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| Title            | Effects of environmental variability on the spawning areas, catch, and recruitment of the Japanese common squid, <i>Todarodes pacificus</i> (Cephalopoda: Ommastrephidae), from the 1970s to the 2000s  |
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Effects of environmental variability on the spawning areas, catch and recruitment of the Japanese common squid, *Todarodes pacificus* (Cephalopoda: Ommastrephidae), from the 1970s to the 2000s

A. L. Rosa, J. Yamamoto, and Y. Sakurai

#### Abstract

The Japanese common squid, *Todarodes pacificus* is one of the most commercially valuable squids in the world. It spawns almost throughout the year, with a seasonal peak in autumn and winter. Long-term changes of sea surface temperature (SST) and its effect on the spawning areas and catch of *T. pacificus* were analysed for 27 spawning seasons (September to April; 1978 to 2006) in the Sea of Japan and East China Sea. The spawning area was inferred using as limitations the 21°-41°N 121°-142°E, the 100-500m depth, the mean Kuroshio axis, and the 19.5°C-23°C SST range. The results showed that the area surrounding Kyushu Island is gaining importance as a spawning area. Also, the discontinuity of the spawning ground in the East China Sea (around 29°N 128°E) during the winter spawning period was shown to be associated with a decrease in the catches by both the Japanese and the Korean fleets. This constriction of the spawning ground would act as an obstacle to either the adult squid, making it difficult for them to reach the most southern grounds, or the hatchlings, which, due to adversary environmental conditions, may not be able to survive the early stages of the feeding migration.

Keywords: Commercial catch; environmental variability; spawning area; sea surface temperature; *Todarodes pacificus*

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## Introduction

The Japanese common squid, *Todarodes pacificus* (Cephalopoda: Ommastrephidae), is distributed in the northwest Pacific between 25° and 50°N near Japan and the Korean Peninsula. It is targeted by both the Japanese and Korean fleets, and catch data are available since the early 1900s from Japan, and since the late 1930s from Korea (Murata, 1989).

Apart from the interannual variation, catch amounts of *T. pacificus* show a long-term variability, which has been related both to overfishing (Murata, 1989) and to regime shifts that have occurred in the North Pacific (Sakurai *et al.*, 2000). This correspondence between catch or stock size and the North Pacific regime shifts has also been observed for other squid species, e.g. spear squid *Loligo bleekeri* (Tian, 2009).

The Japanese common squid stock comprises three cohorts based on the spawning period: summer, autumn and winter. The last two cohorts, especially the winter cohort, make up most of the stock's biomass (Murata, 1989; Kawabata *et al.*, 2006). As with the red (or neon) flying squid (*Ommastrephes bartamii*; Ichii *et al.*, 2004), the different cohorts have different spawning areas, with the autumn cohort spawning in a more northern area than the winter cohort.

Eggs of the autumn cohort are spawned between September and December in the Tsushima Strait and in the Sea of Japan off southern Honshu Island (Goto, 2002; Yamamoto *et al.*, 2002; see Fig. 1). The hatchlings are then transported northward by the Tsushima Warm Current (Okutani, 1983; Goto, 2002). They reach the Hokkaido area during summer, and then return to the spawning ground through the same route.

The winter cohort spawns mainly in the East China Sea from Kyushu to Taiwan (Fig. 1) during January to April (Murata, 1989; Sakurai *et al.*, 2000). The main migration route of the hatchlings is the Pacific Ocean along the Japanese islands via the Kuroshio Current. Some hatchlings are also transported to the Sea of Japan and east coast of the Korean Peninsula (Tameishi, 2003). Juveniles migrate north to the feeding grounds around Hokkaido, and at the end of summer, the squid return to the spawning grounds through the Sea of Japan (Bower *et al.*, 1999; Kawabata *et al.*, 2006; Kidokoro and Sakurai, 2008).

By combining results from larvae surveys and captivity experiments Sakurai *et al.* (2000) proposed the following reproduction process, which is summarized in Fig. 2. After resting on the sea floor, adult females swim ascend and spawn. The spawned egg masses sink until they reach a neutrally buoyant depth. Once hatched the hatchlings (ML<1mm) swim to the surface, being abundant in the surface and mixed layer (Yamamoto *et al.*, 2007). This depth range allows the hatchlings to maintain a higher swimming activity, as well as providing a better feeding environment (Yamamoto *et al.*, 2007), and transportation to the feeding grounds by the currents. Laboratory experiments have shown that hatchling survival rates are highest at 19.5°-23°C (Sakurai, 2006).

Larval surveys can be used to estimate the stock's status (Kidokoro, 2010), but they require substantial investments of money, energy and time. Advances in remote sensing technology have improved data resolution and quality, which enable detailed fisheries oceanography studies, e.g. Japanese scallop in Funka Bay, Japan (Radiata, 2008). Sea surface temperature (SST) is one of the easiest physical parameters to measure, and its distribution has been related, either directly or indirectly, to the life cycle and fisheries

of many cephalopods (Robin and Dennis, 1999; Yatsu *et al.*, 2000; Arkhipkin *et al.*, 2004; Ichii *et al.*, 2004).

The purpose of this study was to monitor the *Todarodes pacificus* spawning grounds of the autumn and winter cohorts from the 1970s to the early 2000s. The size and distribution of the inferred spawning area were used to analyse the variation in commercial catch, and an explanation for the variation of recruitment, and consequently catch, of the winter cohort is proposed.

#### Data and methodology

The inferred spawning area (hereafter referred to as spawning area) was calculated using invariable and variable parameters. To account for the autumn and winter cohorts, the geographical limits for the spawning area were set at 21° and 40°N, and at 121° and 142°E. Sakurai *et al.* (2000) suggested that females rest on the seafloor before spawning, so a depth limitation to the spawning area was imposed. In the study the spawning was considered to occur in areas with depth between 100m to 500m.

Previous studies (e.g., Bower *et al.*, 1999) have shown that hatchlings are found in higher density in areas west of the Kuroshio axis, and that larger paralarvae are caught near the Kuroshio Front. Hence, in order to analyse the areas where the spawning is most likely to occur, the Kuroshio axis was also considered as a limitation to the spawning area distribution. For the purpose of this study, the location of the axis was considered its mean location as indicated by Yamashiro *et al.* (1993). This location will only influence the spawning area south of Kyushu Island (see Fig. 3a).

Finally, the spawning area was defined to occur where the SST ranged between 19.5°C and 23°C. This range was based on laboratory experiments, which have shown that higher survival rates of hatchlings occur within this range (Sakurai, 2006). SST data was obtained from the Japan Meteorological Agency. It comprised grid data with 1°x1° resolution during 1970-84 and MGDSST (Merged satellite and in-situ data Global Daily Sea Surface Temperature) 0.25°x0.25° resolution during 1985-2006. The MGDSST data is derived from satellite's infrared sensors (AVHRR/NOAA), microwave sensor (AMSR-E/AQUA) and in-situ SST (buoy and ship).

In summary the spawning area was inferred as the area where three invariable parameters, 21-40°N 121-142°E, 100-500m depth and the Kuroshio axis, and one variable parameter, 19.5-23°C SST range, were superimposed. It was calculated monthly between January 1970 and December 2006, a total of 36 spawning seasons.

The spawning area considered in this study includes a wide geographic area, consisting of the Sea of Japan, Tsushima Strait and East China Sea. For study purposes, the total spawning area was divided into four sub-areas (A to D). Sub-area D represented the spawning area in the Sea of Japan (including the northern part of the Tsushima Strait). Sub-area C represented the area surrounding Kyushu Island (including the southern part of the Tsushima strait, which is a potential spawning area for both the autumn and the winter cohorts). Sub-area B represented the central part of the East China Sea, and sub-area A was the southernmost part of our study area. The four sub-areas and their limits are shown in Fig. 3b. The size of these sub-areas was analysed both individually and in combination (C+D for the autumn cohort, and A+B and A+B+C for the winter cohort).

For the purpose of this study, a spawning season was considered to be between September of year  $n$  and April of year  $n+1$ , with the autumn cohort between September and December and the winter cohort between January and April.

Commercial monthly catch data between 1979 and 2007 from the Japanese and Korean fleets were obtained from the Japanese Fisheries Agency, and used to compare periods with different spawning conditions. The peak of catch was considered to be June to September for the autumn cohort and October to January for the winter cohorts.

Based on the definition described above, the spawning area was plotted monthly on SST maps, and its distribution was analysed. From these plots two patterns of the winter spawning area distributions were observed and their influence on the catch was analysed using Kruskal-Wallis ANOVA by ranks.

## Results

After inferring the monthly spawning area the total seasonal spawning area was calculated. The results are plotted in Fig. 4 together with the total (Japanese and Korean) commercial catch. Apart from the interannual variation, the results showed a long-term tendency of the spawning area size, with a minimum of  $65 \times 10^3 \text{ km}^2$  in the 1983/1984 spawning season. This season occurred during the cold regime, when catches were also lower. Increases in the spawning area in the late 1980s and early 1990s corresponded to increases in the total catch.

Figure 5 shows the spawning area for the sub-areas combinations, together with the linear tendency lines. The combination for the autumn spawning (C+D) showed an



increasing tendency. However, a similar trend was not observed for the two combinations associated with the winter spawning area: A+B, and A+B+C. Although both combinations showed a decreasing tendency, the rate of decrease was not so strong when the combination included the sub-area C, which combined with the autumn period data, suggests that the area surrounding Kyushu is gaining importance as a spawning area for both spawning periods.

Figure 6 shows examples of the two patterns of spawning area distribution for both the autumn (upper panels) and winter (down panels) periods. This figure was obtained by superimposing the inferred spawning area (represented by the black and white checked area) in SST maps. Regarding the autumn spawning ground distribution, no discontinuous zones can be observed and no apparent differences between the two patterns were observed. However, when observing the winter spawning ground distribution, a clear difference between the two patterns was observed. This difference consisted in a discontinuity of the spawning area in the central area of the East China Sea (approximately 29°N 128°E). For convenience the two patterns will be referred to as favorable and unfavorable pattern, corresponding to continuous and discontinuous pattern, respectively. Table 1 shows which of the two patterns were present in the four months included in the winter spawning period for spawning seasons between 1970/1971 and 2005/2006. Here the favorable pattern is represented by O and the unfavorable by X. Also marked are the limits of the different regime shifts that are said to have occurred in the North Pacific, as used in this study: until 1975/1976 (inclusive) warm regime, from 1976/1977 to 1987/1988 cold regime, and from 1988/1989 to 2005/2006 (end of the study period) warm regime. When thinking of these regimes, it is

clear that in the present warm regime there was an increase in the number of months with the good spawning area distribution pattern (from about 36% to 68%).

The existence of the two patterns of the spawning area distribution is likely to influence the commercial catch. In fact the catch data shows that the mean catch between October and January (corresponding to the peak of the winter cohort catch) is much larger in the years where the favorable pattern was observed (Fig. 7). Moreover, the Kruskal-Wallis ANOVA by ranks showed that there is a significant difference in the commercial catch between the two patterns ( $p < 0.05$ ). To analyse the individual importance of each month, Kruskal-Wallis ANOVA by ranks was computed for January, February, March, and February-March combined (a total of four computations). The results only showed significant differences in the winter cohort catch when considering the month of January individually ( $p < 0.01$ ). Since the winter cohort is responsible for the majority of the biomass it is expected that the two patterns will influence not only the winter cohort catch but also the total Japanese common squid catch. As expected, the Kruskal-Wallis ANOVA by ranks analysis for the total catch showed similar results for the three-month combination (January-March) and January ( $p < 0.01$ ). In the case of the total catch, the month of March also showed significant results ( $p < 0.05$ ).

## Discussion

Before analysing the influence of the spawning area on recruitment and catch of the Japanese common squid, *T. pacificus*, it is necessary to locate the area. To

accomplish this, the reproduction hypothesis of Sakurai *et al.* (2000) and Sakurai (2006) was used. Comparison of the different sub-areas suggests that the spawning area surrounding Kyushu Island has been gaining importance as a spawning area. This location could be considered as an advantageous spawning area since that it can be used by both cohorts, and it is close to both the Sea of Japan (the autumn cohort's feeding ground) and the Pacific Ocean (feeding migration route of the winter cohort). The increase of commercial catch observed in Fig. 4 may be a result of these favorable spawning conditions in a well-situated area.

The main result of this study regards not the size of the spawning area but its distribution, especially regarding the winter spawning season. Two spawning-area distribution patterns were identified. These patterns can be characterised by the continuity or discontinuity of the spawning-ground distribution on the central East China Sea, around 29°N 128°E. The results suggest that a discontinuous pattern (unfavorable pattern) during January to March, but mainly in January, will significantly lead to a decrease in the commercial catch. These two patterns are directly related with the sea surface temperature during winter. Robin and Dennis (1999) showed the importance of the water temperature, especially during winter, for the *Loligo forbesi* and *Loligo vulgaris* in the English Channel.

The following mechanism is proposed to explain the importance of the central East China Sea spawning area for the winter cohort spawning success and consequently higher catches. In the case of the favorable pattern, the adult squid return to the spawning area and encounter favorable spawning conditions from the Tsushima Strait to the southern part of its spawning range. After hatching, the hatchlings are transported by the currents to their feeding grounds. This transport is mainly done by the Kuroshio

Current, following a migration route along the Pacific coast of Japan. However, a smaller percentage of hatchlings is transported by the Taiwan Warm Current or the Yellow Sea Warm Current to the west coast of the Korean Peninsula. This process is summarised in Fig. 8 (left panel).

When the unfavorable pattern is present, the spawning area is divided into a northern area (around Kyushu Island, sub-area C) and a southern area (southern East China Sea, sub-area A). The adult squid, when returning to the spawning ground through the Tsushima Strait, would still find favorable conditions for spawning in the area south of Kyushu. However, the discontinuity in the spawning area distribution on the central East China Sea (sub-area B) may prevent the squid from reaching the most southern available spawning ground. This could lead to an increase in egg mass density in a single zone, and possibly reduced survival. In the case that the spawning stock is able to reach the southern spawning ground and successfully spawn, the hatchlings would not find good environmental conditions during the early stages of their feeding migration through the Pacific migration route, reducing their survival, and consequently reducing catch. The reduction of stock abundance associated with larvae exposure to lower SSTs is also observed in other species (Hatfield *et al.*, 1998; Yatsu *et al.*, 2000). With the reduction of the Pacific route, the hatchlings would be transported more successfully by the Taiwan Warm Current, and consequently increasing the recruitment in the western coast to the Korean Peninsula (Fig. 8 right panel). This would transform what was before a secondary migration route into the main route. The influence of oceanographic conditions in the migration route was also reported by Onitsuka *et al.* (2010) in a numerical simulation study of the diamond squid (*Thysanoteuthis rhombus*).

Choi (2003) analysed Korean catch data for the *T. pacificus* in both the west and the east (Sea of Japan) coast of the Korean Peninsula, from 1980 to 2000. This temporal range includes both the cold and the present warm regime, which this study showed to be associated with the bad and good patterns, respectively. Their results showed a clear difference in the catch between the two regimes, which was especially visible in the western coast. Although still representing a small percentage of the Korean catch (in average less than 10%), catches off the west coast almost doubled during the cold regime. During the warm regime, associated with a good pattern and therefore higher catches in both the western and the eastern coast of Korea, there was almost no catch off the west coast. This may be because in the presence of good spawning conditions the northern (around Kyushu island; sub-area C) and the central (central East China Sea; sub-area B) spawning areas may be sufficient for the entire cohort to spawn, reducing the use of the southern (sub-area A) spawning ground. These two areas (sub-areas C and B), unlike the southernmost area (sub-area A), are not strongly influenced by the Taiwan Warm current, which is mainly responsible for transporting of hatchlings to the western coast of Korea. Squids have been reported to show active movement to maintain a physiological preference (Garrison *et al.*, 2002). In this case the adult stock's active choice of spawning ground might be the reason for the clear separation of catch in the Korea Peninsula between warm and cold regimes.

Our results suggest that the continuity/discontinuity of the spawning area in the Eastern China Sea can influence the catch amounts of the *T. pacificus* winter cohort. Waluda *et al.* (2001) showed a correlation between the proportion of hatching area and the abundance of fishery for the *Illex argentinus*. The present study did not focus on the hatching area but on the spawning area. However, since the spawning and hatching area

of the Japanese common squid is relatively similar, the results presented are in agreement with *Waluda et al.* (2001).

The use of spawning area in predicting commercial catch of the *T. pacificus* has some limitations. First, the inferred spawning area is relatively shallow (100-500m). This makes it very vulnerable to atmospheric conditions, which have been shown to be important in other cephalopod species (e.g. *Illex illecebrosus*, Dawe *et al.*, 2000). Another obstacle is that other oceanographic conditions (e.g., wind, current speed, presence of eddies) may influence the Japanese common squid distribution, as with other species (Agnew *et al.*, 2005; Dawe *et al.*, 2007), and hence its survival and mortality, both during the feeding and the reproductive migration. These other factors may vary interannually making it difficult to make a direct connection between the spawning ground and the yield.

This study shows that the distribution (rather than size alone) of the *T. pacificus* spawning ground, as calculated using the 100-500m depth range, the Kuroshio axis mean position and the 19.5°-23°C SST range, can be a good qualitative indicator in inferring the catch of this species. However, further studies are necessary to analyse the dispersion due to current transport during early life stages.

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#### List of tables and figures

Table 1 – Matrix spawning area distribution pattern in the January to April from 1970/1971 to 2005/2006 spawning season. Favorable pattern represented by O and unfavorable pattern represented by X. Also marked are the limits of the different regimes shifts as used in this study: until 1975/1976 (inclusive) warm regime, from

1976/1977 to 1987/1988 cold regime, and from 1988/1989 to 2005/2006 (end of the study period) warm regime.

Figure 1 – Schematic migration pattern of the *Todarodes pacificus* autumn and winter cohort. Figure adapted from Murata (1989) and Sakurai *et al.* (2000).

Figure 2 – Reproductive hypothesis for the Japanese common squid, *Todarodes pacificus*, initially proposed by Sakurai *et al.* (2000) and complemented by Sakurai (2006). Figure adapted from Sakurai (2006).

Figure 3 – Limits of the study area. (a) Total inferred spawning ground (grey area); (b) four sub-areas used in the study. Also plotted is the mean Kuroshio axis location based on Yamashiro *et al.* (1993).

Figure 4 – Total inferred spawning area (with 5-year running mean) and total (Japan and Korean combined) commercial catch of the *Todarodes pacificus*. Data on commercial catch obtained from the Japanese Fisheries Agency.

Figure 5 – Inferred sub-area combination for the autumn (sub-area C combined with D) and winter (sub-area A combined with B, and sub-area A combined with B and C) cohort.

Figure 6 – Examples of the two spawning area distribution patterns: favorable (left panels) and unfavorable (right panels), for the autumn (upper panels) and winter (lower

panels) cohorts. Grey scale represents SST and the inferred spawning area is marked in black and white checkers.

Figure 7 – Japanese, Korean and total commercial catch for the months of October to January in favorable (grey) and unfavorable (black) spawning area distribution pattern. Data on commercial catch obtained from the Japanese Fisheries Agency.

Figure 8 – Hypothesised mechanism occurring in years with favorable and unfavorable spawning area distribution pattern.

|             |           | Jan | Feb | Mar | Apr |
|-------------|-----------|-----|-----|-----|-----|
| Warm regime | 1970/1971 | 0   | X   | X   | 0   |
|             | 1971/1972 | 0   | X   | X   | 0   |
|             | 1972/1973 | 0   | 0   | X   | 0   |
|             | 1973/1974 | X   | X   | X   | 0   |
|             | 1974/1975 | 0   | 0   | X   | X   |
|             | 1975/1976 | X   | X   | X   | 0   |
| Cold regime | 1976/1977 | X   | X   | X   | 0   |
|             | 1977/1978 | 0   | X   | X   | X   |
|             | 1978/1979 | 0   | 0   | 0   | 0   |
|             | 1979/1980 | 0   | X   | X   | 0   |
|             | 1980/1981 | X   | X   | X   | 0   |
|             | 1981/1982 | X   | X   | X   | 0   |
|             | 1982/1983 | 0   | X   | X   | 0   |
|             | 1983/1984 | X   | X   | X   | X   |
|             | 1984/1985 | X   | 0   | 0   | 0   |
|             | 1985/1986 | X   | X   | X   | 0   |
|             | 1986/1987 | 0   | 0   | X   | 0   |
|             | 1987/1988 | 0   | 0   | 0   | 0   |
| Warm regime | 1988/1989 | 0   | X   | X   | 0   |
|             | 1989/1990 | 0   | 0   | 0   | 0   |
|             | 1990/1991 | 0   | X   | 0   | 0   |
|             | 1991/1992 | 0   | X   | X   | 0   |
|             | 1992/1993 | 0   | 0   | X   | 0   |
|             | 1993/1994 | 0   | X   | X   | 0   |
|             | 1994/1995 | 0   | X   | X   | 0   |
|             | 1995/1996 | 0   | X   | 0   | 0   |
|             | 1996/1997 | 0   | 0   | 0   | 0   |
|             | 1997/1998 | 0   | 0   | 0   | 0   |
|             | 1998/1999 | 0   | 0   | 0   | 0   |
|             | 1999/2000 | 0   | X   | X   | 0   |
|             | 2000/2001 | 0   | 0   | 0   | 0   |
|             | 2001/2002 | 0   | X   | 0   | 0   |
|             | 2002/2003 | 0   | 0   | 0   | 0   |
|             | 2003/2004 | 0   | X   | 0   | 0   |
|             | 2004/2005 | 0   | X   | X   | 0   |
|             | 2005/2006 | 0   | 0   | 0   | 0   |

Table 1 Rosa et al.

Autumn

Winter

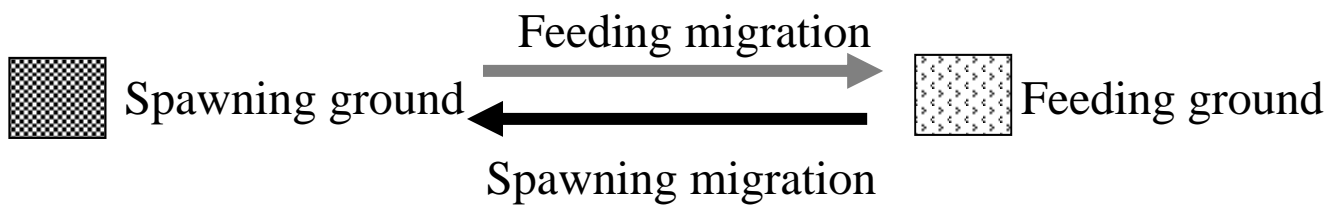
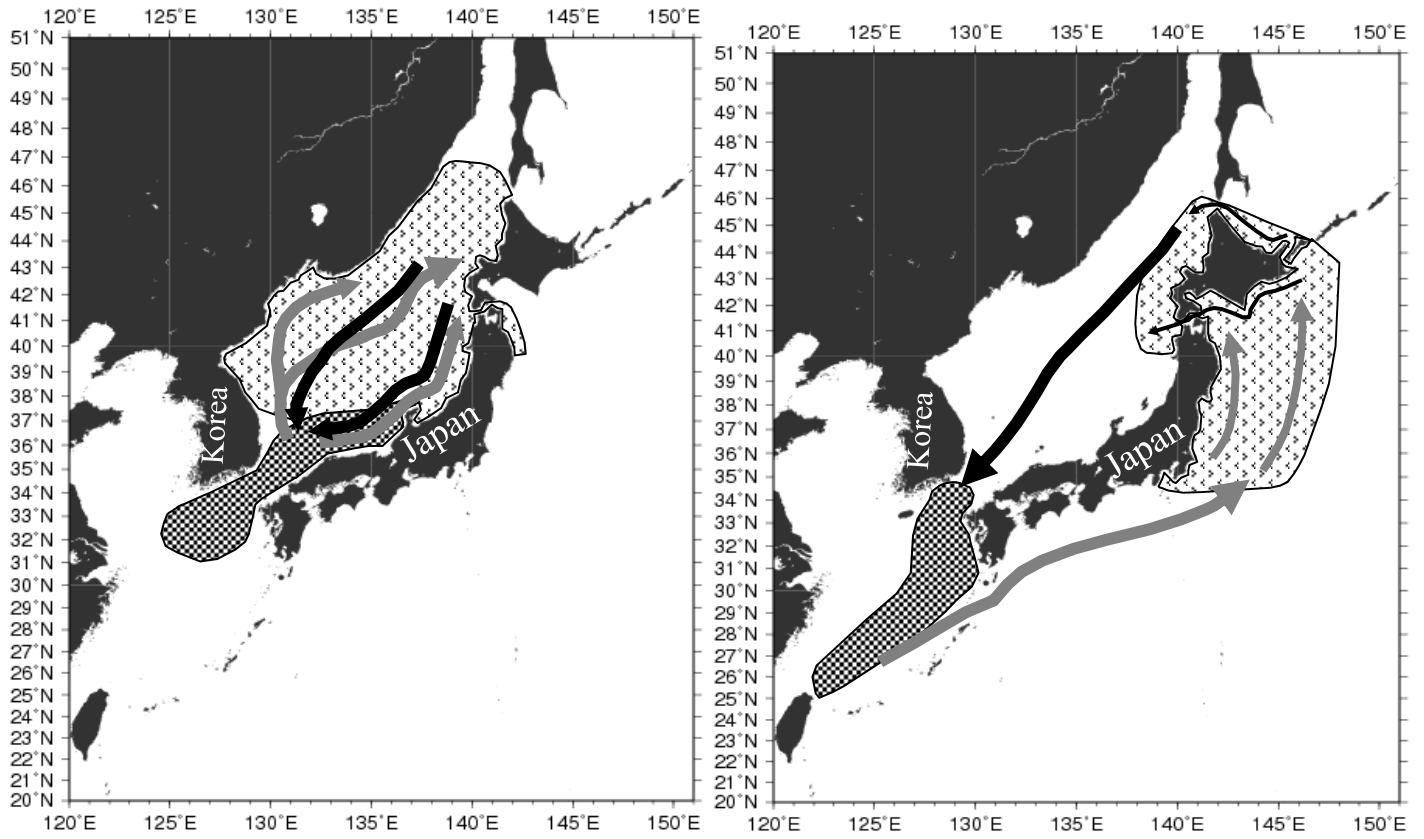


Fig. 1 Rosa et al.

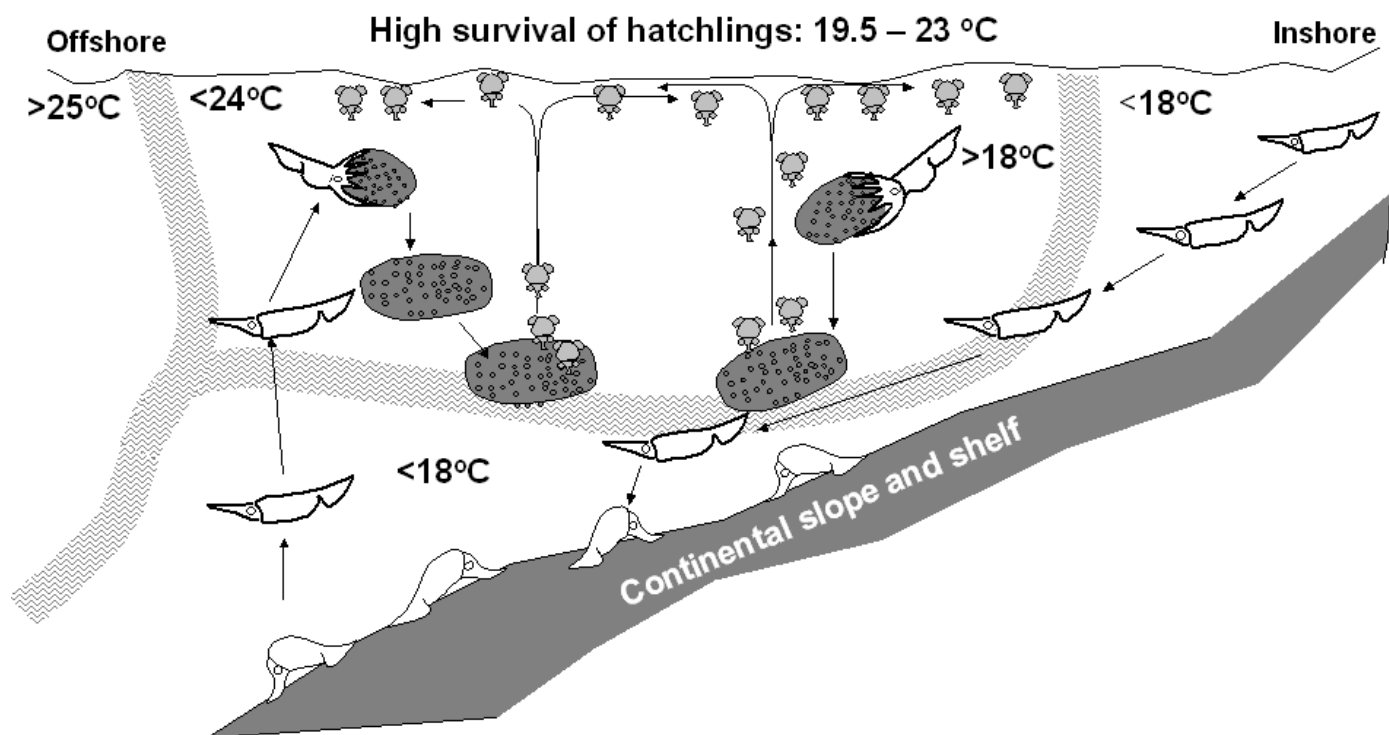
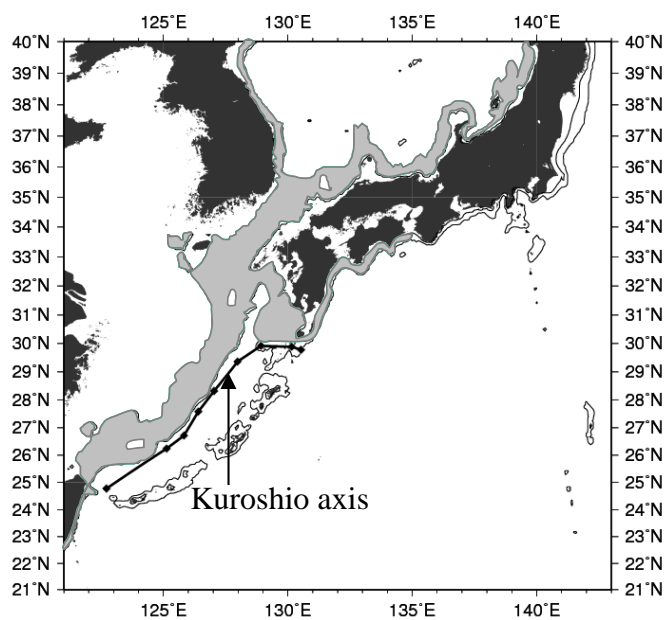
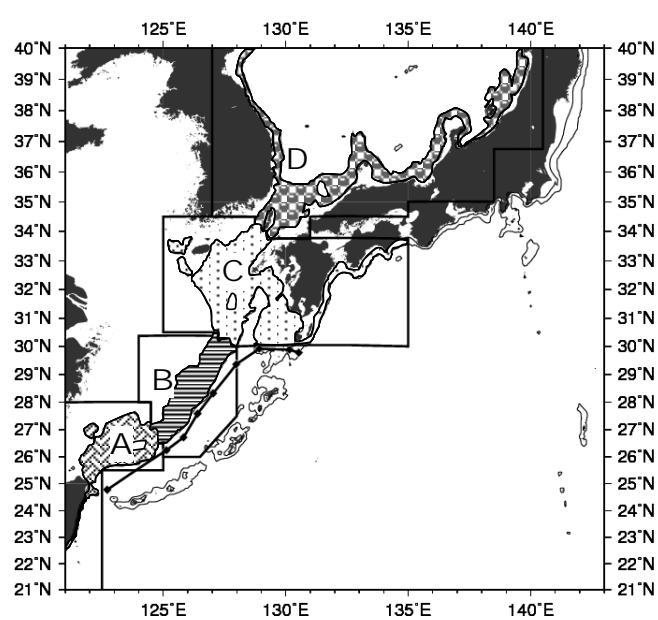


Fig. 2 Rosa et al.





a



b

Fig. 3 Rosa et al.

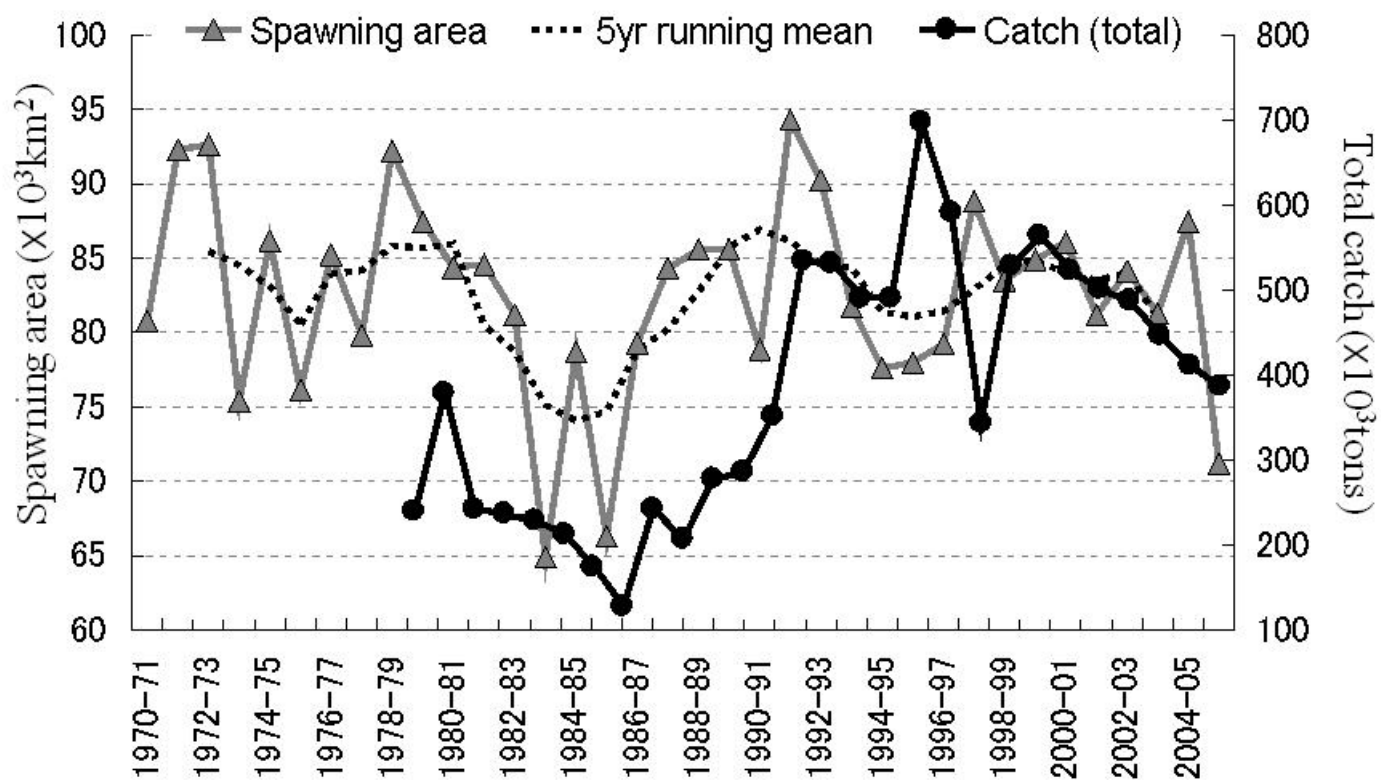


Fig. 4 Rosa et al.

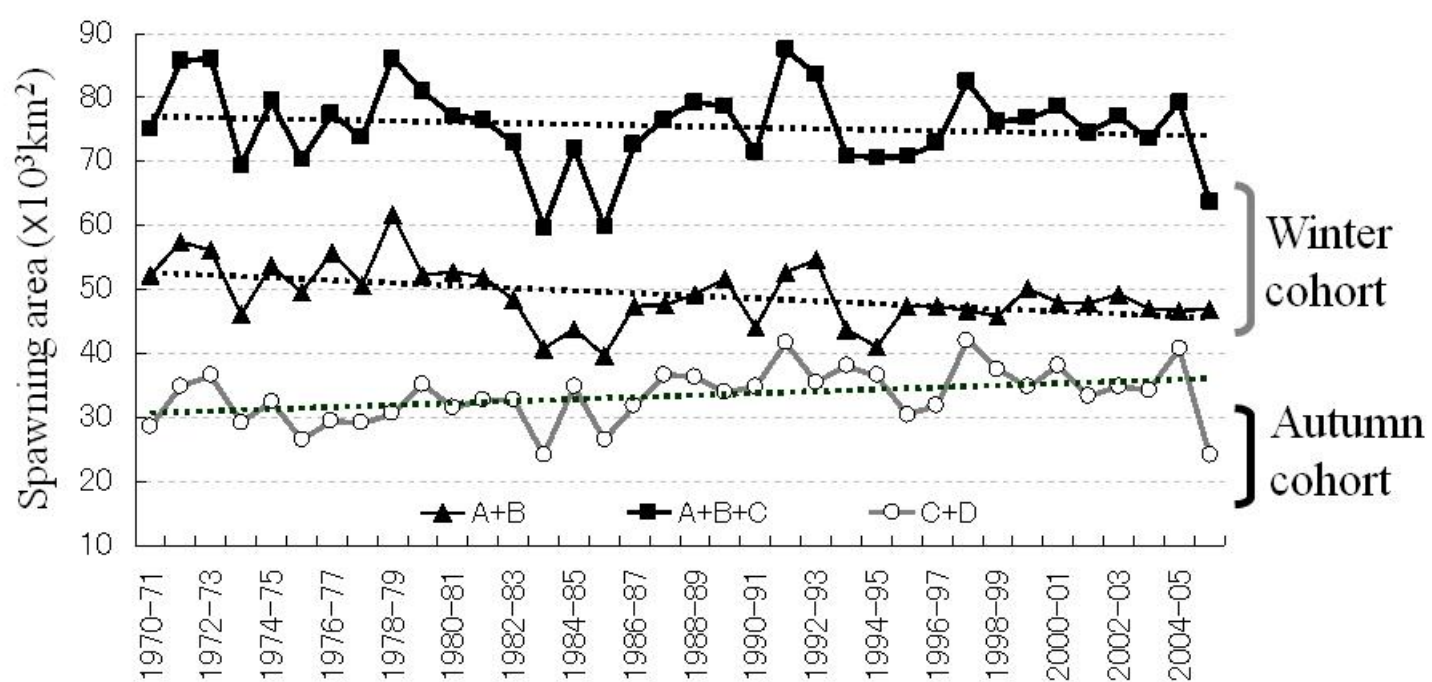


Fig. 5 Rosa et al.

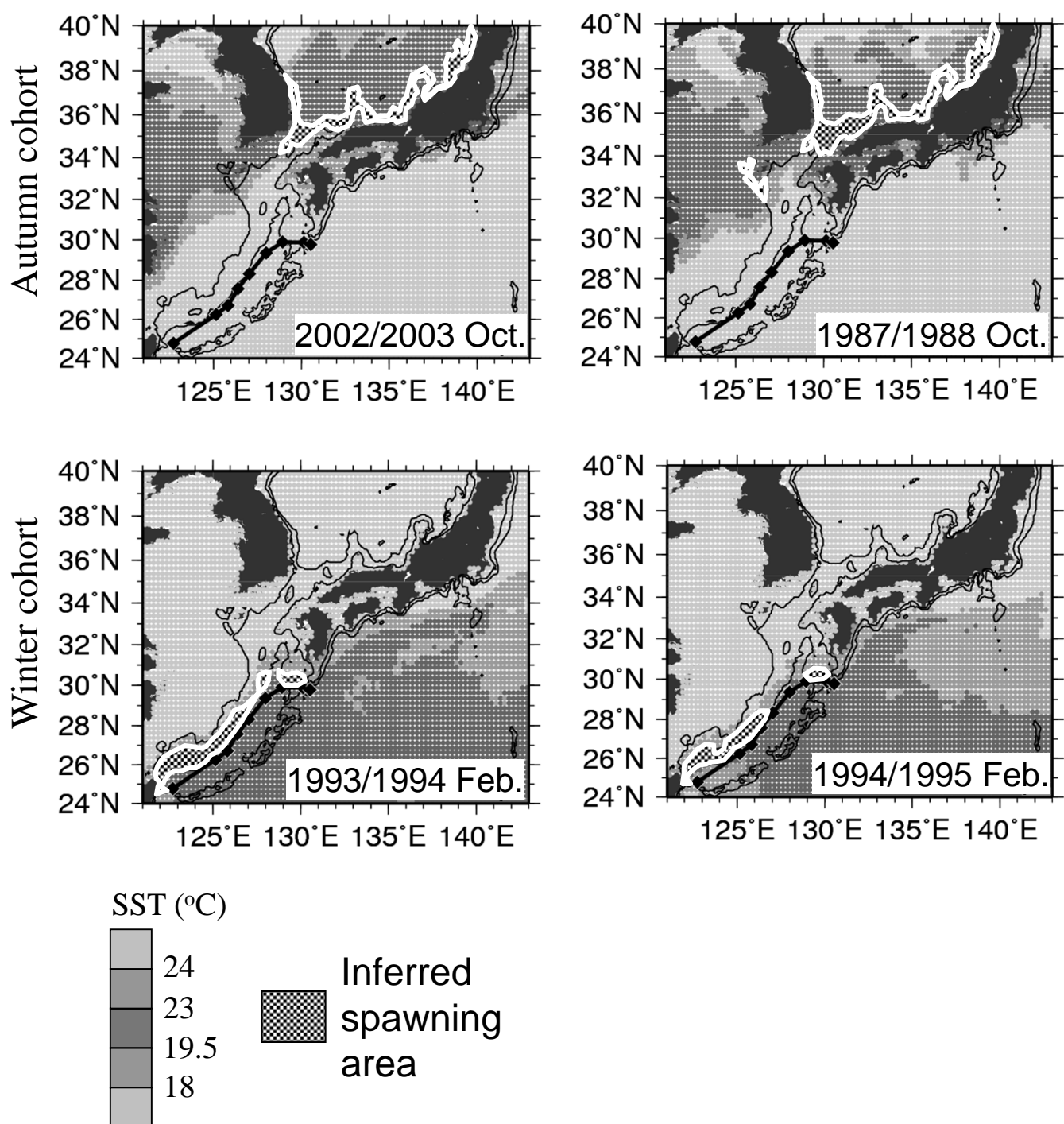


Fig. 6 Rosa et al.

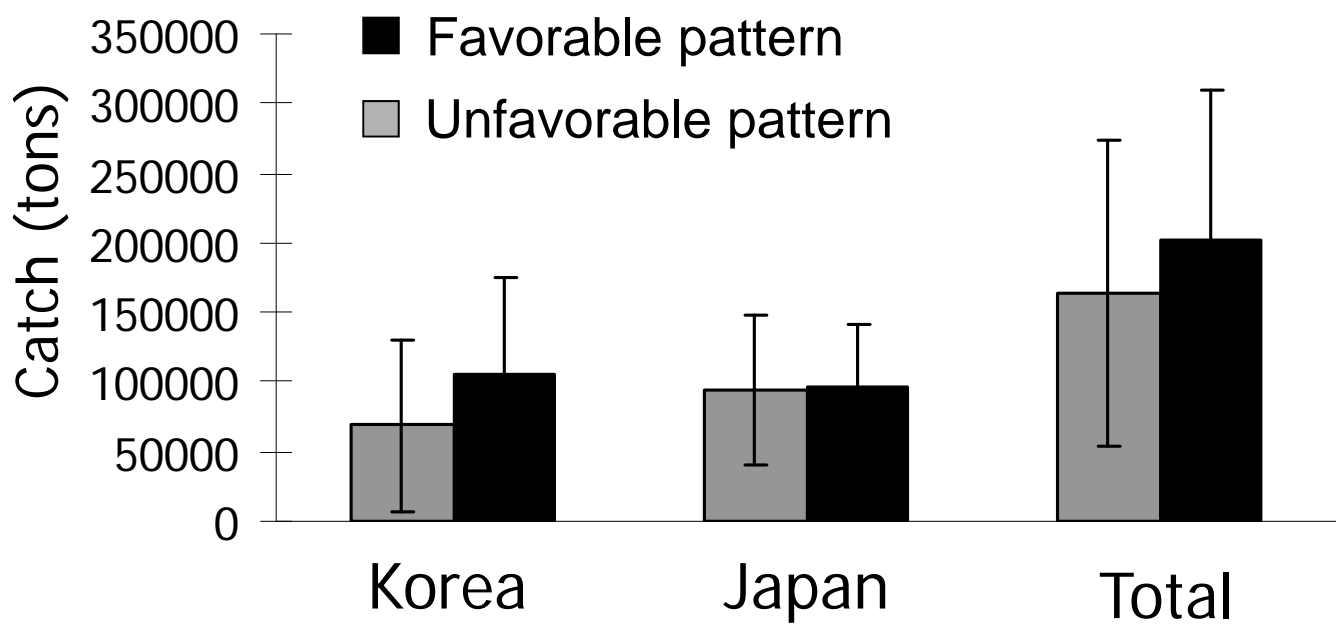
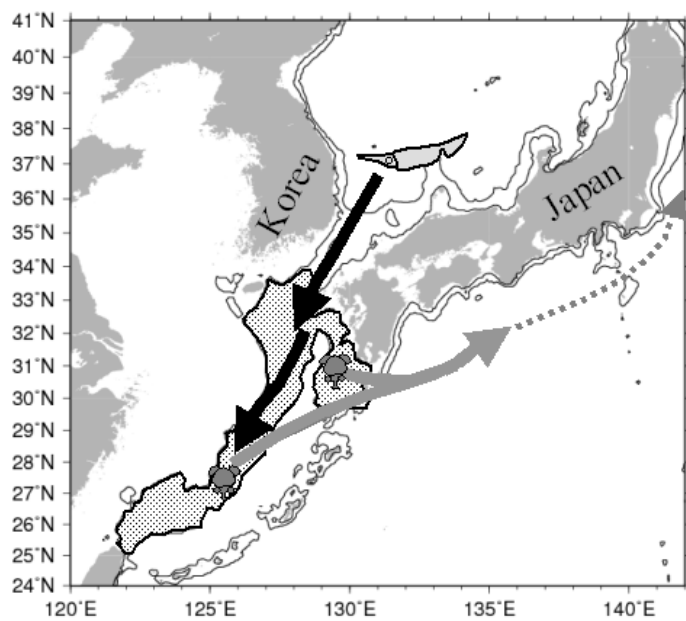
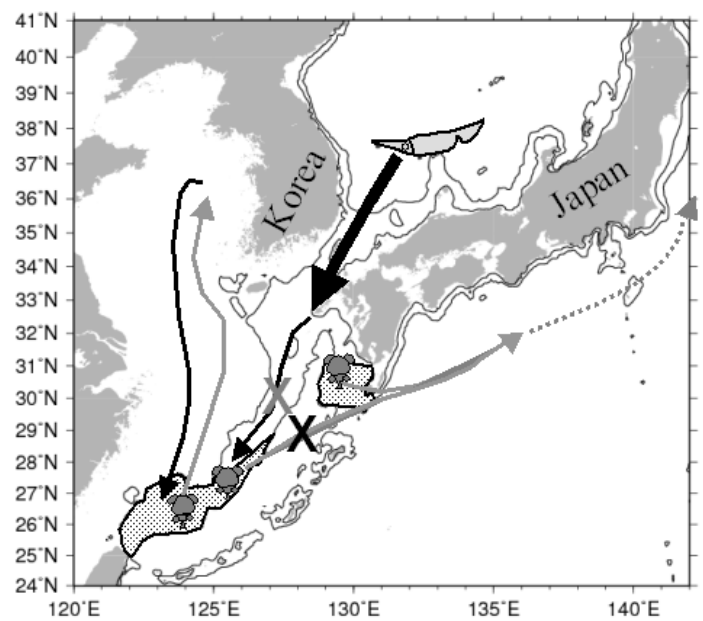


Fig. 7 Rosa et al.

### Favorable Conditions



### Unfavorable Conditions



→ Spawning migration  
→ Paralarvae migration

▨ Spawning ground

Fig. 8 Rosa et al.