NOTES AND COMMENT

AIRBORNE TEMPERATURE SURVEYS OF LAKE MICHIGAN, OCTOBER 1966 AND 1967[1]

ABSTRACT

Low-altitude flights to map surface water temperature were carried out over Lake Michigan on 18 October 1966 and 25 October 1967. During the 1966 flight, a strong surface water thermal gradient (4.4C/6,000 m) was observed. This gradient was accompanied by a distinct color change. Dynamic height currents computed from a bathythermograph transect through the gradient indicated a northward current of the order of 10–12 cm/sec in the gradient zone. The thermal structure persisted for a week. A similar temperature gradient–color separation–dynamic height current feature was observed during 1967. Data from *Nimbus II* meteorological satellite for 7 September and 6 October 1966 show a large, weak structure in the radiation temperature patterns that might be interpreted as precursors of the temperature–current structure. This thermal structure might be a recurring seasonal characteristic of Lake Michigan.

INTRODUCTION

This paper presents a summary of the results of flight programs carried out over Lake Michigan by the U.S. Naval Oceanographic Office in 1966 and 1967. High resolution infrared radiometer (HRIR) data from *Nimbus II* meteorological satellite were examined to confirm the prior existence of large-scale thermal features observed on the 1966 flights. The flight program was carried out as a pilot experiment over freshwater, both to demonstrate the capabilities of the airborne instrumentation for research and to provide information for calibrating the instruments to other than completely marine environments. Details of the 1966 flight have been presented (Wilkerson and Ropek 1967).

AIRBORNE MEASUREMENTS

During the 1966 program, an infrared airborne radiation thermometer (ART) (Barnes Eng. Co. Model 14-320) was used to map surface temperature on 23 east–west transects equally spaced over the lake. In addition, wave spectra were measured with wave height radar and the applicability of several cartographic cameras and filter combinations was investigated. Only surface temperature mapping could be carried out in 1967. During both years of operation, calibrations of surface temperature were provided by ship support, and bathythermograph (BT) transects were

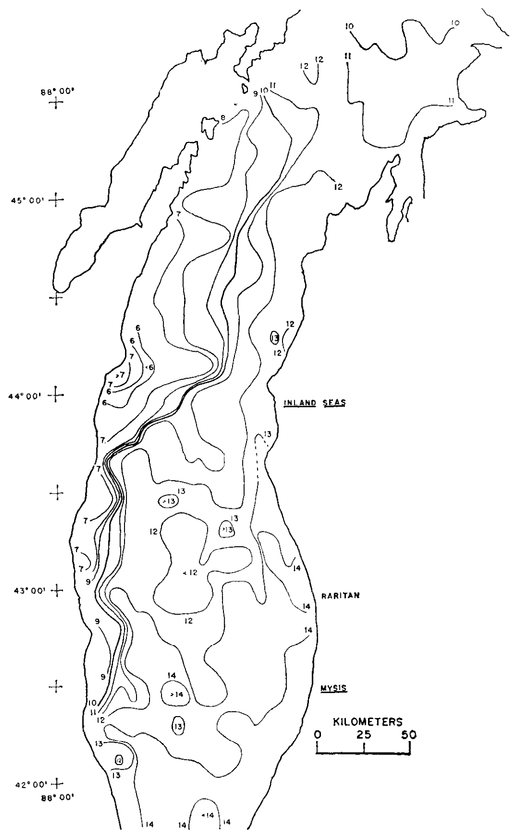

FIG. 1. Isotherms plotted from 1-min average ART temperatures. Lake Michigan, 18 October 1966 (from Noble 1967*b*; Wilkerson and Ropek 1967).

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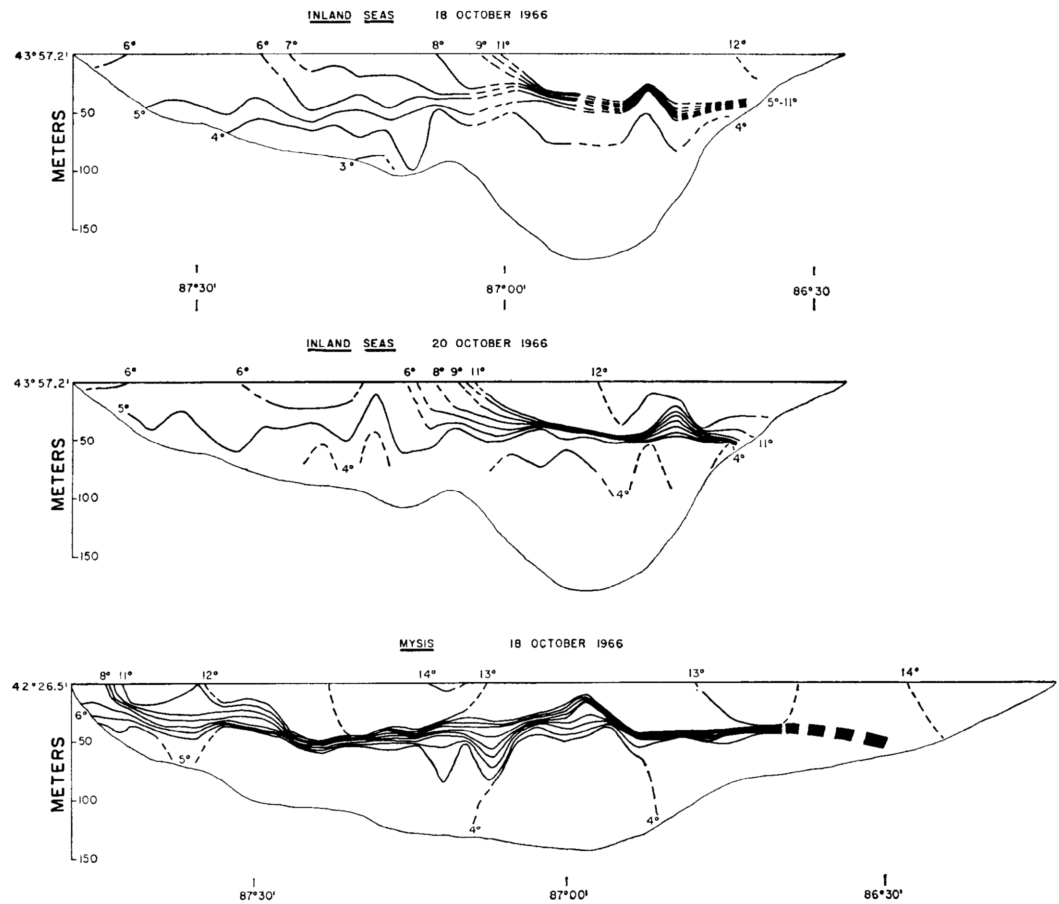

FIG. 2. Temperature structure of Lake Michigan along sections identified above.

made across the lake basin along flightpaths in the south end and north end.

During both years, flight altitudes were 300 to 100 m as required to stay under the existing overcast. Cloud bases were of the order of 300 m. When the flightpaths were in rain showers, the apparent ART surface temperatures were rejected as uncalibrated. In both years, the apparent ART temperatures were corrected for atmospheric absorption by direct comparison (by overflights) with surface temperatures from thermistors towed by three support ships in the southern, middle, and northern thirds of the lake. The environmental correction term was +0.4C for each of the three comparisons during both flights.

Figure 1 shows the contours of the distribution of surface temperature for 1966. The dramatic packing of the isotherms along the west side of the lake extending from Milwaukee to Sheboygan, then turning northeastward to its center, was accompanied by a sharp color separation; east of the thermal front, the water was warm and green, west of it, cold and blue. Calculations from BT casts along the flightpath gave evidence of a strong current along the temperature gradient.

Geostrophic currents were calculated by using the dynamic height method (Ayers 1956; Ayers and Bachmann 1957). The reference depth (level of no motion) was taken to be 70 m; dynamic heights are computed with respect to this depth for each 10-m depth increment for each BT cast. To compare such currents with surface temperature measurement, the dynamic heights so computed are determined for the 0- to 10-m depths of adjacent BT casts. These computed dynamic heights are used to calculate the geostrophic current component normal to the line of the BT section in the 0–10-m layer of the water column (Noble 1967*a*).

The flight mapping the surface temperature pattern was made on 18 October 1966. The RV *Inland Seas* transected the lake on the flightpath, taking BT readings at 3.2-km intervals on 18, 19, and 20 October 1966. No further aerial mapping was done after 18 October, but flights showed that the general pattern persisted to 21 October. The temperature structure determined from the BT transects on 18 and 20 October along this flightpath and along a southern flightpath determined by BT transects from

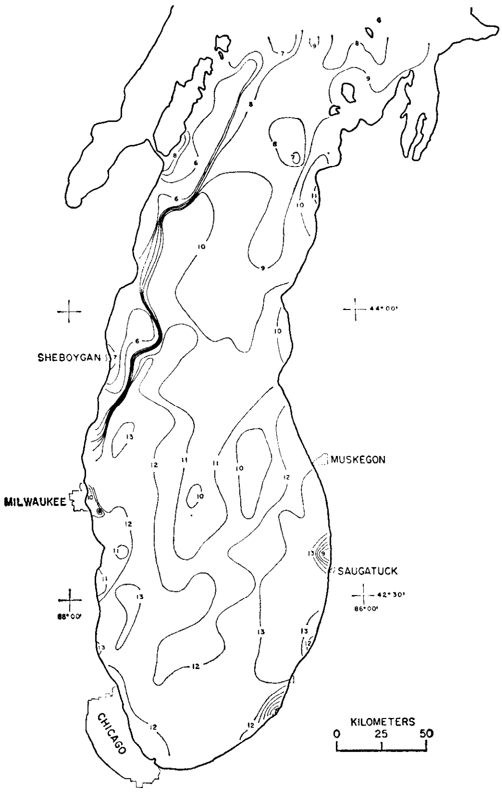

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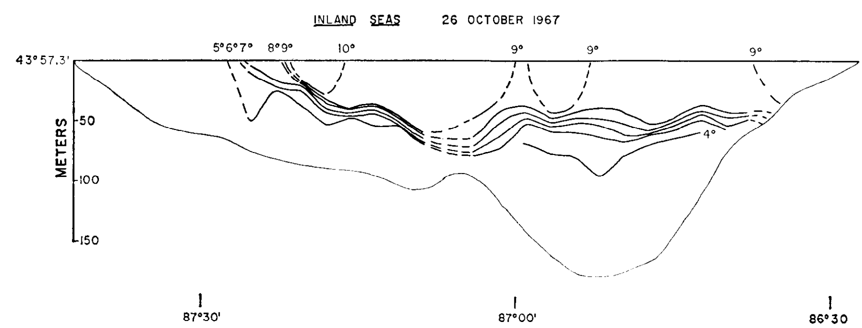
FIG. 3. Isotherms plotted from 1-min average ART temperatures. Lake Michigan, 25 October 1967.



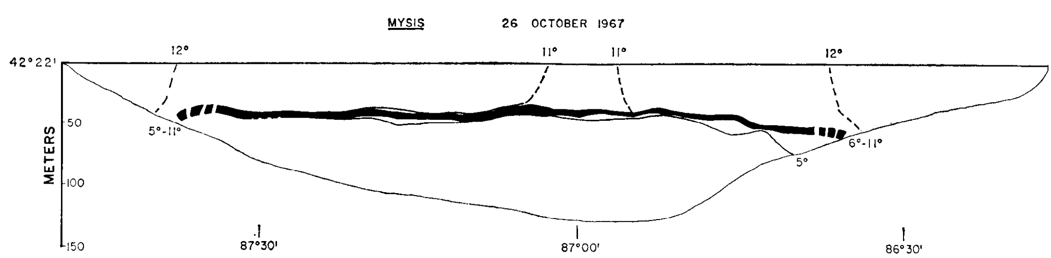


FIG. 4. Temperature structure of Lake Michigan along sections identified above.

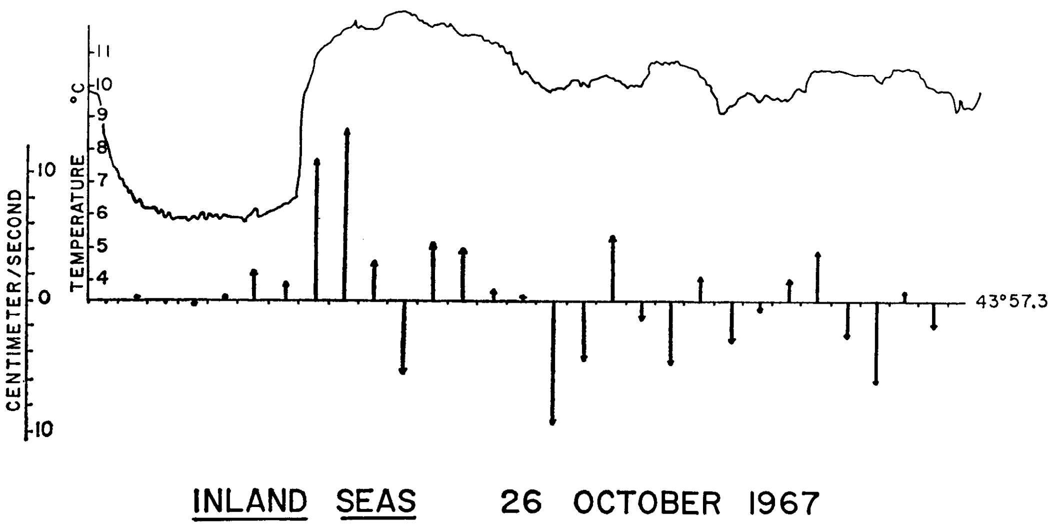


FIG. 5. Pattern of surface temperature and components of 0–10-m layer dynamic height current normal to the cruise track.

the RV *Mysis* on 18 October 1966 are shown in Fig. 2.

After observation of the surface temperature pattern and the computation of the geostrophic current in 1966, we wondered whether this might be a recurrent seasonal feature. Accordingly, we planned a similar flight during October 1967. The late summer–early fall in 1967 was significantly cooler than in 1966. Further, the flight operations in 1967 were scheduled for a date one week later than in 1966, but circumstances prevented a series of flights in 1967. The single 1967 flight, therefore, took place under conditions approximating those of two weeks later in 1966.

Figure 3 shows the surface temperature contours for 25 October 1967. Figure 4 shows the temperature structure of the lake determined from the BT transects carried out on 26 October 1967.

The general surface temperature of the lake in 1967 was approximately 2C cooler than that of 1966. The temperature gradient on the west side was much sharper in 1967 than 1966, being of the order of 6C/4,800 m at its sharpest point in 1967 and 4.4C/6,000 m in 1966. There was color separation along the thermal gradient similar to that of 1966. Figure 5 shows a comparison between the pattern of surface temperature and components of the dynamic height current calculated for one BT transect on 26 October 1967.

While the surface temperature structure observed in 1967 shows certain similarities to that of 1966, it is not yet known whether this phenomenon of a sharp temperature gradient accompanied by a computed geostrophic current is, in fact, a significant structure in the seasonal characteristics of Lake Michigan. After the 1966 flight, it was suggested that the temperature structure may have been the result of upwelling, but the phenomenon seems of too large a scale and too great a persistence to be the result of a simple upwelling. The 1967 structure is closer to the shoreline and more nearly resembles what would be expected from upwelling; however, the surface temperature profile (Fig. 5) shows that the warmest surface water was found

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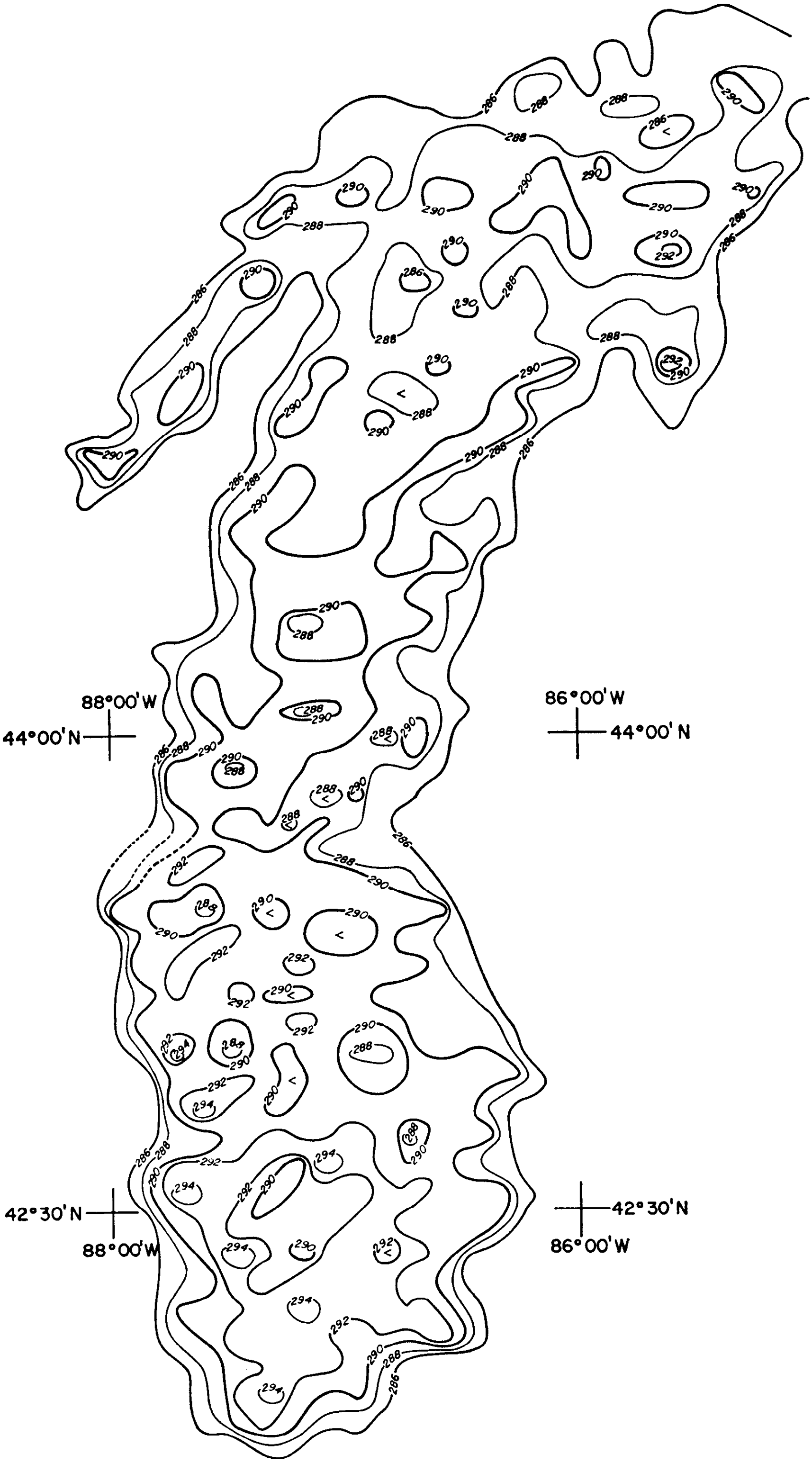
FIG. 6. Isotherms plotted from digital grid-print map of radiation temperatures (in °K) from the HRIR scanner on *Nimbus II*. Data orbit 1530, 7 September 1966.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at the thermal gradient on the west side of the lake rather than at the east shore, as would be expected if the process were wind-generated upwelling.

CORRELATED SATELLITE DATA

To obtain an estimate of the buildup of the thermal feature documented during the week of 18–21 October 1966, we examined data from the *Nimbus II* meteorological satellite from September and October 1966. We sought thermal imagery of Lake Michigan preceding the flights that would permit comparable analysis of the surface temperature structure of the entire lake basin and provide confirmation of a prior existence of this dramatic thermal feature.

Two sets of data from nighttime, clear-sky *Nimbus II* HRIR (3.5–4.1 μ) were available for Lake Michigan preceding the ART flight of 1966. These were data orbits 1530 (7 September 1966) and 1916 (6 October 1966). The resolution element of subsatellite HRIR is 8.6×9.7 km, with an error in point position of about 1° of latitude and longitude. As the look angle of the scanner is swept through an arc transverse to the satellite track, the scan spot changes from rectangular at the subsatellite point to an elongated trapezoid at larger look angles.

Digitized grid-print maps were obtained from Goddard Space Flight Center for selected portions of data orbits 1530 and 1916 showing Lake Michigan. In this presentation of data, the elongated, overlapping resolution elements are averaged to yield a single digital value for the radiation temperature of the equivalent minimum resolution element (8.6×9.6 km) plotted on a rectified Mercator projection (here, 1 : 500,000 scale). Radiation temperatures contoured from the grid-print maps of Lake Michigan are shown in Figs. 6 and 7.

Figure 8 compares temperatures from the cruise track of the RV *Inland Seas* (2-m

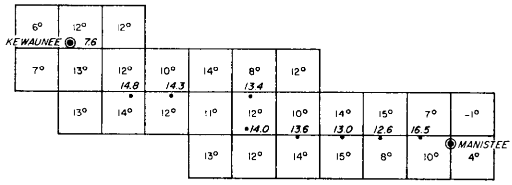

FIG. 8. Comparison of values of grid-print temperature from the HRIR scanner on *Nimbus II* (data orbit 1916, 6 October 1966) with readings of surface temperature from RV *Inland Seas* (along cruise track from Manistee to Kewaunee, 6 October 1966).

depth) during the daytime of 6 October 1966 with the digitized grid-print values from the *Nimbus* orbit of the early morning of 6 October 1966. Note that the low grid-print temperatures near the shoreline at Manistee and the high values near Kewaunee reflect the averaging of up to four resolution elements to obtain a single grid-print value. (Because the sky was clear that night, the radiation temperatures of the land mass are much colder than the water.)

With averaging of the resolution elements, problems in accurate positioning of the satellite and of atmospheric absorption of the infrared radiation, comparison of radiation temperature values from the digital grid-print with readings of point surface temperature from ships is difficult. However, large-scale patterns of radiation temperature have been shown to be meaningful in application to Lake Michigan (Strong 1967).

The pattern of 7 September 1966 (Fig. 6) shows a tongue of warm water trending northeastward from the west side of the lake at about 44° N lat, delineated by the 290°K contour. The pattern of 6 October 1966 (Fig. 7) shows a similar tongue delineated by the 284°K and 286°K contours. In this case, the temperature contrasts are somewhat stronger and the tongue is more northward than on the previous date. This warmer tongue that appeared in the *Nim-*

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FIG. 7. Isotherms plotted from digital grid-print map of radiation temperatures (in °K) from the HRIR scanner on *Nimbus II*. Data orbit 1916, 6 October 1966.

bus data of 7 September and 6 October may be the precursor of the temperature gradient structure defined by the thermal mapping flight of 18 October 1966.

DISCUSSION

The persistence of the thermal structure along 43° 57.2′ N lat for 48 hr between 18 and 20 October 1966 (Fig. 2) indicates sufficient equilibrium for computation of a geostrophic current by the dynamic height method (approx 35 hr pendulum day). Therefore, in spite of a lack of direct measurement, the existence of this current and its relation to the surface temperature structure can be inferred.

The evidence of a precursor thermal pattern as derived from the radiation data of *Nimbus II* is somewhat weak because of the obvious limitations of the data, but the scale and persistence of the thermal feature would seem to imply a process more significant than simple, irregularly occurring, wind-generated upwelling.

Finally, in spite of the differences between the observations of 1966 and 1967, the scales of the thermal features and the magnitudes of the computed geostrophic currents seem to suggest a similarity of causal forces. We would like, therefore, to suggest that the possibility of the seasonal recurrence of this temperature and circulation feature in Lake Michigan is sufficiently strong to warrant reexamination of this phenomenon. If additional experiments should document the seasonal recurrence of this feature, we suggest that it be named the Coyote Current (Noble 1967*b*) after *El Coyote*, the research aircraft that carried out the flights.

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GREAT LAKES THERMAL STUDIES USING INFRARED IMAGERY

ABSTRACT

Examples of mosaics of infrared imagery of the western end of Lake Ontario are used to demonstrate their value in revealing detailed surface thermal patterns. Additional data from airborne thermometry and shipboard measurements confirm the interpretation of large-scale dynamic processes. Smaller scale phenomena, such as internal wave patterns and small eddies, are also interpretable.

During spring to autumn 1968, seven airborne surveys of western Lake Ontario were made with an infrared scanner. The main instrument was a modified Singer Reconofax IV scanner, flown and maintained by the National Aeronautics Establishment, National Research Council, Ottawa. Other instruments included a Barnes PRT-5 infrared thermometer, upward- and