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METALIMNETIC OXYGEN MINIMA IN LAKE ONTARIO, 1972[1]

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ABSTRACT. Dissolved oxygen profiles taken in Lake Ontario in 1972 indicate the presence of a distinct and persistent metalimnetic oxygen minimum during the stratified season. Evidence indicates the phenomenon occurred in previous years as well. The depth and magnitude of the minimum were closely related to the thermocline depth and strength of stratification. Lowest minimum values in 1972 occurred in early to mid September and were 8.6 mg/l dissolved oxygen and 82% saturation. Offshore the minimum decreased from west to east across the lake and was lesser in magnitude nearshore and in the northeast. During the nonstratified period oxygen concentrations remained relatively constant with depth at approximately saturated values.

INTRODUCTION

Metalimnetic oxygen minima have been observed in a variety of North American, European, and Japanese lakes (summarized in Hutchinson 1957 and Kuznetsov 1970). None of these lakes, however, is comparable in size to the Great Lakes. Oxygen profiles collected in Lake Ontario during the 1972-73 International Field Year on the Great Lakes (IFYGL) show a distinct lake-wide oxygen minimum during thermal stratification which was absent during isothermal periods. Data from previous years indicate the phenomenon was not unique to 1972 (Dobson 1967, Allen 1969, Sweers 1969). This paper describes some of the characteristics of the 1972 minimum and relates them in a preliminary way to causes identified in other smaller lakes and in the ocean. A complete understanding of the phenomenon awaits further research.

METHODS

Electrobathythermograph and dissolved oxygen meter data from the 1972 USRV *Researcher* IFYGL cruises were obtained from IFYGL Data Management, National Climatic Center (NCC), Asheville, NC 28801. Depth and temperature values, already converted to meters and degrees centigrade, required little processing except for elimination of obviously bad values. Claimed accuracies were ± 1.0% and ± .02% respectively (Robertson 1974). Oxygen data, however, were in volts and required considerable processing.

Four factors were considered in processing the oxygen data:

1) Salinity and temperature corrections
2) Calibration factors
3) Flow sensitivity
4) Instrument response time

Salinity and temperature corrections were done as described in Pijanowski (1973). Calibration of the probe, a MINOS DOM, was assumed done as described in Section 4.4.1.2c of the MINOS DOM Operating and Maintenance Instructions (Beckman Instruments, Inc. 1971). All cruises had a recorded calibration factor of 2.0. The resulting oxygen values in mL (STP)/L had a claimed accuracy of ± 0.3 mL/L (National Oceanographic Instrumentation Center [NOIC] 1972).

The accuracy, however, was dependent upon the instrument's moving sufficiently rapidly in the water, a condition not always met. Readings taken at less than .25 m/sec were not considered reliable (NOIC 1972, and my empirical results). Data values were retained for one response time after a decrease in speed below .25 m/sec, then rejected

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for one response time after an increase in speed above .25 m/sec. Response times were calculated according to Pijanowski (1973). Oxygen and temperature data were then averaged over 2 m depth intervals, a depth range corresponding roughly to one response time of the oxygen probe at the average speeds and temperatures encountered. A final correction for the response time lag was then made by shifting the depth of the downcast oxygen values up 2 m and depth of the upcast oxygen values down 2 m. Downcast and upcast values for both oxygen and temperature were averaged to produce a corrected profile and any missing values were linearly interpolated. Oxygen values in mL (STP)/L were converted to mg/L by multiplication by 1.4286. Oxygen percent saturation was calculated according to Table 74 in Hutchinson (1957). The resulting data for a maximum of 57 stations on 12 cruises is available in Boyd and Eadie (1978).

RESULTS

The lake averaged profiles in Figure 1 illustrate the seasonal development of the oxygen minimum in 1972 (profiles begin at 6 m because oxygen data above this depth were unreliable). Since these are whole lake averages, station specific features have been eliminated and only large scale features remain. However, a sequence of profiles at any particular station appears qualitatively similar. During the cruise in June only weak thermal stratification exists and no evidence of a metalimnetic minimum is seen. If anything, there is a suggestion of an oxygen maximum. During succeeding cruises from August through September a well defined thermocline develops and a definite metalimnetic oxygen minimum appears and intensifies. After the first part of October the oxygen minimum disappears as the thermal stratification weakens.

Thermocline depth (defined as depth of maximum density gradient) and minimum dissolved oxygen and percent saturation depths were determined for each station-cruise combination. Meteorological conditions induce large variations in thermocline depth at individual stations; however, good linear correlations between thermocline and minimum oxygen depths for most cruises (Table 1) imply that the motions of the oxygen minima tended to follow the motion of the thermocline. Lakewide averages of these depths for each cruise (Figure 2) removed station specific features and illustrate the temporal changes in the positions of the oxygen minima relative to the thermocline. Consistently the average depth of minimum percent saturation lay below the average thermocline depth. Through mid August it lay 2-10 m below; from the end of August to October it lay 2-4 m below. The average depth of minimum dissolved oxygen, on the other hand, tended to lie at the average thermocline depth or a few meters above with the exception of the late June cruise. Both minima were found closer to the thermocline during September.

Temporal variations showed in the magnitudes of the dissolved oxygen and percent saturation minima (Figure 3). Minimum dissolved oxygen and percent saturation values varied considerably from station to station, but tended on the whole to decrease throughout the summer until sometime in September, then began to increase again. In terms of dissolved oxygen, the lowest minimum value in 1972 occurred about 4 September, with an average value of 8.6 mg/L. In terms of percent saturation

TABLE 1. Correlation coefficient r for depth of oxygen minima versus depth of thermocline for Researcher *Lake Ontario cruises, 1972.*

Researcher Cruise	Dates	Dissolved Oxygen r	Dissolved Oxygen Significant/Not Significant linear correlation (α=.10)	Percent Saturation r	Percent Saturation Significant/Not Significant linear correlation (α=.10)
9	6/26 - 6/28	.52	NS	.59	NS
14	7/31 - 8/3	.49	S	.48	S
16	8/14 - 8/17	.55	S	.06	NS
19	9/5 - 9/8	.77	S	.67	S
20	9/11 - 9/14	.85	S	.80	S
21	9/18 - 9/22	.81	S	.92	S
22	9/25 - 9/27	.69	S	.80	S
24	10/10 - 10/11	.70	S	.17	NS

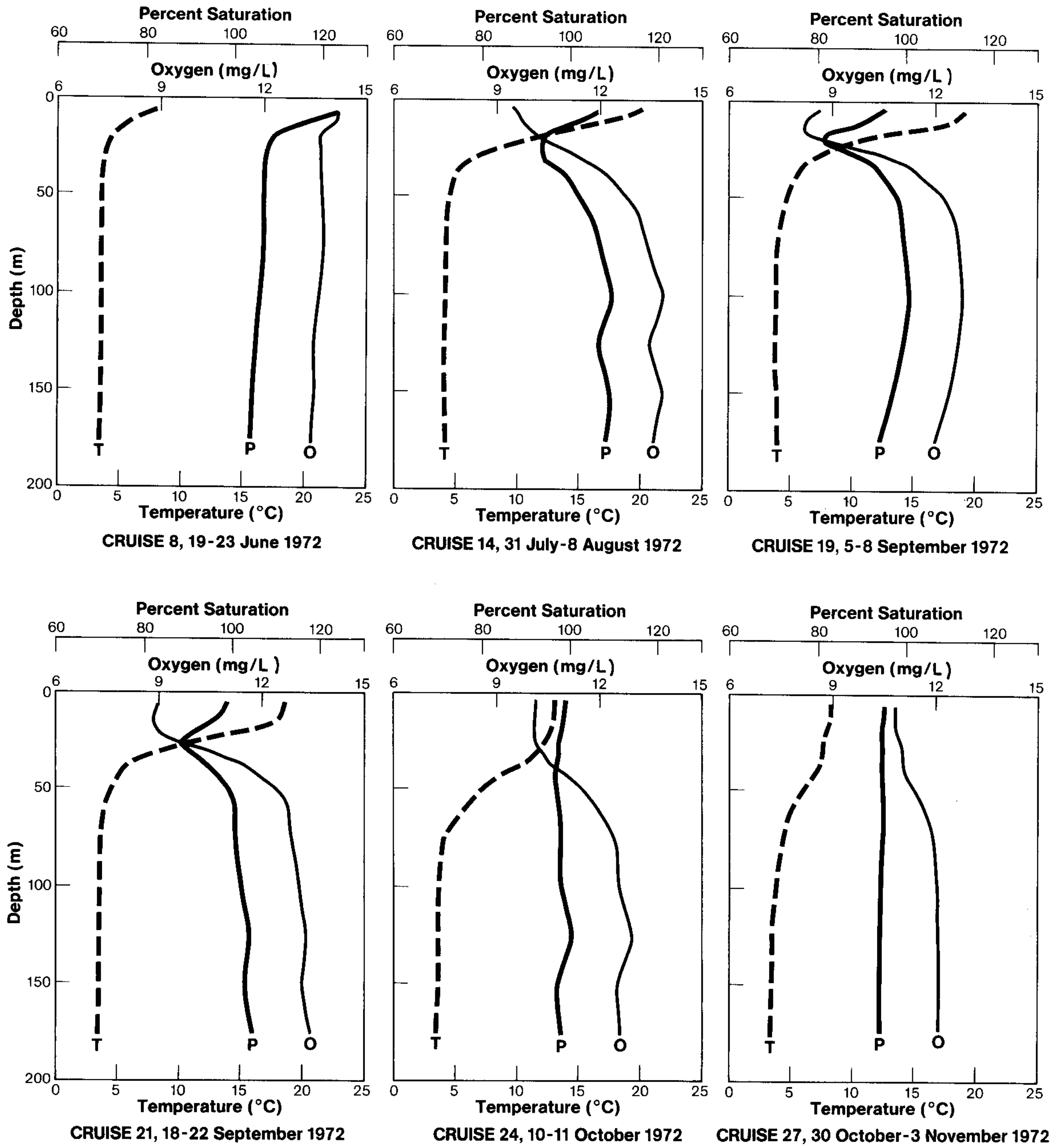

FIG. 1. Lake averaged profiles of dissolved oxygen (O), percent saturation (P), and temperature (T) versus depth for selected Researcher *Lake Ontario cruises, 1972. Profiles at individual stations are similar.*

the lowest minimum was around 11 September, with a value of about 82%. Oxygen minima in 1964, 1966, and 1967 were lowest at approximately the same time (Allen 1969, Dobson 1967, Sweers 1969), although the 1966 values in Dobson were not as low.

A definite correlation (significant at $\alpha < .01$) was found between the average strength of stratification and the average magnitudes of the dissolved oxygen and percent saturation minima (Figure 3). Strength of stratification was defined in terms of the Brunt-Väisälä frequency N at the thermocline,

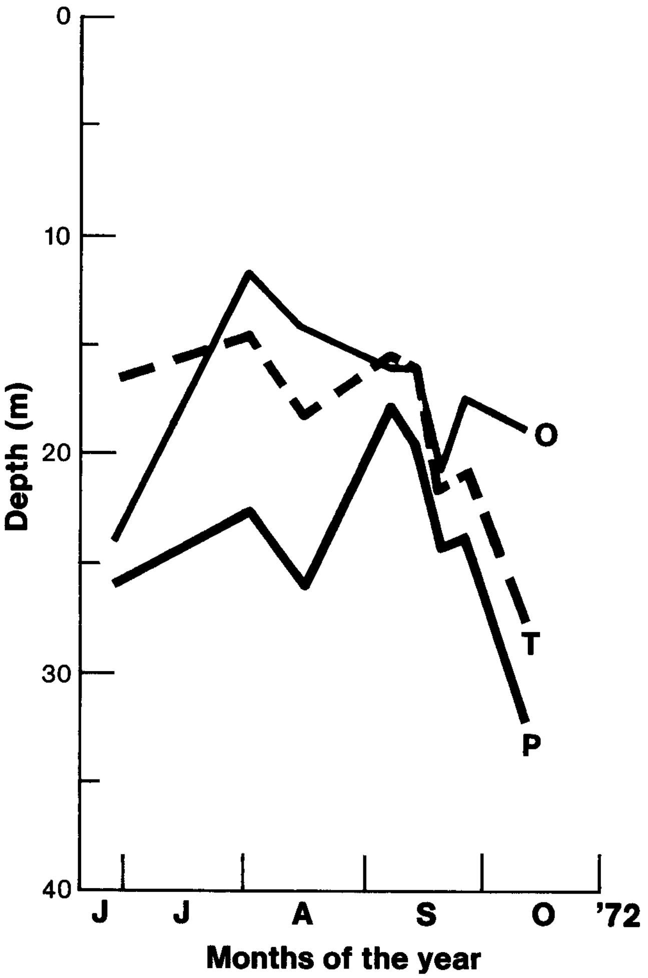

FIG. 2. Average thermocline (T) and minimum dissolved oxygen (O) and percent saturation (P) depths for Lake Ontario, 1972.

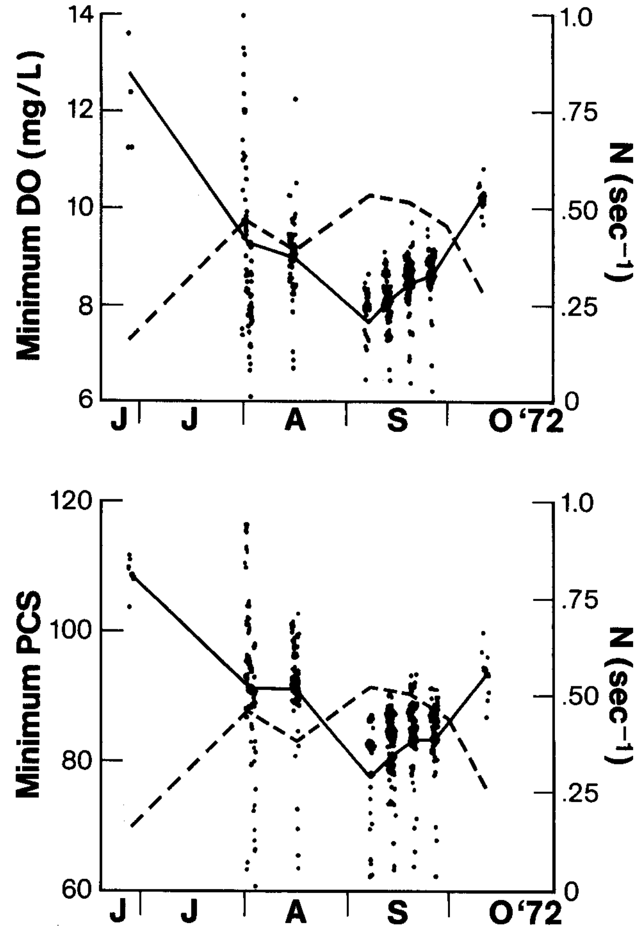

FIG. 3 Lake Ontario minimum metalimnetic dissolved oxygen and percent saturation values (points and solid lines) and average thermocline stability (broken line) from June through October 1972. Points are individual station values; lines represent cruise averages.

$$N^2 = \frac{g}{\rho}\frac{\partial \rho}{\partial z}$$

where ρ=density, g=gravitational acceleration and z=depth (Pond and Pickard 1978). During September when N was at a maximum, minimum oxygen and percent saturation were lowest, and as mentioned, depths of the minima occurred closest to the thermocline.

Figure 4 illustrates typical spatial patterns found for the oxygen minima. In general, minima were lower near shore and in the eastern part of the lake, and were particularly low in the northeast near the St. Lawrence outlet. Proceeding westward along the northern shore from Prince Edward Point up to Presqu'Ile, minimum oxygen values continued to be especially low, although becoming higher towards the west.

DISCUSSION

The main factors mentioned in the literature as contributing to a metalimnetic oxygen minimum are lake productivity (e.g., Kusnetzow and Karzinkin 1931, Ruttner 1933, Hutchinson 1957, Shapiro 1960); kinematic consequences of the temperature gradient (e.g., Ruttner 1933, Czeczuga 1959, Gordon and Skelton 1977); and water transparency (e.g., Ruttner 1933, Czeczuga 1959). All are likely factors in Lake Ontario, but a determination of the relative importance of various mechanisms at different times and places awaits further research. This section presents a summary of these proposed mechanisms and the evidence in support of them from this study. A fourth mechanism of importance in the oceans is also mentioned.

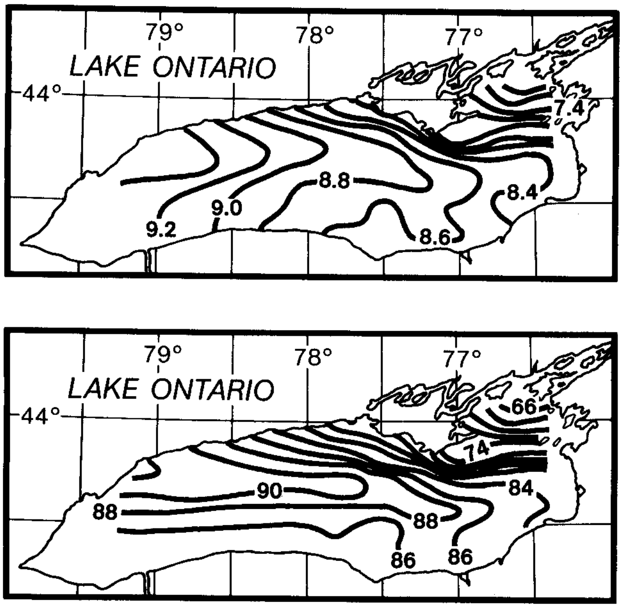

FIG. 4. Lake Ontario metalimnetic oxygen (above) and percent saturation (below) minima, Researcher *cruise 21 (18-22 September, 1972).*

Earlier investigations have linked lake productivity to an oxygen minimum through various combinations of phytoplankton and zooplankton respiration and bacterial decomposition in the metalimnion. In support of this mechanism in Lake Ontario in 1972 is the tendency for minimum values to decrease from west to east, corresponding to the direction of increasing lake productivity. In addition, the generally more productive nearshore regions (Munawar and Nauwerck 1971; Glooschenko *et al.* 1974; Stadelman, Moore, and Pickett 1974) have lower metalimnetic minima, and the lowest metalimnetic oxygen values were found in the most highly productive area, the northeastern corner near the St. Lawrence outlet (Munawar and Nauwerck 1971, Glooschenko *et al.* 1974, Stoermer et al. 1975). Besides clarifying the significance of this mechanism, research is needed to determine the relative contributions of zooplankton, phytoplankton, and bacterial respiration.

Kinematic consequences of the temperature gradient include decreased seston settling velocities due to increased density and viscosity and greatly suppressed vertical advection and turbulent diffusion across the metalimnion. The former results in an increased metalimnetic seston concentration as material settles into the layer faster than it settles out, at least until a steady state is reached. Such accumulations have been observed in the Great Lakes, including Lake Ontario (Pinsak 1967, GLERL unpublished data). For organic material an increased oxygen demand is possible—through respiration of organisms feeding on it or through respiration of the material itself. The greater the change in settling velocity from epilimnion to metalimnion, the greater the concentration of material in the metalimnion, and hence the greater the potential oxygen deficit. Herein may lie the explanation for the relationship between intensity of stratification and magnitude of the oxygen minimum. In addition, suppressed vertical motion across the metalimnion, i.e., reduced vertical diffusion, causes the zone to be relatively isolated from epilimnion and hypolimnion. Consequently, any oxygen consumption or production in the region is not balanced by a flux of oxygen from or to the adjacent region.

The third factor in the development of a metalimnetic minimum is the location of the thermocline below the euphotic zone during the most highly productive months. In a study of two similar Polish lakes (Czeczuga 1959), one having an oxygen maximum in the metalimnion, the other having an oxygen minimum, the main difference between the two lakes was the location of the compensation point i.e. where production equals respiration or the 1% light level. In the case of the lake with the metalimnetic oxygen maximum, the compensation point lay below the thermocline and phytoplankton trapped in the region thrived on the nutrients released from decomposing organic matter. In the other lake with a shallower compensation point only oxygen consuming processes occurred in the metalimnion and an oxygen deficit developed. Because of its moderately high productivity and because of $CaCO_3$ precipitation, epilimnion transparency in Lake Ontario is very low in July, August, and September ($\sim$2 m) (Dobson, Gilbertson, and Sly 1974). Only Western Lake Erie is comparably low. Thus the compensation point in Lake Ontario is likely to be above the metalimnion.

A final cause of a metalimnetic oxygen minimum can be horizontal advection of oxygen depleted water from one region to another. This commonly occurs in the ocean (Miyake and Saruhashi 1956, Menzel and Ryther 1968) and may explain the lower metalimnetic oxygen values along Lake Ontario's northern shore. The cause or causes of the very low minima in the northeast or the oxygen depleted water itself appear to have been carried westward along the Canadian shore by the dominant counterclockwise current regime observed in 1972 by Pickett and Bermick (1977).

SUMMARY

During summer 1972 a distinct and persistent oxygen minimum occurred in the thermocline region of Lake Ontario. The depth of the oxygen minimum was directly related to the depth of the thermocline and its magnitude inversely to the strength of stratification. Lowest minimum oxygen values occurred in early to mid September. Horizontal gradients in magnitude were similar to horizontal gradients in lake productivity. Possible causes include zooplankton, phytoplankton, and bacterial respiration; reduced vertical advection and turbulent diffusion; accumulation of material in the metalimnion; location of the compensation point above the metalimnion; and horizontal transport of oxygen depleted water.

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