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Population Structure of Surface Swarms of the Euphausiid *Euphausia pacifica* Caught by Drum Screens of Uljin Nuclear Power Plant in the East Coast of Korea

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In February and April 1997, three temporary interruptions of electric power production at the Uljin Nuclear Power Plant in the east coast of Korea were caused by the malfunction of the cooling-water supply unit. The clogging of the drum screens inside the unit caused by the surface swarm of the euphausiid *Euphausia pacifica* Hansen might be responsible for the malfunction. These incidents were of particular interest since such interruption of reactors' operation by krill swarms had not previously been reported. Using samples caught by the drum screens inside the cooling water-supply unit, we investigated the population structure of surface swarms. One occasion of nighttime and three occasions of daytime surface swarms were found in February and April 1997, respectively. The foreguts of more than 60% of *E. pacifica* in nighttime surface swarm were in full condition. This evidence suggests that *E. pacifica* aggregates to the surface water at night for feeding. In daytime surface swarms consisting of mature *E. pacifica*, however, foreguts in full condition were only found in less than 10% of krill examined, suggesting that daytime surface swarms are closely related to breeding activity. During the study period, the growth rate of mature females was more than twice higher than that of mature males. Analyses of the sex-ratio and length-frequency data show a decrease in the portion of males with increasing size. There was a decline in the number of males of 19 mm in length. Energy loss during spermatophore transfer may result in the death of male *E. pacifica*, as found in male *E. superba*.

INTRODUCTION

Korea has so far 12 reactors in four nuclear power plants (NPPs), which are responsible for 36% of the nation's electricity supply. To further reduce dependence on imported oil, Korea has a plan to build more reactors fueled by uranium (KEPCO, 1997). At the Uljin NPP in the east coast of Korea, interruption of electric power production took place three times between February and April, 1997. Such incidents occurred because of clogging the drum screens inside the cooling-water supply unit of reactor caused by swarms of *Euphausia pacifica* Hansen. This event has not been reported yet.

Approximately 18 species of euphausiids studied in various parts of the oceans are known to form a swarm at the surface during the day (Mauchline, 1980), but the frequency of their swarming varies from species to species. *Euphausia superba* of the Antarctic, most well known species so far, may aggregate at the surface during the day throughout most of its life cycle (Marr, 1962); the others, such as *E. pacifica*, appear to swarm only seasonally (Komaki, 1967; Endo, 1984). The mechanisms of their swarms are not fully understood yet and may not be same in all species.

Komaki (1967) proposed four hypotheses to explain the swarming phenomenon: (1) euphausiids congregate at the surface to feed; (2) or to escape predators; (3) they are passively transported to the surface by physical processes or move to feed on organisms that are passively brought to the surface, or (4) they actively search out the surface for some factors related to reproduction. These hypotheses are difficult to test because many aspects of the swarming phenomenon should be considered for the experimental investigation. Also, most previous studies did not provide direct hydrographic evidence and comparative information on the vertical distribution of various components of the population before, during and after swarming (Smith and Adams, 1988).

There have been several studies on daytime surface swarms of euphausiids, mostly detected by red surface patches and often accompanied by numerous predators such as birds, whales and fishes (Mauchline and Fisher, 1969), however, few studies on nighttime surface swarms. This scarcity of information on nighttime surface swarms may be due to difficulty in visual detection and the unpredictability of onset and duration of swarms. Although daytime swarms of *E. pacifica* are often easily visible at the surface and have frequently occurred in the East Sea (Sea of Japan), little information is available on population structure. The only published report consists of brief accounts of swarms from the southern waters of the East Sea (Uda, 1952). Moreover, there is no information on population structure of surface swarms at night.

The present study explored surface swarms of *E. pacifica* in the coastal waters off eastern Korea. The objectives of this study were to investigate the occurrence of the daytime and nighttime surface swarms, to describe the population structure of this phenomenon, and to examine the possible functions of swarming.

MATERIALS AND METHODS

Surface swarms are usually categorized into four basic types of aggregation: patches, shoals, swarms and schools, with the last two types corresponding to high-density aggregations of more than 1000 animals m^{-3} (Mauchline, 1980). Schools were composed of one species as swarms, but differed from swarms in the aspect that schools were moving through the water whereas swarms were stationary. Because of the similarity in these two types of aggregations, high-density aggregations were termed as swarms unless a point is being made about their orientation (Nicol, 1984).

All krill samples were taken from the water passing the drum screen (12 m diameter, 7 m length, 4×4 mm aperture), equipped inside the cooling water-supply unit (Fig. 1) in the Uljin NPP (37° 15'N, 129°23'E). In intake canal (250 m in length and 8 m in depth), flow speeds at the mouth were measured at a range between 30 and 60 cm/s. Drum screens rotated at a speed of one revolution per 16 min. Since the surface water from 0 to 8 m in depth was used for the cooling water, the screens collected

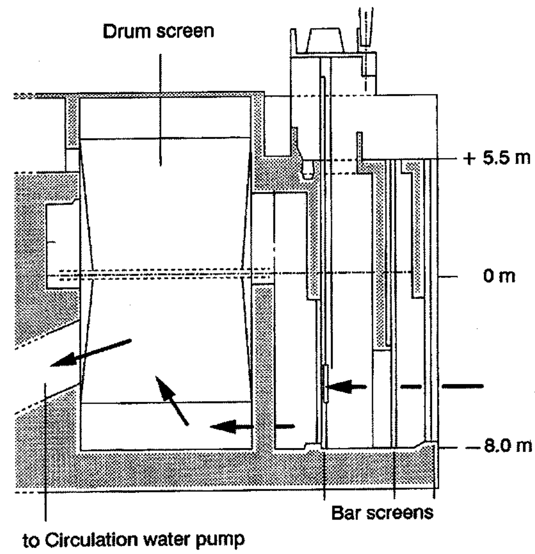

Fig. 1. Diagram of the drum screen inside the cooling-water supply unit at the Uljin NPP. Arrowheads indicate the flow direction of cooling water.

surface swarms. A subsample (N>5000 if possible) was preserved in 10% formalin in seawater. More than 300 euphausiids (where possible) were examined from each preserved sample using a plankton splitter. Each individual was identified to species level and sexed using the key provided in Mauchline and Fisher (1969) and a micrometric binocular microscope. The sex ratio was expressed as % female and compared to a theoretically normal sex ratio of 50% female.

Copulation of euphausiids is completed by transfer of spermatophore to female. All males in each subsample were examined for the presence of spermatophores, either in the ejaculatory ducts, extruded or attached to the appendages. All females in each subsample were examined for attached spermatophores on the thelycum.

The length of the sixth abdominal segment (X) along the dorsal margin of each individual was measured, and converted to total length (Y) using the equations by Endo (1984): $Y=0.82+6.81X$ for females and $Y=3.84+5.36X$ for males.

Foreguts of approximately 100 specimens randomly selected were removed and examined under a dissecting microscope to measure fullness. Foregut fullness was scored into five categories: empty, one-fourth, half-full, three-fourths, and full. Then foregut was immersed in distilled water for several hours, transferred into gum-chloral medium on a slide glass, and covered with a cover slip. After drying for more than 10 d at a room temperature

Table 1. The hydrographic and meteorological data when the samples of surface swarms of *Euphausia pacifica* were taken from the water passing the drum screens inside the cooling-water supply unit at the Uljin NPP in 1997

Date (d/m/y)	Time (h)	Water temp. (°C)	Salinity (psu)	Wind	
				Direction	Speed (m/s)
01/02/97[1]	02:00	8.3	34.2	N	3.1
10/04/97[1, 2]	17:00	12.4	34.4	SSW	5.3
24/04/97[1, 3]	05:30	12.6	34.5	ENE	3.7
29/04/97	13:30	12.4	34.5	SW	4.4

[1]The interruption of electric power production was accompanied by the presence of surface swarms.
[2]Local time of sunset was 18:52 h.
[3]Local time of sunrise was 05:37 h.

(approximately 20°C), foregut contents were analyzed under a differential interference and phase contrast microscope (Zeiss Axioskop).

RESULTS

The minimum surface temperature of waters off the Uljin NPP was 8.3°C on 1 February, while the maximum 12.6°C on 24 April, 1997. The seas were relatively calm when samples were taken: the range of wind speeds was 3.1 to 5.3 m/s (4.1 m/s on average) (Table 1).

All euphausiids from samples of surface swarms at the Uljin NPP were *Euphausia pacifica*. The ranges of mean total length of males and females, 16.2 to 16.6 mm and 17.1 to 18.0 mm, respectively (Table 2), were very narrow. The size range in the surface swarms appeared to occupy a restricted portion of the size range of the normal population, comprising only mature male and female individuals larger than 16 and 17 mm, respectively. This phenomenon may be a result of the length dependency of the swimming speed in euphausiids leading to an assortment of the swarming population by size (Hamner *et al.*, 1983).

There were significant changes in mean total lengths between samples collected on 1 February and 24 April; (males: $t=-4.335$, $p<0.001$; females: $t=-11.113$, $p<0.001$). According to changes in body size for 82 d, the growth rates of males and females were 0.005 and 0.011 mm/d, respectively.

All samples taken in 1997 were predominated by females. The sex ratio ranged from 53 to 93% female with a mean of 73% female (Table 2). Samples taken in late April showed highly skewed values of the sex ratios than the others: The portions of females in samples collected on 24 and 29 April were more than 85% but those on 1 February and 10 April were less than 60%.

Most males examined in the present study were in breeding condition, as indicated by the presence of two spermatophores in the ejaculatory ducts. In the April samples, 24 to 29% male appeared to be in the process of spermatophore transfer, as indicated by the extrusion of one or more spermatophores and attachment to the appendages. In the February sample, however, no males were in the process of spermatophore transfer (Table 2). In only the 24 April sample, 15% female were copulated, as generally evident by the presence of a spermatophore on the thelycum. But, females with attached spermatophore were not found in the other three samples (Table 2). Our data on sexual characteristics show that *E. pacifica* caught in April were in breeding condition, while krill taken in February were not yet.

The great majority (66 to 97%) of foreguts in daytime surface swarms were in foregut fullness less than half, whereas a small percentage (24%) in nighttime swarming (Table 3). This evidence suggests that *E. pacifica* in the surface swarms did not feed actively during the day, but did actively at night. Detritus was most frequently found in the foregut contents, and crustacean spines were in the next place.

DISCUSSION

The swarms observed at the Uljin NPP in 1997 were formed solely by *E. pacifica*. There are six species of euphausiids so far reported in the East Sea of Korea: *Euphausia pacifica*, *E. mutica*,

Table 2. The characteristics of the populations of *Euphausia pacifica* in swarms collected from the water passing the drum screens inside the cooling-water supply unit at the Uljin NPP in 1997 (Numbers of individuals examined are in parentheses)

Date (d/m/y)	Total length (mm) (mean±SD)		Sex ratio (% female)	% female with spermatophore	% male without spermatophore
	Female	Male			
01/02/97	17.1±1.0 (197)	16.2±0.7 (131)	60	0	0
10/04/97	17.4±0.9 (209)	16.3±0.6 (188)	53	0	24
24/04/97	18.0±0.8 (305)	16.6±0.6 (55)	85	15	26
29/04/97	18.0±0.8 (93)	16.4±0.5 (7)	93	0	29

Table 3. *Euphausia pacifica.* Foregut fullness in 100 randomly selected individuals of surface swarm caught by the drum screens inside the cooling-water supply unit at the Uljin NPP in 1997. Foregut fullness is scored into five categories: empty, one-fourth full, half-full, three-fourth full and full

Date (d/m/y)	Foregut fullness				
	Empty	1/4	1/2	3/4	Full
01/02/97	9	5	10	13	63
10/04/97	76	18	3	1	2
24/04/97	7	28	31	24	9
29/04/97	49	25	16	8	2

Pseudeuphausia latifrons, *Stylocheiron affine*, *Thysanoessa longipes* and *T. inermis*. Of these, *E. pacifica* is the most abundant species (Komaki and Matsue, 1958; Hong, 1969). In the East Sea, the daytime surface swarms of *E. pacifica* (Komaki, 1967) and *T. inermis* (Hanamura *et al.*, 1989) have been reported.

Both nighttime and daytime surface swarms of *E. pacifica* occurred (Table 1). According to an analysis of foregut fullness (Table 3), we suggest that the major portion of *E. pacifica* in nighttime surface swarm observed on 1 February performed the high feeding activity. In contrast, all swarms obtained during the day in April were composed of individuals of adults in breeding condition: males with developed spermatophores and ovigerous females (Table 2). This evidence suggests that daytime surface swarming of *E. pacifica* was mainly related to reproduction. It is likely that, in the coastal waters off eastern Korea, the breeding of this species occurs in April. This coincides with the swarming season (Endo, 1984) and agrees with the results of Endo (1984) and Terazaki *et al.* (1986) for *E. pacifica* in the Pacific coast of northern Japan, of Nicol (1984) for *Meganyctiphanes norvegica* in the Bay of Fundy, Canada, of O'Brien *et al.* (1986) for *Nyctiphanes australis* in the southeast Tasmanian waters, of Gendron (1992) for *N. simplex* in the Gulf of California, Mexico, of Smith and Adams (1988) for *Thysanoessa spinifera* in the Gulf of the Farallones, California, and of Hanamura *et al.* (1989) for *T. inermis* in the northern Japan. All these authors concluded that daytime surface swarming was related to reproduction.

As discussed in Gendron (1992), daytime surface swarming could be related to reproduction in different ways: (1) for more effective transfer of spermatophores; (2) for release of eggs at the surface; or (3) for maturation of sexual product in adults in warm surface layers. There are arguments for and against all of these possibilities. Smith and Adams (1988) suggested that one of the functions of surface swarming was to prolong exposure of reproductive individuals of *T. spinifera* to the warmer surface layers, where maturation of sexual products would be accelerated. But, the advantage gained by this strategy would have to outweigh the disadvantage of being highly vulnerable to predation at the sea surface during the day.

The low portion (< 1%) of females with spermatophores attached to the thelycum have been found generally in the surface swarms of *E. pacifica* (Komaki, 1967; Endo, 1984; Terazaki, 1980; Hanamura *et al.*, 1984). However, Terazaki *et al.* (1986) found, from the Pacific coast of northern Japan, that 14 to 45% female have spermatophores attached to the thelycum in the samples taken below 15 m depth, and they concluded that main breeding location of *E. pacifica* was the shallow waters near the coast and their copulation occurred in mid-water. In the 24 April sample, 15% female had a spermatophore on the thelycum (Table 2), suggesting that copulation of *E. pacifica* takes place at the surface of coastal waters in the East Sea. However, we did not confirm the depth of egg release because of no data on eggs and larval distribution.

Egg release at the surface by euphausiids which do not carry eggs in sacs would provide more time for eggs to develop and hatch before reaching the sea floor (Nicol, 1984). However, if eggs were released at the surface in shallow waters, eggs would reach the sea bottom before hatching. Also, if *E. pacifica* takes this strategy, released eggs faced high vulnerability for predation on the sea bottom. Instead, this species would benefit from releasing eggs high at the surface of offshore waters, thus providing more time for eggs to develop and hatch before reaching the sea floor. However, this suggestion of egg release at the surface of offshore waters was not confirmed because no data on egg and larval distribution were available.

Lasker (1966) calculated from the information of Ponomareva (1963) that the growth of juveniles of *E. pacifica* attained 0.02 mm/d. In this study, growth of mature females, 0.011 mm/d, more than twice higher than that of mature males, 0.005 mm/d. Moreover, a decrease in the number of reproductive males in relation to body size was evident from sex-ratio data for individuals collected from February to April in the east coast of Korea (Table 2). There was a sharp decline in numbers of males

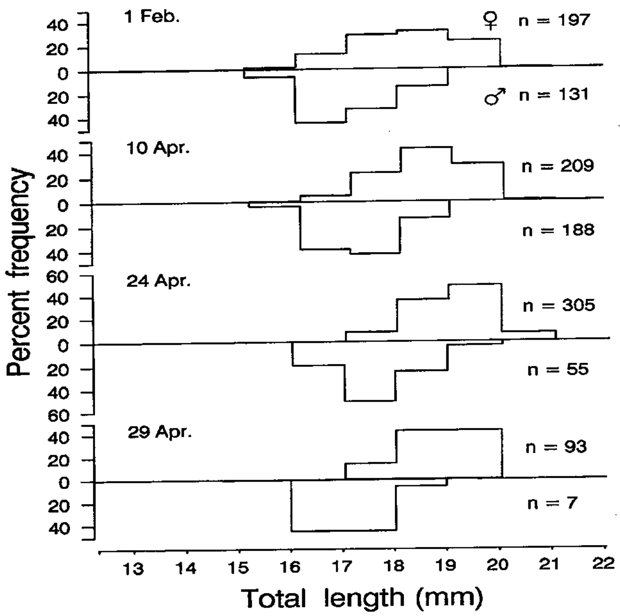

Fig. 2. Length-frequency histograms comparing total lengths in four samples of surface swarms of *Euphausia pacifica* collected from the water passing the drum screens inside the cooling-water supply unit at the Uljin NPP in 1997.

once they attained a length of 19 mm (Fig. 2). In general, males of this size are actively reproducing during the breeding season. Changes in sex ratios within krill populations have been reported suggest an association between mortality and breeding (Mauchline, 1980). Marr (1962) suggested that male *E. superba* die immediately after spermatophore transfer. Recently, Virtue *et al.* (1966) reported, based on the mortality and biochemical data, that energy loss during spermatophore transfer and production may be responsible for reduction in the lipid reserves which ultimately results in the death of male *E. superba*. Marr's suggestion would be confirmed by the results of our investigation on length-frequency and sex-ratio of *E. pacifica*.

Terazaki (1980) found that daytime surface swarms of *E. pacifica* moved with speed ranging 14.3 to 22.2 cm/s (18.5 cm/s on average). Flow speeds of seawater at the intake canal, ranging 30 to 60 cm/s, was two to three times faster than swimming speeds of krill swarms. Thus if swarms moved into the intake canal, swarms would be entrained in the flow of water. Although krill swarms are unpredictable nature of their onset and duration, reduction of flow speed at the intake canal below 15 cm/s may prevent krill swarms from entraining in cooling waters. Perhaps this helps the Uljin NPP avoid the interruption of electric power production.

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