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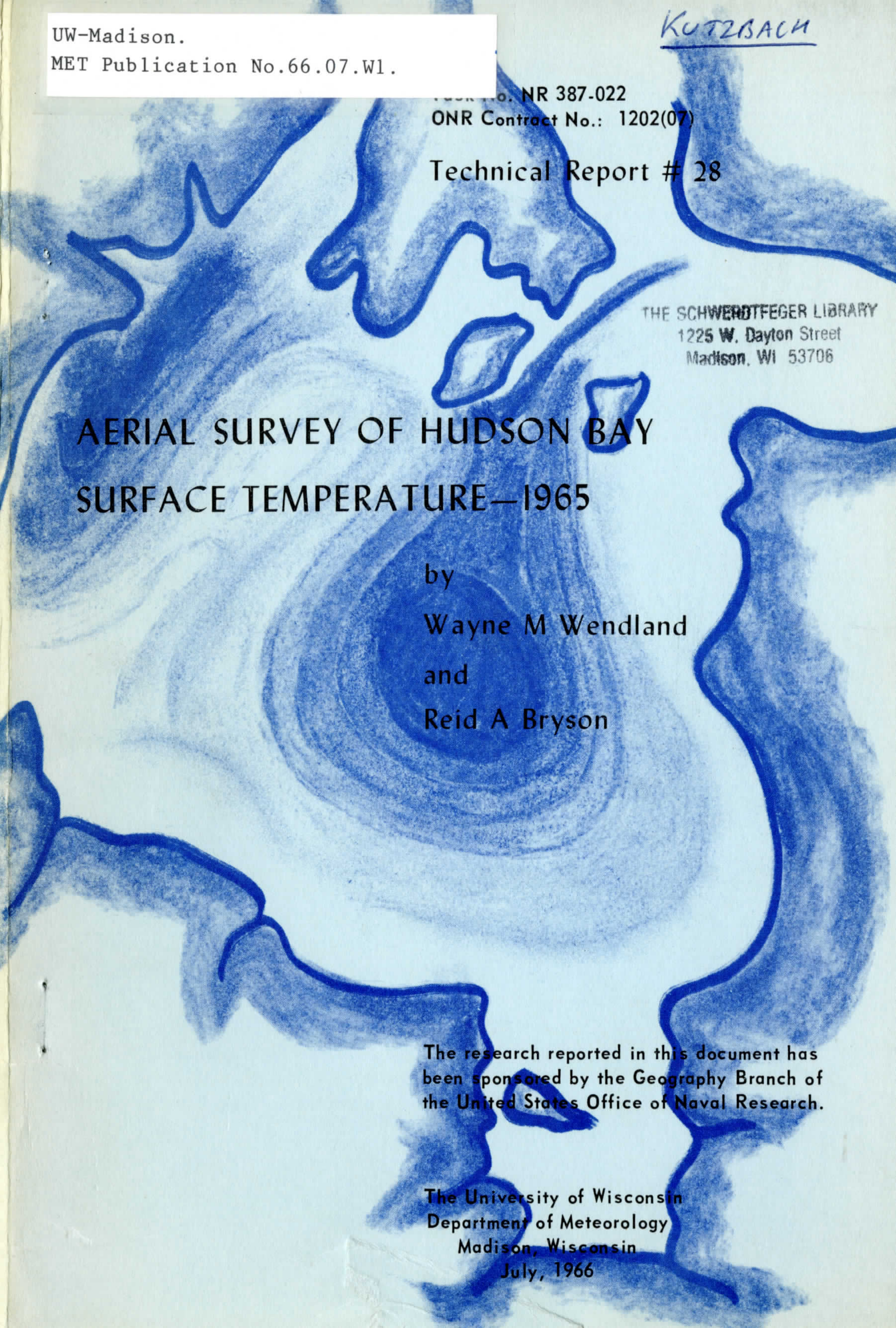

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Technical Report # 28

AERIAL SURVEY OF HUDSON BAY SURFACE TEMPERATURE—1965

by
Wayne M Wendland
and
Reid A Bryson

The research reported in this document has been sponsored by the Geography Branch of the United States Office of Naval Research.

The University of Wisconsin
Department of Meteorology
Madison, Wisconsin
July, 1966

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I. INTRODUCTION.

Most published information on the hydrography of Hudson Bay is limited to water temperatures at particular locations or to ice conditions in bays and other specific areas (U.S. Navy Hydrographic Office, 1951; Hare et. al., 1949; Arens, 1956). A notable exception is the report by Barber and Glennie (1964) which presents the results of the cruises of the "Calanus" and the "Theta" in Hudson Bay during the navigation season of 1961. The distributions of temperature, salinity and dissolved oxygen are presented graphically for part of the Bay for the periods 22-31 July and for nearly all the Bay for the period 3 August to 3 September. Limited data are given for mid-September and early October. Despite the completeness of the areal coverage of the Bay during August, the length of the time period (32 days) raises serious questions about the synopticity of the resulting maps. Nevertheless, these data represent the main body of hydrographic information on this unique arm of the northern ocean and are therefore very valuable.

The purpose of the present investigation was to map the surface temperature pattern of Hudson Bay during as short a time period as possible in August and again in September, 1965.

If the gross features of August and September patterns compared favorably with each other and with the maps of Barber & Glennie from 1961, this would strongly suggest that the large scale surface temperature pattern of Hudson Bay changes slowly within a season, and/or changes little from year to year.

August and September were chosen to help estimate the time of maximum water temperature, and yield some information on the magnitude of surface temperature changes with time.

The isotherm patterns were to be used in two ways. First, they were to be correlated with the depth distribution to investigate a relationship suggested for mid-latitude, fresh water lakes. Second, surface circulation patterns of the immediate past were to be investigated since surface isotherm deformations are frequently indicative of past circulation patterns.

Unfortunately, mechanical problems limited the August operation to only one of three planned flights, and only a very small portion of the Bay was observed. The September operation consisted of three flights in three days and yielded a temperature pattern for the entire Bay.

II. INSTRUMENTATION.

The surface temperature was measured remotely with an airborne Barnes IT-2 Infrared Thermometer (Barnes Engineering Co. 1963), carried aboard a U. S. Navy P2E aircraft. An altitude of 1000 feet was maintained except when low clouds dictated lower flight levels. The upward and downward total radiation fluxes were measured by the Suomi-Kuhn "economical" radiometer (Suomi-Kuhn, 1958), and the upward and downward short wave (solar) radiation fluxes were measured by Kipp and Zonen solarimeters.

The Barnes bolometer was mounted in the bow section of the aircraft, and the measurement recorded on a paper tape analog recorder. The radiation temperatures of the "economical" radiometer were sensed with thermocouples, referenced against a measured water-ice bath and recorded on a strip-chart potentiometer, along with the solarimeter outputs. Colored 35mm photographs and weather observations were taken along the route to preserve information regarding the Bay's surface condition and cloud coverage.

III. FLIGHT TRACKS.

All flights originated at Fort Churchill, Manitoba.

The three flight tracks of the September series are shown in Figure 1. The "blue" track was completed on 22 September, the "green" on the 23rd and the "red" track on the 24th. The 8 August flight was similar to the September "blue" flight. About 85% of the track yielded usable data. The planned tracks were primarily radials from Churchill, and were chosen so that the large scale temperature patterns would be discernable. Due to the length of the over-water tracks, magnetic declination changes, and the winds at flight altitude, deviations from the planned track occurred. Positions were obtained whenever possible, e. g., when crossing over known land locations. When flying the rather long tracks over the Bay, drift was closely observed and dead-reckoned positions were recorded. It is possible that some mid-Bay temperatures are plotted as much as thirty miles from their true location, since only dead-reckoning navigation was possible. Considering the gross scale of the analysis this uncertainty is not considered serious.

IV. CALIBRATION OF THE BOLOMETER.

The Barnes bolometer was calibrated before the first flight and after each flight. The instrument was in operation at least two hours before each calibration and

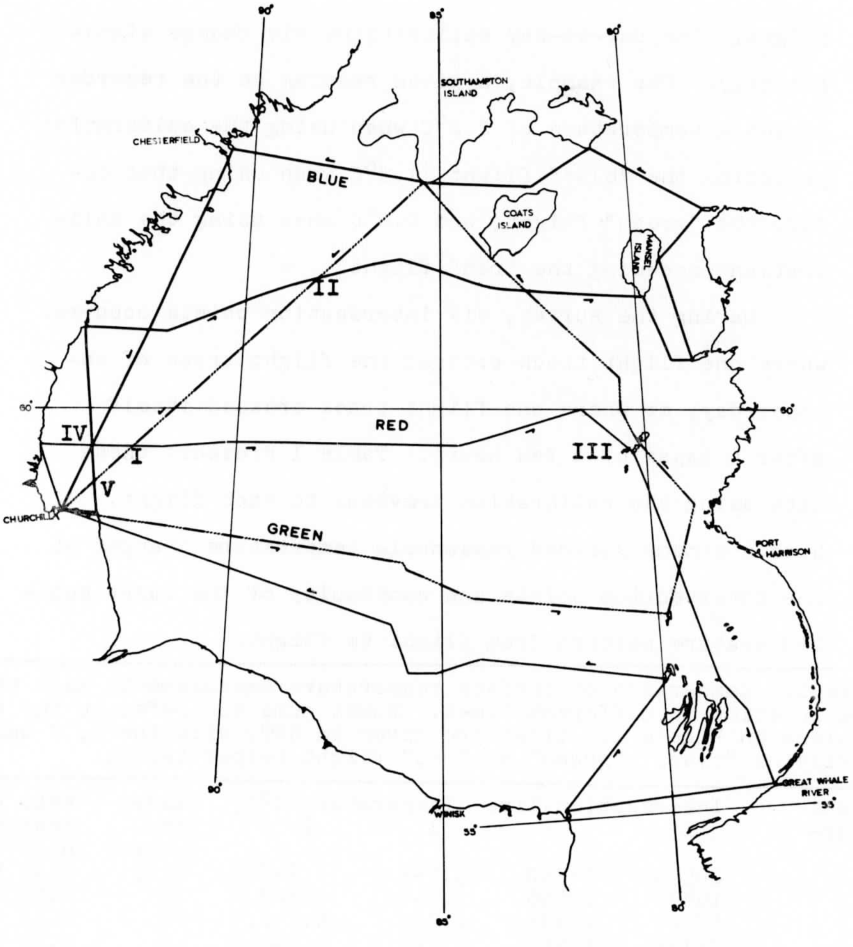

Figure 1. Flight tracks of the September series. "Blue" flight completed 22 Sept., "Green" completed 23 Sept., and "Red" completed 24 Sept. 1965.

flight. The day-to-day calibrations did change significantly. For example, a given reading on the recorder yields a temperature of 2.2°C when using the calibration preceding the "blue" flight, 1.3°C when using that before the "green" flight, and 0.0°C when using the calibration preceding the "red" flight.

During the survey, six intersection points occurred where one flight track crossed the flight track of another day, or where one flight track crossed itself after a lapse of a few hours. Table 1 presents these data using the calibration previous to each flight. Such a scheme yielded reasonable temperature changes at the intersection points and continuity of the large scale temperature pattern from flight to flight.

Table 1. Comparison of surface temperature measurements made at the same location at different times. Roman numerals refer to the intersections on Figure 1. Times are given in GMT, with the B, G and R signifying "blue," "green" or "red" flight respectively.

Locater on Figure 1	Intersection Time 1	Intersection Time 2	Temperature (°C) 1	Temperature (°C) 2	Lapsed Time (hours)	Rate of change per hour (°C)
I	2057G	1438R	3.6-4.8	5.4-6.0	17.5	0.03 to 0.13
II	1547B	1955G	3.0-4.1	1.8-3.6	28	0.00 to 0.08
III	1732G	1704R	2.2-2.6	0.7-1.8	24	0.02 to 0.08
IVa	1417B	2155B	2.7-3.4	2.4-3.0	8	0.00 to 0.04
IVb	2155B	1428R	2.4-3.0	4.3-5.4	41	0.03 to 0.07
V	1406B	2110G	3.6-4.8	3.5-4.2	31	0.00 to 0.02

The temperatures are given as intervals rather than discrete values since the aircraft location at any given time over water could be in error by as much as thirty miles.

The temperature ranges include the recorded temperatures within fifteen miles either side of the calculated intersection point.

The temperature north of Churchill (case IV^a) was sampled twice during the "blue" flight. The lapsed time was about eight hours, and the temperature was essentially equal each time, indicating that the calibration did not change during the time of the "blue" flight. A laboratory study of the characteristics of the Barnes bolometer by R. L. Steventon indicated that the instrument is rather unstable in its readings during the first two hours of operation, but thereafter the calibration is essentially constant. This also suggests that an abrupt shift in calibration is more probable than a continuous change, and that this event probably does not occur when the instrument is in continuous operation.

The temperature ranges overlap in cases II, IV^a and V (see Table 1), and small differences were noted in cases I, III and IV^b. Three possibilities could explain these deviations, i. e., instrumental error, heating/ cooling of the water, and/or water advection. In the latter three cases, the trend of the temperature change is opposite to the normal diurnal temperature trend, suggesting that solar induced heating of the water was not the cause of the temperature change.

Advection of surface water is a possible cause for the apparent changes. This hypothesis was tested in the following manner. Using the recorded temperature changes (cases I, III and V), the isotherm spacing on Figure 3, and the lapsed time between samplings, the apparent surface movement was calculated. These computed surface currents vary from 0.3 to 0.6 knots. These values are reasonable in magnitude, and suggest that the temperature changes could be due to advected thermal patterns.

The temperature differences found in Table 1 could therefore be real (caused by advection) or implied (due to the calibration shift of the bolometer from flight to flight). Since no bucket temperatures were available for comparison with the aerial measurements, the true cause of the temperature deviations in cases I, III and IVb cannot be determined.

The range of temperatures observed during the survey was at least four times the magnitude of the deviations found in Table 1. This together with the fact that the gross features of the September survey were observed on all three flights lends credence to the mapped temperature values.

V. RESULTS.

A. Surface Temperature Pattern and Surface Currents.

Geostrophic currents of a saline water body cannot be made from a survey of surface temperatures alone. The configuration of the surface isotherms does yield suggestions about apparent past surface currents, even though the density distribution remains unknown. Obviously a current flowing away from a cold area will deform the surface isotherms and will show areal extensions of colder water invading adjoining waters. Although vertical thermohaline motions can occur, the deformation of surface isotherms will indicate past movements of surface water. This approach then, is used in the analysis of the surface thermal patterns from 22 through 24 September. No attempt was made to analyse the currents from the August survey because the isotherm configuration is uncertain with so few data points.

Figures 2 and 3 present the surface temperature patterns of the Bay as observed on the August and September flights respectively. The general character of Barber and Glennie's charts of 1961 data reappear on the maps of this survey. The data of the two different years tend to complement each other. This would suggest that the surface temperature configuration of the Bay follows a similar annual trend and changes slowly with time, since some of the 1961 data were gathered over a month's time, and the present survey was accomplished in three days.

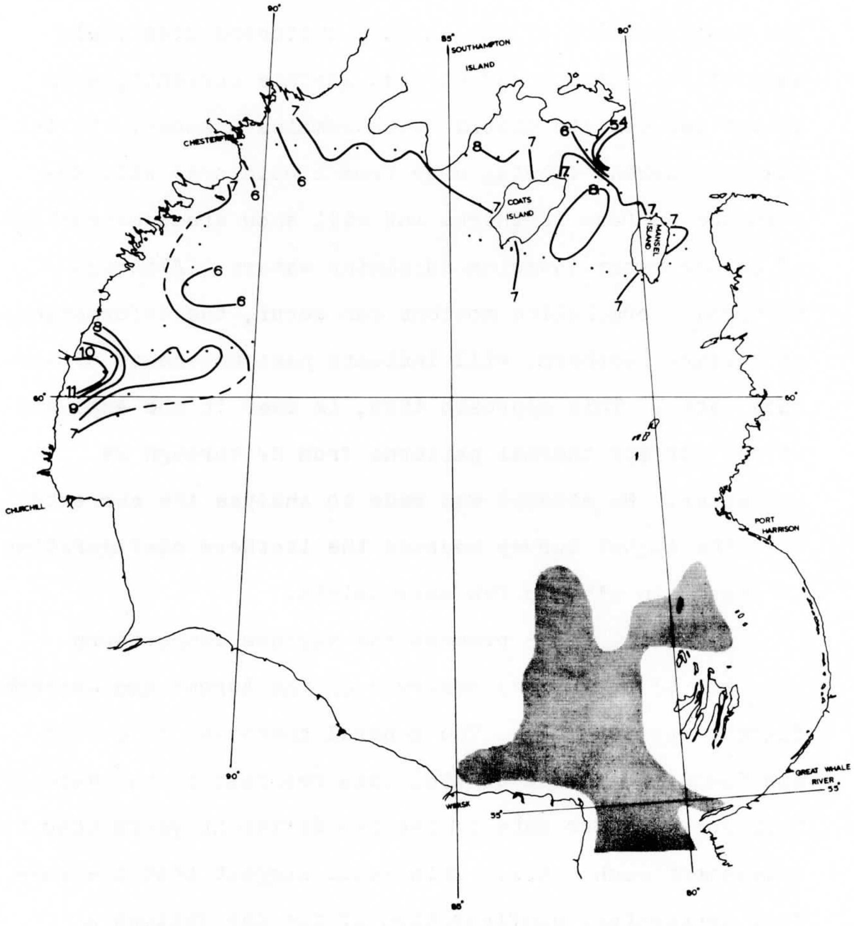

Figure 2. Surface isotherm configuration of 8 August 1965. Shaded area represents major area of pack ice accumulation.

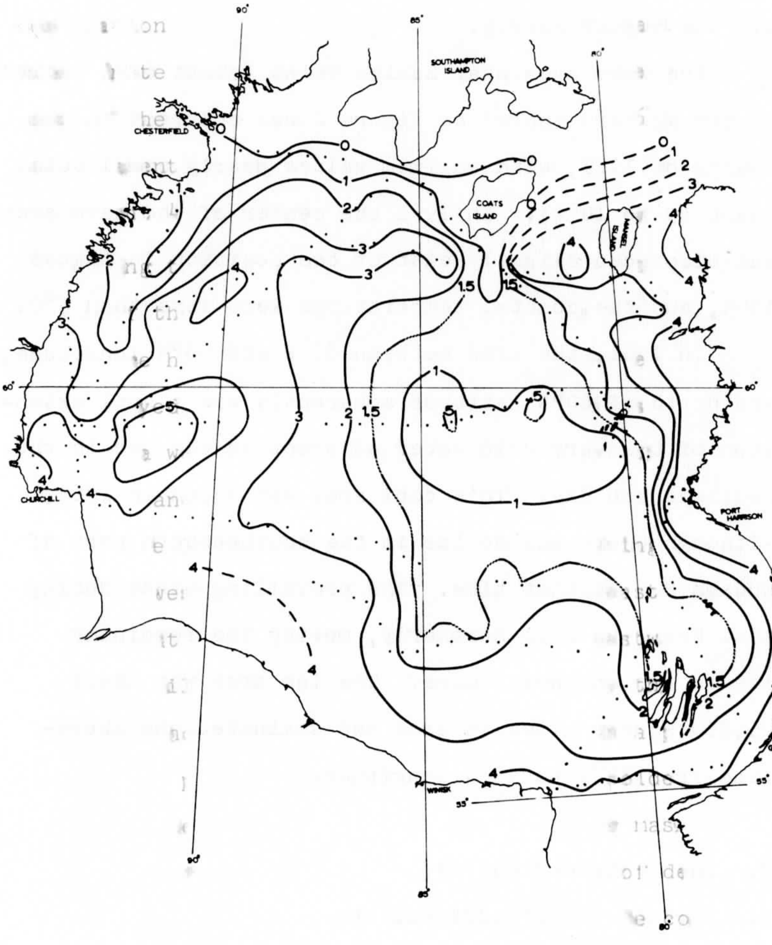

Figure 3. Surface isotherm configuration of 22, 23 and 24 September 1965.

B. The August Survey.

The warm area near Eskimo Point (about 61°N latitude on the western shore) on Figure 2 was apparent on the charts of 1961, with maximum values nearly equal both years (9 to 10°C). In 1961 the center of the warm area was displaced slightly east of the position in August 1965, and the coastal temperatures were less than 5°C.

In 1961, the area between 85°W and 90°W longitude, and north of 60°N latitude apparently was a cool extension of the very cold water adjacent to the ice in the southwestern Bay. This cool area was noted in 1965, although there was no ice in the southwestern part of Hudson Bay at that time. The prevailing winds during 1961 break-up were northerly, moving the remaining ice to the southern shore. The ice area was about 25,000 square miles in area and dominated the shoreline from 85°W to 93°W longitude.

C. The September Survey.

1. Surface Temperature Pattern.

The water temperature immediately north of Cape Churchill was between 4° and 5°C in both September 1961 and September 1965.

About fifty miles south of Chesterfield Inlet, one observation of 2°C in 1961 indicated cold coastal water (note the similarity in Figure 3). The water west of the Belcher Islands (approximately 56°N, 80°W) was apparently warmer in 1961 than in 1965. Temperatures were about 4° to 5°C during the former survey and 2° to 3°C during the latter. It is possible that the temperatures of the shoaling inter-island water in the Belcher group were higher than 3°C in 1965, but these areas were not surveyed. These are the only comparisons possible since data were not available for other locations in both 1961 and 1965.

Figure 3 suggests a cold southward moving current along the western Bay shore. Immediately eastward of this current is a warm arm reaching northeastward from Cape Churchill to Coats Island. Apparently this warm intrusion once extended to Mansel Island in a previous circulation pattern, but was severed by a colder water mass from the north. Presumably the colder mass overflowed the previous warm extension because of density differences. The colder water appeared to be coming from southeast of Southampton Island were melting pack ice was probably a source of colder but less saline water than the surrounding surface waters. Northerly winds persisted over this area the week preceding the survey.

It is interesting to note that the two large warm areas in the northern Bay during September 1965 are also found on Barber & Glennie's temperature map for 20 meters depth observed from 3 August to 3 September 1961. The pattern was quite diffuse at 10 meters and 30 meters and was not found at the surface or below 30 meters. The thermocline was found at about 25 meters suggesting that this subsurface feature was confined to the mixed layer.

The most prominent feature of the temperature pattern in September is the cold area in the east-central Bay. No temperatures were observed below zero, but over an area of about 6,000 square miles the surface temperature was less than 1°C.

2. Ice Cover.

In August 1965, there was a small accumulation of pack ice surrounding the southeastern tip of Southampton Island, and a larger area of about 25,000 square miles west of the Belcher Islands and continuing south into James Bay. The pack ice in August near Southampton Island had an area on only tens of square miles (extending into the Bay). In September it had increased to hundreds of square miles, varying from 1/10 to 7/10 coverage and consisting of floes 5 to 15 meters in diameter with rounded edges. The ice in the southeastern Bay disappeared between August and September.

3. Surface Temperature and Depth.

During September, the cold area in the east-central Bay (see Figure 3) appears to very roughly coincide with the shoaling area of the Bay as seen in the chart of Hudson Bay depth published by Barber & Glennie shown in Figure 4. A relationship of cool water overlying the shallow areas would be expected during the cooling period, just as shallow lakes cool more rapidly than deep lakes as shown by Scott (1964) and McFadden (1965). When discussing small scale fresh water bodies, Millar (1952) states:

> "At the times of the early warming phase or the late cooling phase, the temperature distribution in a lake is a blurred image of the depth distribution."

This idea has been under investigation more recently by Rodgers (1965,1966) who has found a "thermal bar" effect in Lake Ontario. A somewhat similar pattern prevails during the heating season in Lake Superior (Ragotzkie & Bratnick, 1965), and presumably again during the cooling season. Rodgers believes that the mechanism for the cold center-warm periphery in spring and early summer in Lake Ontario (and possibly other Great Lakes) is due to surface

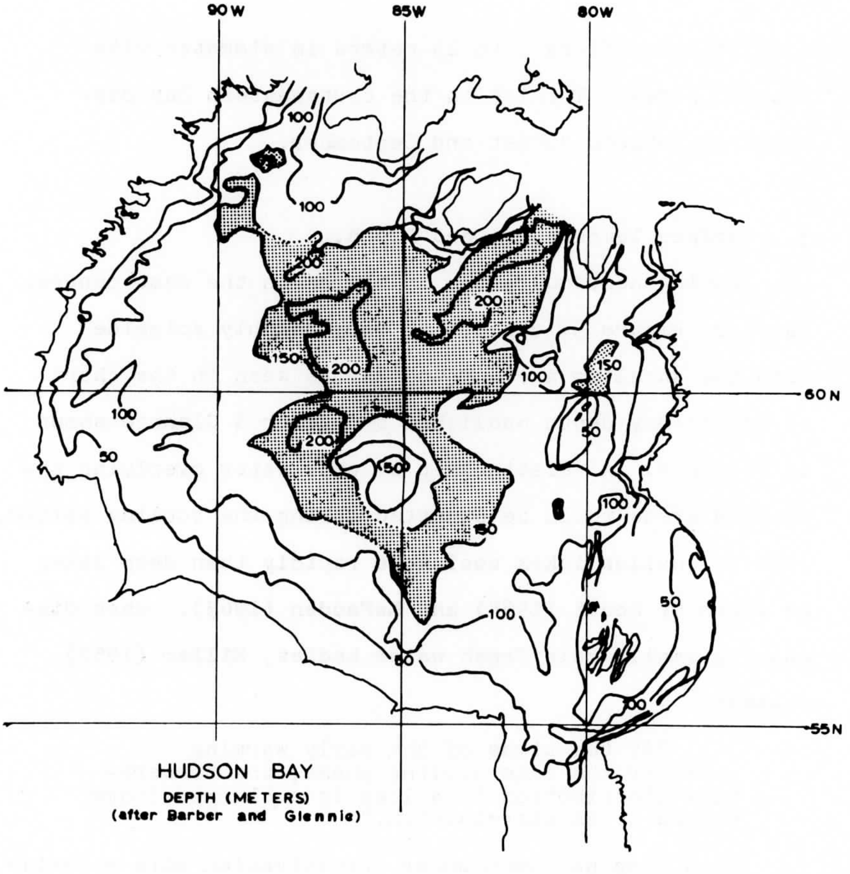

Figure 4. Depth of Hudson Bay with areas of depths greater than 150 meters shaded.

heating of the water. Water with temperatures less than 4°C (temperature of maximum density for fresh water) causes subsequent convection to great depths in deep water, while in the shallower water, the entire column quickly exceeds 4°C and stratification takes place. Once the cold central water reaches 4°C, further heating causes stratification and the entire pattern breaks down. In Lake Superior, Ragotzkie & Bratnick found that the pattern of a cold center does not disappear even after the entire lake surface exceeds 4°C. They believe that a dynamic equilibrium is achieved which tends to maintain the observed thermal pattern.

Although the surface thermal pattern of Hudson Bay during its cooling season suggests a relationship with depth, linear correlation techniques yield poor results. The shallow areas of Hudson Bay north of 62°N latitude were cooler than the deeper areas, a relationship which would be expected during the Bay's cooling season if one were to extend the hypothesis derived for the Great Lakes. South of 62°N latitude however, the relationship was reversed, i.e., the shallow areas were in most cases warmer than the regions of greater depth. This apparent paradox within Hudson Bay during the cooling season of 1965 is probably the result of complicating factors not found in smaller and perhaps more southerly fresh water lakes. In saline waters, the temperature and density patterns are not necessarily coincident, therefore the temperature survey alone may not be sufficient to describe the depth distribution.

Perhaps more important is the short ice-free period of Hudson Bay, and the large areal coverage of pack ice remaining in part of the Bay through August. In both 1961 and 1965, the southern part of the Bay exhibited generally colder surface temperatures than the northern portion. The reason may be similar to the explanation given above for the cold tongue of surface water between Coats and Mansel Islands. The rather large area (about 25,000 square miles) of melting ice in the southern part of the Bay in August 1965 was a source of cold and relatively fresh melt water which overflowed the surrounding warmer but more saline (therefore more dense) water. This overflow persisted as a surface feature presumably because the mixing along the outer edges of this area was not sufficient to destroy the density contrast, nor was the intensity of summer's radiation sufficient to destroy this rather large area of small heat content. The cold pool in September in the east-central part of the Bay thus may be the lingering remains of the cold water-ice mixture located in the southern part of the

Bay in August, substantiating the idea of a cyclonic circulation gyre on the Bay's surface (see Hachey, 1935; U. S. Naval Ocean. Off., 1951; Arens, 1956). The foregoing discussion indicates, in part, why the temperature-depth relationship of the southern part of the Bay is not similar to that of fresh water lakes.

The data of 1961 and 1965 suggest that August is the month of maximum heat content and maximum surface temperature as apposed to previous suggestions of September (Arens, 1956).

4. Net Radiation Measurements.

Net radiation was continuously measured during all flights in September. These measurements accounted for a total of eight to nine hours of the twelve hour daylight period. The nocturnal net radiation is very close to -5 ly/hour for these latitudes during late summer and early fall (Wendland, 1965). Values for the three to four daylight hours without net radiation measurements were estimated, and their absolute values were necessarily small because of the low sun angle. Net radiation values for the three days were within 7% of + 70 ly/day. This value compares with the three year monthly means of + 80 ly/day at Yellowknife (62.5°N), + 25 ly/day at Ennadai (61.1°N) and + 117 ly/day at Knob Lake (54.5°N) (op. cit).

5. Solar and Long Wave Radiation Measurements.

The measured downward short wave radiation for the three flights was 185 to 190 ly/day, compared with the calculated values of 183 ly/day (Budyko, 1955), 180 ly/day (Houghton, 1954) and 287 ly/day (List, 1963, with cloudless skies).

The downward long wave radiation observations showed large fluctuations in time and space. All observations during precipitation are unusable since the radiometer then measured the radiation temperature of the precipitation. The effective blackbody radiation temperature of space above the aircraft was calculated by means of the Stefan-Boltzmann relationship from the downward long wave component. Table 2 presents the mean values of measured effective blackbody radiation temperatures for various sky conditions above the aircraft. The coldest temperatures were observed under clear skies. When only low clouds were present, the mean radiation temperature

Table 2. Mean effective blackbody radiation temperatures above the aircraft with various cloud conditions.

Number of Cases	Cloud Cover	Mean Temperature (°C)
12	Clear skies	-68
47	Scattered, broken or overcast middle or high clouds	-21
24	Scattered low clouds	-59
35	Broken low clouds	-34
54	Overcast low clouds	+ 1

varied directly with cloud amount. Figure 5 gives the means and the variability of the effective blackbody radiation temperatures measured above the aircraft under various conditions. The range is smallest with clear skies (about 50C^{o}), and only somewhat larger with overcast low clouds (about 82C^{o}). The range is very large (greater than 150C^{o}) with decreasing amounts of low clouds and with all amounts of middle and/or high clouds. The reason why some of the temperatures with various cloud conditions are lower than any temperatures observed under clear skies is unknown. Considering the mean values only, there is a clear relationship between the effective blackbody radiation temperature and the height of the cloud base or amount. However, due to the large variability of values, in part caused by the relatively small number of cases, estimation of the bases and/or amount of clouds from the radiation temperature data is impossible.

6. Surface Water Features.

On thirty-seven occasions references were made in the flight logs to banded or streaked water, or slicks on the water. These situations were only found when the surface winds were less than about fifteen knots. The bands and streaks were usually narrow (about ten meters),

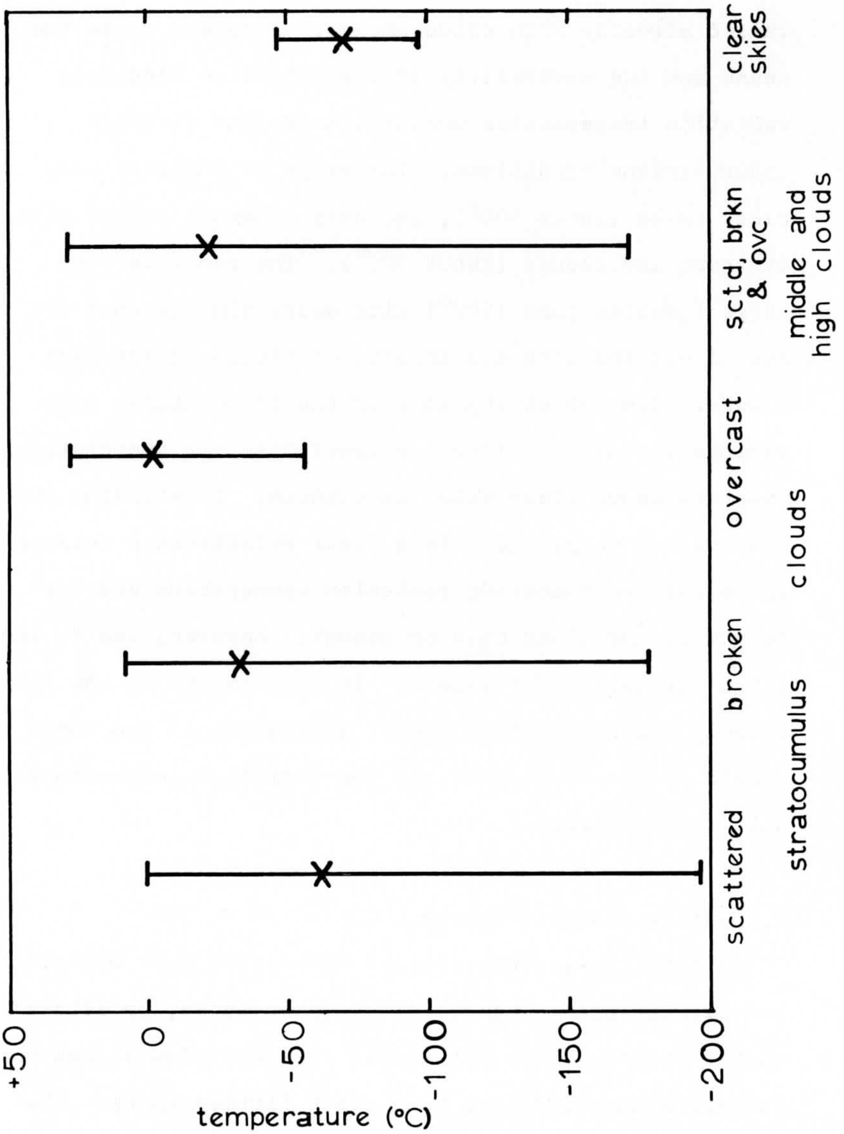

Figure 5. The mean (X) and the range of values of the blackbody radiation temperature above the aircraft with different amounts and types of clouds.

whereas the large areas with distinct color differences were more than fifteen miles across.

Some streaks had a smooth surface while the surrounding area exhibited small waves. Other lines apparently were of a different hue from the surroundings but had similar surface conditions. Some slicks were as much as 3.5°C warmer than the surroundings, others were observed 2.6°C colder than surroundings, and some exhibited no change from the surrounding water. No conclusions can be drawn at this time from the data available.

7. Albedo Measurements.

Both upward and downward short wave fluxes were measured, and the albedo calculated for 225 five-minute interval data points. The overwater measurements varied from 0.016 to 0.120. The attitude of the aircraft and low sun angle presumably account for the relatively high values, although no clear relationship between sun angle and albedo was found. The mean albedo of all flights was 0.061. The rock and gravel surface of the southern tip of Southampton Island yielded an albedo between 0.158 and 0.228. The freshly covered snow surface around Chesterfield Inlet gave a value of 0.254. The snow was thin and much of the ground structure, even the low vegetation, projected above the snow.

8. Radiation Temperature of the Earth's Surface as Determined by the "Economical" radiometer.

The measured upward long wave radiation varied from 0.45 to 0.51 ly/min. It is assumed that the sensing surface of the "economical" radiometer is in radiative equilibrium with whatever surface or space volume it "sees". Both long and short wave radiation are measured by the radiometer. By subtracting the measured short wave radiation (reflected) from the total upward flux measured with the "economical" radiometer, the upward long wave radiation component was obtained. This was assumed to be the emitted radiation, and was converted to the effective blackbody radiation temperature via the Stefan-Boltzmann relationship. In 88% of 242 data points considered, the radiation temperature so obtained was greater than the bolometric measurement, and differences of 3 to 5C^{o} were not uncommon. A lapse condition in the lower 1000 feet was observed during all flights, implying that the temperature "seen" by the "economical" radiometer should have been less than that of the bolometer, since it is broad-band and should respond also to the radiation from the atmospheric constituents. The trend of one instrument did not follow the trend of the other.

The Kipp & Zonen instrument measures essentially all the radiation between 0.3 and 2.5 microns. The polyethylene surface of the "economical" radiometer transmits about 75% of the radiation between 0.2 and 1 micron, and 80% or more from 1 to 15 microns, with narrow absorption bands at 3.5, 7 and 14 microns. The subtraction of the Kipp & Zonen value from the "economical" radiometer reading introduces an error in the calculated long wave component, but this error should yield a blackbody temperature lower than the true value. In 88% of the observations however, the radiation temperature determined from the "economical" radiometer measurements was greater than the bolometric measurement.

This discrepancy and the poor correlation between the two values of temperature suggest that the instantaneous measurements of the "economical" radiometer are not sufficiently precise to substitute for the bolometer measurements.

VI. CONCLUSIONS.

An aerial survey of Hudson Bay was completed during September 1965, measuring water surface temperatures and short and long wave radiation. A record from all of the sensors was obtained during about 85% of the total overwater track. Although a change in the calibration of the bolometer occurred during the survey, repeated samplings of similar locations, experience with the instrument, and the relatively small calibration shift compared to the range of observed values lend credence to the survey.

The temperature survey showed a southward protrusion of cold water along the western shoreline, and a warm arm reaching northeastward from Cape Churchill to Mansel Island. These probably are related to the major current pattern. The eastern half was dominated by the large cold pool centered about 60°N, 83°W with central temperatures less than 0.5°C. A small scale cold arm extended southward into the Bay between Coats and Mansel Islands.

During mid-August the ice in the Bay was located near the southeastern tip of Southampton Island (very small area), and over an area of about 25,000 square miles located west of the Belcher Islands and extending into James Bay. The ice observed during all flights in the September series was located along the southeastern shores of Southampton Island.

The relationship of surface temperature to water depth does not appear to follow the relationship derived for smaller mid-latitude fresh water lakes. This is presumably because Hudson Bay is ice-free for a relatively short time and ice lingers in quantity through mid-August and leaves its mark on the surface temperature pattern throughout the time of heat maximum. The influence of the melted ice on the temperature pattern persists until cooling again takes place.

The mean albedo for all sea surface measurements was 0.061. No relationship between albedo and sun angle or sea condition was found.

Effective blackbody radiation temperatures determined from the long wave component sensed by the "economical" radiometer showed little correlation with the bolometric measurements.

The measured values of net radiation obtained during all flights compared favorably with values sensed at the surface at nearby stations. The measured direct plus diffuse solar values were very similar to the calculated monthly mean values of Budyko and Houghton computed from mean cloud conditions.

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13. ABSTRACT

Airborne temperature surveys of Hudson Bay were accomplished on 8 August 1965 and between 22 and 24 September 1965. The temperature of the surface water was remotely sensed with a Barnes IT-2 Infrared Thermometer, and radiation components were measured with a Suomi-Kuhn net radiometer and Kipp and Zonen solarimeters. (U)

The northern part of the Bay cooled about 5C° from August to September. In September, the surface water temperatures ranged from slightly more than 5°C to slightly less than zero. The temperature pattern showed a cold water tongue extending southward along the western shore. A relatively warm arm extended from Cape Churchill to the northeast part of Hudson Bay. A relatively cold protrusion extended southward between Coats and Mansel Islands in the northeastern part of the Bay. The east-central portion was dominated by a rather large (about 6,000 square miles) cold area with temperatures less than 1°C. (U)

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bolometer						
Hudson Bay						
solar radiation						
Suomi-Kuhn net radiometer						
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