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FIELD DETERMINATION OF UPPER THERMAL TOLERANCE FOR CLADOCERA RESIDING IN A RESERVOIR RECEIVING THERMAL EFFLUENTS

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ABSTRACT — The upper thermal tolerances of several species of Cladocera were determined from observations made in a cooling pond of a nuclear production reactor at the Savannah River Plant near Aiken, South Carolina. *Bosmina longirostris* had an upper tolerance limit of 36°C; *Ceriodaphnia lacustris* and *Diaphanosoma brachyurum*, 38°C; and *Moina micrura*, 40°C. Each species appeared to maintain a position in the water column at a depth where temperatures were below their upper tolerance limits. Data on thermal tolerance are useful for predicting the consequences of passage of Cladocera through a heat exchanger of a reactor, passage through a cooling canal of a reactor, and residence in the littoral zone of a cooling reservoir. However, the data have little or no value for predicting the consequences for an organism inhabiting the limnetic portion of such a reservoir.

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INTRODUCTION

Thermal tolerance limits of Cladocera have received recent attention because of the concern over the environmental impact of thermal effluents from electrical power plants (Bunting, 1974). Most of the data on upper thermal tolerance limits come from laboratory studies (e.g., Goss and Bunting, 1976). Upper thermal tolerance limits have recently been observed in a field situation at the Savannah River Plant (SRP) where the problems of artificiality inherent in a laboratory study could be avoided.

The Par Pond system (Fig. 1) was created in 1958 as an impoundment for cooling water from a nuclear production reactor (P reactor) at SRP near Aiken, South Carolina. The cooling water, a mixture of 17/18 Par Pond water and 1/18 water taken from the Savannah River, leaves P reactor at ∿80°C and passes through 7.1 km of canals and six precooler ponds (Babcock and Neill, 1971). The cooling water enters Par Pond about 10°C higher than ambient temperature.

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Pond C, the last of the precooler ponds, is 56.7 ha (140 acres) in area and has a mean depth of 3 m. The entire water column of Pond C may be as much as 20°C above ambient temperature, while the upper 3 m of the thermally affected middle arm of Par Pond (average depth, ~6 m) may attain a maximum of 8°C above ambient. When the reactor is not operating for approximately one week, all species of limnetic Cladocera found in Par Pond are transported through the reactor and the canal system into Pond C. When the reactor comes back into operation, hot water enters as a sheet across the surface of the pond. The effluent water heats the entire water column of Pond C from above, sometimes in 3 to 4 days. The hot water eventually enters Par Pond, forming a surface plume (Lewis, 1974). The arm of Par Pond receiving the thermal effluent may take 1 week to reach maximum temperature. Cooling canal temperatures are monitored from a road approximately 4 km upstream from Pond C. This distance allows sampling in Pond C to begin as soon as the reactor is operating, but before hyperthermal effluent reaches the Pond C sampling station.

In this paper, we present results which describe the thermal tolerance of Cladocera from observations made in both Pond C and Par Pond from 1975 to 1977. The rapid heating of Pond C to high temperatures above ambient allows us to make observations of thermal tolerance similar to critical thermal maxima studies. The thermally affected middle arm of Par Pond simulates more closely the thermal situation created by a power generating plant, and allows us to test the values of our critical thermal maxima data for the prediction of consequences of thermal waste water additions.

METHODS AND MATERIALS

Cooling Canal and Pond C Sampling

On March 15-18, 1976, we sampled for Cladocera in the cooling canal (Fig. 1) with a #10, 13-cm-diameter plankton net which was allowed to drift out with the current. On each of these four sampling days, we took four vertical tows at the Pond C station (depth, 7 m) with a 1/2-m-diameter, #10 net. During July 27-29, 1976, we sampled every 12 hours (beginning at noon on the 27th) using a 13-cm-diameter, #10 net to take a series of vertical tows from depths of 1 to 7 m at one-meter intervals. This procedure allowed us to observe the vertical depth distribution of Cladocera in the water column. We continued with this sampling method during September 20-28, but sampled only once a day, around noon.

Par Pond Sampling

Two separate periods in Par Pond itself have relevance to our investigation of thermal tolerances. Concurrent to the March 1976 sampling of Pond C, four vertical tows were taken at a station in the middle arm of Par Pond (Station MA-1), the arm which directly receives thermal effluent, and at a station in the ambient portion of the lake (Station CD, Fig. 1). Samples were taken with a 1/2-m-diameter, #10 net on three dates: March 15, 21, and 28. By March 28, temperatures at our middle arm station had stabilized.

In the summer of 1975, we began a study of fish predation on littoral zone Cladocera in the middle arm. We used funnel traps to collect the Cladocera at two locations, Stations M-1 and M-2 located 100 m and 1500 m, respectively, from the Hot Dam (Fig. 1). Funnel traps consisted of four 8-cm-diameter polyethylene funnels placed at the four corners of a 0.36-m-square, #2-hardware cloth, mesh tray. One trap was placed in 1 m of water, 20 cm above the sediments at each station, at 1600 EDT. The trap was retrieved at 0800 EDT approximately once every 4 days from June 20 to August 16, 1974. The traps were therefore exposed to daily maximum and minimum temperatures (and, coincidentally, to two periods when the reactor was not operating).

Counting Methods and Treatment of Data

Samples from Par Pond in the summer of 1975 and from Pond C in July and September 1976 were counted in their entirety. The samples taken from Par Pond and Pond C in March 1976 were subsampled using a 2-mL Hensen-Stempel pipette. One subsample was counted from each sample. Relative abundance of Cladoceran species in a sample was determined by frequency counting each species in the first 200 Cladocera encountered in subsamples.

All counts represent nonparametric estimates of abundance. Cladocera species were identified according to Brooks (1959), Deevy and Deevy (1971), and Goulden (1968).

Temperature Measurements

Temperatures from 1975 were taken using maximum-minimum thermometers suspended in the littoral zone. All other temperature measurements were made with a thermister probe.

RESULTS

March 15-28 Thermal Tolerance

All limnetic Cladoceran species present at the Cold Dam of Par Pond were found in the cooling canal on March 15, 1976, when the reactor was not operating. By March 17, canal temperatures had risen 6°C, and the number of animals alive in the canal was reduced. On March 18, the canal temperature had risen 23°C (to 44°C) at our monitoring station, and no living plankton was found.

In Pond C samples taken on March 15, we found all the Station CD species to be present in similar relative abundances (Table 1). By March 18, the upper two meters had been heated 6.5°C (Figure 2). A trend of decrease in abundance of *Bosmina longirostris* and *Ceriodaphnia lacustris* began on this date so that by March 21 both species were rare in the tows (Fig. 3). In contrast, *Chydorus sphaericus* varied less in standing crop throughout the period sampled. The species which were rare on March 15 (designated "other" on Table 1) were still rare (less than 10% of the total

Cladocera) on March 21. The temperature of the entire 8-m water column was above 35°C by this date. All depths had undergone a change in temperature of at least 7.8°C over a 24-hour period, and all but the 4-m and 5-m isobaths had undergone a temperature change of at least 9.3°C in 24 hr (Fig. 2).

Temperatures in the middle arm, Station MA-3, of Par Pond did not reach a maximum until March 28 (Fig. 4). By this date at Station MA-3, observed changes were a significant drop in standing crop of *Bosmina* and *Ceriodaphnia* and a definite increase of *Daphnia* (Fig. 5, Mann Whitney – U – Test; $p < 0.05$, Siegel, 1956). Also during this period, standing crops of *Chydorus*, *Diaphanosoma*, and *Holopedium* did not change relative to March 15. In contrast, almost all species at Station CD remained at the same level of standing crop throughout the sampling period. Only *Ceriodaphnia* decreased in abundance. The standing crop fluctuations at Station MA-3 resulted in a drop in total standing crop of Cladocera to the level of Station CD.

July 26-29 – Vertical Distribution and Thermal Tolerance

On July 26, the water temperature was almost uniformly 32°C to the bottom of Pond C (Fig. 6). On July 26 and 27, tows taken in the upper 5 m of our Pond C station contained approximately 70% *Bosmina longirostris*, 16% *Ceriodaphnia lacustris*, 12% *Diaphanosoma brachyurum*, and 2% *Moina micrura*. Water temperatures on July 27 ranged from 35.5 to 32°C between the surface and the 8-m isobaths. By noon on July 28, *Bosmina* was still the most abundant (approximately 40% of the total Cladocera captured). *Ceriodaphnia* and *Moina* still had similar standing crops at all depths sampled below 4 m. At noon, July 29, *Bosmina, Diaphanosoma,* and now *Ceriodaphnia* were all reduced in number and were rare throughout the water column. Only *Moina* continued to maintain a constant, but low, standing crop. Except in one instance, when all but the last meter of the water column was close to or above 38°C (noon, July 29), *Bosmina* and *Diaphanosoma* were never found in that part of the water column. These Cladocera were found in greatest abundance in that part of the water column below 34°C. In contrast, *Moina* and *Ceriodaphnia* were found in higher temperatures (greater than 38°C but less than 41°C). *Ceriodaphnia* was found in greatest abundance below the 37°C isotherm, but *Moina* was always rare.

September 20-27 — Thermal Tolerance

Pond C temperatures during the September observation period rose slowly and did not exceed 37°C even at the surface (Fig. 7). Although there appeared to be large fluctuations in standing crops at our station on Pond C during the sampling period, the abundances of *Ceriodaphnia lacustris, Diaphanosoma brachyurum,* and *Moina micrura* in our tows on September 27 were not different from those in tows taken on September 20 (Fig. 8). *Bosmina,* however, was not found in our tows on September 26 and 27. On September 28, we took four 7-m vertical tows with a 1/2-m-diameter #10 net and confirmed the absence of *Bosmina.* *Bosmina* disappeared two days earlier (September 26) from the upper 2 m of the water column than from tows of the entire water column (Fig. 8). The upper 2 m had heated to more than 36°C on September 24; the entire water column exceeded that temperature by September 26.

Par Pond — Summer 1975

In the summer of 1975, eleven species of Cladocera were captured in the funnel traps in the littoral zone of the middle arm of Par Pond, but only four, *Alona intermedia*, *Bosmina longirostris*, *Ceriodaphnia lacustris*, and *Diaphanosoma brachyurum* were present often enough in sufficient abundance for analysis (Figs. 9-10). Due to reactor operations, the median water temperatures ranged over a 9°C interval at Station M-1 and over a 7°C interval at Station M-2 over the course of the sampling period (Fig. 11). If we define a peak in standing crop as a value which exceeds 90% of all other values, and this peak is separated by at least one sampling date from another peak (to assure independence of observation), then 11 of 13 of these identified peaks fall within the median temperature range of 29°C to 32°C. This number is significantly more often than chance alone would predict ($X^2 = 4.71$, $p < 0.05$).

DISCUSSION

There are three general thermal situations created by power plants utilizing cooling lakes: the temperatures in the heat exchangers, the temperatures in the cooling canals, and the temperatures in the lake itself. Our data can be applied to the latter two situations.

Cooling Canals

All species we observed can withstand temperatures up to 36°C for at least 24 hr. We would, therefore, expect these species to be able to tolerate the thermal stress of a cooling canal below this temperature.

Cooling Lakes

Heated effluents may affect the water-column temperatures of cooling lakes to different extents. The water of a mixing zone or the littoral areas of the lakes will be heated completely by the effluent, while the deeper, nonmixing areas (>4 m) may be heated only in part. In the latter case, the effluent is called a surface plume. Our data from Pond C can be used to predict the consequences of heated effluent on the species composition of the littoral zones or mixing areas, but are probably not useful for predicting the consequences of surface plumes.

Of the species we observed more than once, *Bosmina longirostris* appears to have the lowest thermal tolerance. Each time (March, July, and September) this species became rare or disappeared when the water column became heated to more than 35°C. *Ceriodaphnia lacustris* and *Diaphanosoma brachyurum* can endure temperatures greater than 35°C (July and September) but not greater than 38°C (July) for several days. *Moina micrura*, however, is able to survive exposure to temperatures up to 40°C for at least 24 hr (July). *Chydorus sphaericus* can tolerate temperatures greater than 36°C for several days (March). July observations suggest that all species are able to maintain a position in the water column below lethal temperatures, but conclusive evidence demands that we observe them reappearing higher in the water column as it cools, a situation which is impossible due to the way the reactor operations proceed.

An alternative hypothesis to these conclusions is that the Cladocerans simply flow through the drainpipe from Pond C into Par Pond (Fig. 1). The sampling station in Pond C is approximately 60 m from the outlet pipe which lies in the bottom of the pond in 9 m of water. This pipe delivers 681.4 cubic meters of water per minute to Par Pond. If we approximate the cross-sectional area of Pond C at our sampling station as the distance across the pond perpendicular to the dam (282 m) times the mean depth of the pond (3 m) and assume uniform flow, the estimated velocity at this sampling station would be 15 mm/sec. This is well below 30 mm/sec, the velocity at which zooplankton are moved as though they were inert suspended particles (Einsele, 1960; as cited by Whitehouse, 1971). The turnover rate of Pond C is conservatively estimated to be on the order of 3 days. If the disappearance of Cladocerans were due to this factor alone, assuming now that the Cladocerans are not able to maintain their position in the water column, we would expect to see a uniform removal of total numbers and species. Only the total Cladocera for the September 1976 sampling period has the appearance of a simple dispersion event; but, even in this period, only *Bosmina* disappeared completely. If *Bosmina* were the only species unable to maintain its position in the water column, we would expect it to disappear at the same rate in each sampling period. However, in March it was present 4 days after the hot water began to enter Pond C; in July, it disappeared completely in 4 days; and in September, it took 6 days to disappear. Each point of disappearance coincided with the water column being heated to above 36°C. We therefore reject this alternative hypothesis.

We can test the utility of our Pond C results for prediction concerning the littoral zone environment in the middle arm by comparing standing crop estimates of species made with the funnel traps at Stations M-1 and M-2 in the summer of 1975. Temperatures in the littoral zone in July and August were near or above 38°C, but not consistently or for any entire 24-hr period (Fig. 11). We would therefore predict that *Bosmina longirostris* would be reduced in numbers at Station M-1 as compared to M-2 (Figs. 9 and 10), while a reduction in numbers would not be expected for *Ceriodaphnia* and *Diaphanosoma*. Data were analyzed with the Wilcoxon-Matched-Pairs-Signed-Rank-Test (Siegel, 1956), with paired samples collected at least three days apart to ensure independence. According to this test, the standing crops of *Bosmina* were significantly lower ($p < 0.05$) at Station M-1, while no difference was observed between Station M-1 and M-2 for *Ceriodaphnia* and *Diaphanosoma*. Vigerstad and Tilly (1977) had concluded from a comparison of Station M-1 data with data from an ambient station in the summer of 1974 that *Bosmina* standing crops were (at least indirectly) reduced by hyperthermal temperatures, while *Ceriodaphnia* and *Diaphanosoma* crops were favored by the higher effluent temperatures. Thus, the Pond C results support the hypothesis that the reduced standing crops of *Bosmina* are directly a result of the hyperthermal temperatures. The mixed results for comparison of *Ceriodaphnia* and *Diaphanosoma* standing crops between stations differing in water temperature suggest that the temperatures in the littoral zone are probably below physiologically stressful levels for those species, a result which is also supported by our Pond C observations.

Our samples from the middle arm station in March (Fig. 5) demonstrate the difficulty of using thermal tolerance data alone to predict the short-term consequences of surface plume additions in the limnetic zone. For example, the Pond C results from March suggest that little or no effect from the surface plume additions to Par Pond should be observable because all species in Pond C were able to withstand temperature increases of 7°C per 24 hr and tolerate temperatures up to 35°C for several days, and Par Pond thermal conditions were less extreme. On the other hand, results from Pond C might be used as a relative index of susceptibility [reasoning from the observation that both species decreased in abundance with increasing temperature in Pond C (Fig. 3)]. We might predict that *Bosmina* and *Ceriodaphnia* would both be affected to some extent by the heated waters, but that no reduction in numbers should be observed for the other species. This latter pair of predictions seems to describe more closely the series of events for the different species. The different species may actually be more sensitive to changes in reactor operations than the observed values for our Pond C results indicate. Based upon our Cold Dam samples, however, we would have expected a decline in *Ceriodaphnia* by March 28 even without the addition of hyperthermal effluents.

Certainly, our Pond C data are not useful to predict long-term consequences of existing thermal conditions at the central middle arm station (Station M-3) during reactor operations. Temperatures within the surface plume are well below observed tolerance limits. Below the 3-m isobath, water temperatures at Stations CD and M-3 are identical. Cladocera could select normal lake temperatures by migration. Furthermore, our funnel trap data from 1975 suggest to us that 29 to 32°C may be a preferred temperature range, at least for summer acclimatized species. This temperature range could be selected by the species by vertical migration into the surface plume in the spring and to just below the surface plume in the summer.

ACKNOWLEDGMENT

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Table 1. Range of percentage relative abundance of Cladocera species in four replica plankton tows taken at Station CD in Par Pond and Station Pond C on March 15, 1976

Species	Range of Percent at Station CD	Range of Percent at Pond C Station
Bosmina longirostris	41 - 33.5	40.5 - 27.0
Ceriodaphnia lacustris	61.5 - 46.5	68.5 - 52
Other (*Chydorus sphaericus* *Diaphanosoma brachyurum*, *Daphnia parvula*, *Eubosmina tubicen*, *Holopedium amazonicum*)	12.5 - 6.0	8.5 - 4.0

Table 2. Number of each Cladoceran species counted from two vertical tows taken at Station Pond C at noon on July 28, midnight July 28, and noon July 29, 1976

Depth, m	Temp, °C	*Bosmina longirostris*	*Ceriodaphnia lacustris*	*Diaphanosoma brachyurum*	*Moina micrura*
			Noon, July 28		
1	41.2	0-0	0-0	0-0	0-0
2	41.0	0-0	0-0	0-0	0-0
3	37.8	0-0	0-0	0-0	0-0
4	36.5	0-0	14-16	0-0	5-2
5	34.6	1-0	15-23	0-1	3-4
6	32.6	58-64	22-13	5-3	6-2
7	32.5	79-139	12-11	7-11	4-10
			Midnight, July 28		
1	43.6	0-0	0-0	0-0	0-0
2	41.8	0-0	0-0	0-0	0-0
3	40.3	0-0	0-0	0-0	0-0
4	38.9	0-0	8-9	0-0	0-1
5	37.9	0-0	10-5	0-0	4-2
6	36.9	8-3	22-11	4-0	4-2
7	34.6	4-11	9-14	5-15	1-3
8	33.2	35-98	9-14	13-35	1-3
			Noon, July 29		
1	43.9	0-0	0-0	0-0	0-0
2	43.9	0-0	0-0	0-0	0-0
3	43.1	0-0	0-0	0-0	0-0
4	42.0	0-0	0-0	0-0	0-0
5	40.8	0-0	0-0	0-0	0-0
6	40.4	0-0	0-0	0-0	0-1
7	39.3	0-1	1-1	0-1	1-2
8	38.2	2-0	2-0	0-1	3-1
9	36.8	0-2	3-3	0-1	2-3

FIGURE CAPTIONS

Fig. 1 - Map of the Par Pond System. Shown are the P reactor, canal system, and precooler ponds, including Pond C and Par Pond. Stations M-3 and CD are limnetic stations used in 1976. Stations M-1 and M-2 are littoral sampling stations used in the summer, 1975.

Fig. 2 - Vertical temperature profiles of the Pond C Station taken at 1500 EST from March 17 to March 21, 1976.

Fig. 3 - Numbers of individuals of *Bosmina longirostris*, *Ceriodaphnia locustris*, *Chydorus sphaericus* and total Cladocera in a 2 mL subsample from each of four plankton tows taken on March 15, and daily from March 17 to March 21, 1976, at Pond C Station.

Fig. 4 - Temperature profiles at Station CD (dotted line) and Station M-3 (solid line) in Par Pond on March 15, 21, and 28, 1976.

Fig. 5 - The number of each species in 2 mL subsamples from each of four samples taken at Station CD and Station M-3 on March 15, 21, and 28, 1976.

Fig. 6 - Temperature profiles at Pond C Station from July 26 to July 29, 1976.

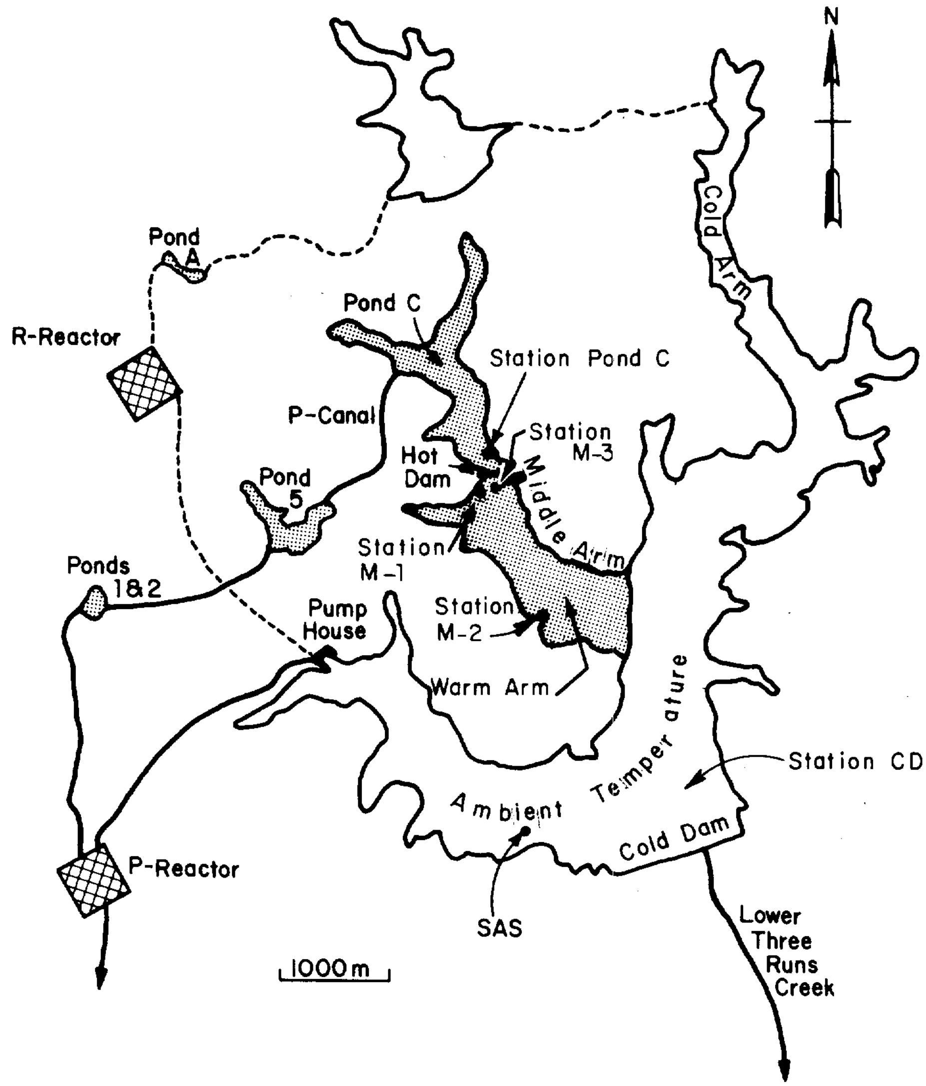
Fig. 7 - Temperature profiles at our Pond C Station from September 20 to 27, 1976.

Fig. 8 - Number of each Cladoceran species counted from vertical tows taken at Pond C Station from September 20 to 28, 1976. (P = present; A = absent in tows which were not quantified.)

Fig. 9 - The number of individuals of the four major species of Cladocera captured in funnel traps at Station M-1 from June 20 to August 9, 1975.

Fig. 10 - The number of individuals of the four major species of Cladocera captured in funnel traps at Station M-2 from June 20 to August 9, 1975.

Fig. 11 - The maximum and minimum temperatures recorded at Stations M-1 and M-2 from June 20 to August 9, 1975.



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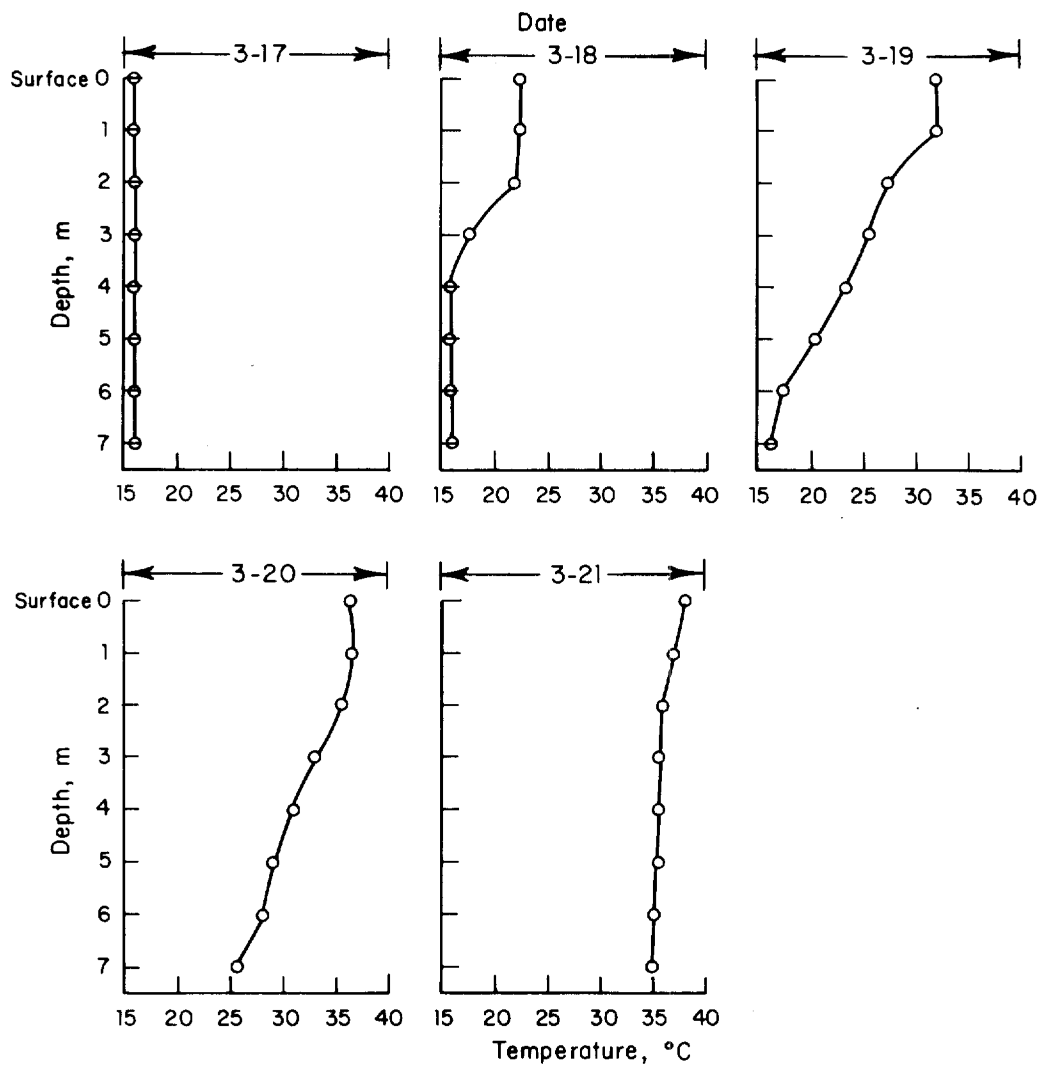

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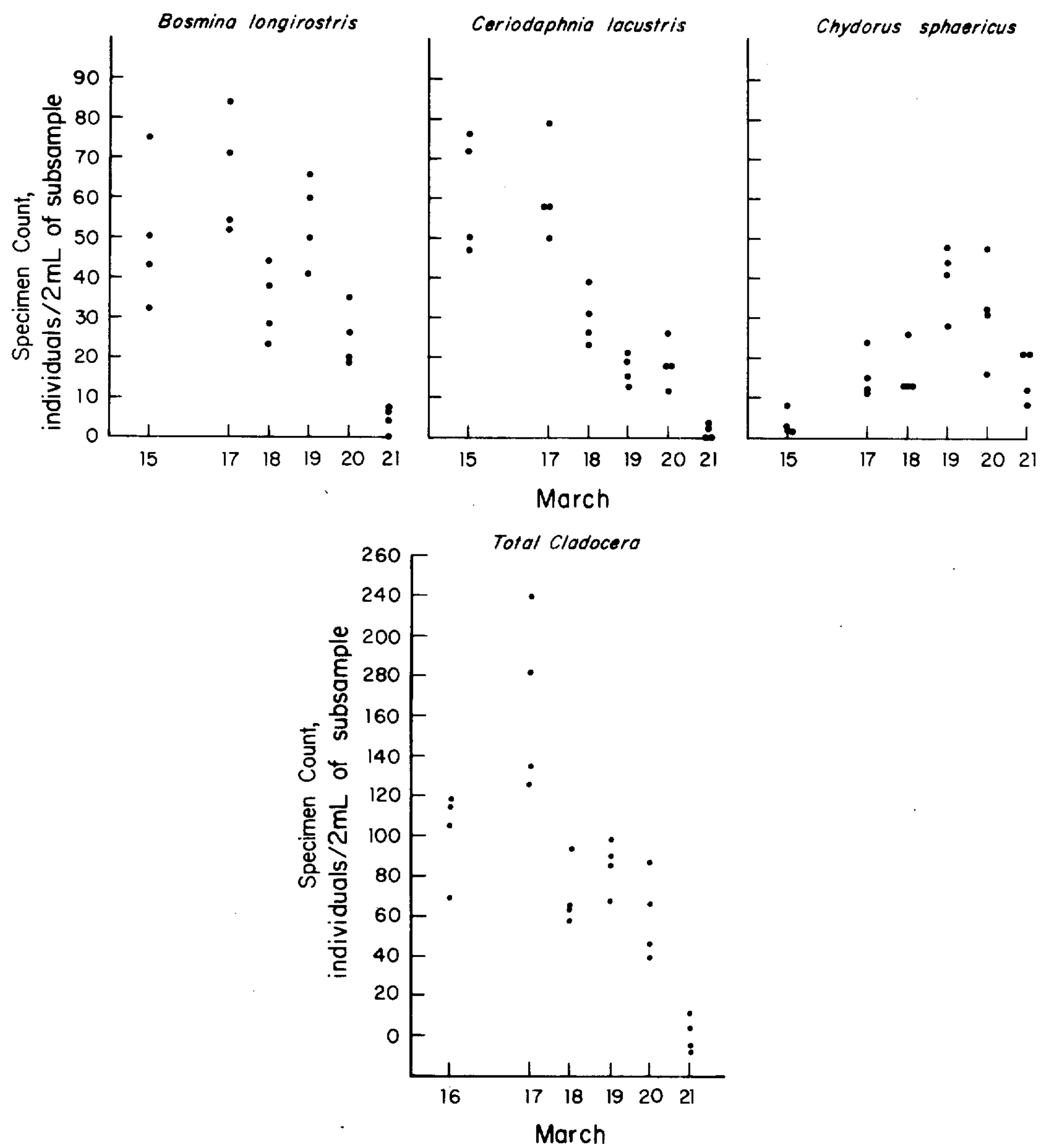

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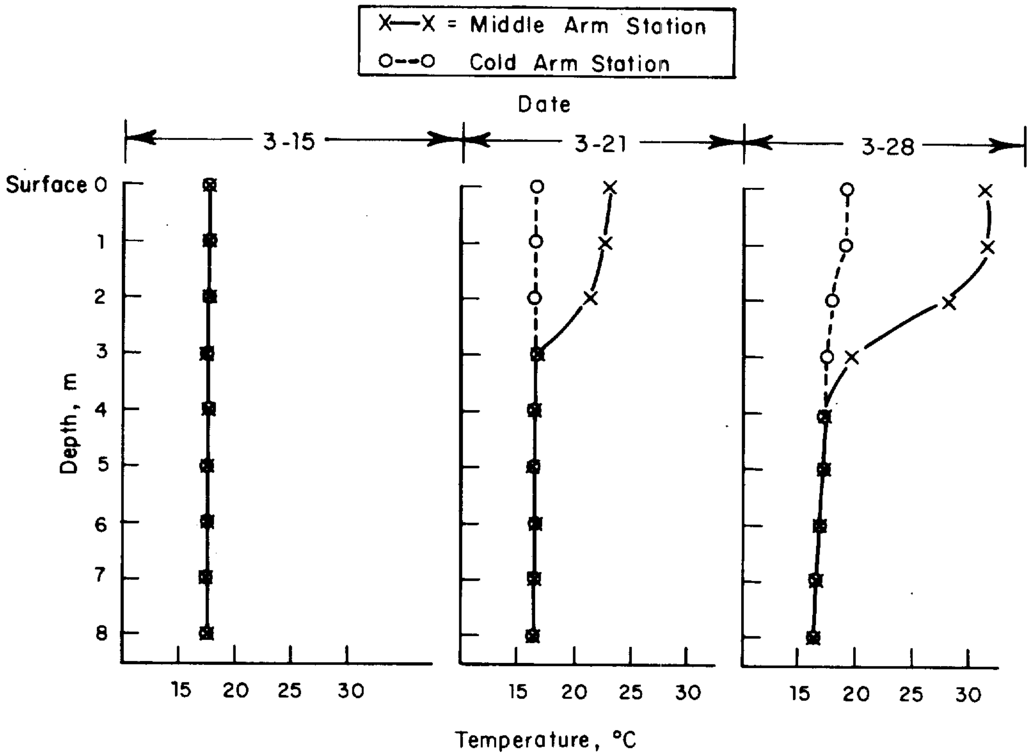

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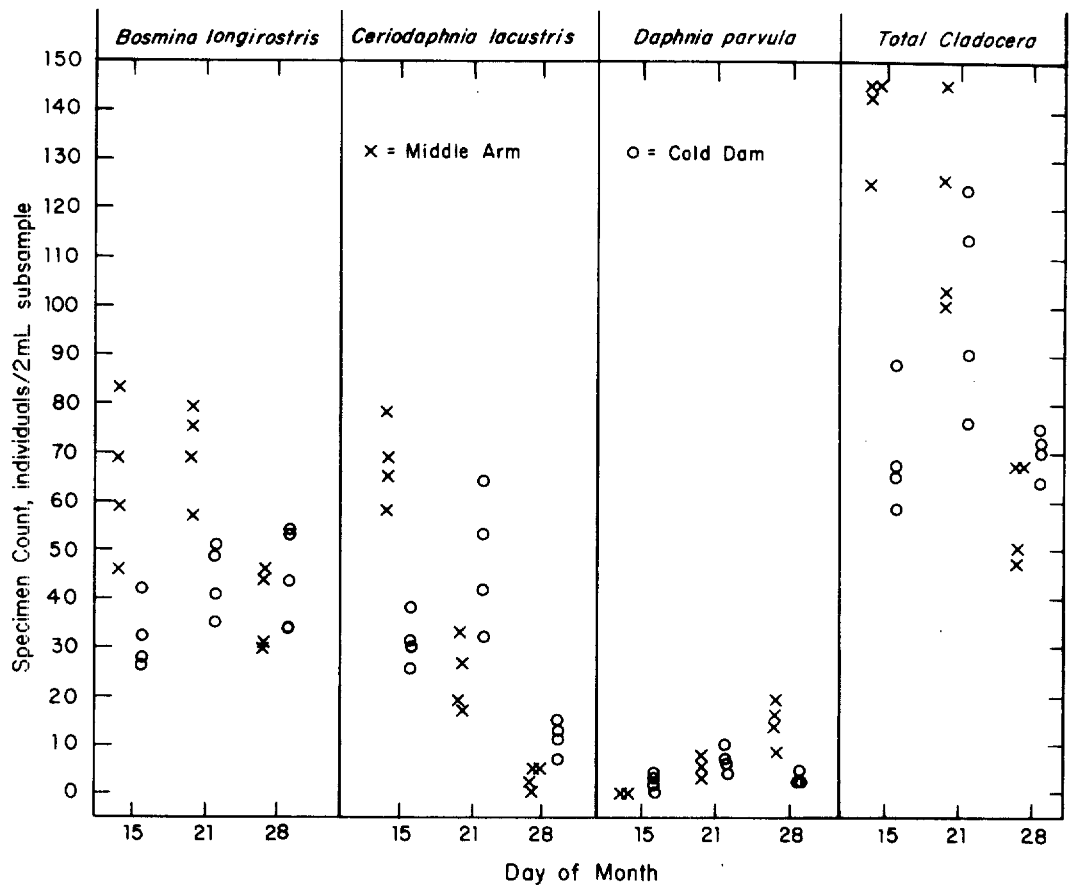


Fig. 5 - The number of each species in 2 mL subsamples from each of four samples taken at Station CD and Station M-3 on March 15, 21, and 28, 1976.

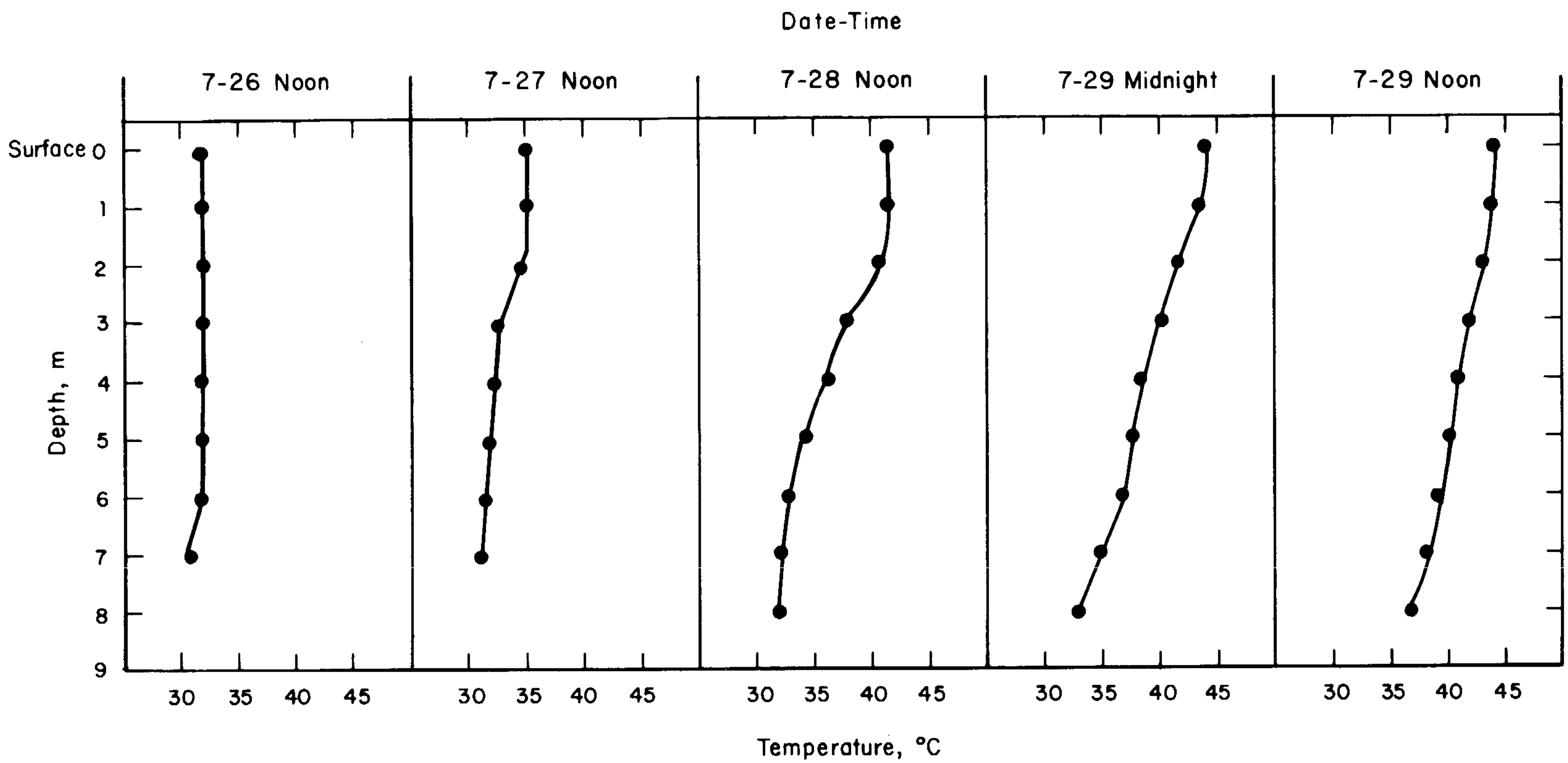
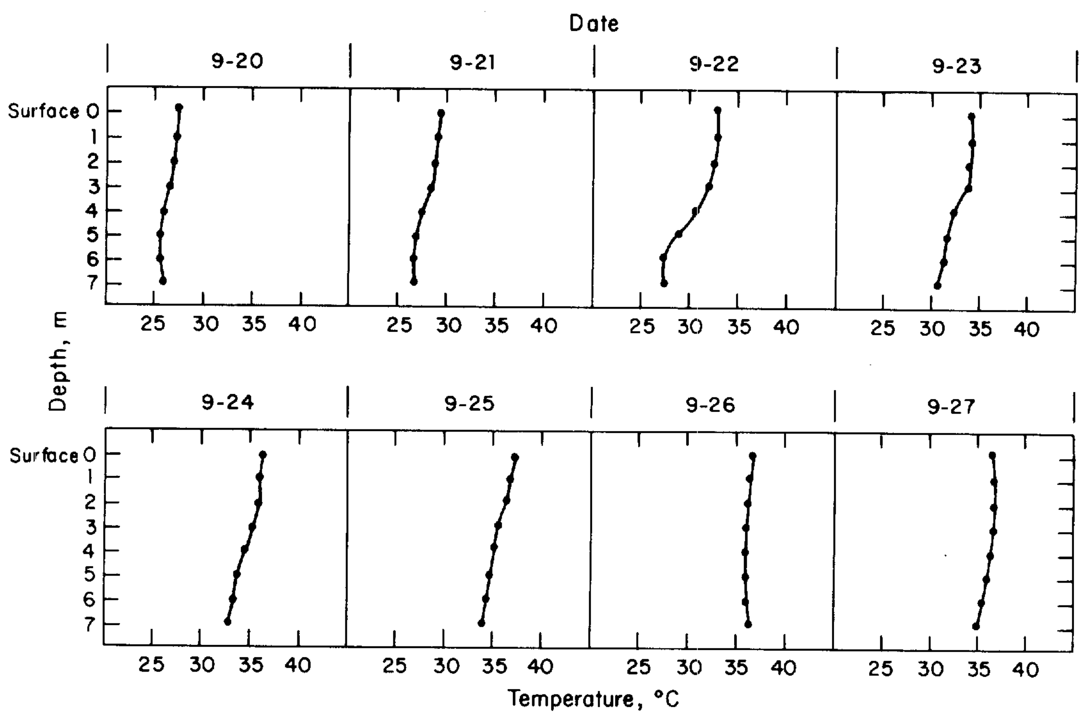


Fig. 6 - Temperature profiles at Pond C Station from July 26 to July 29, 1976.



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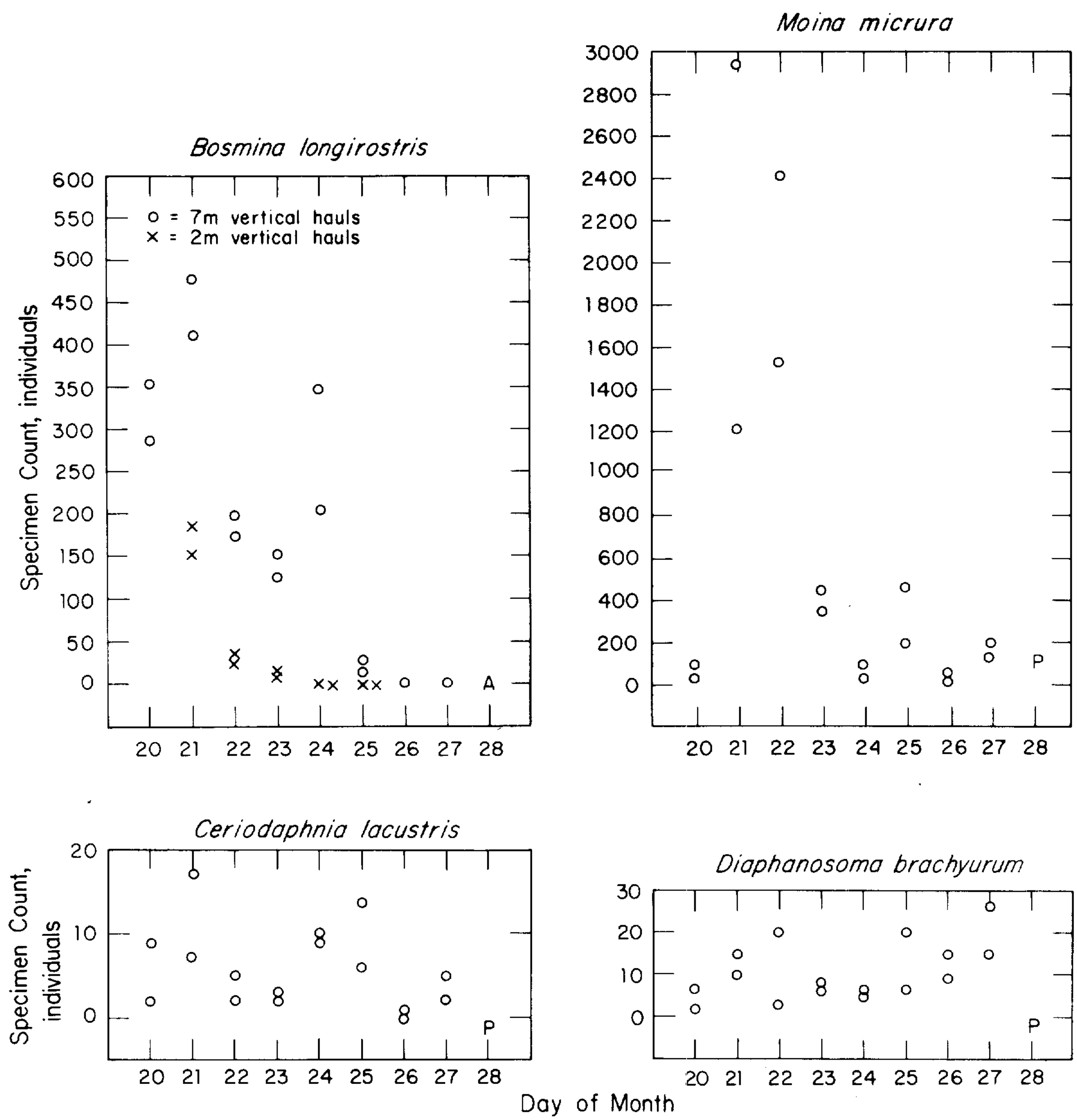

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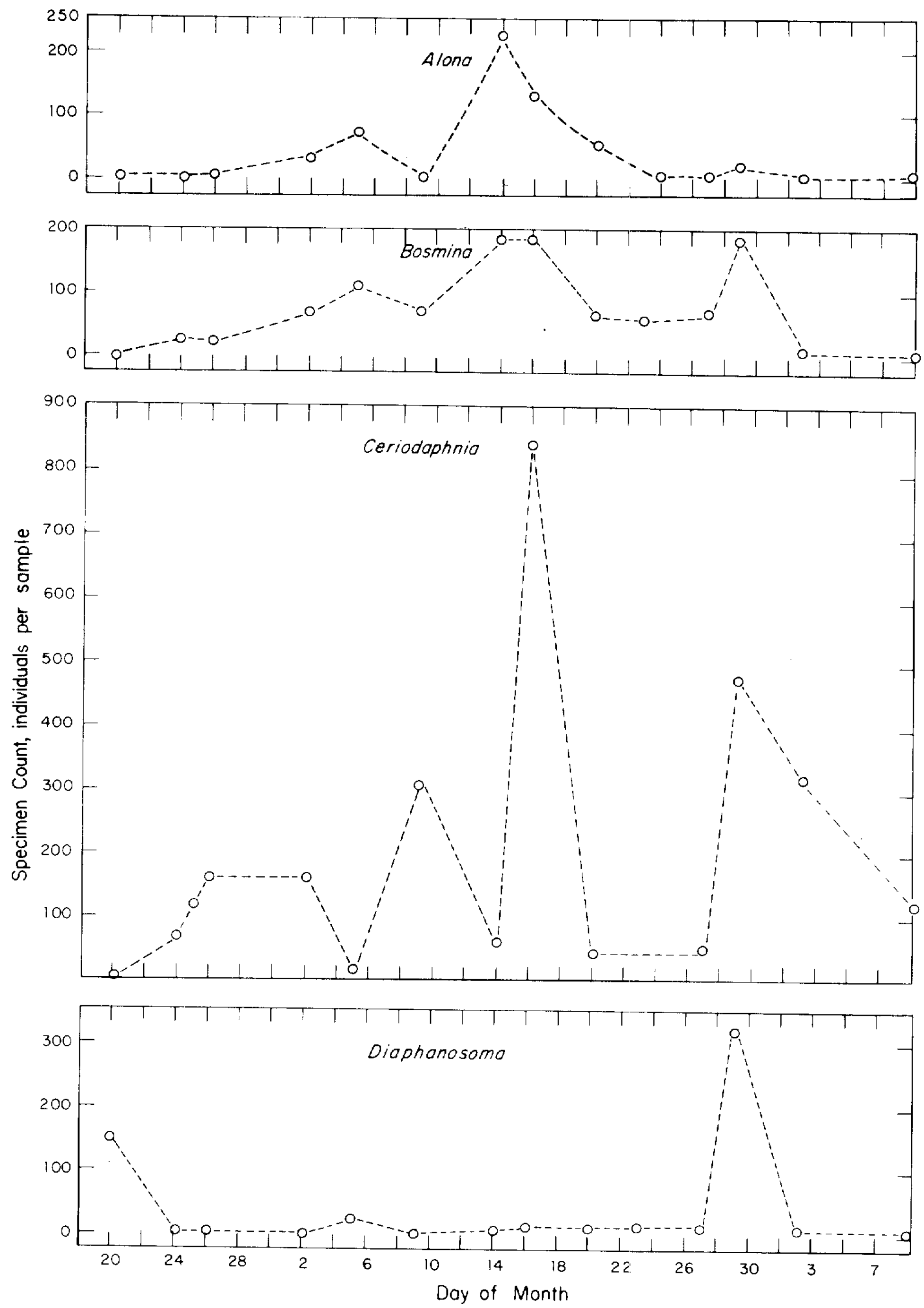

Fig. 9 - The number of individuals of the four major species of Cladocera captured in funnel traps at Station M-1 from June 20 to August 9, 1975.

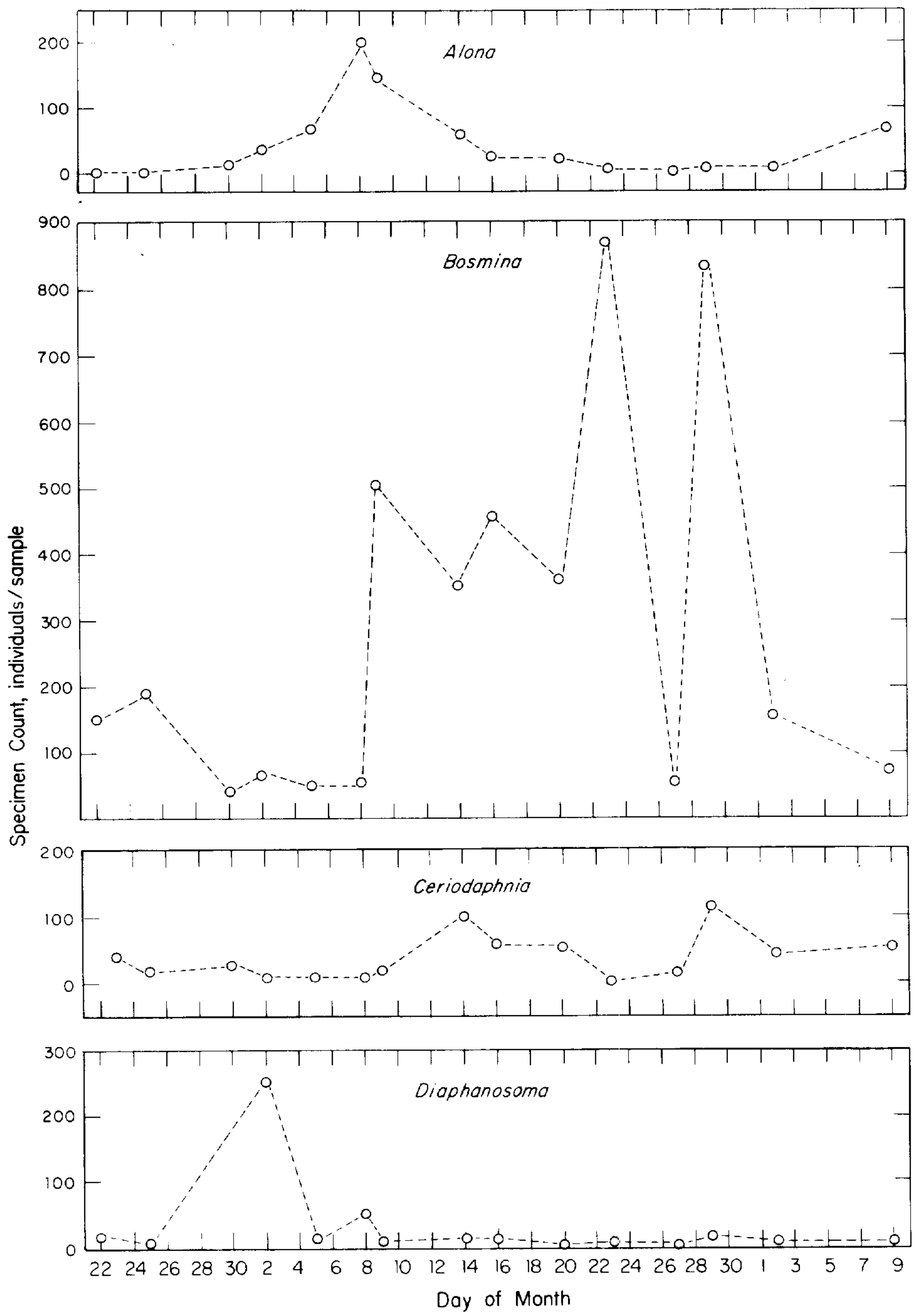

Fig. 10 - The number of individuals of the four major species of Cladocera captured in funnel traps at Station M-2 from June 20 to August 9, 1975.

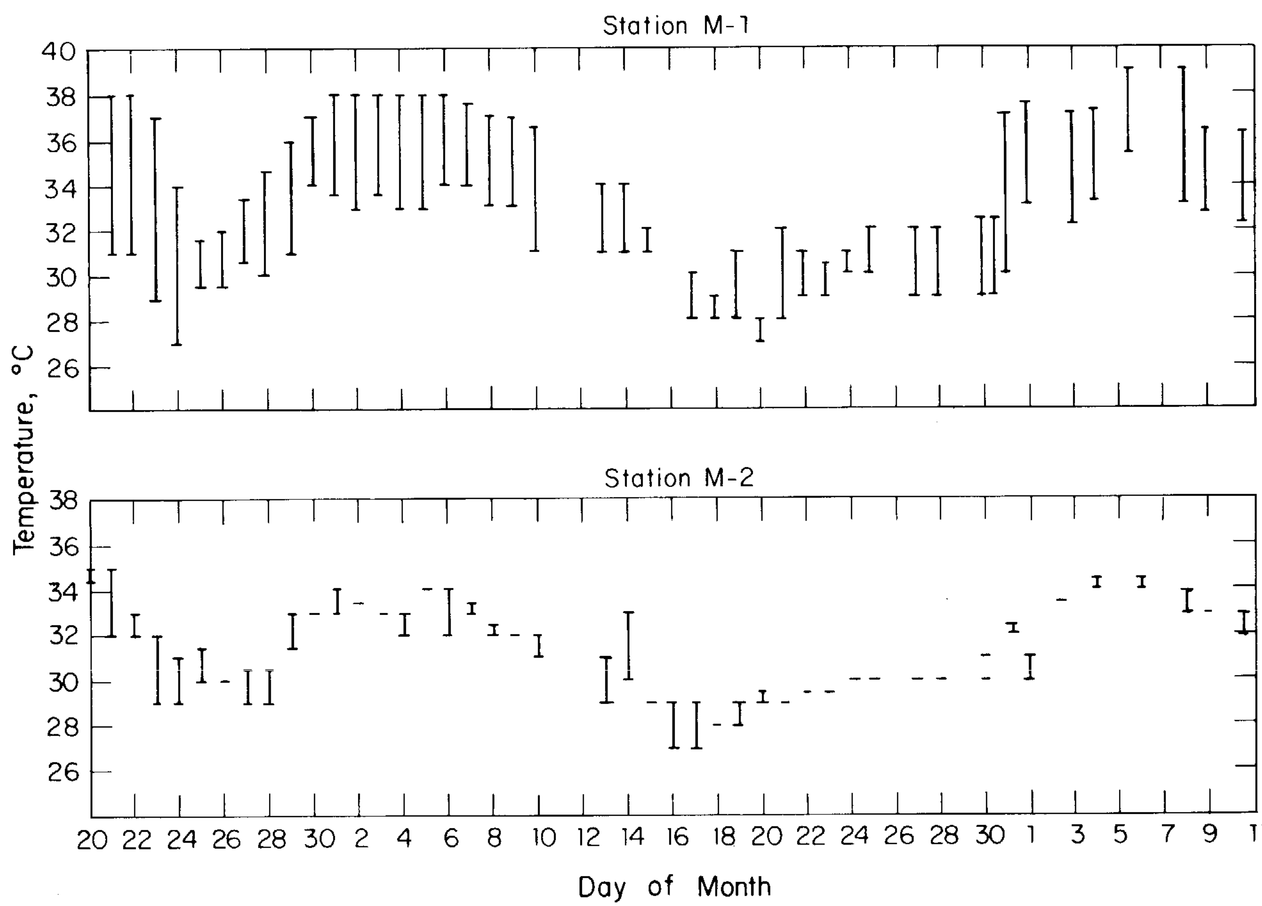

Fig. 11 - The maximum and minimum temperatures recorded at Stations M-1 and M-2 from June 20 to August 9, 1975.