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EFFECTS OF WIND STRESS, WIND SPEED AND DIRECTION ON PHYTOPLANKTON ABUNDANCE IN THE NEARSHORE ZONE OF LAKE MICHIGAN

A Thesis
Presented to the Faculty of the Department of Biological Sciences
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in Partial Fulfillment for the Degree of
Master of Science

by
David S. DeVault III
January 1982

THESIS DEFENSE

FOR

David S. DeVault
Master's Degree Candidate

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Table of Contents

List of Tables

List of Illustrations

Abstract

Phytoplankton data from a shore and offshore intake in the nearshore zone of Lake Michigan at Chicago were examined to determine the effects of wind speed and direction on phytoplankton density. Over the entire year, regression analysis indicated that a small (4.2 and 5.5 percent) but statistically significant portion of the daily variation in phytoplankton density at both sites occurred with densities increasing with increasing north winds. On days with only a north wind, wind speed accounted for 34.9 and 42.1 percent of the variation in phytoplankton abundance. During short periods ($<$ one month) of relatively constant water temperature (e.g., January), wind stress, independent of wind direction, explained nearly 50 percent of the daily variation at the shore intake with phytoplankton density increasing with increasing wind speed.

In the Chicago area during periods of thermal stratification, southwesterly winds produced upwellings which were accompanied by higher densities of both diatoms and blue-green _Oscillatoria_. The higher densities of blue-green algae caused by upwellings have not, to our knowledge, been previously reported in Lake Michigan.

INTRODUCTION

The process of eutrophication in Lake Michigan and the other Great Lakes differs considerably from that in smaller lakes (Beeton 1965, Stoermer and Ladewski 1976, Stoermer and Tuckman 1980). Due to the large size of the Great Lakes and to their slow horizontal mixing (Boyce 1974), the entire lake ecosystem does not initially respond to increases in nutrient loadings. Instead, a nearshore impact zone develops while offshore waters remain relatively unaffected (Schelske and Stoermer 1971, Rousar and Beeton 1973, Gannon 1975).

The nearshore impact zone is a result of the proximity of nutrient sources and of physical phenomena unique to large lakes. Within the nearshore zone, an area up to 10 km from shore (Csanady 1970, 1975), surface currents are generally parallel to shore and will flow in the same direction until a wind of sufficient strength produces a reversal in current direction (Csanady 1970, 1975; Boyce 1974). The nearshore currents typically have velocities that are significantly higher than those offshore (Csanady 1968, 1970). As a result, the water in the nearshore zone tends to move up and down the shore, with significant onshore to offshore mixing limited to periods of current reversal (Csanady 1970, Mortimer and Csanady 1975). In spring and autumn, horizontal mixing may be further inhibited by formation of the thermal bar (Rodgers 1965, Boyce 1974, Mortimer and Csanady 1975).

As in the open lake, the primary source of kinetic energy to the nearshore zone is wind. However, the nearshore water responds more dramatically to changes in wind speed and direction with wind shifts often being accompanied by major (and often rapid) readjustments in the current regime (Haung 1971, Boyce 1974, Sato and Mortimer 1975). This may result in the relatively rapid transport of water via longshore currents, as well as the movement of surface water from the open lake toward the shore (Csanady 1970, Mortimer and Csanady 1975). During stratified periods, the shoreward movement of surface water along one coast may result in upwelling along the opposite shoreline (Murty and Rao 1970, Boyce 1974). Because nutrient concentration and temperature are important growth factors for phytoplankton, the intrusion of relatively nutrient rich hypolimnetic water at the surface during upwelling and the resulting temperature decreases may be of biological importance (Boyce 1974). Thus the nearshore is subject to substantial variation in chemical and physical parameters due to wind action (Boyce 1974).

The nearshore zone phytoplankton populations are generally characterized by higher densities and eutrophic forms (Davis 1962; Holland and Beeton 1972; Holland 1968, 1969; Beeton and Edmondson 1972; Stadelmann _et al_. 1974; Stemberger 1974) caused by the warmer waters and nutrient trapped shoreward of the thermal bar (Rodgers 1965, Munawar and Munawar 1975, Lorefice and Munawar 1974). However, as is the case with chemical and physical parameters, nearshore daily phytoplankton densities may be extremely variable (Griffith 1955, Tarapchak and Stoermer 1976, Stoermer and Tuckman 1980). At least a portion of this daily variability in phytoplankton abundance should be a result of wind generated water movements. Such water movement has been shown to affect the horizontal and vertical distribution of both zooplankton (Andrews 1948, Colebrook 1960) and phytoplankton (Small 1967, Gronberg _et al_. 1974, Theriault _et al_. 1978).

Despite the high variability of nearshore phytoplankton populations and the knowledge that wind generated water movements may affect the spatial distribution and abundance of phytoplankton, phytoplankton studies have concentrated on the effects of nutrients and temperature on abundance. There have been few studies of the effects of wind on nearshore phytoplankton populations. The objective of this study was to determine the effect of wind on the phytoplankton abundance in the nearshore region of Lake Michigan at Chicago.

METHODS

Daily data on phytoplankton and water temperature from the offshore and shore intakes of the Central Filtration Plant of the City of Chicago were obtained for the year 1975. The offshore (Carter Harrison Crib) is located in 9 m of water at a distance of 4.5 km from shore, while the shore intake is located at the shore in 4 m of water (Ginsberg, personal communication) (Fig. 1). Phytoplankton analysis was performed by plant personnel using the Sedgewick-Rafter Method (American Public Health Association 1960, Makarewicz and Baybutt 1981). Organisms were identified to genera with colonial greens and blue greens reported as colonies or filaments/ml and diatoms and unicellular forms as cells/ml.

Daily mean wind speed and wind direction recorded at Midway Airport (12 km west of Lake Michigan) were also obtained from the City of Chicago for 1975. Two conversions were applied to the wind data. The first created a single variable representative of both speed and direction. The direction from which the wind originated was converted to its compass bearing in degrees. By rotating the usual compass bearing assigned to a direction and taking the sine function of that bearing, different weights could be created to represent direction. For example, the usual assignment of 0/360 to north, 90 east and 180 south would produce weights of 0, 1 and 0 (i.e., sine 90 = 1, sine 360 = sine 180 = 0). If the number of degrees assigned to a direction were rotated clockwise by 90° (north = 270, east = 0/360, south = 90), weights of -1, 0 and 1 would be generated for north, east and south, respectively. The weights thus created were then multiplied by the wind speed (cm/sec) to create a variable representative of speed weighted by direction. The creation of these weights resulted in an unambiguous indicator of direction that could not be generated using wind bearings as a low wind speed from a high bearing could equal a high wind speed from a low bearing.

As any effect produced by wind on the phytoplankton population would ultimately result from energy input at the air water interface, the wind data were also converted to wind stress ($gm/cm^2/sec$) following Ayers' _et_ _al_. (1958) equation. This equation is applicable at wind speeds below 7 m/sec, a condition that was exceeded on only three days (April 2, 8.9 m/sec; September 24, 9.4 m/sec; November 14, 8.9 m/sec) in 1975.

Regression analyses employed the various forms of the sine-velocity function, wind direction, wind speed and wind stress as predictors of phytoplankton density at both the crib and shore site. Phytoplankton data were transformed to $\log_{10}(x + 1)$ to better meet the assumptions of normality and equal variance.

In January, the effects of changing temperature, light and nutrient regimes of phytoplankton density would be minimal (e.g., temperature range 1.1 to 2.2°C). Much of the daily variation in phytoplankton density should be due to wind effects. In January, regression analysis using wind stress and correlation analysis using the following adjusted density (AD) were used: AD = (daily genera density - mean monthly genera density). This variable may be viewed as a measure of the variance about the monthly mean density. Analysis using the AD function assumes that over a short time period (1 month) of fairly constant temperature and nutrient concentrations, the daily density would closely approach the monthly mean density in the absence of wind effects. The Mini-Tab Statistical Package on a Prime 400 computer was used for data analysis.

RESULTS

Wind Effects

The sine-velocity function allowed each wind direction (N, NE, E, SE, S, SW, W, NW) to be weighted on a scale of 1 to -1. These weights were then multiplied by the corresponding wind speeds and regressed against phytoplankton density. Only the north weighting (wind direction = 1) was significant ($P < .01$), explaining 4.2 and 5.5 percent of the daily variation in the phytoplankton density over the entire year at the offshore and shore sites, respectively (Table 1). On days with only a north wind, wind speed accounted for 34.9 and 42.1 percent of the variation in the phytoplankton abundance (Table 1).

As any effect on the phytoplankton density produced by wind would be the result of energy transfer at the air/water interface, the wind data was converted to stress ($gm/cm^2/sec$) and the regressions with the data separated by wind direction rerun. As expected, significant results were found only on days with north winds (Table 1, Fig. 2) at the shore and offshore sites.

Because temperature can be an important factor affecting phytoplankton density (Damann 1966, Stoermer and Ladewski 1976, Makarewicz et al. 1979), regressions using water temperature as the predictor of phytoplankton density ($\log_{10}x+1$, where x = number of organisms/ml) were run at both sites over the entire year. These regressions were highly significant ($P < .01$) and explained over 15 percent of the daily variation at both sites. Because the effect of temperature is relatively large compared to wind, a period of relatively constant water temperature should provide for a more precise evaluation of wind effects on phytoplankton abundance. January 1975 was chosen as a study period because water temperatures ranged only a few tenths of a degree (1.1 to 2.2°C). Ice cover near Chicago during this period was minimal with no ice observed through January 5 and only open pack ice from January 6 through the middle of February (Leshkevich 1976).

No significant relationships existed between the sine-velocity function and phytoplankton density at either site in January. This was not totally unexpected as there was only one day when north winds prevailed. However, wind stress (independent of direction) as a predictor of phytoplankton abundance in January was highly significant at the shore, explaining 49 percent of the daily variation (Table 1). During this period <u>Tabellaria</u> spp., <u>Fragilaria</u> spp. and <u>Stephanodiscus</u> spp. were the dominant taxa comprising 30, 16 and 29 percent of the total population, respectively. Regressions of wind stress versus taxa abundance at the shore yielded significant results for <u>Tabellaria</u> spp. and <u>Fragilaria</u> spp. (Table 1, Figs. 3 and 4). No significant results were found for <u>Stephanodiscus</u> spp. or other taxa at the shore or crib stations.

As wind stress appears responsible for a large portion of the daily variation of the abundant genera at the shore, the effects of wind stress on the less important (< 10 percent of the total population) genera were investigated. Regression analysis failed to yield significant results, possibly due to the relatively low counts and frequent occurrence of zeros in the data base. Phytoplankton abundance of both the abundant and less abundant genera was, therefore, converted to the adjusted density (AD = daily - mean monthly phytoplankton density) form and used in correlation analysis with wind stress. Of the genera comprising more than 0.05 percent of the total mean population in January, only Navicula spp. and Stephanodiscus spp. were not positively correlated with wind stress using the adjusted density function at the shore site (Table 2). For the abundant genera during January (Fragilaria spp. and Tabellaria spp.), density increased as wind stress increased at our shore site. Both abundant and other, less abundant, genera were observed to exhibit higher counts (closer to or above the monthly mean) with higher wind stress during this period. This approach yielded no significant results for any genera at the offshore site.

Upwelling

By arbitrarily defining an upwelling as a decrease in water temperature of 6°C or more over a period of 48 hours, one major and two minor upwelling events were observed in the July and August temperature data (Fig. 5, Panel C). The first and largest of these events began on July 14 at the offshore site and was observed at the shore site beginning July 18. During this event water temperatures decreased 13°C and 11°C at the offshore and shore sites, respectively. The second event began on August 10 with temperature decreases of 4°C and 7°C at the shore and offshore sites, respectively. The third event was barely noticeable at the shore while a 6°C temperature decrease occurred at the offshore site on August 24.

All three events appeared to have been initiated by southwesterly winds between 200 and 400 cm/sec (Fig. 5, Panel B). Southwesterly winds move surface water in a northeasterly direction and have the net effect of causing the thermocline to tilt downward along the eastern shore and upward along the western shore (Mortimer and Csanady 1975).

Panel A of Figure 5 illustrates the total phytoplankton density at both sites. While there is a great deal of daily variation, it is clear that phytoplankton densities at both sites generally increase in response to upwelling and decrease in the intervening warm periods. To better elucidate the effect of upwelling on the phytoplankton population, five-day mean water temperatures and cell counts for the most common genera are plotted in Figures 6 and 7. These figures again illustrate that the population increases as water temperatures decrease. Most of this increase is a result of the diatoms *Tabellaria* spp. and *Fragilaria* spp. Surprisingly, the Cyanophyte *Oscillatoria* spp. also increases during the upwelling.

DISCUSSION

An understanding of the vertical and temporal distribution of phytoplankton requires the determination of the factors influencing phytoplankton abundance. Generally, nutrient availability, temperature and quantity and quality of light are considered to play fundamental roles in affecting algal abundance over the long and short periods of time. However, the structure of the plankton population at a give location within a lake may be markedly affected by currents and other wind generated phenomena. For example, Andrews (1948) observed changes in the horizontal distribution of _Cyclops_ spp., _Diaptomus_ spp. and turbidity in western Lake Erie following a storm with high winds. Ayers and Seible (1973) concluded that small scale water masses, each with different chemical and biological characteristics, moved through their sampling crib at Beeton Harbor (Lake Michigan). In general, plankton populations have been observed to move with their associated wind driven water masses in several lakes including Lake Erie (Andrews 1948), Lake Huron (Schelske _et al_. 1974), Clear Lake (Iowa) (Small 1967), Windemere (Great Britain) (Colebrook 1960) and Clear Lake (California) (Horne and Wrigley 1975).

Occurrences of shoreward movement of water and accumulation of phytoplankton at the downwind shore have also been observed. In Clear Lake (Iowa), Small (1963) observed that chlorophyll tended to accumulate near the downwind shore. In Lake Malaren (Sweden)

Gronberg et al. (1974) observed that NNE winds caused the movement of surface water containing large amounts of phytoplankton towards the southwest shore.

Our results suggest that over the entire year only a small but significant portion of the daily variation in phytoplankton density at both the offshore and shore sites of Lake Michigan at Chicago can be attributed to daily variation in wind speed and direction. However, on those days with a north wind only, a large portion of the daily variation is explained by increasing wind speed.

The effect of wind on lake water is a function of both the speed and fetch of the wind. In general, the greater the wind speed and fetch, the greater the speed of the currents generated and the volume of water moved (Hutchinson 1957, Boyce 1974). Also, observations of surface currents indicate a movement at an angle of approximately 72 degrees to the right of the prevailing wind (Federal Water Pollution Control Association 1967). The location of the Chicago water intake cribs in the southwestern portion of the north to south oriented Michigan basin provides the greatest fetch for northerly winds resulting in a shoreward movement of water. This shoreward movement could occur within 1.5 hours after a shift of the wind to a northerly direction (Sato and Mortimer 1975).

In Lake Michigan, both theory and observation suggest that northerly winds should cause surface waters to move towards the western shore of the lake causing phytoplankton to accumulate there. We have no completely satisfactory mechanism explaining the accumulation of phytoplankton in the nearshore zone as a result of northerly wind generated currents. One interesting possibility is that the accumulation of phytoplankton results from the change in current structure and nutrient concentration encountered as an organism moves from the open lake toward the shore. The nearshore current regime is characterized by shore parallel currents produced by the interaction of shoreward currents with the shoreline (Csanady 1970). During periods of shoreward flow (as during north wind events at Chicago), a cross current of shoreward flow at the surface and lakeward flow at the bottom are superimposed on the shore parallel current structure (Csanady 1975). Thus a planktonic organism under the influence of north winds would first move toward the western shore of Lake Michigan. Once in the nearshore zone, the organism would be expected to move parallel to the shore or alternatively back towards the open lake with the returning bottom cross flow current. Whether an organism remains in the shore parallel currents or is moved lakeward near the bottom may depend in part on the density and resulting sinking speed of that organism. Titman and Kilham (1976) have reported a decrease in sinking speed for several phytoplankton species in culture within a few hours of relaxing nutrient limitations. A phytoplankton moving from the relatively nutrient poor open lake to the relatively nutrient rich nearshore (Rockwell _et al_. 1980) would probably experience some relaxation in nutrient limitation. Due to the resulting decrease in sinking speed, the organism would be less likely to be returned lakeward with the returning bottom cross flow current leading to an accumulation of phytoplankton in the nearshore zone.

While wind speed and direction may account for a small amount of the daily variation in phytoplankton over the entire year, wind stress, independent of wind direction, was a major source of variation in phytoplankton abundance at our shore station over periods of one month or less when temperatures were relatively constant. Because there was not a significant wind direction effect due to the lack of north winds in January of 1975, it is not possible to suggest that wind produced surface currents tended to accumulate phytoplankton at the downwind side of the lake (i.e, Chicago).

Total phosphorus concentrations at the South District Filtration Plant (Chicago) are positively correlated with wind speed (Snow 1974). This correlation suggests that the observed concentrations in the nearshore water are determined partly by resuspension of bottom sediments which Schleicher and Kuhn (1970) have shown to contain phosphorus. The possibility exists that increased wind speed and thus wind stress nearshore may cause resuspension of bottom materials, increase nutrient concentrations and stimulate phytoplankton growth.

However, if the increase in algal density associated with higher wind speeds were due to nutrient stimulation, a time lag between nutrient and phytoplankton increase would be expected. In _in situ_ nutrient addition experiments on Lakes Michigan (Schelske _et al._ 1974), Superior (Schelske _et al._ 1972) and Huron (Lin and Schelske 1978), a time lag of approximately two days has been observed. A two-day time lag between change in wind direction and higher abundances of phytoplankton was not observed in this study. Increases in phytoplankton density occurred on the same day as the increased wind stress. As mentioned earlier, the shoreward movement of water could begin within 1.5 hours after a shift to northerly winds. We do not imply that increased nutrients are not responsible in part for increased phytoplankton densities in the long term. We simply suggest that the sudden increase over a short period with higher wind speeds is not caused by nutrient stimulation of phytoplankton growth.

At least a portion of the increase in plankton density at the shore intake is a result of resuspension of bottom organisms. Several of the abundant species of *Tabellaria* and *Fragilaria* common near Chicago frequently occur as members of the periphyton. These include *F. intermedia, F. pinnata, F. capucina, T. fenestrata* and *T. flocculosa* (Hustedt 1932, Stoermer and Yang 1970, Lowe 1974). With the possible exception of *Asterionella* spp., the less abundant (*Asterionella, Synedra, Oscillatoria*) genera that increased with wind stress also contain species that are associated with attached or benthic communities for at least part of their life cycles (Prescott 1968, Stoermer and Yang 1970, Lowe 1974). At the offshore site, the greater water depth and distance from shore would be expected to reduce such resuspension. We found no relationship between wind speed and phytoplankton density in January at the offshore site.

While winds from the north generally increase phytoplankton density at both sites, wind from other directions may affect algal densities temporarily when the lake is thermally stratified. Upwelling and subsequent increases in phytoplankton density were observed in response to southwesterly winds. The association of southwesterly winds with upwelling along the west coast of Lake Michigan agrees with the upwelling pattern reported by Murty and Rao (1970) and Csanady (1972).

Upwelling events were accompanied by increased densities of Tabellaria spp., Asterionella spp. and Fragilaria spp. at both sites. The Cyanophyte, Oscillatoria spp., also increased during these events. Increased diatom populations as a result of upwelling have also been observed by Schelske et al. (1971). Increased densities of blue-green algae as a result of upwelling have not, to our knowledge, been reported in Lake Michigan.

The observed changes in phytoplankton density during and immediately following upwelling may result from increased nutrient concentrations and/or the organisms being carried into the sample area by the water upwelling. Phosphorus and silica, elements considered to limit phytoplankton growth in Lake Michigan, typically exhibit higher concentrations in the hypolimnion during summer stratification (Hutchinson 1957, Schelske et al. 1971, Rockwell et al. 1980). As epilimnetic silica has been depleted to levels limiting to the diatoms in recent years (Stoermer 1974, Parker et al. 1977, Rockwell et al. 1980), the infusion of silica rich hypolimnetic water may explain the increased diatom populations. This does not, however, explain the observed increase in Oscillatoria spp.

While increased phosphorus levels remain as a possible contributor to increased algal densities, the alternate hypothesis that at least a part of the increase is a result of horizontal and vertical movement of organisms into the sampling area must be considered. By definition, upwelling is the horizontal and vertical movement of hypolimnetic water toward the shore and surface as a result of tilting of the thermocline (Mortimer and Csanady 1975). Recently, a deep chlorophyll maxima has been observed in the lower metalimnion of Lake Michigan (Brooks and Torke 1977, Mortonson and Brooks 1980) and in the eastern basin of Lake Erie (DeVault, unpublished data). In Lake Michigan this maxima was composed of *Dinobryon sociale*, *Tabellaria fenestrata*, *Fragilaria crotonensis* and green and blue-green filamentous algae (Brooks and Torke 1977). Species of *Oscillatoria* spp. also occur in the metalimnetic region (Klemer *et al*. 1981). The genera *Fragilaria*, *Tabellaria* and *Oscillatoria* increased in our data. It is not unreasonable to suggest that the surface and shoreward movement of metalimnetic and hypolimnetic water was accompanied by phytoplankton organisms inhabiting these areas. This would result in the sudden increase in algal densities observed. With time, the availability of nutrient from the nutrient rich hypolimnetic water would probably further enhance growth of the phytoplankton population.

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Table 1. Statistically significant relationships between wind and phytoplankton at the offshore and shore intakes. Phytoplankton units are $\log_{10}x+1$ where x = organisms/ml. Wind speed units are cm/sec. Wind stress units are $gm/cm^2/sec$.

Independent Variable	Dependent Variable	Regression Equation	R^2	Significance
Offshore				
Sine-velocity(north weight=1)	Total phytoplankton	$y = 2.93 + .0114x$	4.2%	$P < .01$
Wind speed(north only)	Total phytoplankton	$y = 2.87 + .0006x$	34.9%	$P < .05$
Wind stress(north only)	Total phytoplankton	$y = 2.998 + .0084x$	41.9%	$P < .03$
Shore				
Sine-velocity(north weight=1)	Total phytoplankton	$y = 3.0 + .0143x$	5.5%	$P < .01$
Wind speed(north only)	Total phytoplankton	$y = 2.9 + .0011x$	42.1%	$P < .05$
Wind stress(north only)	Total phytoplankton	$y = 3.1098 + .0962x$	41.3%	$P < .03$
Wind stress[1]	Total phytoplankton(January)	$y = 2.91 + .149x$	49.9%	$P < .01$
Wind stress[1]	*Fragilaria* spp. (January)	$y = 2.145 + .125x$	22.9%	$P < .05$
Wind stress[1]	*Tabellaria* spp. (January)	$y = 2.40 + .1433x$	43.0%	$P < .05$

[1] Independent of wind direction

Fig. 1. Lake Michigan and the Chicago nearshore area showing the shore and offshore water intakes.

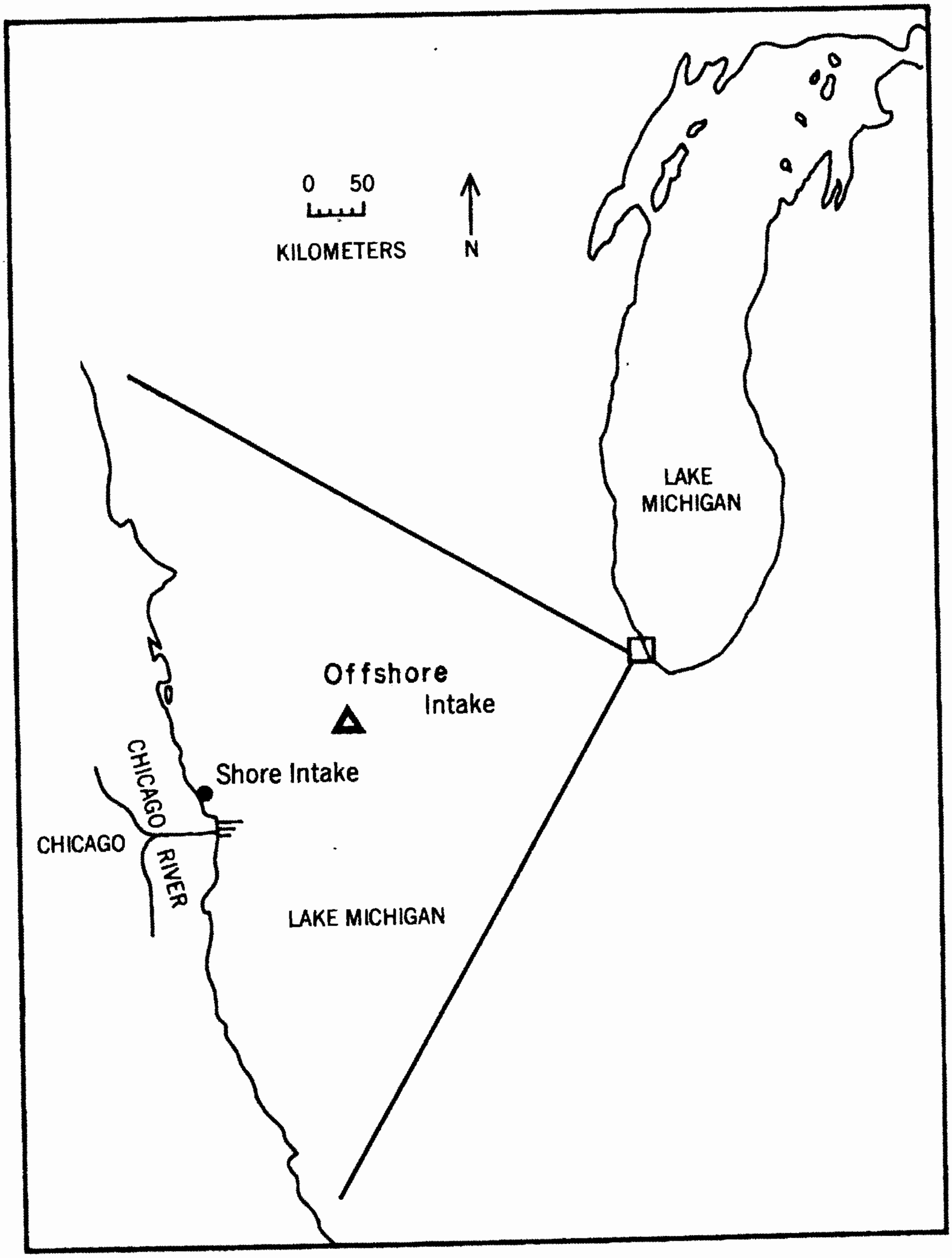
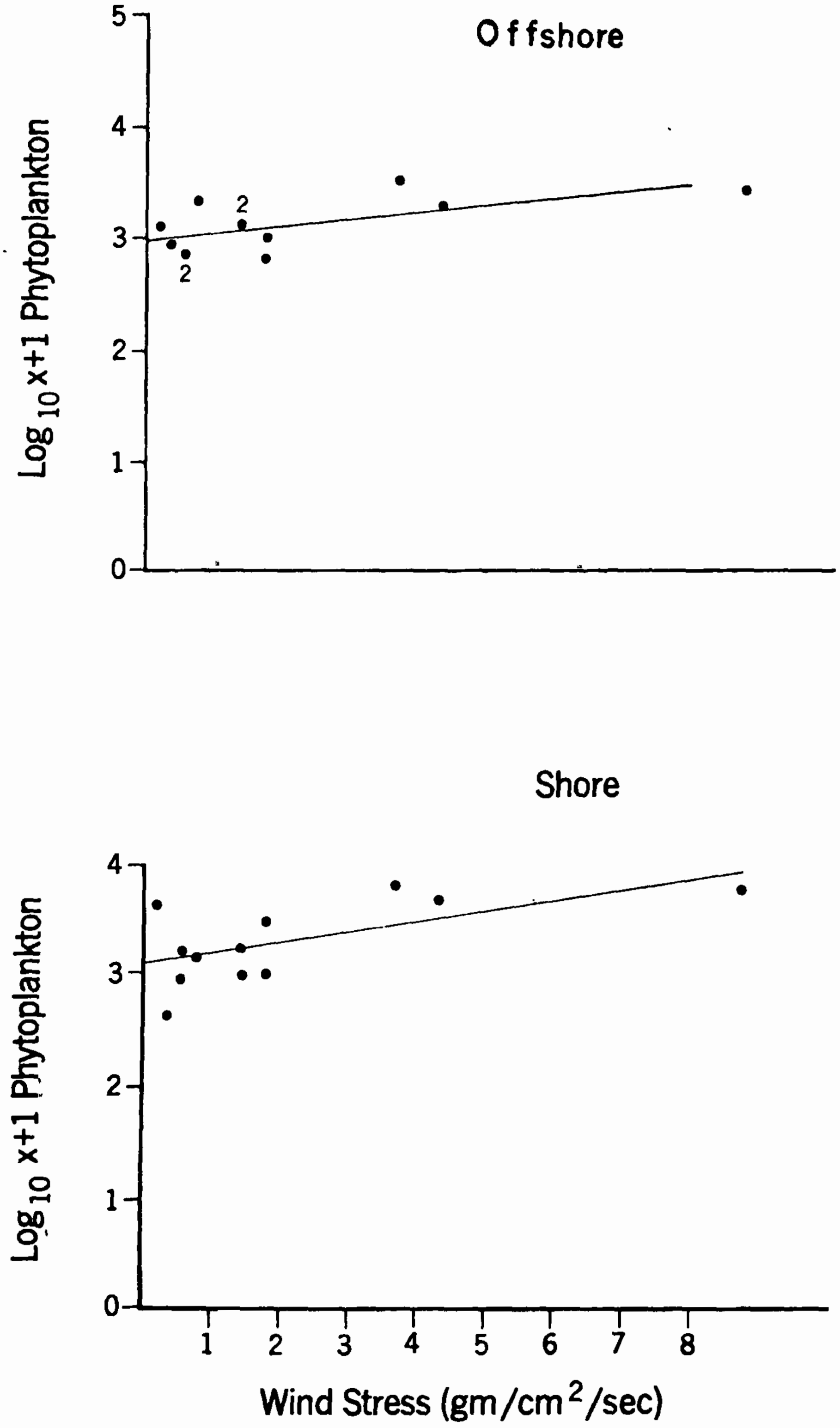


Fig. 2. Total phytoplankton and wind stress on days with north winds in 1975. x = organisms/ml.



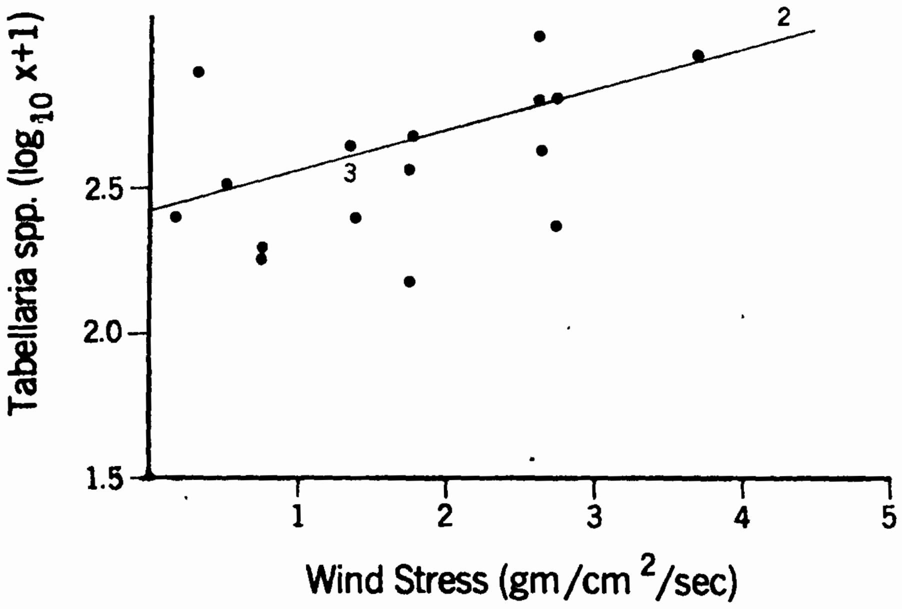


Fig. 3. The relationship between Tabellaria spp. and wind stress at the shore intake in Lake Michigan, January 1975. x = organisms/ml.

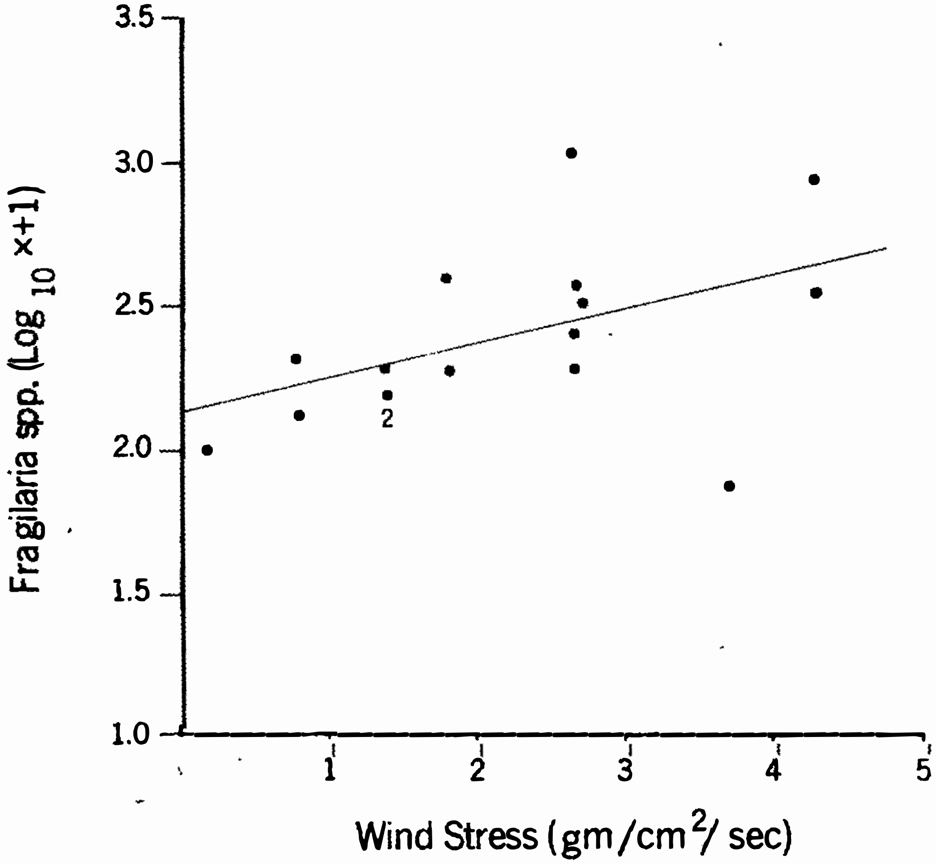


Fig. 4. The relationship between *Fragilaria* spp. and wind stress at the shore intake in Lake Michigan, January 1975. x = organisms/ml.

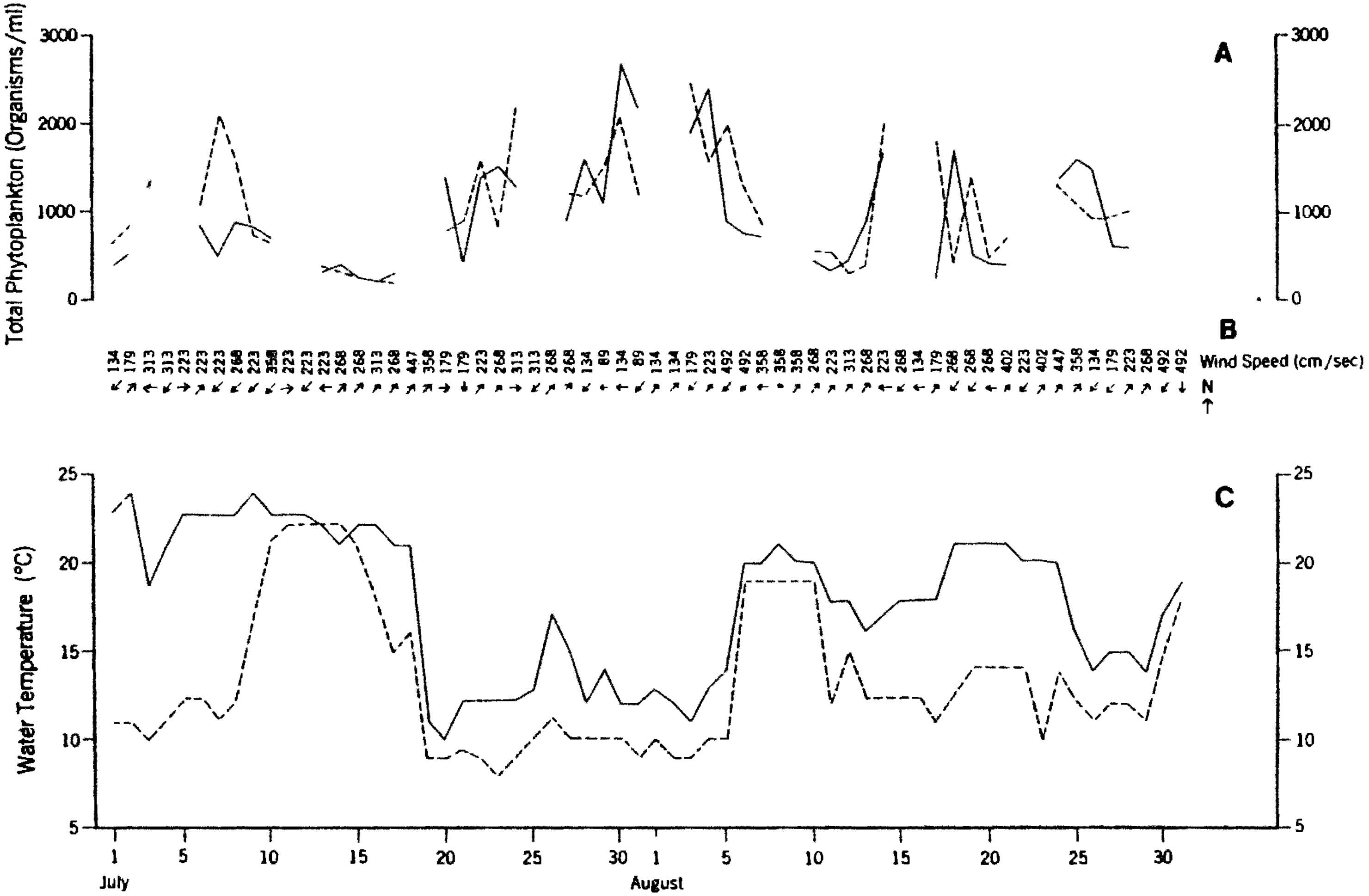


Fig. 5. Phytoplankton, wind and water temperature at the shore (---) and offshore (——) intake in Lake Michigan at Chicago (1975). Arrows indicate wind direction. Breaks indicate no available data.

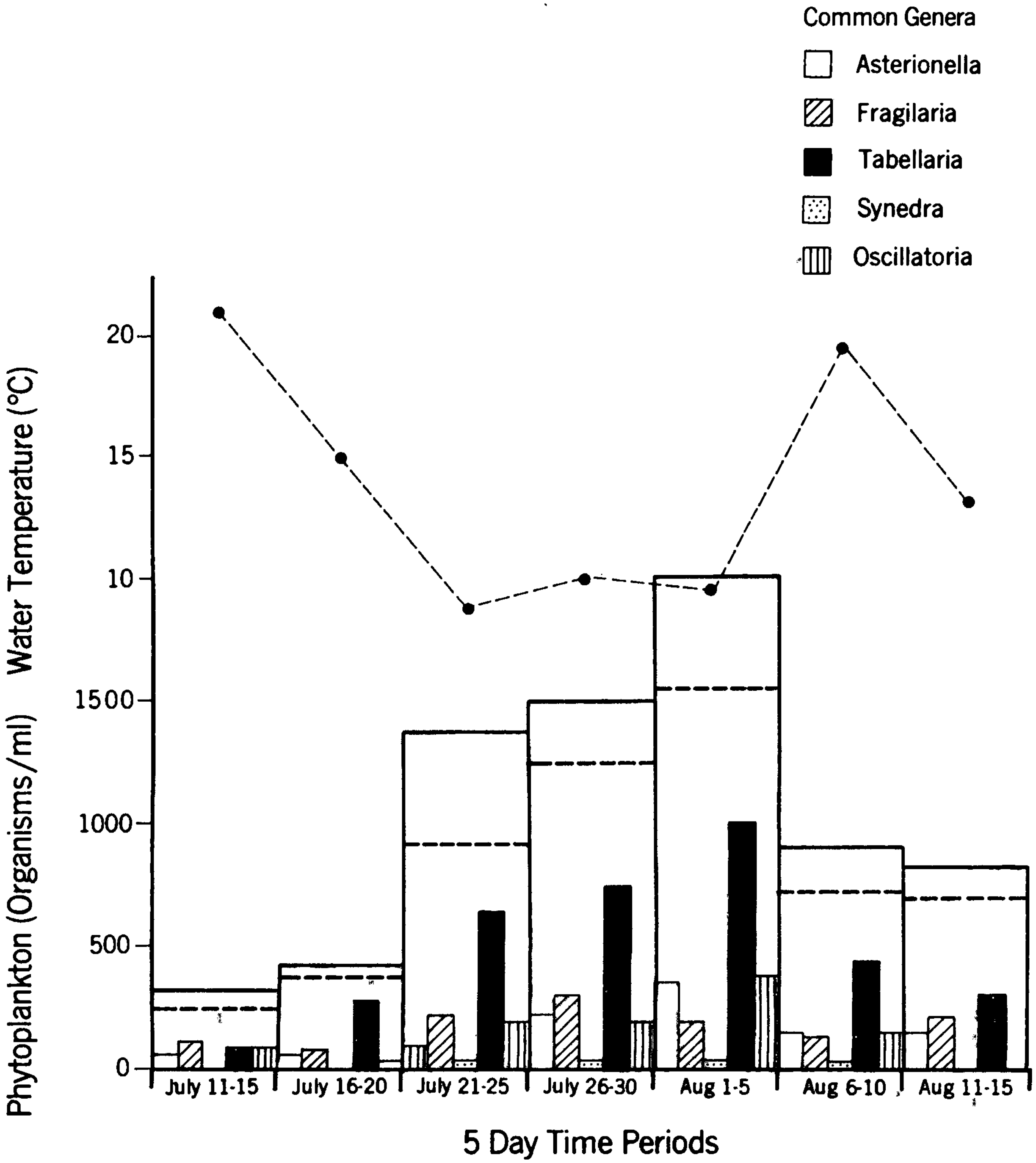


Fig. 6. Five day mean water temperature (●--●), total phytoplankton (——), total diatoms (---) and abundant genera at the offshore intake. July 11 - August 15, 1975.

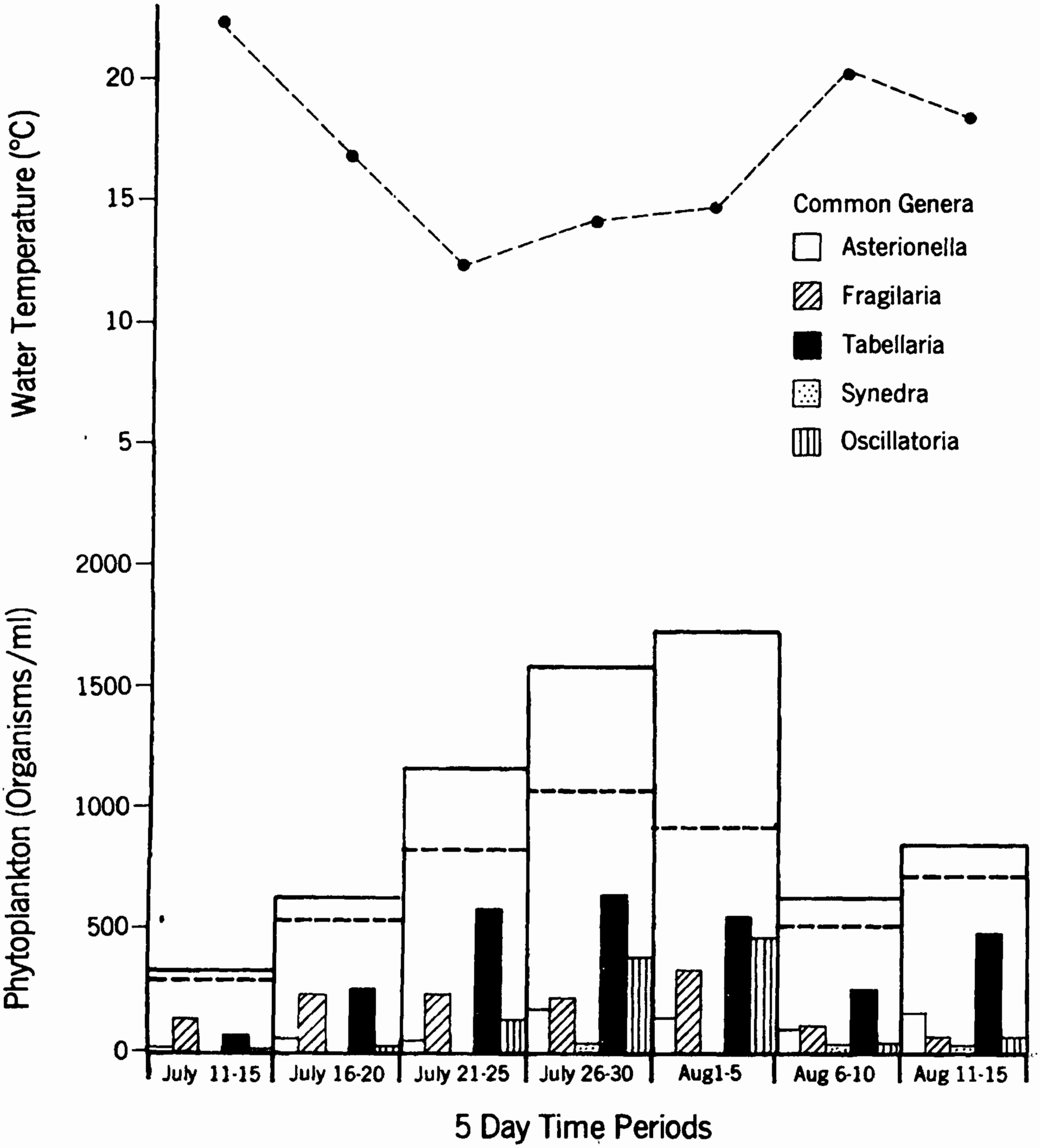


Fig. 7. Five day mean water temperature (●---●), total phytoplankton (——), total diatoms (---) and abundant genera at the shore intake. July 11 - August 15, 1975.