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Relationship between sea-surface temperature and catch fluctuations in the Pacific stock of walleye pollock in Japan

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ABSTRACT: This paper investigates the relationship between sea-surface temperature (SST) and catch fluctuations in the Pacific stock of walleye pollock *Theragra chalcogramma* in Japan. Incorporating time lags between years of birth and harvest, the correlation coefficients between the catch and SST in two regions off the east coast of Hokkaido were calculated. The catch in year *t* had a high negative correlation with the SST during January–April and November–December of the years *t*-2 and *t*-3 in the spawning area. These results coincided well with the correlation observed in the northern 'Sea of Japan' stock. Both analyses suggested that the long-term catch fluctuations of the two stocks could be explained by the same mechanism, that is, the fluctuations would be explained by the SST in their spawning area during the spawning season using 2–3 or 3–5 years time lags, which corresponded to the dominant age of the catch within these two stocks.

KEY WORDS: **catch fluctuation, correlation coefficient, Pacific stock, sea-surface temperature, Walleye pollock.**

INTRODUCTION

Walleye pollock *Theragra chalcogramma*, which is an important fisheries resource in Japan, is widely distributed around Japan, Korea and Russia.[1–3] Since 1997, Japan has introduced a total allowable catch (TAC) system and applied it to seven species, including walleye pollock. The total walleye pollock catches in Japan reached 3 000 000 tons in the early 1970s. However, these decreased by 300 000 tons in the late 1990s (Fig. 1); that is, the recent catches are only one-tenth of those in the early 1970s. In order to rehabilitate the population and manage it at a suitable level, the mechanisms behind the population fluctuations must be elucidated. The walleye pollock in Japan consists of four stocks:[4–6] (i) the northern Sea of Japan; (ii) Pacific; (iii) Nemuro Strait; and (iv) off-Kitami. The Pacific stock is distributed from the area off-Chiba Prefecture to Etoroff Island. Its main spawning grounds include the areas off-Kinka Mountain, Funka Bay, Erimo Cape, off-Akkeshi, and Etorofu. Along the coast of north-eastern Honsyu, and south-eastern and eastern Hokkaido, walleye pollock is harvested by gill net, long line, and set net fisheries. Walleye pollock is also harvested with the trawl and Danish seine fisheries in the offshore waters.[6]

Few studies have treated the relationship between fluctuations of catch (as an index of stock abundance) and water temperatures. Inada and Murakami[7] investigated the relationship between the bottom water temperature and stock abundance of walleye pollock in the Tohoku region. They clarified that the abundance of this stock was greatly influenced by the southern position of the first branch of the Oyashio current in this area. Matsuishi *et al.*[8] investigated the relationship between the strength of the cohort of walleye pollock around Funka Bay and the water temperature in winter. They concluded that there was a tendency that the lower the water temperature in January, the higher the strength of the cohort. Furthermore, they indicated that the water temperature in the year when the fish was hatched could explain much of the variance in the cohort

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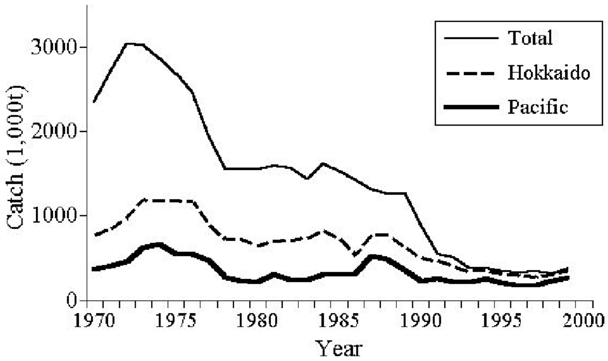

Fig. 1 Catch trajectories of walleye pollock. Thin line, total catch in Japan; broken line, total catch in Hokkaido; thick line, coastal catch from Pacific stock defined in this study.

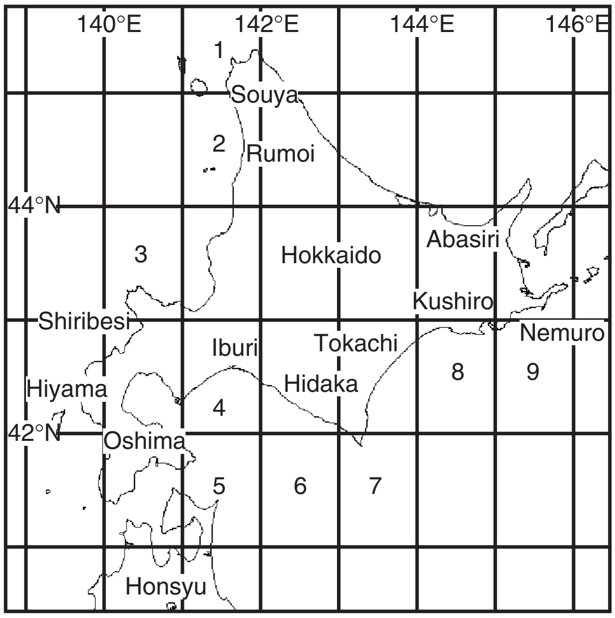

Fig. 2 Map of the area around Hokkaido, Japan.

strength. Oh *et al.*[9] examined the relationship between sea surface temperature (SST) and the coastal and offshore catches for the northern 'Sea of Japan' walleye pollock stock. The results clearly indicated that the catches in the spawning and operating areas in year t had a high negative correlation with the SST in the spawning area in January, February and September of the years t-3, t-4, and t-5, whose time lags corresponded to the dominant age of the catch.

The purpose of this study was to investigate the relationship between SST and fluctuations in this stock's catch, which construct the largest proportions of walleye pollock catches in Japan. The authors also investigated the mechanism of the long-term catch fluctuations through comparing the relationship for this stock with that for the northern 'Sea of Japan' stock.

MATERIALS AND METHODS

Catch and effort data and sea-surface temperature

In this study, the authors defined 'coastal catch' from the Pacific stock as the total catch by gill net, long line, and set net fisheries along the coast of north-eastern Honsyu, south-eastern Hokkaido (Oshima, Iburi, Hidaka) and eastern Hokkaido (Tokachi, Kushiro). The authors also defined the 'offshore catch' from this stock as the total catches by the trawl and Danish seine fisheries in the offshore waters. The catches by pelagic trawl fisheries were excluded from this analysis because these fisheries operating in the waters at a great distance from Hokkaido are likely to exploit different stocks. The catch and effort data used in this analysis were obtained from the fisheries statistics in Hokkaido.[10] The statistics have recorded the catches by district (e.g. Oshima, see Fig. 2), month and fishery type from 1970 to 1999 as well as effort (number of hauls) of offshore catches in south-east off-Hokkaido and east off-Hokkaido (Fig. 2) from 1987 to 2000. To exclude the social effect of implementation of the 200-mile exclusive zone in 1977 on the catch, the catch data after the year was used for latter analysis. The catch data was sorted based on the place where the catch was landed.

The SST data are available from the Meteorological Agency from January 1970 to December 1999.[11,12] These cover the north-west Pacific Ocean (the regions from 100° E to 180° and from the equatorial line to 60° N) by one degree square (Fig. 2). In this study, the correlation coefficient between the mean SST in month m of year t-τ in each one-degree square area and catches in year t in each district were calculated. Here, τ denotes a time lag ($\tau = 1, 2, \ldots, 6$ years), of which range is determined from the observed age-composition in catches.

RESULTS

Figure 3 shows the yearly trajectories of offshore catch and the corresponding catch per unit of effort (CPUE) in the two waters of south-east off-Hokkaido and east off-Hokkaido. The trends of the catch coincided well with that of CPUE in each of the two waters. Furthermore, the trend of the catch

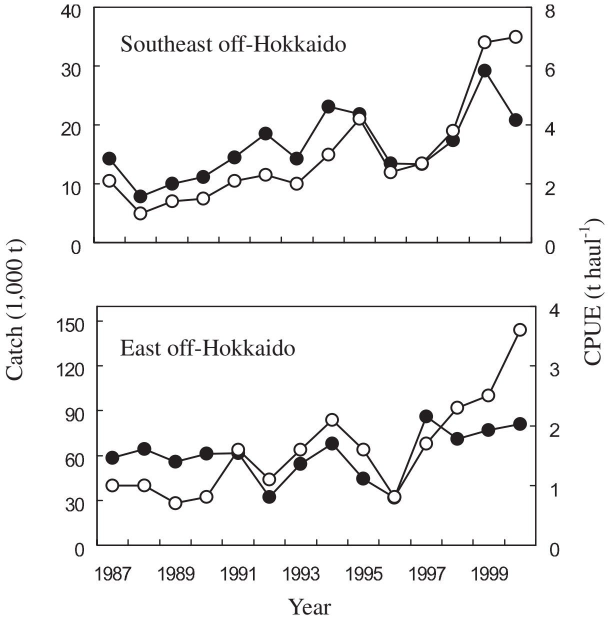

Fig. 3 Yearly changes in catch and catch per unit effort of walleye pollock in two areas of Hokkaido, Japan.

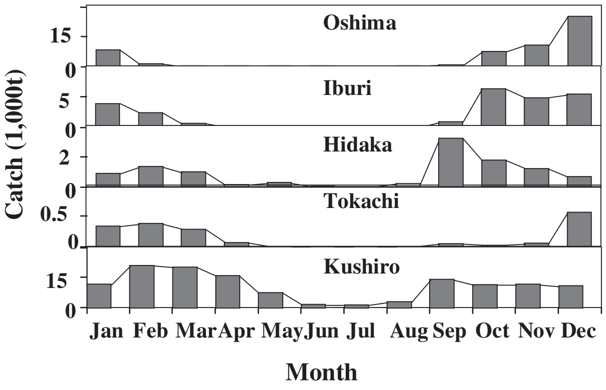

Fig. 4 Monthly changes in the average catch of walleye pollock for the period of 1990–1999 in each district of Hokkaido, Japan.

was quite similar between the two waters. These trends suggest that catch can be safely used as an index of stock abundance or stock density. Hereafter, the authors examine the relationship between SST and the catch fluctuations to investigate the relationship between SST and stock fluctuations.

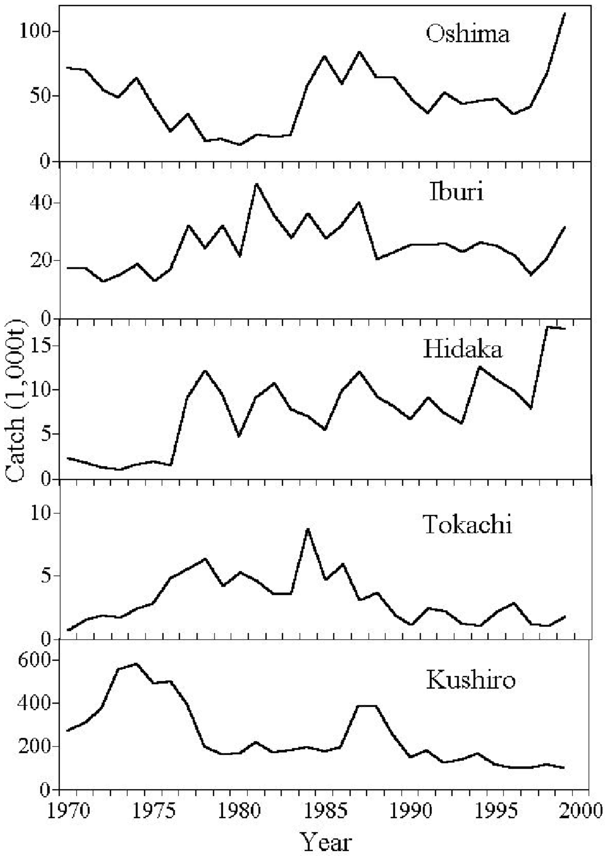

Fig. 5 Yearly changes in catch of walleye pollock in each district of Hokkaido, Japan.

Figure 4 shows the monthly changes in the mean catch for the period of 1990–1999 in each district. Geographical differences were observed in the peak month with the highest catch: September in Hidaka, October in Iburi, and December in Oshima, which is spawning ground. As a whole, geographic shifts of months with increases or decreases in the catch were considered to reflect migration of adult individuals that came back to Oshima via Hidaka and Iburi.[13–17]

Figure 5 shows the catch trajectories in five districts from 1970 to 1999. The catch in Kushiro before 1977 was very high but after 1977 it decreased to almost half of the previous level. This means that some parts of the catch that landed in Kushiro contained the catch harvested in the area of the Russian 200-mile exclusive fishing zone. The catch in Kushiro has still been the highest in the other five districts, and that was about 10-fold larger than that of Iburi, Tokachi and Hidaka.

Table 1 shows the matrix of the correlation coefficients between the catches in five districts. The correlation between Iburi and Tokachi, and between Tokachi and Kushiro was significant with a 5% significance level.

Taking into account that of Table 1, Fig. 5 and the level of catches, these five catches were grouped into two groups. One is the total catch in Oshima, Iburi and Hidaka (catch in area F) and the other is the total of Tokachi and Kushiro (catch in area K). Furthermore, the areas for calculating the mean SST for these two areas were defined. That is, the

Table 1 Correlation coefficients between the catch in a district and that in a different district in Hokkaido from 1977 to 1999

	B	C	D	E
A: Oshima	0.03	0.38	–0.25	0.08
B: Iburi		0.11	0.44†	0.33
C: Hidaka			–0.28	–0.07
D: Tokachi				0.35†
E: Kushiro				

†5% significance level.

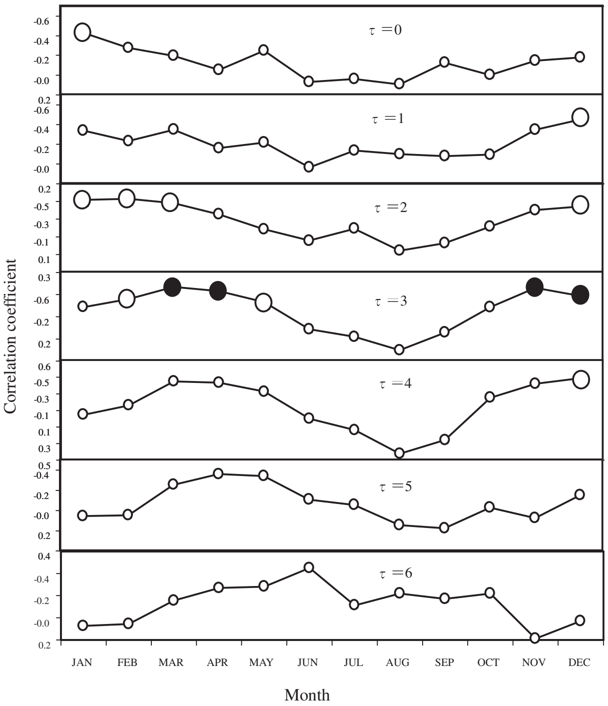

Fig. 6 Monthly correlation coefficients between sea-surface temperature in area F in year *t* and catch in F and K in year *t*-τ. Closed and large open circles indicate that the correlation is significant at the 1% and 5% levels, respectively.

mean SST of one-degree squares of 4, 5, 6 and 7 shown in Fig. 2 were used as the SST in area F, and the mean SST of 8 and 9 is used for area K. Area F is a spawning and nursery ground of this stock. In Fig. 2, area A is also shown, which is constructed with one-degree squares of 1, 2 and 3. Oh *et al.*[9] used this as one of the three areas and regarded it as a spawning ground for the northern 'Sea of Japan' stock. The authors refer to area A later when comparing the results of this analysis with that of Oh *et al.*[9]

Figure 6 shows the correlation coefficient between SST_{jt} and $C_{j,t-\tau}$, where SST_{jt} is SST in month *j*, year *t* and area F. Another symbol $C_{j,t-\tau}$ is catch in month *j*, year *t*-τ, area F and K. The lag τ was introduced, taking into account the ages of captured fish. Negative correlations were observed in December–March in the case of $\tau = 2$ (5% significant level) and November–May except January in $\tau = 3$ (1% or 5% level). Table 2 summarizes the months with negative correlations under combinations of area concerning SST and concerning catch. Many months had negative correlations when τ was 2 or 3 years. Table 2 summarizes the months that showed the significant correlations using the different area combinations for the SST and catches. Many months with significant correlation appeared when the time lags of 2 and 3 were taken. Especially when the time lag was 3 years; March, April, November, and December showed very high negative significant correlations. In the case of the SST in F (spawning area) and catch in area F, the time lags that showed the significant correlation had two patterns. One appeared with time lags of 0 and 1, and another appeared with a time lag of 6. This result is similar to those obtained by Oh *et al.*[9]

DISCUSSION

Table 3 summarizes the correlation analyses for the northern 'Sea of Japan' walleye pollock stock.[9] In the case of the northern 'Sea of Japan' stock, the SST in area A had a significantly higher negative correlation with the catches in areas A, A + C, and A + B + C in January, February and September with time lags of 3, 4 and 5 years, respectively. Area A is the spawning area off north-west Hokkaido, and areas B and C are located in the south-west off-Hokkaido and in the Sea of Japan off northern Honsyu, respectively.[9] Tables 2 and 3 indicated that the months and the time lags showing a high correlation were slightly different between these stocks, however, the essential patterns were very similar to one another. The northern 'Sea of Japan' stock is distributed in the waters, which are strongly affected by the Tsushima warm current, whereas the pacific stock is distributed in the waters, which are strongly influenced by the Oyashio current. It is guessed that the catch fluctuations in these stocks could be explained by the same mechanism caused by the SST in the spawning area during the months of the spawning season with time lags 2–3 or 3–5 years.

Why does the water temperature influence the fluctuation of catches and perhaps also the fluctuation of population abundance so greatly? The details of the mechanism have not yet been elucidated at this stage, however, the same phenomena

Table 2 Months with significant negative correlations between sea-surface temperature in year t and catch in t-τ

Area		Time lag τ (years)							
SST	Catch	$\tau = 0$	$\tau = 1$	$\tau = 2$	$\tau = 3$	$\tau = 4$	$\tau = 5$	$\tau = 6$	$\tau = 7$
F	F	**1**, **2**, 3	**3**, **12**	–	4	–	–	**6**, **8**, **9**	9, 10
F	K	–	–	1, 2, 3	**3**, 4, **11**, **12**	12	–	–	–
K	K	–	–	–	–	–	–	6	–
F	F +K	1	12	1, 2, 3, 12	2, **3**, **4**, 5, **11**, **12**	12	–	–	9

Bold numbers are the months that showed the significant correlation coefficient with 1% significance levels; regular numbers are the months that showed the significant correlation coefficient with 5% significance levels.

–, the correlation is not significant at the 5% level; SST, sea-surface temperature.

Table 3 Months with significant negative correlations between sea-surface temperature in year t and catch in t-τ

		Time lag τ (year)							
Temperature	Catch	$\tau = 0$	$\tau = 1$	$\tau = 2$	$\tau = 3$	$\tau = 4$	$\tau = 5$	$\tau = 6$	$\tau = 7$
A	A	1, **9**, **11**	1, 9, 11	–	1, **2**, 6, 9	**1**, **2**, 3, 6, **9**	**1**, **2**, 9	1, 2	2, 6
A	A + C	1, **9**, **11**	1, 9, 11	–	1, **2**, 6, 9	**1**, **2**, 3, 6, **9**	**1**, **2**, 9	1, 2	2, 6
A	A + B + C	1, 9, 11	1, 11	–	1, 2, 6, 9	**1**, **2**, 3, 6, **9**	**1**, **2**, 3, 9	**1**, 2	2, 6
A	B	6, 9, **10**, 11	9	–	–	–	11	–	–
A	C	10	–	11	**11**	1, 5, **11**, 12	**1**, 2, **11**,12	**1**, **2**, 3, 11, 12	1, 2, 3
B	B	3	–	–	–	–	–	–	8
C	C	**1**, 3	–	–	7	7	–	–	–

Bold numbers are the months that showed the significant correlation coefficient with 1% significance levels; regular numbers are the months that showed the significant correlation coefficient with 5% significance levels.

–, the correaltion is not significant at the 5% level (modified from Oh *et al.*[9]).

have been detected in several species and stocks of fishes. Sakuramoto *et al.* indicated that the huge fluctuation of sandfish catch in Akita Prefecture could be explained well by the water temperature in September at 200–300 m depths at 5 km off the Oga Peninsula of Akita Prefecture.[18,19] Noto and Yasuda discussed the population decline of the Japanese sardine and indicated that the winter-spring SST in the Kuroshio Extension is a controlling factor that determines the strength of the year-class.[20] They also noted as follows: ‘From egg to early larva, positive correlation, implying that high SST leads to high mortality, were observed in the spawning grounds around the Kuroshio Extension from January to March when sardines spawn and hatch, but the correlations were not significant’. Watanabe developed a model that could forecast the recruitment in sandfish of the northern ‘Sea of Japan’ stock using the water temperature in spring and winter, and their spawning stock biomass.[21] He also analyzed the relationship between water temperature, which showed significant correlation with catch fluctuations in Akita and Korea, and the depth of the mixed layer off-Akita Prefecture and the east coast of the Korean Peninsula. He showed that the water temperature at 75–150 and 200–300 m depths in winter and spring had a high positive correlation with the depth of the mixed layer. The relationship between catch and SST obtained and the methodology used here are very similar to those obtained by Sakuramoto *et al.*,[18,19] Oh *et al.*,[9] and Watanabe.[21] These studies may indicate the existence of a general mechanism that can explain the fluctuation of the marine fish population abundance.

The data of age-composition the authors used were limited in the period and area. That is, the data collected over long periods of time and wide areas are not available. In the northern waters of Shakotan Peninsula (west coast of Hokkaido), walleye pollock migrating for spawning is from November to February in the following year. The fish sampled from this area in October were almost mature, and the range of ages was from 4 to 6 years.[22–26] In this area, larvae and juveniles were collected from February to May, and it was estimated that the hatching time of the larvae and juveniles in this area was during late February to early March.[25,26]

In contrast, the spawning season in Funka Bay is November or December to the following March.[27,28] In Funka Bay and Iburi, the adult fish are harvested, however, in Tokachi and Kushiro, immature fish of 1–3 years old are mainly harvested. Hamatsu and Yabuki investigated the spawning migration and spawning ground along the Pacific coast of eastern Hokkaido, concluding that the peak of the spawning season was March.[15] The spawning season in the west coast of Hokkaido is slightly earlier than that in Funka Bay, and this may influence the differences in months obtained in this study and those in the Oh *et al*. study.[9]

Matsuishi and Isoda investigated the relationship between the strength of the cohort of walleye pollock around Funka Bay and the water temperature in winter.[8] They concluded that there was a tendency that the lower the water temperature in January, the higher the strength of the cohort. Furthermore, they indicated that the water temperature in the year when the fish were hatched could explain much of the variance in the cohort strength. This result supports the argument that a time lag introduced in this study is meaningful for calculating the correlation coefficient between the catch and water temperature. As mentioned before, the reason why the SST affects the variation of the catch has not yet been clarified. One possibility is that the SST would influence the survival rate during the initial stage of larvae.[20] However, even though it is true, the details of the mechanism as to how the water temperature influences the survival rate during the initial stage remains unknown.

Recently, a large amount of research has been conducted on the relationship between catch fluctuations and regime shifts. For instance, the catch fluctuations of sardine not only in the Pacific Ocean but also in the Atlantic Ocean coincided with one another.[29] This is one piece of strong evidence that global-scale changes such as regime shifts really exist. From the viewpoint of long-term fluctuations, the walleye pollock catch in Hokkaido from the end of the 1960s to the middle of the 1970s was very high ('the first period'). From the middle of the 1970s to the 1980s it had been stable at around 700 000 tons ('the second period'). However, it decreased again at the beginning of the 1990s and now it has been fluctuating around 300 000 tons ('the third period'). Yasunaka and Hanawa reported that the regime shift has occurred at least six times within the past 100 years in the north Pacific Region;[30] that is, in 1925/26, 1945/46, 1957/58, 1970/71, 1976/77 and 1988/89. These regime shifts may explain the fluctuation in the catch of this stock. That is, the periods from 1970–1976, 1977–1988 and 1989–1999 roughly coincide well with the latest three periods mentioned above. However, the difference in the catch before and after 1977 would also be influenced by the implementation of the 200-mile exclusive fishing zone. In order to clarify the relationship between the fluctuation of the walleye pollock catch in Hokkaido and the regime shift, a much more detailed and larger-scale analysis should be conducted, however, the relationship between catch and SST shown here would not conflict with the existence of a regime shift, which may really control the catch fluctuation.

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