The Seasonal Life Cycle of *Sinocalanus tenellus* (Copepoda : Calanoida) in a Brackish-water Pond[1,2]

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Abstract

The seasonal life cycle of a calanoid copepod *Sinocalanus tenellus* (Kikuchi) was studied during the period from June 1983 to July 1984 in a brackish-water pond in Fukuyama, Hiroshima Prefecture. Except for summer, the species was present in the plankton throughout this period, with a small peak in April and a large peak in November. The seasonal variation in abundance of benthic resting eggs was directly related to that of the adult population. Most eggs isolated from the bottom sediments and those spawned directly by females in the laboratory hatched out subitaneously without any seasonal difference in egg physiology. Since considerable numbers of quiescent resting eggs were present in the bottom sediments during summer, the planktonic population could be reestablished in fall from these eggs. During the period when the planktonic population was abundant, the population was predominantly composed of adults. Sex ratio (male: female) was generally 1.0. The prosome length of *S. tenellus* was larger in fall and spring and smaller in winter and early summer.

The zooplankton community in estuaries and other brackish-water systems, in general, consists of a small number of species compared to marine and freshwater environments (MILLER & WILLIAMS 1972, BOUSFIELD et al. 1975). In south-western Japan, only two species of calanoid copepods are known to appear commonly in a brackish-water environment (mixomesohaline, according to the Venice System, cf. SMAYDA 1983). One is *Sinocalanus tenellus* (Kikuchi) which will be dealt with in this paper and the other is *Pseudodiaptomus inopinus* Burckhart (MASHIKO 1954, YAMAZI 1956), both belonging to Centropagidae. *S. tenellus* is relatively slender in form about 1 mm in prosome length and 0.2 mm in maximum width, and lays eggs freely into the water. This species has been reported to occur in estuaries and brackish-water ponds of Japan, Korea, Kurile Islands and Sakhalin (KIKUCHI 1928, MASHIKO 1954, MIZUNO 1984). A high abundance of this species in these waters suggests that this species may play an important role in the food webs of brackish-water environments.

For detailed quantitative surveys of the population dynamics and production of planktonic copepods, we should know the seasonal life cycle of the species of interest as fundamental knowledges. Information on the seasonal life history of *S. tenellus* is not adequate at present. Some 30 years ago, MATSUDAIRA (1957) first attempted to rear this species under laboratory

conditions, and briefly described the environmental conditions of a brackish-water pool in Matsushima, Miyagi Prefecture, where he collected experimental animals. Later, KUWASAKI (pers. comm.) investigated the seasonal variation in abundance of various zooplankton including *S. tenellus* in Shinhamako Lake near Tokyo during the period from May 1977 to January 1978, and found this species to be present throughout the period except for August and November with peak abundance in May. Its growth and reproduction have been preliminarily investigated by MATSUDAIRA (1957) and WATANABE (1964). Recently, a more detailed study of its growth and reproduction has been carried out by KIMOTO et al. (1986, in preparation) in relation to temperature and salinity. In order to elucidate the life cycle of *S. tenellus*, we investigated the seasonal changes in numerical abundance including benthic resting eggs, population structure, size of adult copepods, nature of spawned eggs, etc., in a brackish-water pond in Fukuyama.

Study Area

The brackish-water pond where our study was carried out is located in Mino-oki reclaimed land (34°25.8′N, 133°26.0′E), Fukuyama, Hiroshima Prefecture. This pond is separated from the adjacent sea with a bank of stone, through which some exchange of water is made according to the tidal cycle. The area is about 0.8 km² and the depth is shallower than ca. 1.0 m.

There is no substantial inflow of freshwater to the pond, except for rainfall. At present, the western part of the pond is being used as a dumping site for trash. The trash sometimes contains organic materials which would decompose there. So, a considerable amount of organic matter oozes into the pond, creating heavily eutrophic conditions.

Materials and Methods

A series of samplings were carried out at a fixed station located at the northern part of the pond at an interval of one week (approximately 2 weeks in winter) during the period from 1 June 1983 to 10 July 1984. Hydrographic data and sediment samples were obtained mainly during daytime (14:00–16:00 h) on each sampling occasion. The surface water temperature and salinity were measured with a thermo-salinometer (YSI, Model 33). For measurement of chlorophyll *a* concentration, the surface pond water was taken in a 1 l plastic bottle. After return to the laboratory, 100–500 ml of the water was filtered with a Millipore filter (Type HA, pore size: 0.45 μm). Extracted with 90 % acetone solution, chlorophyll *a* concentration was determined by using a spectrophotometer (Hitachi, Model 220A).

Zooplankton sampling was carried out in the evening (18:00–20:00 h) to minimize the possible underestimation of *S. tenellus* abundance, since many copepod species tend to be distributed more homogeneously throughout the water column during the night. Zooplankton was sampled ten times (total volume: 25 l, filtered with a 40 μm mesh net) with a 2.5 l water-sampler. Zooplankton samples were immediately preserved in 5 to 10 % formalin-pond water solution. Later, *S. tenellus* were staged, sexed and counted from the whole or split samples

under a stereoscopic binocular microscope. The prosome length of adults was measured using an eyepiece micrometer. Rotifers (*Brachionus* spp.) and a mysid (*Neomysis japonica*), major planktonic animals other than *S. tenellus*, were also counted.

In order to estimate the number of resting eggs of *S. tenellus* in the bottom sediment, triplicate samples of bottom mud were collected with a KK-core sampler (inner diameter: 4.1 cm, KIMATA et al. 1960). After return to laboratory, the superficial water in the cores was gently siphoned out to avoid turbulence of the surface mud. Only the top 1.5 cm of the mud was sampled with a small spoon. The mud was suspended in filtered (Whatman GF/C) water (salinity: 13‰) and sieved first through 106 μm and then 46 μm sieve. The residue on 46 μm sieve was washed into centrifuging tubes with 100% W/V sugar solution and centrifuged at 3,000 rpm for 5 minutes (ONBÉ 1978). The eggs that had floated onto the surface of the solution were pipetted out into a 40 μm sieve. This procedure was repeated twice for each sample in order to recover most of the eggs. The eggs of *S. tenellus* that had been retained were washed into a counting tray and counted under a stereoscopic binocular microscope. The eggs were counted within 24 h after collection.

To clarify the possible existence of a seasonal difference in egg types (i.e., subitaneous or diapause egg, GRICE and MARCUS 1981), hatching experiments were carried out at intervals of 1 to 5 weeks during the period between August 1983 and June 1984. Eggs isolated from the bottom mud or spawned by females just after collection were individually placed in a well (diameter: 6.4 mm) of Cell Wells (Corning Co.) containing about 0.2 ml glassfiber filtered water (salinity: 13‰). They were incubated at 5 different temperatures ranging from 10 to 30°C and observed at intervals of 3-9 h to determine the time for 50% hatch and the hatching success. The period of egg incubation was 4, 4, 6, 8 and 14 days at 30, 25, 20, 15 and 10°C, respectively. Illumination was not specially controlled during the experiments; daytime light intensity in the laboratory was ca. 100-500 lx. After incubations, unhatched eggs which looked viable, were transferred to other wells and incubated at 20°C in order to check the occurrence of further hatching.

Results

1. *Environmental Variables*

The seasonal fluctuation in water temperature was remarkable due to shallowness of the pond (Fig. 1A). Water temperature was usually higher than 30°C in summer, began to decline in September and further decreased during fall and early winter. It was relatively constant throughout mid-winter (ca. 5°C) and began to increase in March. The highest temperature recorded was 36.5°C on 10 August 1983 and the lowest 4.2°C on 7 February 1984. Salinity was relatively constant throughout the study period ranging from 10.1 to 14.6‰ with a mean salinity of 12.6‰ (Fig. 1A). It was more variable from June to September, because of heavy rainfall and high evaporation rate during this season. Chlorophyll *a* concentration was usually higher than 4.0 μg l⁻¹. It was high from May to July and low in January and February (Fig. 1B). The highest concentration recorded was 30.0 μg l⁻¹ on 13 July 1983 and the lowest
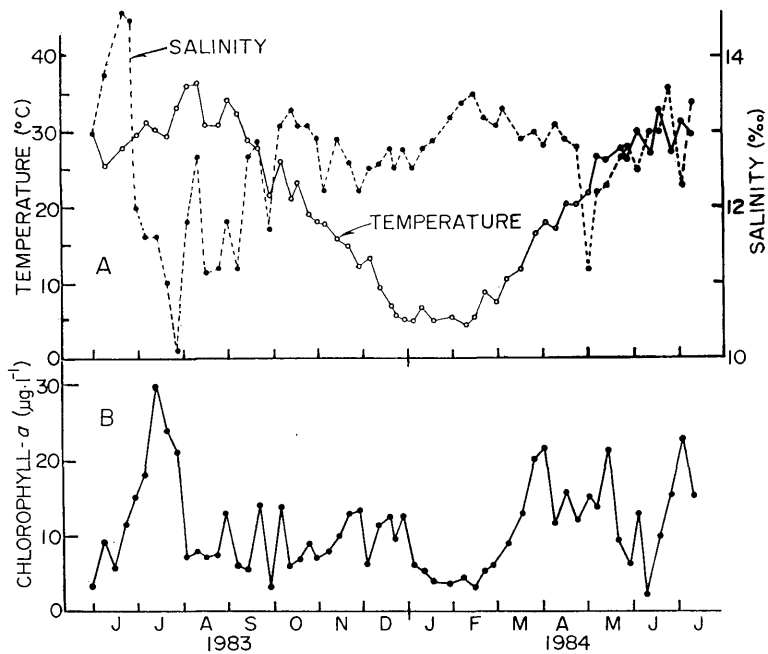
Fig. 1. Seasonal changes in (A) surface temperature and salinity, and
(B) chlorophyll *a* concentration at the regular sampling station in a
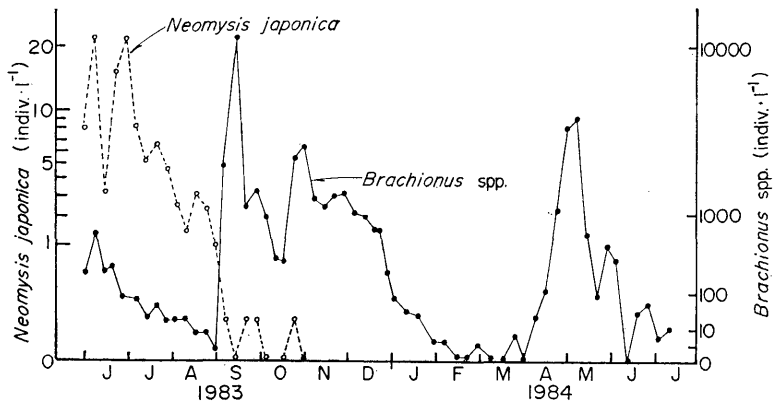brackish-water pond in Mino-oki reclaimed land, Fukuyama.

Fig. 2. Seasonal changes in abundance of *Neomysis japonica* and *Branchionus* spp.

1.7 μg l^{-1} on 12 June 1984.

2. *Abundance of* Neomysis japonica *and* Brachionus *spp.*

Neomysis japonica was abundant when the present investigation started. The highest density
of 22 indiv. l^{-1} was recorded on 29 June 1983. However, the population began to decline in
July 1983, decreased through summer and disappeared after 14 October 1983 (Fig. 2). The
reason for its disappearance was unknown, but the high water temperature (36°C) in summer

of 1983 might have been responsible to the extinction of this species.

The rotifer populations which probably consisted of two *Brachionus* species also fluctuated seasonally, being abundant in fall and spring and less abundant in summer and winter (Fig. 2). The highest density was 1.1×10^4 indiv. l^{-1} on 14 September 1983. Many rotifer eggs were found in the bottom mud throughout the year, but they were not counted.

3. *Abundance of* Sinocalanus tenellus

The seasonal fluctuation in the planktonic population of *S. tenellus* was remarkable (Fig. 3). The population was abundant from October to June with two peaks in fall and spring, and less abundant in winter. Only a few individuals were occasionally present in summer. After a decline of the population in summer, the recovery of the planktonic population was very quick. No *S. tenellus* was present on 21 September 1983, but two weeks later (5 October 1983), the population increased to 250 indiv. l^{-1}. The instantaneous rate of population increase during the period was calculated as 0.561 d^{-1}. Once the population attained its maximum, its level fluctuated somewhat during fall and declined from December to a winter minimum in February. Then, it increased again and reached a spring peak in April. On 12 June 1984, this species again disappeared almost completely from the plankton, and a reestablishment of the population was observed on 2 November 1984. The highest density (330 indiv. l^{-1}) was recorded on 7 November 1983.

4. *Adult Ratio of* Sinocalanus tenellus

In a zooplankton population, the mortality is generally higher in the early developmental stages (LANDRY 1978, UYE 1982), so that older stages are less abundant than younger stages. However, longer stay in adult stage sometimes modifies such an age composition of the population.
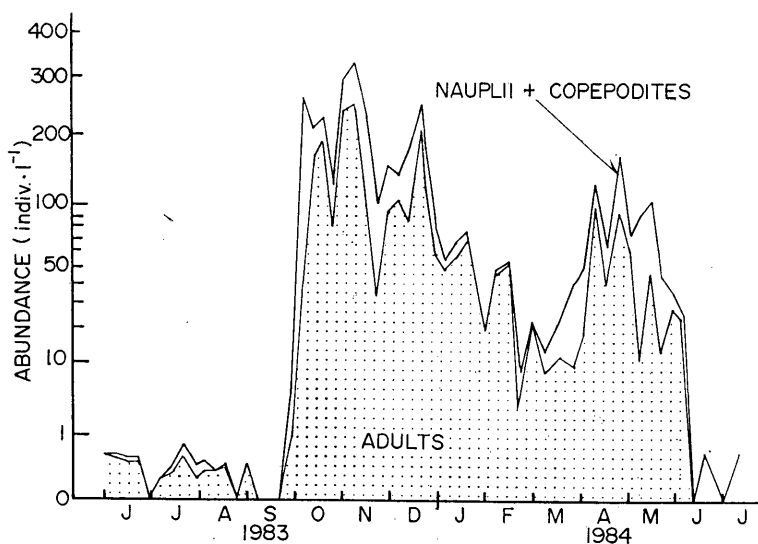

Fig. 3. Seasonal change in abundance of *Sinocalanus tenellus*.

In the *S. tenellus* population, adult stage accounted for the largest numerical proportion (mean: 64.9 % between September 1983 and May 1984, Fig. 4A). The adult ratio fluctuated extremely during fall and spring, but constantly higher in winter. When it declined below 50 %, a quick recovery followed. The highest adult ratio was 97.7 % on 27 February 1984 and lowest 11.2 % on 7 May 1984.

5. *Adult Sex Ratio of* Sinocalanus tenellus

The sex ratio (male:female) of adult *S. tenellus* varied from 0.471 to 3.695 with a mean of 1.167 (Fig. 4B). Although the ratio fluctuated in fall, 1983, it was usually higher than 1.0. During winter and early spring, it gradually decreased and a minimum value was recorded on 26 March 1984. After that, extreme fluctuations occurred at short intervals ranging from 0.538 to 3.695.

Previous studies indicate that temperature is an important factor determining copepod sex ratio (TAKEDA 1950, EGAMI 1951, KATONA 1970). HEINLE (1969) also found that the ratio of males to females was directly related to an increasing population density for *Acartia tonsa* in the Patuxent River estuary, U.S.A. Hence, analyses were made to examine the relation of the sex ratio of *S. tenellus* to water temperature or population density. However, no clear relationship was established.

6. *Prosome Length of Adult* Sinocalanus tenellus

It is commonly recognized that the body size of the planktonic copepods is smaller in summer
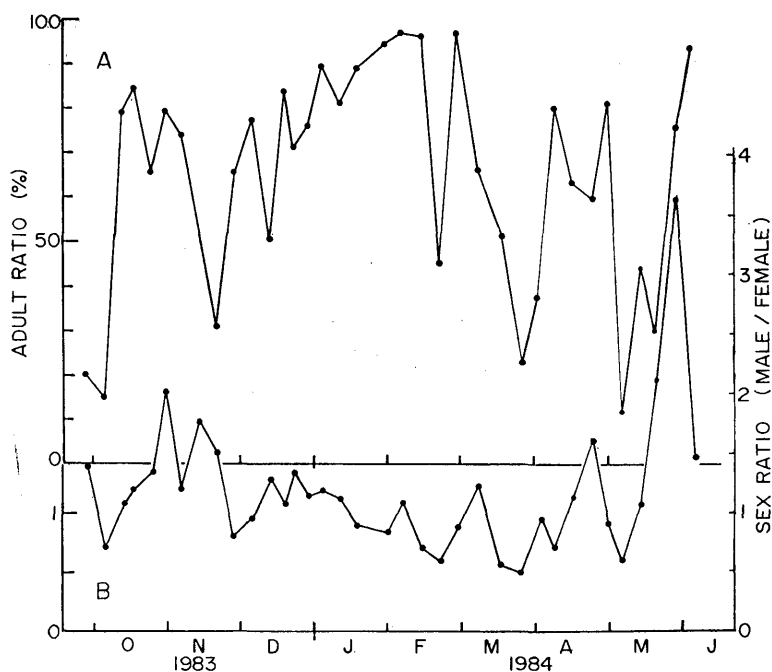

Fig. 4. Seasonal changes in (A) adult ratio and (B) sex ratio (male:female) of *Sinocalanus tenellus*.

and larger in winter, i.e. negatively correlated to the temperature of their habitat if food is reasonably abundant (DEEVEY 1960, McLAREN 1974). The reason for this is generally explained by the fact that increased water temperature produces a reduced intermolt period, which results in less growth during each instar (KURATA 1962).

However, the seasonal change in size of *S. tenellus* appeared to be inconsistent with those previous results, being larger in fall and spring, and smaller in winter and early summer (Fig. 5).
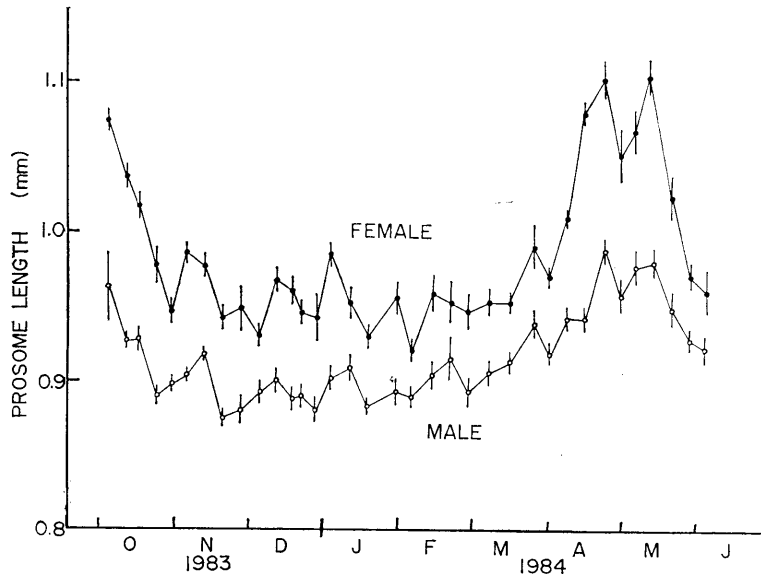
Fig. 5. Seasonal changes in prosome length of adult female and male of *Sinocalanus tenellus*. Vertical line denotes standard error.
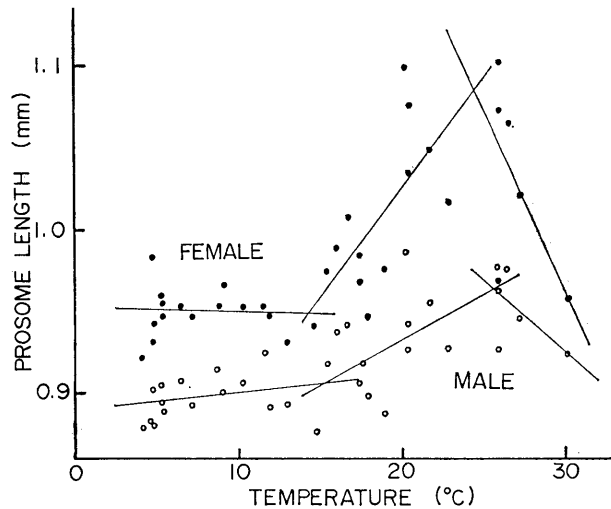
Fig. 6. Relationship between prosome length of adult female and male of *Sinocalanus tenellus* and water temperature when copepods were collected.

The prosome length was plotted against the water temperature of the pond when copepods were collected (Fig. 6). The size seemed to be positively related to water temperature below 26°C, but above this the relation looked negative.

7. Abundance of Eggs of Sinocalanus tenellus in Bottom Mud

The seasonal change in the abundance of eggs of *S. tenellus* in the bottom mud was directly related to the seasonal change in abundance of the planktonic population, being highest in spring and fall and lowest in summer (Fig. 7). The eggs were most abundant on 21 May 1984 at a density of $1.4 \times 10^7 \text{ m}^{-2}$, when the planktonic population began to decline. Although numerous eggs remained in the mud after the copepods disappeared from the plankton, they decreased rapidly at a rate of about $10\% \text{ d}^{-1}$, reaching minimum density of 3.1×10^3 eggs m^{-2} on 24 August 1983.
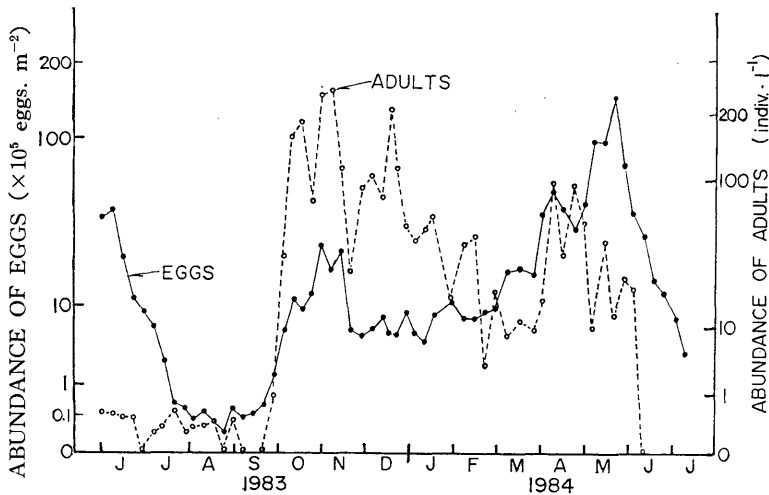

Fig. 7. Seasonal changes in abundance of eggs in bottom mud and adults of *Sinocalanus tenellus*.

8. Difference in Property of Eggs Spawned by Sinocalanus tenellus

Most eggs which had been obtained from different months throughout the period of the investigation hatched out after a relatively short incubation period at various temperatures between 10 and 30°C (Table 1). There was no significant difference in hatching success between eggs isolated from the mud and those spawned in the laboratory. Hatching success was generally higher than 80% within the temperature range tested. These facts suggest that the eggs spawned by *S. tenellus* are always subitaneous and the 'resting' eggs in bottom mud are those whose hatching is suppressed by unfavorable environmental conditions. Since the eggs of *S. tenellus* can hatch over a wide range of temperature, neither lower nor higher temperature may inhibit the hatching. The hatching inhibition by darkness (LANDRY 1975, UYE & FLEMINGER 1976) was not observed for this species. Low oxygen concentration within the bottom sediments may probably cause the hatching inhibition (UYE & FLEMINGER 1976, Uye et al. 1979,

TABLE 1. OVERALL HATCHING SUCCESS AT TEMPERATURES BETWEEN 10 AND 30 °C
OF *Sinocalanus tenellus* EGGS FROM DIFFERENT MONTHS AND SOURCES.

Date collected	Source	Number of eggs	Percent hatched
1983			
Aug. 3	Mud	40	82.5
Sept. 7	Mud	32	71.9
Oct. 5	Mud	80	71.3
Oct. 25	Lab.	230	97.0
Oct. 31	Mud	120	90.0
Nov. 16	Lab.	120	89.2
Dec. 22	Mud	120	91.6
1984			
Jan. 19	Lab.	240	85.0
Feb. 7	Mud	240	76.7
Mar. 8	Lab.	120	86.7
Mar. 21	Mud	160	86.9
Apr. 11	Lab.	120	92.0
May 1	Mud	120	99.0
May 21	Mud	120	93.3
June 12	Mud	120	87.5

$$D = 499 (T + 3.2)^{-1.76}$$
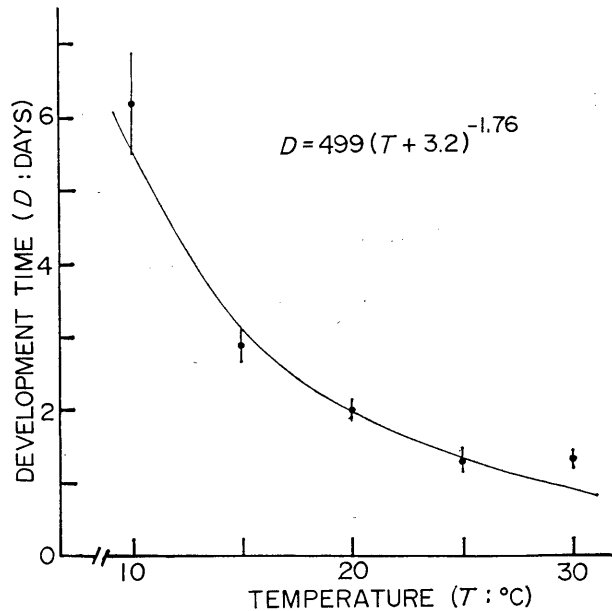
Fig. 8.   Relationship between temperature and development
time to hatching of *Sinocalanus tenellus* eggs.

AMBLER 1985), since the bottm sediments contain rich organic matter.

Most eggs that had remained unhatched during the initial incubation period did not hatch later on. However, in a few cases, additional hatching was observed just after the changing of water in wells. Factors which stimulate additional hatching are still unknown. However,

unhatched eggs were often observed to have many detrital particles over the egg surface. Micro-scale environmental deterioration (e.g. low oxygen concentration) surrounding the egg owing to the decomposition of detrital particles might inhibit egg hatching.

The development time to hatching was dependent on temperature (Fig. 8). It decreased exponentially with increasing temperature, but was slightly prolonged at 30°C. Belĕhrádek's equation, which has been commonly used to describe the relationship between development time and temperature (McLAREN et al. 1969), was fitted. A total of 65 sets of data were available for fitting the equation, which was expressed as:

$$D = 499 (T+3.2)^{-1.76}$$

where D is the development time in days, T is temperature in °C.

Discussion

The zooplankton community in a brackish-water pond in Fukuyama was very simple, and consisted of a single species each of mysid (*Neomysis japonica*) and copepod (*Sinocalanus tenellus*), with probably two species of rotifers (*Brachionus* spp.). Small benthic cyclopoids were occasionally collected in summer. *S. tenellus* appeared in the plankton mainly from October to May with a prominent peak in November and less conspicuous peak in April. In summer, the planktonic population almost disappeared, but many resting eggs remained in the bottom sediments.

One of the characteristic features in the seasonal life cycle of *S. tenellus* is an enormously high rate of population increase. In this study, after the population fall in summer, *S. tenellus* increased at an instantaneous rate of 0.561 per day which accounts for a 75 % increase in population abundance per day. This rapid population increase is due to a high potential of egg production and a short development time to adulthood. KIMOTO et al. (1986, in preparation) demonstrated that the maximum egg production by an adult female of *S. tenellus* was ca. 60 eggs d⁻¹ and the minimum development time from egg laying to adult was ca. 8 d at ca. 25°C, which corresponds to the in situ water temperature in September and October. In addition, a recruitment from benthic resting eggs was also possible. A high standing stock of phytoplankton supported the population increase during this period.

A second characteristic feature is the large numerical proportion of adults in the planktonic population. Generally, large-sized adult copepods are selectively preyed by planktivorous fish and their ecological longevity would become much shorter than their physiological longevity (LANDRY 1978, JOHNSON 1981, UYE 1982). In the pond we investigated, the possible predators of *S. tenellus* were *Neomysis japonica* and a mullet (*Mugil cephalus*). However, the former was present only during the first few months of the present investigation and the latter might be too large (they were larger than ca. 30 cm in length) to prey on *S. tenellus*. Hence, it is likely that adult *S. tenellus* did not receive any significant predation pressure in this pond. We also found that adult *S. tenellus* heavily preyed on their own newly hatched nauplii. This implies that the adult population prohibits the development of new generation

by cannibalism. It is concluded therefore that once *S. tenellus* becomes adult, they may live nearly as long as their physiological longevity.

The third characteristic point is a puzzling seasonal change in body length of *S. tenellus*. A negative relationship between prosome length and temperature has been confirmed to *S. tenellus* reared at different temperatures with excess food in the laboratory (KIMOTO et al. 1986). On the contrary, a positive relationship was observed at temperatures below 26°C for field population (Fig. 6). CORKETT & McLAREN (1978) criticized the use of temperature at the time of capture as a habitat temperature, since it can be a poor indicator of copepod size under that habitat temperature, especially for long-lived species. Because of the absence of detailed data about the generation length of *S. tenellus* in the pond, we could not determine the habitat temperature (average temperature experienced during development). A relation of the size to temperature two weeks before capture was again positive. A similar positive relationship between temperature and adult size was found for a planktonic harpacticoid copepod, *Microsetella norvegica* (EVANS, 1978). EVANS suspected that food abundance is more important in determining the size of this species in waters of Northumberland, England. In our study, no clear relationship was found between the size of *S. tenellus* and chlorophyll *a* concentration of the pond water, although chlorophyll *a* value does not indicate a real abundance of food suitable for *S. tenellus*. Since *S. tenellus* is omnivorous, the abundance of animal food such as *Brachionus* spp. and *S. tenellus* nauplii may also be factors causing change in body size.

Another important aspect in the life cycle of *S. tenellus* is the occurrence of benthic resting eggs. Almost all the eggs of *S. tenellus* isolated from the bottom mud and those spawned directly by females in the laboratory hatched subitaneously without any significant seasonal variation in their hatching property. Therefore, it can be concluded that this species does not produce diapause eggs in the pond. In such a shallow water body, eggs after spawning sink to the bottom and are buried within the bottom sediments. The bottom deposit of the pond is rich in organic matter; so oxygen would be quickly used during its decomposition especially when warm. Hence, the eggs remain quiescent owing to the anoxic condition until they are washed free from the bottom. The viability and hatching of resting eggs of neritic calanoid copepods have been reported to be greatly affected by organic pollution of the bottom sediments (UYE et al. 1984). The storage of eggs of *S. tenellus* in the mud for a prolonged period certainly reduced the egg viability, i.e., the number of eggs decreased steeply from a peak (1.4×10^7 eggs m^{-2}) to ca. 3,000 eggs m^{-2}, and the hatching success was slightly reduced from 82.5 % for eggs taken on 3 August 1983 to 71-72 % for those taken on 7 and 21 September (Table 1). But some eggs could apparently survive over the resting period of ca. 3 months and contribute to a new planktonic population in fall. Hence, resting eggs may play an important role in maintaining the population of *S. tenellus* during periods unfavorable to the existence of the planktonic form. In addition to the role of resting eggs as an aestivation mechanism, the existence of benthic resting eggs may also contribute to the maintenance of the population of *S. tenellus* within a certain region of estuaries, because estuarine zooplankton populations are always facing to extinction due to river water flushing.

Acknowledgement

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