LIMNOLOGY OF SOME MADISON LAKES: ANNUAL CYCLES

Kenton M. Stewart and *Arthur D. Hasler*

ABSTRACT

Detailed studies of Lakes Mendota, Monona, and Waubesa at Madison, Wisconsin, provide a comparison of their annual cycles and the influence of climatic variations on their thermal regimes. Lake Waubesa integrates the influence of wind velocity, air temperature, and solar radiation most rapidly whereas Lake Mendota responds most slowly. Although Lake Monona is still dominated generally by climatic influences, the cultural influences of thermal discharges now causes the ice to depart in spring at a significantly earlier date than the other two lakes. The clarity of the Madison lakes generally decreases from Mendota to Monona to Waubesa.

Although all three lakes are basically eutrophic dimictic lakes with anoxic conditions developing in the lower waters during summer stratification, Lake Waubesa may have aperiodic overturns during summer.

Comparisons of temperature, oxygen, Secchi disk, photometer readings, and ice thickness in Lake Mendota show relatively little change from the early studies of Birge and Juday several decades ago.

I. *Introduction and Background*

The fascinating thing about lakes is that they provide their own variety. The task of the limnologist is to measure and interpret this variation whether it concerns physical, chemical, or biological phenomena.

This paper is an attempt to compare the annual cycles of selected variables, measured during the same time period, in Lakes Mendota, Monona, and Waubesa at Madison, Wisconsin.

In temperate dimictic lakes, the greatest range of variation for any variable occurs sometimes during the annual cycle. Therefore, an examination of selected variables over the course of at least one annual cycle, provides some tentative limits by which to judge past, present, and future events in the system. As the number of years of investigation increases, the limits and expected changes become defined more clearly and valuable base line data are established. In addition to the fluctuations of the annual cycle,

there are seasonal, daily, and some second-by-second changes that challenge the interpretation of the investigator. A lake may serve as a multi-ring circus in which it is impossible to observe everything at one time, but if one attends frequently a more thorough appreciation and understanding of the whole system can be gained.

Early illustrations of annual cycles in Lake Mendota were provided by Birge and Juday (1911), and some unpublished data of Birge (Neess and Bunge, 1956, 1957). In the latter references, several years data on lake temperatures were presented. Even these data, though extensive, were accumulated mostly during the ice-free season of the year. The general lack of winter data, when compared to those of the summer season, is common for limnological investigations throughout the world and provides a summer bias in our interpretation of lake events.

In addition to their studies of annual cycles of temperature and oxygen, the contributions of Birge and Juday (1929, 1931, and 1933), concerning solar radiation and transparency in water, were significant.

It is surprising, in light of Birge's interest in comparative lake studies, that investigations of other Madison lakes besides Mendota were so slighted. How much better would we have been able to understand lakes generally and changes in the Madison lakes specifically if Birge had concentrated his efforts in comparative studies there?

II. *Methods and Procedures*

The thermal measurements were made with a Whitney thermometer at four selected stations (Fig. 1) in the three Madison lakes considered in this paper. The accuracy of the thermometer was maintained at $\pm$ 0.1°C and rechecked frequently with precision mercury thermometers.

Measurements of transparency and light were made by several different instruments. A Secchi disk (20 cm diameter, all white) was used to gather general transparency information. The G. M. Photometer with a Weston photronic cell (Model N. 8564R) and cosine filter were used to measure the 1% level and extinction coefficients. Measurements for microstratification were taken with a Whitney transmissometer or turbidimeter (one meter path length, a modified version of the earlier instrument by Whitney, 1938).

Physical and chemical data were secured during the summer by use of a boat and during the winter by hauling the equipment over the ice on a toboggan. During dangerous periods of winter, e.g., at the time of initial ice formation or in the last several days of rotting ice, a small aluminum boat with a motor was dragged over the ice to the sampling site(s). Whenever the ice broke K. M.

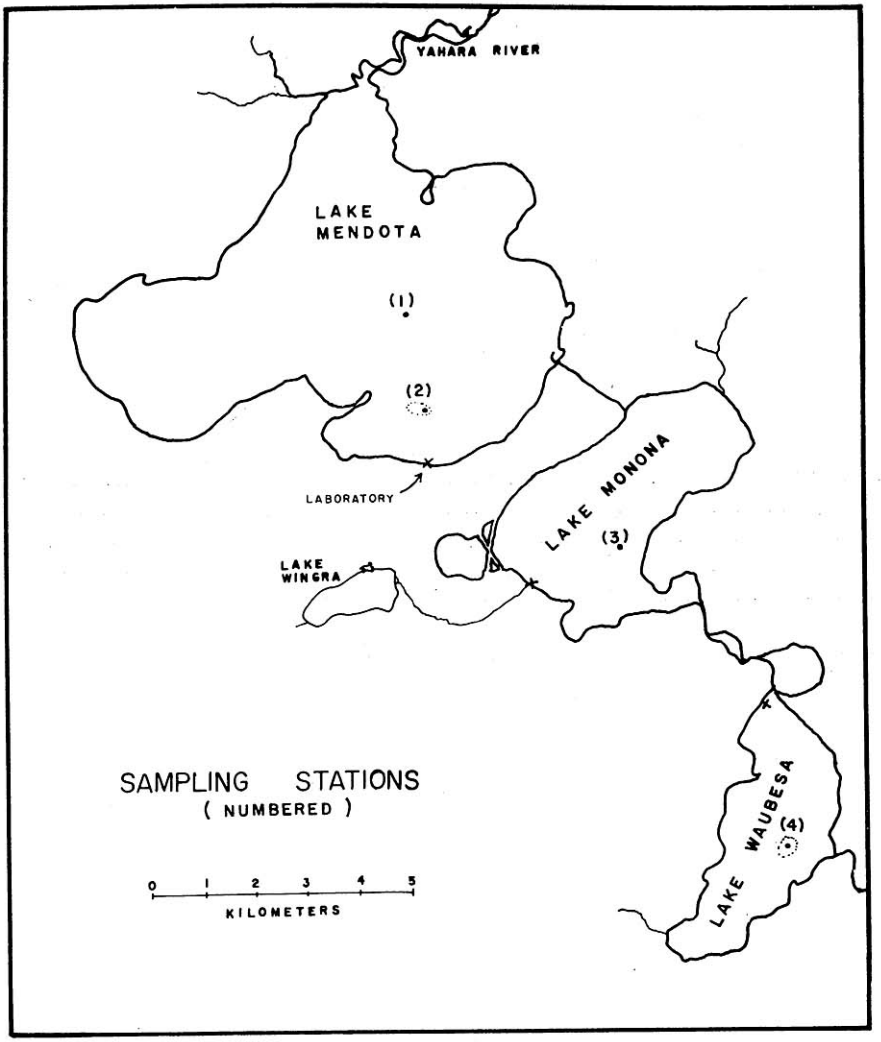

FIGURE 1. The Madison lakes and the sampling stations.

Stewart got into the boat and used the powered boat as a miniature icebreaker until the ice was firm enough to hold or until the sampling site or shore was reached. Under certain conditions of smooth but thin sheet ice, it is possible to sit in a boat and push oneself along with a spiked pole. However it is advisable to have a dependable motor along in case the boat breaks through the ice—as it usually does. These practical expediencies allowed acqui-

sition of data at a most interesting and little studied time in the annual cycle of a lake. As a further bit of practical information, the period of risk (depending on meteorological conditions) is usually shorter during early ice formation than when the ice is wasting.

The water samples were acquired with a Kemmerer sampler from preselected depth intervals in each of the lakes investigated. The azide modification of the Winkler method was used for all oxygen determinations (Standard Methods, 1960). Reagents were added in the boat and the samples were titrated immediately upon return to the laboratory.

Information concerning solar radiation, air temperature and wind velocity (means of 24 measurements daily for 1960–1963 and eight measurements daily for 1966), was obtained from the published data of the U.S. Weather Bureau Station at Truax Field in Madison, Wisconsin (Annual Climatological Data, 1959–1966). Radiation data of the Weather Bureau were compared to and augmented occasionally by the data of the Solar Energy Laboratory at the University of Wisconsin when the radiometer at the Weather Bureau malfunctioned.

III. *Results and Discussion of Harmonic Time Series*

A. *Annual Cycle: Weather Data*

In most of the graphs in this paper concerning annual cycles, the day-to-day variation of air temperature, wind velocity, and solar radiation has been smoothed by plotting only the moving ten-day averages.

However, one year (1962) has been selected to illustrate the enormous detail apparent when comparing daily readings of wind velocity and direction, air temperature, and incoming radiation over an annual cycle. The daily means of 24 measurements of wind velocity and direction have been plotted (Fig. 2). Solid lines above and below the zero value indicate winds from the south to west, and north to east respectively, with the maximum velocity for that date indicated by a solid dash. Winds from the east–southeast to south–southwest and west–northwest to north–northwest are indicated by dotted lines above and below the line respectively, with separate dots for the fastest velocity.

The 24-hour daily means of weather data (Fig. 2), owing to their great variability and without further smoothing, would tend to mask the plots of lake data. Therefore computer calculations of moving ten-day means for winds, air temperature, and solar radiation have been plotted for easier comparison of climatological variables and lake trends over an annual cycle.

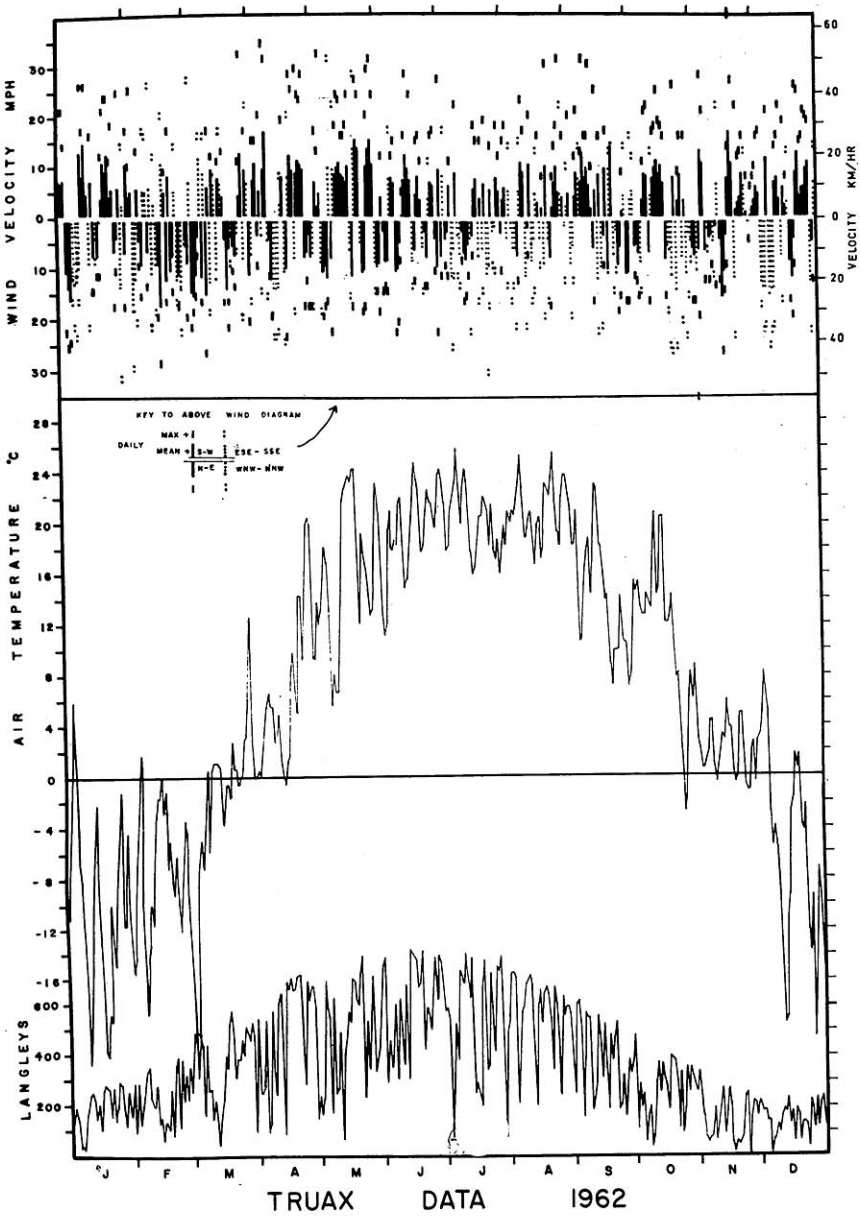

FIGURE 2. Data from the U.S. Weather Bureau at Truax Field in Madison, Wisconsin. Values of wind velocity and direction are the resultant (this figure only) means of 24 hr with maximum velocities for each day indicated by dots. The 24 hr mean of air temperature and 24 hr total of solar radiation both demonstrate great variability.

B. *Annual Cycles: Temperature and Oxygen, 1960–1964 and 1966*

1. Lake Mendota, Temperature and Oxygen

(a) 1960

The initial program for gathering data on temperatures began in 1960 (Fig. 3). Less information was collected in that year than in the succeeding ones. No measurements were made of dissolved oxygen in 1960 and all data were gathered at station 1 (Fig. 1). The 1960 climatological data from the U.S. Weather Bureau Station at Truax Field ($\approx$ 3.2 km from Lake Mendota) in Madison, Wisconsin, were plotted as moving ten-day averages on the tenth day.

The temperature of the water at 18 meters was about one to two degrees cooler in 1960 than the temperature at the same depth in 1961–1963 and 1966. This difference was not associated simply with a change in sampling position from station 1 (1960) to station 2 (1961–1963 and 1966). Both stations were compared occasionally in 1960 and only slight differences were noted. Furthermore, the data of Birge and Juday (1911) show temperatures at 18 meters from the area of station 1 in 1906 and 1907 similar to those of the latter years of this study. Therefore, specific episodes of wind velocities, air temperatures, and solar radiation must have combined during the critical vernal circulation to control the warming of the hypolimnetic waters. This supports some of the conclusions in Birge's (1916) paper on the work of the wind in warming the lake.

The response of the lake to the ten-day mean of air temperatures is illustrated best by temperatures in the first six meters (Fig. 3). The lag of water temperature, compared to that of the air, was prominent in all years and on all lakes to a varying degree.

(b) 1961

Temperature data were collected from Lake Mendota in 1961 (Fig. 4) more frequently than they were in 1960. Measurements were made of dissolved oxygen also. Data on both variables were relatively sparse during the first few months of 1961. Consequently the data taken during the spring missed completely the dramatic change in stratification normally associated with the disappearance of the ice.

More heat was distributed to the lower depths during spring circulation so that the lower waters began the summer season warmer than they were in 1960.

The depth of the lake where these data were collected was about 18.5 meters (Fig. 1, station 2) compared to about 21.5 meters

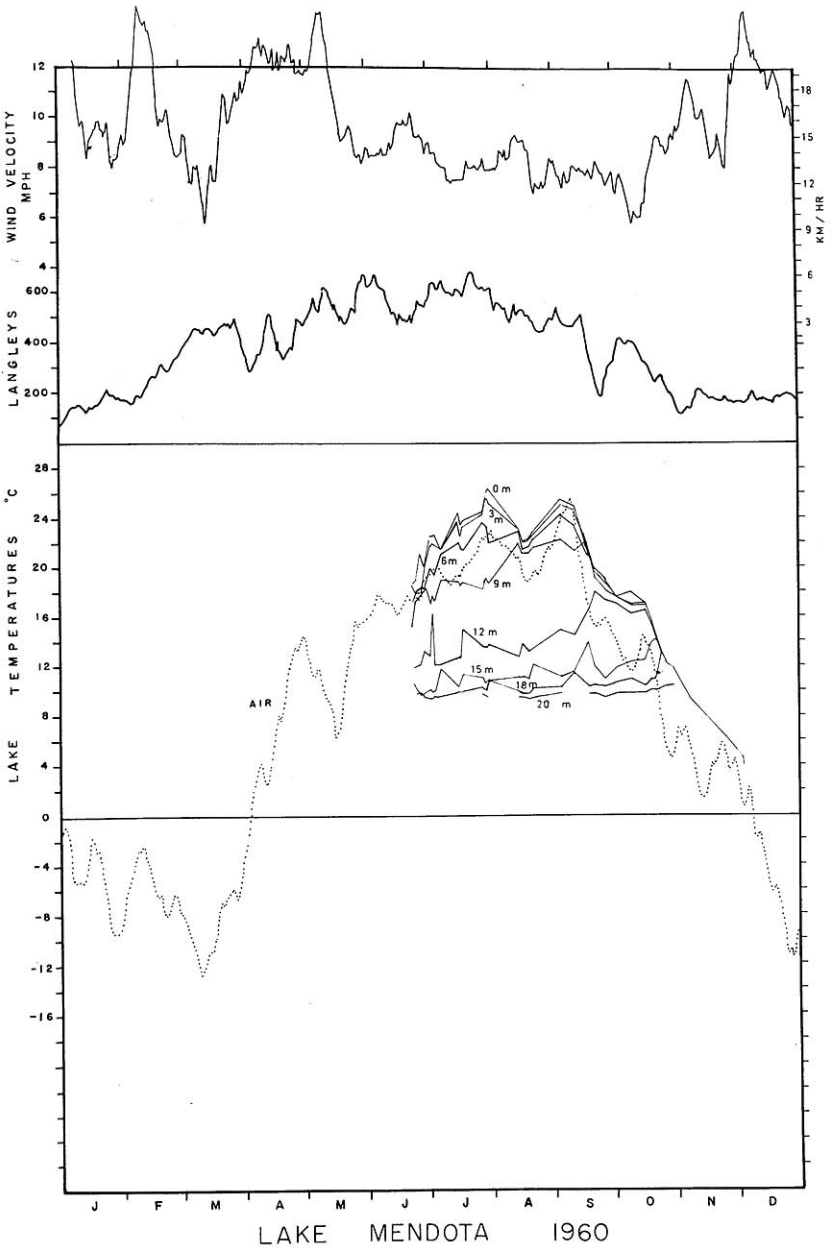

FIGURE 3. Lake Mendota temperature 1960. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day means plotted on the tenth day.

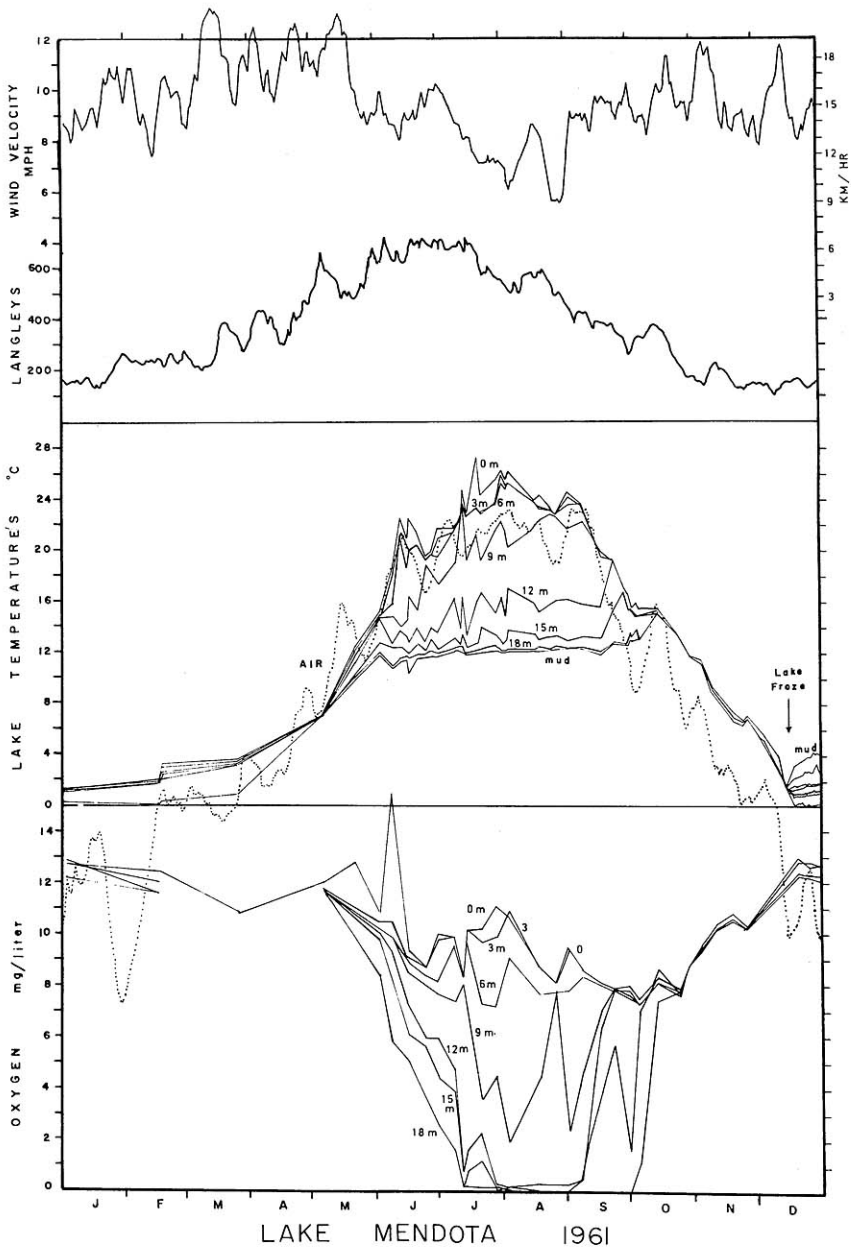

FIGURE 4. Lake Mendota temperature and oxygen 1961. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day means plotted on the tenth day. Mean wind velocities are generally lower in summer.

for station 1, 1960. The probe of the Whitney thermometer was dropped into the mud for measuring the mud temperature. The depth of penetration by the perforated head of the thermistor probe varied with sediment-composition and rate of lowering. The penetration at these depths was approximately 20 to 30 centimeters. In soft bottoms, the mud–water interface felt poorly defined from a cable.

On 15 December 1961 the entire surface of Lake Mendota froze. The temperature of the water on the preceding day was 1.4°C. No measurement was made on the day of freezing. Note the immediate stratification of temperature following freezing. The mud and lower waters are warmer than the surface waters owing to the density anomaly.

There is a rapid stratification of oxygen after the spring "overturn". "Occasional blooms" of algae may cause super saturation as is indicated in early June. The dominant causative organism of that bloom was the blue–green alga, *Aphanizomenon*. The dissolved oxygen of the hypolimnion is utilized rapidly through decomposition of organic and planktonic material. A continuous "rain" of decomposing organisms from the epilimnion, contributes to an anaerobic condition in the hypolimnion of many lakes, as has been indicated by previous studies (Birge and Juday, 1911; Ruttner, 1966; Hutchinson, 1957).

(c) 1962

Thermal data were gathered from Lake Mendota on all but three days in 1962 (Fig. 5). The data were collected at station 2 (Fig. 1). The average time of sampling during the day for the entire year was 1418 hours with a standard deviation of one hour and 34 minutes.

Following the rapid freeze in December of 1961, the lake gradually increased its content of heat as noted by the slight rise in temperatures at most depths.

In the spring, two days before the ice melted completely, there were large areas of open water at the sampling station. However, a big sheet of ice moved across the lake the following day and arrived over the sampling station when the measurement was taken. Thus, there was no apparent refreezing on 10–11 April as Figure 5 might suggest. The remainder of the ice vanished during the night. Following the departure of the ice, vernal circulation occurred and the lake took that big inspiration of air, as Birge (1908) described, until the density differences overcame the influence of the wind and stratification began.

In 1962 and 1963 the calm clear days stand out in the form of sharp peaks (Figs. 5 and 6), as much heat is absorbed at the sur-

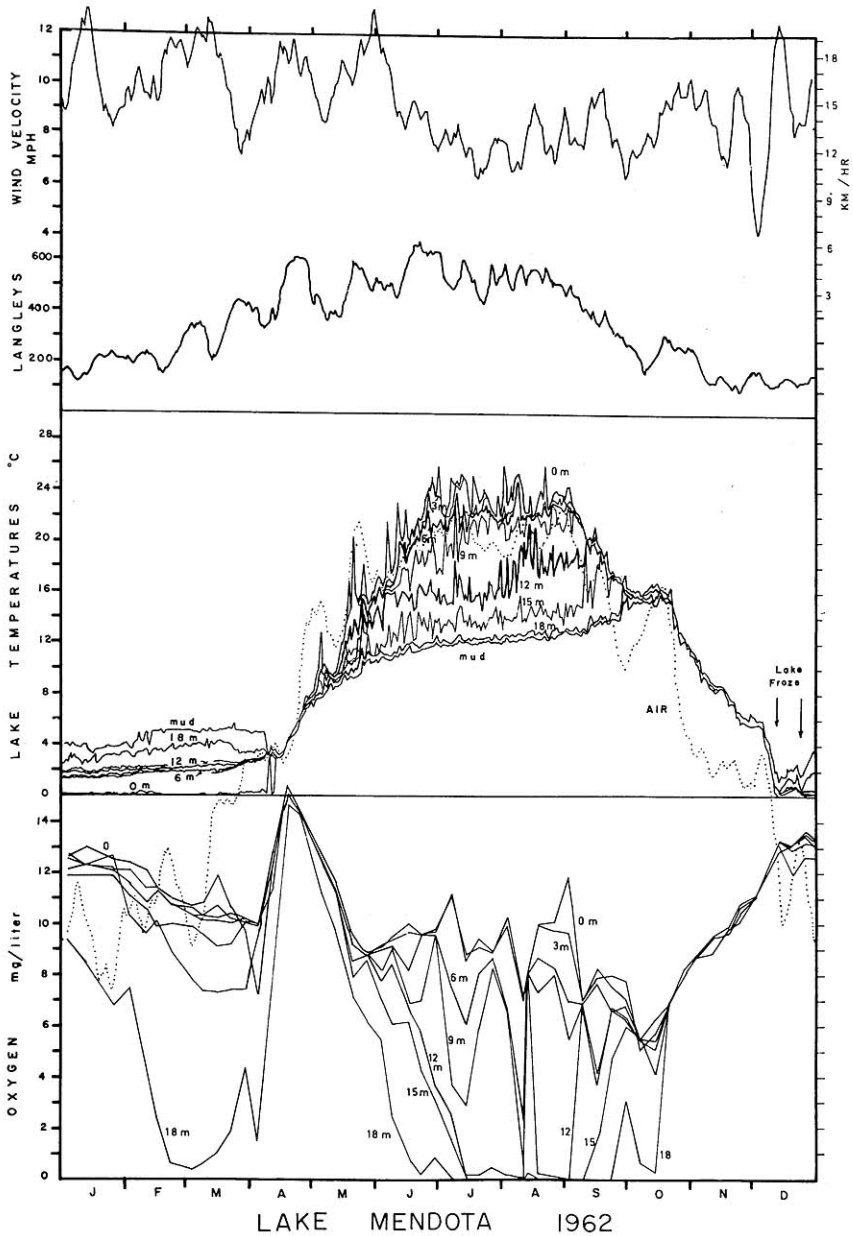

FIGURE 5. Lake Mendota temperature and oxygen 1962. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day means plotted on the tenth day.

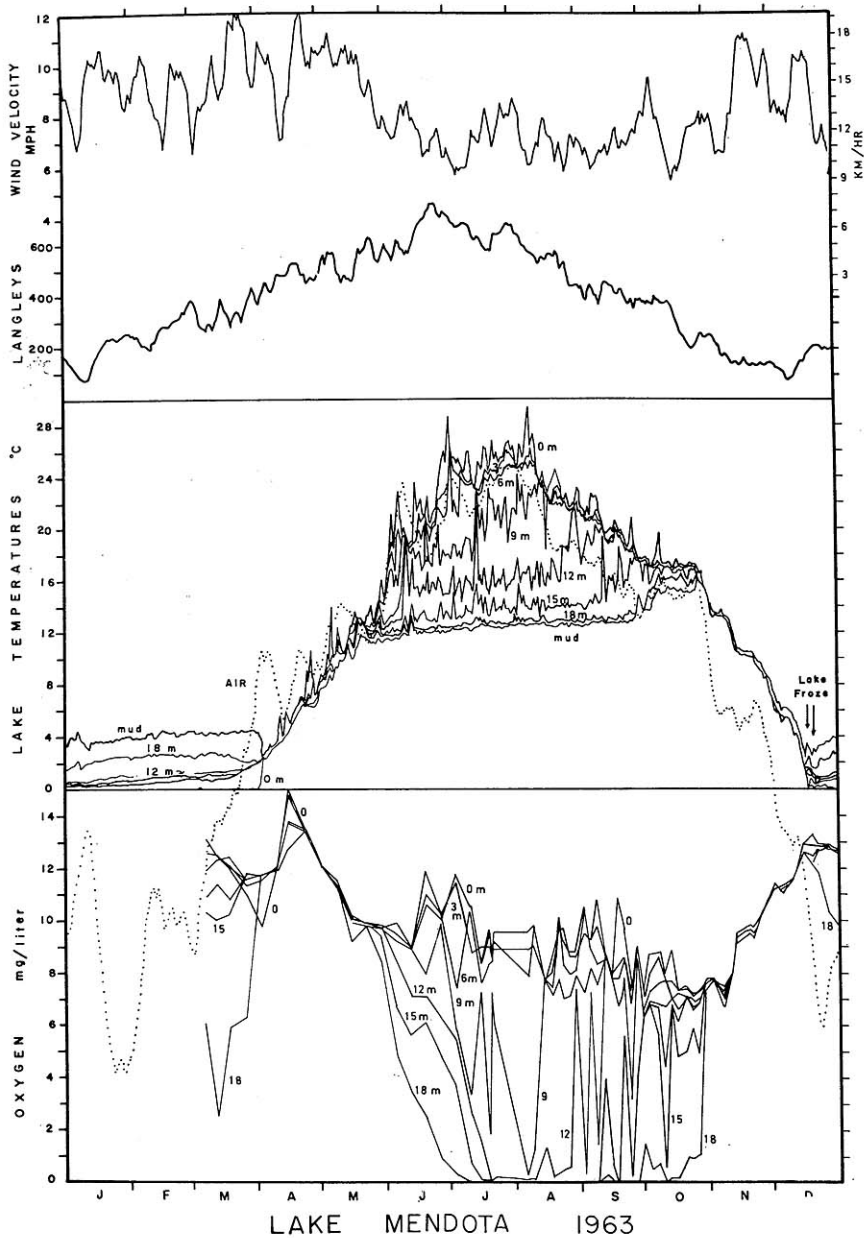

FIGURE 6. Lake Mendota temperature and oxygen 1963. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day means plotted on the tenth day.

face. This sharp stratification at the surface is destroyed easily by winds. Temperatures on these calm days were taken within one centimeter of the surface with the bead thermistor of the Whitney thermometer. Diurnal variations at the surface are significant on calm days, particularly days associated with clear nights, owing to heat loss by long wave radiation. On windy days, the surface temperature was measured within the first 10 to 20 centimeters of the surface when a similar displacement either way made no difference in the value.

Thermal changes at the surface appear to be more rapid and dramatic in 1962 than in 1960 and 1961. However, these fluctuations reflect the plot of daily measurements instead of weekly or scattered data, as was the case in 1960 and 1961. Below six meters of depth, there is rarely any indication of diurnal variation. The temperature at 12 meters fluctuates greatly, but this fluctuation is a function of internal waves and not diurnal heat flux.

The rise of air temperature in the fall, during the period commonly known as "Indian Summer," does little to raise the temperature of Lake Mendota. Although the temperature of the air during the day may exceed considerably the temperature of the water, the evenings are usually cool. Consequently the average daily air temperature may differ but slightly from the water temperature. The integrating effect the heat capacity of water provides, may allow the mean water temperature to remain similar for several days. This is illustrated fairly well in 1962 but to a lesser extent in 1960 and 1961 owing to less frequent sampling. Lake Monona (Figs. 8–10), and Lake Waubesa (Figs. 11–13) particularly, tend to respond more rapidly than Lake Mendota to changes in air temperature owing to their lesser volumes and heat budgets.

After the relatively warm period, usually in October, there is a precipitous drop in air and water temperatures preceding the winter months. The remaining stratification is eliminated and complete autumnal overturn commences. Heat is then lost at a relatively rapid rate at all levels until freezing.

About 20% of the lake surface froze on 12 December. The water temperature was 0°C from the surface down to 10 meters on that day. This unusually cold temperature was verified with a precision mercury thermometer. This thickness (10 m.) of water at such low temperatures was apparently quite unusual for as Birge (Neess and Bunge, 1957, page 61) remarks:

> "It is not impossible, theoretically, that the water of a lake should reach, in whole or in great part, a temperature of 0 degrees C., but it is very improbable that such a low temperature should actually occur before the lake froze. When the temperature has fallen below 1 degree, ice forms

on the lake if the air is cool, even during considerable wind. . . Still more easily does freezing occur if no wind blows. In either case the rate of conduction in water is so slow that the layer at a temperature of 0 would be very thin."

However, Birge (Neess and Bunge, 1957, pages 70–71) in the same article provided data (29 Dec 1911, the day after freezing) for a thermal structure which was remarkably similar to that recorded on 12 Dec 1962. Birge stated, "It is not likely that a lower temperature at freezing will be found than that of 1911." Obviously, time has at least provided an equal.

By 14 December, about 60 to 70% of the lake was frozen but strong winds broke up the ice-cover and reduced it to about 40% by 15 December. The lake did not freeze completely until 24 December. The circulation from 15 to 24 December set the stage for cooler water temperatures during the winter than the previous 1961–1962 winter.

Measurements of dissolved oxygen were made weekly at depth intervals of three meters (Fig. 5).

The utilization of dissolved oxygen in the lower waters proceeds more slowly in the winter owing to reduced temperatures. However, there is a significant reduction in the concentration of oxygen in the lower waters during the ice-cover.

Within a few days after the ice has melted, higher values of oxygen are present than at any other time of the year. This feature, recorded each year when timely data were available, is common to the three Madison lakes discussed and was recorded to a lesser degree by Birge and Juday (1911). However, the magnitude and rapid formation of this 1962 peak was somewhat unexpected because a winter oxygen deficit had to be removed before the peak and concomitant supersaturation with oxygen could occur. No similar peak occurred a few days prior to freezing even though the water was colder, could have held more dissolved oxygen, and the summer oxygen deficit had long since been repaid. In fact, compensation for the oxygen deficit of summer is seen at the end of the summer stratification when upper waters are mixing to greater depths with entrainment of hypolimnetic water and resultant lowering of upper oxygen values. Therefore, the main reason for the high values of oxygen after the ice goes out lies in the phytoplanktonic production of oxygen.

(b) 1963

Measurements of temperature were made at station 2 (Fig. 2) in Lake Mendota every day in 1963. The mean time of sampling was 1418 hour with a standard deviation of 1 hour and 37 minutes. The time of sampling was nearly identical to that of 1962.

After a relatively cold winter, the ice melted in a single day. Following this striking change in the thermal structure (Fig. 6), vernal circulation began and continued as in 1962 until the differences in density between the upper and lower waters required more energy than was available to maintain complete mixing. This period was described carefully by Birge (Neess and Bunge, 1956).

The two peaks of surface temperature on 1 July and 8 August were 28.8°C and 29.5°C respectively. The four highest surface maxima ever recorded on Lake Mendota by Birge, (Neess and Bunge, 1957) were 34.3°, 32.1°, 29.0°, and 29.9°C on 29 July 1916, 30 June 1910, 23 June 1911, and 20 June 1913 respectively. All of the above surface maxima were recorded between the hours of 1300 and 1600.

The general summer curve of both air and upper water temperatures is more abrupt in 1963 than 1962. This abruptness illustrates the correspondence between air and surface temperatures. As Birge (Neess and Bunge, 1956) noted:

> "There is far less correlation between the air and surface during autumn than during spring and summer. In spring, and especially in summer, the surface follows the air pretty regularly, though always with smaller range and with a decided lag which sometimes obscures the relation. But in autumn no such close relation is to be affected after the lake has become homothermous, partly also to the increased evaporation of warm periods which uses up more heat, and thus prevents a corresponding rise of surface temperature."

An extended warm period maintained a partial thermal stratification for three weeks in October. Note the step-like shape of the graph after the autumnal circulation commenced (Fig. 6). The lake froze initially on 17 December and finally on 20 December. With this fairly rapid closure, the temperatures at the six and 12 meter level were somewhat higher than they were in the first three months of 1963.

Measurements of dissolved oxygen in 1963 were initiated in March and, with the exception of one two-week period in late July and early August, were taken weekly until August after which time the lake was sampled every three to five days. Consequently the total number of measurements of oxygen in 1963 exceeded that of 1962. Again note the peak of dissolved oxygen shortly after the ice melted.

The more frequent sampling in 1963 provides additional detail that was not apparent from the 1962 graph of Lake Mendota (Fig. 5). Oscillations of the standing internal wave were responsible for some of the internal variation at the 9 and 12 meter level during August and September. The step-like variations of oxygen during autumn correspond fairly well to those of water tempera-

ture. Immediately after the lake froze, the lake restratified rapidly with respect to temperature and oxygen.

(e) 1966

Data were gathered weekly at station 2 (Fig. 1) in Lake Mendota from 19 March (three days after an early ice-out) to 30 August (Fig. 7). Cold weather followed the warming trend, which induced an early opening of the lake, and air temperatures dropped rapidly. Thus the lake actually lost heat in the first week after measurements were initiated. Then the customary rise in temperatures began during vernal circulation and the summer stratification developed later.

The winds certainly aided the loss and gain of heat to the lake during spring after ice-out but their reduced effect during summer provided no particular contrast to most previous years.

The maximum surface temperature recorded was 29.4°C on 1 July. The lack of several sharp temperature peaks, as noted in 1962 and 1963 (Fig. 5 and 6) reflects the longer interval between sampling and not the complete absence of hot calm days.

The concentrations of dissolved oxygen did not increase in such a striking manner shortly after ice-out as was noted in 1962 and 1963. In fact the 1966 spring curve was similar to the one recorded (Birge and Juday, 1911) in 1907. However, a prominent sub-surface maximum of oxygen was recorded at three meters on 1 July 1966. The dominant alga during mid-June and early July was *Aphanizomenon flos-aquae*. Lesser amounts of *Anabaena* and *Staurastrum* were also present during this period.

2. Lake Monona, Temperature and Oxygen

(a) 1961

All the sampling from Lake Monona was carried out in the deepest (21 meters) area at station 3 (Fig. 1). This deep zone of the lake is in a small area and is somewhat difficult to locate, there being less than 0.01% of the volume below 18 meters. Fewer measurements were made in 1961 (Fig. 8) than in either of the following two years.

The average depth of Lake Monona (7.7 meters) is intermediate to that of Lake Mendota (12.4 meters) and Lake Waubesa (4.6 meters). Its response to air temperature is intermediate also, i.e., it warms and cools more rapidly than Lake Mendota but less rapidly than Lake Waubesa. This is also substantiated by comparing the dates of freezing and opening of Lake Monona with Lakes Mendota and Waubesa (Bunge and Bryson, 1956, Parts I and II). The highest surface temperature recorded in 1961 was 28.8°C on 28 July.

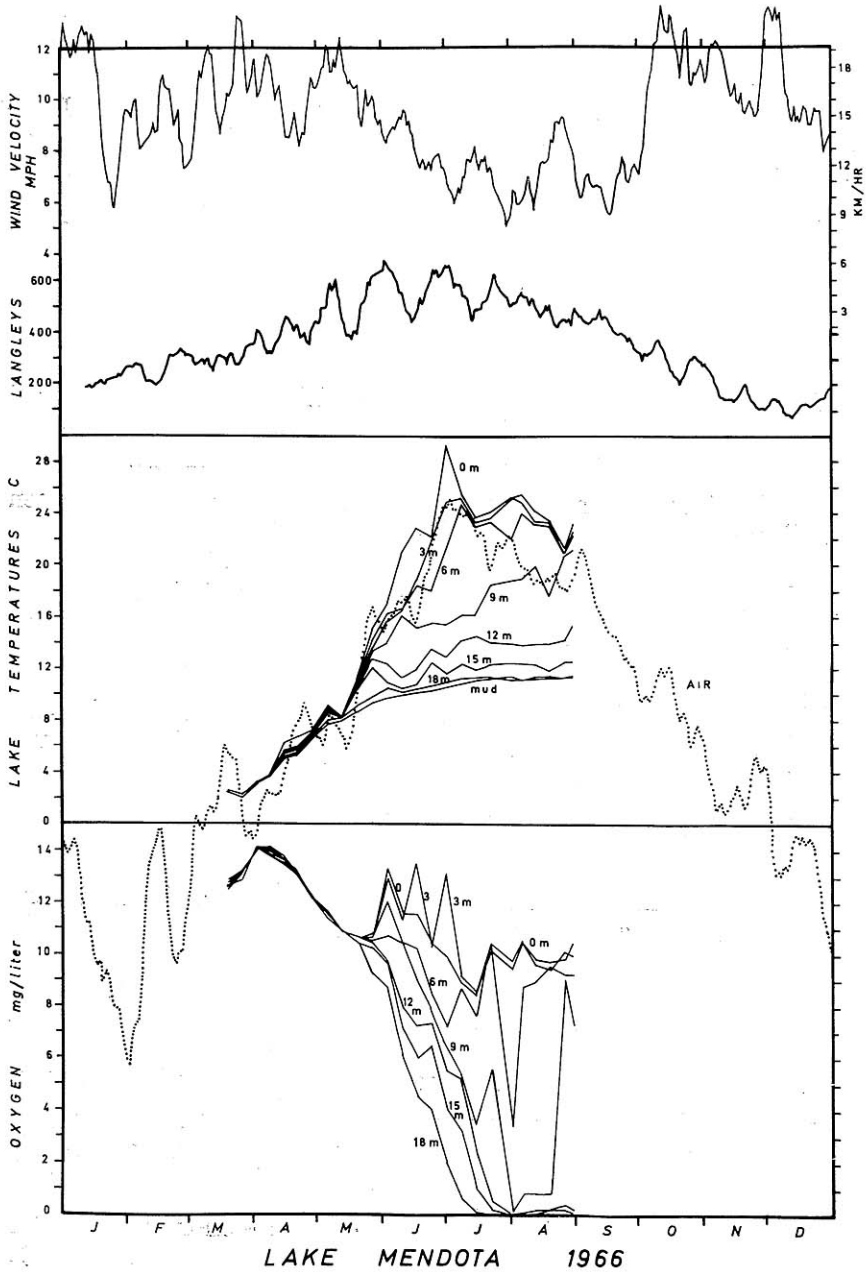

FIGURE 7. Lake Mendota temperature and oxygen 1966. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day means plotted on the tenth day.

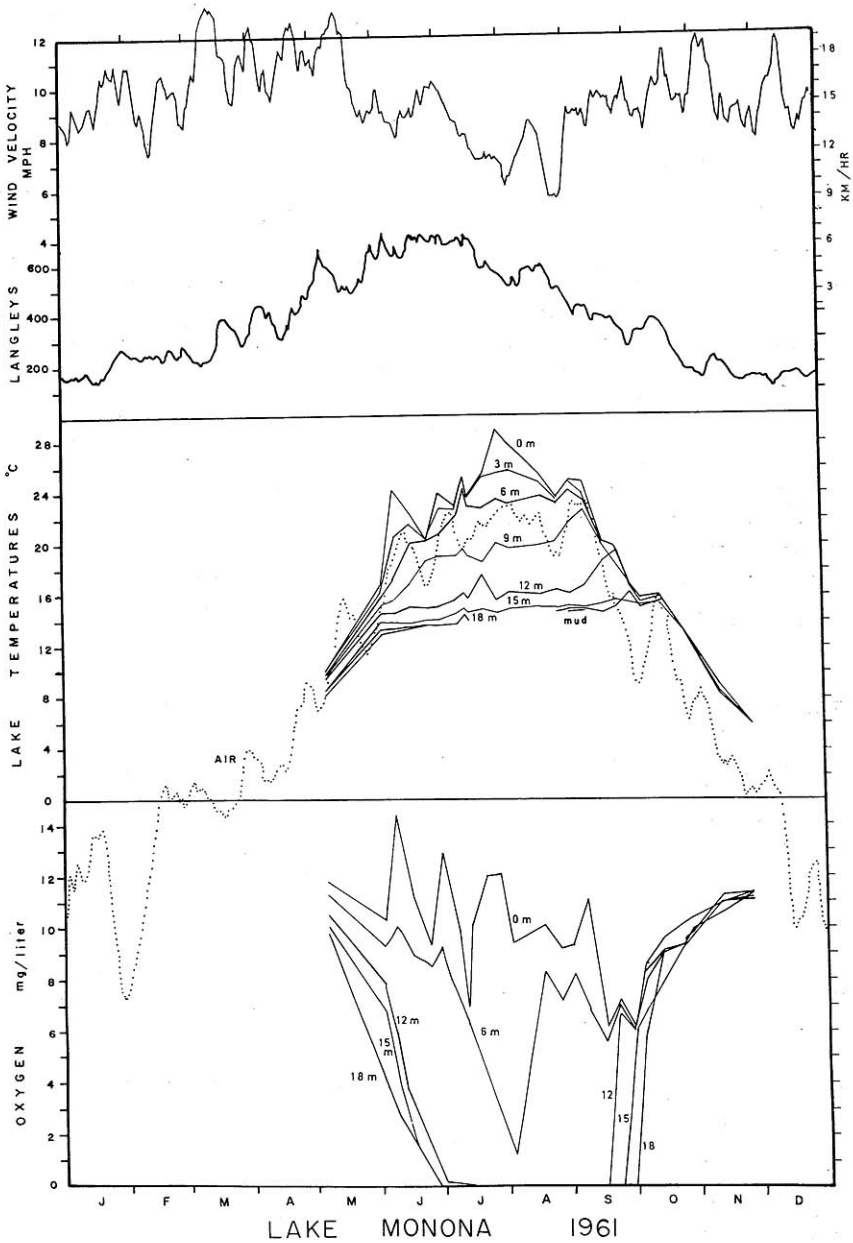

FIGURE 8. Lake Monona temperature and oxygen 1961. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day means plotted on the tenth day.

Lake Monona has apparent "plankton blooms" more frequently than Lake Mendota but less commonly than Lake Waubesa.

The dissolved oxygen becomes depleted rapidly in the lower waters. Furthermore, it is not uncommon to have low oxygen values within six meters of the surface.

The early onset of anaerobic conditions in the lower waters of Lake Monona reflects the small hypolimnetic volume and slightly warmer temperatures when compared to Lake Mendota.

Lake Monona receives an unnatural inflow of warm water year round. The major source of this warm water is the thermal discharge from the Madison Gas and Electric Company. Water is withdrawn from Lake Monona at a depth of approximately 4.6 meters through two intakes located about 106 meters from shore off Blount and Livingstone Streets.

The cooling water from Lake Monona is heated in the condensers of the power plant and returned to the lake with its temperature increased about 10°C above the ambient lake temperature. The power plant, with a maximum capacity of 594×10^3 m^3/day (157 mgd), discharges the heated water through two surface outfalls, also at Blount and Livingstone Streets (Zeller, 1967).

The thermal discharge of the Madison Gas and Electric Company appears to have an influence on the departure of ice from Lake Monona. This influence is apparent in spring when the area of open water, expanding outward from the thermal discharge, allows wind and wave activity to break up the remaining ice more readily. Although the mean opening date of Lake Monona (5 April) over the past 115 years precedes Lake Mendota (6 April) by only one day, the opening date in the 15 year period (1950–65) for Monona (20 March) precedes Mendota (8 April) by 19 days (Data from Ragotzkie, 1960; personal records of K. M. Stewart; and records of Capital Times Newspaper, Madison, Wisconsin, 1966).

A second minor source of heated water is from a local meat packing company which discharges some water through a viaduct into the Yahara River, which in turn empties into Lake Monona. The physical and biological impact of this water may be important at the immediate site of the discharge but, owing to its lesser volume and irregular nature, appears to have little significance for Lake Monona with respect to thermal structure.

In fact, other than locally, the overall influence of the relatively warm water from both of these companies to Lake Monona was slight at the time of this study when compared to the influence of the general climatological conditions. However, it is likely that the thermal discharge of the Madison Gas and Electric Company will have an increasing impact on the formation and departure of ice on Lake Monona as the power demands of the City of Madi-

son, and consequently the volume of cooling water increases. Some detailed information on the local biological effects is being studied (Magnuson, 1970).

(b) 1962

Measurements of temperature and dissolved oxygen in Lake Monona in 1962 began in April and continued until early December (Fig. 9).

The thermocline is usually less dictinct in Lake Monona than it is in Lake Mendota. The maximum surface temperature recorded in 1962 was 28.4°C on 30 June.

The general profiles of dissolved oxygen were fairly similar to those of 1961. The two highest concentrations of oxygen at the surface were 15.5 and 15.9 mg/l on 7 June and 30 June respectively. Water withdrawn from the hypolimnion in Lake Monona in August smells more strongly of H_2S than anaerobic water from either Lakes Mendota or Waubesa. The stronger odor of H_2S at this time follows a longer period of anaerobiosis in Lake Monona than the other two lakes. The quantity of dissolved oxygen in the upper waters is lowered prior to full autumnal circulation. The amount of lowering or raising of the oxygen content reflects the oxygen demand of the hypolimnetic waters and sediments.

(c) 1963

Over 80 trips were made to Lakes Monona and Waubesa in 1963 (Fig. 10 and 13). Temperature and oxygen measurements were made twice a week except for a two week period in the latter part of July and early August, when only temperatures were measured. To determine the daily variation, temperatures were measured 20 out of 21 consecutive days during late June and early July.

The highest temperatures at the surface were 29.6°C, 29.9°C and 28.8°C on 1 July, 19 July, and 8 August respectively. The temperatures in the lower waters of Lake Monona were roughly 2 degrees higher than those in Lake Mendota and 4 degree lower than those in Lake Waubesa. Note the very rapid restratification of temperature and oxygen after the freezing date on 16 December 1963.

The high value of oxygen (15.7 mg/l) on 16 April, represents at least a portion of the early peak after complete ice-out (3 April, 1963). This supersaturated condition indicates a large production of oxygen by phytoplankton as was noted in Lake Mendota and as will be apparent in Lake Waubesa. The other high value of oxygen recorded was 14.4 mg/l and occurred on 8 September.

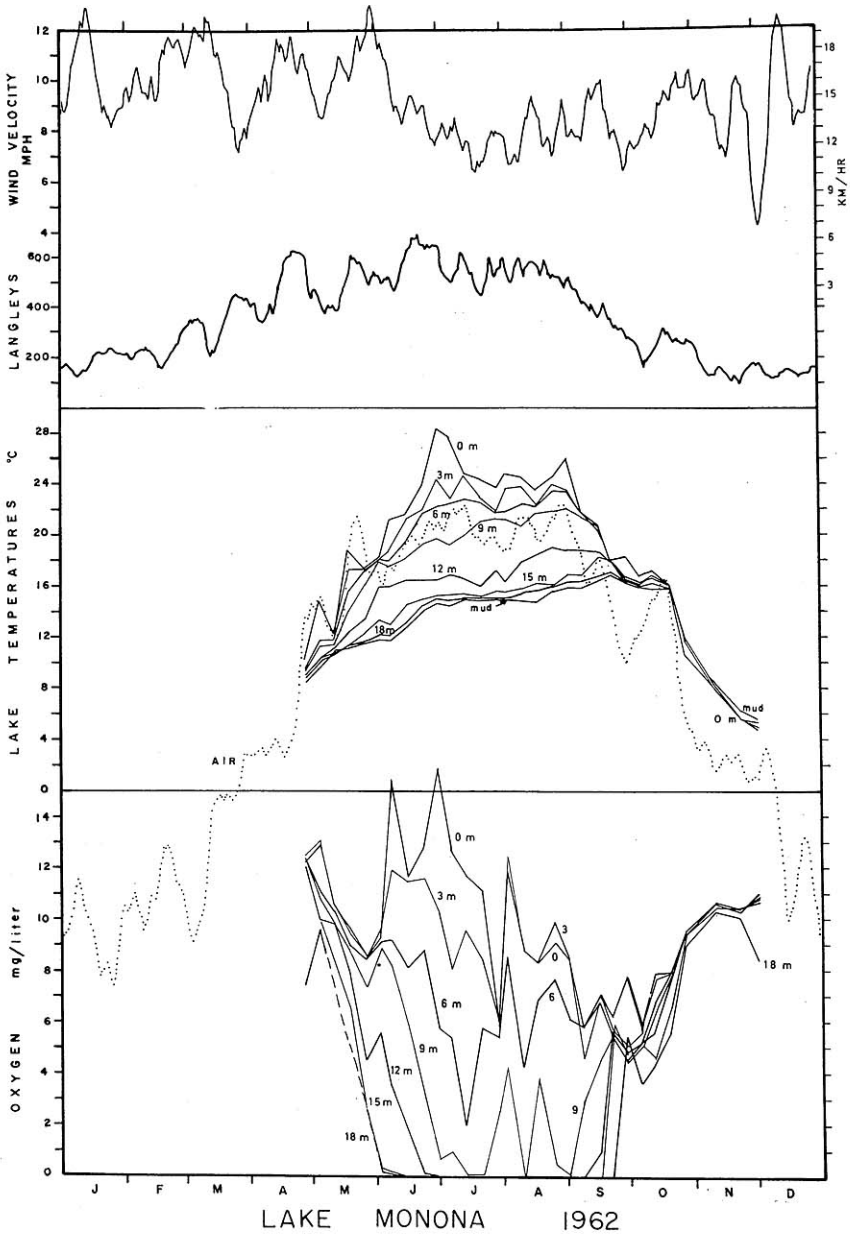

FIGURE 9. Lake Monona temperature and oxygen 1962. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day averages plotted on the tenth day.

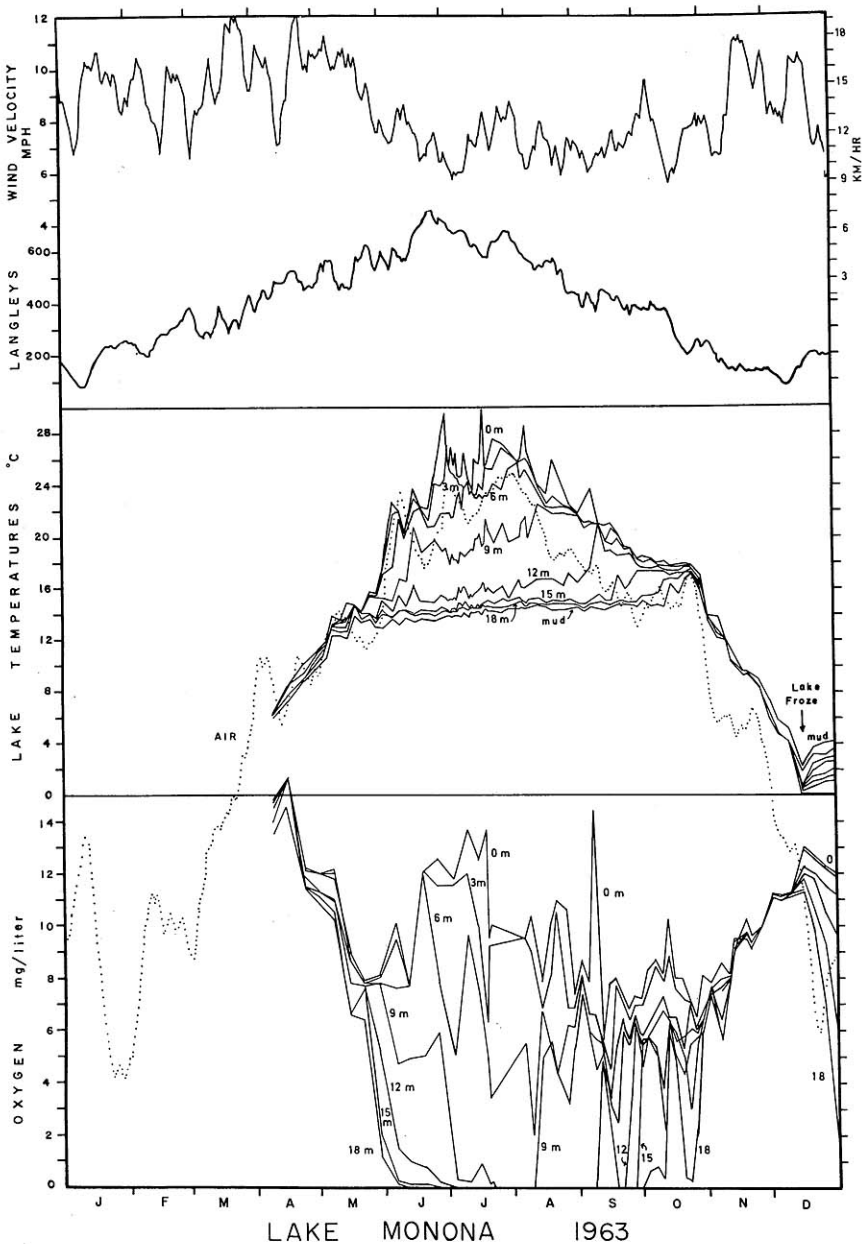

FIGURE 10. Lake Monona temperature and oxygen 1963. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day averages plotted on the tenth day.

3. Lake Waubesa, Temperature and Oxygen

(a) 1961

The sampling position for all years in Lake Waubesa is indicated at station 4 (Fig. 1). Some prominent limnological features of Lake Waubesa (Fig. 11), when compared to Lakes Mendota and Monona, are the high mean summer temperatures and the rapid response to wind and air temperature changes as reflected by dramatic changes in stratification.

The highest temperature recorded on the surface was 29.5°C on 28 July. Lake Waubesa stratifies but this stratification may be broken down even in mid-summer. Less difference exists in Lake Waubesa between the temperature of the surface and of the lower waters than in Lakes Mendota or Monona. Lake Waubesa would actually be quite stable during summer were it not for changing air temperatures. However, as the air temperature drops the water temperature also falls. Because a small change in temperature is associated with a relatively large change in density at higher water temperatures, the stability of stratification can change quickly and the lake circulates.

Lake Waubesa begins its autumnal overturn about one month earlier than Lakes Mendota or Monona.

Oxygen concentrations were measured at three depths during this first year of sampling on Lake Waubesa. Frey (1940) noted a thermal and marked oxygen stratification in Lake Waubesa earlier. Figures 11–13 (this paper) show this even more clearly. We mention this because there is a local belief that Lake Waubesa circulates freely all summer and does not stratify.

(b) 1962

The relatively rapid response of Lake Waubesa to climatological conditions is noted again this year (Fig. 12). For example, the spring warming of Lake Waubesa exceeded the rate of warming in Lakes Mendota and Monona. A practical index of this warming is noted by the earlier swimming in Lake Waubesa. During October, the temperature of Lake Waubesa rose briefly but there was no corresponding rise in Lakes Mendota or Monona. Waubesa is generally the first of the Madison lakes, excluding little Lake Wingra, to freeze and open. The highest surface temperature recorded in Lake Waubesa during 1962 was 28.7° on 6 July.

Lake Waubesa appears to be in a state of almost perpetual algal "bloom" and the concentration of dissolved oxygen varies considerably. The surface waters are supersaturated frequently. Continuous measurements of dissolved oxygen were not made on Lake Waubesa, but if they were, greater diurnal variation of oxygen in the surface waters would be expected than in the other

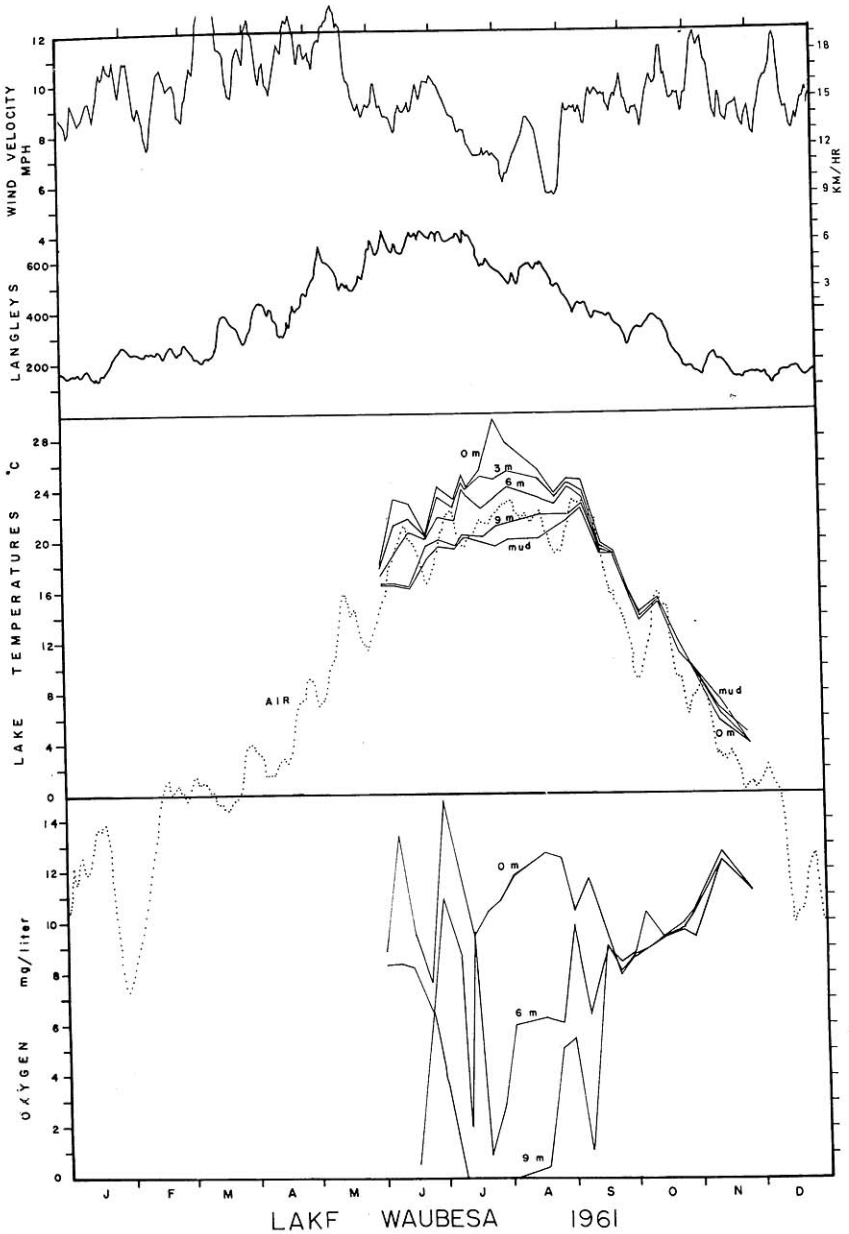

FIGURE 11. Lake Waubesa temperature and oxygen 1961. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day averages plotted on the tenth day.

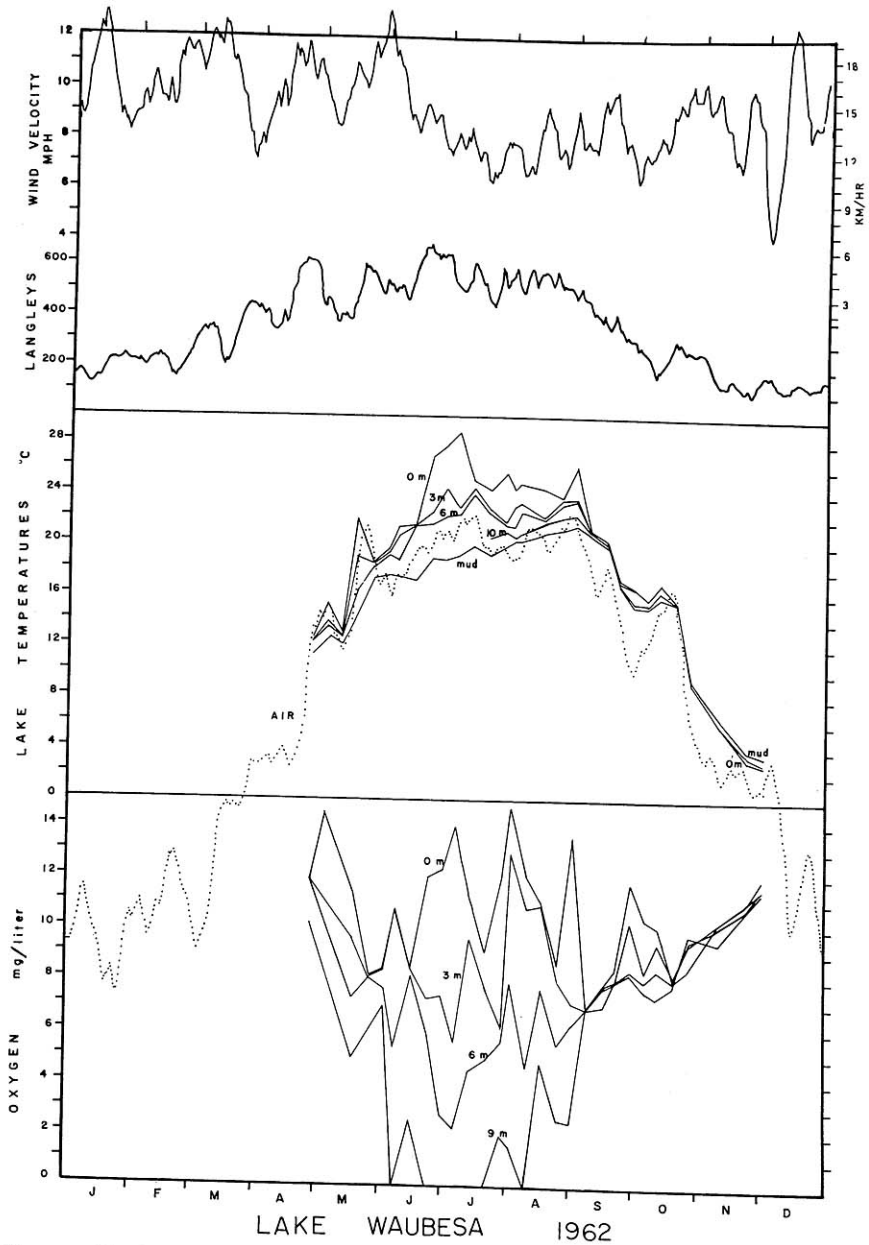

FIGURE 12. Lake Waubesa temperature and oxygen 1962. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day averages plotted on the tenth day.

two lakes. Therefore, potential programs for sampling Lake Waubesa should retain limits on the time of sampling to provide relative data.

(c) 1963

The ice disappeared 3 April 1963 and the measurements of temperature and dissolved oxygen began on 9 April (Fig. 13). Data were collected more intensively and over a longer period of time than in any previous year. The highest temperatures recorded at the surface were 29.8°C and 30.4°C on 29 June and 1 July respectively. The many sharp peaks and general variability of lake temperatures in early July also reflect the limited period of increased sampling.

In conjunction with changes in air temperature, it is interesting to note how much more closely the crest of water temperatures in Lake Waubesa follows the crest of solar radiation (Langleys) than in Lakes Monona or Mendota.

Following the departure of the ice, high values of dissolved oxygen are prominent. However, within the next six weeks the oxygen content of the lower waters plummets nearly to zero. A few days after this, the passage of a cool front caused a lowering of the water temperature. Then, even with relatively low winds, the lake essentially "turned over". This pattern, which affects the mid-summer stratification of temperature and oxygen, is demonstrated several times in 1963. The algal "blooms" create supersaturated conditions quickly. For example, the concentration of dissolved oxygen on 21 August was 21.7 mg/l, which after correcting for water temperature (25.8°C) and altitude, meant a saturation of 271%.

The somewhat intermittent summer stratification and mixing in Lake Waubesa may raise serious problems for individuals trying to interpret deposition in sediment cores.

The lake froze completely on 14 December.

C. *Ice Thickness: (Lake Mendota only)*

The earliest studies of ice on Lake Mendota were conducted by Buckley (1900) and Birge (Neess and Bunge, 1957) and his co-workers. Buckley was concerned with fracturing and expansion of ice as well as the physical effects of ice ramparts on the shores of lakes. Birge investigated the rates of growth and decay, thickness of ice, temperatures within the ice-layers, and insolation beneath the ice. Measurements of the thickness of the ice were conducted over 12 to 14 winters prior to and including the winter of 1916–17. The data from nine of those years were plotted (Fig. 14) by Birge* (Neess and Bunge, 1957, Fig. 45). The maxi-

*Birge continued his interest in ice beyond 1916–17 and, as Bunge and Bryson (1956, Part I) noted, "Collected at least 27 years of ice thickness data and about 30 years of winter water temperatures from 1894 to 1930".

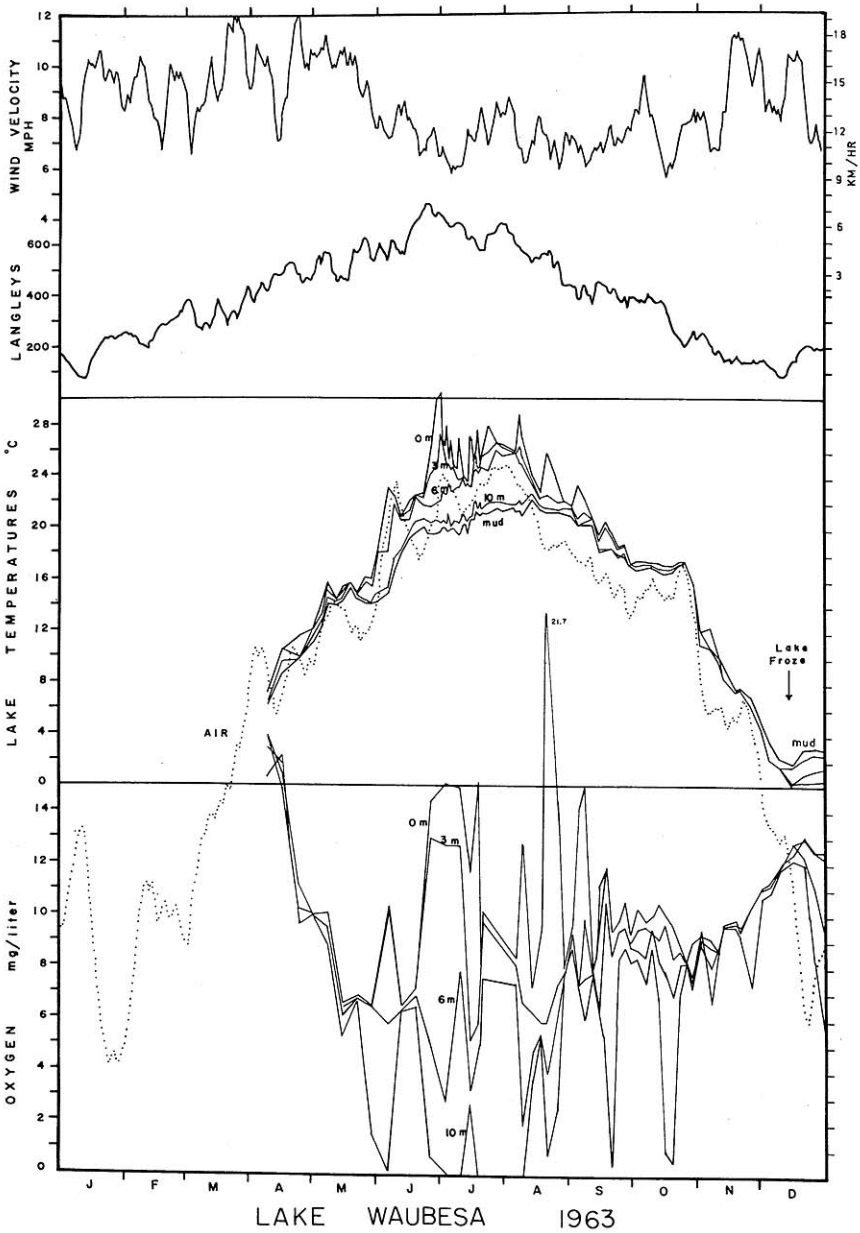

FIGURE 13. Lake Waubesa temperature and oxygen 1963. Wind velocity, solar radiation (Langleys), and air temperature are moving ten day averages plotted on the tenth day.

mum thickness recorded by Birge in those years was 75 cm in 1899. Only 30 cm were found in 1913. The maximum thickness recorded in this more recent study was 64 cm in 1963.

Birge (Neess and Bunge, 1957) separated winter into three periods with respect to ice, namely, a period of increase in thick-

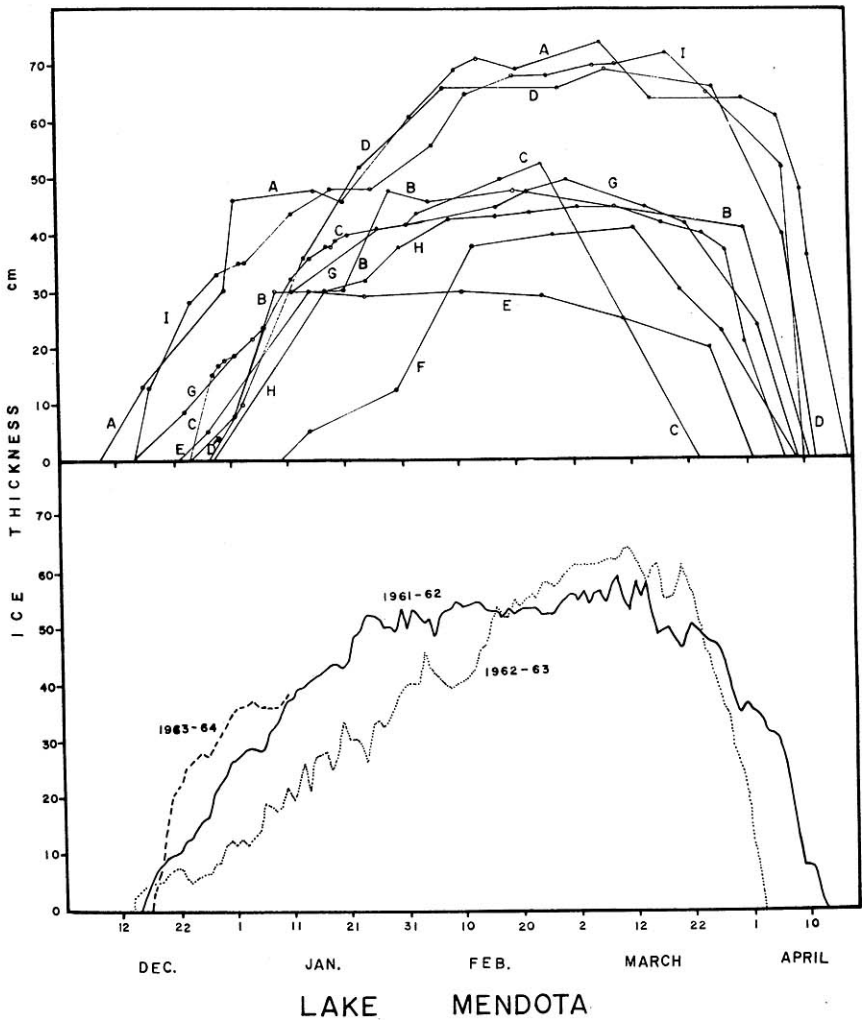

FIGURE 14. Ice thickness on Lake Mendota. Top half of figure illustrates earlier data of Birge for the years 1898–99 (A), 1900–01 (B), 1902–03 (C), 1911–12 (D), 1912–13 (E), 1913–14 (F), 1914–15 (G), 1915–16 (H), 1916–17 (I). Lower half of figure illustrates more recent data on ice thickness, measured every day in the winter of 1961–62, 1962–63, and the first portion of 1963–64.

ness, a period of stationary thickness during February and part of March, and the period of rapid decrease in thickness.

During 1912, Birge (Neess and Bunge, 1957) observed that the melting of ice took place mainly at the surface with but a small fraction of ice melting at the ice-water interface. In a more recent ablation experiment, Scott and Ragotzkie (1961) found that during approximately the last two weeks prior to ice out, the total ice melt on the surface exceeded the bottom melt about two-fold. Independent of whether the ice melt from the bottom is less than or equal to one half of the surface melt, it is apparent that most of the calories required for melting the ice do not come from the water itself. Juday (1940) was aware of this when evaluating the annual energy budget of Lake Mendota.

The inverse correspondence between ice thickness and air temperature is fairly obvious during the early growth and later wasting of ice. However, the period of "stationary thickness" appears less subject to change from fluctuating air temperatures.

Following the rapid freeze of smooth sheet ice on 15 December 1961, measurements of the ice thickness were made daily from 20 December 1961 for the remainder of the ice cover. The thickness of the ice was also measured daily in 1962 and 1963, and for part of the 1963–64 winter. All data were collected at or near Station 2 (Fig. 1). The measurements were made by inserting a meter stick, with a bar at right angles to the base of the stick, through a hole in the ice. The thickness was that distance from the bar, brought up against the underside of the ice, to the top of the ice.

The curve (Fig. 14) for 1961–62 is based on an average of two measurements each day taken approximately 200 meters apart. The curves for 1962–63 and 1963–64 are based on one measurement each day in new holes that were chopped or drilled in an area of fairly uniform ice thickness. Care is required during measurement because it is easy to have day-to-day differences in the measured thickness of ice that are not indicative of climatic changes. Scott and Ragotzkie (1961) have shown that significant variations in ice thickness may exist a few meters apart when clear ice (thicker) and snow-covered ice (thinner) are compared. Birge (Neess and Bunge, 1957) would have noticed this difference also had his ice data been collected more frequently during the winter.

Rather dramatic increases in ice thickness are noted after a midwinter melting of snow followed by refreezing. This "quick" growth of new ice is not always apparent when drilling a hole unless the lake is sampled regularly or unless a bubbly or crusty surface remains.

A "lens" of warm water beneath the ice is a common phenomenon in the last few days of ice cover. This warm "lens" is usually over and underlain with colder water thereby giving an impression of hydrostatic instability. For example, on 7 April 1962, five days prior to the disappearance of ice, a water temperature of 5.7°C was recorded at 53 cm below the ice-water interface. The ice was 22 cm thick. The temperature at 128 cm below the ice was 3.2°C. Birge (Neess and Bunge, 1957) also recorded these warm layers during late winter. Doubts as to the stability of these layers are usually allayed by measurements of electrical conductivity, which when converted to a common temperature, indicate an increase in electrolytes which counters the thermal differences.

The mean dates of freezing and opening for the years from 1852 to 1965 are 19 December and 6 April respectively. (Ragotzkie, 1960; Capital Times, 1966; and personal records of senior author, K.M.S.) The specific days at which these events take place are influenced greatly by weather conditions in the immediate preceding days. Thus, as mentioned earlier, Lake Mendota may freeze partially, then reopen partially, and so on until complete closure.

D. *Aspects of Light*

1. Secchi disk

Although the results of Secchi disk readings will be described in more detail elsewhere (manuscript in preparation), it is of interest to note that the clarity of Lake Mendota in 1961, 1962, and 1966 was equivalent to or better than it was in 1916 from the data of Birge (Neess and Bunge, 1957).

Comparing 45 measurements in Lake Mendota and 30 in both Lakes Monona and Waubesa, all in 1962, the mean values of the Secchi disk were 4.6, 2.0, and 0.92 meters respectively. Generally there is a noticeable decrease in transparency as one travels from Mendota to Monona to Waubesa.

The Secchi disk was viewed at 13.2 meters in Lake Mendota on 22 March 1969 while the lake was covered with ice. This is a new record for transparency on the Madison lakes.

2. Submarine Photometer

Separate results from the submarine photometer were also utilized to measure changes in the clarity of water over time (Fig. 15). From the variability observed, it is obvious that measurements of the extinction coefficients (computed as in Hutchinson, 1957, p. 381) (ranging from .303 to 1.227 for data between 1 to 5 meters) may be valid for only one day. "Representative" slopes on a semi-log graph may be difficult to obtain for one lake. The

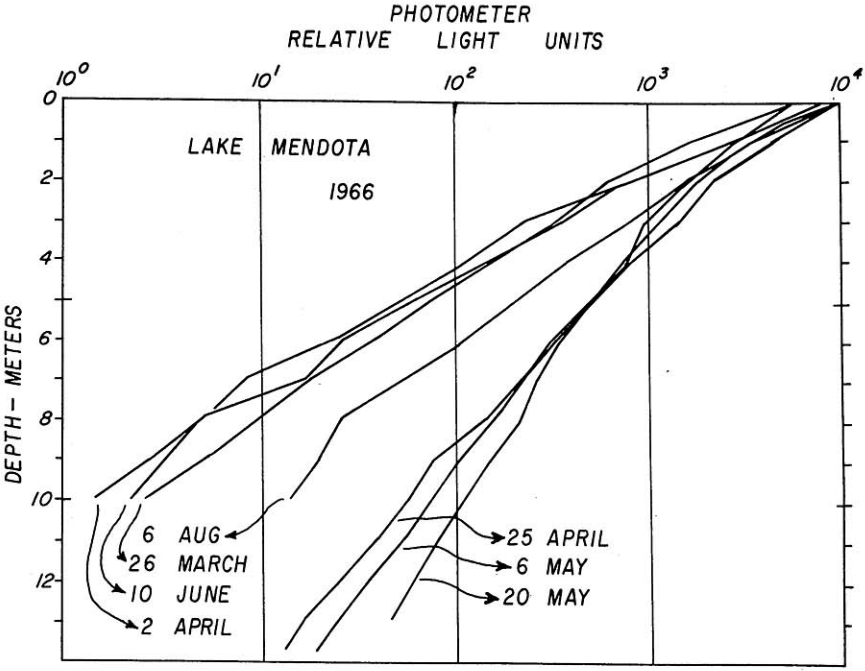

FIGURE 15. Range of variation in the submarine photometer readings in Lake Mendota (1966).

excellent early investigations by Birge and Juday (1929) on the transmission of solar radiation would have shown this overlap more clearly if several readings had been taken on each lake besides Mendota.

3. Transmissometer

A transmissometer (one meter path length) was lowered horizontally to measure microstratification within the three lakes, at half meter intervals, from August through December 1963. This period extended from times of significant thermal, chemical, and biological stratification, through the autumnal overturn, and into the initial stages of ice-cover. The results for Lake Mendota are illustrated in greatest detail by isometric projection in Figure 16. Separate standard inserts in the upper left and lower right of the same figure provide comparisons with Lakes Monona and Waubesa.

During late summer, Lakes Mendota and Monona were still stratified but the water clarity improved markedly below the thermocline. Although very slight thermal stratification remained in

Lake Waubesa on 14 August 1963, the microstratification, as measured by the transmissometer was gone and the water was very turbid from top to bottom.

The relatively turbid epilimnetic waters of Lakes Mendota and Monona might be expected owing to the normally increased quantity of phytoplankton in the euphotic zone. However, Whitney (1938) using essentially the same instrument in Lake Mendota, found a decrease in transparency below the thermocline. He attempted to relate microstratification to bacterial populations.

There were occasions, noted by Whitney (1938) and in this more recent study, when there was a temporary decrease in transparency within or just below the thermocline during the descent of the thermocline. One explanation for this metalimnetic decrease might be some greater planktonic, bacterial, or detrital densities in that zone of rapid thermal transition. Another or combined possibility, since the thermocline may separate anaerobic and aerobic water, is a redox zone of dissolution and precipitation of ferric hydroxide. Mortimer (1941) noted a turbid layer at the upper level of the hypolimnion and did attribute it to a zone of iron oxidation.

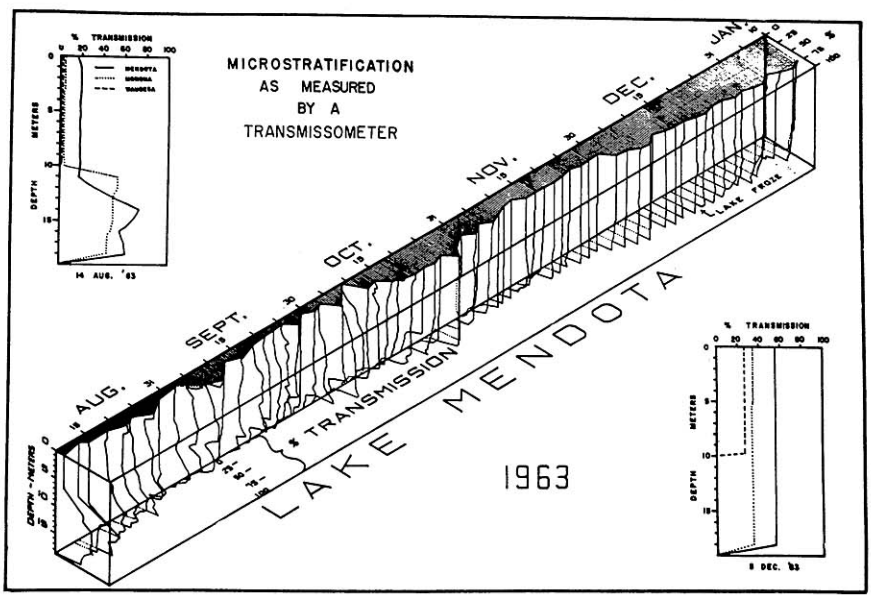

FIGURE 16. Microstratification in Lake Mendota as measured by a transmissometer (one meter light path) in 1963. Separate inserts in the upper left and lower right corners provide some comparison of Lakes Mendota, Monona, and Waubesa.

In 1938 and 1963 the water immediately over the mud-water interface was more turbid. The turbid water near the mud-water interface may reflect boundary layer disturbances from oscillations of standing waves as well as possible density or turbidity currents along the slopes (Hutchinson, 1941).

The general pattern of light transmission for the latter half of 1963 in Lake Mendota, as indicated by the transmissometer, was roughly inverse to that of the thermal profile. That is, the clarity of the water improved in the colder lower waters in summer and throughout the lake as the lake cooled during autumn. The Secchi disk transparency increased during the fall of the previous year (1962) as well. The relationship between cold water and better transmission may have been merely fortuitous for those lakes on those years because algal blooms do occur during autumn and under ice as well (Sawyer, 1947).

Changes in the development and disappearance of layers in a lake can be noted by the changes in transmission of light with time and depth. For example, the clarity of the lower water on 4 August and the clearer, more uniform condition on 25 December are readily apparent (Fig. 16 and 17).

On 26 September (Fig. 17) there was a turbid layer at one to one and one-half meters that was overlain with unusually clear water in the first half meter. The clear water at the surface may have allowed or created light inhibition of a certain algal community there while augmenting prolific algal activity at one to one and one-half meters.

Another unexpected feature was recorded on 8–9 October 1963. On these dates, a turbid and coffee-colored layer extended from the surface to about two meters (Fig. 17). This unusually dark water was most common in the southeastern portion of Lake Mendota near the University of Wisconsin. However, the discoloration extended quite some distance across the lake as well. Therefore, it is not likely that it was something "simply washed in" from rain. More probably the dark water was an intensive surface algal bloom although its specific composition was not determined at that time. The turbid layer of 8–9 October disappeared by 10 October.

The general significance of these findings and those of others (Whitney, 1938; Sauberer, 1962; Mahringer, 1963; Stewart et al. 1966; and Pinsak, 1967) is that the transmissometer can be used to trace or monitor the development or disposition of these layers. Furthermore rapid changes in Secchi disk and photometer values are understood and interpreted more readily when it is realized that such changes may reflect a microstratified zone or narrow layer as well as a general change in water clarity from the quantity and size of algae or inert suspensoids.

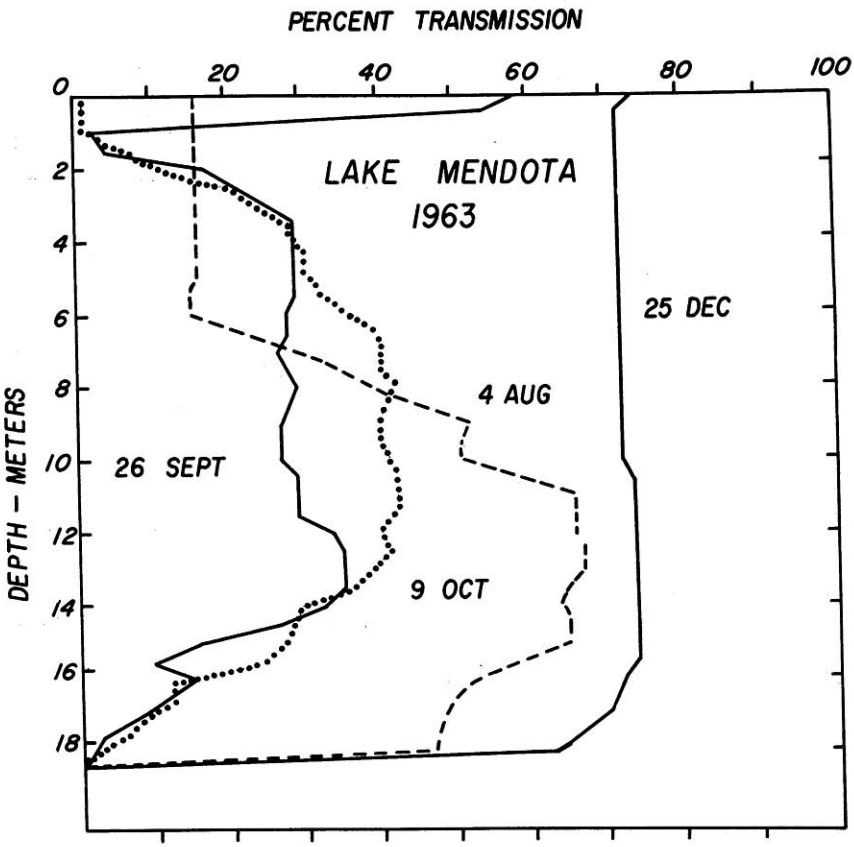

FIGURE 17. Microstratification in Lake Mendota as measured by a transmissometer (one meter path length) on four dates in 1963.

Had Secchi disks and submarine photometer readings been taken in Lake Mendota on 26 Sept 1963 or 8–9 Oct 1963, their results alone may have been puzzling to the investigator and might have given a skewed general picture of the clarity of the water.

IV. *General Significance*

Lake Mendota is a dimitic eutrophic lake in the north temperate zone. By the beginning of the year, the lake is normally frozen. The ice gains in thickness rapidly from the time of freezing through January. During February and early March, the rate of gain in ice-thickness decreases. In the latter part of March and early April there is a precipitous decrease in ice-thickness until the ice disappears.

The mean temperature of the water column under the ice rises gradually through the winter owing to absorption of solar radiation and heat flow from the mud. The concentrations of dissolved oxygen in the lower waters declines during periods of ice-cover.

When the ice departs, dramatic changes occur in the lake. The inverse thermal stratification of winter ceases and a relatively short period of homoiothermy follows. There is rapid heating of the entire water column during vernal circulation.

An interesting feature observed in all three lakes is indicated by the rapid rise in the content of dissolved oxygen at all levels within a few days after the ice melts. The total column of water has values of dissolved oxygen that are higher than at any other time of the year. On the basis of greater solubilities at lower temperatures one would expect theoretically that the highest values of oxygen would occur in the last few days just prior to freezing. This sudden increase in oxygen reflects increased photosynthetic activity of phytoplankton.

As vernal circulation continues, rapid increases in density differences between the developing epilimnion and the hypolimnion establish limits on the depth of mixing. Lakes Mendota and Monona are relatively stable, thermally, during late June and July and August. Lake Waubesa, although primarily a dimictic lake as are Lakes Mendota and Monona, has a shorter period of summer stratification and may be subject to aperiodic turnovers. The total quantity of dissolved oxygen in the lower waters of all three lakes generally decreases rapidly after the onset of stratification.

There is usually a period during the partial autumnal overturn during which the temperatures of Lakes Mendota and Monona remain relatively unchanged. Lake Waubesa shows this to a lesser degree because of its more rapid response time to climatological influences. The physical response of Lake Monona to climatological variables is intermediate to that of Mendota and Waubesa.

At this point in the annual cycle of the lakes, it usually happens that a cold northerly wind cools the remaining epilimnion further, overcomes the remaining density differences, and permits complete mixing. The oxygen deficit in the hypolimnion is repaid quite rapidly and an extended period of complete circulation usually follows. With decreasing water temperatures and increasing oxygen content, the lake proceeds toward the day or days that it freezes. Birge (1908) described appropriately the periods of autumnal and vernal circulation as the "inspiration" periods during a respiratory process.

The day each lake freezes, usually during December, as the day each lake opens in the spring is "critical" in the sense that

physical and chemical conditions change dramatically following this event.

Lake Waubesa is in a state of almost perpetual algal "bloom" and demonstrates the most rapid variability of any of the three lakes during their annual cycles. The algal conditions generally are reflected in the descending clarity of the lakes from Mendota to Monona to Waubesa.

V. *Summary and Conclusions*

These studies on some physical (temperature, light, and ice) and chemical (oxygen) variables in the Madison lakes provide detailed data on the annual cycles in Lake Mendota and the relatively little studied Lakes Monona and Waubesa.

The patterns of physical change within the Madison lakes are dictated primarily by morphometric and cyclic climatological influences. Prominent among the climatological influences are the temperature of the air, wind velocities and directions, and solar radiation. Even a cursory examination of these variables illustrates the huge changes that they can impress upon the lakes. The lakes respond to these cyclic external changes but do so through an integrating process.

These more recent data of Lake Mendota, especially when compared to those of Birge and co-workers several decades ago, are for the most part surprisingly similar. The thermal structure, oxygen profiles, and light readings of the lakes resemble those recorded by earlier investigators of the Madison lakes and do not in themselves indicate a significant change in the lakes.

The role of the thermal discharge into Lake Monona from the Madison, Gas and Electric Company may have an increasing effect as the population of Madison grows. This will be most obvious visually in the earlier disappearance of ice.

Owing to the useful information transmissometers provide concerning microstratification of organisms, turbid layers, and possible chemical and thermal stratification, it is unfortunate these instruments are not utilized more widely.

Owing to the vast scientific, recreational, aesthetic, and economic importance of the Madison lakes, it is advisable, as suggested (Sawyer, 1947; Stewart and Rohlich, 1967), to devote a small fraction of the research efforts and funds of a laboratory to a program of systematic surveillance for physical, chemical, and biological variables. These efforts would provide basic limnological data, vital for good management considerations, as well as knowledge of trends or changes in the lakes which may affect the direction of future research.

ACKNOWLEDGMENTS

The helpful comments of C. H. Mortimer during his Brittingham Fellowship at the University of Wisconsin and constructive criticism of H. H. Lettau (Meteorology Dept.) and J. C. Neess (Zoology Dept.) at the University of Wisconsin contributed greatly.

Grants to A. D. Hasler from the National Science Foundation (G-14530), U. S. Public Health Service (5T1-WP-2), and the Wisconsin Conservation Department and to K. M. Stewart from the Monroe Co. Conservation Council (9505–3236) N. Y., supported this research and appreciation is expressed for funds which made it possible.

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