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FALL AND WINTER THERMAL STRUCTURE OF LAKE SUPERIOR

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ABSTRACT. Temperature surveys were made along the normal upbound (westward) and downbound (eastward) shipping lanes across Lake Superior to document fall and winter thermal structure of that lake. This work was done as part of the Congressionally-funded Demonstration Program to Extend the Navigation Season on the Great Lakes and the St. Lawrence Seaway. Surveys were made aboard ore carriers using a portable bathythermograph (BT) system and expendable BT probes. Surveys usually took 2 to 4 days to complete. Twenty-one surveys were made during the winters of 1973 to 1976 and 25 surveys were made during the falls of 1976 to 1979. Mean seasonal temperature trends identified from these data include: (1) approximately exponential increase in fall mixed layer depth through early to mid-November, (2) maximum value of average mixed layer and upper 25-m layer temperatures between the end of August and mid-September, (3) maximum value of average water column temperature in late September, (4) isothermal conditions between mid-November and mid-December, (5) completion of fall overturn in December and winter restratification in December or January depending primarily upon winds, (6) average winter [January to March] monthly mixed layer depth between 60 m and 100 m and, (7) minimum value of average water column temperature in late March. Midlake and nearshore thermal regimes were identified. These thermal regimes show agreement in trend with lake bathymetry, wind fetch, and lake circulation patterns. Deeper areas with longer wind fetch in both thermal regimes have the deepest mixed layers during winter. Areas having the combination of greater depth and larger wind fetch, midlake areas in most cases, also tend to have higher column temperatures and ice cover of short duration in winter and lower column temperatures in summer relative to adjacent areas.
ADDITIONAL INDEX WORDS: Water temperature, thermal stratification, ice cover, ice formation.

INTRODUCTION

Lake Superior has a volume of 12,230 km^3 and a surface area of 82,100 km^2, giving it a mean depth of 149 m. It is divided into eastern and western basins by the Keweenaw Peninsula and a prominent subsurface ridge parallel to and extending from the Keweenaw Peninsula (Fig. 1). The length of the lake is 563 km in an east-to-west direction, while its breadth is 257 km in the eastern basin and only 115 km in the western basin. Winter winds usually have a westerly component at the western end of the lake and an easterly component at the eastern end of the lake (U.S. Department of Commerce 1959); this is in agreement with the general cyclonic circulation pattern along the lake perimeter. Niedringhaus (1966) attributed the winter wind pattern partly to land-water temperature differences. In winter, winds are usually from the cold land to the relatively warm lake waters.

Surface water temperatures have been documented by Millar (1952), Richards *et al.* (1969), Irbe (1972), and Feit and Goldenberg (1976), and the thermal structure of the lake at depth has been investigated by Smith and Ragotzkie (1971), Smith (1972), Hubbard and Spain (1973), Ragotzkie and Niebauer (1975), Spain *et al.* (1976), Bennett (1978), and others, but most of these investigations were made in the spring and summer. In this paper the fall and winter thermal structures of Lake Superior are investigated. Data collection and analysis methods are presented and seasonal comparisons, general seasonal trends, and spatial

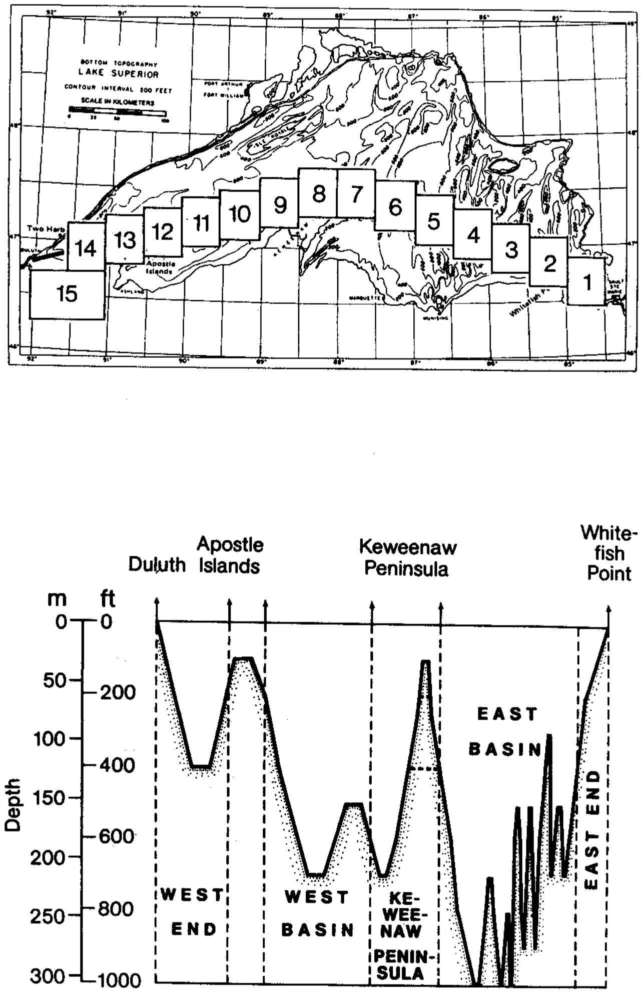

*FIG. 1. **Bottom topography and location of 15 discrete areas along the survey route used in spatial analysis of thermal structure.***

trends in midlake and nearshore thermal regimes are discussed.

DATA COLLECTION

Temperature surveys were made along an east-to-west transect of Lake Superior as part of the Congressionally-funded Demonstration Program to Extend the Navigation Season on the Great Lakes and St. Lawrence Seaway (see U.S. Army Corps of Engineers 1979). A portable bathythermograph (BT) recording system using expendable BT probes was used aboard U.S. Steel Corporation ore carriers to obtain temperature profiles to a depth of 200 m between Sault Ste. Marie, Michigan, and Duluth or Two Harbors, Minnesota. Temperature accuracy of this system is ± 0.2 C° and depth accuracy is ± 2 percent of depth or 4.57 m, whichever is greater. Surveys normally took 2 to 4 days to complete as half the lake was sampled in each of two consecutive transects along the normal upbound (westward) and downbound (eastward) shipping lanes. Twenty-one surveys were made during the four winters of 1973 to 1976, and 25 surveys were made during the four fall seasons of 1976 to 1979. Temperature profiles were normally taken at hourly intervals. An average of 24 temperature profiles were made per survey over the 46 surveys. Average distance between profiles was approximately 25 km. Data reports by Leshkevich (1975) and Assel (1983a) presented tabulations of over 1,000 temperature profiles, and Assel (1983a) also included isothermal contour analysis charts of the temperature field for each survey and temperature station position charts for each survey.

DATA ANALYSIS

A mean profile was calculated for each survey made across the lake and these data are given in Assel (1985). In this paper the structure of mean thermal profiles is examined in terms of three vertically averaged temperatures (VAT): (1) the VAT of the mixed layer, (2) the VAT of the upper 25-m surface layer (called the 25-m layer in the rest of the paper), and the VAT of the water column down to 200 m, called the column temperature in this paper. Because BT temperature measurements are only accurate to ± 0.2 C°, the mixed layer is arbitrarily defined by the depth at which the temperature is within 0.5 C° of the surface temperature. The 25-m layer is significant to summer thermal structure because it is near the center of the summertime thermocline (Smith 1972). The thermal structure for each survey is given in Table 1 and seasonal trends are illustrated in Figures 2a-g. Dates on which the mixed layer reaches the 100-m depth, temperatures on those dates for the fall seasons, and the dates of the end of fall overturn (defined as the date the column temperature was 3.98°C) are given in Table 2. That information is estimated from the data in Table 1. Supplementary air temperature and wind speed data are given in Table 3. Temporal regression analysis of the fall mixed layer depths, fall mixed layer temperatures, 25-m layer temperatures, and column temperatures

TABLE 1. Mean survey route thermal structure for each of the 21 winter surveys and the 25 fall surveys. Thermal structure is characterized by mixed layer depth and vertically averaged temperatures for the mixed layer, the 25-m surface layer (fall only), and the column down to 200 m.

Winter surveys (1973–1976)	Mixed layer		Column
	Depth (m)	Temp. (°C)	Temp. (°C)
1972–73			
20–21 Dec.	34	3.01	3.57
27–28 Dec.	105	3.30	3.45
15–16 Jan.	76	1.84	2.20
31 Jan.–1 Feb.	60	1.32	2.02
1973–74			
19–20 Dec.	200	3.90	3.90
10–12 Jan.	58	2.36	2.85
22–23 Jan.	59	1.52	2.40
1974–75			
19 Dec.	200	4.18	4.18
27–28 Dec.	200	4.11	4.11
7–8 Jan.	200	3.79	3.79
21–24 Jan.	110	2.97	3.10
5–7 Feb.	68	2.47	2.80
18–20 Feb.	50	1.73	2.44
11–12 Mar.	57	1.05	1.91
1975–76			
17–19 Dec.	200	4.03	4.03
6–8* Jan.	96	3.39	3.50
8–9 Jan.	169	3.24	3.27
27–29 Jan.	58	1.84	2.48
21–22 Feb.	71	1.35	1.81
25–27 Mar.	111	1.00	1.26
27–29 Apr.	139	1.96	2.01

Fall surveys (1976–1979)	Mixed layer		25-m	Column
	Depth (m)	Temp. (°C)	Temp. (°C)	Temp. (°C)
1976				
18–20 Aug.	2	15.65	12.27	5.74
7–9 Sept.	5	14.52	12.96	6.10
28–29 Sept.	16	9.54	9.32	5.62
20–22 Oct.	38	7.48	7.54	5.65
14–16 Nov.	175	4.96	5.03	4.94
5–7 Dec.	112	3.61	3.41	3.71
1977				
30–31 Oct.	42	7.85	7.95	5.88
1–2 Nov.	37	7.57	7.65	5.64
17–22 Nov.	95	5.77	5.89	5.45
16–17 Dec.	200	4.29	4.21	4.29
19–20 Dec.	200	4.31	4.31	4.31
1978				
22–23 Aug.	4	13.60	9.56	5.12
11 Sept.	4	13.29	9.82	5.30
28–29 Sept.	12	10.29	9.82	5.67
17–18 Oct.	30	8.70	8.74	5.62
16–17 Nov.	61	6.13	6.22	5.31
30 Nov.–1 Dec.	195	4.63	4.66	4.64
15–17 Dec.	161	4.13	4.00	4.14
1979				
23–24 Aug.	2	12.15	8.45	4.85
11 Sept.	10	12.58	10.56	5.33
25–26 Sept.	7	11.55	10.34	5.55
16–18 Oct.	25	7.99	7.98	5.36
30–31 Oct.	41	6.07	6.16	5.17
16–18 Nov.	131	4.76	4.88	4.72
13–15 Dec.	191	3.96	3.84	3.94

*survey route along the north shore of the lake and not representative of normal route

are summarized in Table 4. Equations given in Table 4 are plotted in Figures 2a-f as solid lines. These graphs illustrate general trends in mean survey route thermal structure for the base period (falls 1976–79, winters 1973–76). Monthly average mixed layer depths for winter are given in Figure 2g along with mixed layer depth for individual surveys. The large scatter about the December and January monthly mean mixed layer depths results from the small vertical water density gradient [in late fall and early winter] which makes mixed layer depth variations sensitive to variations in wind speed.

The individual temperature profiles collected over the 46 surveys were partitioned into 15 areas along the survey route for spatial analysis (Fig. 1). Mixed layer and 25-m layer temperatures and mixed layer depths and column temperatures (to 200 m or lake bottom, whichever was smaller) were calculated for each temperature profile, and then monthly averages of these quantities were calculated for each area (Figs. 3 and 4). Assel (1985)

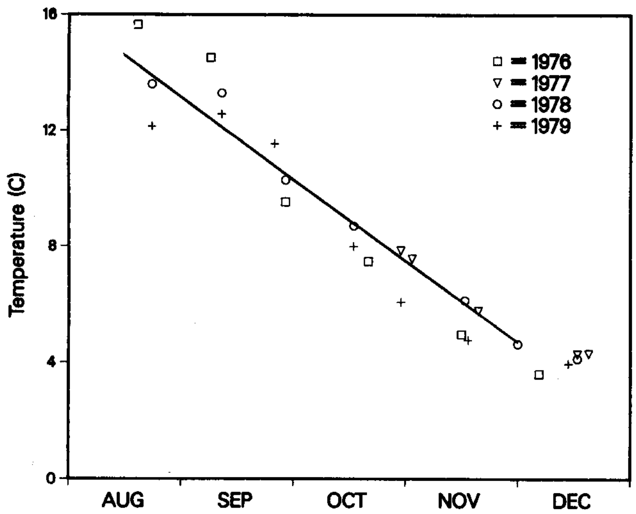

FIG. 2a. Mean survey route mixed layer VATs for individual fall surveys. The solid line is the general trend defined by equation FMX-VAT given in Table 4.

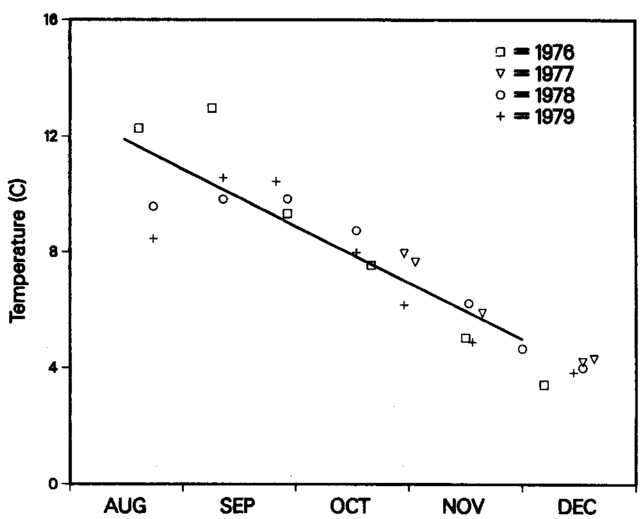

FIG. 2b. Mean survey route 25-m layer VATs for individual fall surveys. The solid line is the general trend defined by equation 25M-VAT given in Table 4.

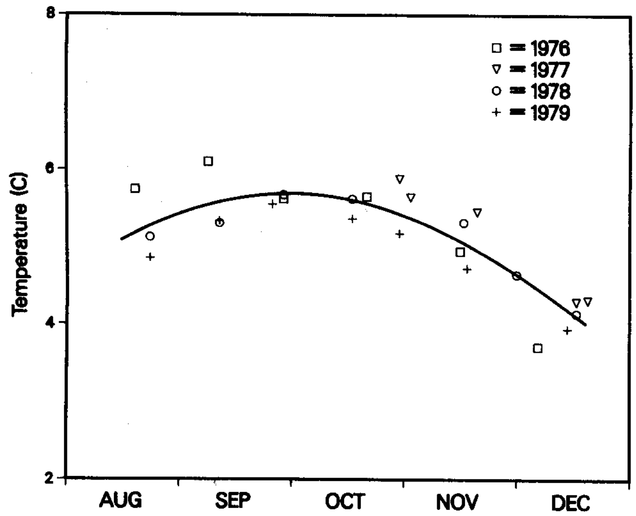

FIG. 2c. Mean survey route column VATs for individual fall surveys. The solid line is the general trend defined by equation FCL-VAT given in Table 4.

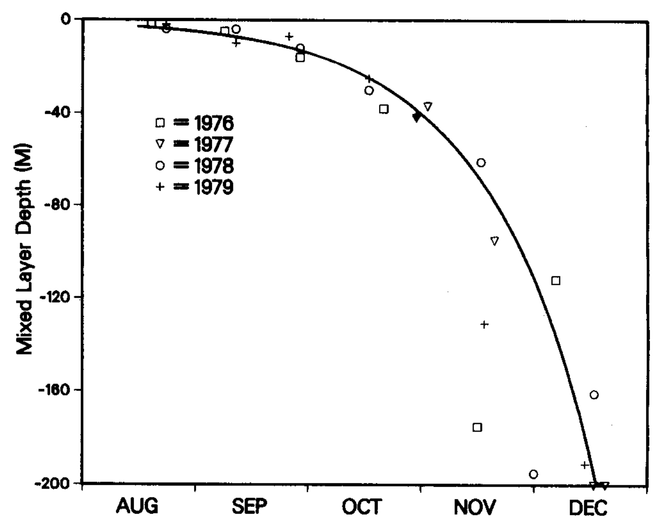

FIG. 2d. Mean survey route mixed layer depth for individual fall surveys. The solid line is the general trend defined by equation FMX-D given in Table 4.

calculated the coefficient of variation of the depth of temperature profiles [standard deviation divided by average] in each of the 15 areas and his analysis indicates that only in areas 1, 2, 13, and 15 does the coefficient of variation exceed 24 percent. Thus in most areas temperature profile depth was relatively uniform and should not affect the calculations of average monthly values of temperatures and mixed layer depth. Areas with high coefficient of variation had shallow average depths (varied from 53 m for area 1 to 105 m for area 15). The average monthly values of temperature and mixed layer depth in these areas is likely to be less representative of any one location within the given area during the period when the lake is well stratified. Historic ice cover data from Assel (1983b) were used to calculate average monthly ice concentration for each of the 15 lake areas (Fig. 5) and to calculate semimonthly lakewide ice concentrations for selected half month periods and years. These ancil-

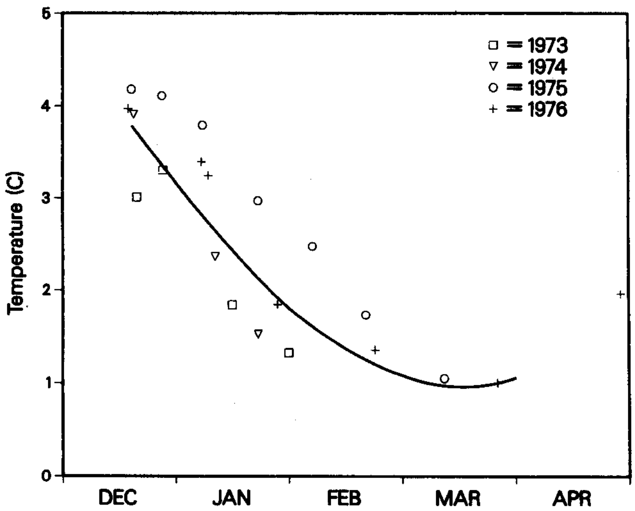

FIG. 2e. Mean survey route mixed layer VATs for individual winter surveys. The solid line is the general trend defined by equation WMX-VAT given in Table 4.

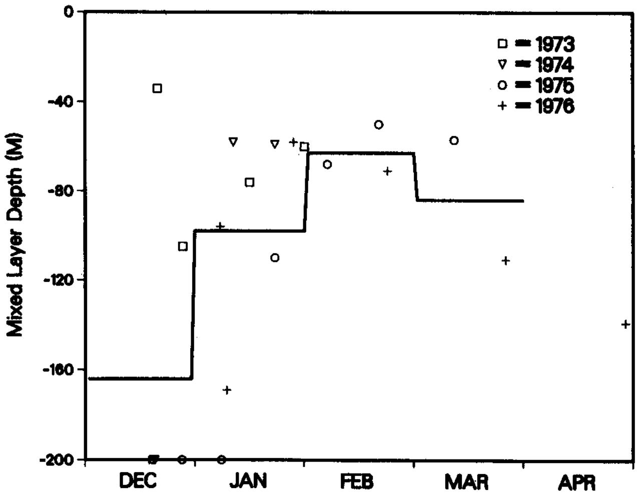

FIG. 2g. Mean survey route mixed layer depths for individual winter surveys. The solid line represents monthly averaged values of winter mixed layer depth.

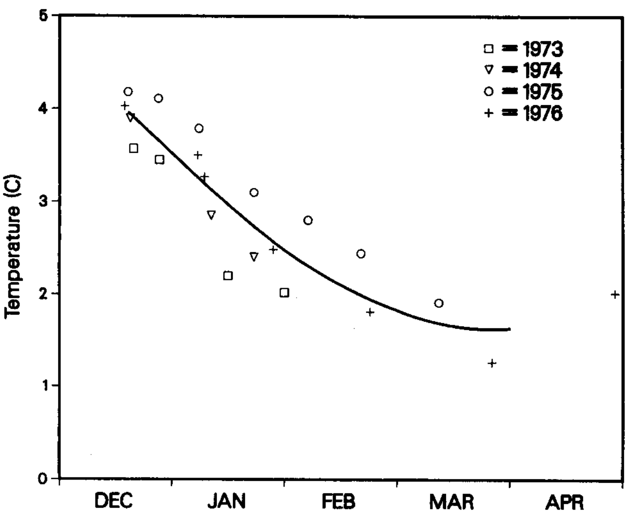

FIG. 2f. Mean survey route column VATs for individual winter surveys. The solid line is the general trend defined by equation WCL-VAT given in Table 4.

lary data aid in interpretation of the observed spatial and temporal trends in lake thermal structure.

DISCUSSION

Seasonal Comparison of Mean Survey Route Thermal Structure

The much-below-normal air temperatures in fall 1976, which are described in Quinn *et al.* (1978), are reflected in the fall thermal structure for that year relative to the other three fall seasons given in Table 1. The maximum temperature in the 25-m layer occurred the second week of September for 1976, 1978, and 1979. However, maximum column temperature, the date the mixed layer was at the 100-m level, and the end of fall overturn all occurred about 2 to 3 weeks earlier in 1976 relative to the three other fall seasons.

During the four winter survey seasons, fall overturn was completed earliest in winter 1972–73 (near the beginning of December) and latest in winter 1974–75 (near the beginning of January) (Table 2).

TABLE 2a. Date and temperature for each fall season when mean survey route mixed layer depth is 100 m, estimated from mixed layer data in Table 1.

Date	Temperature (°C)
1 November 1976	6.34
21 November 1977	5.70
21 November 1978	5.69
11 November 1979	5.21

TABLE 2b. Date fall overturn completed for mean survey route temperature profile, estimated from column temperatures in Table 1.

Winter surveys	(season)	Fall surveys
1 December 1972	(1972–73)	1 December 1976
17 December 1973	(1973–74)	26 December 1977
1 January 1975	(1974–75)	21 December 1978
20 December 1975	(1975–76)	13 December 1979

TABLE 3. Monthly air temperatures and wind speed averaged for Sault Ste. Marie, Michigan, and Duluth, Minnesota, for the winters of 1973 to 1976 and falls of 1976 to 1979.

Winter	Air temperatures (°C)				Wind speed (m s^{-1})			
	1973	1974	1975	1976	1973	1974	1975	1976
Dec.*	-10.58	-9.17	-5.66	-9.00	4.02	4.09	4.36	4.09
Jan.	-9.22	-12.25	-10.61	-13.59	4.30	4.32	5.01	4.81
Feb.	-9.92	-12.05	-9.47	-6.80	4.02	3.96	4.38	4.56
Mar.	0.78	-5.92	-6.92	-5.31	4.12	4.98	5.16	5.52
Fall	**Air temperatures (°C)**				**Wind speed (m s^{-1})**			
	1976	1977	1978	1979	1976	1977	1978	1979
Sept.	12.47	11.89	13.56	13.36	3.56	3.92	4.43	3.98
Oct.	4.00	6.95	6.89	5.95	3.51	4.45	4.09	4.12
Nov.	-4.06	-0.44	-1.67	-0.67	4.29	4.61	4.27	4.18
Dec.	-13.79	-9.14	-10.00	-4.94	4.32	4.70	4.43	4.58
Jan.**					4.18	4.60	4.09	4.78

*December winter values are for the previous year
**January fall values are for the next year

In the winters of 1973–74 and 1975–76, fall overturn was near completion during the third week of December in both of these winters. High wind speeds in January 1975 (Table 3) in conjunction with the late end of fall overturn (Table 2) resulted in a deeper January mixed layer that year relative to the other three winter seasons (Fig. 2g). Mixed layer depths had decreased to the 60-m level by the end of January in 1973, 1974, and 1976, but the mixed layer for January 1975 was still at the 110-m level during the third week of January. Between the first and third weeks of February 1975, mixed layer depth was similar to end of January values for 1973, 1974, and 1976 and by the third week of February 1975 column and mixed layer temperatures [2.44°C and 1.73°C respectively] were similar to the end of January values for 1973, 1974, and 1976. Monthly air temperatures in January 1975 (Table 3) was higher than for January 1974 or January 1976 and the 2-month average of the December 1974 and January 1975 average monthly temperature was higher than similar averages for the winters of 1972–73, 1973–74, and 1975–76. It appears that the effects of the higher air temperatures in combination with the higher wind speeds for December 1974 and January 1975 (with respect to the other three winters given in Table 3) include later end of fall overturn and later start of winter restratification. Lake Superior began to warm up in April 1976 as indicated by the increase in both mixed layer and column temperatures between the end of March 1976 survey and the end of April 1976 survey (Table 1). It was not possible to estimate the time of the beginning of spring warm up for the winters of 1972–73, 1973–74, and 1974–75 because surveys were not continued into spring.

General Seasonal Trends in Mean Survey Route Thermal Structure

Mid-August to early November mixed layer depths for the fall seasons given in Table 1 were fit to an exponential function (Table 4). That function implies there is a 3-m mixed layer near the middle of August, and a doubling of that layer nearly every 20 days (Fig. 2d). That function may not be valid in November and December, because the weakened vertical temperature and density gradients and the occurrence of episodic high winds associated with fall storms result in large mixed layer depth variation. Mixing layer depths greater than 170 m were observed as early as mid-November in 1976 [175 m] and as late as 8 January 1975 [200 m]. The mixed layer depth regression equation in Table 4 indicates the occurrence of mixed layer depths of 175 m and 200 m on 13 December and 17 December, respectively. In winter [January to March], average monthly mixed layer varies from approximately 60 m to 100 m (Fig. 2g). Large variations from the monthly average mixed layer depth occur in December and January because the small vertical water

TABLE 4. Regression analysis of mean survey route thermal profile characteristics given in Table 1, including fall mixed layer depths (FMX-D) and vertically averaged temperatures for (1) fall mixed layer (FMX-VAT), (2) 25-m layer (25M-VAT), (3) winter mixed layer (WMX-VAT), (4) winter column (WCL-VAT), and (5) fall column (FCL-VAT).

Eq. type	N	SE	R	C1	C2	C3
FMX-D	15	4.1	0.96	1.76	0.034	–
FMX-VAT	25	1.01	0.93	16.01	-0.092	–
25M-VAT	25	1.11	0.71	12.85	-0.064	–
WMX-VAT	20	0.54	0.88	3.02	45.30	3.98
WCL-VAT	21	0.37	0.91	2.14	36.00	3.76
FCL-VAT	25	0.34	0.85	2.07	30.39	3.62

N = Number of observations.
SE = Standard error of estimate.
R = Percentage of variation accounted for by regression.
C1, C2, and C3 are coefficients of regression.

Eq. type defined		Valid dates for usage from	to
FMX-D	$D = C1 * \exp^{C2*t}$	15 Aug.	2 Nov.
FMX-VAT	$T = C1 + C2 * t$	15 Aug.	6 Dec.
25M-VAT	$T = C1 + C2 * t$	15 Aug.	6 Dec.
WMX-VAT	$T = C1 * \text{Sin} (W * [C2 + t]) + C3$	19 Dec.	31 Mar.
WCL-VAT	$T = C1 * \text{Sin} (W * [C2 + t]) + C3$	19 Dec.	31 Mar.
FCL-VAT	$T = C1 * \text{Sin} (W * [C2 + t]) + C3$	15 Aug.	19 Dec.

t = time in days past 31 July
D = Depth in meters
T = Temperature (°C)
W = (2 * Pi/365) where Pi = 3.14159
* = multiplication operator

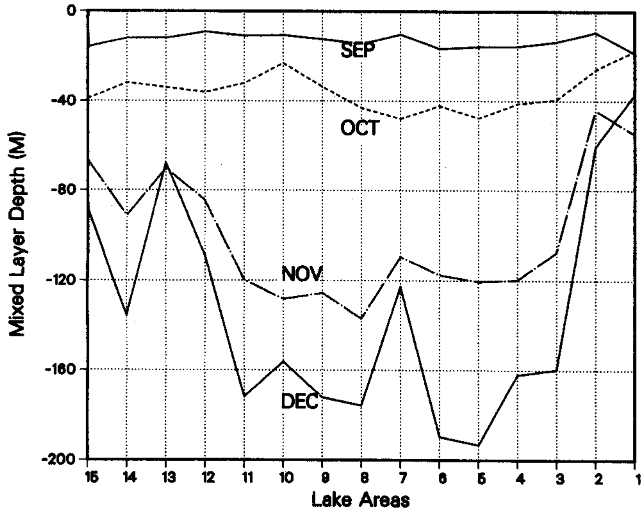

FIG. 3a. Monthly mixed layer depth (m) averaged over all fall seasons for each of the 15 discrete areas along the survey route. These data illustrate spatial trends in fall mixed layer depth.

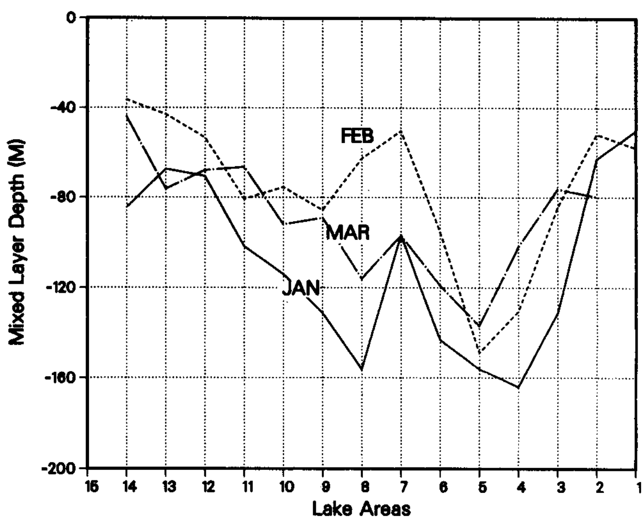

FIG. 3b. Monthly mixed layer depth (m) averaged over all winter seasons for each of the 15 discrete areas along the survey route. These data illustrate spatial trends in winter mixed layer depth.

density gradient continues to make the mixed layer depth sensitive to variations in wind conditions. The mixed layer depth on 20 December 1972 was only 34 m, while on 20 December 1973 it was 200 m. Monthly average mixed layer depth for December is near 160 m. The mixed layer depth on 10 January 1974 was 58 m while on 8 January 1976 it was 169 m. Monthly average mixed layer depth for January is near 100 m. Surface cooling in January, February, and March results in winter restratification and ice formation, both of which impede further deepening of the mixed layer. During some winters, such as 1979 (Quinn *et al.* 1978), large portions of the lake remain ice covered in March. In other years, such as 1975, the large midlake areas of Lake Superior remain ice free (Leshkevich 1976). The mixed layer depth in February and March presented in Figure 2g is more representative of the latter condition since in both years with surveys in February and March, 1975 and 1976, ice cover was much below normal. [Normal ice cover the first half of March is 67 percent (Assel *et al.* 1983). In the first half of March 1975 and 1976 Lake Superior ice cover is estimated to be 20 percent and 36 percent, respectively.] February mixed layer depths varied

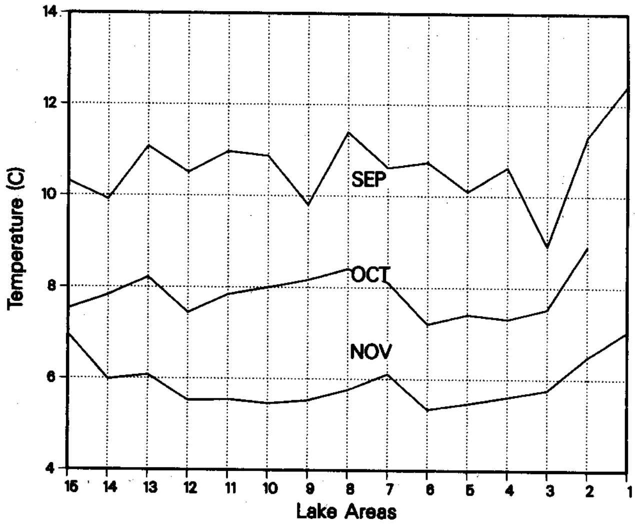

FIG. 4a. Monthly 25-m layer VATs (°C) averaged over four fall seasons for each of the 15 discrete areas along the survey route. These data illustrate spatial trends in fall 25-m layer temperatures.

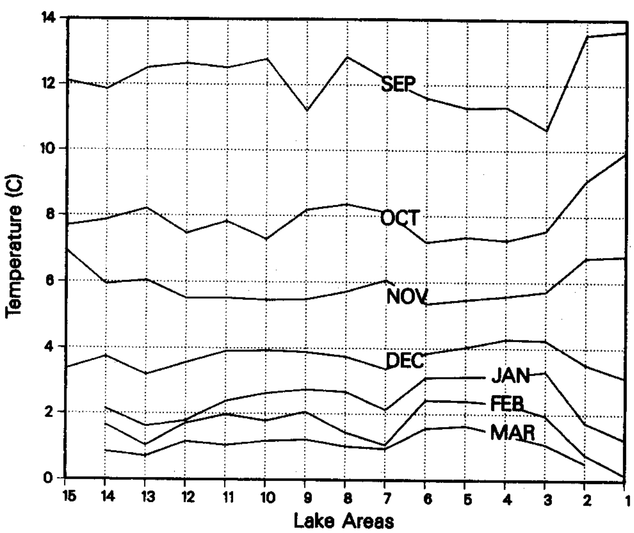

FIG. 4b. Monthly mixed layer VATs (°C) averaged over four fall seasons for each of the 15 discrete areas along the survey route. These data illustrate spatial trends in fall mixed layer temperatures.

from 50 m (18 February 1975) to 71 m (21 February 1976) and March mixed layer depths varied from 57 m (11 March 1975) to 111 m (25 March 1976). Monthly average February and March mixed layer depths are 63 m and 84 m, respectively.

The date of maximum temperature in the mixed layer varied from late August to mid-September over the four fall seasons. A linear regression analy-

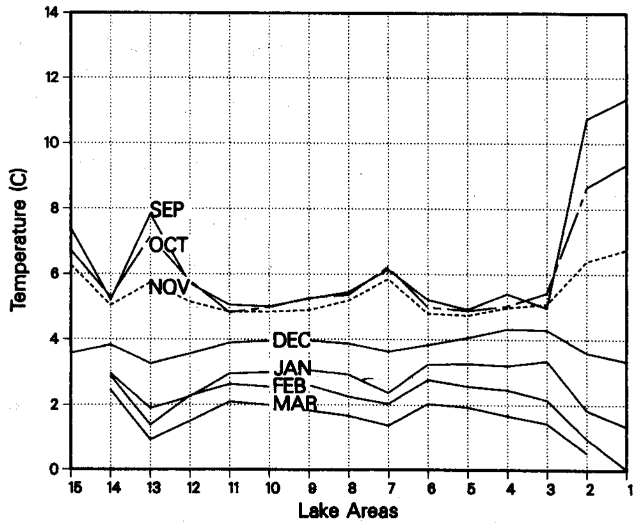

FIG. 4c. Monthly column VATs (°C) averaged over all available data for each of the 15 discrete areas along the survey route. These data illustrate spatial trends in column temperatures over the fall and winter seasons under study.

sis indicates that the average fall temperature decline of the 25-m and mixed layers is -0.064C°/day and -0.092C°/day, respectively (Table 4). Winter mixed layer temperature is usually within 1C° of column temperature (Table 1).

The column temperature equations in Table 4 [FCL-VAT and WCL-VAT] are used to estimate the average value of maximum and minimum column temperatures and the end of fall overturn date. Maximum column temperature (5.7°C), and by implication maximum heat storage, occurs near the end of September, in general agreement with Bennett (1978). The column temperature approaches the temperature of maximum density and the end of the fall overturn on 20 December. Minimum column temperature (1.6°C) is attained near the end of March.

Thermal Regimes

Field observations by Ragotzkie and Bratnick (1965), Richards *et al.* (1969), and Irbe (1972) indicated that there are pools of cool water in summer and warm water in winter in the midlake regions of the eastern and western basins of Lake Superior. These studies showed that large horizontal temperature gradients perpendicular to isobaths exist along shore, indicating two thermal regimes: a midlake regime and shore zone regime. The development and movement of the thermal bar from shore

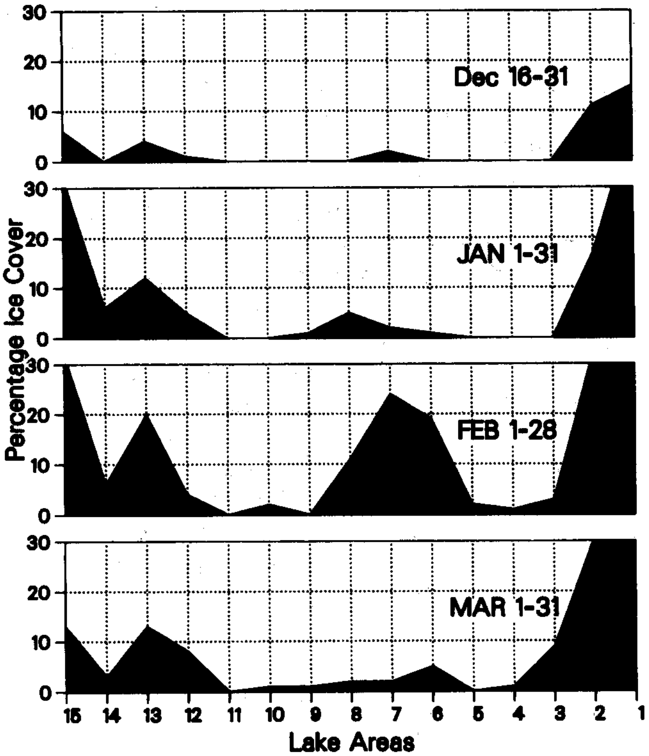

FIG. 5. Monthly average ice cover for each lake area averaged over the four winter seasons with temperature surveys (1973–76). These data illustrate spatial trends in ice cover concentration over the survey route during the winters under study.

toward the middle of the lake in spring (Hubbard and Spain 1973, Spain *et al.* 1976) also support the concept of two thermal regimes. Simulations and observations of the circulation pattern for the epilimnion and hypolimnion described by Lam (1978) and Hoopes *et al.* (1973) and winter circulation simulated by Pickett (1980) indicate that the midlake thermal regime consists of two domains defined by the two lake basins. The two thermal regimes in Lake Superior then show agreement in trend with variations in lake bathymetry and to a lesser degree with variations in wind fetch and lake circulation patterns.

Midlake Thermal Regime Along The Survey Route

Midlake areas in the eastern lake basin include areas 3 to 6 and in the western lake basin include areas 8 to 11 and area 14. Bathymetry is much smoother and somewhat shallower and wind fetch more limited in the western lake basin than in the eastern lake basin. Average temperature profile depths in areas 3 to 6 are 151 m, 195 m, 253 m, and 221 m, respectively while average temperature profile depths in areas 8 to 11 and area 14 are 224 m, 190 m, 177 m, 177 m, and 171 m, respectively. Higher mixed layer temperatures and a shallower mixed layer occur in the midlake areas of the western lake basin in September. Average September midlake temperature averaged over west basin areas is 12.2°C and average September midlake temperature averaged over east basin areas is 11.2°C. Average September midlake mixed layer depth for areas 8 to 11 and area 14 is 12.1 m (west basin) and average September mixed layer depth for areas 3 to 6 is 15.4 m (east basin). Lower mixed layer temperatures occur in the western midlake basin areas compared to the eastern midlake areas in December and the winter months (Fig. 4b). The lower September 25-m layer and mixed layer temperatures in areas 3 and 9 (Fig. 4a-b) relative to adjacent areas can be explained by the shoreward drift of midlake surface waters associated with the general counterclockwise circulation pattern (see Bennett 1978).

The thermal regime of area 14 is unique among midlake areas because of summer and winter upwelling events (see Ragotzkie 1974, Ragotzkie and Niebauer 1975) and because the prevailing counterclockwise shore circulation results in water being advected into area 14 from the vicinity of the deep trough along the northwest shore. The narrow breadth of the western end of the lake (west of the Apostle Island shoal) significantly limits areas 14's exposure to over water wind fetch. The September monthly 25-m and mixed layer temperatures in area 14 are lower than midlake west basin areas and these lower temperatures are likely due to upwelling events (Fig. 4a-b). The mixed layer depth in area 14 in November through March is shallower than other midlake areas because of its protected shore location relative to over water wind fetch and prevailing westerly winds. Mixed layer depth in area 14 is at a maximum in December (136 m) and at that time it is 20 m to 39 m shallower than the mixed layer depths for other midlake west basin areas. The spatial pattern of increasing mixed layer depth going from west to east (area 14 to area 8) in the months of January, February, and March, and the temporal pattern of a general decrease in mixed layer depth from January to February and then an increase in mixed layer depth from February to March in areas 14 to 8 (Fig. 3b) is in agreement with the spatial pattern of decreasing ice cover going eastward from area 15 to area 8 and with the temporal pattern of increasing ice concentration from December to February and decreasing ice concentration from February to March (Fig. 5).

Ice cover is less extensive and of shorter duration in midlake areas (Fig. 5), and ice cover normally forms earlier and is more extensive in the western lake basin (Assel *et al.* 1983) because of the more limited wind fetch and generally shallower water depths.

Nearshore Thermal Regime Along The Survey Route

Nearshore areas include areas 15, 13, and 12 in the western end of the lake, area 7 along the northern tip of the Keweenaw Peninsula, and areas 2 and 1 at the eastern end of the lake. Temperatures in area 2 and area 1, the lake's outlet, are higher in summer (11.3°C and 10.7°C September column temperatures) and lower in winter (0.2°C and 1.0°C February column temperatures) than in other lake areas. This is due to their shallow depth (average temperature profile depth is 53 m for area 1 and 61 m for area 2) and because of advection of shore surface waters to Lake Superior's outlet. Winter temperature profiles in areas 1 and 2 are virtually isothermal as indicated by January and February mixed layer depths which approach average temperature profile depths for these areas. Area 7 at the northern tip of the Keweenaw Peninsula has an average temperature profile depth of 142 m. Temperatures in this area are lower in fall and higher in winter than temperatures for areas 1 and 2 and mixed layer depths are greater because of area 7's greater depth and greater exposure to the mass of the open lake. September and February column temperatures in area 7 are 6.1°C and 2.0°C, respectively. During the winter, mixed layer depths in area 7 are at a maximum in December (123 m) and at a minimum in February (50 m). Winter restratification occurs in area 7 as evidenced by its February mixed layer depth. Areas 13 and 12, located on the Apostle Island shoal at the west end of Lake Superior, have average temperature profile depths of 79 m and 110 m, respectively. The column temperatures of area 13 are higher in September and October and lower in December through March relative to area 12. Average monthly column temperature in area 13 ranges from 7.8°C (September) to 0.9°C (March) while similar values for area 12 are 5.7°C (September) and 1.5°C (March). The lower September and October column temperatures in area 12 (compared to area 13) are due to its greater depth. Advection of waters into area 12 from the deeper water mass of the northwest shore may also be a contributing factor. Mixed layer depth is at a maximum in area 13 in November (70 m) and at a winter minimum in February (43 m), in good agreement with ice cover trends. Ice concentration increases from December to February (Fig. 5). Mixed layer depth in area 12 is at its maximum in December (109 m) and it is at a winter minimum in February (53 m), also in good agreement with ice cover trends noted above for area 13. The February mixed layer depths for areas 12 and 13 also indicate that winter restratification forms in the deeper waters of the Apostle Island shoal. Area 15 at the west tip of Lake Superior has an average temperature profile depth of 105 m. Its average September column temperature (7.4°C) is similar to that of area 13. There were insufficient data to calculate averager monthly temperatures and mixed layer depth in area 15 for the months of January through March.

In the nearshore thermal regime of Lake Superior it is likely that wind induced mixing continues throughout virtually the entire water column until an ice cover is formed. Stewart (1973) provided evidence of this for the winter thermal structure of Lake Erie. That lake, with a mean depth of 19 m, was observed to be virtually isothermal at a temperature slightly above 0°C in winter 1972 even though an extensive ice cover formed. Stewart attributed this lack of winter restratification in part to the fact that the ice did not cover 100 percent of the lake's surface for extended periods of time and so it tended to act as a giant movable sieve.

SUMMARY AND CONCLUDING REMARKS

During September, mean survey route temperature profiles are characterized by mixed layer depths less than 20 m because of strong thermal stratification. The mixed layer and 25-m surface layer temperatures reach their maximum values by mid-September. The column temperature is near its maximum value by late September or early October. Changes in thermal structure in October through January are similar to three stages in the fall and winter cooling period described for Babine Lake by Farmer and Carmack (1981).

In the first stage, summer stratification is broken down by surface cooling and mixing with lower layers. On Lake Superior, this stage usually starts by mid-September and is near completion during November. The general trend of increasing mixed layer depth during this first stage can be described by an exponential function, with an average doubling time of about 20 days. However, mixed layer depth may deviate greatly from this average trend during a given date in a given fall season because it is dependent upon daily variation in the energy exchange both at the water surface and within the water column.

The second stage starts when the water column becomes isothermal. The mean temperature profile usually becomes isothermal between mid-November and mid-December. As the temperature of the water column approaches the temperature of maximum density, surface wind stress can cause mixing to great depths because of the small vertical density gradient. Heat loss in the surface layer can now be rapidly redistributed throughout the entire water column. It is likely that in most years there is no clear-cut demarcation between the end of isothermal conditions and winter restratification, because restratification is dependent upon wind conditions. In 1975, when the mean temperature profile was still isothermal in early January, high winds maintained isothermal conditions to the 110-m depth through the end of January 1975. During winter 1972–73, stratification was evident by the end of the third week of December 1972 but high winds the following week, 27 December 1972, produced nearly isothermal conditions once more (see Assel 1985).

The third stage in the cooling period is winter restratification. It can start as early as the last half of December or as late as the third week of January. During stage three the surface waters cool sufficiently for ice formation. During January 1977 an January 1979 extensive [above normal] ice cover formed in January in the western basin of Lake Superior (see Quinn *et al.* 1978, and DeWitt *et al.* 1980) while in January 1975 the midlake area of the western basin of Lake Superior remained virtually ice free in January (see Leshkevish 1975). The winter thermal structure described in this paper is more representative of open water midlake conditions and the winter thermal structure of Lake Superior during winters of extensive early season ice cover may be significantly different than what is described here.

Variations in lake bathymetry, wind fetch, and the prevailing counterclockwise shore circulation result in the midlake and shore thermal regimes. The midlake regime is characterized by smaller September to March column temperature range, later end of fall overturn, and ice cover of shorter duration and lower concentration, relative to the nearshore thermal regime. The midlake western basin, with its smaller wind fetch and shallower bathymetry, has a shallower mixed layer and higher mixed layer temperature in September and a shallower mixed layer with lower mixed layer temperature in winter, relative to the midlake eastern basin. Upwelling waters from the deep trough along the northwestern shore and advection of those waters to the western end of the lake appear to be responsible for the relatively low September and October mixed layer and 25-m layer temperatures in areas 14 and 15. In late fall and during winter when stratification is weak, areas with the combination of greatest over water wind fetch and depth have the deepest mixed layers. Winter restratification and the formation of an ice cover reduce the effects of wind induced mixing to some degree but it is not possible to quantify the significance of these factors at this time. If a solid, 100 percent ice cover does not form and remain in shallow areas the mixed layer (which may include virtually the entire water column in some locations) will continue to cool most of the winter. If a solid ice cover does form, temperature near the lake bottom may increase due to warming by bottom sediments.

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