sign and magnitude at all times of year. The results of Table 5-1, however, show imbalances ranging from a net loss of 4600 ly to a net gain of 6500 ly. Even in the month closest to balance, April, a net gain of 200 ly is shown.

Despite the imbalances, several encouraging indications should be noted:

(i) The net efflux of energy which begins in August does not continue to increase as time goes by. Instead, it reaches a maximum in November and then begins to decrease so that, finally, in April, a net gain of energy takes over for a four month interval. Although the influxes do not quite equal the effluxes which occurred at the beginning of the budget year, nevertheless, the fact that the sign does change is an indication that the atmosphere and ocean are attempting to maintain a surface heat balance.

(ii) The Q_W and Q_F terms should be zero when summed over the year. Indeed, the results show that they come reasonably close. Compared with the annual heat influx due to ice export and water transport, those due to the cooling of water and freezing of (non-exported) ice are practically negligible.

(iii) Out of an annual energy loss of 31, 300 ly by radiation and turbulent exchange, all but 6600 ly (or 21 per cent) can be accounted for by oceanic energy import.

TABLE 5-1. Energy Budget of the Baffin Bay Surface, 1919-42.

(hundreds of langleys)

Budget Component	S	O	N	D	J	F	M	A	M	J	J	A	Year	Remarks
Q_N	-3.0	30.6	42.7	29.7	29.7	24.8	27.4	9.5	-16.9	-50.2	-83.6	-51.1	-10	Vowinckel, Orvig, 1964b
Q_E	26.7	31.4	23.6	15.0	15.0	8.3	9.2	11.5	17.1	3.1	-2.2	4.7	163	Avg. Ice Con 1919-42
Q_H	13.7	30.7	27.2	23.5	23.5	8.6	9.6	15.2	10.4	-0.8	-1.6	-0.1	160	Avg. Ice Con 1919-42
Total Energy Efflux, Q_A	37.4	92.7	93.5	68.2	68.2	41.7	46.2	36.2	10.6	-47.9	-87.4	-46.5	313	
Q_W	25	43	22	6	1	0	0	1	-2	-11	-28	-48	9	Avg. Ice Con 1919-42
Q_F	-25	4	14	17	12	19	14	10	1	-11	-19	-31	5	Avg. Ice Con 1919-42
Q_F (X)	0	0	1	5	8	12	17	18	17	15	12	1	106	Avg. Ice Con 1919-42
Q_I	0	0	1	1	1	0	2	2	0	-2	-2	-2	1	Avg. Ice Con 1919-42
Q_T	13	14	10	8	8	7	7	7	8	10	15	19	126	Smith et al., 1937
Total Energy Influx, Q_S	13	61	48	37	30	38	40	38	24	1	-22	-61	247	
Net Energy Influx	-24	-32	-46	-31	-38	-4	-6	2	13	49	65	-14	-66	See Fig. 5-2.
Accum. Net Influx	-24	-56	-102	-133	-171	-175	-181	-179	-166	-117	-52	-66	-66	

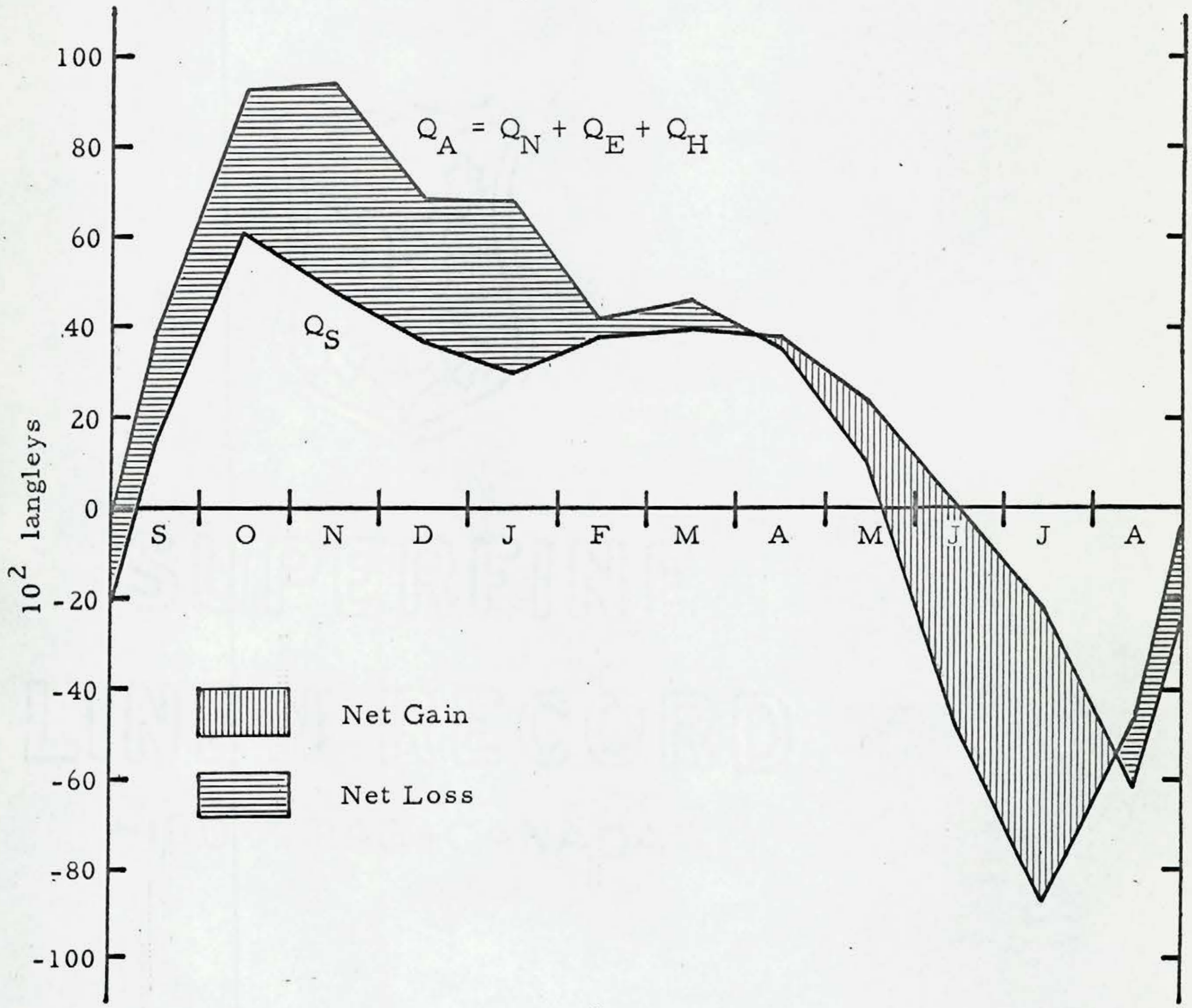

FIG. 5-2. Energy Gains and Losses at the Surface of Baffin Bay, 1919-42.
(Refer to Table 5-1.)

The imbalance in the annual energy budget figures may be explained in three possible ways:

(i) The latent and sensible heat calculations may be high estimates.

(ii) The heat gain by water transport may be too small.

(iii) The heat gain by ice export may be too small.

Several indications discussed in Section 4. 2 point to the fact that the latent and sensible heat results must be a reasonable approximation to the true fluxes, although it should not be claimed that they are better than that. Some error, therefore, may be assumed, although the error may just as easily be negative as positive. Furthermore, when an examination of the possibility of reducing the efflux of heat by a change in the original data was made, it was found that, short of making drastic changes, it would be quite difficult to cause significant reductions in the results.

It is very possible, however, that the calculated water transport term, Q_T , differs from the actual flux. As noted in Section 5. 2, the average temperature of the West Greenland Current appears to vary over a large range (e. g., 1. 20C in one year compared with 4. 08C in another). A value of 2. 7C was used in the calculations; but a value one degree warmer or colder may be used and, naturally, quite different results would be obtained.

Uncertainties in the volume of water transported in and out through Davis Strait also exist. Smith, Soule, and Mosby (1937) was the only source located which gave volumes of water entering and leaving

TABLE 5-2. Net Outflow of Water through Davis Strait.

Source	Net Outflow ($km^3 day^{-1}$)	Outflow, relative to Smith
Smith et al. (1937)	115	1.00
Timofeyev (1956)	86	0.75
Dunbar (1960)	117	1.02
Zaitsev (1961)	638	5.55

the Bay; and so their results were used in the calculations. Other studies, concerned mainly with the water balance of the Arctic Ocean, quote only net outflow figures. Table 5-2 shows some of these figures and their relation to those of Smith et al. (1937). From the close correspondence of the results of Dunbar (1960) and Smith, it seems that the decision to use the latter was a good one. Zaitsev (1961), however, argues from water balance considerations that the results of Timofeyev (1956) should be as much as eight times larger. With the same outflow-inflow ratio as obtained from Smith (about 2.5 : 1), a tremendous increase in the energy influx would result if Zaitsev's figures were used. In fact, the annual energy budget would be a net influx of more than 50,000 ly, rather than the net efflux of 6600 ly which is the present result. It can be seen, therefore, that only a small increase in the volume of water exchanged between Baffin Bay and the Labrador Sea could account for the 6600 ly. An increase in the net outflow from 115 to 175 km^3 day^{-1} (which, using the same ratio as before, would mean an inflow of 114 and an outflow of 289 km^3 day^{-1}), with no change in any other terms, would cause the annual energy budget to be balanced.

An important contribution to the ice export at any given time is due to the wind. The fact that this contribution was neglected in the rough estimations of the oceanic fluxes, however, should not cause significantly different values of heat gain by ice export. Since Davis Strait lies in the region of frequent cyclone migrations (U.S. Navy, 1963), the northward and southward components of the wind should cancel, on the average. The ocean currents, therefore, appear to be the principal cause of ice export from Baffin Bay.

Although the imbalance in the annual energy budget cannot be explained conclusively at this time, three possibilities have been suggested. It seems that the budget may be balanced most easily by an increase in the volume of water exchanged between the Bay and the Labrador Sea, or by an increase in the value used for the average temperature of the West Greenland Current. Smaller contributions may result from a decrease in the latent and sensible heat fluxes or an increase in the heat gain by ice export. The problem of determining a reasonable energy balance for Baffin Bay, nevertheless, remains a very difficult, yet very intriguing one. It is hoped that the present results have helped to unveil at least a corner of it.

In conclusion, it should be repeated that the results of this study ought to be regarded as rational estimates of the true values. The uncertainties, however, cannot be avoided at present. "The infinite variety of natural conditions can never be accounted for completely, and generalisations and simplifications are the price paid" (Vowinckel and Taylor, 1965). "We cannot wait until we observe everything before we try to explain what is going on . . ." (Sphilhaus, 1966).

Appendix I

CONSTRUCTION OF A SEA-LEVEL GEOSTROPHIC WIND SCALE

The sea-level geostrophic wind is directed parallel to the surface isobars with low pressure on the left (relative to the direction of motion). It's speed is given by:

$$V_g = \frac{\alpha}{f} \frac{\partial p}{\partial n} \approx \frac{\alpha}{f} \frac{\Delta p}{\Delta n} , \quad (1)$$

where α is the specific volume of the air,
f is the Coriolis parameter,
Δp is the isobar interval, and
Δn is the distance apart of the isobars on the earth's surface.

The terms α , f , and Δn may be further defined as follows:

$$\alpha = \frac{RT}{p}$$

$$f = 2\Omega \sin\phi$$

$$\Delta n = \frac{\Delta N}{S K_\phi}$$

where R is the gas constant for dry air,
T is the absolute temperature,
p is the atmospheric pressure,
Ω is the angular speed of rotation of the earth,
ϕ is the latitude,
ΔN is the distance apart of the isobars on the map,
S is the map scale, and
K_ϕ is the distortion factor at latitude ϕ.

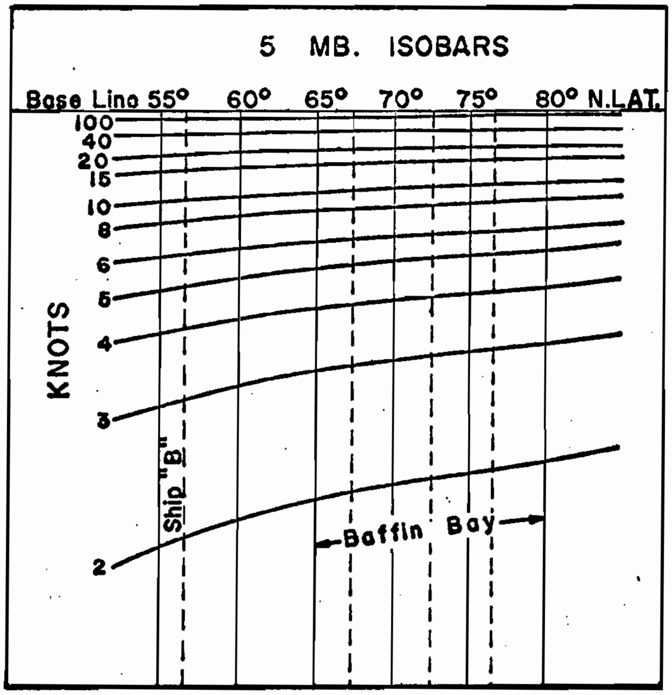

FIG. 1. Sea-Level Geostrophic Wind Scale.
(Polar Stereographic Projection of Scale 1:50,000,000 at 60N).

In order to calculate α, average annual values of ρ and T were chosen for Baffin Bay. The maps used are found in Täglicher Wetterbericht,' the daily series of the German Weather Service. The projection of these maps is polar stereographic.

After substitution and grouping of terms, Eq. (1) becomes:

$$V_g = \left(\frac{RT\Delta p S}{2\Omega\rho}\right)\left(\frac{K_\phi}{\sin\phi}\right)\frac{1}{\Delta N} \quad , \quad (2)$$

where $R = 2.87 \times 10^6$ erg gm^{-1} (deg K)$^{-1}$,
$T = 262$K,
$\Delta p = 5$ mb,
$S = (50,000,000)^{-1}$,
$\Omega = 7.29 \times 10^{-5}$ sec^{-1}, and

$$p = 1010 \text{ mb.}$$

The first bracketed term in (2) is therefore constant and has a value of 9.9 kt cm. Values of $K_\phi / \sin\phi$ are given in Peterssen (1956).

Values of ΔN were then computed for latitudes 50, 60, 70, and 80N for wind speeds of 2, 3, 4, 5, 6, 8, 10, 15, 20, 40, and 100 kt. The wind scale is shown in Fig. 1. The isobar spacing is measured from the baseline and the wind speed in knots is read directly. For practical use the scale must be drawn on a transparent overlay material.

Appendix II

OUTLINE OF A FORTRAN PROGRAMME FOR SURFACE HEAT FLUX CALCULATIONS

Explanation of the variables:

AREA(J)	The area covered by the reference "point", J, in relative units.
BAY	The total area of Baffin Bay, in relative units.
QH	Sensible heat flux, positive upward.
QE	Latent heat flux, positive upward.
QN	Net radiation, positive upward.
CONC	Ice concentration.
I	One of the ten periods of the year for which the calculations were performed.
J	One of the 72 reference points.
TW	Water temperature (punched "99" when at freezing point).
TA	Air temperature.
SAL	Salinity, in parts per thousand.
TD	Dew Point.
V	Wind Speed.
K	One of the five ice periods:

K = 1 . . . 1919-42
K = 2 . . . 1952-56 (first half of months)
K = 3 . . . " (last " " ")
K = 4 . . . 1957-65 (first " " ")
K = 5 . . . " (last " " ")

TI	Ice surface temperature.
DIFF	Values given in Table 3-1.
EW	Vapour pressure at the water surface.
EI	Vapour pressure at the ice surface.
EA	Vapour pressure in the air.
RLV	Latent heat of vaporization.
RLS	Latent heat of sublimation.
RK	Evaporation coefficient.
QEW	Latent heat flux over water.
QEI	Latent heat flux over ice.
RKUP, RKDOWN	Sensible heat coefficients.
QHW	Sensible heat flux over water.
QHI	Sensible heat flux over ice.
QEBAR, QHBAR, QNBAR, CBAR	Areal averaged values of QE, QH, QN, CONC, respectively.

Main Programme:

```
   COMMON AREA(72), BAY, QH(72, 5), QE(72, 5), QN(72), CONC(72, 5)

   DO 1  I = 1, 10
   READ BAY, RLV, RLS, and other constants.
   READ in dimensions of data to follow.
   READ AREA

   DO 2  J = 1, 72
   READ TW, SAL, TA, TD, V, QN(J), (CONC(J, K), K = 1, 5)
   IF(TW. NE. 99.) GO TO 10
   TW = (-0.0543)*SAL
10 CONTINUE
```

Next follows a section which converts TW, TA, TD to degrees Celsius and V to m sec^{-1}, if they do not already have these dimensions.

```
   TI = TA + DIFF
   IF(TI. GT. 1.)TI = 1.
   CALL VAPOR (EW, RLV, TW)
   CALL VAPOR (EI, RLS, TI)
   CALL VAPOR (EA, RLV, TD)

   RK = 0.145
   IF(V. LE. 6. 2)RK = 0.090

   QEW = 0.1*RLV*RK*(EW-EA)*V
   QEI = 0.1*RLS*RK*(EI-EA)*V

   RKUP = 30.24
   RKDOWN = 0.42*V
   RATIO = RKDOWN/RKUP
   QHW = RKUP*(TW-TA)
   QHI = RKUP*(TI-TA)
   IF(QHW. LT. 0.)QHW = QHW*RATIO
   IF(QHI. LT. 0.)QHI = QHI*RATIO

   DO3  K = 1, 5
   CALL WEIGHT(QH(J, K), QHW, QHI, CONC(K))
   CALL WEIGHT(QE(J, K), QEW, QEI, CONC(K))
3  CONTINUE
2  CONTINUE
   DO 4 K = 1, 5
   CALL AVG(QEBAR, QHBAR, QNBAR, CBAR)
   QSBAR = QNBAR + QEBAR + QHBAR
   WRITE headings for table
   WRITE QNBAR, QEBAR, QHBAR, QSBAR, CBAR
4  CONTINUE
1  CONTINUE
   END
```

Subroutine to compute vapour pressure (in millibars) from temperature for dew point (in degrees C).

```
      SUBROUTINE VAPOR(E,RL,T)
      T = T + 273.
      ARG=(RL/0.1102)*((1./273.)-(1./T))
      E = 6.11*EXP(ARG)
      RETURN
      END
```

Subroutine to compute fluxes weighted by the ice concentration.

```
      SUBROUTINE WEIGHT(A,B,C,D)
      A = B*(1.-D)+ C*D
      RETURN
      END
```

Subroutine to compute mean values weighted with respect to the size of the area each of the 72 reference points represents.

```
      SUBROUTINE AVG(A,B,C,D)
      COMMON AREA(72),BAY,QH(72,5),QE(72,5),QN(72),CONC(72,5)

      SUMA = 0.
      SUMB = 0.
      SUMC = 0.
      SUMD = 0.

      DO 1  J = 1,72
      SUMA = SUMA + QE(J,K)*AREA(J)
      SUMB = SUMB + QH(J,K)*AREA(J)
      SUMC = SUMC + QN(J)*AREA(J)
      SUMD = SUMD + CONC(J,K)*AREA(J)
    1 CONTINUE

      A = SUMA/BAY
      B = SUMB/BAY
      C = SUMC/BAY
      D = SUMD/BAY
      RETURN
      END
```

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U.S.H.O.	United States (Navy) Hydrographic Office, Washington. (Until 1963).
U.S.N.O.O.	United States Navy Oceanographic Office, Washington, (From 1964).

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