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Influences of Climate Factors and Water Temperature in Squid Spawning Grounds on Japanese Common Squid (*Todarodes pacificus*) Catches in the East (Japan) Sea

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Data on squid catches, water temperature, and climatic factors collected for the Northwest and subtropical North Pacific were analyzed to examine the influence of oceanic and climatic conditions in spawning grounds on catches of Japanese common squid, *Todarodes pacificus*, in the East (Japan) Sea. The main spawning ground was divided into four sub-areas: the South Sea of Korea (R1), the southern waters off Jeju, Korea (R2), the southwestern part of Kyushu, Japan (R3), and the northern part of Okinawa, Japan (R4). Interannual and decadal fluctuations in water temperatures correlated well with squid catches in the East/Japan Sea. In particular, water temperatures at a depth of 50 to 100 m in sub-areas R3 and R4 showed higher correlation coefficients (0.54 to 0.59, $p<0.01$) in relation to squid catches in the East/Japan Sea than for R1 and R2, which had correlation coefficients of 0.40 or less ($p>0.05$). Air temperature and wind velocity fluctuations in each sub-area are correlated with water temperature fluctuations and were closely connected with variations in the surface mixed layers. Water, air temperatures and wind velocities at the main spawning grounds are linked to the Southern Oscillation Index (SOI) with higher signals in the ca. 2-4-year band. Strong changes in a specific band and phase occurred around 1976/77 and 1986/87, coincident with changes in squid catches.

Key words: East/Japan Sea, *Todarodes pacificus*, Spawning grounds, Water temperatures, Climate conditions

Introduction

The East/Japan Sea (EJS) is located in the Northwest Pacific (NWP) and is well-known for its fishing grounds, especially for the Japanese common squid, *Todarodes pacificus* (hereafter 'squid'). This is due to particular environmental characteristics of the EJS, such as the presence of a subpolar front. Squid are commercially very important in Korea and Japan (Sakurai et al., 2000; Kiyofuji and Saitoh, 2004) and make up approximately 56% of the total cephalopod catch in Japan (Kiyofuji and Saitoh, 2004). The life span of a squid is less than 2 years (Boyle, 1987), and a significant number of squid from the EJS are spawned in the East China Sea (ECS) and the Korea/Tsushima Strait from the EJS (Okutani, 1983; Nasu et al., 1991; Sakurai, 2000). Therefore, fishing success in the EJS may be closely connected with oceanic conditions within the spawning grounds.

Squid have three different migration and spawning seasons in the NWP, especially between the EJS and the ECS (Okutani, 1983; Nasu et al., 1991): summer, autumn, and winter (Okutani, 1983; Nasu et al., 1991; Kim and Kang, 1995); spawning is mainly concentrated during autumn and winter (Araya, 1976; Okutani, 1983). Sakurai et al. (1996) demonstrated through laboratory experiments that temperatures between 14.7°C and 22.2°C provide the highest embryonic survival rate for squid. Based on this result, the waters between the ECS and the Korea/Tsushima Strait are inferred to be the main spawning grounds (Murata, 1989; 1990; Nasu et al., 1991). In particular, there is evidence for a relationship between variations in squid stocks and regime shifts. Paralarval abundance and catch increase during warm regimes but decrease during cold regimes (Sakurai, 2000). Water temperature exerts a strong influence on recruitment and migration of *Loligo gahi* on the Falkland shelf (Agnew et al.,

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2000; Arkhipkin et al., 2004). These reports seem to indicate that spawning and recruitment are highly dependent on water temperature. In relation to variations in water temperature in the NWP, a most intriguing result is that variations in water temperature in the South Sea of Korea and the EJS appear to coincide with El Niño events in 3-5 year bands (Lee, 2003); this means that the NWP is affected by climatic changes through both the atomsphere and the ocean. Therefore, environmental conditions in the main squid spawning grounds within the influence of the Kuroshio Current, which originates from the equatorial current system and is an important factor in variations of oceanic conditions in the NWP, seem to have a close relationship with climate variability.

The main purpose of this work was to describe the relationships between climate factors and water temperature in the main spawning grounds of *Todarodes pacificus* during winter and their effects on catches in the EJS.

Materials and Methods

To analyze annual variations in squid catches in the EJS and the NWP and to estimate the proportion of the total Northwest Pacific catch that is collected in the EJS, data on squid catches by Korea and Japan in the EJS from 1970 to 2000 were obtained from the National Fisheries Research and Development Institute (NFRDI, Republic of Korea, http://www.nfrdi.re.kr/) and from the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFFJ, 1971-2000). Data detailing NWP catches (statistical area no. 61 of the Food and Agriculture Ogranization [FAO]) for the same period was released by the FAO in 2005 (http://www.fao.org/fi/statist/statist.asp).

In this work, the main squid spawning areas, identified on the basis of previous reports (Murata, 1989; 1990; Nasu et al., 1991; Sakurai et al., 2000), were divided into four sub-areas, R1, R2, R3, and R4 (Fig. 1), auording to water temperature, air temperature and wind data for each potential sub-area. In the case of R5, part of the main winter spawning grounds suggested by Nasu et al. (1991) and Sakurai et al. (2000) seems to be located in the farthest northern extremity compared to R4 which includes the spawning grounds around Okinawa (Japan). With regard to the central part of the ECS (R5) adjacent to R4, the relevant data to this study were few and therefore was excluded from our analyses.

Water temperature data for the winter (January-March) season are derived from two different sources (see also Fig. 1):

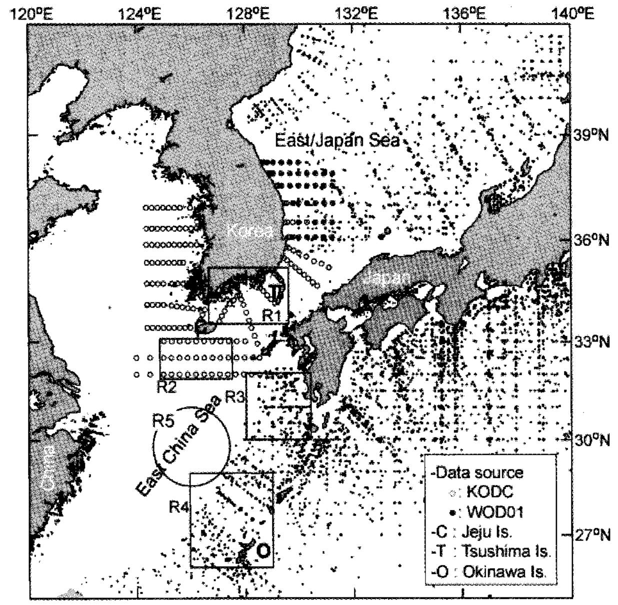


Fig. 1. Study areas from R1 to R4 based on main spawning grounds of Japanese common squid, *Todarodes pacificus* in winter inferred by Nasu et al. (1991) and Sakurai et al. (2000). The open circles and dots represent oceanographic locations. In each of the R1 to R4 regions, regular field observations have been carried out by the NFRDI and by the JMA (Japan Meteorological Agency). The East/Japan Sea is the main fishing ground of the Japanese common squid, *Todarodes pacificus*.

1. Data released by the Korea Oceanographic Data Center (KODC, http://kodc2.nfrdi.re.kr:8001/home/kor/near-goos/step1.php) for the period 1970-2000, and water temperatures measurements at standard depths by NFRDI once in two month (i.e., February, April, June, August, October and December).
2. Data released by the World Ocean Database 2001 (WOD01 http://www.nodc.noaa.gov/OC5/WOD01/pr_wod01.html) for the period from 1971 to 2000. WOD01 is an update of the World Ocean Database 1998 (WOD98) and contains climatological data at standard depths within World Meteorological Organization (WMO) squares. Average conditions at were calculated depth were calculated during the winter seasons from 1970 to 2000 in each sub-area.

Air temperature and wind data for each sub-area for the period of 1970-2000 were taken from Mitchell and Jones (2005) and from the NOAACIRES Climate

Diagnostics Center (CDC, 2005, available at 'http://www.cdc.noaa.gov/index.html') respectively, for comparison to water temperature variation. The surface mixed layer was calculated using water temperature, and the maximum depth of the surface mixed layer was defined as the depth at which the temperature reached to 0.5 degrees C below the surface temperature (Monterey and Levitus, 1997). The SOI (Southern Oscillation Index) is an index of El Niño events that is published by the Climate Research Unit (http://www.cru.uea.ac.uk). The SOI was used to examine the influence of climate variability on the atmospheric conditions and water temperature in the study areas. The relationships between environmental factors in each sub-area and the SOI were calculated using wavelet spectrum analysis (Torrence and Webster, 1999; Grinsted et al., 2004)

Results and Discussion

Fluctuations in squid catch

The total squid catch fluctuated greatly between 1970 and 2000 (Fig. 2). Squid catches in the EJS and the NWP decreased gradually from the early 1970s to the mid-1980s, then increased until the mid-1990s; however, after 1996, the catch again began to decrease. Fluctuations in catch per unit effort (CPUE, calculated as weight-per-fishing boat-per year) in the EJS by Korean and Japanese fishing boats showed almost a perfect match with fluctuations in total catch (Kang et al., 2002). That is, squid resource conditions are equally represented by both the total catch and the CPUE data. Thus, squid resource data in the EJS and in the NWP may be substituted for squid catch data as shown in Fig. 2, and *vice versa*. Furthermore, since the EJS squid catch constitutes a large proportion of the total NWP squid catch, squid fishing by Korea and Japan is concentrated in the EJS.

In the NWP, sudden climate changes occurred after the 1970s, and, as a result of these changes, marine ecosystems were shocked (Brodeur and Ware, 1992; Minobe, 1997; Sugimoto and Tadokoro, 1997; Kim and Kang, 2000) and experienced changes. In particular, the paralarval abundance of squid changed with decadal climate variability (Sakurai et al., 2000). The changes in squid catches shown in Fig. 2 correlate well with the occurrence of warm and cool regimes in the North Pacific described by Minobe (1997). This indicate that the changes in the climatic and marine environment influenced marine organisms significanthy and especially the spawning and survival of paralarvae in early stages of the life cycle.

Water temperature

The study areas, all of which were component of the main spawning ground, showed common variations in water temperature (Fig. 3). Focused around the middle of the 1980s, there were decadal periods of warmer and cooler water temperatures as well as *ca.* 2-4years periodical fluctuations. In particular, waters in the southern part of Korea, regions R1 and R2, which were shallower than 100m, showed narrow temperature ranges compared to those in regions R3 and R4.

Laboratory experiment have shown that temperatures between 14°C and 22°C are optimal for

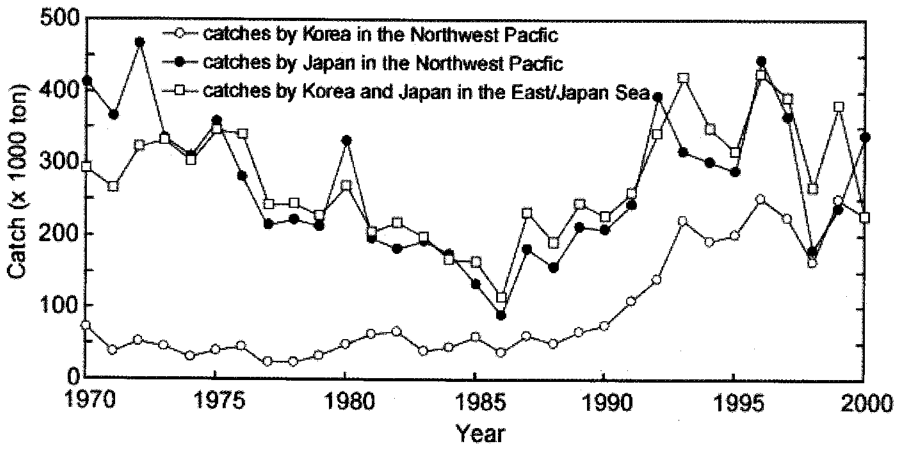


Fig. 2. Annual fluctuations of Japanese common squid, *Todarodes pacificus*, in the East/Japan Sea and the Northwest Pacific from 1970 to 2000. Squid catch data for the North West Pacific are from FAO, and for the East/Japan Sea from NFRDI and MAFFJ.

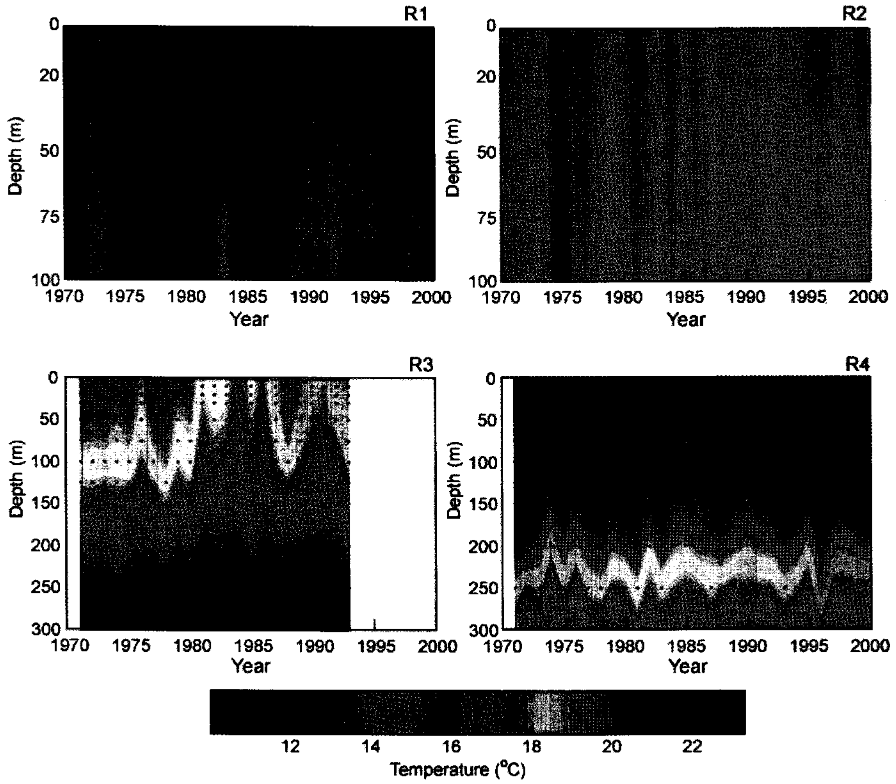


Fig. 3. Fluctuation of mean temperature with depth in winter seasons from 1970 to 2000. The dots in each figure represent the standard depths, i.e., 0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250 and 300 m.

survival of embryonic squid (Sakurai et al., 1996). In regions R1 and R2, these ideal conditions for spawning and paralarval survival seem to be limited to a shallower layer with a narrower temperature range compared to regions R3 and R4. In addition, temperatures lower than 14°C in regions R1 and R2 often occurred within the surface to 100m depth range. However, in regions R3 and R4, temperatures greater than 14°C existed from the surface to 200m during this study period. In particular, lower temperatures often occur in R1 because of its close connection with upwellings and expansions of cold bottom water by northerly winds during the winter season (Na et al., 1990). These between-region environmental differences may produce differences in correlations between water temperature and squid catches. Actually, correlation coefficients differ among various regions (Table 1). Each region was divided into two sub-regions based on the significance level of its correlation. Lower correlations were found in regions R1 and R2. Whereas, R3 and R4 showed relatively higher correlations within the surface to 150 m range. Correlation coefficients for the 50 m and 100 m zones for R3 and R4 were higher than for the other depths.

Table 1. Correlation coefficients between water temperature and squid catches in the East/Japan Sea by Korean and Japan fishing fleets with depths

Depth (m)	Region			
	R1	R2	R3	R4
0	0.29	0.12	0.54*	0.47**
10	0.27	0.04	0.53**	0.51**
20	0.32	0.04	0.52**	0.53**
30	0.38	0.03	0.54*	0.55*
50	0.35	0.16	0.56*	0.57*
75	0.26	0.16	0.56*	0.59*
100	0.16	0.06	0.54*	0.59*
125	-	-	0.54*	0.55*
150	-	-	0.54*	0.41
200	-	-	0.51	0.17
250	-	-	0.32	0.17
300	-	-	0.21	0.06

*p<0.01; **p<0.05.

Air temperature and wind

Air temperature fluctuations over decadal periods seem to be similar to fluctuations in squid catches and water temperatures (Fig. 2 and Fig. 3) and indicate close connections between individual factors in relation to the shifts between warm and cold regimes.

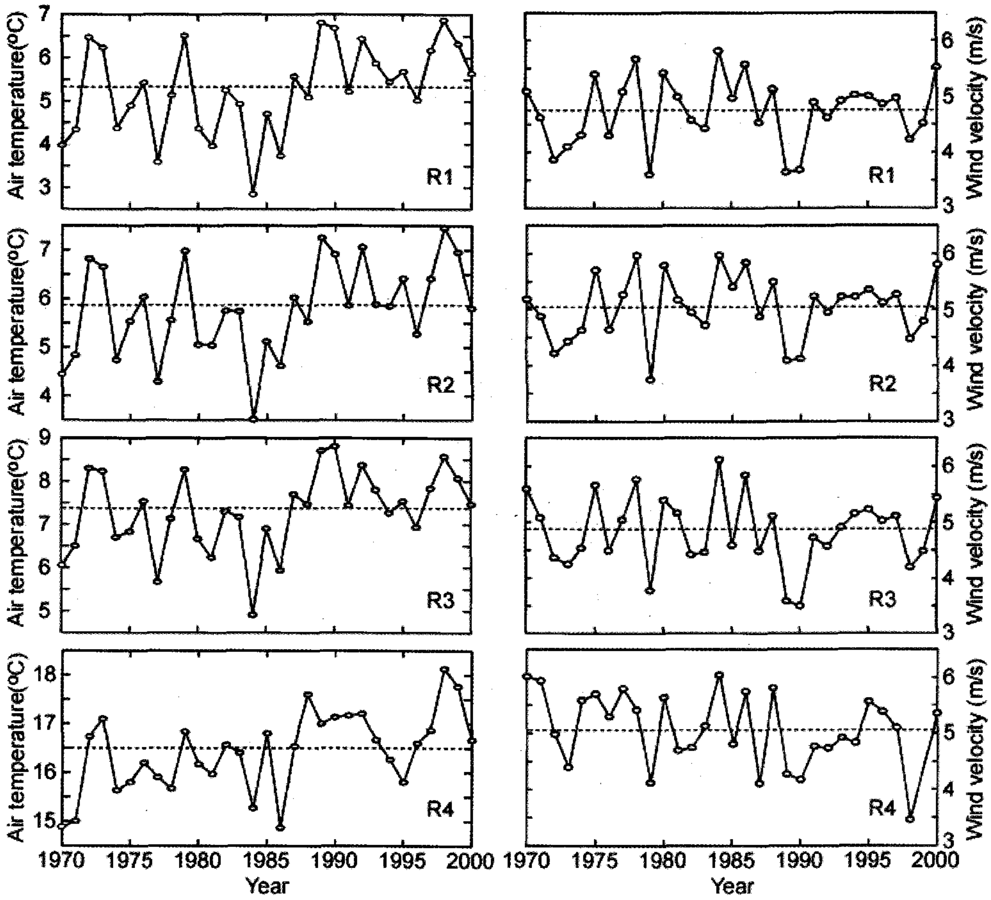


Fig. 4. Fluctuation of air temperature (left panel) and wind velocity (right panel) during winter seasons from 1970 to 2000 at each sub-area. The broken lines indicate the mean value of each factor. In the case of air temperature, data in regions R1 and R2 indicate temperature during winter seasons in Tsushima Island and Jeju Island, and in R3 and R4 in the coastal areas of R3 and Okinawa Islands shown in Fig. 1.

A cold regime began in the middle of the 1970s and continued until the warm regime started in the middle of the 1980s. These changes in environmental conditions within the study areas matches well with changes that occurred throughout the entire Northwest Pacific as shown by Minobe (1997).

These results suggest that changes in environmental conditions at the main spawning grounds exert an influence on spawning and paralarval survival which is directly connected to squid recruitment. In particular, fluctuations in wind speed showed an opposite pattern compared to water and air temperatures. Stronger winds result in a deeper sea surface (Fig. 5), decreasing water temperature and causing instability in the water column. These phenomena may result in poor conditions for spawning and paralarval survival. The combination of stronger cooling effects such as a drop in air temperature and wind-induced surface to bottom mixing in regions R1 and R2, compared to the other regions seems to result in lower water temperatures throughout the entire water column. In particular, higher correlations between squid catches and water temperatures (Table 1) exist at 75 m, a depth that is shallower than the lower limit of the mixed layer (thermocline; Fig. 5). If adult squid spawn eggs below the thermocline, eggs are subjected to higher pressures and insufficient light. Therefore, higher correlations in the 75 m depth zone, above the thermocline are considered the results of a survival strategy.

The study area, which constitutes the main spawning ground for squid, is generally shallower than 200 m. In the case of R1 and R2, the depth is generally shallower than 100m, and cooler waters are found throughout the water column when lower air temperatures and stronger winds predominate, as occurred during 1976/77, 1980/81, 1984, 1986, 1994/95, and 2000.

As stated in previosly, changes in environmental

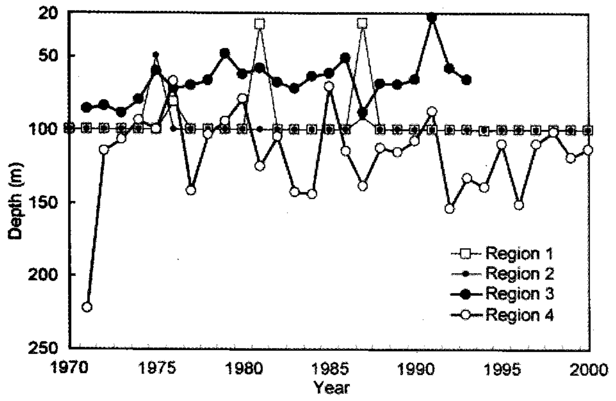


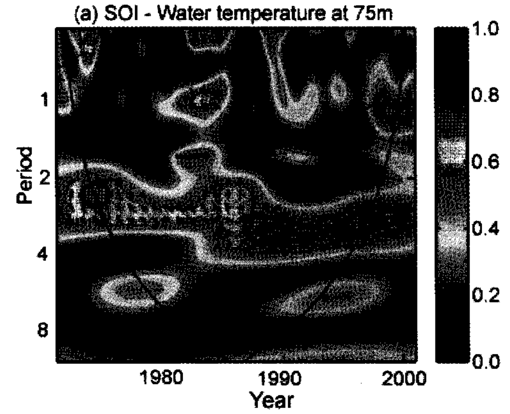
Fig. 5. Fluctuations of the surface mixed layer during winter seasons from 1970 to 2000. The bottom depth of surface mixed layer is defined as the depth at which the temperature falls to 0.5 degrees C below the surface temperature. In the regions R1 and R2, the whole depth in the water column during all of the winter seasons except for 1975 was defined as the surface mixed layer based on this criterion.

conditions in R1 and R2 have more serious consequences than in the other regions. Therefore the spawning ground may be further reduced towards the southwest of Kyushu and the ECS due to the advent of cold regimes and interannual changes in environmental conditions which that negative effects on spawning and paralarval survival.

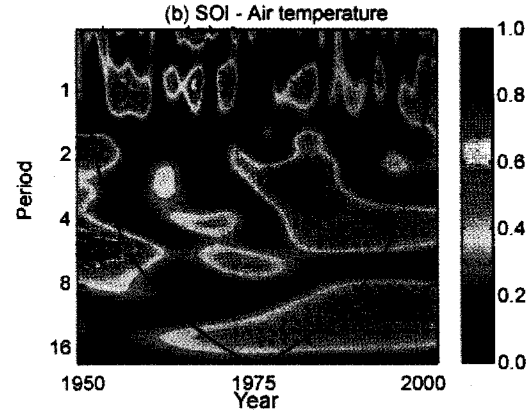
Influence of climate change on water temperatures and climate factors

The inferred main spawning grounds for squid in the NWP are located between the eastern part of the ECS, the southwestern part of the Kyushu Islands, and the South Sea of Korea. Oceanic conditions in these areas are affected by multiple factors such as the Taiwan Warm Current, the Kuroshio, the Tsushima Warm Current and the Changjiang River. In summer, upper layer circulation in these regions changes from year to year due to the interannual variations in Changjiang River discharge. The situation is further complicated in winter by the Tsushima Warm Current which branches off the Kuroshio, and by the Kuroshio itself which originates from the equatorial current system. These are considered as the most important factors in determining circulation patterns (Ichikawa and Beardsley, 2002).

(a) SOI - Water temperature at 75m



(b) SOI - Air temperature



(c) SOI - Wind

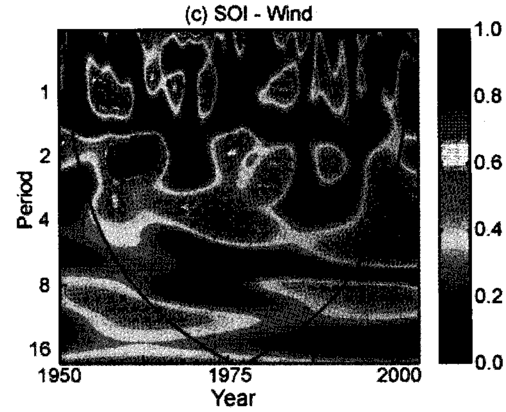
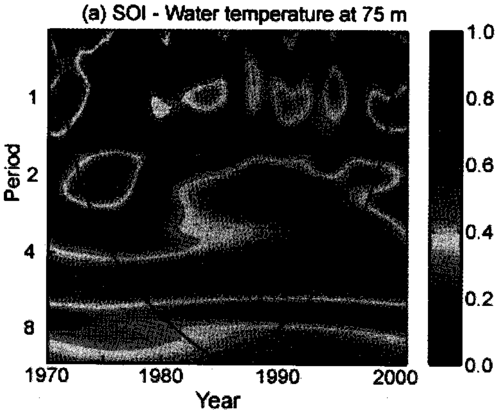
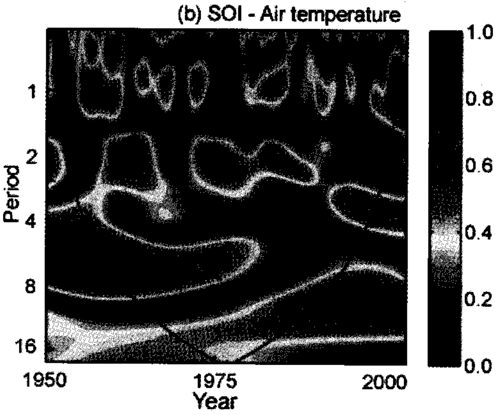


Fig. 6. The wavelet coherency and phase between SOI and water temperature and climate factors in region R4. (a) between SOI and water temperature at 75 m, (b) between SOI and air temperature, (c) between SOI and wind velocity. Colors from dark blue to dark red are wavelet coherencies. The vectors indicate the phase difference between SOI and the other factors with in-phase pointing right, anti-phase pointing left, an arrow pointing vertically means the second time series lags the first by 90° (i.e., the phase angle is 270°). The 5% significance level against red noise is shown as a tick contour, and the thin black line indicates the cone of influence.

Fig. 6 shows wavelet coherence and phase between SOI and water temperature and climate factors in region R4, where the correlation coefficient between squid catch and water temperatures was highest and the Tsushima Warm Current branches off from the Kuroshio. Of note in each figure is that air temperature, wind, and especially water temperature,


(a) SOI - Water temperature at 75 m


(b) SOI - Air temperature

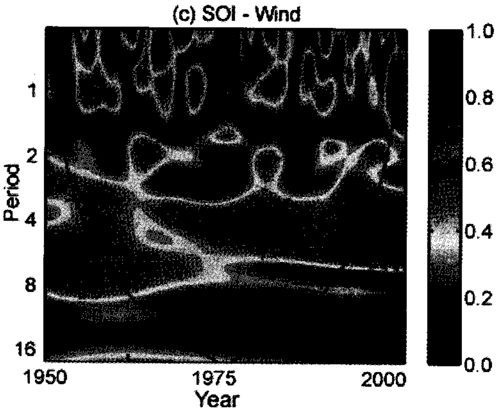
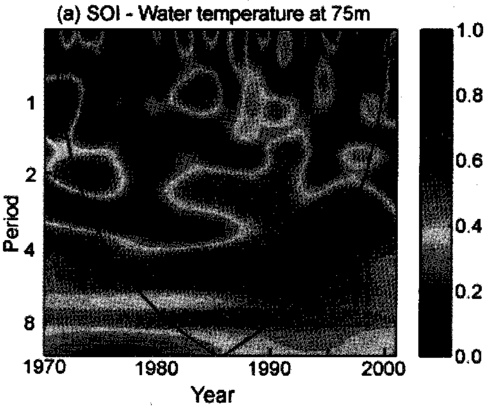
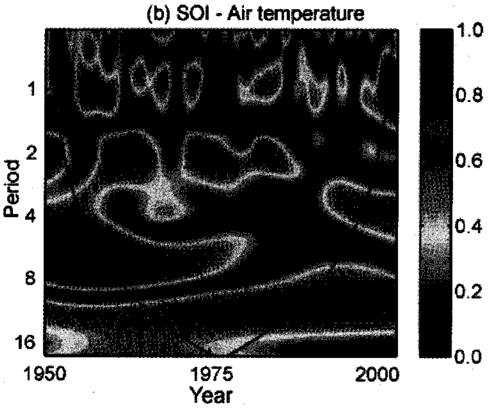

(c) SOI - Wind

Fig. 7. The wavelet coherency and phase between SOI and water temperature and climate factors in region R1. (a) between SOI and water temperature at 75 m, (b) between SOI and air temperature, (c) between SOI and wind velocity. Colors from dark blue to dark red are wavelet coherencies. The vectors indicate the phase difference between SOI and the other factors. The 5% significance level against red noise is shown as a tick contour, and the thin black line indicates the cone of influence.


(a) SOI - Water temperature at 75m


(b) SOI - Air temperature

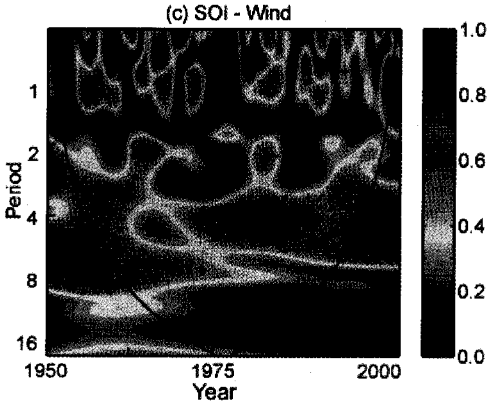
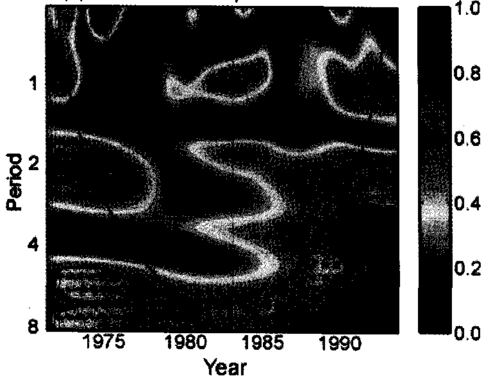

(c) SOI - Wind

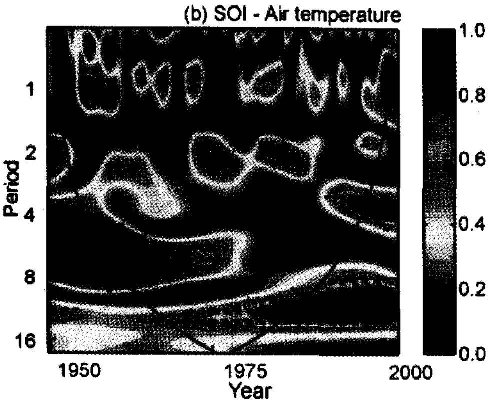
Fig. 8. The wavelet coherency and phase between SOI and water temperature and climate factors in region R2. (a) between SOI and water temperature at 75 m, (b) between SOI and air temperature, (c) between SOI and wind velocity. Colors from dark blue to dark red are wavelet coherencies. The vectors indicate the phase difference between SOI and the other factors. The 5% significance level against red noise is shown as a tick contour, and the thin black line indicates the cone of influence.

which is highly connected with squid catches in the EJS, have higher coherency with SOI in signals over 2-4-year periods. Considering the relation between SOI and water temperature, there is a consistent phase angle for the period 1971-85 associated with signals during the ca. 2-3 year band and, between 1984-98, during the ca. 3-4 year band. Thus, the 2-4 year oscillations seen in SOI are linked to a 2-4 year

(a) SOI - Water temperature at 75m



(b) SOI - Air temperature



(c) SOI - Wind

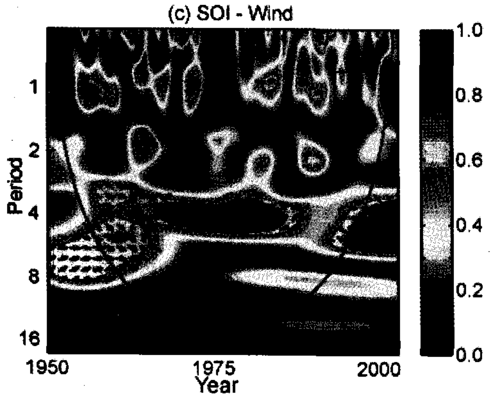


Fig. 9. The wavelet coherency and phase between SOI and water temperature and climate factors in region R3. (a) between SOI and water temperature at 75 m, (b) between SOI and air temperature, (c) between SOI and wind velocity. Colors from dark blue to dark red are wavelet coherencies. The vectors indicate the phase difference between SOI and the other factors. The 5% significance level against red noise is shown as a tick contour, and the thin black line indicates the cone of influence.

amplitude modulation of water temperature in region R4.

Air temperature is linked to 2-4 year oscillations of SOI for the period 1976-86 and about 4 year oscillations for the period 1987-98. Unlike water temperature, the coherency of air temperature and wind linked to SOI oscillations seems to be more random with time. In particular, there was general upheaval in a specific band and phase at about the 1976/77 and 1986/87 periods when squid catches changed suddenly (Fig. 6) and these phenomena seem to be connected to climate regime shifts occurring in the Northern Hemisphere.

Higher coherency between SOI and water temperature within a specific band is shown in Fig. 6, suggesting that climate change in the tropical region transfers to the main squid spawning ground through multiple sources including water currents and the atmosphere. Nakata and Hidaka (2003) demonstrated that a climate regime shift accompanied by a climate change in the tropical region influenced the interannual variation of copepod biomass in the Kuroshio at periods of 2-4 years.

Wavelet coherence and phase between SOI, water temperature and climatic factors in region R4 differ from those in the other regions R1, R2, and R3 (Figs. 7-9), where these relationships are almost identical. In these latter regions, water temperature and climate factors show a higher coherence with SOI in signals over 2-4-year periods, as occurs in region R4, but the coherence of water temperature linked to SOI oscillations seems to be more random over time compared to that for region R4.

In short, this study demonstrates the effects of environmental conditions on Japanese common squid fluctuations in spawning areas in the South Sea of Korea, the southern waters off Jeju, Korea, the southwestern part of Kyushu, Japan, and in the northern part of Okinawa, Japan. These spawning areas show different environmental characteristics and a close correlation with climate variability. Water and air temperature, and wind in these spawning areas are linked to a periodic 2-4 year amplitude modulation of the El Niño Southern Oscillation. Furthermore, water temperature in the northern part of Okinawa is highly connected to squid catches in the EJS. Spawning and recruitment of squid are highly dependent on the marine environment. However, other than through a few limited laboratory experiments, very little is known about the actual *in situ* effects of spawning ground water temperature and climate factors on squid catches in the NWP. It is particularly apparent from this study that water temperature is crucially important in determining squid spawning and catch. This relationship between water temperature at the spawning grounds and squid catch is extremely important in predicting the variability of squid recruitment and populations.

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