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Technical Report No. 29

THE KEWEENAW CURRENT, A REGULAR FEATURE OF SUMMER CIRCULATION OF LAKE SUPERIOR

Robert A. Ragotzkie

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The University of Wisconsin
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August, 1966

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OF
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by

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Task No. NR 387-022   ONR Contract No.: 1202 (07)

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INTRODUCTION

This is a report on the continuing investigation of the thermal structure and circulation of Lake Superior. Ragotzkie and Bratnick (1965) reported on a series of four closely spaced airborne temperature surveys of Lake Superior during the latter part of July, 1964. In particular, the existence and short-term persistence of "cold pools" or regions of cold surface water in the central parts of the east and west basins of Lake Superior was demonstrated. It was shown that these could only be maintained by a general upward motion of cold water in these areas. In addition, a steep horizontal temperature gradient directed normal to the coast was found along the north side of the Keweenaw Peninsula. This temperature gradient persisted during the passage of a cyclonic storm with its associated wind shifts and suggested the existence of a current flowing northeastward parallel to the coast of the Keweenaw Peninsula.

The field program during the summer of 1965 had two purposes: first, to determine if the "cold pools" were a regular characteristic of the summer pattern of Lake Superior, and if so when they formed, and second, to investigate in more detail the surface temperature pattern and its relation to the sub-surface thermal structure in the region along the north side of the Keweenaw Peninsula.

FIELD OPERATION, 1965

A series of seven airborne surveys of the surface temperature of Lake Superior was flown between 15 June and 3 August. The limitations and validity of this technique have been discussed elsewhere (Clark, 1964, Ragotzkie & Bratnick, 1965). Four of these flights yielded excellent results and the other three provided limited to poor coverage of the lake because of weather interference or instrument difficulties. In all but one flight, detailed coverage was obtained in the region along the north side of Keweenaw Peninsula.

In addition to the airborne observations, four temperature cross-sections normal to the Keweenaw Coast were obtained on 30 July by bathythermograph from the USCGC Naugatuck. Due to advance aircraft scheduling this set of observations was not made on the same day as an airborne survey but fell midway between two surveys a week apart. Despite this time difference, good agreement with the airborne results was obtained by comparing the patterns observed before and after the BT sections.

"COLD POOLS"

The surface temperature maps of the lake as a whole (Figs. 1-6) show that the lake was still very cold in June with a band of warmer water along the south shore with the maximum horizontal gradient along the Keweenaw Peninsula. By mid-July, the north-south temperature gradient extended over more of the lake except near the Keweenaw where the gradient remained very steep. Not until 26 July did the cold pools appear and then only weakly. By 3 August the two cold areas were better developed, resembling quite closely the pattern observed on 29 July, 1964 (Fig. 7). In general the cold pools developed as expected but about a week later than in 1964. These observations have strengthened the suggestion (Ragotzkie and Bratnick, 1965) that these two cold areas are regular features of the summer thermal structure of Lake Superior.

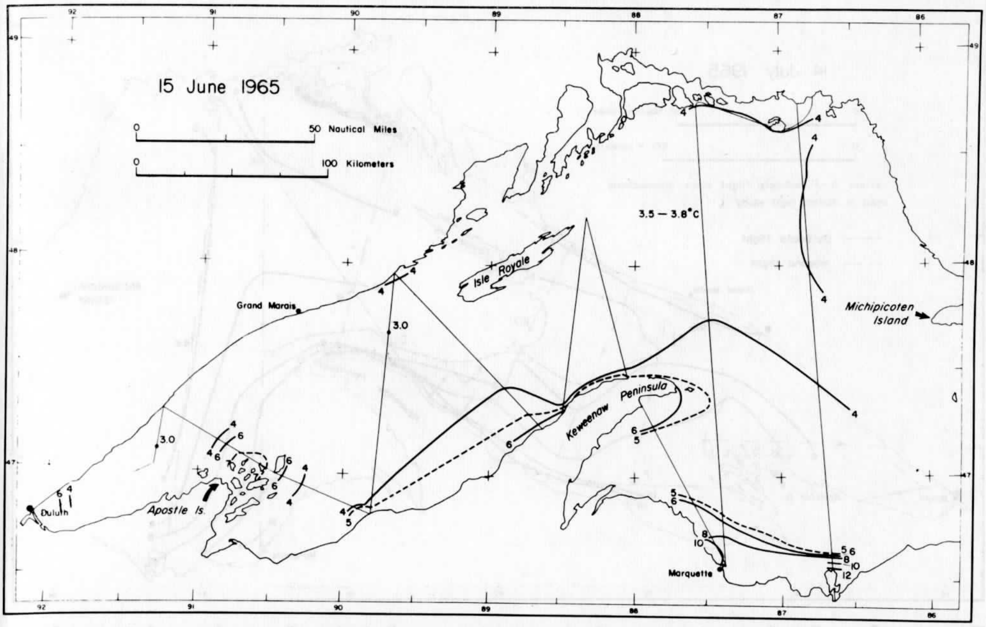


Figure 1. Surface temperature pattern of Lake Superior obtained by airborne infrared radiometer on 15 June 1965. Flight tracks are shown by light lines, isotherms are °C.

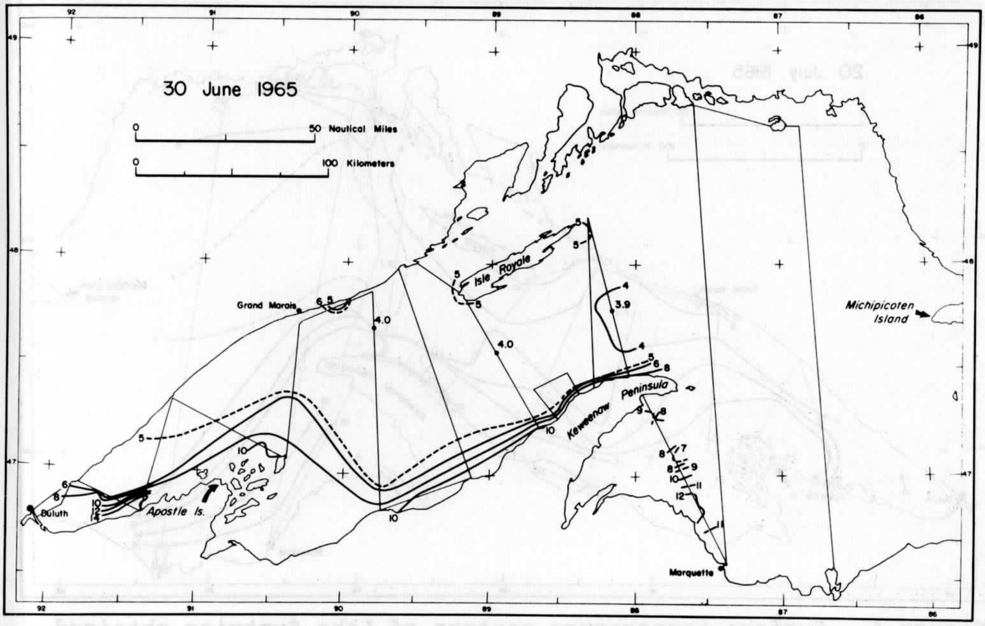


Figure 2. Surface temperature pattern of Lake Superior obtained by airborne infrared radiometer on 30 June 1965. Flight tracks are shown by light lines, isotherms are °C.

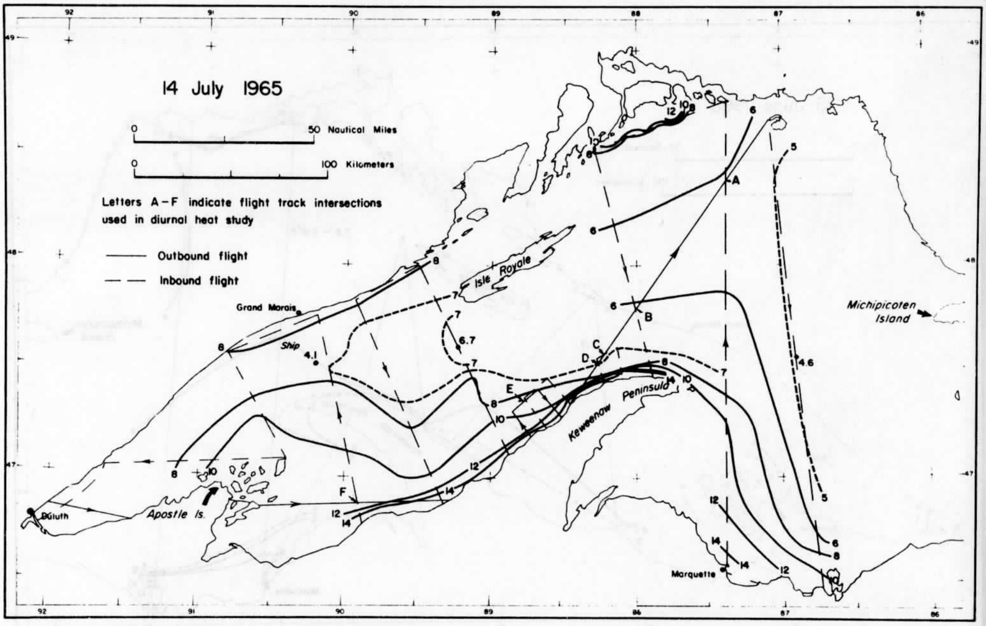


Figure 3. Surface temperature pattern of Lake Superior obtained by airborne infrared radiometer on 14 July 1965. Flight tracks are shown by light lines, isotherms are °C.

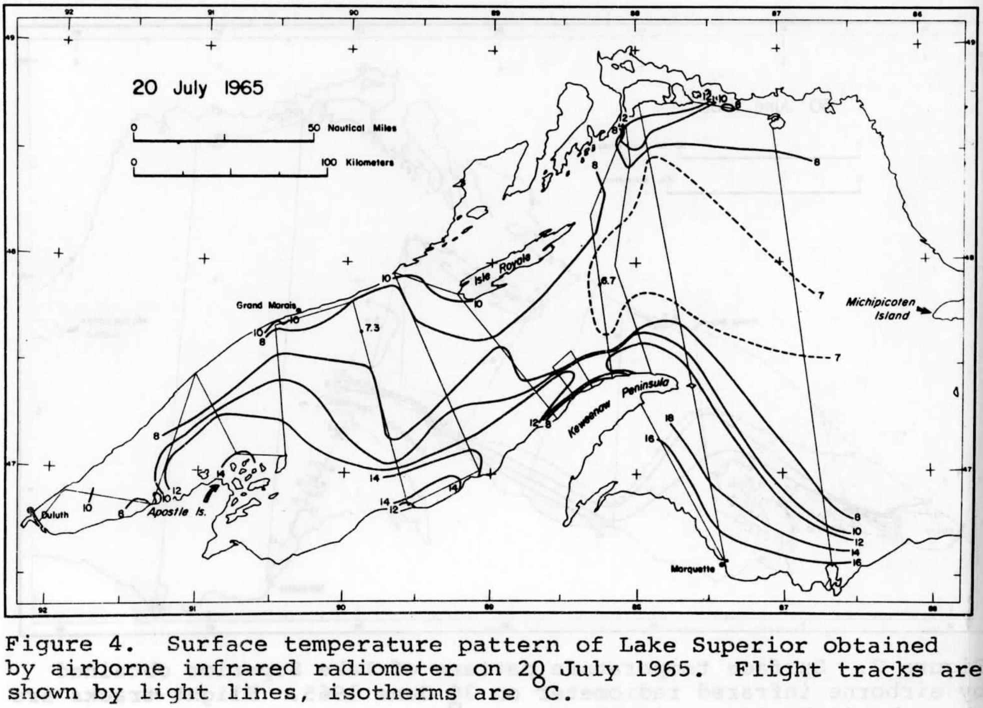


Figure 4. Surface temperature pattern of Lake Superior obtained by airborne infrared radiometer on 20 July 1965. Flight tracks are shown by light lines, isotherms are °C.

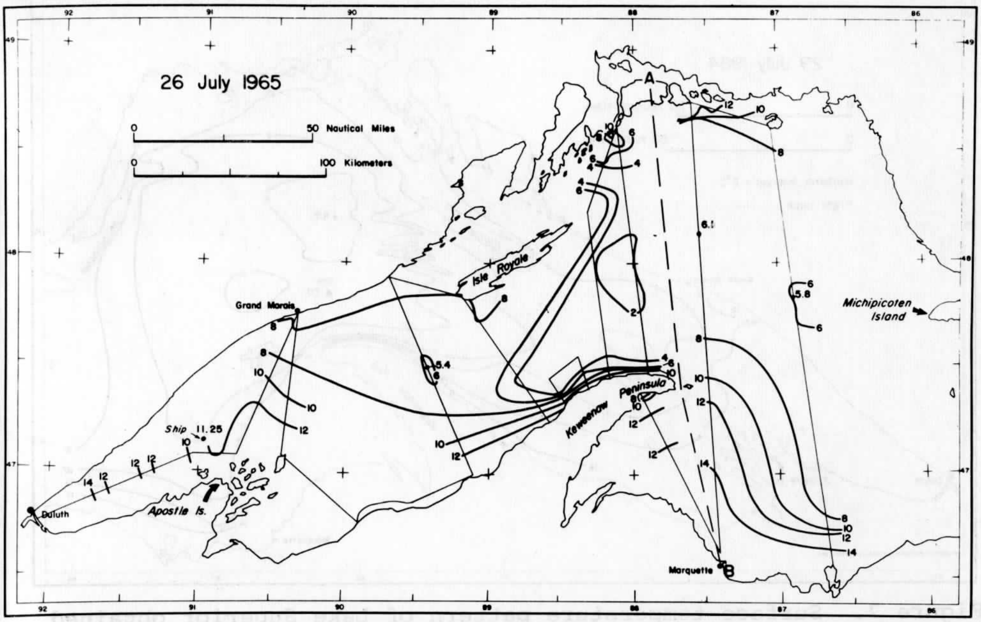


Figure 5. Surface temperature pattern of Lake Superior obtained by airborne infrared radiometer on 26 July 1965. Flight tracks are shown by light lines, isotherms are °C.

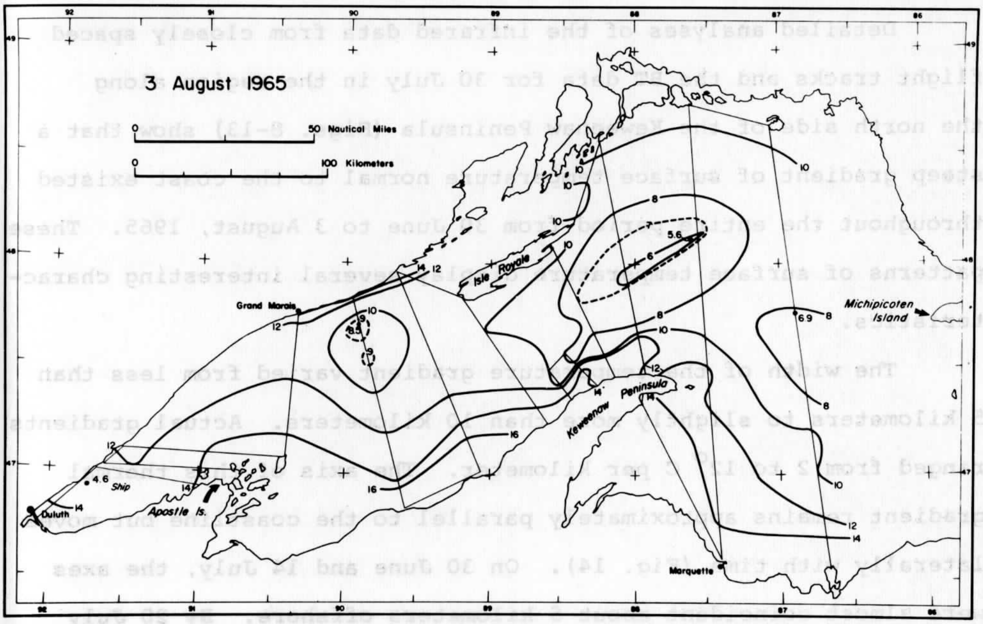


Figure 6. Surface temperature pattern of Lake Superior obtained by airborne infrared radiometer on 3 August 1965. Flight tracks are shown by light lines, isotherms are °C.

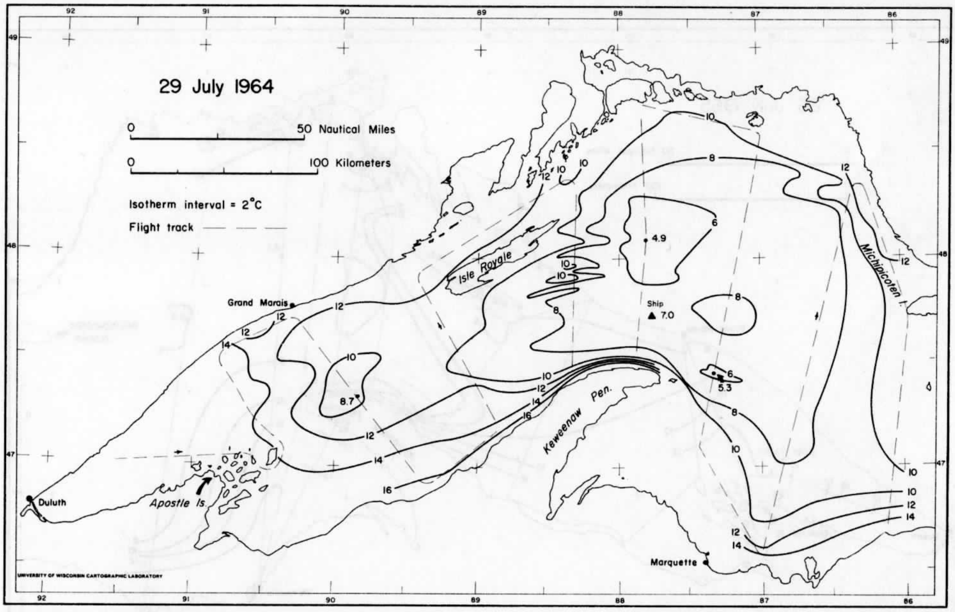


Figure 7. Surface temperature pattern of Lake Superior obtained by airborne infrared radiometer on 29 July 1964 (from Ragotzkie and Bratnick, 1965). Flight tracks are shown by light lines, isotherms are ^{o}C.

KEWEENAW REGION

Detailed analyses of the infrared data from closely spaced flight tracks and the BT data for 30 July in the region along the north side of the Keweenaw Peninsula (Figs. 8-13) show that a steep gradient of surface temperature normal to the coast existed throughout the entire period from 30 June to 3 August, 1965. These patterns of surface temperature display several interesting characteristics.

The width of the temperature gradient varied from less than 5 kilometers to slightly more than 10 kilometers. Actual gradients ranged from 2 to 12^{o} C per kilometer. The axis of this thermal gradient remains approximately parallel to the coastline but moves laterally with time (Fig. 14). On 30 June and 14 July, the axes were almost coincident about 5 kilometers offshore. By 20 July

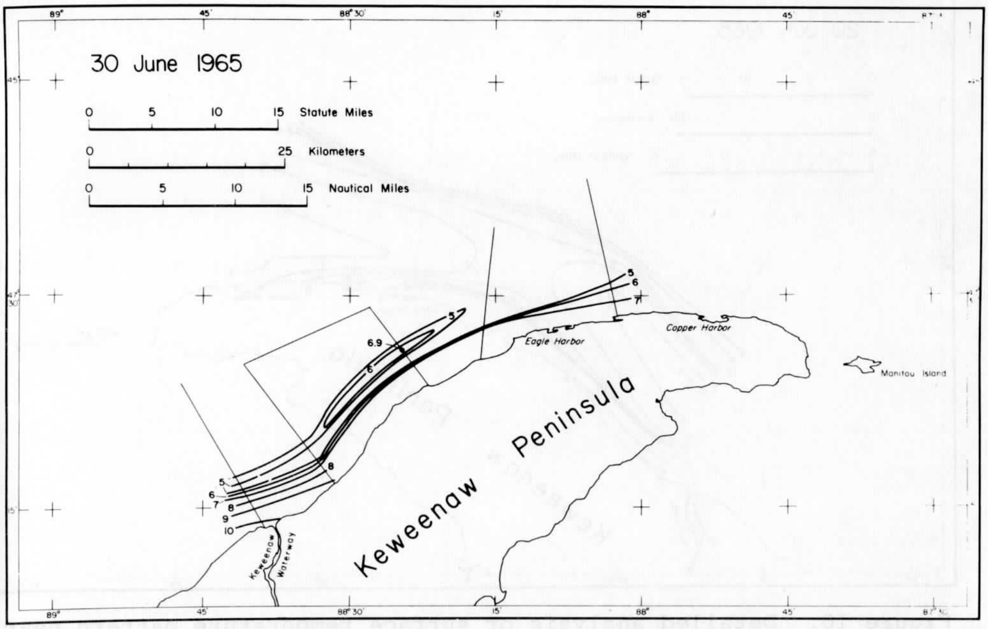


Figure 8. Detailed analysis of surface temperature pattern near Keweenaw Peninsula from infrared data, 30 June 1965.

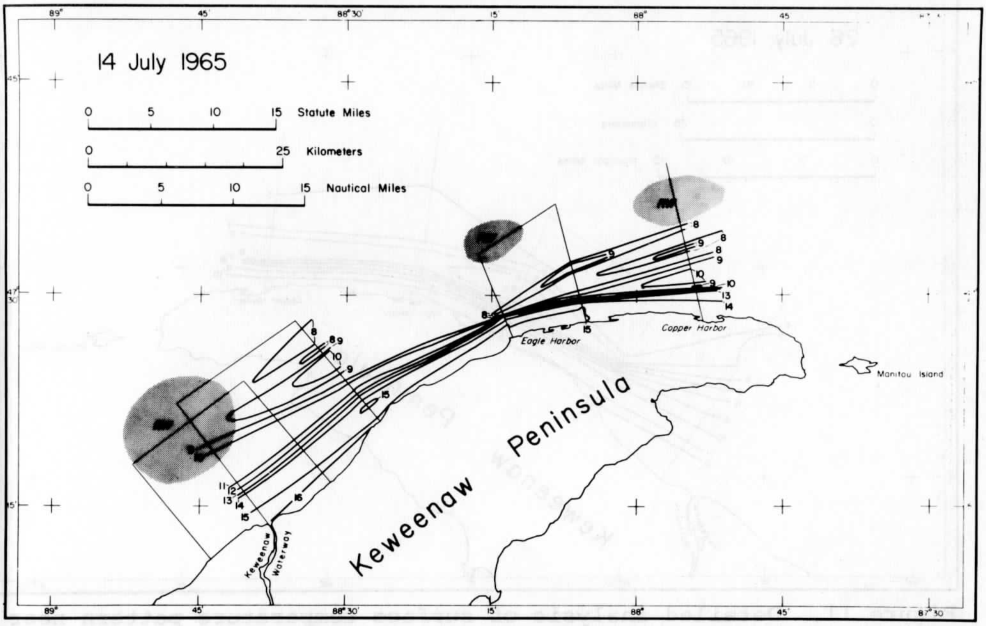


Figure 9. Detailed analysis of surface temperature pattern near Keweenaw Peninsula from infrared data, 14 July 1965. Shaded areas represent rain showers.

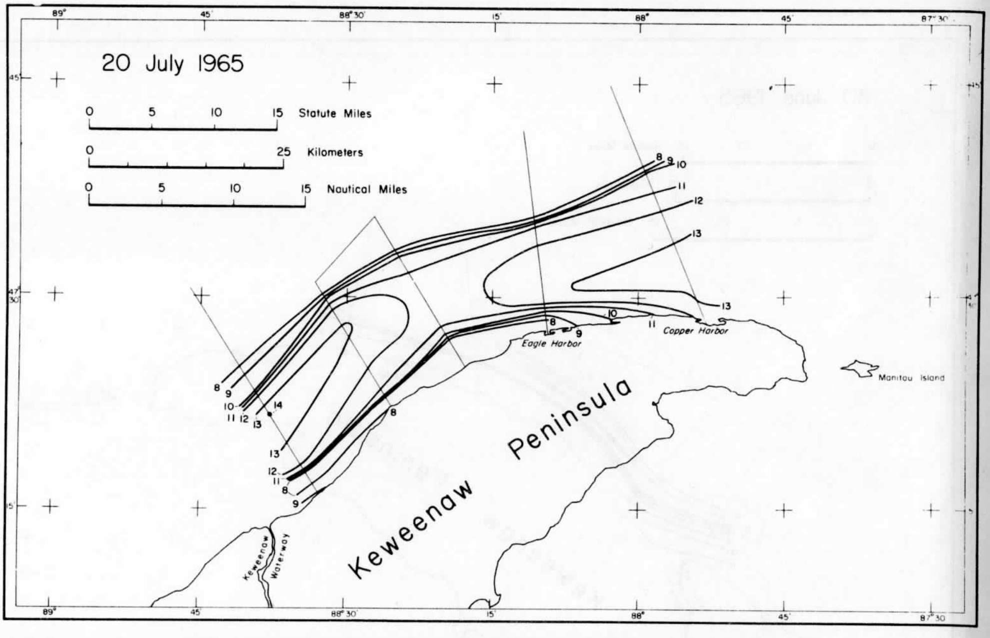


Figure 10. Detailed analysis of surface temperature pattern near Keweenaw Peninsula from infrared data, 20 July 1965.

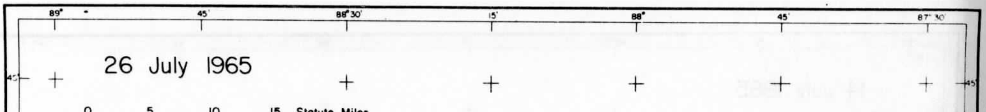


Figure 11. Detailed analysis of surface temperature pattern near Keweenaw Peninsula from infrared data, 26 July 1965.

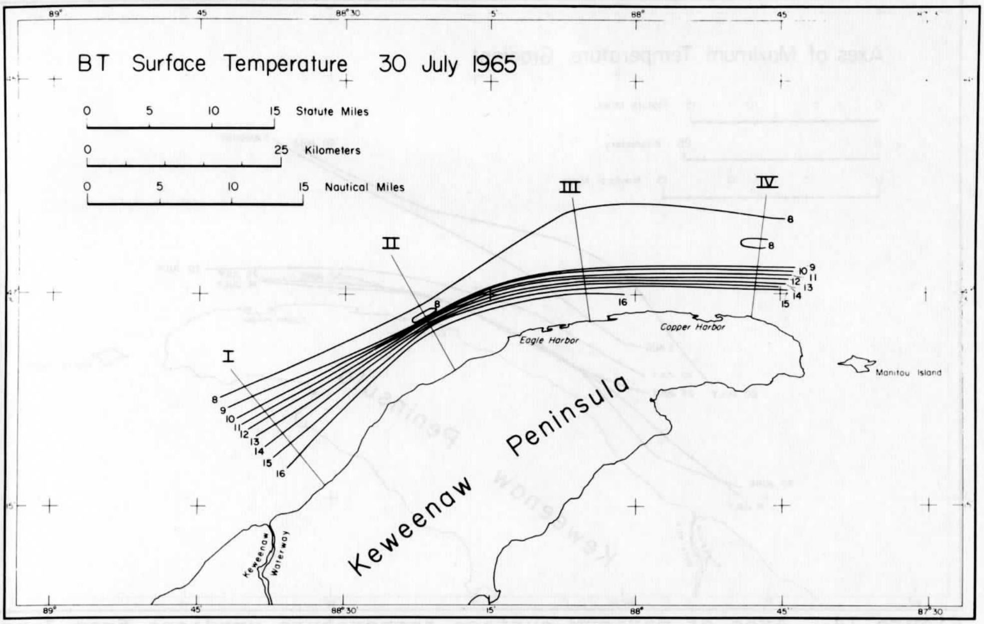


Figure 12. Detailed analysis of surface temperature pattern near Keweenaw Peninsula as obtained from BT data, 30 July 1965. Straight lines and Roman numerals indicate location of BT sections shown in Figures 15-18.

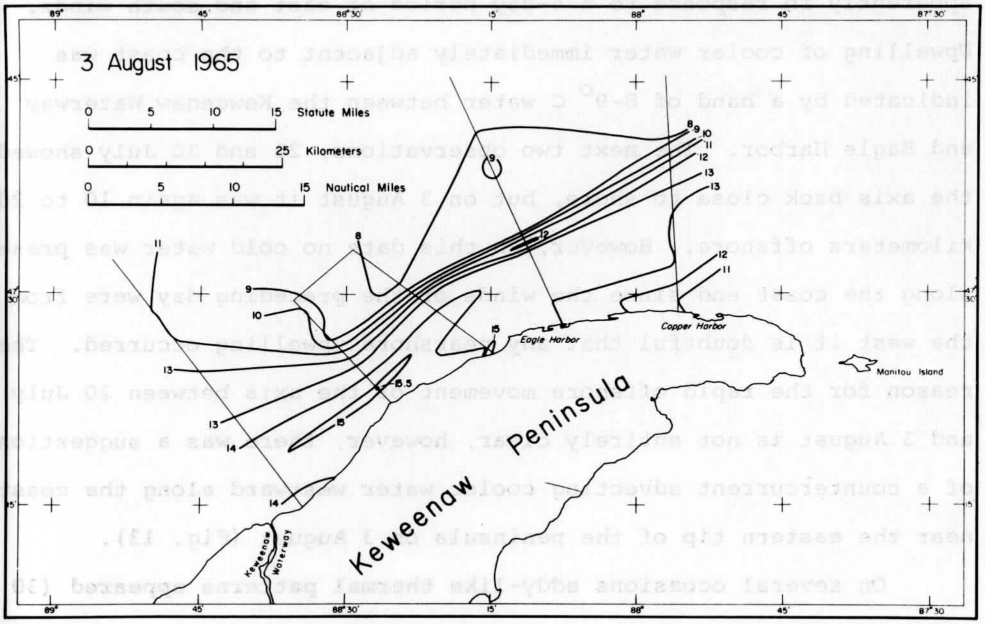


Figure 13. Detailed analysis of surface temperature pattern near Keweenaw Peninsula from infrared data, 3 August 1965.

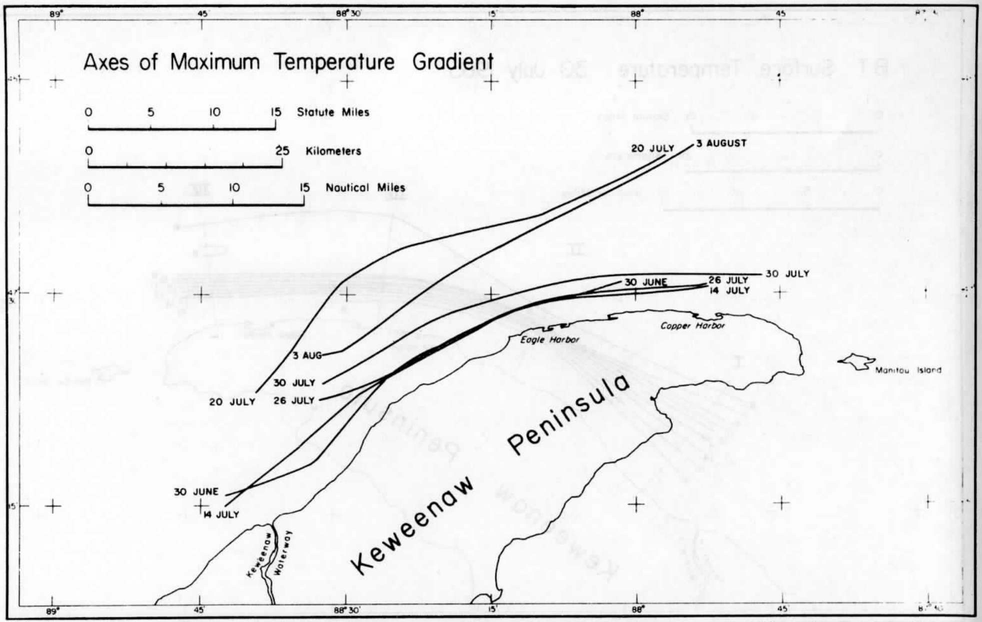
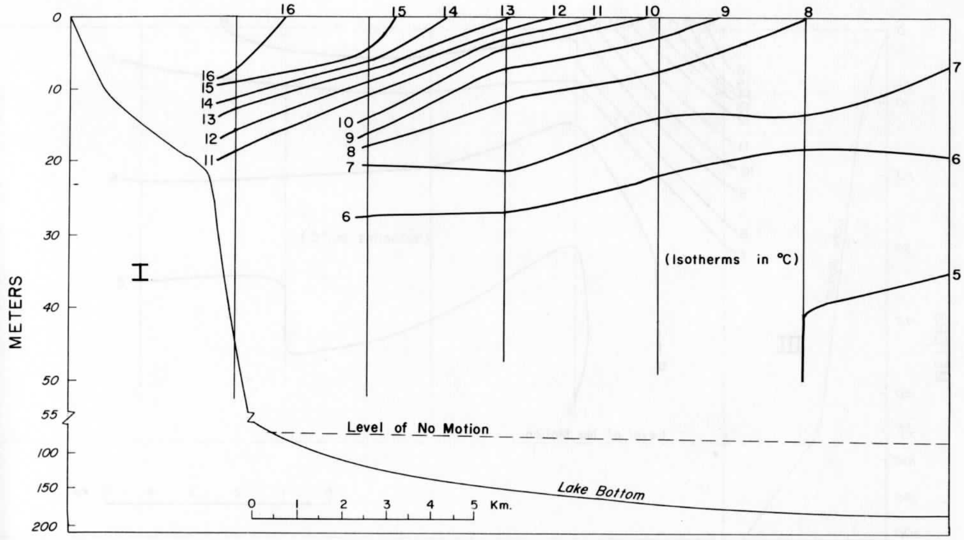


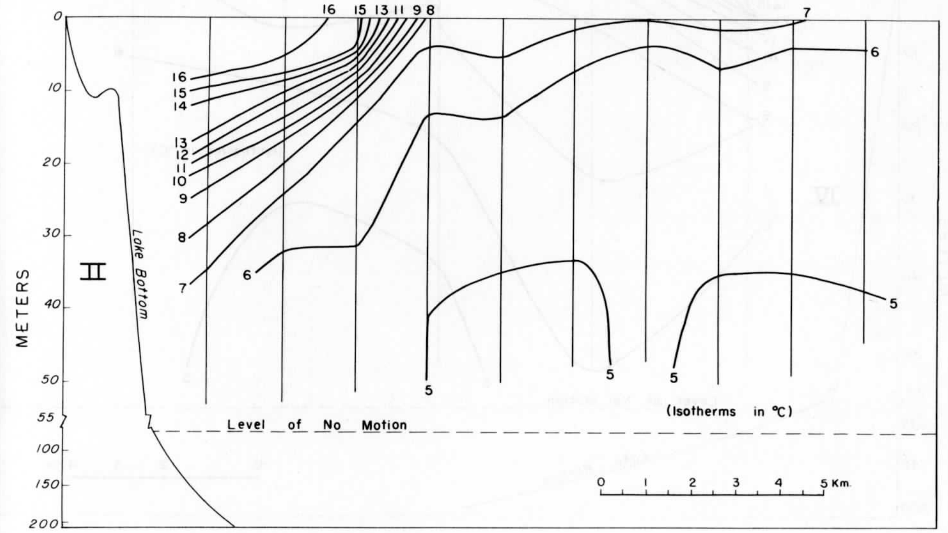
Figure 14. Axes of maximum surface temperature gradient from June to August 1965. Axis on 30 July from BT data, all others from infrared data.

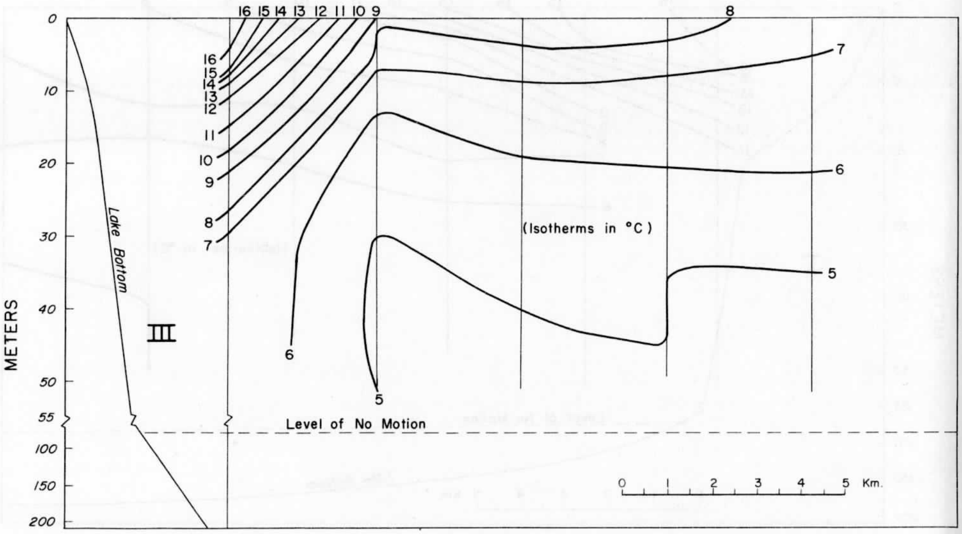
the axis had moved to a position 15 to 20 kilometers offshore apparently in response to a 4-day period of east and south winds. Upwelling of cooler water immediately adjacent to the coast was indicated by a band of 8-9° C water between the Keweenaw Waterway and Eagle Harbor. The next two observations, 26 and 30 July showed the axis back close to shore, but on 3 August it was again 10 to 20 kilometers offshore. However, on this date no cold water was present along the coast and since the winds of the preceding day were from the west it is doubtful that any nearshore upwelling occurred. The reason for the rapid offshore movement of the axis between 20 July and 3 August is not entirely clear, however, there was a suggestion of a countercurrent advecting cooler water westward along the coast near the eastern tip of the peninsula on 3 August (Fig. 13).

On several occasions eddy-like thermal patterns appeared (30

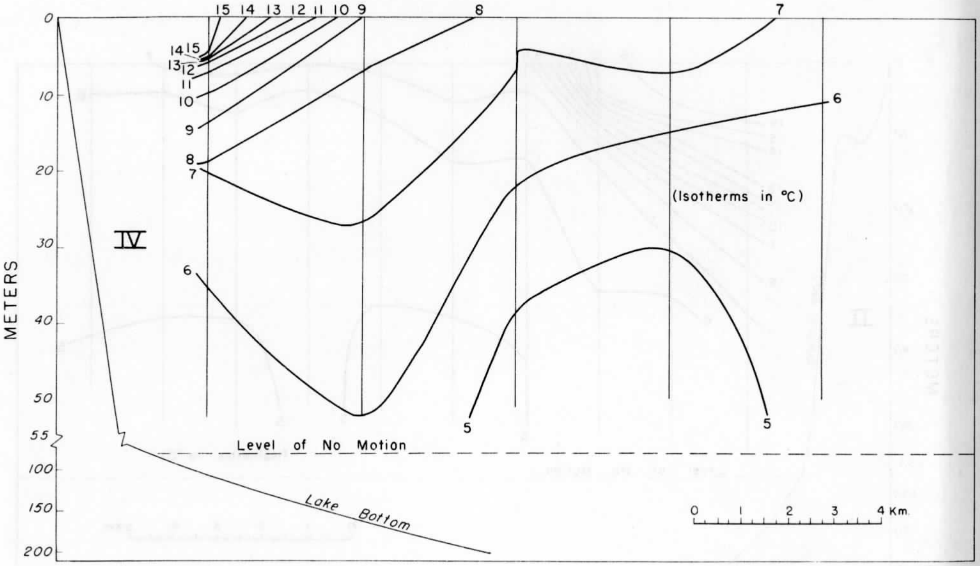


Figures 15-16. Temperatures cross-sections (BT) off Keweenaw Peninsula on 30 July 1965. See Figure 12 for location of sections.





Figures 17-18. Temperature cross-sections (BT) off Keweenaw Peninsula on 30 July 1965. See Figure 12 for location of sections.

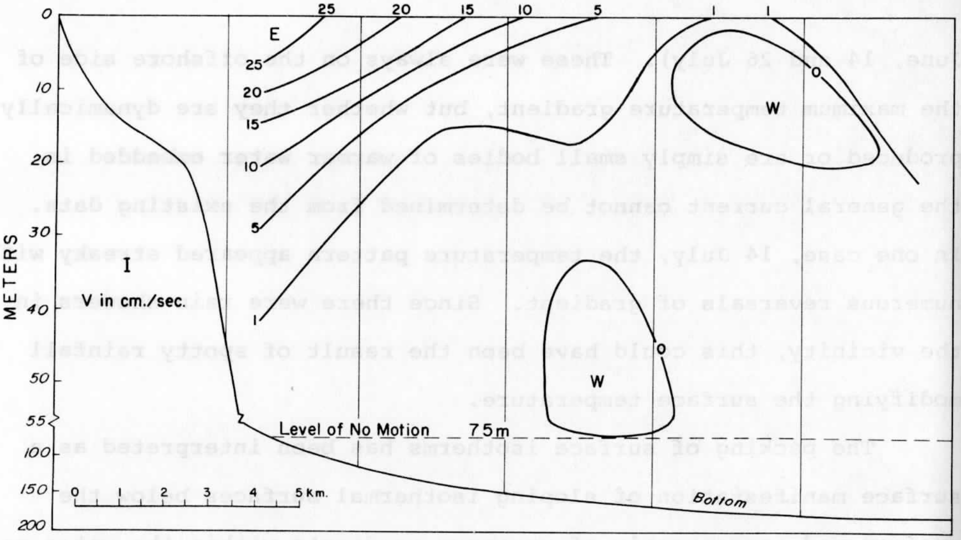


June, 14 and 26 July). These were always on the offshore side of the maximum temperature gradient, but whether they are dynamically produced or are simply small bodies of warmer water embedded in the general current cannot be determined from the existing data. In one case, 14 July, the temperature pattern appeared streaky with numerous reversals of gradient. Since there were rain showers in the vicinity, this could have been the result of spotty rainfall modifying the surface temperature.

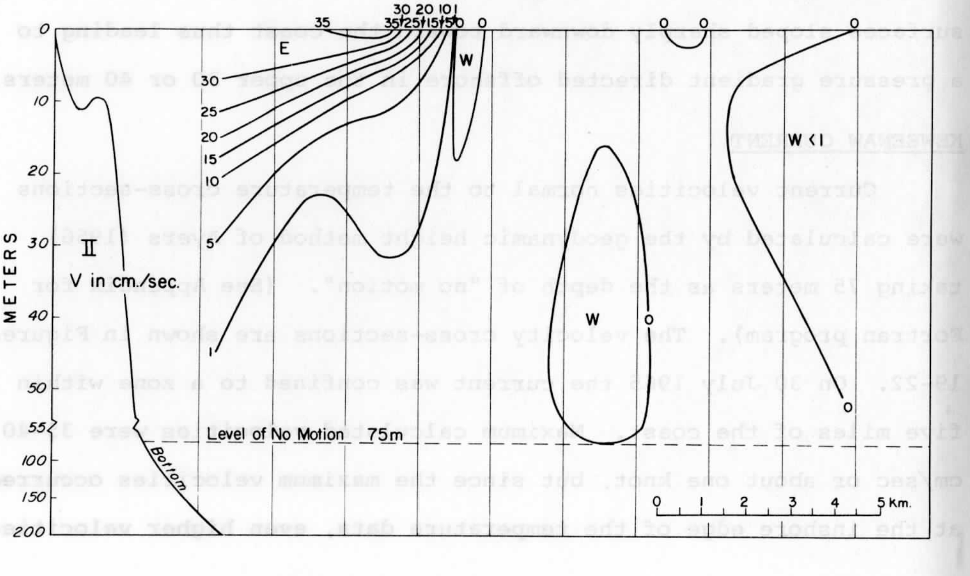
The packing of surface isotherms has been interpreted as a surface manifestation of sloping isothermal surfaces below the surface and consequently of pressure gradients within the water mass. A current parallel to the coast and flowing northeastward has been hypothesized on the basis of the geostrophic relationship. In order to verify the assumed internal thermal structure, four bathythermograph sections across the gradient were obtained on 30 July 1965. These sections (Figs. 15-18) showed that, as expected, the isothermal surfaces sloped sharply downward toward the coast thus leading to a pressure gradient directed offshore in the upper 30 or 40 meters.

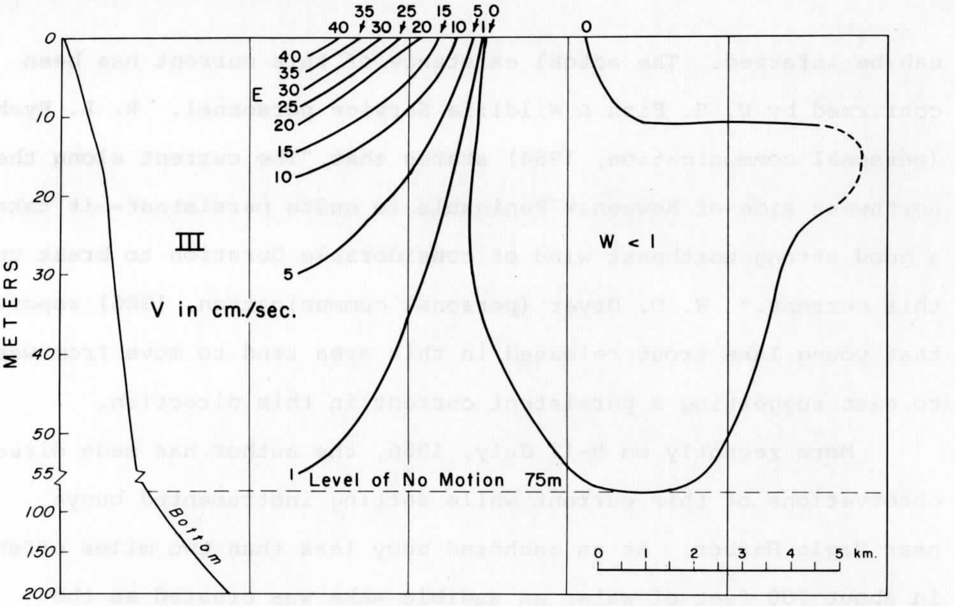
KEWEENAW CURRENT

Current velocities normal to the temperature cross-sections were calculated by the geodynamic height method of Ayers (1956) taking 75 meters as the depth of "no motion". (See Appendix for Fortran program). The velocity cross-sections are shown in Figures 19-22. On 30 July 1965 the current was confined to a zone within five miles of the coast. Maximum calculated velocities were 35-40 cm/sec or about one knot, but since the maximum velocities occurred at the inshore edge of the temperature data, even higher velocities

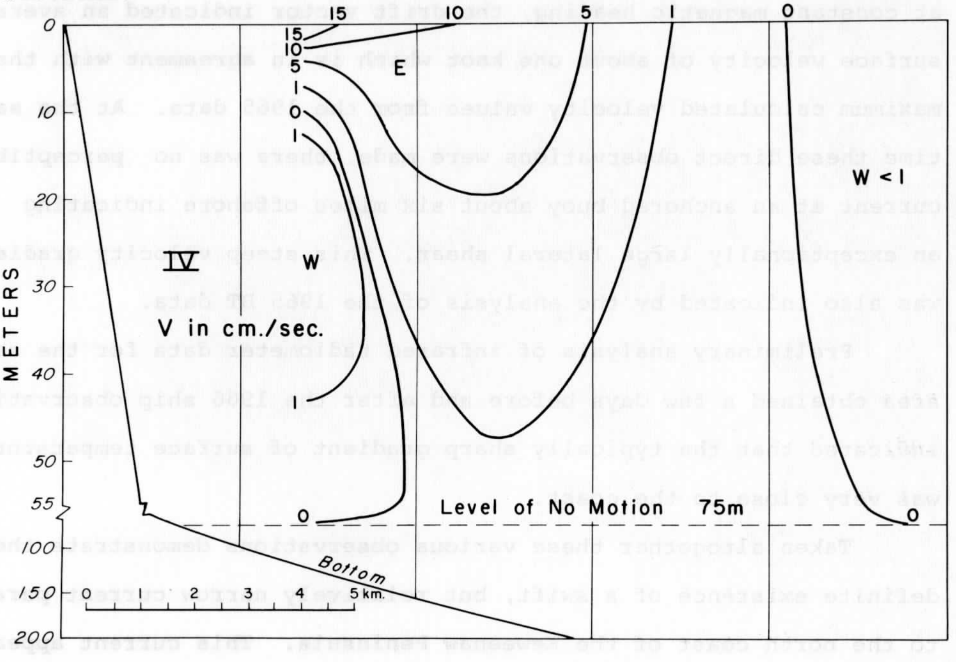


Figures 19-20. Velocity cross-sections across Keweenaw Current for 30 July 1965. Velocities are calculated by geodynamic height method using 75 meters as the level of no motion. Light lines show the locations of BT soundings. See Figure 12 for location of sections.





Figures 21-22. Velocity cross-sections across Keweenaw Current for 30 July 1965. Velocities are calculated by geodynamic height method using 75 meters as the level of no motion. Light lines show the locations of BT soundings. See Figure 12 for location of sections.



can be inferred. The actual existence of this current has been confirmed by U. S. Fish & Wildlife Service personnel. R. L. Pycha (personal communication, 1964) states that "The current along the northwest side of Keweenaw Peninsula is quite persistent--it takes a good strong northeast wind of considerable duration to break up this current." W. D. Dryer (personal communication, 1966) reports that young lake trout released in this area tend to move from west to east suggesting a persistent current in this direction.

More recently on 9-11 July, 1966, the author has made direct observations of this current while setting instrumented buoys near Eagle Harbor. At an anchored buoy less than two miles offshore in about 700 feet of water an audible wake was created as the surface water swept past. The current velocity was estimated to be between one and two knots. From a ship crossing of the current at constant magnetic heading, the drift vector indicated an average surface velocity of about one knot which is in agreement with the maximum calculated velocity values from the 1965 data. At the same time these direct observations were made, there was no perceptible current at an anchored buoy about six miles offshore indicating an exceptionally large lateral shear. This steep velocity gradient was also indicated by the analysis of the 1965 BT data.

Preliminary analysis of infrared radiometer data for the same area obtained a few days before and after the 1966 ship observations indicated that the typically sharp gradient of surface temperature was very close to the coast.

Taken altogether these various observations demonstrate the definite existence of a swift, but relatively narrow current parallel to the north coast of the Keweenaw Peninsula. This current appears to be confined to the upper 30 meters and persists from late June to early August and probably longer. Since this current is a regular and persistent feature of the summer circulation of Lake Superior, it is suggested that it be called the "Keweenaw Current".

The outer edge of the current is characterized by the packing of the surface isotherms with colder water offshore. This feature constitutes a surface "signature" of the Keweenaw Current and is readily detectable by infrared radiometry. As shown in Figure 14 the axis of the current "signature" moves offshore from time to time apparently in response to offshore winds and subsequent upwelling near the coast or to the intrusion of colder water along the coast from the northeast.

Despite its lateral movements, the current remains narrow and coherent. The geometry of the lake undoubtedly exerts some effect, but it is difficult to see how this alone could cause a narrow surface current to persist up to 20 kilometers offshore where depths exceed 200 meters. Referring to the thermal maps of the entire lake (Figs. 1-6) it is obvious that during summer a large expanse of warm surface water is found in the south portion of the lake west of the Keweenaw. This water may originate from the shallower water in the Apostle Island region or from the stripping off of heated surface water in the central region by Ekman transport or both. As this warm water flows eastward it is apparently constricted between the Keweenaw Peninsula and the cold central water to the north resulting in the development of exceptionally steep geodynamic slopes. Since the water depth in this area is several times the depth of the thermocline, bottom friction is small. Therefore, it seems reasonable to assume that the Keweenaw Current is in geostrophic equilibrium.

RELATION TO THE "THERMAL BAR"

Rodgers (1965) has proposed that the sharp horizontal temperature gradient frequently observed parallel to the coast in the Great Lakes is the same as the "thermal bar" described by Tikhomirov (1963). This phenomenon requires that water masses above and below 4° C be present simultaneously. In the spring situation a convective circulation is set up which results in sinking along the cold side of the horizontal temperature gradient parallel to the shore and a general slow upward motion in the cold central portion of the lake. Inshore of the temperature gradient region the water is above 4° C and sinking also occurs along the warm side of this gradient where lateral mixing lowers the surface temperature below that of the underlying water. In cross-section the thermal bar is characterized by reversal of slope of the isothermal surfaces from one side to the other with the surfaces being vertical in the center of the gradient. As surface warming proceeds the "thermal bar" moves steadily offshore. Presumably when the surface temperature of the central portion of the lake exceeds 4° C, the entire system "flips over" into the usual epilimnion-hypolimnion thermal structure.

This phenomenon may occur in Lake Superior up to early July, but by mid-July the temperature of the central water has increased to above 4° C. Therefore, this effect can no longer operate. This is clearly shown in the BT sections of 30 July (Fig. 12) when the isothermal surfaces all slope upward away from the coast. Also the horizontal temperature gradient did not move outward until 20 July, but then returned to a nearshore position by 30 July and back offshore by 3 August, (Fig. 14). Thus instead of moving steadily offshore, the thermal gradient migrated back and forth, probably in response to transient wind changes. Furthermore, the gradient persisted even after the temperature of the central water rose above 4° C. Therefore, the temperature gradient normal to the Keweenaw Peninsula and its associated equilibrium current must be viewed as a dynamic feature of the lake which persists from late June to early August at least.

DIURNAL HEATING OF THE SURFACE WATER

Since the infrared thermometer senses only radiation in the 8 to 14 micron band, the temperature measured is primarily that of the upper 10 microns of the water (McAllister, 1964). Even in the presence of considerable wind action this layer is strongly affected by heat exchange processes such as evaporation, radiation and conduction to the air. This problem is discussed by several authors in the "Techniques for Infrared Survey of Sea Temperature" J. Clark ed. (1964). During all daytime flights over Lake Superior the effects of diurnal heating were suspected of introducing a bias into the results. The following test was made to determine the magnitude of this effect.

The flight of 14 July (Fig. 3) originated and terminated at Duluth. Several flight path intersections were planned so that surface temperatures on the outbound and inbound tracks could be compared. These are lettered in Fig. 3, and the results are summarized in Table 1. Point F is omitted because of a navigational uncertainty. At points A, B, C, and D the average heating rate was 0.24° C per hour. This value applies to clear to partly cloudy sky conditions during the middle part of the day. At point E the

TABLE I

DUIRNAL HEATING RATES OBSERVED AT FLIGHT TRACK INTERSECTIONS ON 14 JULY, 1965.

Intersection	Time	Temperature	Heating Rate	Weather
(See Fig. 3)	(CDT)	(^{o}C)	(^{o}C/hr)	
A	1157	5.1	0.21	clear
	1545	5.9		clear, 2/10 stratus NW
B	1140	5.4	0.21	clear
	1631	6.4		clear, 4/10 stratus SE, S, SW
C	1134	5.6	0.25	clear, 5/10 stratus W, SW
	1649	6.9		clear, 10/10 stratus & rain shower W
D	1132	5.5	0.27	10/10 stratus
	1650	7.0		10/10 stratus, rain shower N
E	1116	6.0	0.49*	8/10 stratus
	1708	8.8 *		10/10 stratus, rain shower nearby

* value unreliable because of rain shower

observed value was about twice as large, but this is attributed to the proximity of a rain shower which could have produced a local increase in surface temperature.

The diurnal heating therefore can cause a gradual increase in the surface temperature of 1 to 2° C in the course of a day. In a survey lasting an entire day a bias would be apparent, but where horizontal temperature differences of 10° C or more are encountered, the overall pattern would not be substantially affected. Due to the short time intervals involved, local gradients would not be significantly affected.

Since the heating rate will vary depending on local meteorological conditions, the rate should be determined for each flight if a correction for this effect is to be made. No correction was applied to the data presented in this paper.

GENERAL DISCUSSION

The primary result of this investigation has been the demonstration of the validity of a remote sensing technique, infrared in this case, for detecting sub-surface features by means of a surface "signature". A sharp horizontal temperature gradient at the surface is a well recognized manifestation of a boundary current. However, all sharp temperature gradients do not necessarily indicate the existence of currents. Other effects such as shallow water, river outflow or onshore winds could cause such gradients. When the gradient occurs in deep water and persists despite wind shifts associated with the passage of cyclonic storms, the probability of a steady equilibrium current is great. Final verification must then be sought from other evidence such as measurements of internal thermal and current structure.

Once the feature is verified then the remote sensing technique becomes a surveillance technique by which the exact position and movements of the current can be determined. The streamline orientation can also be observed directly by flights which identify a particular group of surface isotherms using the infrared radiometer as a tracking device, as is being done, for example, on the Gulf Stream (Niblock, 1966). A high precision air navigation system such as a doppler radar or inertial platform navigation system will be required in order to document the actual ground track of the aircraft.

At the same time, detailed investigation of the current, e.g. its velocity structure, depth, transport and so forth, can be conducted from ships or buoys. The effectiveness and efficiency of these vehicles can be greatly enhanced by making use of the data from the remote sensing surveillance technique. For example, infrared surveys of the thermal gradient associated with the Keweenaw Current suggest the occasional occurrence of eddies and a counter-current. (Figs. 8 and 13). Ideally whenever these secondary features appear to be present, a ship could be directed to the proper location to make direct measurements. Lacking the aerial surveillance capability, the possibility of a ship locating these features would be left to chance or would require a "brute force" type of operation involving several ships or a very tight buoy array. Either of these alternatives is prohibitively expensive in terms of both personnel and money.

In summary, remote sensing is a powerful technique which can be used to detect interesting and significant thermal and circulation features in large bodies of water. By maintaining surveillance, the effectiveness of ship-borne operations can be greatly increased.

CONCLUSIONS:

At this stage of the investigation the following conclusions can be drawn:

1. The thermal structure of Lake Superior during summer displays features which occur regularly each year. Two of these are the two "cold pools" in the central portion of the lake and the steep surface temperature gradient along the Keweenaw Peninsula.

2. There is a narrow, swift current flowing northeastward along the north coast of the Keweenaw Peninsula. This current appears to be in dynamic equilibrium and persists from late June until at least early August.

3. Infrared radiometry is a valid and powerful technique for examining the surface temperature patterns of large bodies of water. These thermal patterns can in some cases be interpreted as "signatures" of internal thermal structure and boundary currents.

4. The concept of a "thermal bar" does not adequately explain the observed thermal structure of Lake Superior.

ACKNOWLEDGEMENTS

Credit is hereby given to Michael Bratnick who devoted much effort to the collection and analysis of the field data. Aircraft support was provided by the Research Aviation Facility of the National Center for Atmospheric Research and by the U. S. Navy through the Service Test Division of the Patuxent Naval Air Station, Maryland. Ship support was provided by the U. S. Coast Guard. The generous help of these three organizations is gratefully acknowledged.

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APPENDIX. COMPUTER PROGRAM FOR DETERMINING CURRENT IN DEEP FRESHWATER LAKES BY THE GEODYNAMIC HEIGHT METHOD.

FORTRAN PROGRAM

```
     DIMENSION  A(250),C(250),DISJ(9),T(36,10),H(36,10),V(36,9)
     Q=10./(.000145*.736*1609.4)
     READ 1001,  (A(J),J=1,250)
     READ 1001,  (C(J),J=1,250)
1001 FORMAT (10F6.1)
     READ 1101,  NI
1101 FORMAT (I2)
     DO 3 I=1,NI
     READ 1102, NJ,(DISJ(J),J=1,9)
1102 FORMAT (8X,I2,21X,9F4.1)
     READ 1103,  ((T(K,J),K=1,36),J=1,NJ)
1103 FORMAT (14X,9F6.2)
     DO 5 J=1,NJ
     P=-.1
     DP=.1
     DO 5 K=1,36
     IF (K-27) 204, 202, 204
202  DP=.5
204  P=P+DP
     TI=10.*T(K,J)+1.
     IT=TI
     FIT=IT
     F=TI-FIT
     TT1=A(IT+1)*F+A(IT)*(1.-F)
     TT2=C(IT+1)*F+C(IT)*(1.-F)
   5 H(K,J)=TT1-P*TT2
     DO 7 J=1,NJ
     DP=100.
     DO 6 K=1,35
     IF (K-26) 6, 206, 6
206  DP=500.
   6 H(K,J)=(H(K,J)+H(K+1,J))*DP*.5*.00001
   7 H(36,J)=0.
     DO 8 J=1,NJ
     DO 8 KC=1,35
     K=36-KC
   8 H(K,J)=H(K+1,J)+H(K,J)
     NJ1=NJ-1
     DO 9 KC=1,36
     K=37-KC
     DO 9 J=1,NJ1
   9 V(K,J)=(H(K,J)-H(K,J+1))*Q/DISJ(J)
     PRINT 3001, I
3001 FORMAT (58H1TEMPERATURES, SIGMA DELTA HEIGHTS, SIGMA DELTA VELO-
     CIT
    1IES/9HO   TRACKI2)
     PRINT 3002, (DISJ(J),J=1,NJ1)
```

(Fortran Program Continued)

```
3002 FORMAT  (/10H0DISTANCES,3X,9F10.1)
     PRINT 3003, (J,J=1,NJ)
3003 FORMAT (8H0STATION,7X,10(I2,8X))
     PRINT 3004
3004 FORMAT (6H DEPTH)
     KP=-1
     KDP=1
     DO 11 K=1,36
     IF (K-27) 303,301, 303
301  KDP=5
303  KP=KP+KDP
     PRINT 3005, KP,(T(K,J),J=1,NJ)
3005 FORMAT (1HO,I3,5H   (T),1X,10F10.2)
     PRINT 3006, (H(K,J),J=1,NJ)
3006 FORMAT (6X,5H(H)   ,10F10.5)
  11 PRINT 3007,(V(K,J),J=1,NJ1)
3007 FORMAT (6X,3H(V),6X,9F10.2)
   3 CONTINUE
     STOP
     END
```

TABLE A

13.0	12.4	11.5	10.8	10.2	9.6	9.0	8.4	7.9	7.4	0
7.0	6.6	6.2	5.7	5.3	4.9	4.6	4.2	3.8	3.5	1
3.0	2.8	2.6	2.3	2.0	1.8	1.6	1.4	1.2	1.1	2
1.0	.9	.8	.7	.6	.5	.4	.3	.2	.1	3
0.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	4
1.0	1.1	1.2	1.3	1.5	1.7	1.9	2.1	2.4	2.7	5
3.0	3.3	3.7	4.1	4.5	4.9	5.3	5.7	6.1	6.5	6
7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	7
12.0	12.6	13.2	13.9	14.6	15.3	16.0	16.7	17.4	18.3	8
19.0	19.7	20.4	21.2	22.0	22.8	23.6	24.4	25.3	26.1	9
27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0	36.0	10
37.0	38.0	39.1	40.2	41.3	42.5	43.6	44.7	45.8	46.9	11
48.0	49.1	50.2	51.4	52.6	53.8	55.0	56.2	57.4	58.7	12
60.0	61.3	62.6	63.9	65.2	66.5	67.8	69.1	70.4	71.7	13
73.0	74.4	75.8	77.2	78.6	80.0	81.4	82.8	84.2	85.6	14
87.0	88.6	90.2	91.8	93.4	95.0	96.6	98.2	99.8	101.4	15
103.0	104.7	106.4	108.1	109.8	111.5	113.2	114.9	116.6	118.3	16
120.0	121.8	123.6	125.4	127.2	129.0	130.8	132.6	134.4	136.2	17
138.0	139.9	141.8	143.7	145.6	147.5	149.4	151.3	153.2	155.1	18

TABLE A (Cont.)

157.0	159.0	161.0	163.0	165.0	167.0	169.0	171.0	173.0	175.0	19
177.0	179.1	181.2	183.3	185.4	187.5	189.6	191.7	193.8	195.9	20
198.0	200.3	202.6	204.9	207.2	209.5	211.8	214.1	216.4	218.7	21
221.0	223.3	225.6	227.9	230.2	232.5	234.8	237.1	239.4	241.7	22
244.0	246.4	248.8	251.2	253.6	256.0	258.4	260.8	263.2	265.6	23
268.0	270.6	273.2	275.8	278.4	281.0	283.6	286.2	288.8	291.4	24

TABLE C

5.250	5.243	5.236	5.230	5.224	5.219	5.214	5.209	5.204	5.200	0
5.195	5.191	5.187	5.183	5.179	5.176	5.173	5.170	5.167	5.163	1
5.160	5.157	5.154	5.151	5.148	5.145	5.142	5.139	5.136	5.133	2
5.130	5.128	5.125	5.122	5.120	5.118	5.115	5.112	5.110	5.108	3
5.105	5.103	5.100	5.098	5.095	5.092	5.089	5.087	5.085	5.082	4
5.080	5.078	5.076	5.074	5.072	5.070	5.068	5.066	5.064	5.062	5
5.060	5.058	5.057	5.055	5.053	5.051	5.049	5.047	5.045	5.044	6
5.043	5.041	5.039	5.038	5.036	5.034	5.033	5.031	5.029	5.028	7
5.027	5.025	5.024	5.023	5.022	5.020	5.019	5.018	5.016	5.014	8
5.013	5.012	5.011	5.010	5.008	5.007	5.006	5.004	5.003	5.001	9
5.000	4.998	4.997	4.996	4.994	4.993	4.992	4.990	4.989	4.987	10
4.985	4.984	4.983	4.982	4.981	4.980	4.979	4.978	4.977	4.976	11
4.975	4.974	4.973	4.971	4.970	4.969	4.968	4.967	4.966	4.965	12
4.964	4.962	4.961	4.960	4.959	4.958	4.957	4.956	4.955	4.954	13
4.953	4.953	4.952	4.951	4.950	4.949	4.948	4.947	4.946	4.945	14
4.944	4.943	4.942	4.941	4.941	4.940	4.939	4.938	4.938	4.937	15
4.936	4.936	4.935	4.934	4.933	4.932	4.932	4.931	4.931	4.930	16
4.929	4.929	4.928	4.928	4.927	4.926	4.925	4.924	4.923	4.923	17
4.922	4.921	4.921	4.920	4.919	4.919	4.918	4.918	4.917	4.916	18

TABLE C (Cont.)

4.916	4.915	4.914	4.914	4.913	4.913	4.912	4.912	4.911	4.911	19
4.910	4.910	4.909	4.909	4.908	4.908	4.907	4.907	4.906	4.906	20
4.905	4.905	4.904	4.904	4.903	4.903	4.903	4.903	4.902	4.902	21
4.902	4.902	4.901	4.901	4.901	4.901	4.900	4.900	4.899	4.899	22
4.898	4.898	4.898	4.897	4.897	4.896	4.896	4.895	4.894	4.894	23
4.893	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	24

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Infrared radiometer surveys of Lake Superior during the summer of 1964 and 1965 have shown that a band of warm water separated by a sharp thermal gradient appears along the north coast of the Keweenaw Peninsula in late June and persists at least into August. The sub-surface thermal structure in this region indicates a steep slope of the geodynamic surfaces with the pressure gradient directed offshore. Calculation of current velocity based on the geodynamic slopes gives velocities up to one knot. Direct observations confirm the existence of this current both with regard to location and estimated velocity. The current, for which the name "Keweenaw Current" is suggested, flows northeastward along the north coast of the Keweenaw Peninsula. It appears to be a boundary current and is probably maintained by the piling up of warm water along the south side of the lake by Ekman transport. (U)

It is shown that although the "thermal bar" effect may exist in early June, this phenomenon does not provide an explanation for the temperature and circulation pattern observed later in the season. (U)

Analysis of infrared radiometer data at intersections of flight tracks on a single day gave diurnal heating rates of 0.21 to 0.27° C. hr.$^{-1}$ (U)

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