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PRELIMINARY STUDY
ON THE DIFFUSIVE MOVEMENTS OF SQUID POPULATION

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Synopsis

From the results of marking experiments on squid carried out by Soeda et al. in 1951, hyperbolic variations of the number of recaptured squids at a fixed fishing ground are indicated. The densities of squid population in two adjacent fishing grounds along the migration path are almost equal to each other at any time. The movements of squid shoals are considered to be "diffusive" and the diffusion source is located in the fishing ground where the commercial catches of squid are comparatively uniform and stable throughout the fishing season.

Introduction

Along the southern coast of Hokkaido, there are formed several highly productive fishing grounds of squid from June to the end of the year. Among them, the fishing ground off Esan is most productive. Many marking experiments have been carried out since 1928, especially in 1950 and 1951 in the several regions including Esan fishing ground, by the members of Hokkaido Fisheries Scientific Institution. The extent of tolerable temperature for squid population is generally considered very wide, the optimum temperature being about 14° C at which the population has highest density.

Soeda (1950) states that the annual travelling of squid population round Japan Islands approximately coincides with that of the optimum temperature region. The extent of tolerable or optimum temperature for an individual squid or for a single shoal, however, may be different from and narrower than that of the population as a whole. The gregarious habit of squid has not hitherto been ascertained, that is, neither the theory which attributes gregariousness to a communal urge to spawn or to feed nor an ingenious

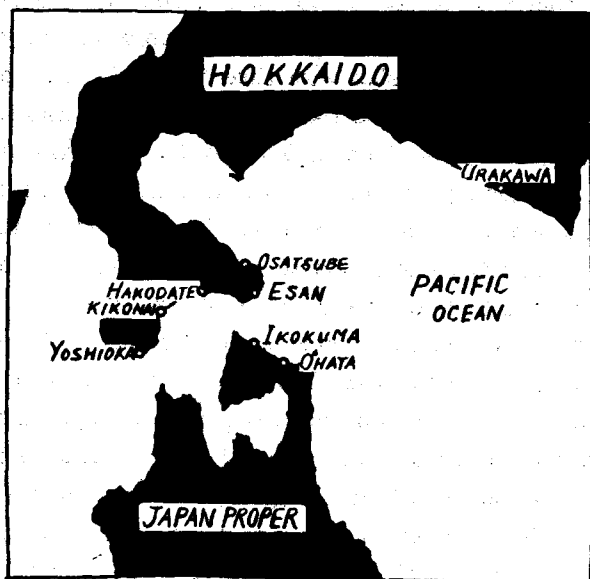


Fig. 1. Sketch map around the Tsugaru Strait showing the location of Esan and others

hypothesis which seeks to define a shoal as a gathering of fish all of which are of like size or of like age, can be applied with sufficient success to squid population, mainly for the lack of biological investigation. The analysis of variation of catches of marked squids, however, presents some remarkable evidence for the gregarious habit of squid, transitory or not. And from the same analysis the author has come to have some idea on the diffusive movements of squid population.

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Fluctuations of Recaptures

Marking experiments have been carried out in several regions along the southern coast of Hokkaido in 1951 by the members of Hokkaido Fisheries Scientific Institution, in which above one thousand marked individuals were liberated in eleven times. Ten out of the eleven liberations were carried out on the Esan fishing ground on Aug. 6, Sep. 8, 21, 24, Nov. 6, 14, 17, 20, 25, and Dec. 1. The marked squids were recaptured in various regions, the recaptures off Esan being greater than in other regions through these ten liberations. The variations of the number of squids recaptured off Esan where they had been liberated, are shown in figures 2-4, each one of which includes the recaptured individuals liberated on the respective same day.

It is apparent from these curves that the number of recaptured squids r being rather great during a few days immediately after liberation, soon decreases very rapidly and the decreasing speed dr/dt also diminishes with time t , resulting in the nearly hyperbolic trend of variation. If one assumes the fishing effort to be constant throughout the fishing season, catches per day can be considered to be proportional to the density of the population in the fishing ground on that day. Provided that marked individuals are distributed homogeneously among the population or shoal in the fishing ground, one can safely say that the curves mentioned above indicate the variation of density of population or shoal that remains within that ground.

Some of the marked squids liberated in the Esan ground were recaptured off Osatsube, 15 miles north of Esan, especially more frequently in August and September. In that season, most of the liberated squids seem to swim north and to be caught there. The daily recaptures off Osatsube are plotted on figures 2-4 with small circles together with the recaptures off Esan of the same liberation group. The tendency of the variation off Osatsube is remarkably similar to that off Esan especially in September and one may say that they coincide with each other, if the difference between the fishing efforts on the two fishing ground is taken into account.

In December when scarcely any liberated squids appear in Osatsube fishing

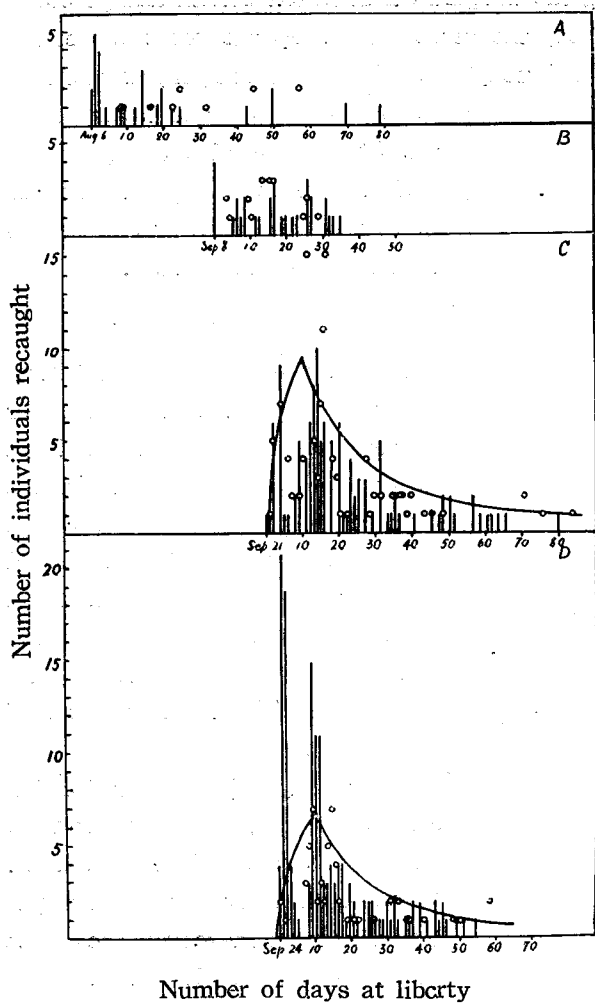


Fig. 2. Fluctuations of the numbers of recaptured squids in the Esan and Osatsube fishing grounds, the former being shown by histograms and the latter by small circles, liberated within the Esan ground on Aug. 6 (A), Sep. 3 (B), 21 (C), and 24 (D), respectively. In C and D, the theoretical curves for the variation of recaptures off Osatsube are also drawn.

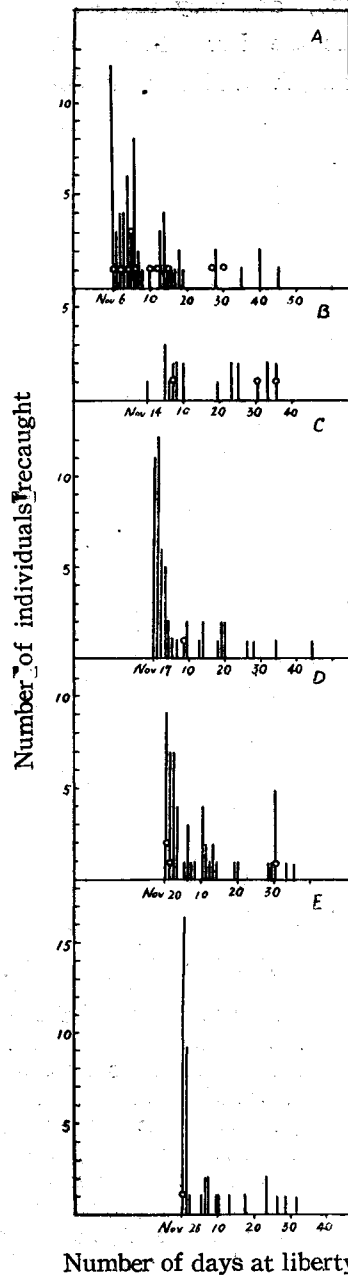


Fig. 3. Fluctuations of the numbers of recaptured squids in the Esan and Osatsube fishing grounds, the former being shown by histograms and the latter by small circles, liberated within the Esan ground on Nov. 6 (A), 14 (B), 17 (C), 20 (D), and 25 (E), respectively.

ground, and they move west along the Tsugaru Strait in one branch and go south across the Strait in the other branch, the recaptures along the coast of western Oshima, from Kikonaji to Yoshioka, and recaptures off Shimokita region, from Ohata

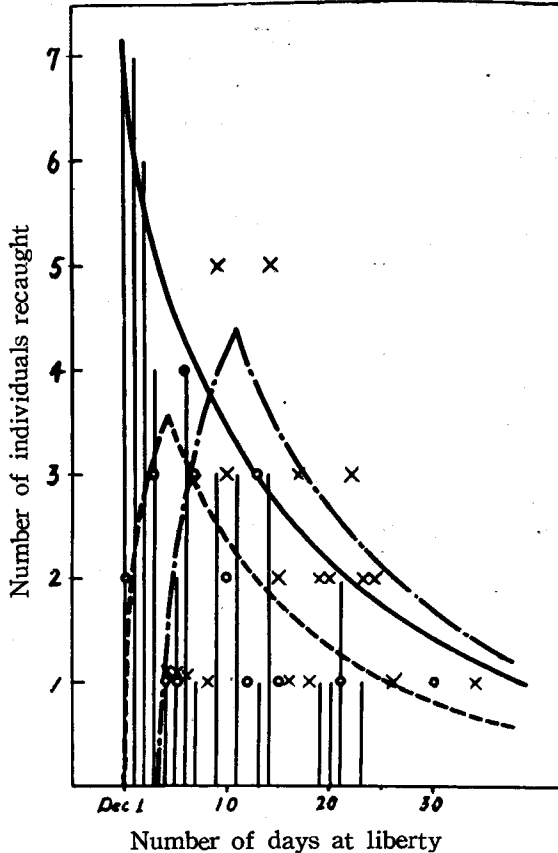


Fig. 4. Fluctuations of the numbers of recaptured squids off Esan, off Shimokita and off western Oshima liberated within the Esan ground on Dec. 1, the former being shown by histograms and the latter two by small circles and small crosses, respectively. The theoretical curves for the variations of recaptures are also drawn by solid line (off Esan), dotted line (off Shimokita) and chain line (off western Oshima), respectively.

swimming about within the fishing ground along the migration path are

$$B.v.t_1.\rho = N.t_1/T_0 + t_1$$

and

$$B.v.T_1.\rho = N.T_1/T_0 + T_1 + t,$$

when the diffusion front is travelling within the ground and when the front has

to Ikokuma, opposite Esan across the Strait, are also of hyperbolic variation respectively, being similar to that on the Esan ground at this time as shown in figure 4.

Diffusive Movements

From the preceding statement that the fluctuation of the number of recaptured squids in the Esan region coincides with that in the Osatsube region, it may be stated that every branch which migrated out of the same source has equal population density to that of the source at any time, and this suggests to one the diffusive movement of the population.

Kuroki (1953) has introduced a simple and ingenuous formula to explain the fluctuations of catches. When a shoal or a part of population begins to move from the source where N individuals are crowding and swimming about not yet starting on the migratory journey as a whole group, with a constant diffusion breadth B and a constant speed V of the diffusion front, the population density ρ at time T may be expressed as

$$\rho = \frac{N}{B.v.T}$$

The number of individuals that are

migrated out of the last end of it, respectively. Here, T_0 and T_1 are the duration of time which the front has needed to pass through the distance L between the source and the entrance of the fishing ground and whole length l of it, respectively and t_1 and t are the lapse of time which the front has needed to reach the present position from the entrance of the fishing ground and from the last end of the fishing ground, respectively.

If the fishing coefficient for the marked individuals in the fishing ground is denoted by f , the number r of recaptured individuals within the ground must be

$$r = f \cdot N \cdot t_1 / T_0 + t_1 \quad (1)$$

and

$$r = f \cdot N \cdot T_1 / T_0 + T_1 + t \quad (2)$$

at respective times. Hence the maximum number of marked individuals is to be recaptured at time $T_0 + T_1$ when the front has just finished leaving the ground, the maximum value being $f \cdot N \cdot T_1 / T_0 + T_1$.

In the present case, the Esan region is considered to be occupied by the diffusion source of squid shoal at the day of liberation and Osatsube to be the fishing ground. In figure 2, C and D, the maximum recaptures off Osatsube occur about 10 days after the liberations and the maximum numbers are 15 and 7 individuals respectively. The length l of the Osatsube fishing ground is estimated about 18 miles and the distance between the center of the Esan source and the entrance of the Osatsube

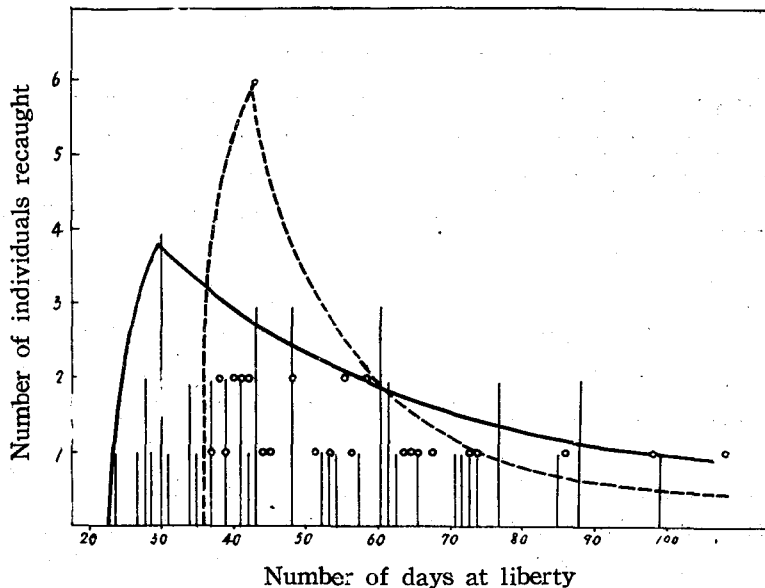


Fig. 5. Fluctuations of the numbers of recaptured squids off Esan and off Osatsube, the former being shown by histogram and the latter by small circles, liberated off Urakawa on Aug. 28. The curves drawn by solid line and dotted line indicate approximate trends of the fluctuations off Esan and off Osatsube, respectively.

ground about ten miles. Hence, T_0 and T_L are estimated to be about 5.5 days and 10 days respectively, but the marked squids have been liberated at various points within the Esan ground in a day and they actually have not needed 5.5 days for diffusing to the entrance of the adjacent Osatsube fishing ground.

From the above data, equations (1) and (2) are plotted as shown in figure 2, C and D, and the diffusion velocity v is calculated 1.8 miles per day in this area.

By the same process, equations (1) and (2) are also applied to the fluctuation of recaptures off Shimokita region where L equals about 20 miles and l about 10 miles, and to the fluctuation of recaptures off western Oshima where L equals about 40 miles and l about 25 miles, the result being shown in figure 4. The diffusion velocities in these areas are calculated to be 5 miles per day and 2 miles per day respectively.

In figure 5 the fluctuations of recaptures on the Esan and Osatsube fishing grounds in the marking experiment on squid liberated off Urakawa on Aug. 29, 1951 are shown. In this case, however, each fluctuation does not coincide and from the former fluctuation L is calculated 97 miles while the actual distance between Esan and the position of liberation off Urakawa is 75 miles, and from the latter fluctuation L is calculated 3 miles which is nearly the actual distance between the Esan and Osatsube fishing grounds. The speeds of the diffusion fronts are also calculated to be 1.2 miles per day from the former and 3 miles per day from the latter.

Discussion and Conclusion

Owing to the inhomogeneity of fishing effort throughout the fishing season, on which the author has little information, and to the influence of oceanographical conditions, the variations of catches of marked squids are not exactly smoothly hyperbolic, which may be due also to the overlooking of marked individuals recaptured. The general trends of catches, however, show approximately hyperbolic variations with time. In August, September and October, most of the squid groups liberated on the Esan ground diffusively moved north and consequently the recaptures off Osatsube showed hyperbolic variation similar to that within the Esan fishing ground.

Though the group liberated off Urakawa has migrated into the Esan and Osatsube fishing grounds with hyperbolic variation with time, each variation does not coincide as in the preceding cases. The diffusive movement into the Esan ground seems to have its source near Urakawa, but the movement into the Osatsube ground seems to have its source off Esan. That is to say, the group liberated off Urakawa seems to have migrated into the Esan ground and rearranged within that ground before beginning the new migratory journey. The difference of the two population densities may be explained by the daily adding of individuals newly arrived at the Esan ground from some source near Urakawa, and they may swim about within the new fishing ground to feed for some days before migrating out of this ground. That

the dates when the diffusion front migrated into the Esan and Osatsube ground are Sept. 25 and Oct. 8 respectively may show that the population hesitated to begin a new migration journey for a rather long time compared to the groups liberated within the Esan ground itself, which migrated out without any remarkable hesitation. The fact that commercial catches of squid off Esan are more stable and more uniform throughout the season (Soeda, 1951) than in other fishing grounds such as the one off Hakodate, may be explained by this hesitation of squid population to migrate out of this area.

The density of the whole population in the source or fishing ground, of course differs from and is greater than the density of a group some members of which were liberated at some certain same day and appeared there, and therefore the variation of total catches does not follow a hyperbolic curve. The density may be expressed as

$$\sum_i \frac{N_i}{T_{oi} + T_r + t_i}$$

where \sum_i means the summation of all shoals which have migrated into the fishing ground from the diffusion sources in diffusive movements.

The diffusion speeds calculated above vary between 1.2 miles and 5 miles per day according to the geographical regions and perhaps to the season of the year, but the accuracy of the calculation is limited.

The shoaling habit of squids, however, seems to be rather weak and the boundary of any single shoal seems to be very vague in these areas.

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