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Changes in inferred spawning sites of *Todarodes pacificus* (Cephalopoda: Ommastrephidae) due to changing environmental conditions

Yasunori Sakurai, John R. Bower, Hidetoshi Kiyofuji, Sei-ichi Saitoh, Tsuneo Goto, Yoshiaki Hiyama, Ken Mori and Yoshikazu Nakamura

Yasunori Sakurai, John R. Bower, Hidetoshi Kiyofuji and Sei-ichi Saitoh: Faculty of Fisheries, Hokkaido University, Hakodate, Hokkaido 041-8611, Japan. Tsuneo Goto, Yoshiaki Hiyama: Japan Sea National Fisheries Research Institute, Niigata 951-8121, Japan. Ken Mori and Yoshikazu Nakamura: Hokkaido National Fisheries Research Institute, Kushiro, Hokkaido 085-0802, Japan. Correspondence to Y. Sakurai: tel: +81 138 40 8863; fax: +81 138 40 8860; e-mail: sakurai@pop.fish.hokudai.ac.jp

Abstract

Annual catches of *Todarodes pacificus* in Japan have gradually increased since the late 1980s despite the lack of catch regulations. Paralarval abundances have also been higher since the late 1980s than during the late 1970s and mid-1980s. We propose a possible scenario for this recent stock increase based on changing environmental conditions. First, we review trends in the annual variations of stock and larval catches, and infer possible spawning sites around Japan, assuming that egg masses and hatchlings occur at temperarures between 15 and 23°C, and above the continental shelf. We then infer possible changes in the spawning sites of *T. pacificus* during 1984-95 based on GIS data. We conclude that as stock size has increased since the late 1980s, the fall and winter spawning sites have overlapped in the Tsushima Strait and near the Goto Isands, and that winter spawning sites have expanded above the continental shelf and slope in the East China Sea.

Keywords: GIS, stock fluctuations, paralarvae, spawning sites, *Todarodes pacificus*, regime shift.

Introduction

Most commercially exploited squids live for a year or less. Reproductive success will depend on the physical and biological environments at the spawning and nursery grounds. Possible causes of the "failures" of *Todarodes pacificus* (Steenstrup, 1880) and *Illex illecebrosus* (Lesueur, 1821) fisheries in the 1980s include changing environmental conditions and heavy fishing pressure (Lipinski *et al.*, in press).

Todarodes pacificus migrates seasonally near Japan and Korea and spawns at the southern end of its distribution (Murata, 1989;1990). Three spawning groups (winter, fall and summer) occur with overlapping spawning grounds. Catches have fluctuated during the 20th century (Fig. 1); during 1986 -96, annual catches near Japan have increased from 99,000 to 444,000 tons.

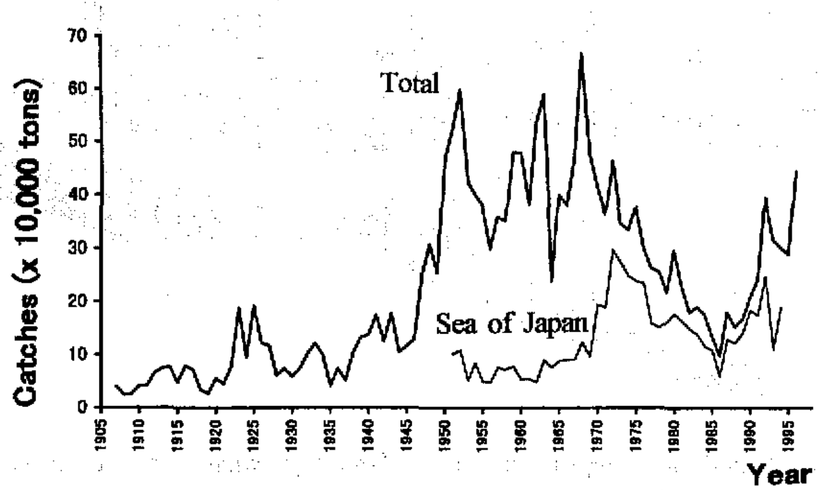

Fig. 1 Annual fluctuations in *Todarodes pacificus* catches in Japan during the 20th Century. Catches before 1951 include other squid species (modified from Murata, 1989).

Episodic "regime shift" involving entire biological community structures occur worldwide (Lluch-Belda *et al.*, 1992). In the western North Pacific, interdecadal regime shifts in water temperature have occurred from a warm regime beginning in the late 1940s, to a cool regime in the late 1970s, and back to a warm regime in the late 1980s (*e.g.* Kodama *et al.*, 1995). Theseregimeshiftsappear to affect the catches of *Todarodes pacificus*, particularly the early 1980s catch decrease and the late 1980s catch increase. Fall paralarval abundances since the late 1980s have been higher than during the late 1970s to the mid-1980s. This increase corresponds to the increase in adult squid catches that has occurred since the late 1980s (Goto and Kidokoro, pers. comm.). These stock fluctuations may be related to the effects of regime shifts on spawning and paralarval survival.

In this paper, wereviewtherecenttrendsofannual variation in stock size and larval density of *Todarodes pacificus*. We then propose a possible scenario for the stock fluctuations related to the effects of changing environmental regimes based on two assumptions: 1) stock size in the western North Pacific increases with a shift to a warm regime, and 2) a warm regime creates favorable environmental conditions for reproduction and recruitment. Finally, we estimate the relationship between the recent seasonal and annual changes in the inferred optimum spawning grounds and water temperatures around Japan.

Materials and Methods

Annual variation in stock and larval densities

Annual variations in stock density of *T. pacificus* have been estimated using average catch weight per fishing boat per day (CPUE) throughout the fishing season (Murata, 1989; 1990). Annual variations in CPUE can reveal trends in the stock index of the fall and winter spawning groups better than annual catch variations (Okutani and Watanabe, 1983; Murata, 1989; 1990). Paralarval abundance has also been used to assess the stock-recruitment relationship (*e.g.* Murata, 1989; 1990). The Japan Sea National Research Institute has conducted paralarval collections of the fall-spawning group in the southwestern Sea of Japan and the northern part of the East China Sea since 1973, and the Hokkaido National Fisheries Research Institute has conducted similar surveys of the winter-spawning group off the Pacific coast of southern Japan and in the East China Sea since 1995.

To analyze recent trends in the stock-recruitment relationship, we examined paralarval density index (PDI) values in the northern part of the East China Sea and the southwestern Sea of Japan during fall, and the annual CPUE values of the fall-spawning group in the Sea of Japan. PDI was calculated as the number of paralarvae per 1,000 m^3 of water filtered in oblique tows of a 80-cm plankton net (0.508 mm mesh) from 75-m depth to the surface. CPUE is the mean catch (ton) per fishing day by 70-100 ton vessels using automatic jigging machines in offshore of the Sea of Japan each August.

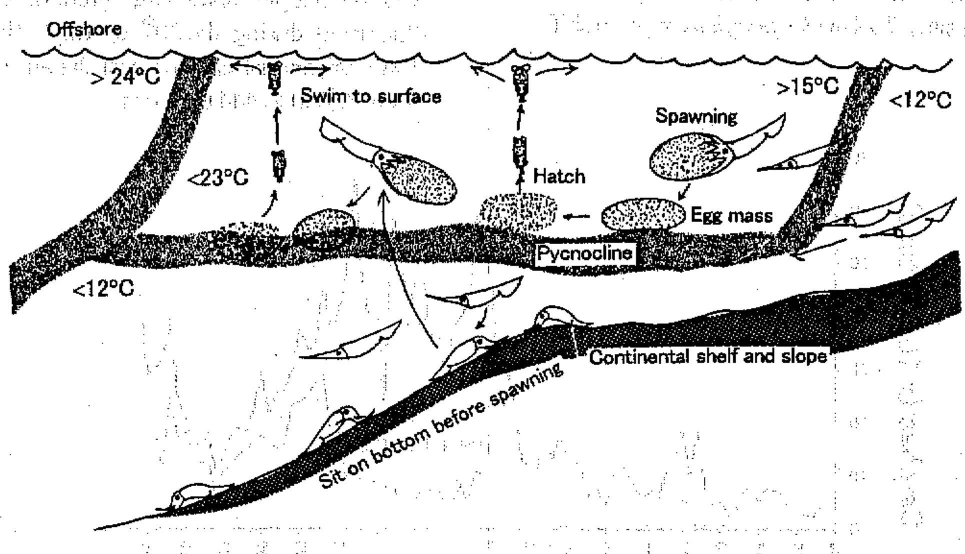

Fig.2 Working hypothesis on reproduction of *Todarodes pacificus* in nature, based on the results of experimental studies.

Determining possible spawning sites

We estimated the possible spawning sites of using information collected from laboratory and field studies. *Todarodes pacificus* produces gelatinous, nearly neutrally buoyant egg masses(Bowerand Sakurai, 1996). The temperature range for normal embryonic development is 15-23°C (Sakurai *et al.*, 1996). Most hatchlings collected off southern Japan where sea surface temperatures range 17 to 23°C (Bower, 1997). In the present study, we used temperatures at 50-m depth to estimate spawning sites, since most paralarvae occur at 25-50 m depth (Watanabe, 1965). We assumed that spawning occurs above the continental shelf and slope around Japan (Fig. 2) because captive females regularly sit on the tank bottom just before spawning (Bower and Sakurai, 1996), and bottom trawls on the continental shelf and slope at 100-500 m depth often collect exhausted spent females (Hamabe and Shimizu, 1966; Yamada, 1998a, 1998b). To estimate the possible spawning areas, we used data of the mean monthly temperature at 50-m depth during 1900-72 (JODC, 1978), and the position of the continental shelf near the Japanese Archipelago.

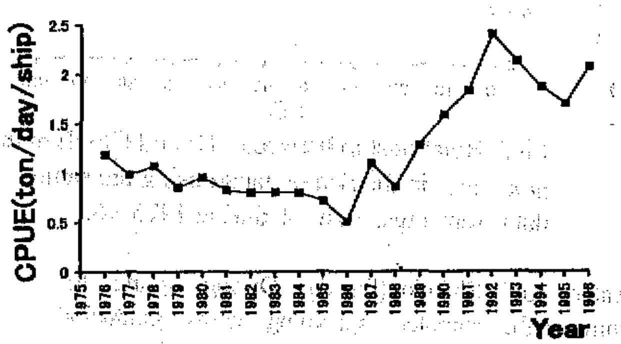

Fig. 3 Annual changes in CPUE of the *Todarodes pacificus* fall spawning group in the Sea of Japan during 1976-96. CPUE: catch in (ton) per fishing day by automatic jigging of medium-sized vessels (70-100 tons) in offshore waters of the Sea of Japan in August.

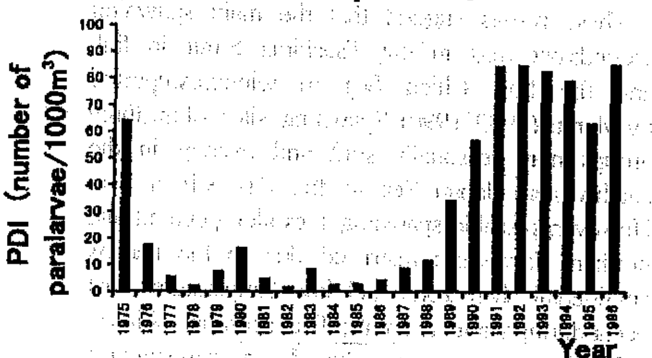

Fig. 4 Annual changes of the *Todarodes pacificus* paralarval density index (PDI) during fall in 1975-1996 in the northern East China Sea and the southwestern Sea of Japan. PDI: number of paralarvae per 1,000m^3 of water, from the results of paralarval collections by oblique tows of a 80-cm plankton net (0.508 mm mesh size) from 75 m depth to the surface.

Recent changes in possible spawning sites based on GIS data

Geographical Information System (GIS) was developed for use in terrestrial fields, but is now increasingly used for oceanographic and fisheries studies (Simpson, 1994; Kiyofuji *et al.*, 1998). We examined the relationship between the monthly and annual changes of spawning grounds and water temperatures at 21-53° N and 121-153° E during 1984-95.

To determine possible spawning sites, we collected three data sets: monthly GMCSST (global multi-channel sea surface temperature), Levitus, climatological oceanographic and topography data. NOAA/NESDIS (National Environmental Satellite Data and Information) and the NODC (National Oceanographic Data Center) produced the GMCSST and Levitus data sets. We determined a linear equation relating temperatures at 0-m and 50-m depth for each grid and then estimated the 50-m depth temperature for each month during 1984-95 using this equation and GMCSST data. We then estimated the surface area where the 50-m depth temperature ranged 15-23°C above the bottom depths of 100-500m.

Results and Discussion

Annual Changes of PDI and CPUE

In the northern East China Sea and the southwestern Sea of Japan, annual PDI values were relatively high in 1975, low during 1976-88, and increased remarkably after 1989, which corresponds to annual changes of CPUE values (Figs. 3, 4). Paralarvae were more widely distributed during 1994-96 than during the late 1970s to early 1980s (Fig. 5), when annual PDI values were low (Goto and Kasahara, 1991).

During 1973-84, positive relationships occurred between both adult catch and the PDI of their offspring and between the PDI and adult catch of the same generation for the fall-spawning group (Murata, 1989). We examined the relationship between PDI and CPUE in the Sea of Japan using data from 1975-96 (Fig. 6). The CPUE in offshore waters of the Sea of Japan and the PDI in waters from the northern East China Sea to the southwestern Sea of Japan in fall were strongly correlated (R^2=0.91). A positive relationship (R^2=0.77) also occurred between PDI

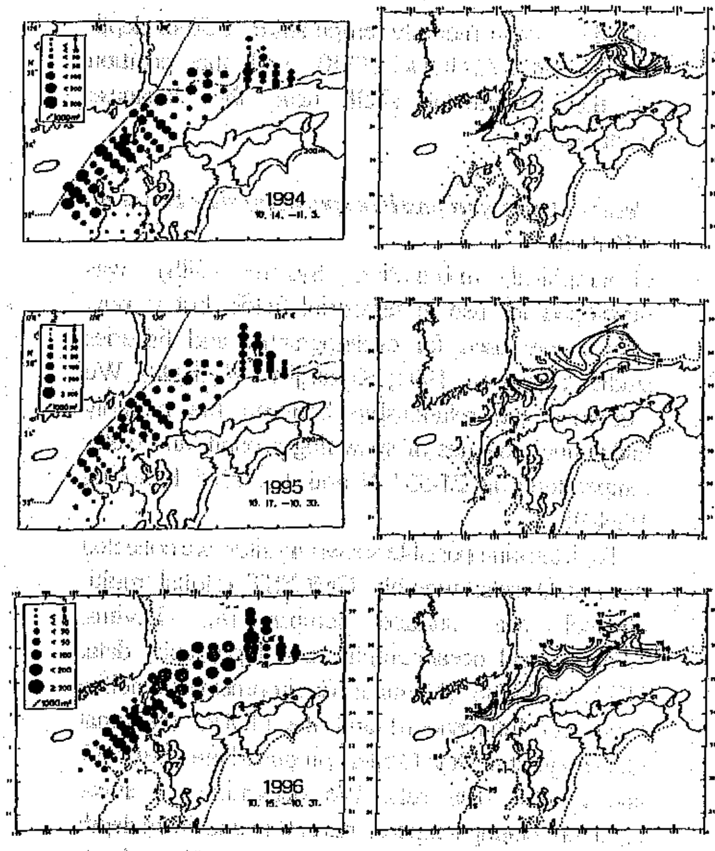

Fig. 5 Paralarval distributions (PDI) of *T. pacificus* (left) and temperatures at 50-m depth (right) during fall of 1994-1996.

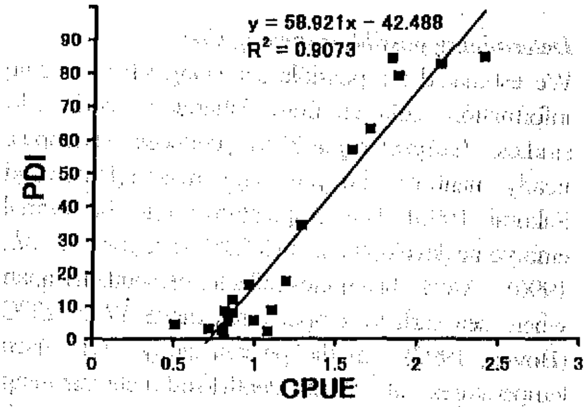

Fig. 6 Relationship between CPUE and PDI in the same year in the Sea of Japan using the same data from Figs. 3 and 4 during 1975-96.

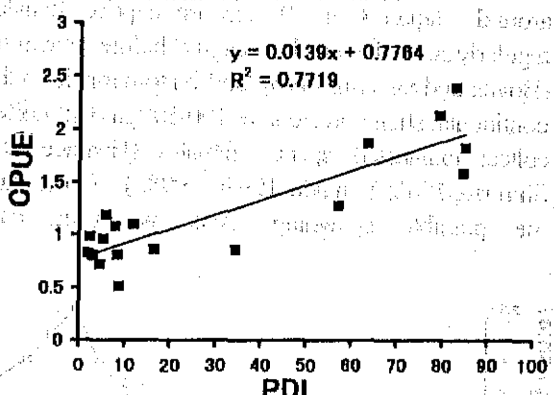

Fig.7 Relationship between PDI and CPUE in the next year in the Sea of Japan using the same data from Figs. 3 and 4 during 1975-96.

and CPUE in the next year (Fig. 7).

These results suggests that the catch increases since the late 1980s may reflect a favorable stock-recruitment relationship. Stock size of the winter-spawning group was the largest of the three groups through the late 1960s, but the fall-spawning group has been the largest since the 1970s (Murata, 1989). The present results suggest that the recent stock increase has occurred in both of the winter- and the fall-spawning groups, and that spawning sites have expanded and overlapped from offshore of the southwestern Sea of Japan in fall to the East China Sea in winter. Thus, we decided to clarify the seasonal changes of spawning sites throughout the year.

Possible spawning sites

The main estimated spawning areas for the winter-spawning group occurred widely along the continental shelf and slope of the East China Sea from Kyushu to Taiwan, and small spawning areas occurred in the western and the southwestern coastal waters of Kyushu and Pacific coastal waters off Shikoku (Fig. 8). During spring to summer, the estimated spawning areas gradually shifted northwards along the continental shelves of the Japan Sea and Pacific Ocean. In fall, the areas occurred around the Tsushima Strait and Noto Peninsula; limited spawning could also have occurred along the coast of northern Japan.

These results suggest that the main spawning grounds occurred in the Tsushima Strait in fall, and the East China Sea in winter, as reported by Murata (1989; 1990). Spawning sites of the three groups may seasonally shift and overlap in the southwestern Japan Sea to the East China Sea. However, possible spawning sites along central and northern Japan are restricted due to the narrow continental shelf zone and low temperatures, that occur during winter to spring. The seasonal shifts in inferred spawning sites based on temperatures changes at 50 m depth and the range of continental shelf around Japan are similar to the changes in paralarval distribution (Murata, 1989).

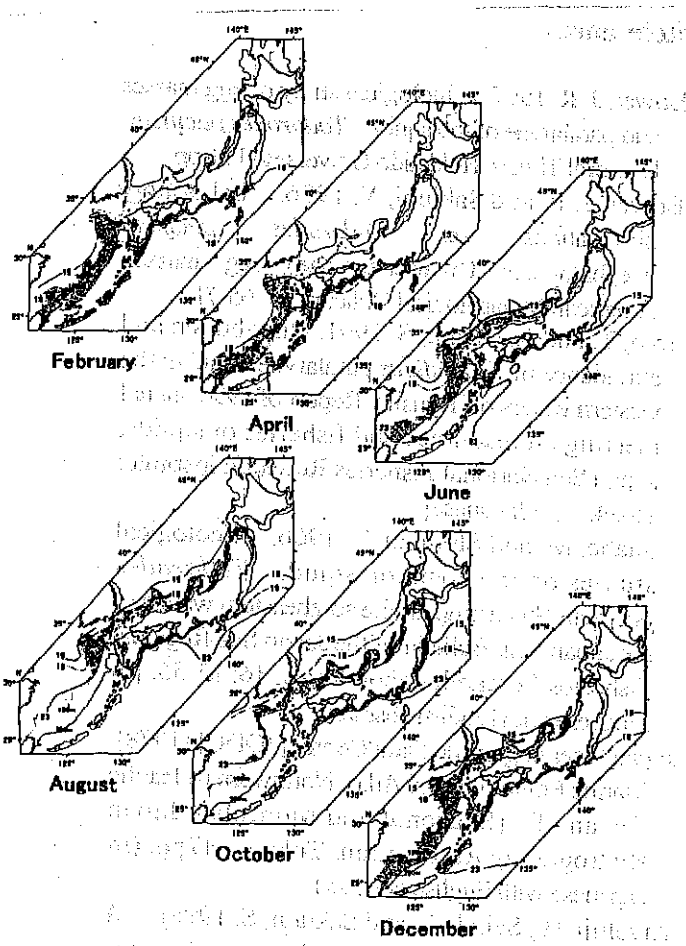

Fig. 8 Estimated monthly spawning sites of *Todarodes pacificus* around Japan based on mean temperature at 50-m depth during 1900-1972 (JODC, 1978). Stippled areas indicate sites of optimum temperature for embryonic development (15-23°C) above the continental shelf and slope surrounded by 100-500 m isobaths.

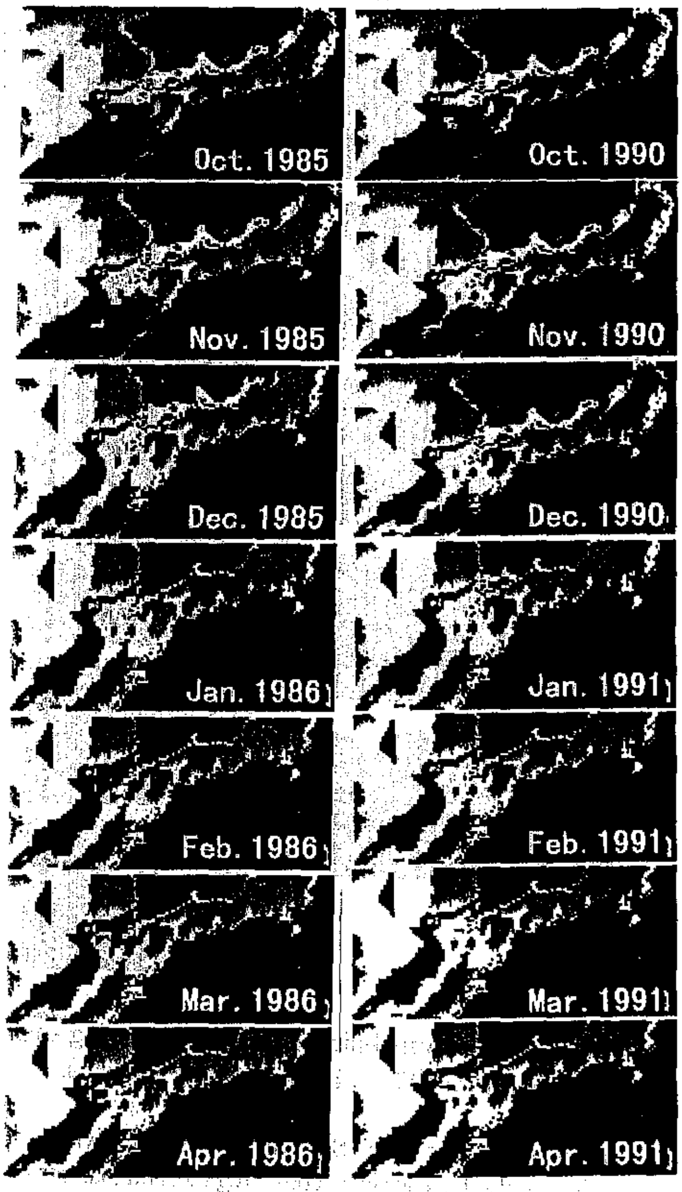

Fig. 9 Comparison of seasonal shifts of inferred spawning sites between October to April in 1985/86 (cold years) and 1990/91 (warm years), based on GIS data.

Recent changes in the possible spawning sites based on GIS data

We used GIS data to examine the relationship between the recent seasonal and annual changes of the optimum spawning grounds and the shift from a cold regime to a warm regime that occurred in the late 1980s by comparing the seasonal and annual shifts of estimated spawning grounds during 1984 to 1995. Kiyofuji *et al.* (1998) concluded that the possible spawning grounds occurred year-round in Tsushima Strait and near the Goto Islands in 1989-91, which was the beginning of the warm regime when fall paralarval abundance and annual catch increased.

From October to December, the possible spawning grounds did not vary geographically between 1985/86 and 1990/91 (Fig. 9). During January and April in 1991, inferred spawning sites occurred in waters from the Tsushima Strait to the East China Sea along the continental shelf, but not in Tsushima Strait in 1986. We then compared the interannual variability of possible spawning sites in February during 1984-94 (Fig. 10), which is the peak of spawning month of the winter-spawning group (Murata, 1989). In February of 1989, 1990, 1991 and 1994, the inferred spawning sites occurred widely from the Tsushima Strait to the East China Sea. Spawning sites in February of 1984, 1986, 1988 and in 1992 occurred above the continental shelf in the East China Sea and southwest of Kyushu.

These results suggest that winter spawning

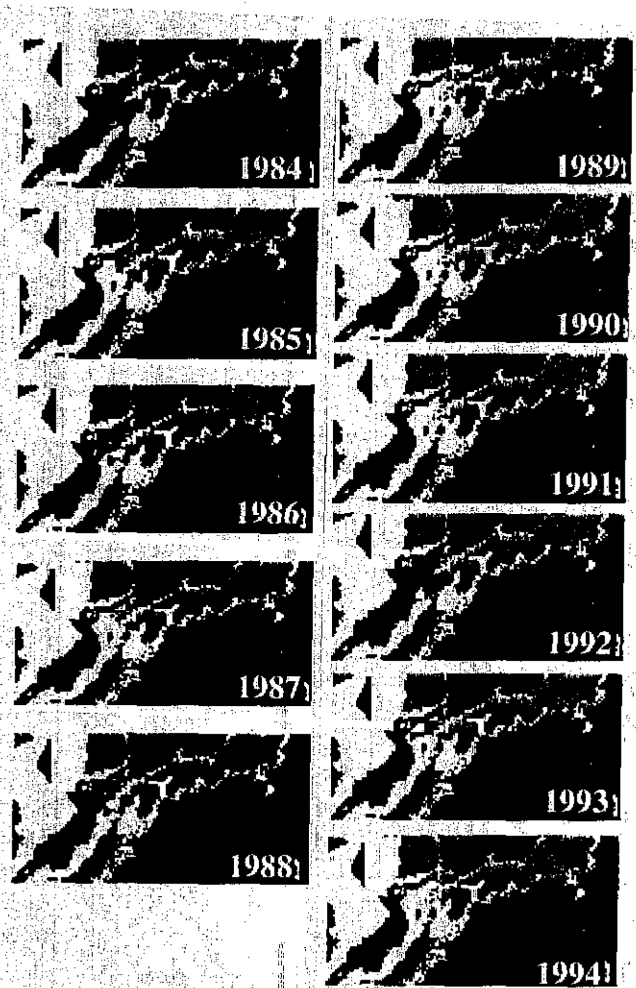

Fig.10 Interannual variability of possible spawning sites in February from 1984 to 1994, based on GIS data.

areas in the East China Sea will grow smaller when adult stocks decrease in a cool regime, and that fall and winter spawning areas will extend and overlap in the Sea of Japan and the East China Sea when adult stocks increase during a warm regime. However, the inferred spawning sites varied annually (*e.g.* 1992 in a warm regime), which might be a cause of the historical catch fluctuations of *Todarodes pacificus* (see Fig. 1).

We showed that GIS can be used to estimate and forecast the stock fluctuations of *T. pacificus* related to climatic regime shift by examining temporal and spatial distribution of the optimum spawning sites. GIS will become an important tool in future studies of stock fluctuations in exploited squid species.

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