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Relationship between temperature and fluctuations in sandfish catch (*Arctoscopus japonicus*) in the coastal waters off Akita Prefecture

Kazumi Sakuramoto, Takeru Kitahara, and
Hideki Sugiyama

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The sandfish (*Arctoscopus japonicus*) catch in the coastal water off Akita Prefecture have fluctuated greatly over the period 1962–1990. The difference between the maximum and minimum catches over those years is more than 200 times. The aim of this paper was to investigate the relationships between water temperature and the fluctuations of the catch. Using the fuzzy logic approach, the water temperatures measured in the different points off the Prefecture were summarized as an index which would indicate the variation of water temperatures. In this study, the sensitivity tests showed that the index inferred using the water temperatures observed in 100–150 and 200–300 m depth at 9 and 65 km off the coast with time lags 1, 2, 3 and 4 years could explain the fluctuation of sandfish catch. That is, large changes in catch can be simply explained by the fluctuation of water temperatures.

Key words: catch fluctuation, fuzzy logic, water temperature.

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K. Sakuramoto and T. Kitahara: Division of fisheries resource management, Tokyo University of Fisheries, Konan, Minato, Tokyo 108, Japan. H. Sugiyama: Akita-Prefectural Government, 4-1-1, Sannou, Akita 010, Japan.

Introduction

Catches of sandfish (*Arctoscopus japonicus*) in the coastal waters off Akita Prefecture (Japan) have exhibited large fluctuations over the last 30 years. As with many other fish stocks, variability in the catch of sandfish may be related to variability in many factors, such as recruitment, survival and oceanographic conditions. Economic factors such as market demand and price should also be taken into account. However, effective management and regulation of the fishery requires knowledge of which of these factors are most important.

In this study we focused our attention on the possible relationships between water temperature off of the Akita prefecture and sandfish catches. Temperature was chosen because the water temperature was considered to be one of the key factors to affect the level of coastal catches (Sugiyama, 1989, 1990). For instance, in the years when the water temperature at 150 m depth, 9 km off Cape Nyudo in Oga Peninsula, in the beginning of December was more than 13°C, the first days of sandfish catch showed a tendency to be delayed. Sugiyama believed that mature fish in water of temperature of around 1.5°C at 250 m depth could not pass (Sugiyama, 1991), and could not move to the coastal waters for spawning when the water temperature at 150 m depth was more than 13°C (Sugiyama, 1991). Recently, new analysis techniques such as neural networks have been used to relate fish catch to ancillary factors (Aoki and Komatsu, 1992; Komatsu *et al.*, 1994). In our study we have used the fuzzy logic method (Zadeh, 1965, 1973; Mamdani, 1974, 1976) to relate fish catch and temperature. Although this methodology has seen only limited use in ecological applications (e.g. Cao, 1995; Sakuramoto, 1995), it promises to be a useful method to model complex systems for which it is difficult to construct a system model, or systems from which data are difficult to collect or are of low accuracy. One famous example of modelling a complex system by fuzzy logic is the subway car controller used in Sendai, Japan (Kosko and Isaka, 1993). The fuzzy logic based controller outperformed both human operators and conventional automated controllers. In our paper we show the usefulness of the fuzzy logic method for investigating relationships between fish catch and temperature.

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Materials and methods

Data

The data used for analysis are as follows:

(1) The monthly catches of sandfish by a set net fishery and a Danish seine fishery off Akita Prefecture from 1962 to 1990 (Anon, 1988).
(2) The mean water temperatures in the depth layers 0–50 m, 100–150 m and 200–300 m at stations 9 and 65 km off Cape Nyudo in Oga Peninsula, Akita Prefecture in July, August and September from 1962 to 1990 (Fig. 1). The water temperatures were originally measured at depths 10, 20, 30, 40, 50, 100, 150, 200 and 300 m in every station, and then mean water temperatures for three depth layers, 0–50 m, 100–150 m and 200–300 m, were calculated. In this study we refer to these mean water temperatures as water temperature in the layer of 0–50 m, 100–150 m and 200–300 m, respectively.

Calculation of mean water temperature

The biology of sandfish in Akita Prefecture has been documented by Sugiyama (1989, 1990, 1992) who suggested that fluctuations in the sandfish catch are related to water temperatures in the coastal waters. We investigated the relationship between water temperature and catch for Akita Prefecture as follows.

Mean water temperature by month for each depth layer and station in year t, $X_{i,t}$, were calculated using the water temperature $W_{i,j,t}$ at position i in month j of year t. Miyazaki (1994) showed that the relationship between the water temperature off Akita Prefecture in August and the coastal catch was very strong with a time lag of 2 or 3 years. Following Miyazaki (1994), we use 3 months, from July to September, for calculating the mean water temperature by month.

$$X_{i,t} = \sum_{j=\mathrm{Jul}}^{\mathrm{Sept}} W_{i,j,t}/3 \qquad (1)$$

Here, subscript i indicates the position as follows:

i=1: position in the layer of 0–50 m depth at 9 km off Cape Nyudo
i=2: position in the layer of 0–50 m depth at 65 km off Cape Nyudo
i=3: position in the layer of 100–150 m depth at 9 km off Cape Nyudo
i=4: position in the layer of 100–150 m depth at 65 km off Cape Nyudo
i=5: position in the layer of 200–300 m depth at 9 km off Cape Nyudo
i=6: position in the layer of 200–300 m depth at 65 km off Cape Nyudo.

Fuzzy logic

The main part of the fuzzy logic method is fuzzy inference, which was proposed by Mamdani (1974, 1976) and a brief explanation and a simple example are presented in the Appendix. In conducting the fuzzy inference, the most important work is determining the proper input variables and their membership functions and then assigning the appropriate fuzzy rules. In this study, we determined the input variables and their membership functions as shown below.

Decision of input variables

Using a fuzzy logic approach, we try to determine the index that would summarize the variation of water temperatures. In this study, we focused on water temperature and used 30 variables at most as the candidates of input variables according to the results of the analysis shown later: the mean water temperatures in the depth of 0–50 m, 100–150 m and 200–300 m both at 9 and 65 km off Cape Nyudo in Oga Peninsula at year t, t − 1, . . ., t − 4. Time lags are incorporated because if the water temperature influences the reproduction of the sandfish stock, the effects would appear in the catches with certain time lag. Hereafter, we will use $X_{i,t-d}$ (d=0, 1, . . ., 4) rather than $X_{i,t}$ for mean water temperatures.

Specification of membership functions

A fuzzy set is a set and a function (membership function) mapping elements of the set into the interval [0, 1]. A fuzzy variable is defined with a fuzzy set or a membership function. In this study, five fuzzy variables (fuzzy sets) are defined for each sampling point i and year t (i=1, 2, . . ., 6, t=1966, . . ., 1990), respectively. The notation for the five fuzzy variables is as follows:

VL = Very low
L = Low
M = Medium
H = High
VH = Very high

The fuzzy variables for $X_{i,t-d}$ (i=1, 2, . . ., 6, t=1966, . . ., 1990, d=0, 1, . . ., 4) are defined with the membership functions determined as follows:

(1) Means and standard deviations up to year t (t=1966 to 1990) are calculated for each sampling point i and year t, respectively. That is,

$$\bar{X}_{i,t} = \frac{1}{t-1962+1}\sum_{\tau=1962}^{t} X_{i,\tau}, \quad i=1,2,\ldots,6 \qquad (2)$$
$$t=1966,\ldots,1990$$

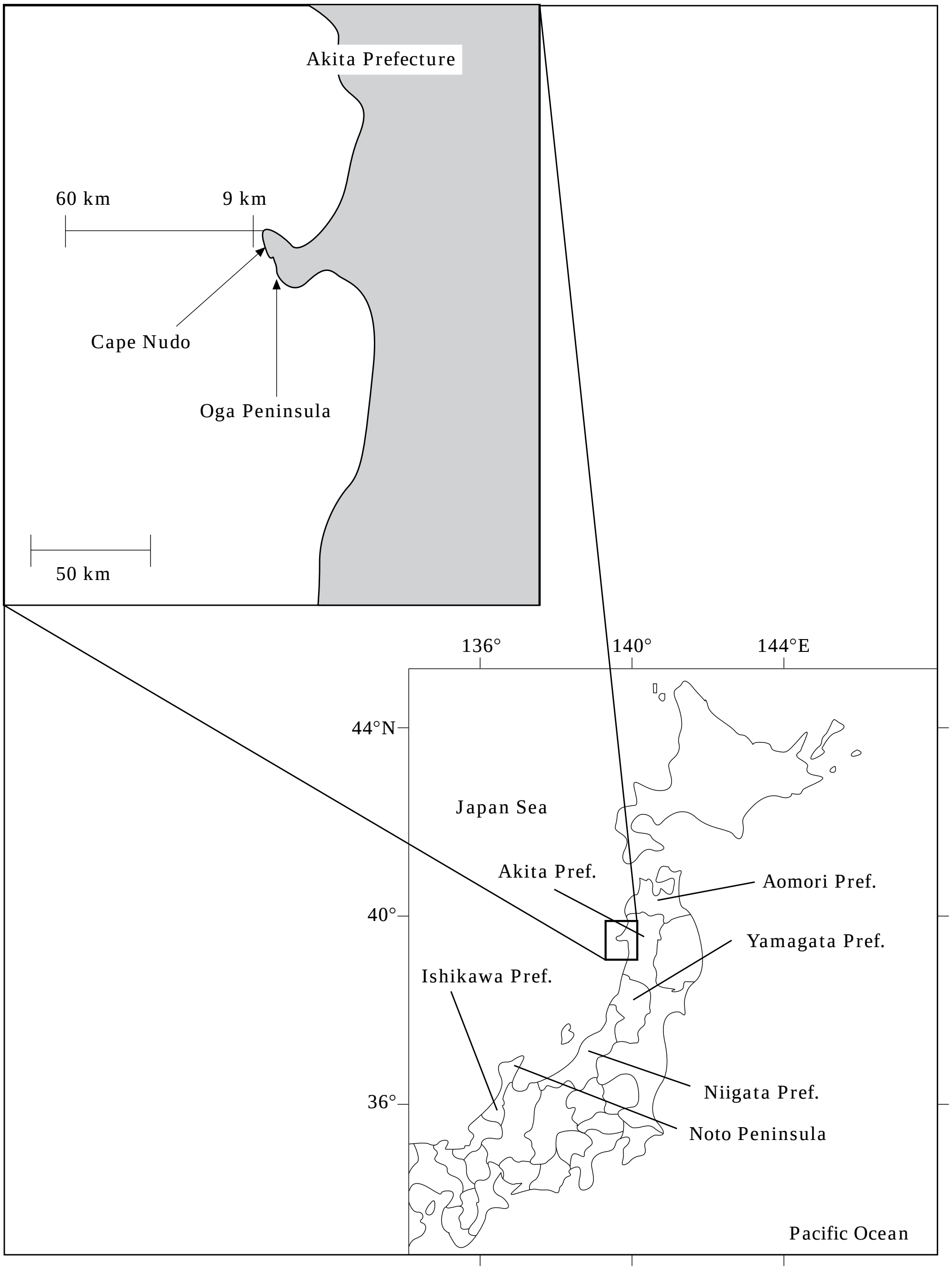

Figure 1. Location of Akita, Yamagata and Niigata Prefectures and the sampling points for water temperature on the west coast of Japan.

$$SD^2_{X_{i,t}} = \frac{1}{t-1962} \sum_{\tau=1962}^{t} (X_{i,\tau} - \bar{X}_{i,\tau})^2, \quad i = 1, 2, \ldots, 6 \quad (3)$$

$$t = 1966, \ldots, 1990$$

(2) One of the parameter values of the membership functions, $b_{F_{i,t}}$, in equation (5), is set for each fuzzy variable. That is,

$$b_{F_{i,t}} = \bar{X}_{i,t} + k \cdot \lambda_F \cdot SD_{X_{i,t}}, \; i = 1, \ldots, 6, \; t = 1966, \ldots, 1990 \quad (4)$$

Here, λ_F is set at -1.0, -0.5, 0, 0.5 or 1.0 for each fuzzy variable F, (F = VL, L, . . ., VH). From the results of sensitivity tests k is set at 2.5. However, the sensitivity tests also showed that the value of parameter k was not sensitive to the results inferred. Several types of function are commonly used as a membership function. In this study, for simplicity, a triangular shape of membership function is used (Fig. 2). That is,

$$\mu_{F_{i,t}}(X_{i,t}) = \begin{cases} \dfrac{1}{SD_{X_{i,t}}}(-|X_{i,t}-b_{F_{i,t}}|+SD_{X_{i,t}}), & 1-\left|\dfrac{X_{i,t}-\bar{X}_{i,t}}{SD_{X_{i,t}}}-k\lambda_F\right|>0 \\ 0 & \text{, otherwise} \end{cases} \tag{5}$$

Here,

$$\mu_{VH_{i,t}}(X_{i,t})=1 \quad \text{for} \quad \frac{X_{i,t}-\bar{X}_{i,t}}{SD_{X_{i,t}}}-k\geq 0$$
$$\mu_{VL_{i,t}}(X_{i,t})=1 \quad \text{for} \quad \frac{X_{i,t}-\bar{X}_{i,t}}{SD_{X_{i,t}}}+k\leq 0 \tag{6}$$

In Equation (5), $\mu_{F_{i,t}}$ $(X_{i,t})$ shows the grade or how strongly the value of $X_{i,t}$ belongs to the fuzzy set $F_{i,t}$ (F=VL, L, M, H or VH, i=1, . . ., 6, t=1966, . . ., 1990).

In this study, the output variable z_t is given by relative value [−1, 1]. Then the membership functions for the output variable are determined by Equation (4) putting mean 0 and standard deviation 0.4, instead of $\bar{X}_{i,t}$ and $SD_{X_{i,t}}$, respectively. That is, for output variable, $b_{F_{i,t}}$ in Equation (5) are given with −1.0, −0.5, 0, 0.5 and 1.0 for each fuzzy set VL, L, M, H and VH, respectively.

Specification of fuzzy rules

In this study, in order to save time in calculation, we constructed the fuzzy rules with two input and one output variables. We will call this inference part an "inference unit". One inference unit is constructed by 25 (=5 × 5) fuzzy rules. For simplicity, the input variables for each inference unit were determined as follows: when the mean water temperatures observed at six sampling points are used, the pairs (x_1,x_2), (x_3,x_4) and (x_5,x_6) are used for each time lag d. Then if 5 time lags are used for each pair of input variables, the total number of variables becomes 30 and then the 15 inference units are constructed. That is, 3 inference units (x_1,x_2), (x_3,x_4) and (x_5,x_6), multiplied by the number of time lag d (d=0, 1, . . ., 4) becomes 15. Other combinations of input variables can also be constructed. This will be discussed later. In each inference unit, the same fuzzy rules developed by Sakuramoto (1995) are applied (Table 1). The result of fuzzy inference is obtained by fuzzy set and then converted to a real number from −1 to 1 (see the Appendix).

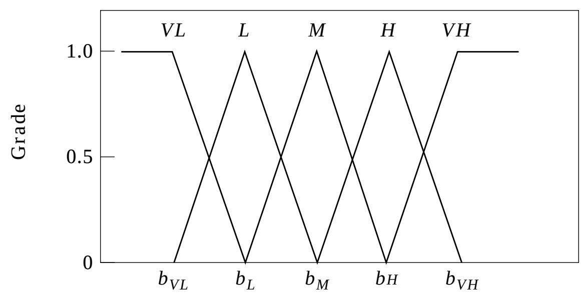

Figure 2. Membership function for 5 fuzzy variables.

Table 1. Fuzzy rules used in each inference unite. VL, L, M, H and VH denote the fuzzy variables, very low, low, medium, high and very high, respectively.

Rule number	Input variables		Output variable Index of water temperature (z_t)
	$x_{1,t}$	$x_{2,t}$	
1	VL	VL	VL
2	VL	L	VL
3	VL	M	L
4	VL	H	L
5	VL	VH	M
6	L	VL	VL
7	L	L	L
8	L	M	L
9	L	H	M
10	L	VH	M
11	M	VL	L
12	M	L	L
13	M	M	M
14	M	H	M
15	M	VH	H
16	H	VL	L
17	H	L	M
18	H	M	M
19	H	H	H
20	H	VH	H
21	VH	VL	M
22	VH	L	M
23	VH	M	H
24	VH	H	VH
25	VH	VH	VH

Evaluation for the output value inferred

Sensitivity tests for the combination of mean water temperatures observed in the different sampling points with different time lags were conducted. In order to judge the best combination of water temperatures that can best explain the fluctuation of the catch, the index of water temperatures z^0_t was converted to the level of coastal catch, according to the following:

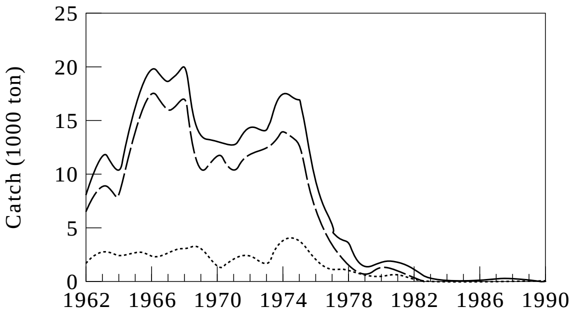

Figure 3. Catch histories of the set net fishery (– – –), Danish seine fishery (·····) and the total catch (——) from 1962 to 1990 in Akita Prefecture, respectively.

$$\bar{C}_t = \frac{1}{n}\sum_{\tau=t-n+1}^{t} C_\tau, \quad t=1966,\ldots,1990, \quad (7)$$

$$SD_{C_t}^2 = \frac{1}{n-1}\sum_{\tau=t-n+1}^{t} (C_\tau - \bar{C}_t)^2, \quad t=1966,\ldots,1990, \quad (8)$$

$$\hat{C}_t = \bar{C}_t + z_t^0 \cdot k \cdot SD_{C_t}, \quad t=1966,\ldots,1990. \quad (9)$$

Here, $\hat{C}_t$ corresponds to the coastal catch reproduced by fuzzy logic approach using the water temperatures. The same value of k in Equation (4) is used. In Equations (7) and (8), the notation n indicates the number of years used to calculate the mean and standard deviation of catch. From sensitivity tests, $n=5$ was chosen. This will be discussed later.

The residual sum of squares between the converted $\hat{C}_t$ and observed catches C_t was calculated to evaluate the fitness of the output variable inferred. That is,

$$SS = \sum_{t=1969}^{1990} (C_t - \hat{C}_t)^2, \quad (10)$$

As shown in the results section, the differences of the converted $\hat{C}_t$ and observed catches C_t were very large for the first three years (1966–1968). The first three years were excluded in calculation of the SS value. If those three years were included, the SS value can mainly indicate the differences of those three years and can not give the basis that we judge the fitness of the converted $\hat{C}_t$ with the observed catches C_t for the years after 1969. All the calculation and inference mentioned above are conducted with the program available from the authors.

Results

Characteristics of yearly fluctuations in catch

The catch histories of the set net and Danish seine fisheries for Akita Prefecture from 1962 to 1990 are presented in Figure 3. The total catch of Akita Prefecture ranged from several hundred to several thousand tons until 1960. It began to increase steeply in the early 1960s and reached more than 20 000 t in the period 1966 to 1968. Then it decreased to about 10 000 t and recovered to a level of nearly 20 000 t in 1974 and 1975. From 1976, however, it began to decrease sharply and fell to only 74 t in 1984. Such great fluctuations in the total catch resulted largely from the catch fluctuations in the set net fishery (Fig. 3). The above data suggest the possibility that few adult sandfish have migrated to the coast from the Taraba area in spawning season.

A correlation matrix of catches from different area and time period was constructed for investigating the inter-relationship between them (Table 2). In Table 2, the variables are as follows. A, B and C denote the catches by Danish seine fishery at year t off the Akita, Yamagata and Niigata Prefectures, respectively. D denotes the catch by set net fishery in the coastal waters

Table 2. Correlation matrix of sandfish catch in Akita, Niigata and Yamagata prefectures. In the items F to K, "1–6" denotes the month when the fishing is operated.

	Amount of catch by	B	C	D	E	F	G	H	I	J	K
A	Danish seine in Akita	0.91**	0.95**	0.70*	0.88**	0.56	0.88**	0.95**	0.87**	0.78*	0.60
B	Danish seine in Yamagata		0.94**	0.63	0.80*	0.42	0.95**	0.93**	0.64	0.65	0.46
C	Danish seine in Niigata			0.61	0.80**	0.56	0.91**	0.99**	0.81**	0.68	0.49
D	Set net in Akita				0.95**	0.19	0.61	0.57	0.68	0.81**	0.87**
E	Total of Akita					0.36	0.77*	0.78*	0.81**	0.87**	0.83**
F	Danish seine 1–6 in Akita						0.65	0.61	0.42	0.06	0.00
G	Danish seine 1–6 in Yamagata							0.91*	0.59	0.51	0.37
H	Danish seine 1–6 in Niigata								0.80*	0.63	0.43
I	Danish seine 1–6 in Akita of next year									0.84**	0.72**
J	Danish seine 1–6 in Yamagata of next year										0.93**
K	Danish seine 1–6 in Niigata of next year										

The correlation coefficients that are significantly different from zero with 5% and 1% significant level are shown by * and **, respectively.

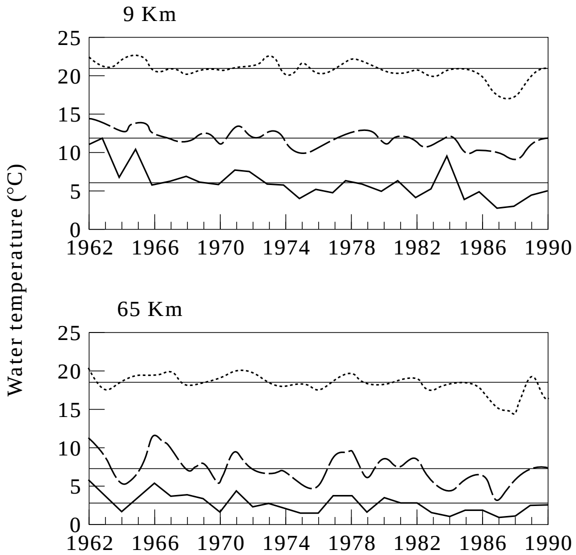

Figure 4. Mean water temperatures at 9 and 65 km off Cape Nyudo. From the top in each Figure, the fluctuating and fixed lines show the mean water temperature by month and the overall average water temperature by year respectively in the layer of 0–50 m (·····), 100–150 m (– – –) and 200–300 m (——) depth of water.

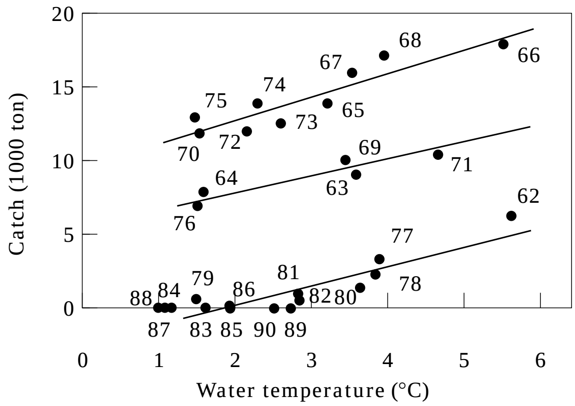

Figure 5. Relationship between mean water temperatures at 65 km, 200–300 m depth off Cape Nyudo and coastal catch. Figures show the years observed.

of Akita Prefecture at year t. E denotes the total catch of A and D above. F, G and H denote the catches by Danish seine fishery during January to June in year t off the Akita, Yamagata and Niigata Prefectures, respectively. I, J and K denote the catches by Danish seine fishery during January to June in year t+1 off the Akita, Yamagata and Niigata Prefectures, respectively. The positive correlations between A and B, A and C, and B and C are very high. The positive correlations between E and I, E and J, and E and K are also very high. That is, when the catch off Akita Prefecture is high, those of the adjacent Prefectures both in the same and next years are also high. These will support, to a certain extent, the hypothesis that sandfish off these prefectures belong to the same population.

The mean water temperatures (Equation 1) for each sampling position over the period of 1962 to 1990 showed cyclical patterns (Fig. 4). In each depth layer at both stations, the mean water temperatures by month tended to decrease with time. We estimated the regression lines of mean water temperature against the year. The slopes of regression lines were -0.172, -0.080, -0.100, -0.098, -0.078 and -0.081 for each variable of $X_{i,t}$ ($i=1, 2, \ldots, 6$), respectively. All the slopes of regression line except that for $X_{4,t}$ were significantly different from zero with 1% significant level. The slopes of regression line for the variable $X_{4,t}$ was significantly different from zero at the 5% significance level.

We compared the above characteristics of yearly fluctuations in the mean water temperatures with those in the total catch described previously. A comparison of Figures 3 and 4 showed that fluctuations in the total catch roughly followed the ones in the mean water temperatures in depth layer 200–300 m at 9 km off Cape Nyudo with the time lag of 2 or 3 years. That is, as stated previously, the total catch steeply increased and reached more than 20 000 t from the early 1960s to 1968 and all the mean water temperatures were above the average by year from 1962 to 1965; the total catch recovered to a level of nearly 20 000 t in 1974 and 1975 and the mean water temperatures were above the average and relatively high in 1971 and 1972; in addition, the total catch sharply decreased from 1976 to 1979 and almost the mean water temperatures were below the average from 1975 to 1977. In the 1980s, the catch level was very low and the water temperature was also below the average.

The relationship between the catch of sandfish by the set net fishery and the mean water temperatures was investigated and the tendency to separate into two or three groups was recognized. The most typical case was shown in the 200–300 m depth of layer 65 km off Cape Nyudo (Fig. 5) where three groups are quite evident. The number of groups was determined by fitting linear models to the set net sandfish catch and mean temperature assuming three groups, two groups and then one group. The goodness of fit for each of these groupings, calculated using the AIC statistic (Akaike, 1973), was 402, 434 and 507, respectively. Therefore we chose the three group model as being appropriate. The regression lines and correlation coefficients for each group from the top were as follows (see also Fig. 5):

$$Y_t = 9610 + 1564\, X_{6,t},\ r = 0.908,$$
$$Y_t = 6018 + 964\, X_{6,t},\ r = 0.932,$$
$$Y_t = -1980 + 1188\, X_{6,t},\ r = 0.878.$$

Table 3. Various combinations of water temperatures and its sum of square values (SS). Bold show the best combination of variables and time lags, and minimum SS value. See text for definition of x_1, x_2, x_3, x_4, x_5 and x_6.

Variables	Time lag	SS (10^7)	Time lag	SS (10^7)
x_1, x_2	0	21.46	1, 3	7.69
x_1, x_2	1	18.98	2, 4	13.08
x_1, x_2	2	13.29	2, 3, 4	7.04
x_1, x_2	3	81.03	1, 2, 3, 4	9.07
x_1, x_2	4	19.41	0, 1, 2, 3, 4	11.56
x_3, x_4	0	15.78	1, 3	4.26
x_3, x_4	1	10.3	2, 4	4.07
x_3, x_4	2	7.32	2, 3, 4	2.95
x_3, x_4	3	7.64	1, 2, 3, 4	1.94
x_3, x_4	4	9.86	0, 1, 2, 3, 4	2.77
x_5, x_6	0	8.38	1, 3	5.10
x_5, x_6	1	5.85	2, 4	5.24
x_5, x_6	2	4.86	2, 3, 4	4.53
x_5, x_6	3	7.54	1, 2, 3, 4	3.98
x_5, x_6	4	8.23	0, 1, 2, 3, 4	4.04
x_3, x_5	0	9.61	1, 3	4.73
x_3, x_5	1	5.55	2, 4	5.77
x_3, x_5	2	3.77	2, 3, 4	4.42
x_3, x_5	3	5.6	1, 2, 3, 4	3.37
x_3, x_5	4	12.57	0, 1, 2, 3, 4	3.50
x_4, x_6	0	25.95	1, 3	12.32
x_4, x_6	1	21.86	2, 4	10.05
x_4, x_6	2	18.30	2, 3, 4	9.66
x_4, x_6	3	18.88	1, 2, 3, 4	10.03
x_4, x_6	4	13.25	0, 1, 2, 3, 4	11.39
x_3, x_4, x_5, x_6	0	12.44	1, 3	4.11
x_3, x_4, x_5, x_6	1	7.71	2, 4	3.71
x_3, x_4, x_5, x_6	2	6.02	2, 3, 4	3.07
x_3, x_4, x_5, x_6	3	7.74	**1, 2, 3, 4**	**1.87**
x_3, x_4, x_5, x_6	4	8.56	0, 1, 2, 3, 4	2.32
x_1, x_2, x_3, x_4, x_5, x_6	0	14.99	1, 3	5.24
x_1, x_2, x_3, x_4, x_5, x_6	1	10.97	2, 4	5.91
x_1, x_2, x_3, x_4, x_5, x_6	2	6.91	2, 3, 4	5.55
x_1, x_2, x_3, x_4, x_5, x_6	3	4.64	1, 2, 3, 4	5.39
x_1, x_2, x_3, x_4, x_5, x_6	4	10.58	0, 1, 2, 3, 4	6.93

Furthermore, we tested whether the differences of each two slopes shown above were significant, and it was found that all of these three slopes are not significantly different from each other at the 10% significance level. This indicates that the effect of water temperature was the same in each three groups and only the level is different.

Sensitivity tests for the combination of input variables $x_{i-d,t}$ ($i=1, 2, \ldots, 6$, $d=0, 1, \ldots, 4$, $t=1966, \ldots, 1990$) were conducted and the results are shown in Table 3. The combinations shown in Table 3 are arbitrarily chosen. For instance, the third row in Table 3 indicates that x_1 and x_2 are used as input variables with time lag 2. That is, the case when mean water temperature was observed at 0–50 m depth of both 9 and 65 km off Cape Nyudo with time lag 2, $x_{1,t-2}$, $x_{2,t-2}$, were used as input variables. In this case, only 2 variables were used to infer the index. Similarly, in the same row with time lags 2, 3 and 4 is the case when $x_{1,t-2}$ and $x_{2,t-2}$, $x_{1,t-3}$ and $x_{2,t-3}$, and $x_{1,t-4}$ and $x_{2,t-4}$ are used. That is, in this case six variables and then three inference units are used to infer the index.

From Table 3 it appears that deep water temperature gives much more useful information to reproduce the variation of coastal catch. When single time lag was incorporated, the case of time lag 2 gave the minimum sum of square values within the groups that utilized the same input variables except one case (third row from the bottom). A large number of input variables did not necessarily give better results. Water temperatures observed at 9 km gave a better index than those observed at 65 km. The best combination here was to use the mean water temperature in the depth of 100–150 and 200–300 m both at 9 and 65 km off Cape Nyudo with the time lags 1, 2, 3 and 4 years. The catch trajectory was reproduced when the best combination

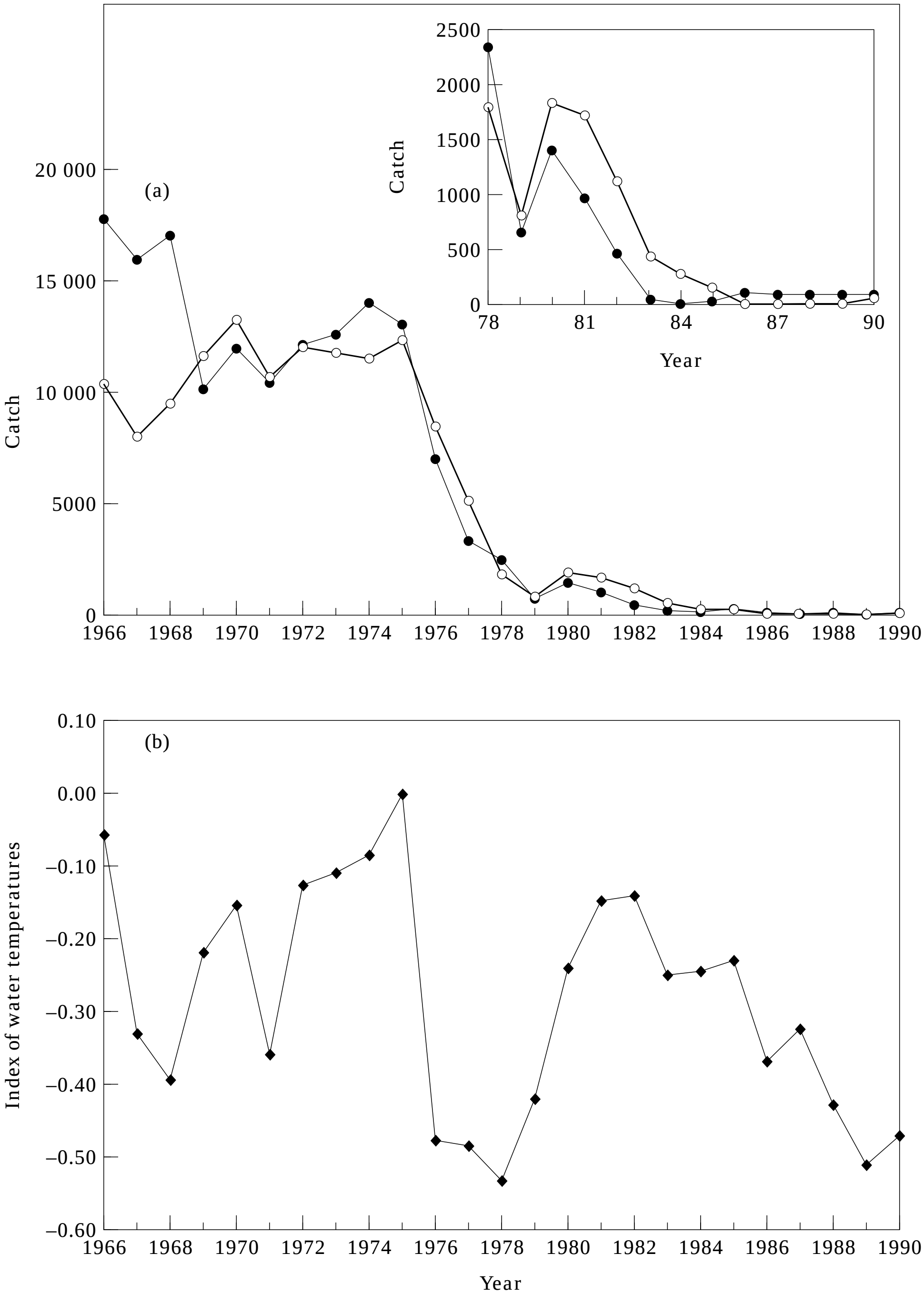

Figure 6. (a) The values of catch observed (—●—) and forecasted (—○—) when the best combination of input variables was chosen. The figure shown in the top right of (a) is the result in which the scale of y-axis is magnified. (b) The index of water temperatures inferred when the best combination of the variable was chosen. The best combination here was to use the mean water temperature in the depth of 100–150 and 200–300m both at 9 and 65 km off Cape Nyudo with the time lags 1, 2, 3 and 4 years (see Table 3).

was used (Fig. 6). The converted and observed catches in the first three years were greatly different because only the short period of data can be used. Then the first three years were excluded in calculation of the sum of square value. The results for the years from 1978 to 1990 are shown in the top right of Figure 6, in which the scale of the y-axis is magnified. It was found that in general the catch fluctuations were well reproduced, particularly in the cases of sharp decline of catch in 1976, 1977 and 1979, or sharp increase in 1980 (Fig. 6).

The index of water temperatures inferred by this method are shown in the bottom of Figure 6. Patterns in the variations of catch and index of water temperature shown in Figure 6 coincided each other. In particular, the steep reduction of catch which occurred in 1976 and 1977 coincided well with the steep reduction of the index of water temperature. In Figure 5, eight cases of switching can be observed, i.e. it occurred in 1962–1963, 1964–1965, 1968–1969, 1969–1970, 1970–1971, 1971–1972, 1975–1976 and 1976–1977. The first two cases and 1969–1970 were shifted from low catch group to high one, and the others were from high to low. Except the first two shifts shown in Figure 5 (1962–1963 and 1964–1965), the index of water temperature shown in the bottom of Figure 6 could well explain the switching, whereas in the 1960s one or two years delay was sometimes observed. That is, the shift from high to low catch group that occurs in 1968–1969 could be explained by the low index of water temperature shown in 1967 and 1968. Similarly, the shift from low to high catch group that occurred in 1969–1970 could be explained by the relatively high index of water temperature shown in 1969 and 1970. The shift from high to low in 1970–1971, 1975–1976 and 1976–1977 coincided with the low index in 1971, 1976 and 1977, respectively. The shift from low to high in 1971–1972 coincided with the high index in 1972. The pattern of catch after 1980 shown in top right of Figure 6 was similar to the pattern of the index.

Discussion

Sandfish in the Sea of Japan are clearly divided into the two populations inhabiting the north-eastern and the western regions separated by Noto Peninsula, Ishikawa Prefecture. The latter population was defined as having spawning waters off of the east coast of Korea (Okiyama, 1970). Sandfish taken off Aomori–Ishikawa Prefecture are assumed to belong to the former population, referred to here as the eastern population. The eastern population spawns on seaweed along the coast in Akita Prefecture during stormy weather conditions in December and January. In Akita Prefecture, the set net fishery in the coastal waters exploits sandfish that migrate to the coast for spawning. Outside the spawning season, the fish are exploited mainly in the "Taraba area" of 200–300 m depth where cod is fished by the Danish seine fishery. In addition, a tagging experiment suggests that the eastern population moves south-westwards for feeding in spring–summer and north-eastwards for breeding in autumn–winter along the coast of Aomori–Ishikawa Prefecture (Okiyama, 1970; Tanaka, 1987).

One or two years before the steep reduction of coastal catch in 1976 and 1977, the catches in offshore fishery were indeed very high (Fig. 3). In the offshore fishery, not only the mature fish but also the younger fish were caught, whereas the coastal set net fishery harvests only the mature fish. Therefore, it may be postulated that the high catch of offshore fishery caused the reduction of population size with the result that the coastal catch decreased with a lag of one or two years. However, the correlation coefficient for the offshore catch and the coastal catch in the same year is very high ($r=0.695$). Therefore, it could also be considered that the high catch of offshore fisheries in 1974 and 1975 were merely caused by high level of population abundance in those years and so the fishing intensity by offshore fisheries in those years would not be extremely large compared with other years. That is, the high catch in offshore fisheries in those years would not necessarily be a cause of the reduction of coastal catch after these years. However, if the high catch in offshore fishery was not immediately the cause of the reduction of population, it might have accelerated the reduction of the population abundance which had already been reduced by low water temperature.

When we converted the index of water temperature ${z^0}_t$ to the catch $\hat{C}_t$ caught by set net fishery in year t, we used the mean and standard deviation of the actual catch from year $t-4$ to t. That is, the information of the recent 5 years including the current year were used ($n=5$). If we use the longer period of catch data, for instance, from $t-9$ to t instead of year $t-4$ to t, the SS value became larger. This would indicate that the recent information is more important than the older years in judging the variation of catch when the age range of the population is short. This may also be explained by the features shown in Figure 5. That is, even though the level of water temperature is almost same, the level of catch is quite different depending on which group the level of population abundance belongs to. Therefore, even the mean water temperatures at the same sampling point are equally judged as, for instance, "very low" with the same grade of membership function in Equation (5), the actual catches are different in 1970s and in 1980s. This would be the reason that the shorter period of data is suitable for calculating $\overline{C}_t$ and SD_{C_t} in order to convert the relative value inferred to the actual levels of catch in the case when the age range of the population is short.

As demonstrated above, one advantage of the fuzzy logic approach is that the criteria can be changed for each era. Then, if relative values are much more important than the absolute one to explain certain phenomenon, the fuzzy logic approach shown in this paper can treat the subject with more flexibility. Another advantage of the fuzzy logic approach is that this approach is robust for the observed noise in data. Sakuramoto

(1995) showed that cohort analysis applying fuzzy logic possessed a more robust nature for the observed noise than conventional method.

In this study, the same fuzzy rules of Sakuramoto (1995) are used for all the inference units. While the input variables used in these two paper are quite different, the same rules are applied and the good inferences have been achieved. This implies that the fuzzy rules will not be sensitive to the subjects that we try to analyse or to input variables treated in the papers. The fuzzy rules constructed by Sakuramoto (1995) and used here were not objectively determined but arbitrarily set based on common sense. This point has been criticized as a weakness of this approach. Further, to save the calculation time and to simplify the computer code for the fuzzy inference, the fuzzy rules were constructed with two input variables and one output variable. However, it may be reasonable to allow any number of input variables in one inference unit. These points should be investigated in a future study.

In this study, we did not analyse the catch-at-age data. The results of the cohort analysis using the catch-at-age data showed that the population abundance of age 1 and 2 were significantly low during the period when the amount of catch had decreased (Kitahara, pers. comm.). This implies that the decrease of the amount of catch reflects the decreases in population abundance, especially decreases in recruitment. A more detailed analysis of the effects of water temperatures or other aspects of the population, such as the composition of age, length, weight, gonad index, etc. would give us more useful information to help understand the large variation in the catches.

The correlations in the amount of sandfish catch among Akita, Niigata and Yamagata Prefectures were very high (see Table 2). The amount of catch in above three Prefectures should be analysed at the same time because these prefectures were considered to be harvesting the same stock. We will do this in a future study.

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Appendix

Fuzzy inference

Let us briefly explain Mamdani's inference method (1974, 1976) in relation to the procedure used in this paper. For simplicity, let us consider the inference which is constructed with two input and one output variable. For instance, $X_{1,t}$ and $X_{2,t}$ denote mean water temperatures from July to September at the positions 1 and 2 in year t (input variables), and z_t denotes the index of water temperature (output variable). For simplicity, we will use the 10 fuzzy rules (Rules 6 to 15) out of 25 in Table 1. The mth fuzzy rules (m=6, 7, . . ., 15) are generally expressed as

$$R^m\text{: if } X_{1,t} \text{ is } F_{m,1,t} \text{ and } X_{1,t} \text{ is } F_{m,2,t} \text{ then } z_t \text{ is } B_m$$

where, $F_{m,1,t}$, $F_{m,2,t}$ and B_m (m=6, 7, . . ., 15) denote fuzzy sets, respectively. When observed values, $X_{1,t}=X^0_{1,t}$ and $X_{2,t}=X^0_{2,t}$ are obtained, the fitness ω_m for fuzzy rule m is defined as follows:

$$\omega_m = \min\ [\mu_{F_{m,1,t}}\ (X^0{}_{1,t}),\ \mu_{F_{m,2,t}}\ (X^0{}_{2,t})] \qquad \text{(A1)}$$

where $\mu_{F_{m,1,t}}\ (X^0{}_{1,t})$ and $\mu_{Fm,2,t}\ (X^0{}_{2,t})$ denote the grade of each variable $X^0{}_{1,t}$ and $X^0{}_{2,t}$ to each corresponding fuzzy set $F_{m,1,t}$ and $F_{m,2,t}$, respectively. Now, define the fuzzy sets $B^*{}_m$ and B^0 as shown below:

$$B^*{}_m(z_t) = \min\ [\omega_m,\ \mu_{B_m}(z_t)] \qquad \text{(A2)}$$

$$B^0 = B^*{}_6 \cup B^*{}_7 \cup \ldots \cup B^*{}_{15} \qquad \text{(A3)}$$

where $\mu_{B_m}(z_t)$ denotes the grade for output variable z_t to the fuzzy set B_m. Equation (A3) shows that the fuzzy set B^0 is defined by the union of fuzzy set $B^*{}_m$. Then, the fuzzy set for the output variable z_t is expressed as below:

$$\mu_{B^0}(z_t) = \max_m\ [\min[\omega_m,\ \mu_{B_m}(z_t)]\ ] \qquad \text{(A4)}$$

In the case when inference units defined as in this paper are more than two, fuzzy set B^0 is defined by the union of each fuzzy set B^0 derived from each inference unit. Therefore the results of fuzzy inference are given by fuzzy set B^0. It is, however, useful to obtain a non-fuzzy variable as a result of fuzzy inference for the purpose of real control. The process of exchanging the result given by fuzzy set B^0 to non-fuzzy variable Z_t^0 is called a defuzzification. One popular way of defuzzification is to calculate the gravity of fuzzy set B^0. That is,

$$z_t^0 = \frac{\int z_t \cdot \mu_{B^0}(z_t)dz}{\int \mu_{B^0}(z_t)dz} \qquad \text{(A5)}$$

Illustration of fuzzy inference

Fuzzy inference through 10 fuzzy rules out of 25 listed in Table 1 is illustrated in Figure A1. Let us consider the case when the mean water temperatures $X^0{}_{1,t}$ and $X^0{}_{2,t}$ are obtained. According to rule 8, for instance, the grades of $X^0{}_{1,t}$ for the fuzzy set ''Low'' is 0.9 and that of $X^0{}_{2,t}$ for the fuzzy set ''Medium'' is 0.3 as shown in Figure A1. Then the value of ω_8 which indicates the fitness of two input variables by fuzzy rule 8 is 0.3. The fuzzy set $B^*{}_8$ which is defined by Equation A2 is the set for which the grade of membership function is $0 \le \mu_{B^*_8}(z_t) \le \omega_8$. This is called ω_8-cut of fuzzy set. In rule 9, the grades for the input variables $X^0{}_{1,t}$ and $X^0{}_{2,t}$ to the fuzzy sets ''Low'' and ''High'' are 0.6 and 0.9, respectively. Then the ω_9-cut of fuzzy set for output variable, that is $B^*{}_9$, is inferred as shown in Figure A1. Fuzzy set B^0 is the union of fuzzy sets $B^*{}_m$ (m=6, 7, . . ., 15) defined by Equation (A3). The value of $z^0{}_t$ is the gravity of fuzzy set B^0 calculated by Equation (A5). That is, $z^0{}_t$ is the index of mean water temperature from July to September inferred by 10 fuzzy rules according to the Mamdani inference method.

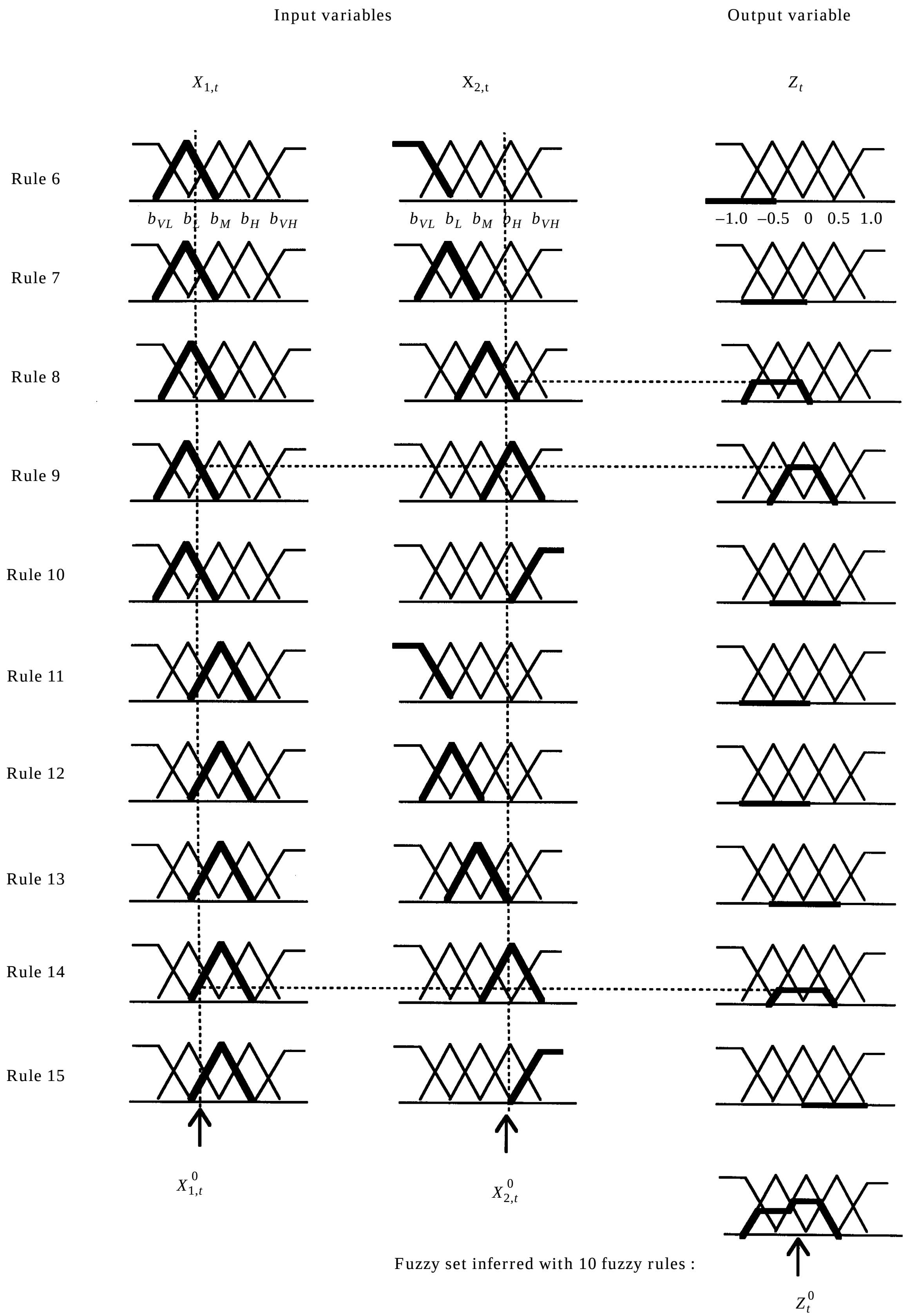

Figure A1. Illustration of fuzzy inference.