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Population dynamics and catch forecasts of sandfish *Arctoscopus japonicus* in the western Sea of Japan

Kyuji WATANABE[†1], Kazumi SAKURAMOTO[2], Takashi MINAMI[3], and Naoki SUZUKI[2]

In this study, we developed catch models that can forecast the fluctuation in the stock abundance of sandfish in the western Sea of Japan using indices of spawning stock biomass (SSB) and ocean environmental conditions. Two assumptions were set in this analysis; (i) the catch harvested from this stock in year t, C_t, consists mainly of 1 and 2-year old fish; (ii) the spawning stock biomass of this stock is proportional to C_t; *i.e.*, C_t can be used as an SSB. We discussed two models assuming the following two cases; Case 1: C_t is determined only by SSB; Case 2: C_t depends both on SSB and the ocean environmental conditions. We used water temperatures as an index of the ocean environmental conditions, because it showed significant correlations with C_t. The model of case 2 showed better performance than that of case 1. For the model of case 2, the accuracy of forecasting was tested by extrapolation. The catches extrapolated using the model of case 2 provided a good forecasting of C_t. In case 2, from the water temperatures in spring and winter at the depths greater than 150 m it was found that the latter water temperature had positive significant correlations with the estimates of surface mixed layer depth (MLD) in winter. The long-term variation in C_t showed a similar trajectory with that of the estimated MLD.

Key words: *Arctoscopus japonicus*, catch forecast, Sea of Japan, regime shift, sandfish, spawner abundance, surface mixed layer depth, water temperature

Introduction

The stock of sandfish *Arctoscopus japonicus* in the western Sea of Japan has been one of the most important commercial resources in Japan. This stock is distributed at depths of 100 to 300 m in waters from the Korean Peninsula to Toyama Prefecture in Japan (Fig. 1, Okiyama, 1970; Fujino and Amita, 1984; Watanabe *et al*., 2004). Spawning grounds of the stock are located along the east coast of the Korean Peninsula (Choi *et al*., 1983). In the spawning season from November to December, mature fish older than age-1 spawn eggs on spawning substrates (Choi *et al*., 1983). Eggs spawned in year $t-2$ hatch in February of $t-1$, and fish become 1-year old recruit to fishing ground in t. Young fish of which body lengths are about 8 cm were found at depths of 0–200 m in the area of Shimane Prefecture in January (Yamazaki *et al*, 1981). However, information on the biology and the stock assessments are very fewer than those of the northern Sea of Japan sandfish stock (Sugiyama, 1989, 1991, 1992; Minami and Tanaka, 1985; Watanabe *et al*, 2005).

In Japan, this stock is harvested both by the Danish seine and the small-scale Danish seine fisheries throughout the year. In the Democratic People's Republic of Korea, this stock is harvested only by offshore fisheries. The statistics of catches harvested in the Republic of Korea are not published. In the Republic of Korea, sandfish are harvested with Danish seine, trawl, and gill net fisheries (The Ministry of Maritime Affairs and Fisheries in the Republic of Korea, 1965–2000). However, these catches are so called by-catches with the walleye pollock fisheries. Sandfish catches in the Republic of Korea began to increase in the late 1960s and peaked at approximately 25,000 tons in 1971. They fell to less than 1,400 tons in 1979 and marked approximately 12,000 tons in 1987 (The Ministry of Maritime Affairs and Fisheries in the Republic of Korea, 1965–2000). It is important to elucidate a mechanism behind the large fluctuation of catch in order to manage the stock effectively.

There would be two key factors induced from the population dynamics for many fisheries stocks: one is spawning stock biomass (SSB) and the other is ocean environmental condition (Kawasaki, 1983; Myers and Barrowman, 1996; Wada and Jacobson, 1998; Sakuramoto, 2005). In the Sea of Japan, it has been indicated that there are significant relationships between fluctuations in stock abundances and ocean environmental conditions (Hiyama *et al*., 1995; Sakuramoto *et al*., 2001).

The purpose of this study is to investigate the mechanism in the catch fluctuation using the SSB and water temperatures. Furthermore, we attempt to forecast the catch

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[1] National Research Institute of Far Seas Fisheires, Fisheries Research Agency, Shizuoka, Shizuoka 424–8633
[2] Tokyo University of Marine Science and Technology, 4-5-7 konann, Minato-ku, Tokyo 108–8477
[3] Tohoku University, Sendai-shi, Miyagi 981–8555
[†] watanabk@fra.affrc.go.jp

using the models constructed in this study.

Materials and Methods

Catch of the western Sea of Japan sandfish stock

In this study, we used the total catches harvested from this stock as an abundance index, due to the fact that the stock abundance has not yet been estimated. The total catch would be proportional to the stock abundance and the SSB explained below. The Japan Sea National Fisheries Research Institute (1974–2000) has calculated the catch per unit of effort using data of the Danish seine fisheries in each 10 min. Longitudinal by latitudinal grid from 1974 to 1999. We call these areas from Shimane to Hyogo Prefectures as area JP (Fig. 1). We calculated the mean density index for the area JP, and calculated the correlation coefficient between the catch and the mean density index from 1974 to 1999. A yearly trend of the density index was very similar to that of the catch ($r=0.82$, $p<10^{-6}$). This implies that the catch could be used as an index of stock abundances after 1974.

In the waters of the Republic of Korea, the yearly fluctuation in the density index of this region coincided with the sandfish catch (Chum, 2002). This implies that the catches in the Republic of Korea also reflect the stock abundance in these areas. In the Korean waters, however, the index is not published. Subsequently, we used the catch data as an index of stock abundance.

In this study, the total catch, C_t (ton), indicates the sum of the catches harvested in the Republic of Korea, Shimane, Tottori, and Hyogo Prefectures, ($t=1960$–1999). The catch statistics are used from the Ministry of Maritime Affairs and Fisheries in the Republic of Korea (1960–1999), the Shimane Statistics Information Office (1960–1999), the Tottori Statistics Information Office of Chugoku-Shikoku Regional Agricultural Administration Office (1960–1999), and the Hyogo Statistics Information Office of Kinki Regional Agricultural Administration Office (1960–1999). In this study, however, the catches harvested in Toyama, Ishikawa, Fukui, and Kyoto Prefectures were excluded, because they would harvest not only the "western" Sea of Japan stock but also the "northern" Sea of Japan stock (Watanabe *et al*., 2004).

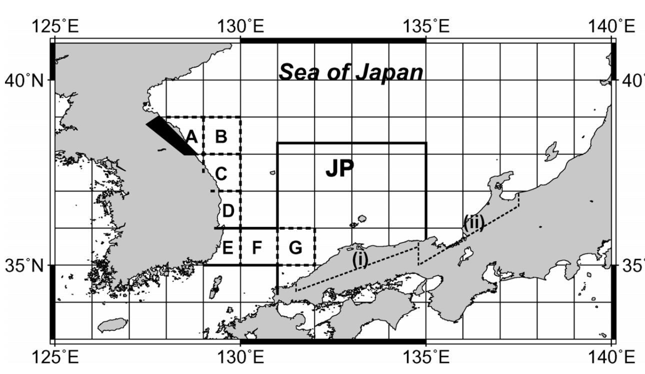

Figure 1. A summary of locations. Dark area, areas A–G by 1° grid, and area JP (thick line) shows the spawning grounds of the western Sea of Japan sandfish stock, the areas sampled for the water temperature, and the waters from Shimane to Hyogo Prefectures, respectively. Area (i) and (ii) which are surrounded with a dotted line indicate the coast of Shimane, Tottori and Hyogo Prefectures, and that of Kyoto, Fukui, Ishikawa and Toyama Prefectures, respectively.

Index of spawning stock biomass

As previously mentioned, in these areas, we can only use the catch data, and the age-structured abundance is not available. Subsequently, we assume the following assumptions: (i) C_t consists of 1 and 2-year old fish (Kuranaga, 1987; Kiyokawa, 1991); (ii) the SSB in year t is proportional to C_t. Therefore, the catch in year t is constructed by the offspring of the SSB in year $t-2$ and $t-3$, that is, $(C_{t-2}+ C_{t-3})$. We defined that SSB index in year t SSB_t is equal to $C_{t-2}+C_{t-3}$. The logarithmic transformation values of SSB_t twere used in the analysis.

Water-temperature data

Near the Korean Peninsula, the water temperature was available from the Korea Oceanographic Data Center (KODC) (see Fig. 1). The data were available for depths of 0–50, 100, 150, 200 and 300 m by month m ($m=$Feb., Apr., Jun., Aug., Oct., Dec.) by 1° grid (area A–G in Fig. 1) from 1960 to 1999. Hereafter, $W_{m,t,h,d}$ denote the water temperature at depth d of area h in month m of year t. Water temperature off Shimane, Tottori, and Hyogo Prefectures, Japan were not available, because the data are not collected by all depth from 0 m to 300 m in the long term since the 1960s.

Correlation coefficients were calculated between C_t and water temperatures in $t-1$ and $t-2$, which would be influenced for the SSB. Many negative significant correlation coefficients were detected (Fig. 2), and only a few cases, when the depth layer was 150 m and 200 m in areas D and E for December with time lag 1, positive correlation coefficients were detected.

In order to build the forecasting model, we summarize the water temperature as follows: W_t (spring) denotes the water temperature that denoted the significant correlations in April, W_t (summer) denotes the water temperature that denoted the significant correlations in June and August, and W_t (autumn) denotes the water temperature that denoted the significant correlations in October. For instance, W_t (spring) was calculated as follows: Firstly, we standardized water temperatures as follows: $W'=(W-\overline{W})/\sigma_W$, where W' is the standardized water temperature, $\overline{W}$ and σ_W are the mean and the standard deviation of water temperatures from 1969 to 1998. W_t (spring) can then be expressed as follows:

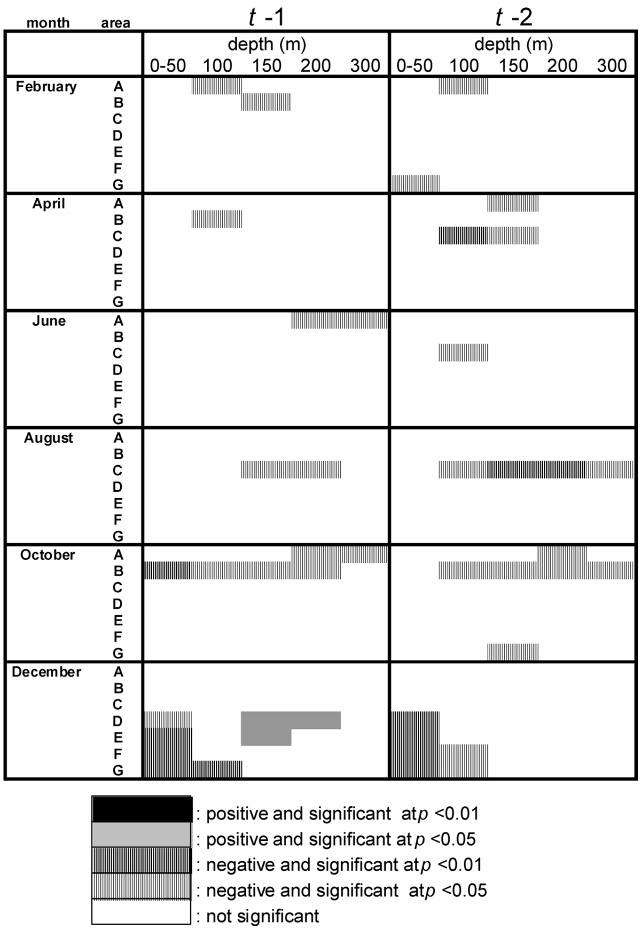

Figure 2. Correlation coefficients for the "western" Sea of Japan sandfish stock catch in year t and the water temperature in year $t-1$ and $t-2$.

$$W_t(\text{spring}) = W'_{\text{Apr.},t-1,B,100} + W'_{\text{Apr.},t-2,\text{A},150} + W'_{\text{Apr.},t-2,\text{C},100} + W'_{\text{Apr.},t-2,\text{C},150} \quad (1)$$

In the case of winter (December and February), positive and negative correlations were observed. Thus, data was separated into negative, $W1_t$ (winter), and positive, $W2_t$ (winter), indices. All the indices were used as independent variables.

Water temperature would be correlated with primary production and the abundance of zooplankton (Venrick *et al*, 1987; Sugimoto and Tadokoro, 1997). In the Sea of Japan, surface mixed layer depth (MLD) is closely related with these ecological conditions, especially in winter and spring (Hirai, 1995; Kim and Isoda, 1998). $MLD_{m,t,h}$ is defined as the depth (m) between the sea surface and a layer of water where the difference in water temperature between these two layers is greater than 1° (Hamawa and Hoshino, 1988; Kim and Isoda, 1998). In order to know the relationships between the $W_{m,t,h,d}$ and $MLD_{m,t,h}$ in April, February, and December, we conducted the correlation analysis between these two variables.

Catch models

Models were built for the following two cases: Case 1; C_t is determined only by SSB_t; Case 2; C_t is determined by SSB_t and water temperatures. The models were evaluated using the coefficient of determination, r^2, adjusted with degrees of freedom.

Y_t denotes the logarithms of C_t.

$$Y_t = \ln(C_t) \quad (2)$$

The regression model is constructed as:

$$\boldsymbol{Y} = \boldsymbol{B}_{\boldsymbol{\nu}} + \boldsymbol{\varepsilon} \quad (3)$$

where $\boldsymbol{Y}$ is the vector with dimension $\delta-\tau+1$ in which τ and δ are the beginning and ending years of data. The vector $\boldsymbol{\nu}$ is the parameter vector with dimension n that depends on the number of predictors, $\boldsymbol{B}$ is the matrix of predictors with dimension $((\delta-\tau+1\times n))$, ε is the vector of error terms that follow the normal distribution with mean 0 and variance σ^2. That is,

$$\boldsymbol{Y} = (Y_\tau, Y_{\tau+1} \cdots Y_\delta)^T, \quad (4)$$

$$\boldsymbol{\nu} = (\alpha_0 \quad \alpha_1 \quad \alpha_2 \cdots \alpha_{n-1})^T, \quad (5)$$

$$\boldsymbol{B} = \begin{bmatrix} 1 & \beta_{\tau,1} & \cdots & \beta_{\tau,n-1} \\ 1 & \beta_{\tau+1,1} & \cdots & \beta_{\tau+1,n-1} \\ 1 & \beta_{\delta,1} & \cdots & \beta_{\delta,n-1} \end{bmatrix}. \quad (6)$$

where T denotes the transpose of the vector. The $\boldsymbol{\nu}$ can be estimated by the least squares method.

In case 2, to investigate multi-co-linearity among the independent variables, a variance inflation factor, VIF, was calculated for each independent variable. Generally, the multi-co-linearity between valuables exists when VIF is over 10 (Armitage *et al*., 2002).

Catch forecasts by extrapolation

To evaluate the model for the catch forecasts, we conducted simulations using the variables employed in the case 2 model from 1980 to 1999. Namely, the vector $\boldsymbol{\nu}$ is estimated using the data from τ to δ by equations (3), and then, $C_{\delta+1}$ in the following year is extrapolated as follows:

$$\hat{Y}_{\delta+1} = [1 \quad \beta_{\delta+1,1} \cdots \beta_{\delta+1,n-1}] \cdot \hat{\boldsymbol{\nu}}, \quad (7)$$

$$\hat{C}_{\delta+1} = \exp(\hat{Y}_{\delta+1}). \quad (8)$$

where ˆ indicates the estimated variables. This procedure from equation (4) to (8) was repeated until $\delta=1998$. This operation is the same as that of Sakuramoto *et al*. (2001) when they examined the forecasting model in the sandfish

Table 1. A summary of catch models using regression analyses and F-tests for the models. P-value is the probability level for the F-tests. r^2 is the coefficient of determination adjusted by degree of freedom.

case	model	F-value	p-value	r^2
1	$\ln(C_t)=0.66\ln(SSB_t)+2.54$	14.82	0.0006	0.32
2	$\ln(C_t)=0.17\ln(SSB_t)-0.08\ W_t\text{(spring)}+0.01\ W_t\text{(summer)}$ $-0.02\ W_t\text{(autumn)}-0.01\ W1_t\text{(winter)}+0.07\ W2_t\text{(winter)}+7.47$	13.29	0.000001	0.71

catches of Akita Prefecture.

To evaluate the closeness of model fitting to the catch data, IFE is defined as follows:

$$\mathrm{IFE}=\frac{\sum_{\delta=1979}^{1998}(\hat{C}_{\delta+1}-\overline{C})^2}{t\sum_{\delta=1979}^{1998}(C_{\delta+1}-\overline{C})^2}. \tag{9}$$

where $\overline{C}$ is the mean of $C_{\delta+1}$ over the years of $\delta=1979$ to 1998.

Results

Catch models

In case 1, a relationship between ln (C_t) and ln (SSB_t) was significant and positive of which r^2 was 0.32 ($p<0.0006$) (Table 1). In case 2, r^2 was markedly higher than that in case 1 ($r^2=0.71$, $p<10^{-5}$). Catches reproduced by case 1 could not coincide with observed ones from 1973 to 1979 and from 1985 to 1990. In contrast, those in case 2 could explain the fluctuations in the observed catches quite well compared with those in case 1 (Fig. 3). Significant independent variables[t] in case 2 were W_t (spring) (F-value$=10.14$, $p<0.004$) and $W2_t$ (winter) t (F-value$=6.81$, $p<0.015$) (Table 2).

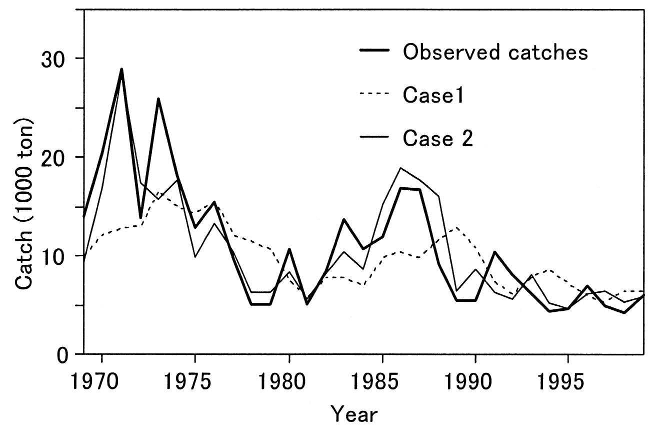

Figure 3. Catch trajectories observed (thick line) and reproduced by Case 1 (dotted line) and Case 2 (thin line).

Table 2. Parameter estimates of water temperature indices from regression analysis in the case 2 model. F-test is used to test the null hypothesis that a parameter value is 0, and p-value is the probability level for the F-tests.

Variables	Partial regression	F-value	p-value
W_t (spring)	-0.08	10.14	0.004
W_t (summer)	0.01	0.11	0.745
W_t (autumn)	-0.01	0.49	0.492
$W1_t$ (winter)	-0.02	2.71	0.113
$W2_t$ (winter)	0.07	6.81	0.015

Yearly variations in the independent variables

Variations in SSB_t showed two peaks in the mid 1970s and the late 1980s (Fig. 4). Long-term trends of W_t (spring), W_t (summer), W_t (autumn), and $W1_t$ (winter) were very similar. They increased from the early 1970s to the early 1980s, decreased markedly in the mid 1980s, and then increased again in the late 1980s. In contrast, $W2_t$ (winter), which consisted of water temperature deeper than 150 m, showed high levels in the early 1970s, declined in the mid 1970s, and increased slightly in the mid 1980s.

Indices of the multi-co-linearity, VIF, at the predictors were lower than 10 (Table 3). The multi-co-linearity was not found although the long-term trends of these predictors showed the similar patterns.

Extrapolation of catch

To evaluate the fitting by extrapolation in the above model, $\hat{C}_{\delta+1}$ the from 1979 ($=\delta$) to 1998 was forecasted using the independent variables of the model in case 2 (Fig. 5). The $\hat{C}_{\delta+1}$ could explain 52 % of the variance of $\hat{C}_{\delta+1}$ (IFE$=0.52$). Plots of relative residuals, $(\hat{C}_{\delta+1}-C_{\delta+1})/C_{\delta+1}$, to $C_{\delta+1}$ indicated that the degree of over-forecasts was higher than that of under-forecasts (Fig. 6). In particular, the relative residuals in 1985 and 1988 were twice as much as the ones observed.

Relationship between water temperature and surface mixed layer depth

The partial regression coefficient of the indices of W_t (spring) and $W2_t$ (winter) were significant in the regression

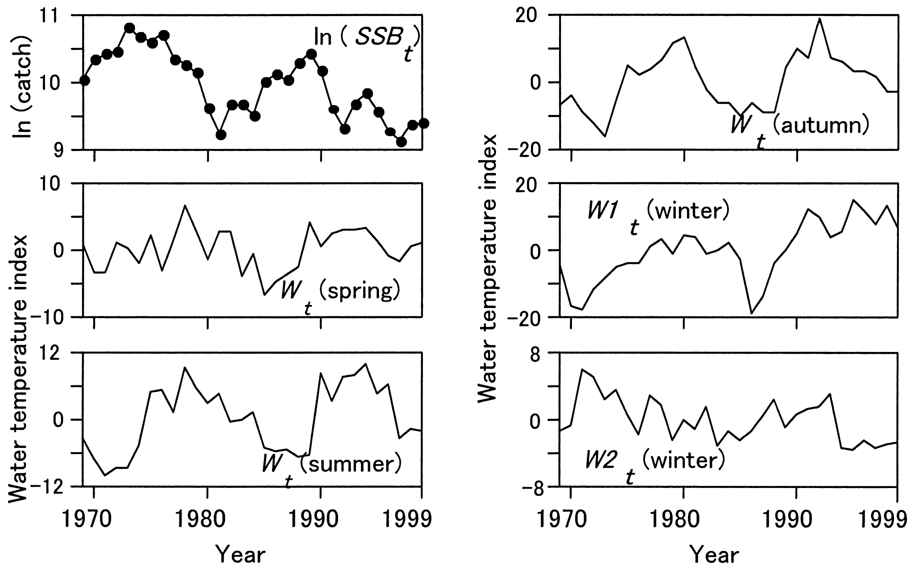

Figure 4. Trajectories of SSB and the indices of water temperature in each season.

Table 3. Variance inflation factors for the predictors in the case 2 model.

Variables	VIF
ln (SSB_t)	2.146
W_t (spring)	1.934
W_t (summer)	3.544
W_t (autumn)	3.198
$W1_t$ (winter)	3.402
$W2_t$ (winter)	1.598

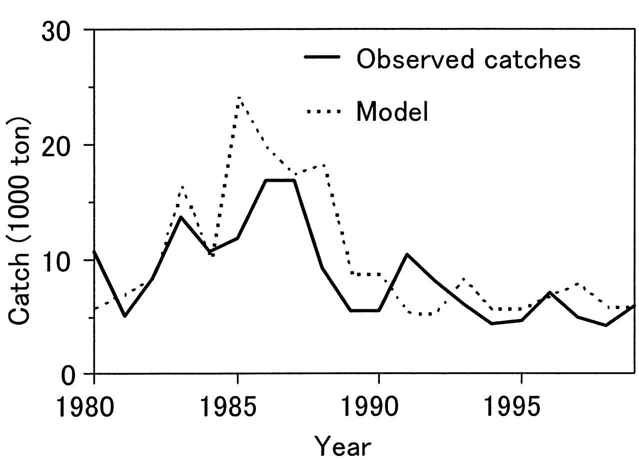

Figure 5. Observed catches (thick line) and extrapolated ones (dotted line) obtained using the case 2 model of the western Sea of Japan sandfish stock. IFE shows the index of fitness by extrapolation.

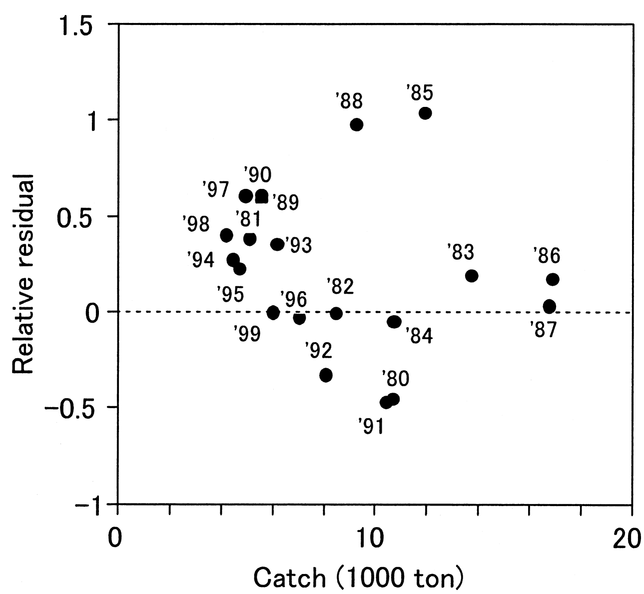

Figure 6. Plots of relative residuals of catches from the forecasting model to catches of the western Sea of Japan sandfish stock.

model (Table 2). It is known that in the Sea of Japan, MLD is active during winter and spring (Kim and Isoda, 1998).

In February, April, and December, the *MLD* had a positive and significant correlation with water temperature at depths greater than 100 m in most areas (Fig. 7). On the other hand, the *MLD* did not have a significant correlation with the water temperatures at the depths of 0–50 m, except in area G for April and December. These results indicate that $W2_t$ (winter) consisted of the water temperatures at the

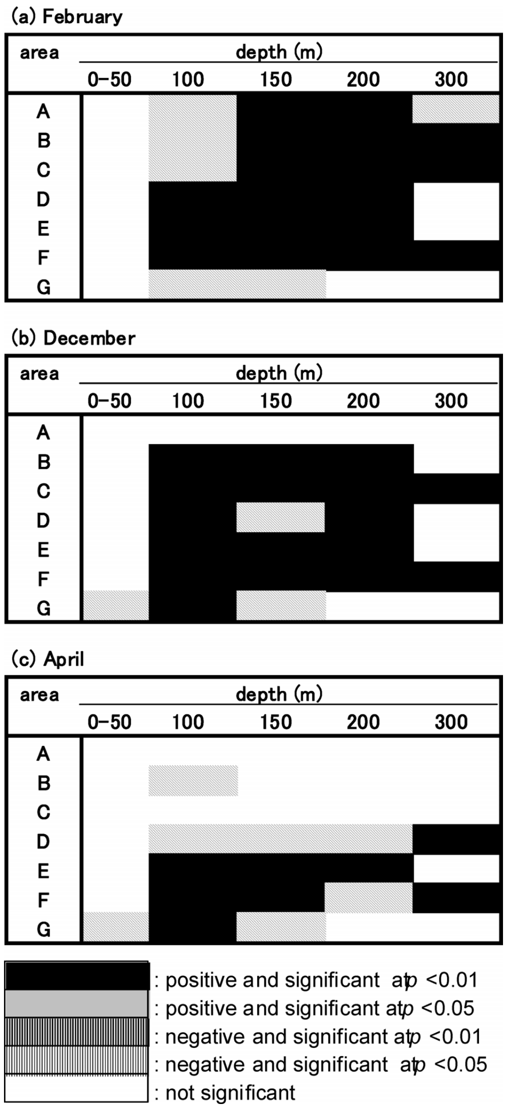

Figure 7. Correlation coefficients between mixed layer depth (MLD) and water temperature in each depth of each area.

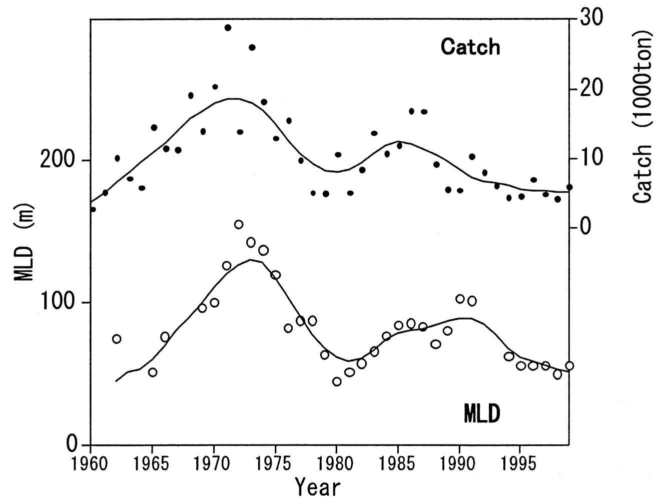

Figure 8. Catches in the western Sea of Japan sandfish stock (closed circle) with smoothed line by LOWESS (when tension parameter is set at 0.25). Means of mixed layer depth (MLD) in areas D and E from year $t-1$ and $t-2$ (open circle) and smoothed one.

depths of 150 and 200 m of area D and at a depth of 150 m of area E in December, correspond to the variations in the *MLD*.

Since Figure 7 suggested that the *MLDs* of area D and E in December are associated with the population fluctuations, a mean of the *MLD* estimates, $(MLD_{12,t-1,D}+MLD_{12,t-1,E}+MLD_{12,t-2,D}+MLD_{12,t-2,E})/4$, were compared with the fluctuation of C_t (Fig. 8). Long-term trends in the mean *MLD* and the C_t, which were the smoothing lines using LOWESS (Cleveland, 1979), showed similar patterns.

Discussion

The model constructed by the ISSB and the indices of water temperature can explain the fluctuation in C_t (Fig. 3). Sakuramoto *et al*. (2001) showed that the fluctuation in the coastal sandfish catch in Akita Prefecture in year *t* can be forecasted using the coastal catch and the water temperature in year $t-1$, $t-2$, and $t-3$. These results indicate that the fluctuations of catches both in the "northern" Sea of Japan and the "western" Sea of Japan stock can be explained in the same mechanism.

Kuranaga (1999) reported that the intensity of the cold-water mass off Shimane Prefecture and the warm-water mass off Oki island in year *t* could affect the sandfish catch fluctuations of Tottori Prefecture in September of year *t*. Ocean environmental factors in year *t* (time lag 0) may influence the distribution pattern of the fish, and thus the fluctuation in the local and seasonal catches.

The index of $W2_t$ (winter), which consisted of water temperature deeper than 150 m, was one of the significant independent variables (Table 2). The water temperatures at depths greater than 150 m had positive correlations with the estimate of *MLD* (Fig. 7). Kim and Isoda (1998) examined the surface MLD in February on the PM line across the center of the Sea of Japan, and showed that the estimated MLD had positive correlations with water temperature at a depth of 200 m. In this study, the variations in $W2_t$ (winter) (Fig. 4) and the mean *MLD* at areas D and E in December (Fig. 8) coincided with the MLD that was observed by Kim and Isoda (1998). $W2_t$ (winter) would have some relation with the MLD.

Generally, MLD is associated with primary productivity and environmental conditions in the ocean (Polovina *et al*., 1995). The long-term changes in *MLD* depicted in Figure 8 and the MLD that Kim and Isoda (1998) estimated were similar to those of the zooplankton biomass (Hirota and Hasegawa, 1999) and the Chlorophyll *a* on the PM line in the Sea of Japan (Chiba and Saino, 2002). *MLD* may determine these ecological conditions and the survival process of this fish, although, the trajectories of C_t in the 1990s did not correspond to the extreme increases of zooplankton biomass in the 1990s in the Sea of Japan (Hirota and Hasegawa, 1999) and the Eastern waters of the Korean Peninsula (Kang *et al*., 2002).

We noted that the long-term fluctuation in C_t had the similarities with that of the environmental conditions observed on the PM line of the Sea of Japan. Furthermore, the C_t roughly synchronizes with the regime shifts that occurred in the Northern Hemisphere in 1970/71, 1976/77, and 1988/89 that Yasunaka and Hanawa (2002) detected. Further investigation should be conducted to elucidate the relationship between the C_t and these large-scale environmental conditions.

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ハタハタ日本海西部系群の資源変動要因と予測に関する研究

渡邉久爾*[1]，櫻本和美[2]，南　卓志[3]，鈴木直樹[2]

ハタハタ日本海西部系群の資源変動を説明するために2つの数理モデルを開発した．モデル1：年tの本系群の漁獲量C_tは親魚量指数により決定される．モデル2：C_tは親魚量指数と環境要因（C_tと有意な相関関係を示した$t-1$と$t-2$における朝鮮半島東岸沖の水温）により決定される．C_tの変動の再現性を検討した結果，モデル2は，モデル1に比べて精度良くC_tの変動を説明した．また，1980–1999年までを予測（外挿）する場合についてシミュレーションを行った結果，モデル2により精度のよい予測が可能であった．モデル2において有意な環境要因として採用した水深150 m以深の冬季水温は，冬季混合層の厚さの推定値(MLD) と有意な正の相関関係を示した．また，MLDとC_tの長期変動は類似していた．以上の結果から，本系群の資源変動は親魚量とMLDの年変動に関連した環境要因に強く影響を受けていることが示唆された．

[1] 独立行政法人　水産総合研究センター　遠洋水産研究所
[2] 東京海洋大学
[3] 東北大学