



The late 1980s regime shift in the ecosystem of Tsushima warm current in the Japan/East Sea: Evidence from historical data and possible mechanisms

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ABSTRACT

A climatic regime shift, an abrupt change from cooling to warming in the Japan/East Sea (JES), particularly in the Tsushima warm current (TWC) region, occurred in the late 1980s. The ecosystem of the JES responded strongly to the changing thermal regime. Many, but not all biological components of the ecosystem, spanning from plankton to predatory fishes, and including both warm-water pelagic and cold-water demersal species responded to this late 1980s climatic regime shift in the JES.

Diatom abundance (cell number) in spring from a monitoring line located in the central part of JES showed decadal variations with a step change from positive to negative anomalies in 1991. Zooplankton biomass in spring and autumn was high in the 1970s, declined during the 1980s, and returned to higher, but quite variable levels during the 1990s. Japanese sardine catch increased after 1974 to its peak level in 1989 and then declined dramatically to 1974 levels by 1997 with step changes in 1979 and 1994. Conversely, catches of other small pelagic species such as Japanese anchovy and common squid, and several higher-trophic fishes, such as yellowtail and tunas increased markedly in the 1990s compared to the early-mid 1980s. Step changes were detected in these pelagic species during 1989–1992. Catch of demersal species (crab, pink shrimp, Pacific cod and walleye pollock) were high during most of the 1970–1980s, but declined at various times in the late 1980s to generally low catches in the 1990s. Detailed analysis of the demersal fish assemblage composition, abundance and distribution indicated a shift in the late 1980s with several years lag in the time of change. Cold-water species (e.g., walleye pollock, Pacific cod) decreased in abundance and the regions in which their abundances remained high became greatly reduced in extent. Conversely, warm-water species (e.g., pointhead flounder, shotted halibut) increased in abundance and/or extended their spatial range (as indicated by trawl catch) during the warm 1990s. A principal component analysis for pelagic and demersal fish assemblages, suggested decadal variation patterns with a step change during 1986–1988. Abundance changes were identified not only in the plankton, but also in small pelagic fishes, and in predatory fishes. These changes were reflected in fish community indicators, and suggest an ecosystem regime shift occurred in the TWC region as a result of the late 1980s climatic regime shift. A hypothesis on the ecological response process to the late 1980s climatic regime shift was proposed.

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1. Introduction

Recent studies have revealed that regime shifts and/or decadal-scale variability in the atmospheric and oceanic environments, as indicated by climatic indices such as Pacific Decadal Oscillation (PDO), are dominant characteristics of the mid-latitude North Pacific (e.g., Mantua and Hare, 2002; Nakamura and Yamagata, 1999) and strongly influence the dynamics of fish populations and ecosystems (e.g., McGowan et al., 1998; Sugimoto et al., 2001; Tian et al., 2004; Zhang et al., 2000). Increasing evidence shows that regime shifts can occur not only in the atmospheric and oceanic fields,

but also in small pelagic species such as anchovy and sardine, fish communities and marine ecosystems (Beaugrand, 2004; Chavez et al., 2003; deYoung et al., 2004). The late 1980s, and particularly the mid-1970s regime shifts were well documented and identified in various Pacific and Atlantic, including the northeast Pacific (Hare and Mantua, 2000), northwestern Pacific (Wooster and Zhang, 2004), Peruvian upwelling ecosystem in the South Pacific (Alheit and Niquen, 2004), Benguela upwelling ecosystem in the Atlantic (Cury and Shannon, 2004), and in the North Sea (Beaugrand, 2004). However, the ecological processes of regime shifts even on a regional scale are still poorly understood, because of the structural and functional complexity of the ecosystem and shortage of long-term biological time series (deYoung et al., 2004). Because the temporal–spatial response of marine ecosystems to climatic

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regime shifts can vary regionally (Yasunaka and Hanawa, 2002), it is particularly important to identify regional variations in the dynamics of the fish community and ecosystem (Sugimoto et al., 2001).

The Japan/East Sea (JES) is one of the marginal seas in the western North Pacific, but it may be thought of as a model or microcosm of large oceanic systems where biogeographic boundaries juxtapose at highly dynamic boundaries. The Tsushima warm current (TWC) and the Liman cold current, which are associated with the subtropical and subarctic circulations in the North Pacific, respectively, are two major currents in the JES, and divide the JES into warm (southern) and cold (northern) regions with the boundary (Polar front) around 40°N (Fig. 1) (Senjyu, 1999). The northern and southern regions of the JES are hydrographically and biologically distinct, with the southern region being more tropical/oligotrophic and the northern region being more boreal/eutrophic (Ashjian et al., 2005). Hence, spatial and temporal variability between the surface Tsushima warm water and the homogeneous cold deep water mass is associated largely with the dynamics of ecosystem from lower trophic level plankton to higher-trophic level fishes in the JES (Chiba and Saino, 2002, 2003; Kubo and Ebara, 1992; Naganuma, 2000; Tian et al., 2006).

The fish community in the JES is diverse with both warm-water pelagic species such as yellowtail (*Seriola* spp.) and Japanese Spanish mackerel (*Scomberomorus niphonius*) and cold-water demersal species such as Pacific cod (*Gadus macrocephalus*) and tanner crab (*Chionoecetes opilio*). Also it is characterized by both coastal species such as horse mackerel (*Trachurus japonicus*), offshore migratory species such as Japanese common squid (*Todarodes pacificus*), small pelagics such as Japanese sardine (*Sardinops melanostictus*) and Japanese anchovy (*Engraulis japonicus*) and top-predators such as yellowtail and tunas (*Thunnus* spp.). However, patterns of the fish community structure and trophic dynamics in the JES have received little attention, because more focus has been given to the effects of environmental changes on the population dynamics of specific single species such as Japanese common squid and yellowtail (Hara and Murayama, 1992; Sakurai et al., 2002).

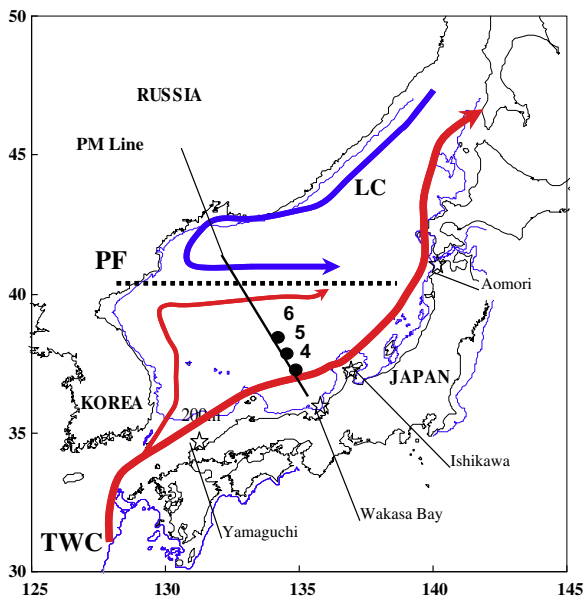


Fig. 1. Schematic diagram showing the oceanographic structures in the Japan/East Sea. Solid arrows indicate the Tsushima warm current (TWC) and Liman cold current (LC). The dotted line indicates the Polar front (PF). Locations of PM Line observation stations and some geographic names mentioned in the text are shown with solid circles and stars, respectively. 200 m depth contour is superimposed. Adapted from Tian et al. (2006).

There is increasing evidence that oceanographic conditions in the JES abruptly changed from a colder to a warmer regime around 1988/1989 (e.g., Katoh et al., 2006) and that this affected the ecosystem (e.g., Minami et al., 1999; Tian et al., 2006). Diatom community structure in the JES changed during the 1980s and was linked with the decadal climatic variability (Chiba and Saino, 2002; Kubo and Ebara, 1992). Ecosystem components in Korean waters of the JES, from zooplankton biomass to fish community structure, also changed around the late 1980s and seemed to link with climatic regime shifts (Kang et al., 2002; Zhang et al., 2000, 2004). Hare and Mantua (2000) assembled 100 biological/physical time series for the Northeast Pacific and Bering Sea, and revealed that a regime shift occurred in the North Pacific and Bering Sea around 1988. Flatfish recruitment in the eastern Bering Sea changed around 1988/89 and was attributed to decadal climatic variability and ocean conditions (Wilderbuer et al., 2002). Moreover, an ecosystem regime shift from phytoplankton to fishes such as horse mackerel and herring accompanied with changes both in abundance level and biogeographical distributions was identified in the North Sea circa 1988 and linked with NAO (Reid et al., 2001; Corten, 2001; Beaugrand, 2004). However, the late 1980s regime shift is relatively poorly understood compared to the mid-1970s global regime shift; the response of the late 1980s shift seemed to have been stronger in the higher latitudes of the western North Pacific than in the eastern Pacific (Minobe et al., 2004; Seo et al., 2006). Although some specific ecosystem components from plankton to small pelagic fishes were affected by the oceanic conditions, few studies have focused on the ecological processes of the late 1980s regime shift in the Northwestern Pacific.

In our previous study, using community indices such as mean trophic level (MTL), we reported that fish community structure in the TWC showed decadal variability with change around the late 1980s, and was largely affected by climatic regime shifts rather than by fishing (Tian et al., 2006). However, the ecological processes involved in the fish community response to climatic regime shifts remain largely unknown. In the present study, we focused on the ecosystem regime shift that occurred in the late 1980s in the TWC. The objectives of this paper are (1) to provide evidence that step changes in abundance occurred across multiple trophic levels spanning from plankton to fishes, and at the level of the community (e.g., pelagic or demersal fish assemblages), (2) to demonstrate their responses to climatic regime shifts, and (3) to propose a possible mechanism that controls the ecological responses in the JES.

2. Data and methods

2.1. Oceanographic data and climatic indices

Sea surface temperature (SST) data from the Japan Meteorological Agency (JMA) for the North Pacific and seawater temperature time series at 50 m and 200 m by region were used to represent the spatial-temporal oceanic variability in the JES. The JMA data set is 10-day-averaged SST in 1° grid (longitude-latitude) over the northwestern Pacific from 100°E to 180°E between the equator and 60°N for the period from 1970 to 2004. These data are used to describe the spatial variation patterns in the SST field in the JES. The 50 m and 200 m seawater temperatures were based on the monthly oceanographic monitoring observations for the JES conducted by Japanese governmental organizations (Watanabe et al., 2002; Katoh et al., 2006). In particular, the area-averaged 50 m seawater temperature for the southwestern (from Wakasa Bay in Kyoto Pref. to Yamaguchi Pref.) and for the northeastern (from Aomori Pref. to Ishikawa Pref.) regions (Fig. 1) is generally used as an indicator of TWC, which greatly influences the oceanographic conditions and fisheries production in the JES (Naganuma, 2000;

Katoh et al., 2006). The 200 m temperature averaged for the northern (138–140°E, >40°N) and southern (132–134°E, <40°N) regions were used to describe the temporal variation pattern in the intermediate water in the JES.

In addition to the oceanographic data, Southern Oscillation Index (SOI), Monsoon Index (MOI), Arctic Oscillation Index (AOI) and Pacific Decadal Oscillation (PDO), were chosen as climatic indices for the North Pacific. These indices are well documented and largely associated with the interannual–interdecadal variability, not only in atmospheric and oceanic conditions, but also in the marine ecosystems in the North Pacific (Beamish et al., 2000; Tian et al., 2006). Monthly values for SOI, AOI and PDO were provided by the Climate Predictive Center of NOAA for the period 1950–2004, and the MOI data for the same period were updated from Tian et al. (2006), which were provided by JMA.

2.2. Biological data

2.2.1. Plankton time series

Oceanographic/biological monitoring along the PM line across the central part of JES (Fig. 1) has been conducted since 1972 (Minami et al., 1999). The PM observations were conducted at up to 11 stations from southern coastal to northern offshore waters in each season (late January to mid-February in winter, late April to mid-May in spring, mid-July to early August in summer, and late September to mid-October in autumn). Data from 1972 to 2004 for Stns. 4–6 only were used in this analysis. Locations of the northern stations (Stns. 7–11) were changed or the station discontinued. The nearshore southern stations (Stns. 1–3) may be strongly affected by more local coastal processes. Stations 4–6 are located south of the polar front within the offshore TWC region and are considered to reflect the effect of large-scale dynamics of the oceanic gyre on the local ecosystem (Chiba and Saino, 2002).

At each station, diatom cell density (cells L⁻¹) was determined from bucket collected surface samples (Chiba and Saino, 2002). Zooplankton were sampled by vertical haul of Norpac nets (0.33 mm mesh, 0.45 m mouth diameter) from 150 m depth to the surface (Chiba and Saino, 2003; Iguchi, 2004). In this study, the wet weight (mg m⁻³) of zooplankton was used as an indicator of biomass.

2.2.2. Statistics of Japanese catch

The Japanese fisheries catch data were based on the “Annual Report of Catch Statistics on Fishery and Aquaculture” supplied by the Ministry of Agriculture, Forestry and Fishery of Japan for the period 1964–2004. Fifty-four species were selected for analysis (modified slightly from the list of Tian et al. (2006) by excluding marine mammals and seaweeds). The taxa include fishes (large predatory, small pelagic and demersal fishes, 38 taxa), crustaceans (shrimps, lobsters and crabs, 6 taxa), cephalopods (squids and octopus, 4 taxa), mollusks (bivalve and gastropod, 4 taxa) and echinoderms (sea urchin and sea cucumbers, 2 taxa), that account for 89% (average for 1965–2004) of the total catch during the last 40 years in the Japanese waters of the JES. These 54 taxa were divided into two habitat type groups: the pelagic (11 large predatory fishes excluding sharks, and 15 small pelagic fishes, total 26 taxa) and demersal (15 demersal fishes including sharks and 13 invertebrates, total 28 taxa) groups. Taxa in pelagic and demersal groups are typically corresponding to warm-water and cold-water species, respectively.

2.2.3. Japan sea offshore bottom trawl data set

The “Japan Sea Offshore Bottom Trawl” (JSOBT) is a fishery licensed by the Ministry of Agriculture, Forestry and Fisheries of Japan. There are two types of fishing gear and methods in this fishery: pair trawlers and single trawlers (Misu, 1974). The fishing

ground of the pair trawl fishery is limited to the continental shelf of 127–135°E in the southwestern JES. The single trawl fishery operates in deeper offshore waters from the southwestern to the northeastern JES and targets more diverse species from warm-water species to cold-water species (Misu, 1974). Catch log information for the target species of these two bottom trawl fisheries is reported to the Japan Fisheries Agency (JFA) as JSOBT database for fisheries management (Misu, 1974). We analyzed the single trawler data set for the period of 1974–2004, during which 27 taxa (Table 1) were arranged for time series analysis. In this data set, monthly catch by species and fishing effort (number of hauls) are available with a grid spatial resolution of 10′ in longitude and latitude, and hence CPUE (catch per unit effort in kg haul⁻¹) was calculated for each 10′ grid cell and used as an index of relative abundance. Using these data, we investigated spatial–temporal changes in demersal fish assemblages. Because we focus on the long-term variability in demersal fish communities, we used annual mean catch and CPUE (January–December averaged) to examine variability and trend in each time series.

These 27 taxa were divided into two groups based on their different life history characteristics (Table 1): a cold-water species group (12 taxa), which included long-lived, endemic, deep water species such as Pacific cod, walleye pollock, tanner crab and pink shrimp, and a warm-water species group (15 taxa), which included short-lived, migratory, coastal–continental shelf habitat dwellers such as righteye flounders, seabreams and redwing searobin (*Lepidotrigla micropetera*) (Misu, 1974; Nishimura, 1966). Proportions of catch between warm- and cold-water species groups were used to examine changes in the species composition of bottom trawl fishery.

2.3. Community indices

Simpson’s diversity index (DI) was used to investigate changes in the fisheries community in the TWC region (Tian et al., 2006), calculated from the 54 species items stated in the previous section for each year of the time series during 1964–2004.

DI is defined as follows (Simpson, 1949):

$$DI = 1 - \sum_i^n \frac{Y_i(Y_i - 1)}{Y(Y - 1)}$$

where Y_i and Y represent the catch of species item i and the sum of total n (54) items for each year, respectively. In general, Y is given as number of individuals, here it is as units of weight (tonnes).

2.4. Statistical analysis and GIS approach

Correlation analysis and principal component analysis (PCA) were used to examine the relationships between climatic/oceanographic indices and biological time series. PCA was used to concentrate much of the variance of the large data set into a small number of interpretable patterns of variability (Hare and Mantua, 2000). PCA were applied to biological data from plankton to fishes, independently, to isolate the most important patterns of common variability in each trophic level. Since the fish community structure in the JES has both migratory warm-water pelagic species and endemic cold-water demersal species (Tian et al., 2006), separate PCA’s were done for the pelagic and demersal assemblages (26 pelagic and 28 demersal species) as well as on the entire fish community (the combined 54 taxa) for the period of 1964–2004. For the bottom trawl data, PCA was done for the 1974–2004 catches of 27 taxa. PCA and correlation analyses were done using SPSS 12 for Windows.

A geographic information system (GIS, Marine Explorer 4 by Environment Simulation Laboratory, Co. Ltd.) was used to examine

Table 1
Target species of the offshore bottom trawl fishery in the Japan/East Sea and their life history characteristics

No.	English name (main species)	Scientific name	Depth (m)	Life span (years)	Spawning season	Age at recruitment	Age at maturation	Age composition (main ages)	Current system
1	Pacific cod	<i>Gadus macrocephalus</i>	200–300	>12	January–March	1	4	1–5 (4–5)	CW
2	Walleye pollock	<i>Theragra chalcogramma</i>	100–500	>11	December–March	2	3	2–10 (3–5)	CW
3	Arabesque greenling	<i>Pleurogrammus azonus</i>	<200	7	September–November	0	2	0–3 (0–1)	CW
4	Japanese sandfish	<i>Arctoscopus japonicus</i>	300–500	5	December–January	1	2	1–4 (2–4)	CW
5	Piked dogfish	<i>Squalus acanthias</i>	150–180	>10	February–May	–	10	–	CW
6	Owenton's rockfish	<i>Sebastes owstoni</i>	190–300	>10					CW
7	Witch flounder	<i>Glyptocephalus stelleri</i>	200–300	>12	January–April	–	2	–	CW
8	Flathead flounder	<i>Hippoglossoides dubius</i>	150–500	>10	February–April	3	5	3–10 (3–5)	CW
9	Brown sole	<i>Pleuronectes herzensteini</i>	30–130	>10	February–May	1	2	1–5 (3–4)	CW
10	Other righteye flounders (slime flounder)	Pleuronectidae (<i>Microstomus achne</i>)	50–400	10	February–April	1	3	–	CW
11	Pink shrimp	<i>Pandalus borealis</i>	200–950	11	February–April	–	4	–	CW
12	Tanner crab	<i>Chionoecetes opilio</i>	200–500	>10	June–July	5	–	–	CW
13	Deepsea smelt	<i>Glossanodon semifasciatus</i>	<200	5	Spr and Aut	1	1	1–3 (2–3)	WW
14	Shotted halibut	<i>Eopsetta grigorjewi</i>	<140	>10	February–March	2	2	1–5 (1–2)	WW
15	Willow flounder	<i>Tanakius kitaharai</i>	80–150	>10	October–July	1	2	1–5 (1–2)	WW
16	Pointhead flounder	<i>Hippoglossoides pinetorum</i>	150–190	8	January–March	1	2	1–5 (2)	WW
17	Bastard halibut	<i>Paralichthys olivaceus</i>	<150	>10	March–June	1	2	1–5 (2–3)	WW
18	Silver seabream	<i>Pagrus major</i>	<100	>10	April–July	1	3	1–5 (1–2)	WW
19	Crimson seabream	<i>Eynniss japonica</i>	30–130	>6	July–September	1	2	1–5 (1–2)	WW
20	Deepsea snapper	<i>Dentex tumifrons</i>	<200	>8	Spr and Aut	0	2	0–3 (1–2)	WW
21	Lizardfish (wanieso lizardfish)	Synodontidae (<i>Saurida wanieso</i>)	<120	7	April–June	–	–	–	WW
22	Croaker (silver croaker)	Sciaenidae (<i>Pennahia argentatus</i>)	20–120	6?	March–June	–	2	–	WW
23	Redwing searobin	<i>Lepidotrigla microptera</i>	70–140	6	February–June	1	1	1–4	WW
24	Largehead hairtail	<i>Trichiurus japonicus</i>	20–140	8	April–October	1	1	1–6 (1–2)	WW
25	Blackthroat seaperch	<i>Doederleinia berycoides</i>	80–150	10	July–August	1	2	–	WW
26	Squids (golden cuttlefish)	(<i>Sepia esculenta</i>)	<200	<2	May–June	1	1	1–2	WW
27	Octopus (North Pacific giant octopus)	(<i>Octopus dofleini</i>)	<200	5	December–November	1	2	1–3	WW

Modified from Nishimura (1966) and Ogata (1980).

Total 27 items.

Note: CW: Cold-Water Species; WW: Warm-Water Species; Spr: Spring; Aut: Autumn; Ages are in years. Information for age composition of catch is based on Fisheries Agency and Fisheries Research Agency (2005).

the temporal–spatial changes in the abundance and distributions of demersal species and their relations to oceanographic conditions. GIS maps for SSTs, and for annual (averaged from January to December) and five year smoothed CPUEs of the 27 taxa bottom trawl catches were prepared for temporal–spatial analyses.

Finally, a sequential *t*-test analysis of regime shift (STARS) developed by Rodionov (2004) was applied to detect step changes in all time series in the JES. STARS uses a *t*-test analysis to determine whether sequential observations in a time series represent statistically significant departures from mean values observed during the preceding period of a pre-determined duration. The change in the confidence of a regime shift is reflected in the value of the regime shift index (RSI), which represents a cumulative sum of the normalized anomalies. STARS results are determined by the cut-off length for proposed regimes (*L*), and the Huber weight parameters (*H*), which defines the range of departure from the observed mean beyond which observations are considered as outliers. By exploratory analyses with STARS, *L* was set here to 10 or 20, and *H* to 1. STARS is written in Visual Basic for Application (VBA) for Microsoft Excel, and is available at www.BeringClimate.noaa.gov (Rodionov, 2004; Rodionov and Overland, 2005).

3. Results

3.1. Features of the late 1980 climatic regime shift in the JES

Oceanographic conditions in the JES, particularly in Japanese coastal waters, are greatly influenced by the TWC (see Fig. 1). The 50 m coastal water temperature in winter in the southwestern JES, which is assumed to be an indicator of TWC, showed negative anomalies during 1966–1986 (−0.56 °C) and positive anomalies during 1987–2004 (+0.62 °C) indicating a change from a cold regime to a warm regime occurred around 1986/1987 (Fig. 2). The trend in summer temperature differed from that in winter; temperatures were generally lower during the late 1970s to early 1990s but higher after the late 1990s. STARS analysis for seasonal temperature in the southwestern and northeastern regions of the JES indicated two regime shifts: one occurred during 1986–1989 in spring–winter water temperatures, and a second was detected during 1996–1998 in summer–autumn water temperatures (Fig. 2c). The trend in 200 m depth water temperature, which was filtered by seven years moving average to remove the effect of the El Niño–Southern Oscillation (ENSO), showed decadal variability, and increased abruptly around the late 1980s, particularly in the northern region (Fig. 3).

The oceanographic structure is substantially different in the northern and southern regions of the JES. Decadal averaged SST anomalies in winter showed a see-saw variation pattern spatially. Cold anomalies were limited to the TWC in the 1970s, then extended to the whole JES during the 1980s. The whole region became warmer in the 1990s, and then the warm areas were reduced to the TWC during the 2000s (Fig. 4). Spatial differences in winter SSTs between 1976–1986 and 1987–2004 showed that the whole JES became warmer after 1987. This change was particularly evident in the TWC. This spatial variation pattern is also evident in the mid-layer depth water temperature.

Among the four climatic indices (Fig. 5), STARS results indicated that a regime shift in SOI and PDO occurred in 1976/77, with a strong El Niño trend (negative SOI) and intensification of Aleutian Low (positive PDO). On the other hand, AOI and MOI showed a regime shift during 1987–1989 with large interannual variations, indicating a weakening Asian monsoon and intensified AO after 1989, but no distinct changes occurred in the mid-1970s.

These results suggest a distinct regime shift in the oceanographic conditions, primarily in winter, in the JES particularly in

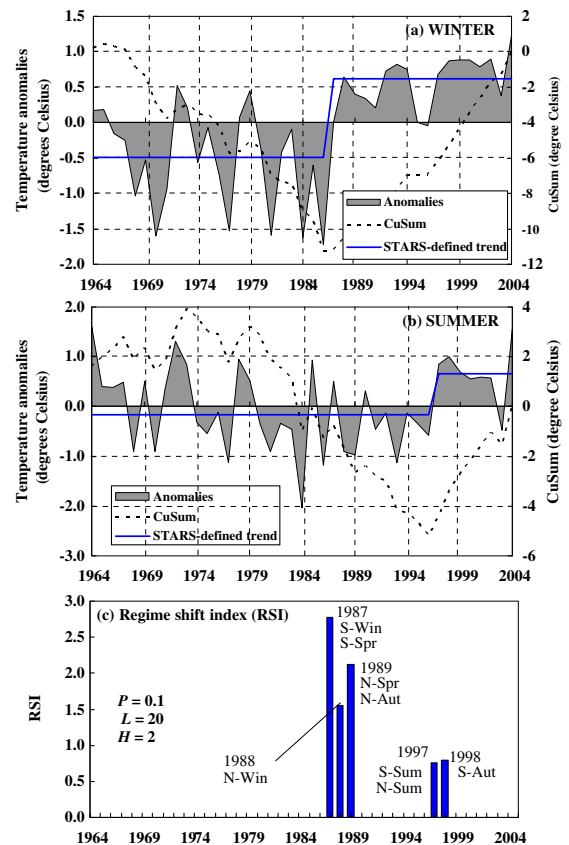


Fig. 2. Anomalies in 50 m depth water temperature in winter (a) and summer (b) in the southwestern Japan/East Sea during 1964–2004, and regime shift index (RSI) estimated by STARS for the 50 m depth water temperature in both the southwestern and northeastern Japan/East Sea by season (c). The solid bold line indicates step changes detected by STARS. The broken bold line indicates the cumulative sums (CuSum) of the anomalies. N(S)-Win, N(S)-Spr, N(S)-Sum and N(S)-Aut in (c) indicate water temperature in the northeastern (southwestern) JES in winter, spring, summer and autumn, respectively.

the TWC region occurred in the late 1980s, as identified by water temperatures from surface to deep waters and linked with MOI and AOI (Tian et al., 2006). On the other hand, the 1976/1977 regime shift in global climatic indices such as PDO and SOI, seemed not to be notable in the oceanographic indices of the JES.

3.2. Interannual–decadal variability in the plankton biomass

Diatom abundance and zooplankton biomass from the PM line (Fig. 1) showed large seasonal and interannual variation (Fig. 6). Despite the large year-to-year variability in diatom abundance, there is indication that springtime diatom abundance was higher during the 1980s than during spring of the 1970s and 1990s. Summer diatom abundance was often of opposite phase to spring diatom abundance, with low abundances during the 1980s and higher abundances after 1990. Autumn diatom abundance was higher during 1976–1995 and lower after 1996. Diatom abundance (excluding the winter for its lower production) showed decadal variability with large interannual variations. STARS results indicated step changes occurred in springtime diatoms in 1979/1980 and 1991/1992 and in autumn diatoms in 1995/1996.

Zooplankton biomass was generally lower during the mid-1970s and 1980s, and after 2001, but higher in the 1990s except in winter (Fig. 6). Despite large interannual variability, zooplankton biomass in spring and autumn also showed decadal variation patterns. STARS analyses indicated step changes in 1981/1982 and 1992/1993 for spring biomass and in 1985/1986 for autumn

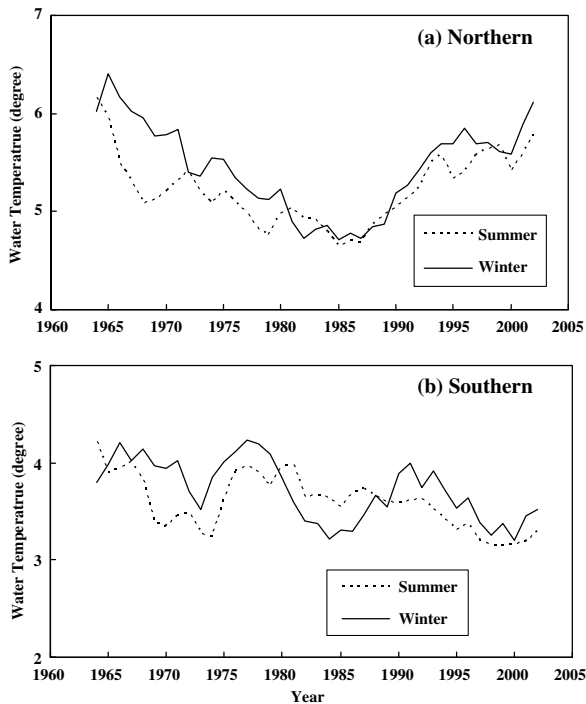


Fig. 3. Changes in 200 m depth water temperature in seven years moving average by season and region in the Japan/East Sea from 1964 to 2003: (a) northern region (138–140°E, >40°N); (b) southern region (132–134°E, <40°N).

biomass, and a possible shift around 2000 for all seasons. It is notable that the direction of step changes were opposite between diatom and zooplankton biomass in both spring and autumn.

The first component (PC1) from PCA (Fig. 6), which accounted for 37% and 43% of the total variance for diatom and zooplankton biomass, respectively, showed decadal variation with a step change in 1990/1991 for diatom (and in 2001/2002 for zooplankton). Decadal variation and step changes in the lower trophic levels in the JES seemed to correspond well with the late 1980s climate shifts.

3.3. Variation patterns in the fish community structure

3.3.1. Decadal variation pattern in the fisheries production

Japanese catch in the JES increased greatly since 1970 with the rapid recovery of Japanese sardine to a peak of 1.76 million t in 1989, and then decreased abruptly with the collapse of the Japanese sardine stock (Fig. 7a). The long-term trend in fisheries production was largely dependent on the Japanese sardine that constituted up to 60% of the total catch in the Japanese waters of the JES during the late 1980s. Mid-trophic level small pelagics (excluding Japanese sardine) and higher-trophic level pelagics were higher during 1964 to early 1970s and 1990s but lower during the late 1970s to 1980s when sardine were dominant. Demersal groups (fishes and invertebrates) were more stable from year to year, with a gradual decline since the early 1970s. Overall, composition of the catch by trophic group (excluding sardine) were relatively stable through time, with a slight decline in demersal species after 1986 (Fig. 7b). STARS analyses for composition of catch by trophic group indicated step changes occurred in 1988 for large and small (excluding sardine) pelagics, and in 1992 for the demersals (not shown).

The first two components (PC1–2) of PCA for the fisheries catches, which accounted for 50% and 69% of the total variance for the pelagic and demersal groups, respectively, showed decadal

variation patterns (Fig. 8). The PC1 for the two groups showed similar patterns with a positive score before the 1970s and a negative value after the 1980s, indicated the most important change particularly in the demersal group (PC1 alone accounted for 53% of the total variance) that occurred during the late 1970s to early 1980s. The PC2 pattern seems to be the opposite between the pelagic and demersal groups, despite their synchronous changes around the late 1980s to early 1990s. The PC1–2 for the entire grouping of 54 taxa were similar to PC1 in the pelagic group and PC2 in the demersal group, respectively. STARS analyses for these PCs ($p = 0.01$, $L = 10$, $H = 1$) indicated that step changes occurred in the pelagic group in 1977/1978 (both PC1 and PC2) and in 1987/1988 (PC1), and in the demersal group in 1972/1973 (both PC1 and PC2), 1981/1982 (PC1) and 1988/1989 (PC2). Although there were lags of several years, these suggested two step changes in the fisheries community: one in the mid-1970s (evident in PC1 for pelagic group and whole taxa) and another in the late 1980s (in all PCs excluding PC1 of demersal group). But see the discussion for caveats about the use of STARS technique applied to smoothly varying data.

As examples of individual species variability, Fig. 9 shows the variation in the catches of 10 major species from migratory warm-water species (tuna and yellowtail), cold-water demersal species (walleye pollock, Pacific cod), small pelagic species (Japanese sardine, Japanese anchovy, horse mackerel and common squid), and deeper water demersal species (pink shrimp and crabs). These major species showed strong variation in biomass at decadal time-scales. The variation pattern was opposite between the pelagic (warm-water) species and demersal (cold-water) species. Warm-water pelagic species such as tunas, yellowtail, horse mackerel and common squid, which generally have spawning grounds in subtropical waters and migrate to the JES during summer–autumn for prey, were lower during the 1980s but higher since the 1990s. Conversely, cold-water demersal species such as Pacific cod, walleye pollack, pink shrimp and crabs (mainly tanner crab *C. opilio* and red snow crab *C. japonicus*), most of which spawn in winter through spring and complete their life in the JES, were higher during the 1980s but lower since the 1990s. This strongly suggested that the responses to oceanic conditions are different for warm-water pelagic species and cold-water demersal species, and seemed to reflect their different life history characteristics.

STARS results indicated that step changes occurred in the catch of many species in the late 1980s to early 1990s with some variability in the time of change (Fig. 9). Small pelagics with short life spans of 1–2 years such as common squid and anchovy showed a step change in 1989/1990. Large species with longer life spans and older age compositions in the catch, such as tuna, Pacific cod and crabs shifted during 1990–1992, several years later than the small pelagics. Catch of Japanese sardine with age composition of 1–5 years shifted around 1994, then the step change in the recruitment can be estimated to have occurred in 1989 (this is supported with Watanabe et al. (1995), in which recruitment failures of sardine occurred during the 1988–1991 year classes). Hence, variability in the time of STARS identified step-changes is largely due to species dependent time lags between the dominant age in the catch and the recruitment age. From this point of view, step changes in recruitment may have occurred in the late 1980s, several years earlier than changes in the catches. The summed regime shift index (RSI) estimated from STARS for all 54 catch time series was higher during 1986–1992 (not shown), strongly suggesting a step change occurred in the fish community structure in the JES at that time.

3.3.2. Changes in community indices

Diversity index (DI) was high and relatively stable until the early 1970s, decreased sharply to the minimum in the late

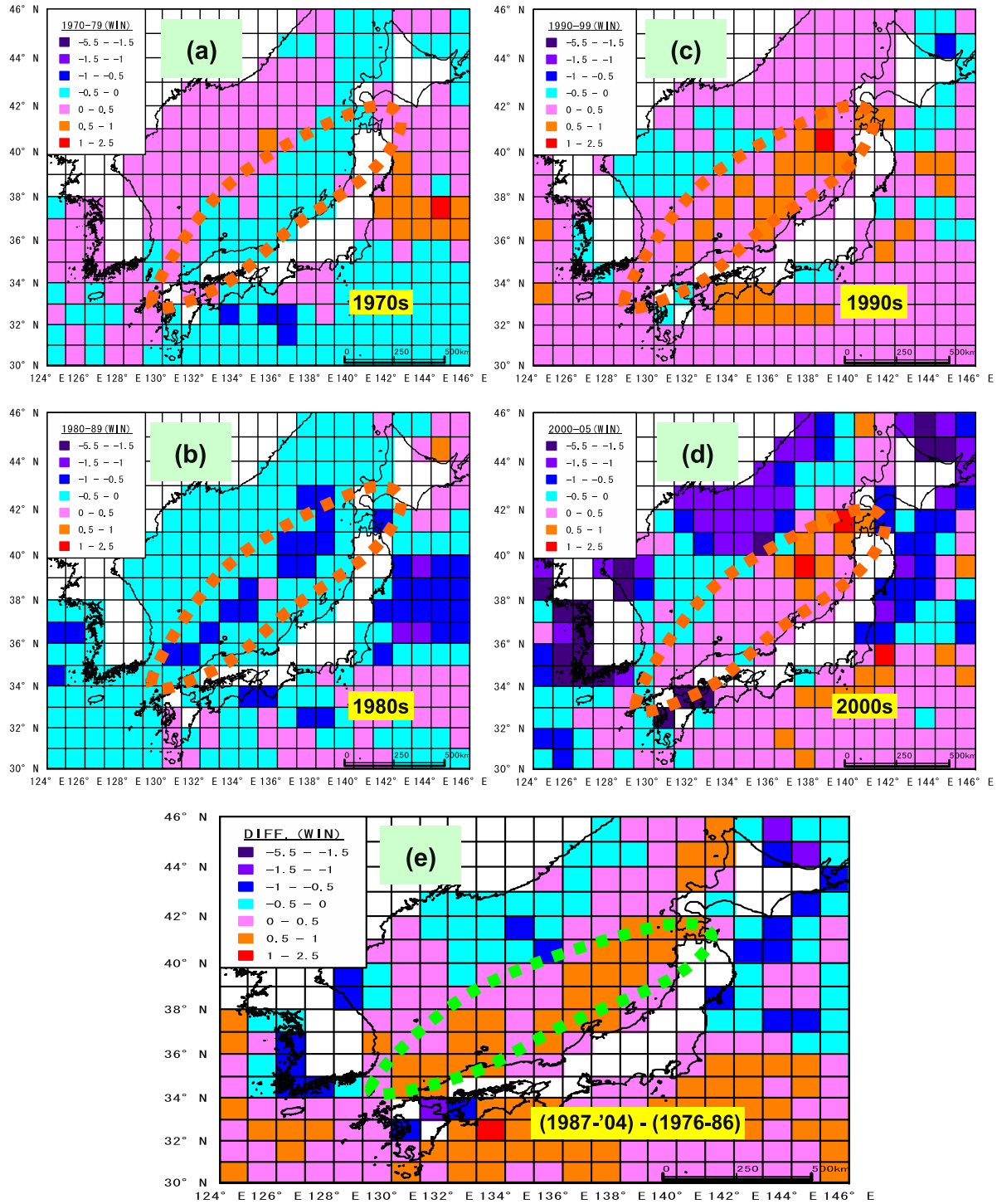


Fig. 4. Spatial distributions in winter SSTs anomalies by decadal mean from 1970s to early 2000s (a–d) and differences between two (1987–2004 and 1976–1986) regimes (e) in the Japan/East Sea. The decadal anomalies were defined as the difference between the decadal mean and 30 years (1970–1999) mean. The dotted ellipses approximately indicate the TWC region.

1980s, then tended to increase to a high level after the mid-1990s (Fig. 10), indicating decadal variability in the community structure with an abrupt change around the late 1980s. The sharp decline in DI during the 1980s was due to the high catch of Japanese sardine, indicating that the abundant Japanese sardine had a marked effect on the community structure (Tian et al., 2006). The DI in the northern region is larger and has less interannual variation than in the southern region, reflecting the different fish community structures, which are characterized in the southern region by warm-water

species with large interannual variations, such as small pelagic fishes, and in the northern region by cold-water, demersal species with small interannual variations.

3.3.3. Temporal–spatial changes in demersal species

The results described above indicate different responses of pelagic and demersal species to climate changes. However, even within the demersal species assemblage, there are large differences in specific life history characteristics such as habitat and spawning

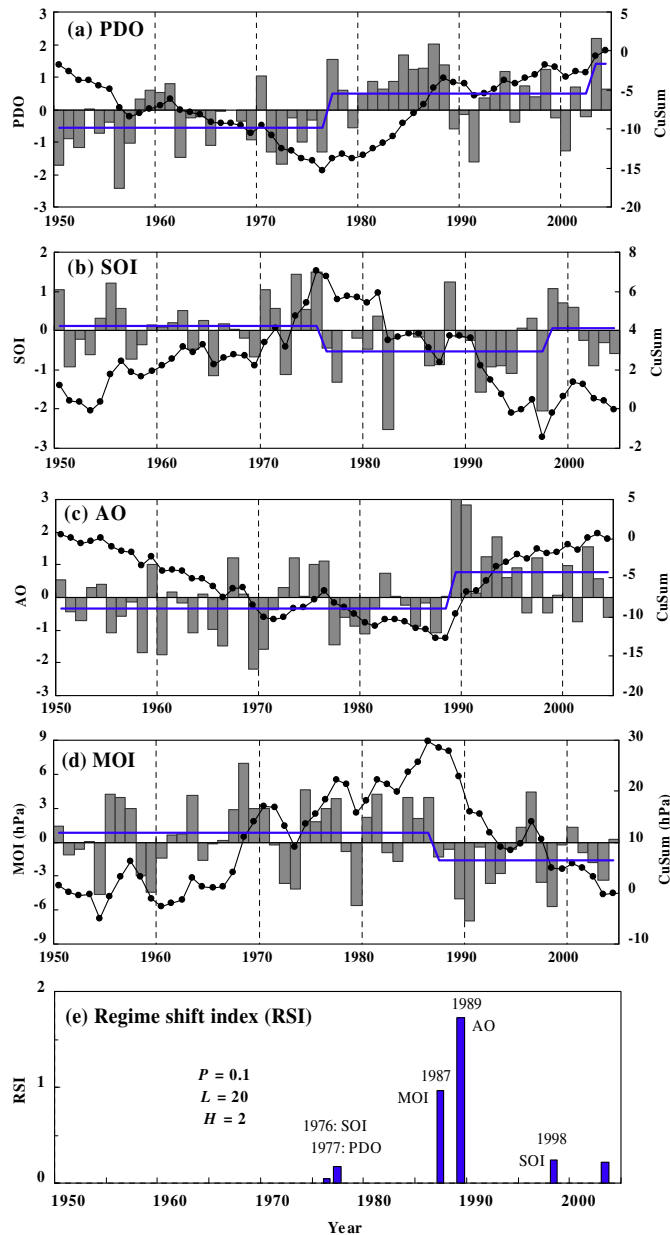


Fig. 5. Anomalies values (vertical bars), their cumulative sums (CuSum, solid circles) and step change detected by STARS (solid bold line) (a–d) and regime shift index (RSI) estimated by STARS for the four climatic indices from 1950 to 2004. (a) Winter Pacific Decadal Oscillation (PDO). (b) Annual Southern Oscillation Index (SOI) averaged during May through April. (c) Winter Arctic Oscillation Index (AOI). (d) Winter Asian Monsoon Index (MOI). (e) Regime shift index. Adapted from Tian et al. (2006).

season. In this section, we report the temporal and spatial responses of demersal species using data from bottom trawls.

The total catch of bottom trawl during 1974–2004 has shown a gradual decline since 1980 with decreasing fishing effort (Fig. 11). The southwestern region, with abundant warm-water species, accounted for a large part of the total catch and effort, while the offshore area had a small contribution. CPUE was higher in the northeastern region, and lower in the southwestern region, but were relatively stable year to year in all regions. No changes occurred during the late 1980s. However, proportions of warm-water species (see Table 1) for each region increased during mid-1980s to early 1990s (Fig. 12). STARS analyses indicated step changes in the species composition occurred in the southwestern region (and the

whole region) in 1988/1989, in the central region in 1985/1986 and in the northeastern region in 1992/1993. Considering lags introduced by the age composition of the catch (see Table 1), this result suggests that species composition changed during the late 1980s with an increase (decrease) in warm- (cold-) water species, corresponding well with the climatic regime shift in the TWC (Fig. 12). This trend was also evident from the PCA for these 27 target species (Fig. 13). The PC1 and PC3, which accounted for 37% and 11% of the total variance, showed strong decadal variability with significant step changes around 1987 ($p = 0.01$ with STARS analyses). The PC2 also showed decadal variation pattern with a significant step change in 1996/1997. Temporal variation of PC1 and PC2 corresponded well with 50 m water temperatures in winter and summer, respectively.

Major cold-water species CPUE showed changes in the late 1980s that varied regionally (Fig. 14). During the warm regime since the late 1980s (Fig. 4), CPUEs of these cold-water species in the southwestern region have largely decreased; while CPUEs in the northern regions have remained relatively constant, indicating a reduced southward range and decrease in the southwestern region. Conversely, warm-water species changed in an opposite sense to the climate patterns. During the warm regime after 1987, CPUEs of these warm-water species largely increased not only in the southwestern region but also in the northern regions, indicating a northward extension of distribution and increase in the abundance (Fig. 15). For the species shown in Figs. 14 and 15, STARS analyses indicated step changes occurred during 1986–1992, such as in 1989/1990 for witch flounder (*Glyptocephalus stelleri*), in 1986/1987 for flathead flounder (*H. dubius*), in 1991/1992 for pointhead flounder (*Hippoglossoides pinetorum*) and red-wing scarobin, and in 1988/1989 for deepsea snapper (*Dentex tumifrons*) (STARS results are not shown in Figs. 14 and 15 for the clarity of figures). The regime shift index (RSI) estimated by STARS for CPUEs of 27 bottom trawl taxa indicated the most evident step change occurred around 1989, but with timing variability of several years (Fig. 16). In considering the several year time lag between CPUEs and recruitment (the age composition of the catch had a range of 1–5 years as shown in Table 1), it suggests that a regime shift in the demersal fish assemblage occurred in the late 1980s.

GIS spatial mapping of CPUE for each species allowed us to examine their changing temporal distribution. As an example, Fig. 17 shows the distributions during cold and warm periods for four indicator species: two cold-water and two warm-water species. For the cold-water species, walleye pollock and Pacific cod, it was notable that their distributions were extended to the southwestern region during the cold regime in the 1980s, but were reduced during the warm regime in the 1990s. On the other hand, the warm-water species, pointhead flounder and shotted halibut (*Eopsetta grigorjewi*), extended their distributions particularly in the southwestern region which experienced the greatest warming after the late 1980s. Variations in distribution patterns were associated with changes in the abundance of warm- and cold-water species (Figs. 14 and 15). For example, of the four righteye flounders, the cold-water species, flathead flounder and witch flounder, showed opposite patterns to the warm-water species, pointhead flounder and willow flounder (*Tanakius kitaharai*). The geographic distributions of cold and deeper water flathead flounder retracted into colder regions during warm periods, while the warm-water and coastal–continental shelf habitat pointhead flounder was expanded, reflecting their different thermal preferences.

Decadal variation patterns in the species composition, abundance level and distribution of major indicator species and PCs suggest that a regime shift occurred in the demersal fish assemblages in the late 1980s associated with an increase (decrease) in the abundance and expansion (reduction) in the distribution for

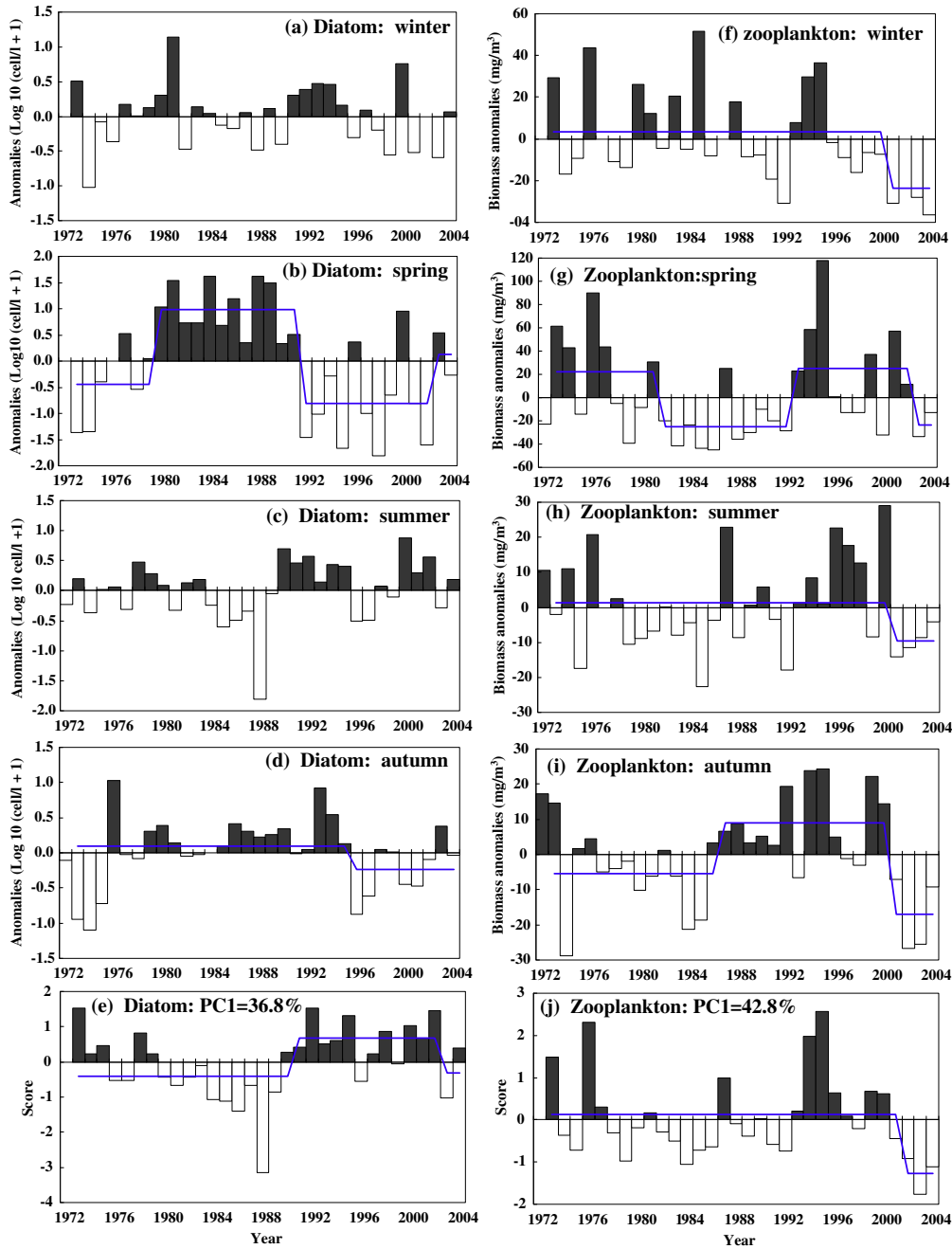


Fig. 6. Annual changes in cell number of diatoms (left panels: a–d) and zooplankton biomass (right panels: f–i) by season and the first principal component (PC1) score (the bottom figures: e, j) from the principal component analysis for the diatom and zooplankton biomass of four seasons from PM line from 1972 to 2004. The black(white) bars represent positive(negative) anomalies. The step changes detected by STARS were shown in solid bold lines.

warm- (cold-) water species. The regime shift detected in the demersal fish assemblage in the late 1980s corresponded well with the climatic regime shift, and opposite responses of warm- and cold-water species indicated that thermal preferences of specific species are important to the response.

4. Discussion

4.1. Data precision and regime shift detection

We examined many biological and physical time series. Fisheries catch data were used as indices of relative abundance or recruitment. Fisheries catch depends on fishing effort as well as

the abundance level. It is difficult to examine the fishing effort for each species because of the mixed target species of the fishery. Effort for three major fisheries (set net, bottom trawl and purse seine) in Japanese waters of the JES showed a slight decline during the 1980s and 1990s. This does not indicate a strong impact of fishing on the long-term trend of the catch (Tian et al., 2006).

The fluctuations in total catch were largely determined by the catch of the dominant Japanese sardine (Fig. 7). However, the fish community structure in the JES is characterized by diverse species from migratory warm-water pelagic species to endemic cold-water demersal species. Our focus is to detect regime shifts at the community level rather than within a single species. PCA is a particularly attractive method for examining a large number of time

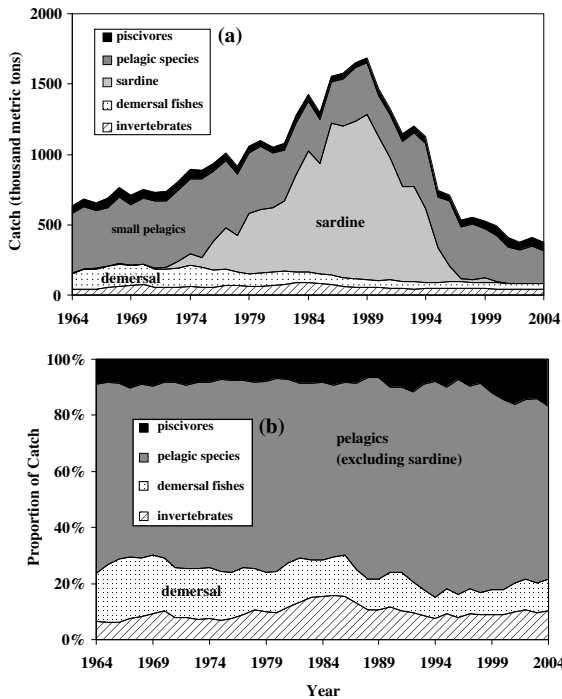


Fig. 7. Annual changes in Japanese fisheries landings by (a) species group, and (b) their proportions in the Japan/East Sea during 1964–2004.

series because it reduces the dimensionality of a data matrix to a small number of uncorrelated and possibly meaningful PC scores (Mantua, 2004). It has been used previously to investigate regime

shifts in large marine ecosystems (Hare and Mantua, 2000). The PC1s for 54 taxa catches and for 27 bottom trawl species accounted for 40% (Fig. 8e) and 37% (Fig. 13a) of the total variance, respectively, indicating strong common variation in the two data sets. Mantua (2004) recommended separate analysis of biotic and abiotic time series in order to identify ecosystem state variables of interest and to better isolate ecosystem behaviors from the influence of environmental change. Hence, we examined PCA for plankton, pelagic and demersal fish assemblages separately. However, identifying statistically significant shifts in the PC scores requires additional time series analyses methods like intervention analysis (Mantua, 2004). Here we applied STARS (Rodionov, 2004) to identify statistically significant shifts in the time series of the JES. We recognize that STARS analysis has some limitations. It forces changes to occur in step fashion, even when the time series exhibits gradual change (trend) over a longer period. For many of our time series, such as the temperature (Fig. 2), atmospheric and ocean indices (Fig. 5), and lower trophic levels (Fig. 6), the changes are rapid, occurring in 1 or 2 years, and thus step-like. For uniformity of approach, we have applied the STARS algorithm to fish data sets (Figs. 8, 9, 12 and 13), which are less clearly dominated by rapid shifts within 1–2 years, but rather have more gradual change that spans multiple years. The risk in doing this is that we may refer to trend changes as step changes. We hope that it is clear from the figures, for example from Fig. 8, when the changes are gradual over many years vs. rapid over a few years. For example, the data in Fig. 8c exhibited a 20 year declining trend from 1969 to 1989, for which STARS reported two consecutive (separated by ca. 8 years) declining step changes.

Despite lags of several years in the time of change, regime shift indices (RSI) estimated by STARS suggest that a regime shift occurred during the late 1980s to early 1990s (Figs. 13–16). It is

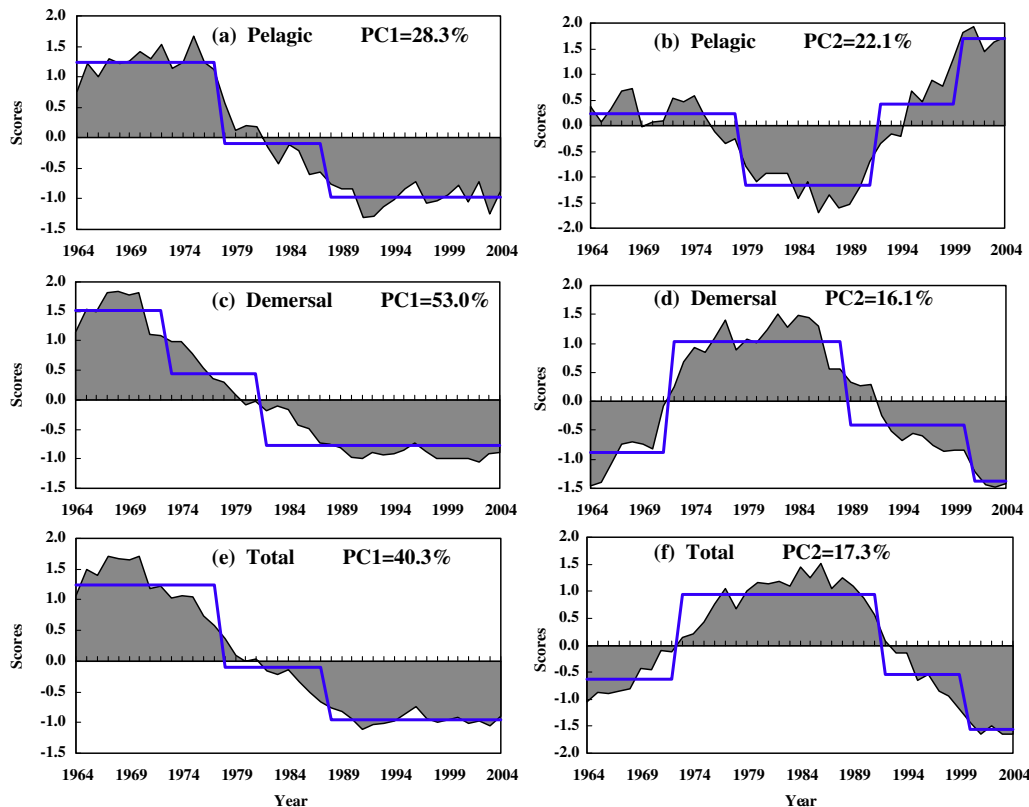


Fig. 8. The first two principal component (PC1–2) scores (shaded area) from the principal component analysis for the pelagic (top panels) and demersal (middle panels), and total (bottom panels) groups during 1964–2004. The solid bold lines represent the step changes estimated by STARS.

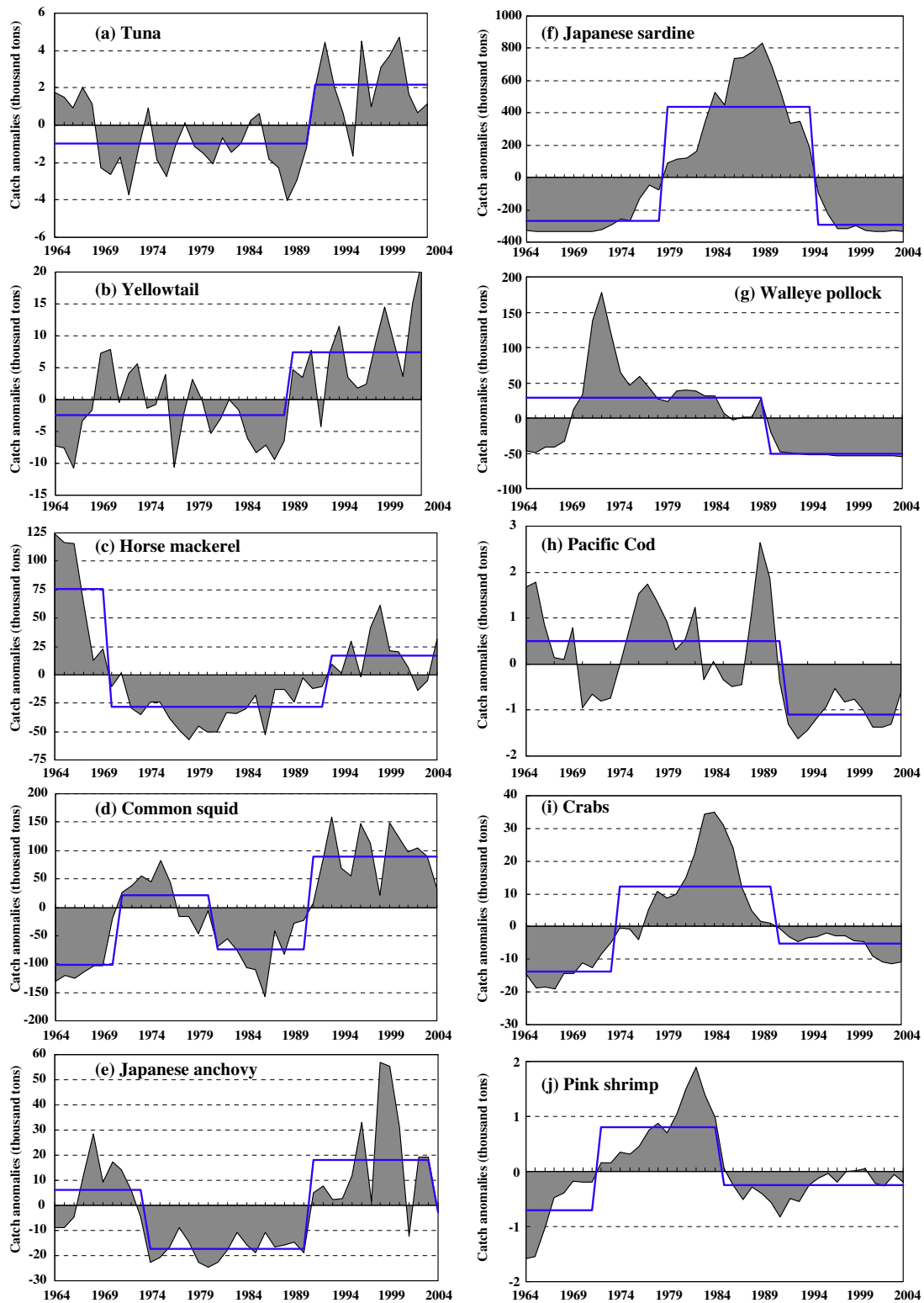


Fig. 9. Annual changes in catch anomalies (shaded area) for tunas (a), yellowtail (b), horse mackerel (c), common squid (d), Japanese anchovy (e), Japanese sardine (f), walleye pollock (g), Pacific cod (h), crabs (i) and pink shrimp (j) in Japanese waters of the Japan/East Sea during 1964–2004. The step changes detected by STARS were showed in solid lines.

not expected that all species will show synchronous regime shifts, because the fisheries catch data for each species have different age compositions (Table 1). There are time lags between recruitment changes and changes in catch created by the dominant age in the catch. Even for long-lived demersal species (Table 1), where the

main age composition of the catch are 1–5 years, lags of several years are expected. The STARS results strongly support that a regime shift not only occurred in major species, but also in most of the time series, suggested a significant impact occurred through much of the fish community.

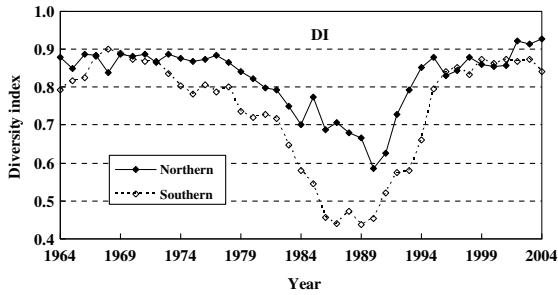


Fig. 10. Annual changes in the estimated biomass diversity index (DI) for the northern (solid line) and southern (broken line) Japan/East Sea during 1964–2004.

4.2. The late 1980s ecosystem regime shift in the TWC region

These results provide strong evidence that the TWC ecosystem, ranging from the lower trophic level plankton to higher-trophic level fish community, shifted as a result of the late 1980s climatic regime shift, which was linked with the Asian monsoon and Arctic Oscillation (AO). To demonstrate that a regime shift occurred in an ecosystem, step changes should be detected (1) across different trophic levels, (2) at the level of the community structure, (3) for key species, (4) in attributes of ecosystems such as diversity and (5) that these ecosystem changes reflect hydro-climatic variability (Beaugrand, 2004). Here we attempt to verify the late 1980s ecosystem regime shift in the TWC in this context.

There is compelling evidence that a step change from colder to warmer water in the TWC region occurred in the late 1980s, and seemed linked to the Asian monsoon and AO (Figs. 2–5). Decadal variability in diatom abundance and zooplankton biomass indicated that a step change occurred in the lower trophic level ecosystem in the JES in the late 1980s (Fig. 6). For the fish community, age composition of the population and the catch will create lagged responses to climate and environmental changes. Step changes were

identified in the mid-trophic level, small-pelagic species such as Japanese sardine, Japanese anchovy, common squid and horse mackerel, in the predatory fishes such as yellowtail and tunas, in demersal species such as Pacific cod, walleye pollock, crabs and pink shrimp, and in the species composition and community indices such as DI (Figs. 8–10). The first PC of PCA for both the fisheries catch of 54 species and for the 27 taxa examined in the bottom trawl dataset indicated step changes in the late 1980s. In particular, both the abundances and distributions of the bottom trawl demersal species changed abruptly around the late 1980s with an increase (decrease) in the abundance and range extension (reduction) in the distribution for warm- (cold-) water species during the warm regime (Figs. 12–15 and 17). These pronounced changes identified in most biological/fisheries indices from lower trophic level plankton to higher-trophic level predatory fishes are associated with the late 1980s climatic regime shift. Moreover, differing responses of warm- and cold-water species, indicated that the effect of the climatic regime shift depended upon habitat changes related to thermal preferences. These results conform well with the criteria of Beaugrand (2004) to suggest that an ecosystem regime shift occurred in the TWC region in the late 1980s as a result of the late 1980s climatic regime shift.

Spatial–temporal differences between the 1980s and 1990s were evident not only in the surface but also in the subsurface to mid-layer waters, suggesting that the water structure in the TWC region changed around the late 1980s (Figs. 2–4). Observations from PM line during 1965–2000 showed the potential temperature of the Japan Sea Proper Water (at depth from 500 to 2000 m) also increased distinctly since the late 1980s with the decline in the dissolved oxygen, indicated a possible shift in the deep waters (Minami et al., 1999; Ishikawa et al., 2003). It is obvious that the climatic regime shift in the late 1980s in the JES was linked with large scale atmospheric circulation as indicated by MOI and AOI (Figs. 2, 5). MOI accounted for 50% of the variance in the winter water temperature in the TWC region (Table 2), indicating that the weakening Asian monsoon since the late 1980s led to the

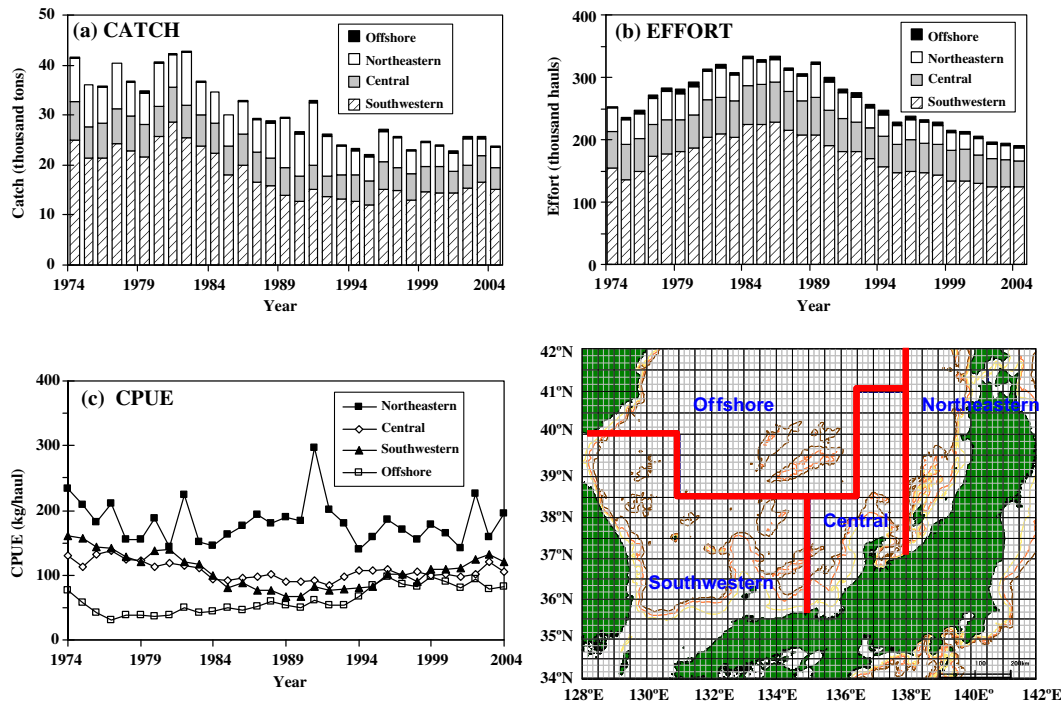


Fig. 11. Annual changes in the catch (a), fishing effort (b) and CPUE (c) by region from the bottom trawl fishery in the Japanese waters of the Japan/East Sea during 1974–2004.

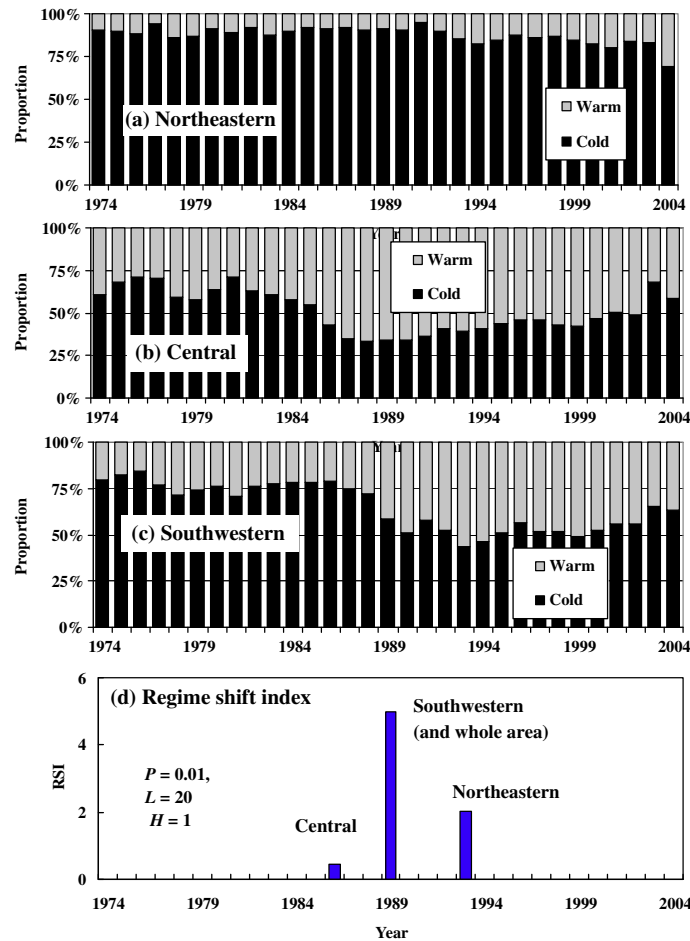


Fig. 12. Annual changes in the proportion of catches for the warm-water and cold-water species for the northeastern (a), central (b) and southwestern (c) regions, and the regime shift index (RSI) for proportion of species compositions estimated by STARS (d) from the bottom trawl in the Japanese waters of the Japan/East Sea during 1974–2004.

warming in the water temperature in the TWC region. This is consistent with Ishikawa et al. (2003), who found that water temperature in the TWC correlated significantly with AOI and MOI, and suggested that water structures of the semi-closed JES linked with large scale interaction between atmosphere and ocean. Using a complex empirical orthogonal function (EOF) analysis for a gridded water temperature, Minobe et al. (2004) identified one interannual and two decadal EOF modes in the JES. The interannual EOF mode was forced by local wind anomalies associated with sea level pressure (SLP) changes over the western North Pacific. The first decadal EOF mode with minimum amplitude around the mid-1970s and maximum amplitude in the late 1980s is likely caused by changes of the east Asian winter monsoon due to the SLP variability of the Siberian high, which is closely associated with the decadal fluctuation of AO and the North Atlantic Oscillation (NAO). The regime shift detected in the surface and subsurface water of the TWC in the late 1980s seemed to correspond to the first decadal EOF mode of Minobe et al. (2004) and is linked with the Asian monsoon and AO.

Despite the large seasonal and interannual variability in diatoms and zooplankton, results of PCA and STARS suggested strong decadal variability and a step change occurred around the late 1980s in the lower-trophic ecosystem in the JES (Fig. 6). Community structure analysis for the same PM line data revealed that the species composition of diatoms was largely different between the 1980s and 1990s and was related to climatic variability (Chiba and Saino, 2002; Kubo and Ebara, 1992). Zooplankton biomass in Korean waters in the JES increased greatly since the early 1990s

accompanied with changes in species composition, especially a decrease in copepods (Kang et al., 2002).

Results of PCA and STARS for fisheries catch data suggested that a regime shift occurred in the late 1980s (Figs. 8, 9 and 12). Our analyses largely depended on long-term fisheries time series. Egg abundance of Japanese sardine abruptly increased in the northeastern JES in 1989 with decline in the southwestern region, indicating northward shift in the spawning ground around 1989 (Goto, 1998), and resulted in the step change in the catch in 1994 (Fig. 9f). The step change in the catch of anchovy (Fig. 9e) in 1989 corresponded well with the trend in the egg abundance, which had negative anomalies during 1978–1989 and positive anomalies after 1990 (Goto, unpublished data). In addition, tagging experiments on long-lived, predatory yellowtail revealed its migration pattern varied among warm and cold regimes: during the warm 1950s and 1960s, they overwintered to the north of the Noto Peninsula, which is near to the Polar Front; however, during the cold 1970s and 1980s no overwintering young yellowtail were north of the Noto Peninsula (Ino et al., 2006). Long-term records of fork length of 0-year old yellowtail indicated interdecadal changes with smaller fish during 1976–1986, and larger during 1968–1975 and during 1988 to mid-1990 (Hiyama, 1998). The step change in the catch of yellowtail around 1989 (Fig. 9b) was accompanied by changes in fork length of young fishes and migration patterns. The large increase in the catch of other warm-water, predatory fishes such as tunas and Japanese–Spanish mackerel coincided with their northward extension in distribution (Tian et al., 2006; Tameishi et al., 2005). These results suggested that step changes in the fisheries

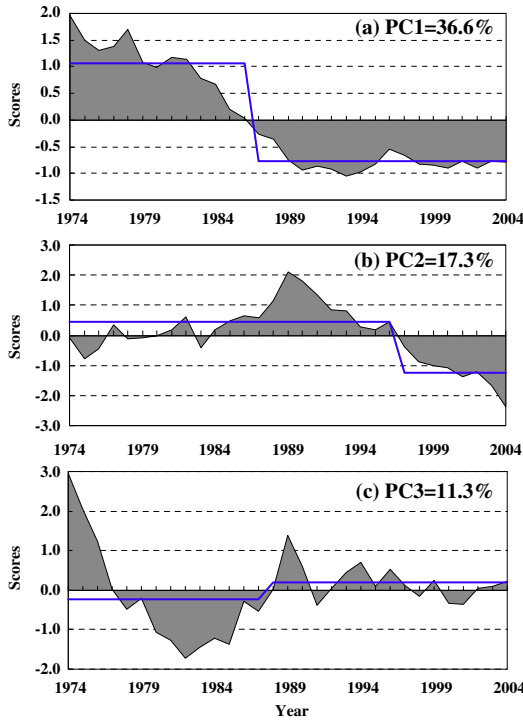


Fig. 13. The first three principal component (PC1–3) scores (shaded area) from the principal component analysis for the target species of the bottom trawl fishery in the Japan/East Sea during 1974–2004. The solid bold lines represent the step changes estimated by STARS.

data and abundance level in the late 1980s are due to changes in migration pattern, distribution and reproductive processes associated with changes in oceanic conditions.

The late 1980s regime shift was also identified in the fish community structure in the Korean waters of the JES (Zhang et al.,

2000, 2004), and in the Kuroshio water with an abrupt change in Pacific saury (Tian et al., 2004). Scale growth rates of chum salmon (*Oncorhynchus keta*) that returned to the east coast of Korea in the JES were higher in the 1990s than in the 1980s (Seo et al., 2006). Moreover, ecosystem regime shifts were detected in the Northeast Pacific and Bering Sea (Hare and Mantua, 2000; Wilderbuer et al., 2002) and North Sea (Reid et al., 2001; Corten, 2001; Beaugrand, 2004) around 1988. This coherency in different ecosystems, particularly in the higher latitude from the North Pacific to North Atlantic, indicated that the late 1980s regime shift in the ecosystem of TWC was a regional response to basin-scale climate–ocean variability, namely the late 1980s climatic regime shift detected in AOI and MOI.

4.3. Ecological response and control mechanism

To identify the control mechanism in the ecosystem, it is desirable to understand the relationships between lower and higher-trophic levels and between ecosystem components and physical factors. There were significant correlations between most of the biological/community indices (diatoms, catches by trophic group, DI, PCs and CPUEs of bottom trawl) and the water temperatures in TWC region, and between diatom and fish assemblages, but no strong correlations between zooplankton biomass and higher-trophic-level indices (Table 2), indicating that biological processes at each trophic level were largely affected directly by ocean conditions rather than through trophic interactions. In particular, decadal variability in diatom abundance (Fig. 6) indicated that the primary production in the TWC region was closely associated with the oceanic environment, implying bottom-up control on lower trophic level ecosystem (Chiba and Saino, 2002, 2003).

Demersal species (fishes and invertebrate) showed negative correlations with water temperature in winter and spring, while pelagic species correlated significantly with water temperature in summer (Table 2). The fish community in the JES is a mixture of warm- and cold-water species (Nishimura, 1966; Naganuma,

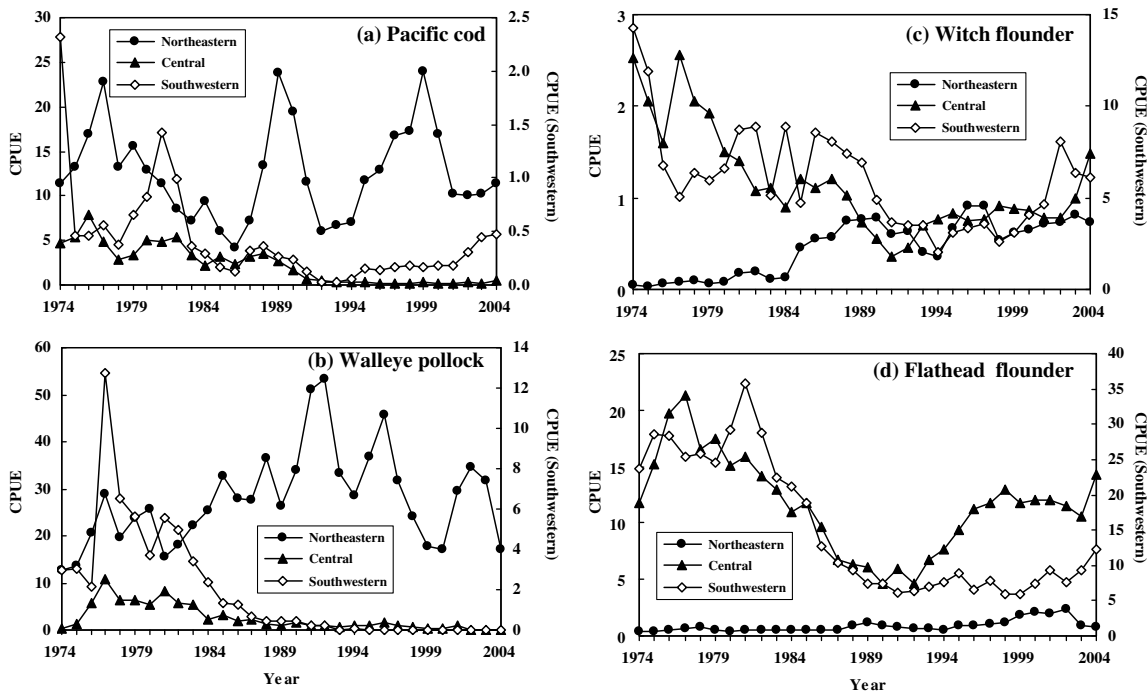


Fig. 14. Annual changes in the CPUEs (kg/haul) by region for four cold-water species during 1974–2004: (a) Pacific cod, (b) walleye pollock, (c) witch flounder and (d) flathead flounder.

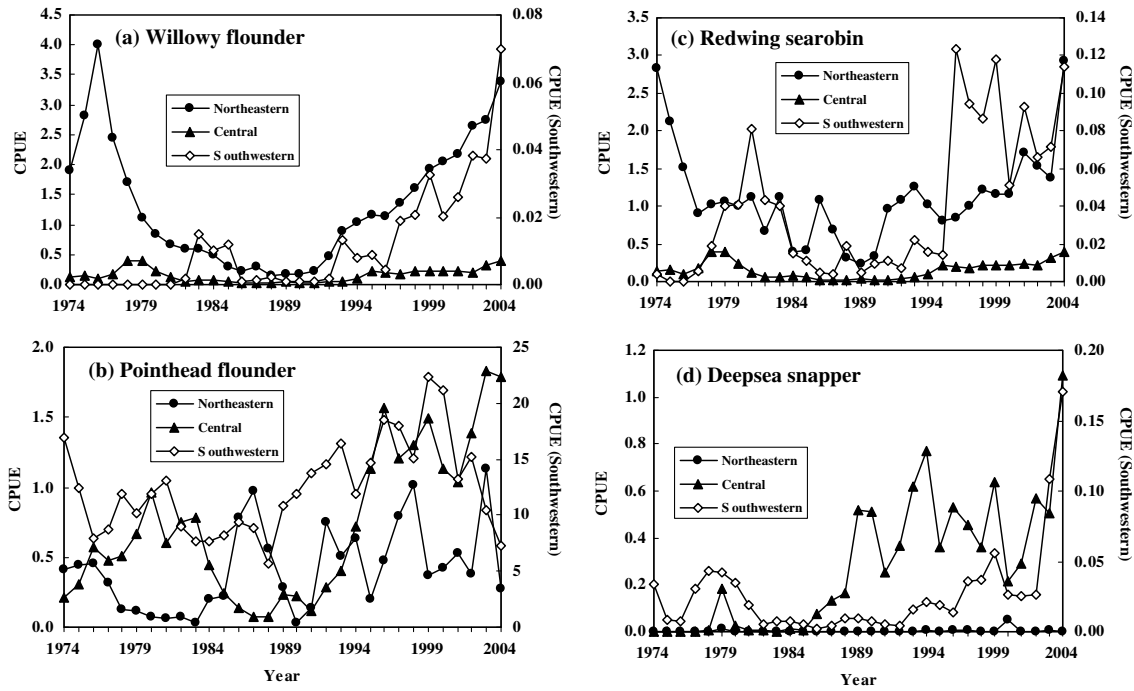


Fig. 15. Annual changes in the CPUEs (kg/haul) by region for four warm-water species during 1974–2004: (a) willowy flounder, (b) pointhead flounder, (c) redwing searobin and (d) deepsea snapper.

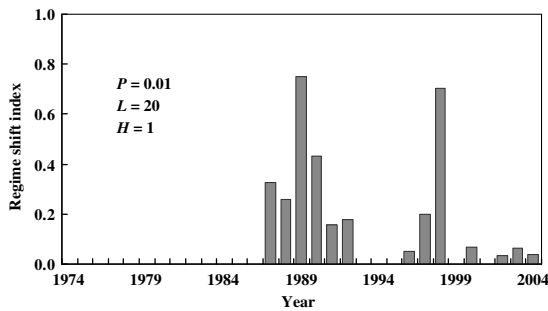


Fig. 16. Distributions of the regime shift index (RSI) estimated by STARS for 27 taxa bottom trawl CPUEs during 1974–2004.

2000); it is desirable to differentiate the warm-water species from the cold-water species because of their different responses to water temperature. Many cold-water species, such as Pacific cod and walleye pollock are demersal, complete their whole lives in the JES, spawn in winter through spring, and have reproduction and recruitment that depend on the ocean conditions in winter through spring. From this context they can be regarded as winter–spring type assemblages. On the other hand, many warm-water species such as yellowtail and common squid are mostly pelagic and migratory, and often only occur in the JES during summer through autumn. Their abundances in the JES largely depend on migration patterns; they can be regarded as summer–autumn type assemblages. As indicated from the CPUEs and catches of the bottom trawl fishery, water temperatures had positive (negative) effect on the warm- (cold-) water species. PC1 and PC2 from the PCA for the bottom trawl species, which were associated with warm- and cold-water species, respectively, had negative correlations with water temperature during winter–spring and summer–autumn, respectively (Table 2).

Our hypothesis for the ecological process of the late 1980s climatic regime shift is illustrated in Fig. 18. Although the role of trophic interactions on the higher-trophic levels needs further

examination, it is clear that the decadal variability in both lower and higher-trophic level ecosystems were directly linked with the climatic regime shift in the TWC region. During the cold regime in the 1980s, the Aleutian Low and Asian monsoon intensified and led to cold-water temperature in the JES, particularly in the TWC region. This cooling resulted in increased recruitment and southward distribution for cold-water species while limiting the northward migration of warm-water species, which had reduced abundance in the JES. With the shift from cooling to warming around the late 1980s, the pattern in the warm 1990s was opposite to that during the 1980s. The weaker Asian monsoon led to warmer winter water temperature and increased volume transport in the TWC (Ishikawa et al., 2003). This had a negative impact on the cold-water species, which were reduced in abundance and less broadly distributed in the southwestern JES. Conversely, warm summer temperature had a positive effect on the warm-water species. Step changes in warm-water species such as tunas, yellowtail and Japanese–Spanish mackerel (Fig. 9) corresponded to the change in summer water temperature (Tian et al., 2006).

Interdecadal patterns of zooplankton biomass are season specific. During winter zooplankton biomass has been lower since 1986 except during 1993–1995 (Fig. 6). On the other hand, zooplankton biomass in summer and autumn were generally higher during 1986–2000. The data from the PM line may be insufficient to identify the relationship between diatoms and zooplankton. Different variation patterns in spring and summer diatoms seemed to reflect different community structure: diatoms in spring are dominated by cold-water species while diatoms in summer are dominated by warm-water species (Kubo and Ebara, 1992). Opposite patterns between diatom abundance and zooplankton biomass in both spring and autumn suggested the complexity of trophic interactions and the need for species level data rather than bulk biomass estimates. The ecological response of the late 1980s regime shift suggests a possible bottom-up control mechanism. It appears that each trophic level may be directly influenced by physical conditions, but it is difficult to rule out trophic interactions (e.g., zooplankton–phytoplankton; predator–prey interactions).

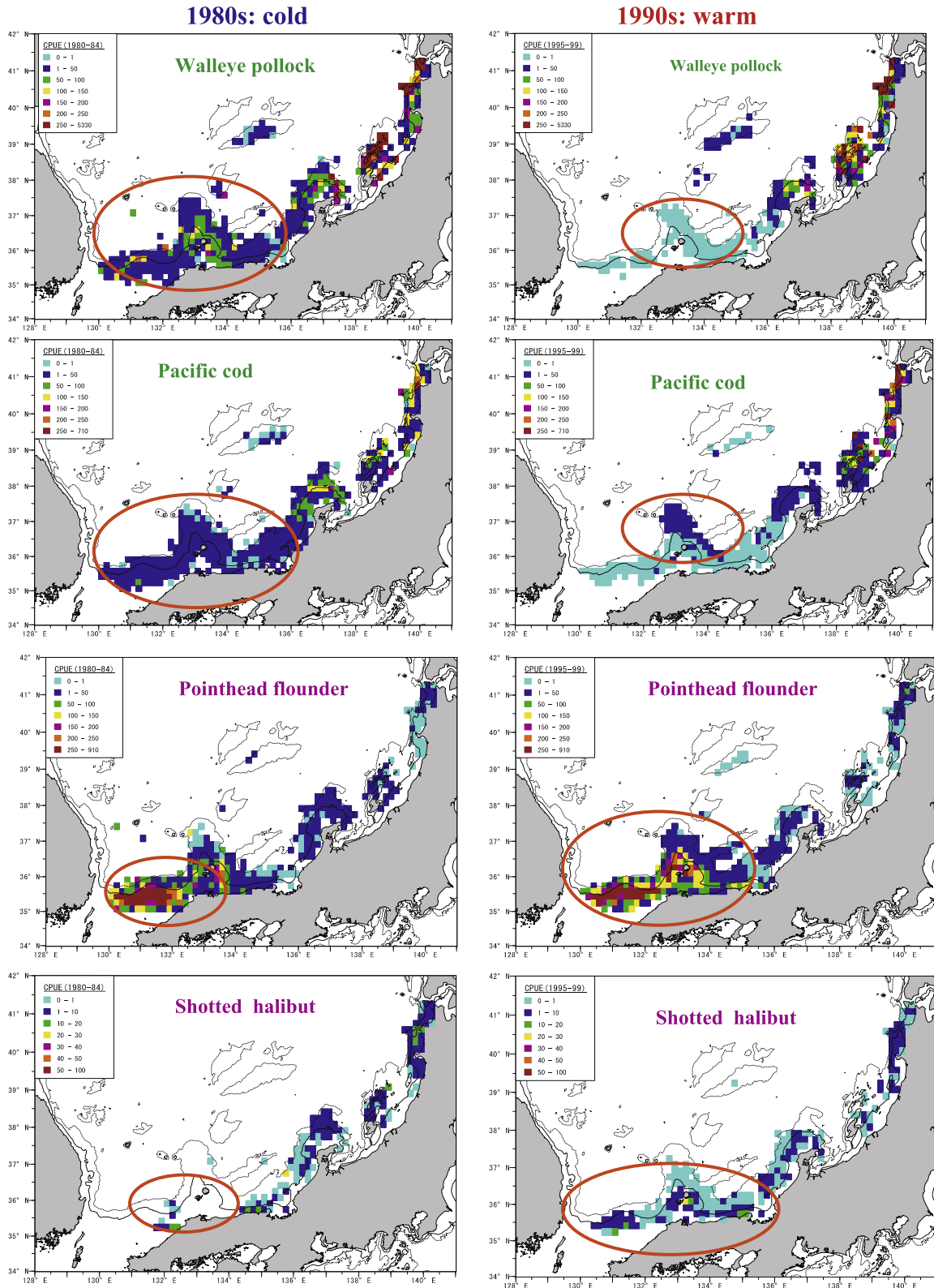


Fig. 17. GIS mappings showing the change in CPUEs (kg/haul) between cold 1980s (the left panel: averages for five years during 1980–1984) and warm 1990s (right panel: averages for five years during 1995–1999) for four indicator species (from top to bottom: walleye pollock, Pacific cod, pointhead flounder and shotted halibut). The yellow circles indicate areas that changed notably.

The 1976/1977 global regime shift was not evident in oceanographic conditions and ecosystem components in the JES compared with the late 1980s regime shift. Yasunaka and Hanawa (2002) identified six regime shifts (1925/1926, 1945/1946, 1956/1967,

1970/1971, 1976/1977 and 1988/1989) in the northern hemisphere SST field in the last century. The 1976/77 regime shift, which largely was associated with ENSO and PDO, was more evident in the central and northeast Pacific than in the western Paci-

Table 2
Correlation coefficients between climatic/oceanographic indices, and biological/community indices

	SOI	PDO	AOI	MOI	WTwin	WTspr	WTsum	WTaut	PHYspr	PHYsum	PHYaut	ZOOspr	ZOOsum	ZOOaut
WTwin	-0.09	-0.25	0.39*	-0.70**	-	-	-	-	-	-	-	-	-	-
WTspr	-0.12	-0.26	0.36*	-0.68**	0.86**	-	-	-	-	-	-	-	-	-
WTsum	-0.08	-0.33*	-0.01	-0.51**	0.56**	0.67**	-	-	-	-	-	-	-	-
WTaut	-0.07	0.06	0.07	-0.45**	0.43**	0.43**	-0.52**	-	-	-	-	-	-	-
PHYwin	-0.07	-0.06	0.05	-0.01	0.07	-0.01	0.06	0.12	-	-	-	-	-	-
PHYspr	-0.06	0.27	-0.17	0.32	-0.47**	-0.56**	-0.52**	-0.32	-	-	-	-	-	-
PHYsum	-0.16	-0.42*	0.32	-0.31	0.43*	0.41*	0.45**	0.41*	-0.40*	-	-	-	-	-
PHYaut	-0.31	0.20	0.10	-0.15	-0.01	-0.04	-0.23	-0.10	0.30	0.04	-	-	-	-
ZOOwin	0.14	-0.01	0.02	0.28	-0.24	-0.20	-0.23	-0.32	0.15	-0.19	0.28	-	-	-
ZOOSpr	0.09	-0.16	0.04	0.24	-0.05	0.15	0.06	0.04	-0.51**	0.18	0.01	-	-	-
ZOOsum	0.05	-0.20	0.11	0.05	0.01	0.13	0.19	0.04	-0.04	0.05	-0.08	0.24	-	-
ZOOaut	0.05	-0.29	0.23	-0.20	0.33	0.30	0.21	0.06	-0.11	0.17	0.09	0.25	0.26	-
Largepela	0.14	-0.42**	-0.15	0.22	0.04	0.07	0.38*	0.12	-0.48**	0.37*	-0.47**	0.23	0.06	-0.01
Smallpela	-0.13	0.28	0.21	-0.11	-0.15	-0.22	-0.51**	-0.20	0.57**	-0.28	0.44**	-0.28	-0.11	0.12
Demersal	0.20	-0.38*	-0.31*	0.42**	-0.49**	-0.33*	-0.02	-0.43**	0.04	-0.13	-0.28	0.15	-0.03	-0.10
Invertebrate	0.02	0.29	-0.30	0.37*	-0.64**	-0.63**	-0.49**	-0.29	0.53**	-0.29	0.06	-0.29	-0.19	-0.25
DI	0.17	-0.28	-0.27	0.20	0.04	0.13	0.41**	0.11	-0.53**	0.22	-0.42*	0.37*	0.16	-0.08
PC1_pela	0.25	-0.38*	-0.33*	0.41**	-0.50**	-0.34*	0.03	-0.34*	0.02	-0.12	-0.26	0.20	0.04	-0.09
PC2_pela	0.13	-0.24	0.02	-0.01	0.36*	0.37*	0.48**	0.35*	-0.60**	0.32	-0.41**	0.30	0.15	-0.04
PC1_deme	0.21	-0.36*	-0.36*	0.40*	-0.47**	-0.34	0.06	-0.40**	0.01	-0.14	-0.29	0.14	0.00	-0.09
PC2_deme	-0.03	0.14	-0.03	0.18	-0.43**	-0.38*	-0.48**	-0.22	0.51**	-0.27	0.08	-0.15	-0.15	-0.11
CPUE_BTcw	0.04	-0.17	-0.30	0.49**	-0.47**	-0.31	-0.25	-0.32	0.15	-0.10	-0.22	0.07	-0.13	-0.45**
CPUE_BTww	0.06	-0.21	0.20	-0.28	0.67**	0.61**	0.55**	0.59**	-0.57**	0.40*	-0.21	0.26	0.18	0.14
CATCH_BTcw	-0.06	-0.02	-0.32	0.49**	-0.64**	-0.50**	-0.44*	-0.45*	0.44*	-0.22	-0.06	-0.11	-0.18	-0.36*
CATCH_BTww	-0.07	-0.17	0.29	-0.36	0.57**	0.50**	0.33	0.45*	-0.27	0.35	0.10	0.10	0.18	0.34
PC1_BT	0.11	-0.03	-0.39*	0.49**	-0.58**	-0.46**	-0.29	-0.34	0.24	-0.18	-0.15	0.03	-0.10	-0.35
PC2_BT	-0.18	-0.06	0.31	-0.11	-0.22	-0.19	-0.44*	-0.37*	0.36	-0.17	0.25	-0.13	0.05	0.28
PC3_BT	0.29	-0.44*	0.41*	0.00	0.13	0.19	0.03	-0.02	-0.40*	-0.01	-0.23	0.32	0.24	0.05

SOI: Southern Oscillation Index; PDO: Pacific Decadal Oscillation Index; MOI: Winter Asian Monsoon Index; AOI: Arctic Oscillation Index; WTwin, WTspr, WTsum and WTaut represent the 50 m depth water temperature in the Japan/East Sea, in winter, spring, summer and autumn, respectively. PHYwin, PHYspr, PHYsum and PHYaut represent cell number of diatoms in winter, spring, summer and autumn, respectively. ZOOwin, ZOOSpr, ZOOsum and ZOOaut represent zooplankton biomass in winter, spring, summer and autumn, respectively. Largepela, Smallpela, Demersal and Invertebrate represent the catch for piscivores, small pelagic, demersal and invertebrate groups, respectively. DI represent estimated Simpson's diversity index in the Japan/East Sea. PC1_pela, PC2_pela, PC1_deme and PC2_deme represent the first two principal components (PC1-2) for the pelagic and demersal groups (Fig. 8), respectively. CPUE_BTcw, CPUE_BTww, CATCH_BTcw and CATCH_BTww represent CPUE and CATCH of bottom trawl for cold-water and warm-water species, respectively. PC1_BT, PC2_BT and PC3_BT represent the first three principal components for the target species of bottom trawl (Fig. 13), respectively. Indices related to bottom trawl are for the period of 1974–2004, diatom and zooplankton are for 1972–2004, the other indices are for 1964–2004, respectively. Single and double asterisks represent significance at $P < 0.05$ and $P < 0.01$, respectively.

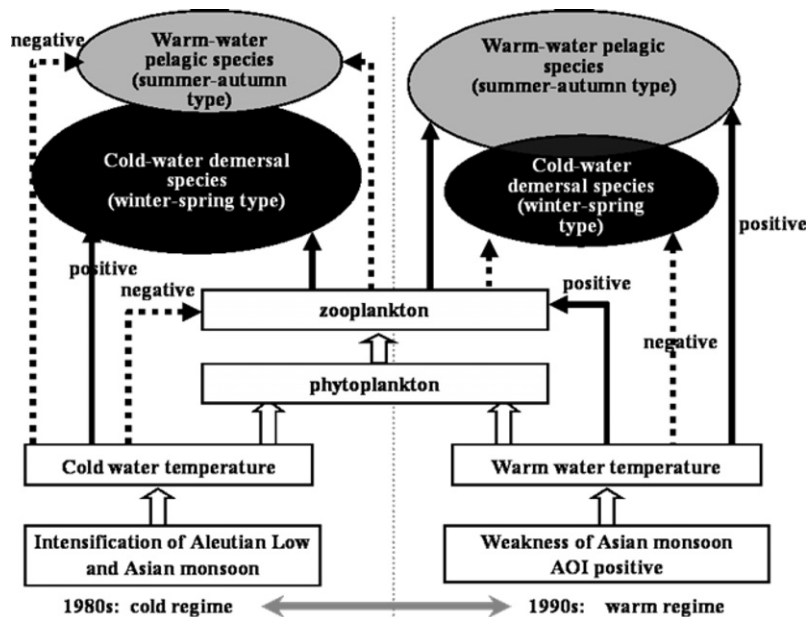


Fig. 18. Illustration showing our hypothesis on the ecological response process to the late 1980s regime shift in the Tsushima warm current of the Japan/East Sea. The solid, broken, and white arrows indicate positive, negative, and direct effects, respectively.

fic. The 1988/1989 regime resulted from the Asian monsoon and AO, and had large impacts on mid-high latitudes of the western Pa-

cific (Yasunaka and Hanawa, 2002; Minobe et al., 2004), and were consequently responsible for the late 1980s changes in the JES. Our

PCA analysis shows that pelagic species, such as Japanese sardine, Pacific saury and common squid responded strongly to the mid-1970s regime shift (Fig. 9). It is known that chlorophyll-*a* concentration and zooplankton biomass changed in the mid-1970s and were associated with ENSO (Chiba et al., 2005; Kang et al., 2002), and hence affected the small pelagic species because they are directly linked to the lower trophic level ecosystem. The late 1980s ecosystem regime shift in the TWC was directly forced by the decadal climatic–oceanic variability, primarily through shifts in distribution and migration patterns.

It is difficult to evaluate the impacts of fishing on the ecosystem in the TWC because we lack appropriate fishing effort data. Analysis on fishing effort for three major fisheries (set net, bottom trawl and purse seine) suggest that the abrupt change in fish community structure in the late 1980s was forced by environmental changes rather than by fishing (Tian et al., 2006). However, the increase in catch during the 1950s and 1960s was associated with increased fishing effort using improved technologies and exploitation of new fishing grounds (Fukataki, 1974). Fishing effort may have been an important driver of the pattern observed in mean trophic level (MTL) when catches increased during the 1960s (Tian et al., 2006). The dramatic changes in the fish assemblages in the late 1980s were obviously connected to climate and not fishing.

5. Conclusions

In summary, the following conclusions may be drawn:

- (1) A climatic regime shift from cold to warm water was identified in the TWC region in the late 1980s and is linked with the Asian monsoon and AO. Cooling was limited in the TWC region during the 1970s but expanded to the whole JES in 1980s. The entire JES underwent warming in the 1990s and the warming tended to be limited to the TWC region during the early 2000s, indicating a decadal-scale variation pattern between the TWC region and continental waters.
- (2) Diatom abundance and zooplankton biomass showed decadal variability with large seasonal and interannual variations. Step changes were detected in springtime diatom abundance and zooplankton biomass in spring around 1991–1992; however, the patterns were opposite between diatom and zooplankton biomass in both spring and autumn. Lower trophic levels in the JES seemed to respond to the late 1980s climatic regime shift.
- (3) For the fish community, step changes during the late 1980s to early 1990s were identified in small pelagics, in predatory fishes, and in demersals. The timing of the step change in the data lagged the environmental change due to the age compositions of the catch, suggesting that recruitment changed in the late 1980s.
- (4) PCA shows that both the pelagic and demersal fish assemblages show decadal variability with a step change in 1988 but different response patterns. The PC1 from the bottom trawl data also indicated a step change in 1987.
- (5) Both abundance and distribution patterns in the demersal species from the bottom trawl fishery changed around the late 1980s. The response was different for cold- and warm-water species: warm-(cold-) water species increased (decreased) their abundance and extended (reduced) their distribution during the warm regime, and vice versa.
- (6) Pronounced changes, identified in most biological/fisheries indices spanning diatoms to top-predators, strongly suggest an ecosystem regime shift occurred in the TWC region in the late 1980s. These changes were directly forced by the decadal climatic–oceanic variability such as the Asian monsoon and AO.

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