J. Great Lakes Res. 13(4):468-486
Internat. Assoc. Great Lakes Res., 1987

SEASONAL THERMAL CYCLE OF LAKE ERIE

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ABSTRACT. A summary of the seasonal water temperature characteristics of Lake Erie and the 1979 and 1980 thermal structure in the central basin is described. Ice cover extends over 90% of Lake Erie most winters. Minimum surface temperature usually occurs in February (0.1°C) but fully mixed conditions at 1°C or less occur in January with isothermal conditions at (1°C) occurring from mid-February to mid-March. The thermal bar advance lasts about 5 to 6 weeks from April to mid-May and permanent stratification usually begins in mid-June with maximum heat storage in mid-August and overturn in mid-September. The central basin thermocline position varies significantly from year to year, the variability of the upper and lower mesolimnion boundaries being as large as 10 m. Thermocline position shows some dependence on prevailing meteorological conditions and has implications to the development of central basin anoxia. Temperature increases and decreases depicted on isotherm plots for stations in the central basin show correspondence with peak wind stress events. During fragile stability conditions, even moderate wind stresses of less than 0.5 dynes/cm^2 are capable of producing upper layer deepening. Episodes of complete vertical mixing in response to high wind stresses of 3 dynes/cm^2 during storm periods are observed. Double thermoclines are evident at several locations within the basin and temperature changes resulting from an influx of hypolimnetic water from the Pennsylvania Ridge is documented. Periods of hypolimnetic entrainment are clearly observed along with thermocline tilting of 1 to 2 meters toward the south.
ADDITIONAL INDEX WORDS: Water temperature, thermal stratification, ice cover.

INTRODUCTION

Characteristics of the seasonal temperature cycle of Lake Erie have been investigated from earliest descriptive measurements (Green 1960) as outlined by Mortimer (1987) to the more intensive process oriented analyses of recent years (Burns and Ross 1972, Boyce *et al.* 1980). Principal among factors affecting temperature is the bathymetry which partitions the lake into three distinct basins (Fig. 1). These physiographic areas exhibit markedly different temporal and spatial distributions in temperature.

During "Project Hypo" (Burns and Ross 1972) *in situ* temperature measurements were analysed by Blanton and Winklhofer (1972) to determine the relationship between the winds, hypolimnetic motions, and the response of the thermocline to these motions. A number of features of the central basin thermal structure were documented. A semi-permanent tilt to the thermocline was observed, with deepest depressions located on the southern half of the lake which was clearly associated with the dominant southwest winds. Hypolimnetic temperature regressions with time showed that the nearshore areas experience temperature increases exceeding 1.2°C/month while increases in the cooler mid-basin locations were less than 0.7°C/month. Thermocline depth was observed to vary over the basin. At a mid-lake station, short-term fluctuations near the local inertial period of 17 hours were observed. Generally, fluctuations in the southwest wind correlated with fluctuations in thermocline position and with maximum current speeds in the hypolimnion.

Other characteristics of the central basin thermal

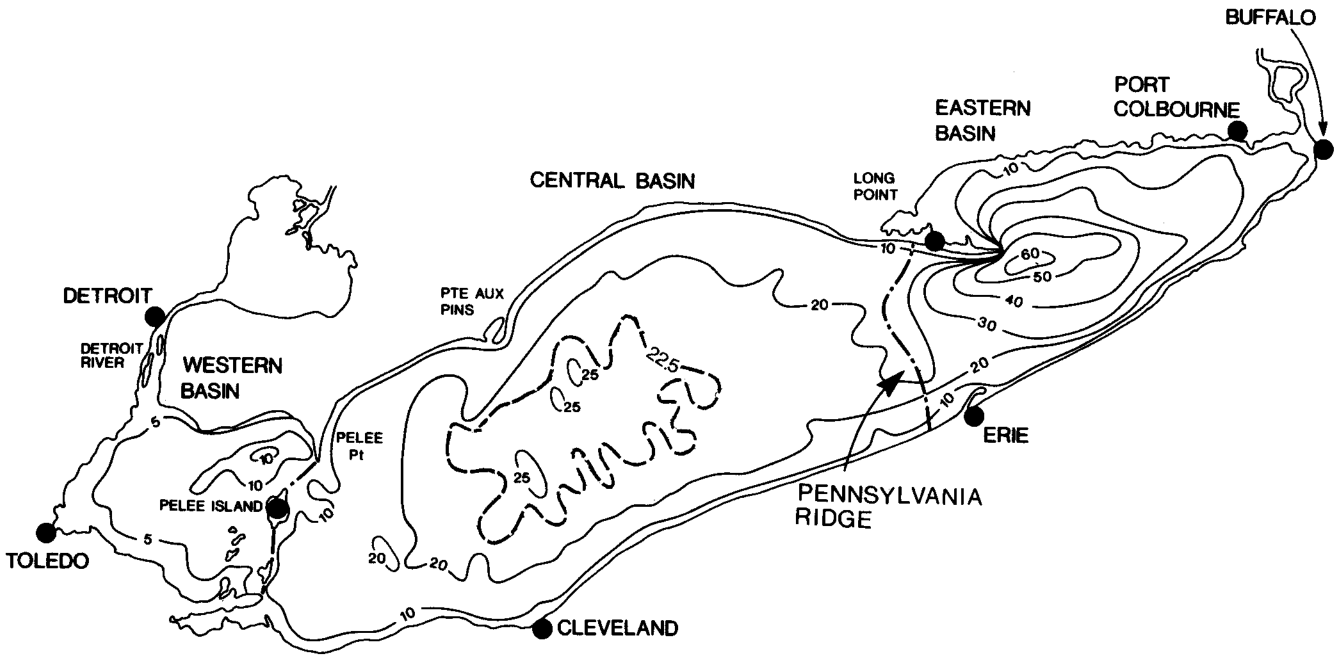

FIG. 1. Lake Erie bathymetry and basin boundaries.

structure have also been documented. Temperature distributions in the hypolimnion indicated episodes of apparent leakage of eastern basin hypolimnetic water into the central basin (Burns 1976, Boyce *et al.* 1980). Observations indicate a tendency for cooler hypolimnetic water to reside in the northwest sector of the central basin which is related to hypolimnion currents which flow predominantly into this region (Simons 1976). Downward entrainment is observed to occur within the hypolimnion under conditions when the thermocline is thick enough so that mixing processes are confined to the upper portion of the thermocline and when hypolimnion currents are strong enough to entrain overlying mesolimnion water down into the hypolimnion (Ivey and Boyce 1982, Ivey and Patterson, 1984).

Meteorological influences on the vertical temperature distribution have been identified by Lam *et al.* (1983) as contributing factors in the development of anoxia within the central basin hypolimnion.

Characteristics of the thermal structure of Lake Erie described above are observed in the intensive measurements during 1979 and 1980. The purpose of this discussion is to provide a description of the central basin thermal structure in these years based on observed thermistor data collected on a large-scale grid and in a locally intensive site in the western portion of the central basin. The general temporal and spatial aspects of the annual temperature cycle of Lake Erie and its basins are described initially.

SEASONAL WATER TEMPERATURE DISTRIBUTION

The temporal distribution of surface temperature and vertically integrated temperature is illustrated in Figure 2 for the period April to November based on 90 lakewide surveys from 1967 to 1982. These curves clearly demonstrate seasonal lags in the mean temperature and are related to the heat storage capacity of each basin. The western basin is the shallowest and heats to a maximum temperature at a faster rate than the other basins and cools at a faster rate due to the more efficient wind-inducing mixing in the fall. The deeper eastern basin lags the central basin in the heating season but retains its heat in storage for longer periods during the cooling phase. Comparison of the surface water temperature and vertically integrated temperature for the western basin reveals nearly identical values and, hence, demonstrates near vertically mixed

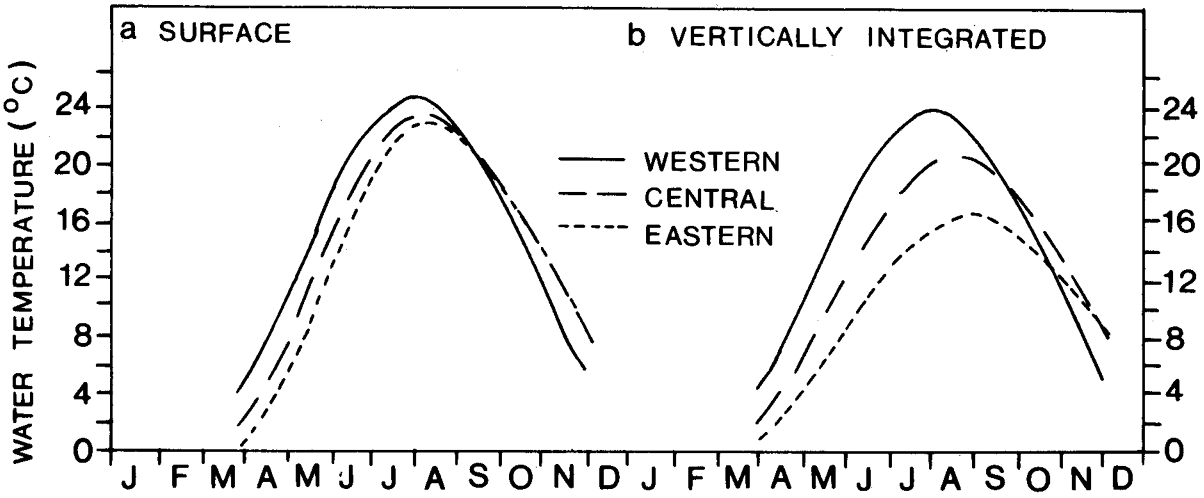

FIG. 2. Long-term mean seasonal cycle of surface temperature and vertically integrated temperature for Lake Erie basins in the period 1967 to 1982 (Lam et al. *1983).*

conditions throughout the year. Comparisons for the other deeper basins show substantial differences in the stratified period.

The difference in temperature between the water surface and the lake bottom can be substantial in the summer months and varies considerably over the lake basins. Figure 3 shows a summary of surface water temperatures and corresponding near-bottom temperatures compiled from surveys from 1960–1970 (Robertson 1973). Since the contours are based on averaged conditions over the lake, they do not show features specific to any particular year. Their utility lies in providing the expected temperature distribution for summer months over the lake. Generally, surface temperature increases progress from the shallower western basin to the east during the spring (April to June). Monthly mean temperature in the summer months (July to September) are rather uniform over the lake and temperature decreases quite rapidly in all portions of the lake in the period October and November. In contrast to the general uniformity of the monthly mean surface water temperature, the spatial distribution of the mean bottom temperatures, taken within 1 m of the bottom, are more complex.

The mean bottom temperatures in April show a similar spatial distribution compared to the surface. The mean temperature of the western basin is above 4°C in contrast to the other basins in which 4°C water exists only in the nearshore zones. Details of the progression of the thermal bar phenomenon in this April period are illustrated later. Bottom temperature values for the summertime period indicate that the western basin has the highest values. The central basin showed higher temperatures generally in the west portion of the basin and the eastern basin has lower average temperatures as a consequence of its greater depth which is particularly apparent in the temperature contours about the deepest section off Long Point.

Figure 4 illustrates characteristics of the bottom temperature of Lake Erie using selected locations within the deeper sections of each basin as indicated in Figure 3. These locations are used to provide examples of extreme differences between surface and near bottom temperatures (Fig. 4) and the seasonal distribution and range of values within each basin (Fig. 5). For the period April to November, the average monthly difference between surface and near-bottom temperatures are very small for the western basin, generally less than 1°C for most months, indicative of vertically mixed conditions. Maximum differences average approximately 9°C for the central basin and 15°C for the deepest location in the eastern basin. Figure 5 illustrates that extreme variability in the near-bottom temperatures can occur as illustrated in the July averages in the central and eastern basins.

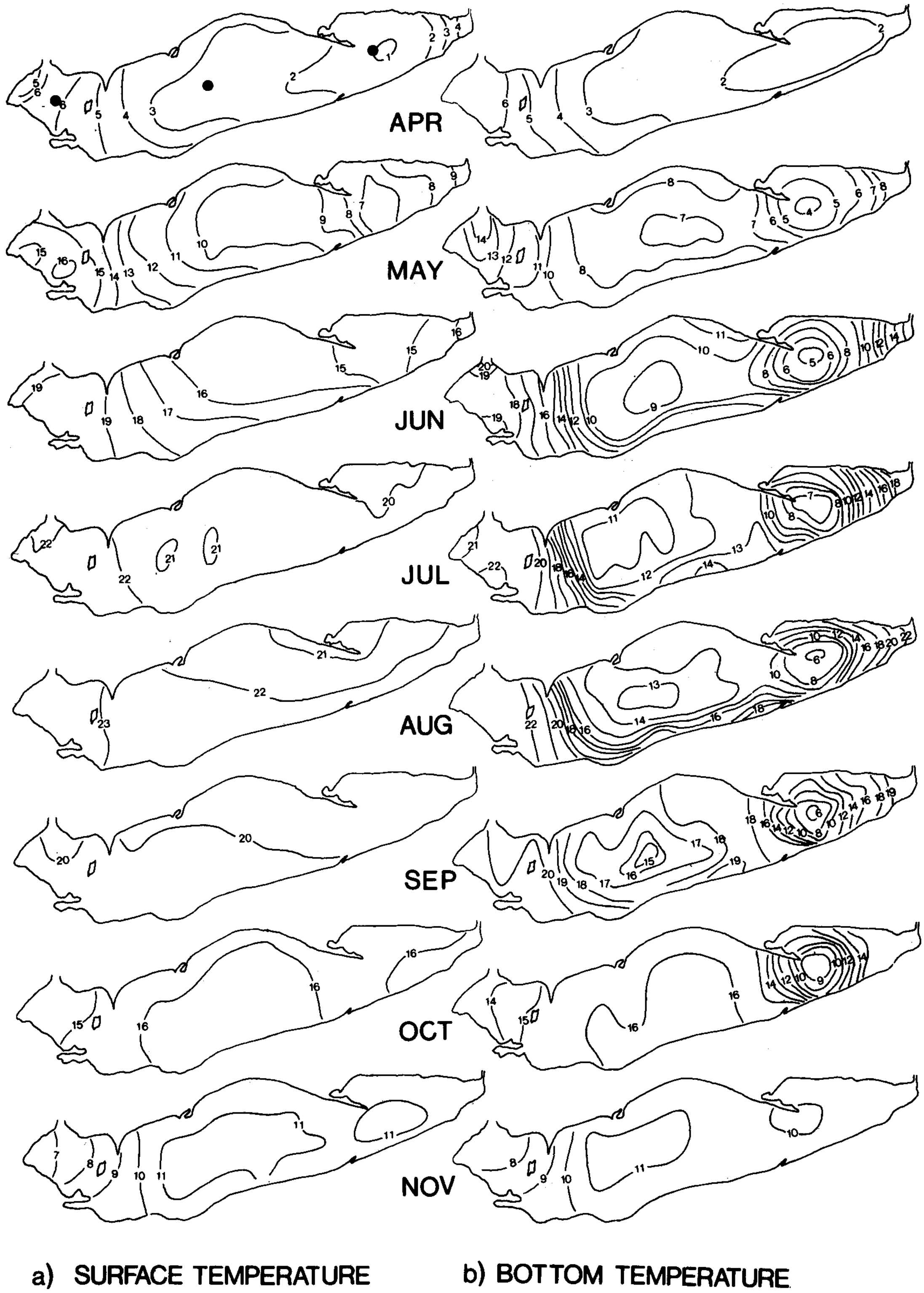

FIG. 3. Average spatial distribution of water surface temperature and near-bottom temperatures based on long-term lakewide temperature surveys. (●) selected mid-basin locations to illustrate differences in the surface and bottom temperature values (see Fig. 4) (Based on Robertson 1973).

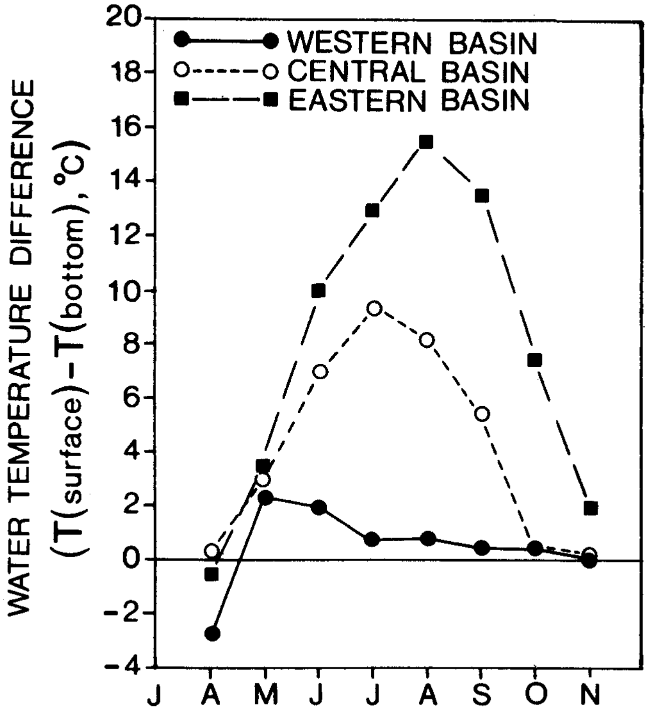

FIG. 4. Long-term monthly means of the average difference between surface and near bottom temperatures for selected deep water locations in Lake Erie basins (see Fig. 3) (based on Robertson 1973).

VERTICAL STRATIFICATION

Ice Cover

Figure 6 shows a summary of the normal ice cover distribution pattern and extremes for Lake Erie (Assel *et al.* 1983). In general, the western basin is usually completely ice covered during winter while the rest of the lake is often entirely covered by floe ice which is subject to movement in response to wind. Ice cover extends over 90 percent of Lake Erie's surface most winters and the ice cover variability is the largest of any of the five Great Lakes (Rondy 1969, Assel *et al.* 1983). Ice cover concentration varies from conditions of open water to 90 to 100 percent concentration. Based on composite ice charts compiled by DeWitt *et al.* (1980) and by Ice Central (1984), Figure 6 illustrates the seasonal ice cover for the winter 1978–79 and 1979–80 in comparison to the long-term conditions. The ice conditions during these winters were greater than normal. In late winter/early spring, wind can cause considerable rafting of ice cover in the eastern end of the lake resulting in rafted ice that lasts past the end of April and into May some years (Assel *et al.* 1983).

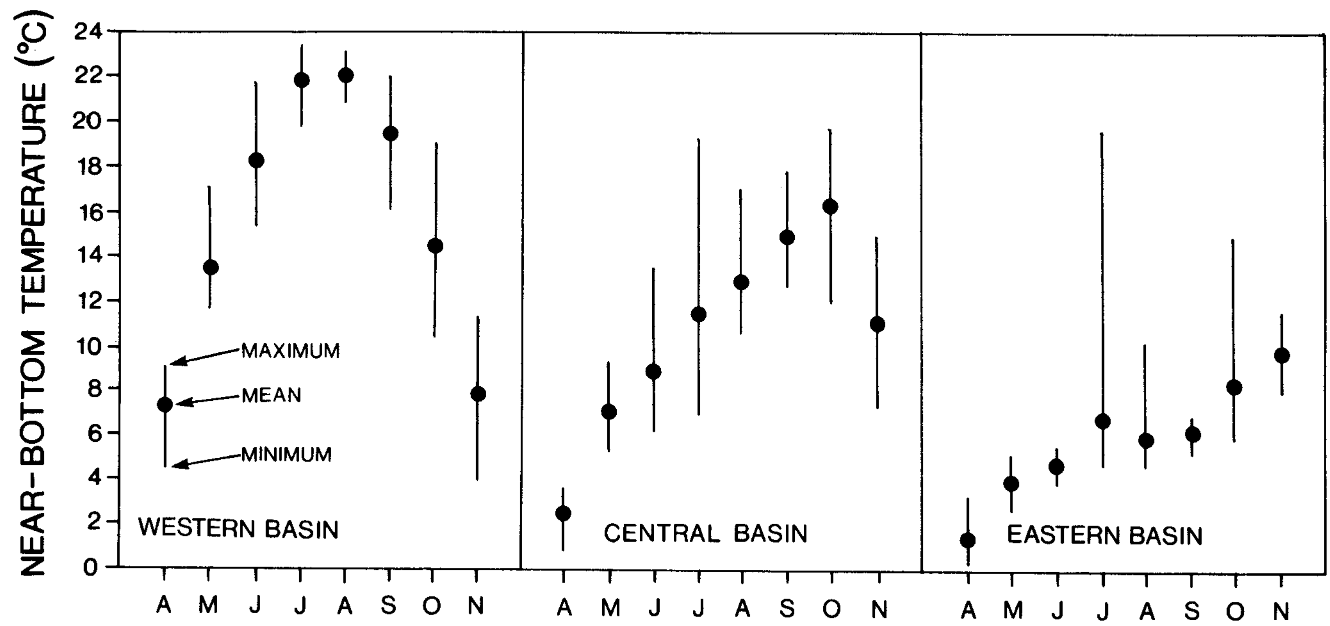

FIG. 5. Long-term averaged seasonal cycle and range of near-bottom temperatures at selected mid-lake stations in Lake Erie (see Fig. 3).

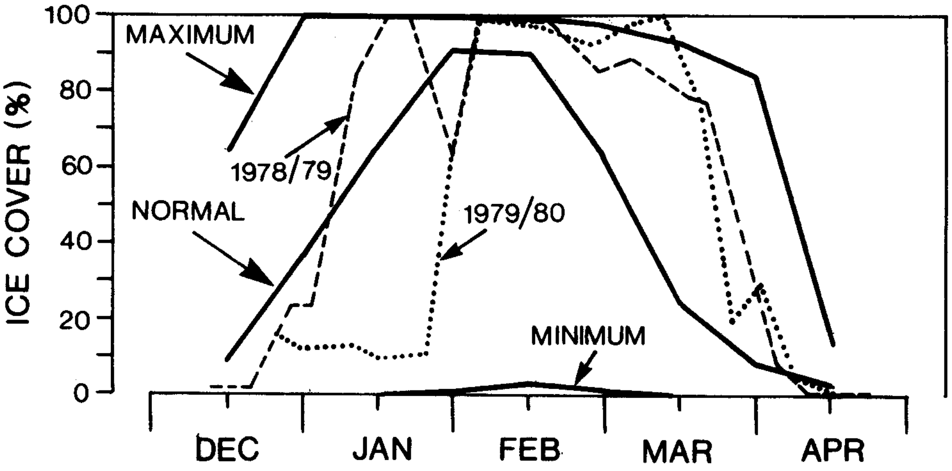

FIG. 6. Normal ice cover distribution pattern and extremes for Lake Erie (Assel et al. *1983).*

Winter Temperature

During the early winter, the lake approaches minimum temperatures in response to large heat losses at the surface and substantial vertical mixing due to high winds (Schertzer 1987). Minimum water temperatures are attained at various times for each basin as indicated in Figure 2. The lakewide minimum surface temperature usually occurs in February (0.1°C) (Jones and Meredith 1972) but fully-mixed conditions at 1°C or less probably occur in January prior to significant ice cover.

Vertical temperature distributions in the winter period have been analysed only in one whole-lake systematic study (Stewart 1973), using a helicopter. In winter, a reverse but weak stratification may occur because water at 4°C is at maximum density and tends to sink to the lake bottom. Stewart (1973) suggested the lake is isothermal or nearly isothermal at 0.1°C or less from mid-February to mid-March. In mild winters, the open-water areas are exposed to wind action which keeps the water column fully mixed in contrast to the weakly stratified condition which develops under complete ice cover.

Spring Temperature

Figure 7 illustrates basinwide averaged temperature profiles for central and eastern basins in 1979 from April to October. These profiles have been derived as depth-averaged values of station observations. In 1979, the western basin was not sampled; however, as indicated in Figure 2, this basin heats and cools at a faster rate compared to the rest of the lake and remains essentially isothermal throughout the year.

During the spring months, a significant heating of the lake occurs as a result of the increased solar radiation (Schertzer 1987). The average temperature profiles in the first cruise (24–26 April show essentially isothermal conditions at (3.5°C) for the central basin and (1.7°C) for the eastern basin. In the period April (cruise #1) to the end of July (cruise #5) basin temperatures steadily increase at all depths. In May, the eastern basin has increased in temperature but remains essentially isothermal while the central basin has undergone significant heat gains. The thermal stratification in this month is weak and is easily perturbed by wind events at the surface. Permanent stratification usually begins in mid-June for the central basin, however, the third cruise from 10–14 June does not show a well-defined thermal stratification. Details of the meteorological events in June are discussed later for specific locations in the central basin in which isotherm plots clearly show a disruption of the thermal stratification in this month. Eastern basin heat gains are evident in June also, with a relatively large temperature gradient between the surface and at 15 m depth.

Summer Temperature

Stratification is firmly established in the central and eastern basins by the fourth cruise in July. Depth-averaged epilimnion depths for the central

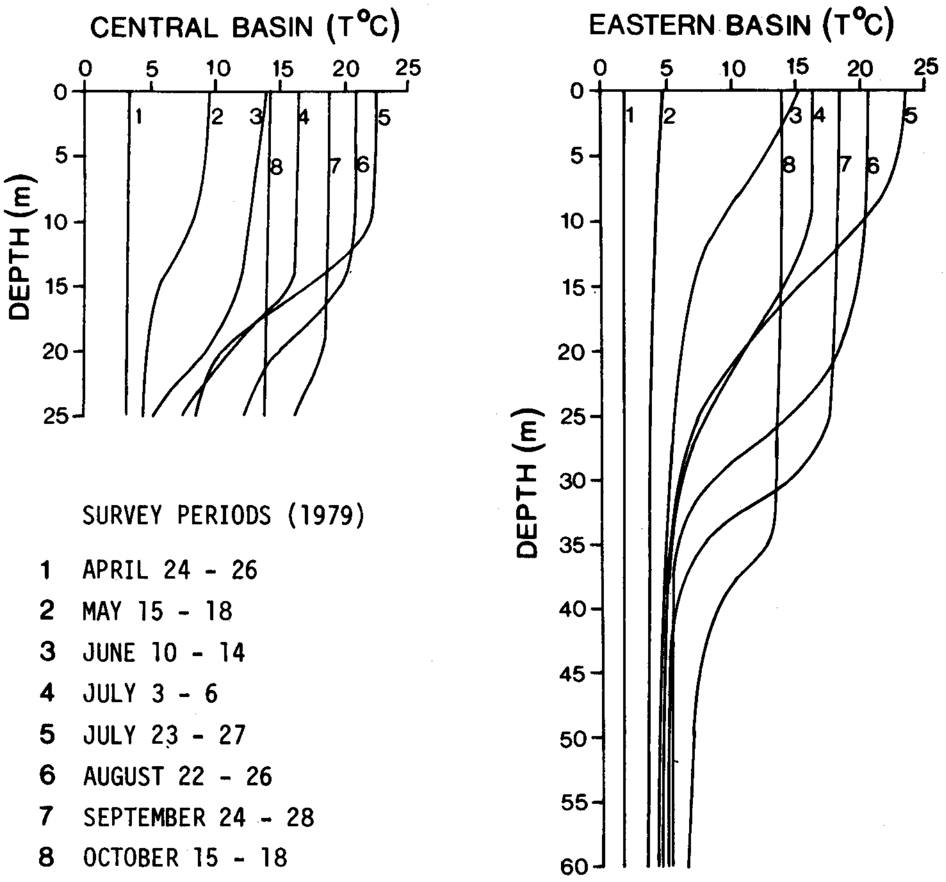

FIG. 7. Basinwide depth-averaged vertical temperature profiles for the central and eastern basins of Lake Erie for lakewide temperature surveys during 1979.

basin average approximately 15 m in the beginning of July. Similar responses are seen in the eastern basin in which the upper mixed layer depth of 10 m in early July is reduced to approximately 5 m at the end of July in response to meteorological forcing. Maximum heat storage generally occurs in mid-August (Schertzer 1987) and, as indicated in the 22 to 26 August survey, average temperatures in the upper layers of both the central and eastern basins are decreasing in response to decreased surface heating and greater heat losses through the surface to the atmosphere.

Fall Temperature

Increased overlake winds during the fall months generally contribute to deepening of the upper mixed layer. Average temperature profiles for the central basin 24 to 28 September indicate nearly uniform surface to bottom temperature. By the last survey from 15 to 18 October, the central basin is isothermal and the eastern basin rapidly approaches an isothermal condition. Further heat losses result in a uniform lowering of temperature in each basin and, by mid-December, Lake Erie continues to approach minimum temperatures thus completing the annual cycle.

THERMAL BAR

The stratification cycle also occurs laterally. The thermal bar described by Rodgers (1965) is a consequence of the anomalous temperature-density relationship of water around 4°C. The thermal bar first forms along the lake's perimeter at a surface temperature of nearly 4°C. As the heating of the nearshore water proceeds, the bar advances off-shore, leaving behind a weakly stratified nearshore water mass. The thermal bar marks the onset of summer stratification in deep temperate lakes. The thermal bar advances toward the center of the lake as heating progresses and when the central portion reaches 4°C the thermal bar disappears. In deep lakes such as Lake Ontario, Lake Huron, and Lake Michigan, this process takes as much as 6 to 8 weeks. Typically, summer stratification is achieved as the surface waters reach greater than 4°C over the entire lake and the heavier 4°C water sinks underneath.

Temperature surveys undertaken in 1979 and 1980 are not frequent enough nor have station densities sufficient to determine the spatial progression of the thermal bar phenomenon over the entire lake. However, 1984 satellite observations of surface temperatures in the Great Lakes have been processed (AES 1984) and allow a description of the process. Figure 8 illustrates surface water temperatures for Lake Erie in the early spring months beginning in April and ending in May at a frequency giving good spatial and temporal resolution. Since the diagrams of Figure 8 refer to a specific year, the timing of the thermal bar's advance can only be compared qualitatively for other years; however, the general pattern of warming should be valid.

At the beginning of April the surface waters are generally below the temperature of maximum density except for the western basin in which the shallow embayments along the west and southwest shorelines have temperatures of 5 to 6°C and the 4°C isotherm is evident in this region. By 10 April, 4°C water in the central and eastern basins of Lake Erie occurs only along the shallower north shore in the region between Pte aux Pins and Port Burwell and to the east of Long Point. Rapid heating of the western basin is apparent as nearly half of the basin is above 4°C as the thermal bar in this region progresses from west to east. By 25 April, any trace of the thermal bar has disappeared in the western basin in which the surface temperatures range from 8°C in the northeast quadrant to 16°C in isolated areas in the south of the basin. Since satellite data are referenced to a specified hour in the day, actual daily averaged temperatures may vary slightly from the diagram in Figure 8. By April the 4°C isotherm in Lake Erie slowly advances to the mid-lake of the central basin with some isolated and transient patchiness of 4°C water. By mid-May, the thermal bar has essentially disappeared.

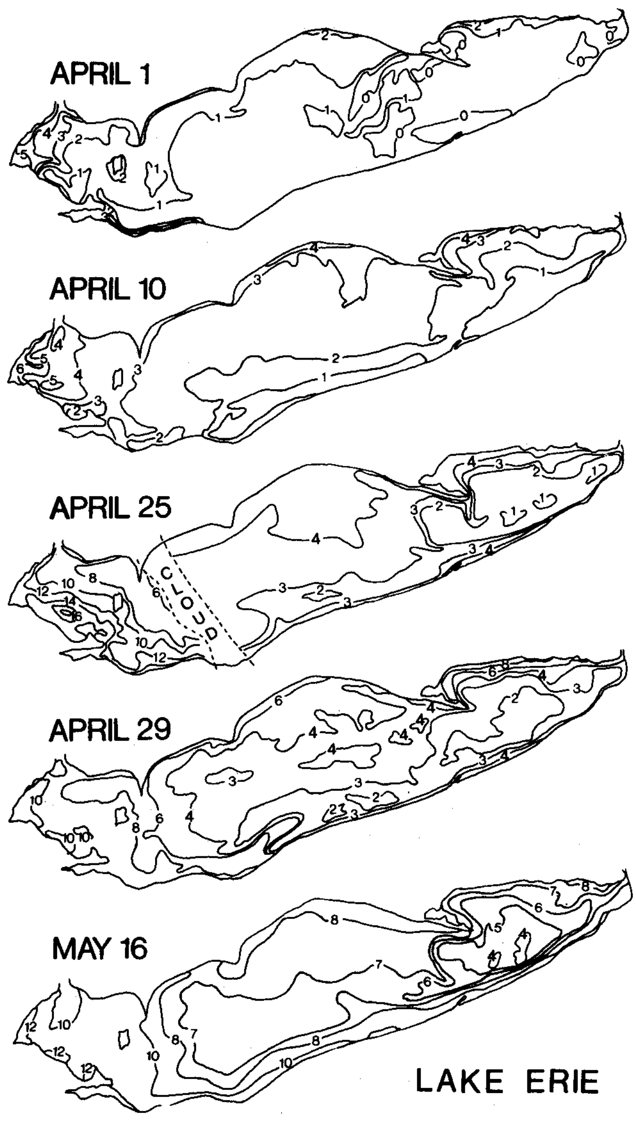

FIG. 8. Satellite observation of surface water temperatures (°C) of Lake Erie and Lake Ontario during 1984 depicting the spatial distribution of temperature and the progression of the thermal bar as illustrated by the 4°C isotherm (AES 1984).

THERMOCLINE POSITION

Analysis of the thermal structure in Lake Erie, especially for the central basin, has application in studies related to interpreting the dynamics of hypolimnion oxygen depletion (Charlton 1980, Lam *et al.* 1983). Determination of the average depth of the thermal interfaces separating the epilimnion, mesolimnion, and hypolimnion can be approached from consideration of observations

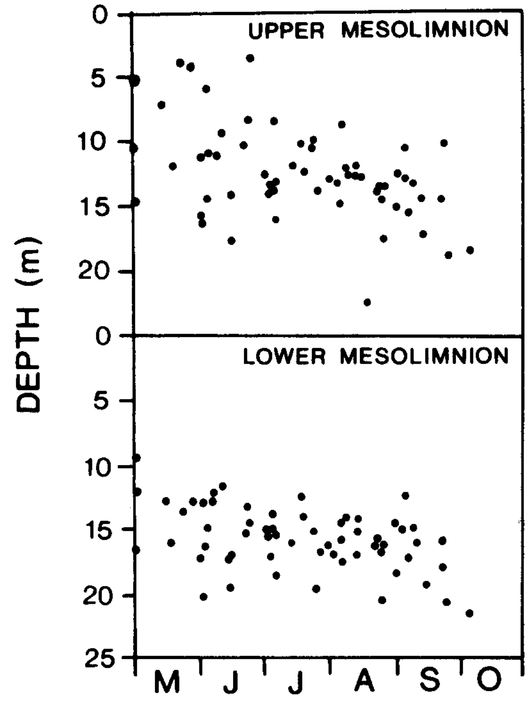

FIG. 9. Long-term variability of the central basin depth of the upper and lower mesolimnion interface based on arithmetic means of station values during temperature surveys from 1970 to 1981.

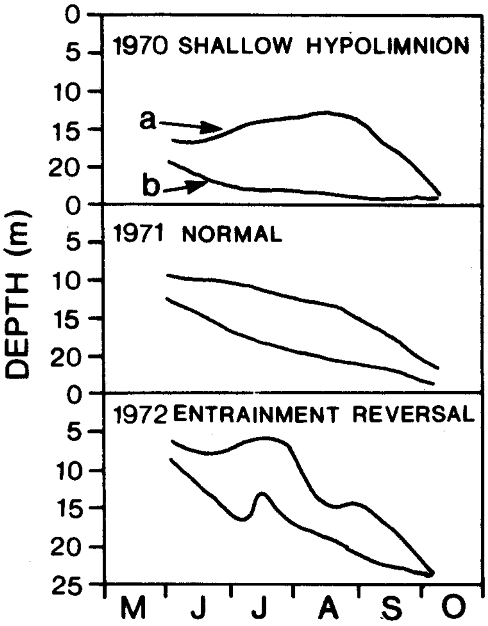

FIG. 10. Examples of identified weather-induced thermocline positions in the central basin based on vertical temperature simulations (Lam and Schertzer 1984), in which (a) represents the top of the mesolimnion and (b) represents the bottom of the mesolimnion.

(Rosa 1984) or from objective analysis based on simulation of the central basin thermal structure (Lam and Schertzer 1987).

Based on temperature profiles, determined by electronic bathythermograph, over a variable grid of stations during the stratified season in the years 1970 to 1981, the depth of the top and bottom of the mesolimnion for each observation site could be subjectively determined (Rosa 1984). An arithmetic mean of station values is derived to delimit the average depth of the thermal layer interfaces for each survey. A summary of central basin survey results from 1970 to 1981 (Fig. 9) illustrates the range of average depth of the upper mesolimnion and lower mesolimnion interfaces, indicating a much wider range in the upper mesolimnion interface depth compared to the lower mesolimnion boundary. A significant aspect of the central basin thermal structure indicated in Figure 9 is that the central basin develops a thermal structure in which the average depth of the upper and lower interfaces of the thermocline layer can vary significantly from year to year. For any particular period during the stratified season, the range in either interface depth can be as large as 10 m. Consequently, analyses of such processes as the dynamics of hypolimnion anoxia, which is dependent on accurate representations of the average thermal layers, requires careful determination of the vertical temperature distribution.

Vertical temperature profiles for the central basin were simulated (Lam and Schertzer 1987) based on meteorological observations in the period 1967 to 1982 (Schertzer 1987). An objective analysis (Papadakis 1981) was used to determine the depths of the layer interfaces defining the thermocline and results were verified against observations (Lam *et al* 1983). The analysis reveals three basic classifications for the observed thermal structure of the central basin illustrated in examples for 1970, 1971, and 1972 in Figure 10. Years in which there is a rapid initial lowering of the thermocline which stabilizes deep in the water column throughout the stratification period (1970) are classified as 'shallow hypolimnion." A situation in which an initial stratification is perturbed by a substantial upward movement of the thermal layers during the stratification period is termed "reverse entrainment" as illustrated in 1972. Intermediate between these two extremes are structures in which there is

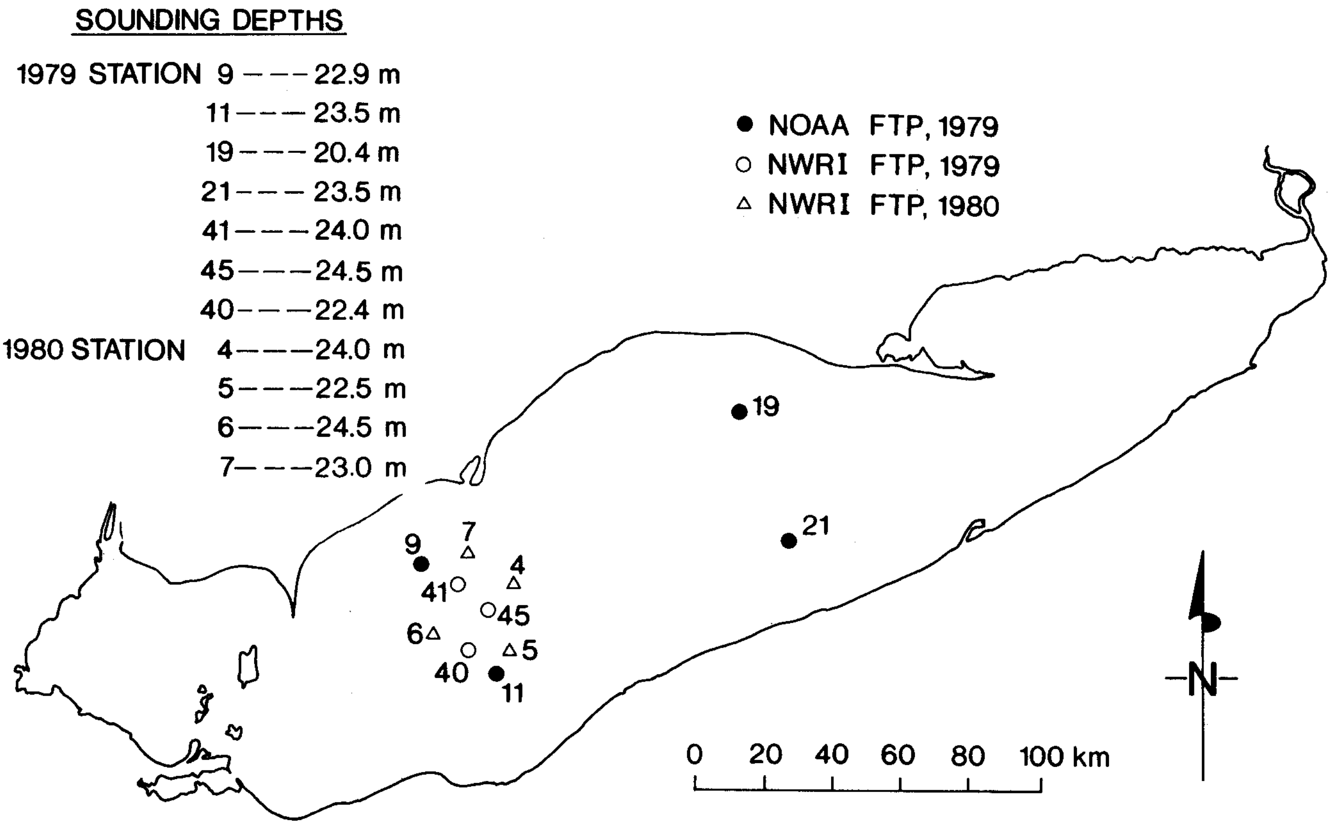

FIG. 11. Location of thermistor chain moorings in the central basin of Lake Erie for 1979 and 1980.

a gradual deepening of the thermocline throughout the stratification cycle considered as "normal" as depicted in 1971. Detailed discussion of the simulation of the vertical thermal structure is given in Lam and Schertzer (1987).

THERMAL STRUCTURE DURING 1979 and 1980

1979 Isotherms

The development and decay of temperature stratification in the central basin was recorded at an array of stations from May to September in 1979 and from July to the beginning of September in 1980 (Fig. 11). The measurements allow comparison of the thermal structure from the large-scale grid of stations 9, 11, 19, and 21 (Saylor and Miller 1983) with observations from a localized area within the western portion of the basin represented by stations 41, 45, and 40 (Boyce 1980). In 1980 temperature was observed in the western portion of the central basin at stations 4, 5, 6, and 7 only (Boyce 1980). Sounding depths for each station are indicated in Figure 11 and vary from 20.4 m in the northwest of the basin at station 19 to a maximum of 24.5 m at station 45.

Description of the fixed temperature profile (FTP) moorings are given in Saylor and Miller (1983) for the large-scale grid stations and in Healy *et al.* (1979) and Mawhinney (1980) for stations within the small scale grid. In general the two systems are similar and compatible. Thermistors were spaced approximately 2 m apart over the length of the thermistor chain. Temperature records are assumed to have an accuracy of the order $\pm$ 0.1°C. Data return in 1979 and 1980 averaged greater than 90 percent.

The plotted isotherms show a well-defined response to surface meteorological forcing. Based on wind speed from six meteorological buoys deployed by NWRI, Schwab (1982) computed an hourly average wind stress vector for 1979. Similar computations are provided for 1980 (Hamblin 1987). These data are included with isotherm plots

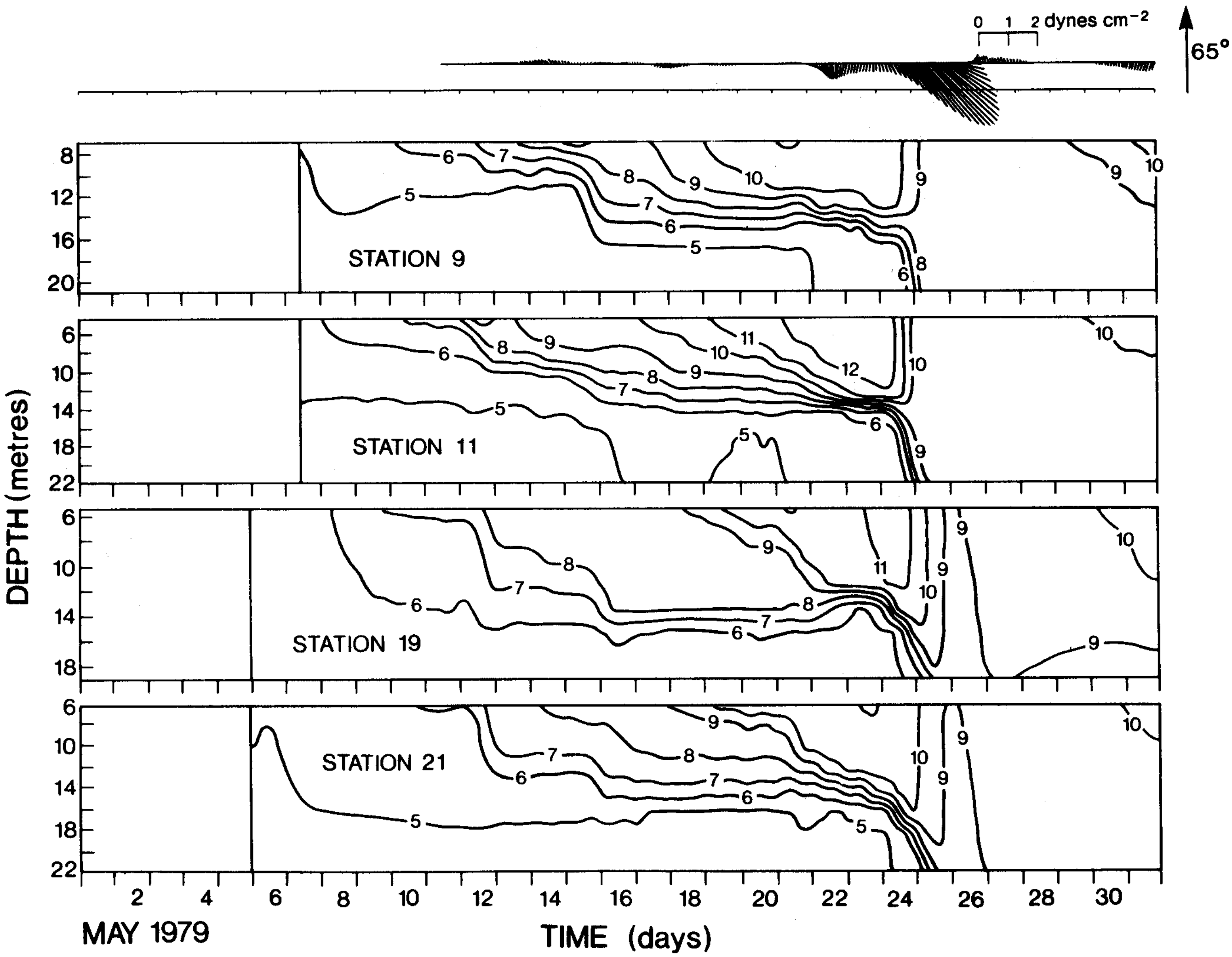

FIG. 12. Isotherms (°C) drawn from the thermistor chain recordings at moorings in the central basin of Lake Erie for May 1979 with low-pass filtered wind stress vectors.

in Figures 11 to 18 to illustrate the correspondence between major wind events and isotherm response. Wind stress vectors are rotated so that the vertical axis aligns with the longitudinal axis of the lake (65°), that is, positive toward the east-northeast. Isotherms are low-pass filtered (Graham 1963).

May 1979 (Fig. 12) reveals a sequence of warming in the central basin in which the developing weak stratification is disrupted by storms. Isotherms show an almost month-long steady increase in surface layer warming, starting from water nearly isothermal throughout the basin at about 5°C. A fragile stability gradually developed as surface water warmed. Moderate wind impulses on 12 and 16 May at less than 0.5 dynes/cm² produced some upper layer deepening but the stratification process ended abruptly with a wind storm that began on 24 May. Intense winds from the north-northeast quickly mixed the whole central basin water mass. The computed wind stresses for the interval show that this was the most intense storm of the 1979 stratified season, with the stress approaching 3 dynes/cm² at the peak of the 3-day-long episode. Currents measured in the lake during this period (Saylor and Miller 1987) are typical of those observed with strong winds transverse to the lake's major axis, i.e., basically return flow at 10 m

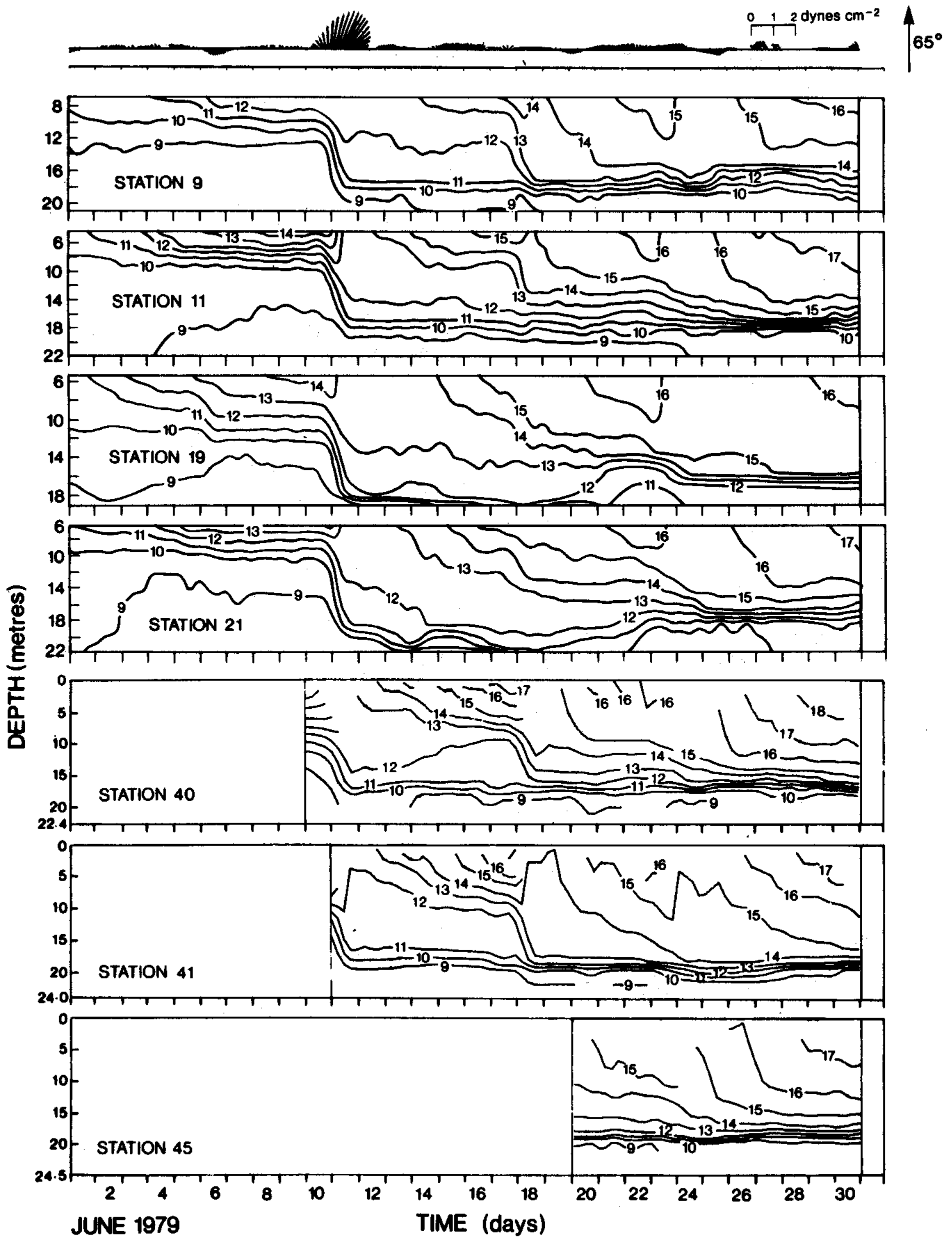

FIG. 13. Same as Figure 12 but for June 1979.

depth and below against the wind stress but with and driven by the surface pressure gradient.

June 1979 (Fig. 13) was a month for rebuilding the thermocline and for establishing stable stratification. The major wind events of the month of the 10th, 11th, 18th, 23rd, and 24th resulted in upper layer mixing and thermocline deepening evident over the whole basin. The process continued into July (Fig. 14) in which wind stresses from the first through the fifth cause a nearly isothermal surface layer to form above a distinct thermocline particularly noticeable in the first half of the month. Continued surface heating and light winds through the remainder of July produced a varied temperature structure throughout the basin. At stations 9, 11, 40, 41, and 45 the initially sharp thermoclines of average thicknesses of 3 m in the first half of the month become thicker with temperature gradients

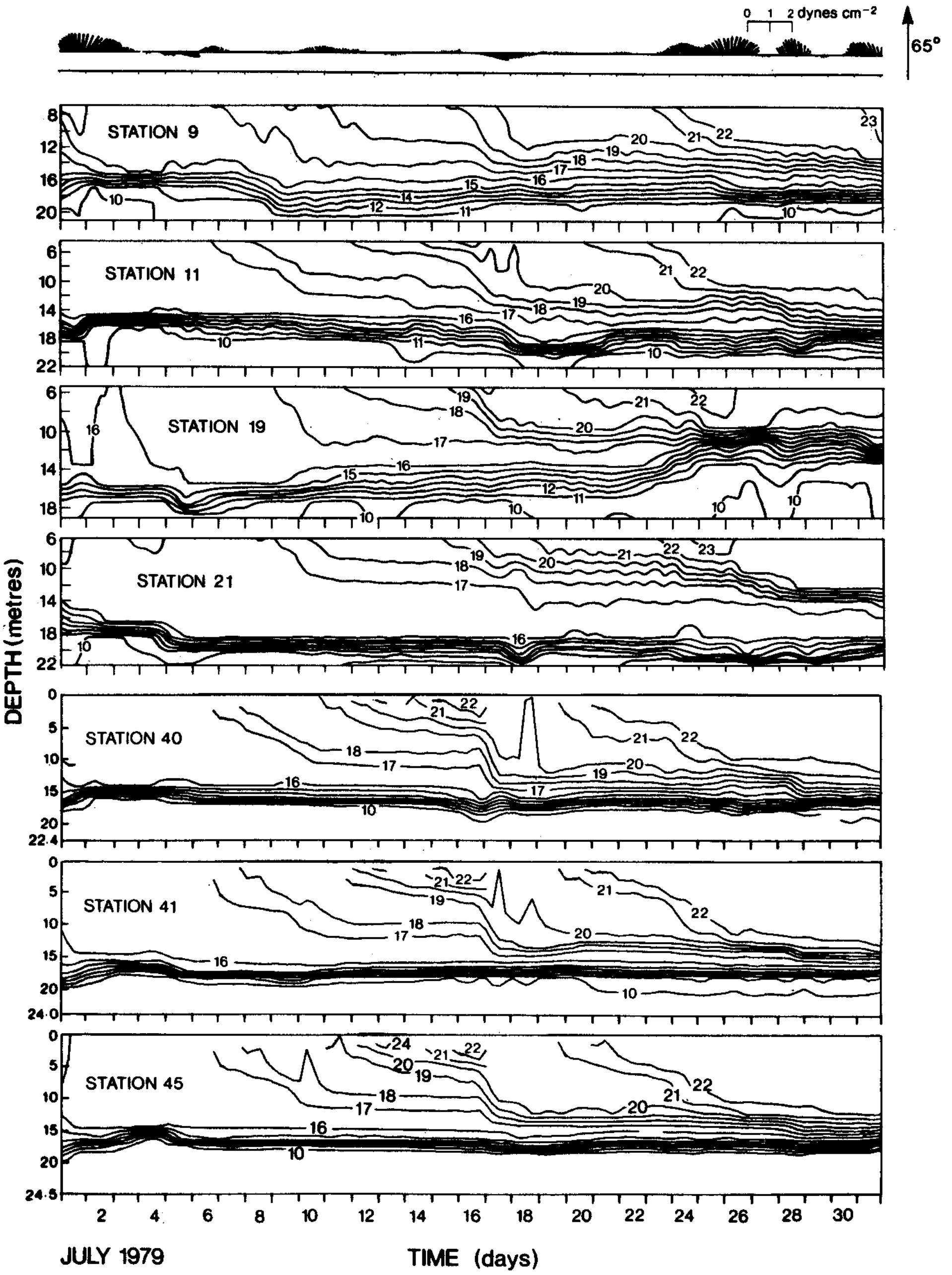

FIG. 14. Same as Figure 12 but for July 1979.

of about 1.3°C m^{-1} with moderate temperature gradients in the lower half of the water column. Stations 40, 41, and 45 show a sharp thermocline about 5 m thick essentially fixed at 15 to 20 m depth which is not evident in the isotherms at the other stations.

At station 19 (Fig. 14) a vertical profile resembling a double thermocline evolved in mid-July that by month's end merged into a thick thermocline with moderate temperature gradients. The biggest difference at station 19 compared to other stations of similar temperature structure was that this layer was pushed up higher in the water column. Based on evidence from earlier studies

(Boyce *et al.* 1980, Chiocchio 1982) and the current meter record at station 19 (see Saylor and Miller 1987), an influx of hypolimnetic water from the Pennsylvania Ridge (Fig. 1), directed northwest to the region of station 19 in the period 21 to 25 July, is considered responsible for this occurrence. Also in July, station 21 showed the clear development of a double thermocline that persisted until a wind storm on 2 August caused its disappearance; the mixing process elevated the lower thermocline and submerged the upper. In the same period, there was a process of hypolimnetic entrainment in the sector between thermistor chains 9 and 11, wherein the hypolimnetic volume and temperature which increased as a thick thermocline layer in the beginning of July was compressed to a thin layer of stronger temperature gradients (Ivey and Boyce 1982). In the transition, the lower layer captured a part of the water formerly in the thermocline. The significance of measurements such as these is that details of this type of thermal structure are not evident from smoothed basinwide depth-averaged profiles as shown in Figure 7.

August 1979 (Fig. 15) was a month of intensifying thermocline gradients coupled with upper layer deepening and clear definition of a hypolimnetic layer 3 to 6 meters thick. Major wind stress impulses during the month are observed and contribute to temperature gradients in the thermocline as high as 6°C m^{-1}. In August, station 45 shows the clear evidence of entrainment of mesolimnion water into the hypolimnion (Ivey and Boyce 1982) which is discussed in detail in Saylor and Miller (1987).

In consideration of the thermistor data on the larger scale grid, the thermocline tilts downward to the south but not greatly so, the southerly stations 11 and 21 showing an average difference of 1 to 2 meters deeper for the month. Monthly temperature averages from current meters at 10 m depth (Saylor and Miller 1987) shows cooler water during July and August along the north shore which supports the thermistor observations. Larger tilts were recorded by Blanton and Winklhofer (1972). At stations 41, 45, and 40 no significant tilt to the thermocline is observed in this month. Whereas stations 45 and 40 show sharp thermocline gradients at about 20 m depth in the latter half of the month similar to the observations at station 11, the isotherms at station 41 show a more moderate thermocline temperature gradient after the high wind stress events at mid-month. The thermistor chain in the shallowest water at station 19 (20.4 m) revealed the weakest stratification. The pulse of bottom water cooling and thermal gradient relaxation here that started on 21–22 August again appeared correlated with a large volume pulse in inflow from the eastern basin across the Pennsylvania Ridge from 17–20 August (Saylor and Miller 1987). By 31 August stratification was rapidly weakening in the northeastern part of the central basin (station 19) where near bottom temperatures were already in excess of 14°C.

September isotherm plots (Fig. 16) document the end of the 1979 central basin stratification. Unfortunately, the temperature record at station 19 at the northeast of the basin ended at the end of August due to malfunction and no September data were recovered. In the southeast (station 21) the hypolimnion was eradicated on 11 September in response to wind-driven mixing associated with the wind stress impulse on that and the previous day. The hypolimnion in the western portion of the basin survived the wind storm on 10 to 12 September but succumbed to the stress in the period 18 to 22 September. The hypolimnion at stations 9 and 11 have essentially disappeared by 19 September while it persists until 21 September at stations 40 and 41. The FTP at the deepest location, station 45, began giving poor data on 16 September (Healey *et al.* 1979), likely a few days before isothermal conditions would have been observed here also. From 22 September onward the central basin was essentially isothermal, with major cooling events evoking in phase vertical temperature reduction such as occurred on 22 September.

1980 Isotherms

Plots of isotherms (Figs. 17 and 18) were constructed from temperature observations in the vicinity of the small-scale grid location (Fig. 11) for the period mid-July through August 1980. Low-pass filtered wind stress vectors were derived to coincide with the temperature observations (Hamblin 1987) and are illustrated in the figures.

Isotherm plots in the latter half of July 1980 during which wind speeds are relatively low (Fig. 17) show a relatively thick thermocline layer at all stations. At stations 4, 5, and 7 the epilimnion layer extends to approximately 10 meters depth and at all stations the top of the hypolimnion is located approximately 18 to 20 meters from the surface. Particularly noticeable in the isotherm plots of July 1980 is the presence of double thermocline formations at stations 6 and 7. The ther-

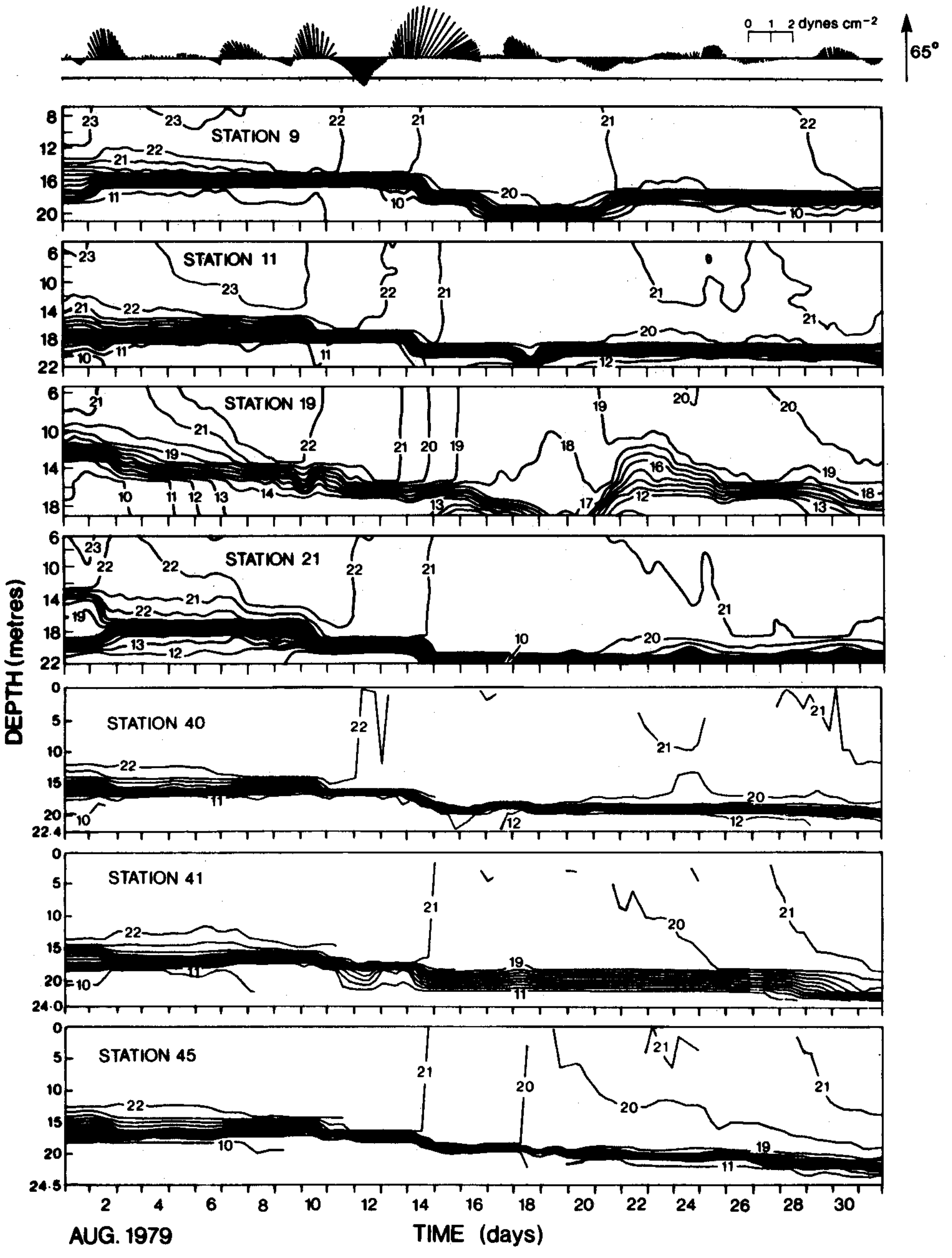

FIG. 15. Same as Figure 12 but for August 1979.

mal structure at all stations persists from mid-July to the first few days of August.

During the first half of August 1980 (Fig. 18), the relatively thick thermoclines observed at all stations during July 1980 undergo a process of downward entrainment of mesolimnion water into the hypolimnion. At all stations near mid-August, the hypolimnion volumes increase, and the thermocline layer is compressed to approximately a 2 to 3 meter thickness showing very steep temperature gradients of about 6 C° m^{-1}. In the period 15 August onward, wind speeds are very low and well defined sharp thermocline layers persist at all stations, ranging from 12 to 16 meters depth from the

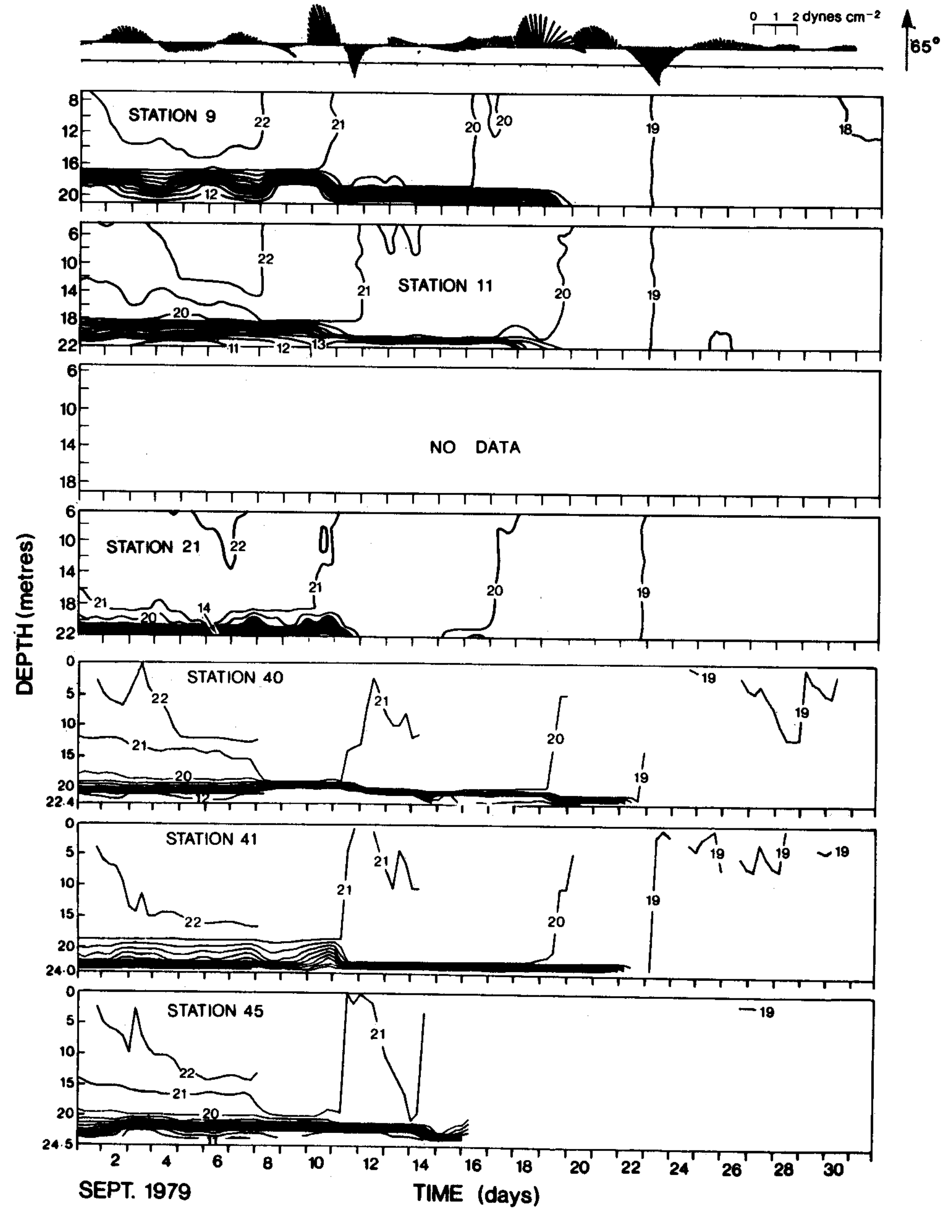

FIG. 16. Same as Figure 12 but for September 1979.

surface, which is substantially higher in the water column in comparison to 1979.

SUMMARY

Characteristics of the seasonal temperature cycle in Lake Erie were described based on long-term data and for specific locations during the 1979 and 1980 stratification season. The surface water temperature and vertically integrated water temperature vary significantly from one basin to another and are related to heat storage and bathymetry. Spatial and temporal characteristics of the average surface and bottom temperatures were illustrated, showing the general progression of temperature increases and decreases. Surface and bottom temperature

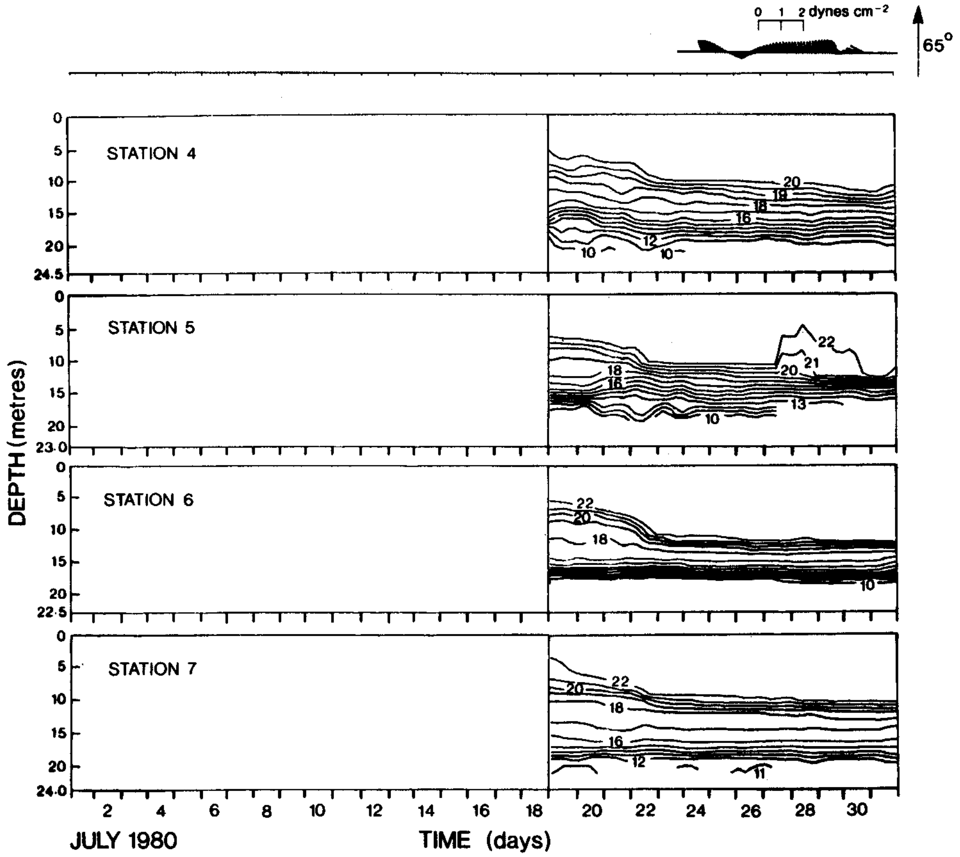

FIG. 17. Same as Figure 12 but for July 1980.

differences from one year to another can show extreme variability in each basin. Lake Erie shows variation in ice cover extent and, during the winters of 1978–79 and 1979–80, experienced greater than normal ice cover. In comparison to Lake Ontario, the thermal bar progresses over the whole lake much faster and is related to the bathymetry. The upper and lower interface depths of the thermocline layer are seen to be highly variable and respond to meteorological forcing. Model simulations of basinwide depth-averaged profiles showed at least three general weather-induced thermal structure classifications: normal, reverse entrainment, and shallow hypolimnion.

Water temperature recordings which were made with thermistor chains at an array of stations in 1979 and 1980 over the central basin documented the complete development of stratification and the squeezing down of the thermocline to form a very thin thermocline. Some general characteristics were observed, as follows. In the early stages of stratification, a fragile stability that slowly evolves in this shallow basin is very susceptible to strong wind impulses. In 1979, a storm in late May with relatively high wind caused the complete mixing of the central basin water mass. It took several weeks to regain the lost stability. These physical events shorten the season of stratification and make it less likely that the hypolimnion layer will develop anoxia. In the eastern part of the central basin the formation of a double thermocline was observed in 1979 and persisted for several weeks. Its eventual decay seemed coupled with hypolimnion volume entrainment (growth) from the thermocline layer, in the manner described by Ivey and Boyce (1982). Similar downward entrainment into the hypolimnion was observed in 1980. Thermocline tilting to the south was also observed in 1980. Thermocline tilting to the south was also observed to occur but was not as great as that reported by Blanton and

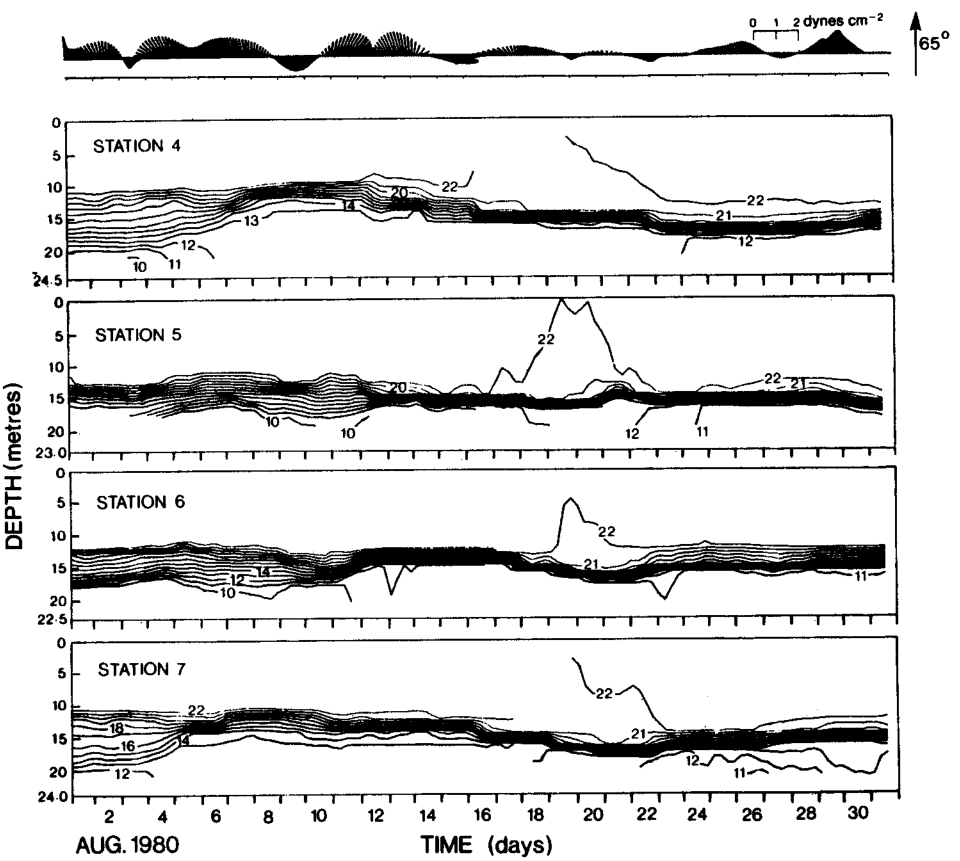

FIG. 18. Same as Figure 12 but for August 1980.

Winklhofer (1972). The dissolution of the hypolimnion appears to occur first in the eastern parts of the basin, in response to wind stress mixing and bottom layer advection.

ACKNOWLEDGMENTS

The authors wish to acknowledge their appreciation to G. Irbe (AES) for use of the satellite data, to G. Leshkevich (GLERL) for supplying information on ice conditions in Lake Erie, and to D. Schwab and P. Hamblin for providing basin averaged wind stress. The efforts undertaken by J. Bull (NWRI) for deriving filtered time series of water temperature and the drafting of J. Van Nynatten are greatly appreciated.

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