

# Japan

Akihiko Yatsu

National Research Institute of Fishery Science, Fisheries Research Agency, 2-12-14, Fukuura, Kanazawa, Yokohama 236-8648, Japan. Email: [yatsua@fra.affrc.go.jp](mailto:yatsua@fra.affrc.go.jp)

## The Fishery

Seafood has always been a significant part of the Japanese diet and today accounts for about 40% of the protein consumed by Japanese people. Domestic marine fisheries are generally divided into coastal fisheries, offshore fisheries, and distant-water fisheries (Table 9). From 1972 to 1988, Japan had the world's largest fisheries. Catches increased through to 1984 with the maximum production of 12,820,000 t. The total catch of all marine species declined from the maximum in 1984 to 3,734,209 t in 2000 (Fig. 17). This was a change from 16.0% of the world's catch in 1984, to 5.1% in 2000. In recent years, the fishery in China reportedly exceeds Japanese production. At present, Japan is the largest importer of fish products in the world. Approximately one third of the world catch in weight is exported, and Japan imports about 15% in weight, or one quarter in value, of all exported fish products. The decline in catch in recent years (Fig. 17) is related to the natural decline in Japanese sardine abundance in the 1990s and the reduced catches in distant-water fisheries (Table 9, Fig. 18).

## Climate and Ocean Influences

A major influence on the production of fish in the Japanese coastal and offshore fisheries is the structure and dynamics of the subarctic current, the Oyashio, the subtropical currents, the Kuroshio and Tsushima, and the transition area between the Oyashio and Kuroshio (Fig. 19). The changes in currents affect vertical mixing, which alters the supply of nutrients to the surface production zone, as well as migration and larvae transportation. Changes in nutrient supply affect primary production which, in turn, changes the abundance and species of zooplankton which are the principal food of fishes. Mechanistic linkages between climate and physical oceanographic changes and stock productivity generally occur through bottom-up scenarios. In the Oyashio area, the major feeding grounds of sardine, chub mackerel, saury, common squid, and many other species, zooplankton density since the 1970s has been negatively correlated with sardine biomass; other processes controlling the sardine population may be occurring (Taniguchi, 1999). Chiba *et al.* (2004) concluded that annual production of copepods

**Table 9** Japanese domestic fishery production.

	Percentage of total					
	1975	1980	1985	1990	1995	2000
Distant water fisheries	31	20	18	14	13	14
Offshore fisheries	43	52	54	56	45	41
Coastal fisheries*	26	28	28	30	43	45
Total (in 1,000 t)	10,346	10,900	11,965	10,843	7,322	6,252

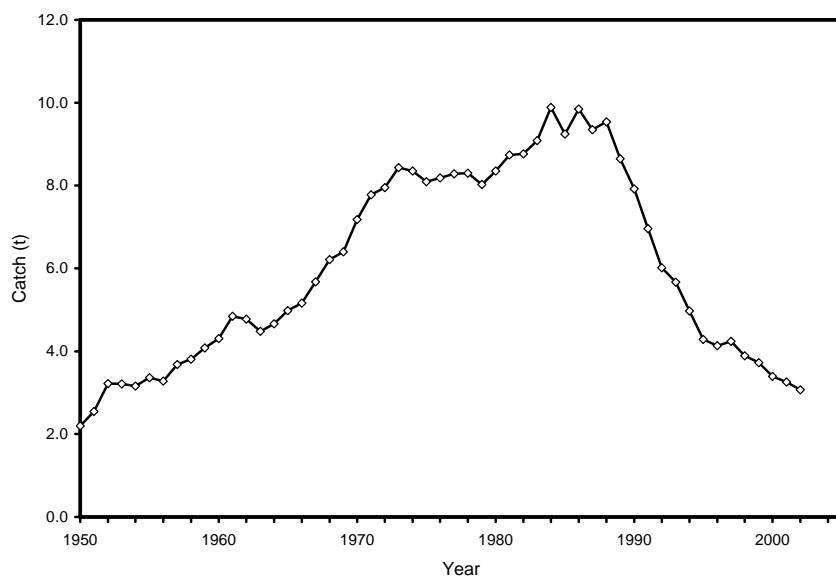
Source: Japan Ministry of Agriculture, Forestry, and Fisheries,  
\* including capture fisheries and aquaculture

since the 1960s, along the “PH line” ( $41^{\circ}30'N$ ,  $142^{\circ}E$ – $147^{\circ}E$ ), representing the Oyashio, has decreased because of the attenuation of winter mixing.

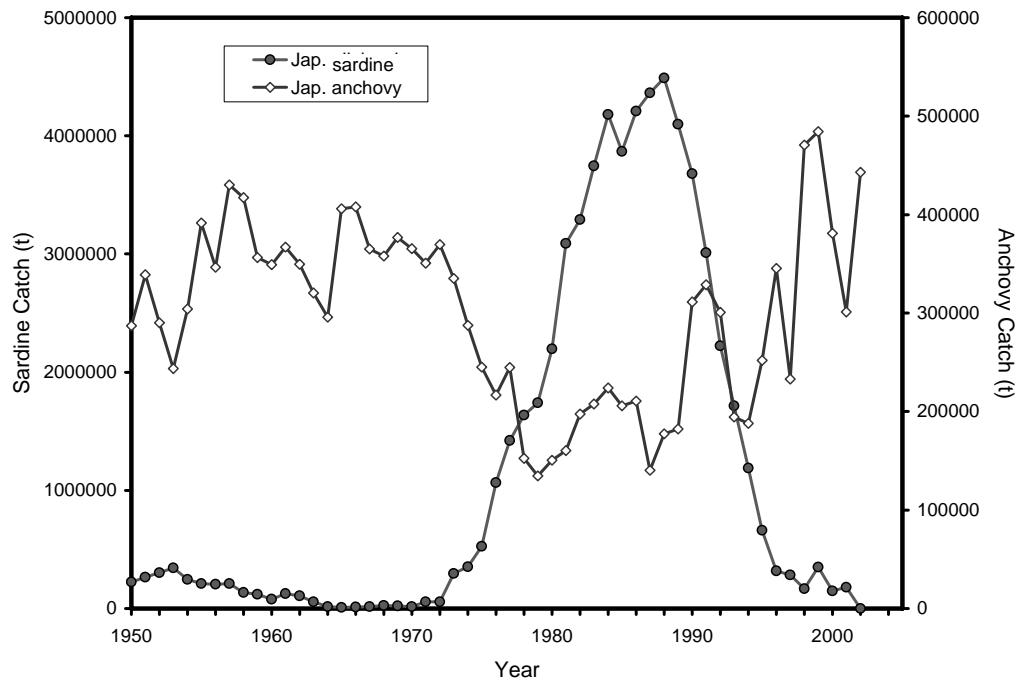
The biomass of large- and small-sized copepods from 1971 to 1989 in Kuroshio area was affected by Kuroshio meandering and winter solar radiation, respectively (Nakata *et al.*, 2001). The composition of zooplankton size and timing of the spring bloom in Tsushima, Kuroshio, and Kuroshio Extension would have significant effects on survival and growth of juvenile fishes, and thus on recruitment. The observed species replacements among small pelagics may be partly explained by such differences in availability of suitable zooplankton. The period of the large Kuroshio meandering, called “A-type”, coincided with that of an intensified subtropical gyre and westerly winds. In the northwestern area of the subtropical gyre, intensification of wind speed and destratification of surface waters generally result in a decrease of zooplankton biomass (Sugimoto and Tadokoro, 1998). The mixed layer depth during the positive Pacific Decadal Oscillation (PDO) period (1977–1988) was 30 to 80% deeper than the negative PDO period (1960–1976) in the subtropical and transition areas of the North Pacific, whereas the mixed layer depth was 20 to 30% shallower in the subarctic area (Polovina *et al.*, 1995). During the positive PDO period, zooplankton production is considered to increase by enhanced nutrient supply in the subtropical area (Taniguchi, 1999). Polovina *et al.* (1995) observed that the mixed layer depth in

the Oyashio area was approximately 10% deeper during 1977–1988 relative to the 1960–1976 level. The decadal change in mixed layer depth did not significantly affect the declining trend in lower trophic level production in the Oyashio area (Chiba *et al.*, 2004). Therefore, the effects of greenhouse gas production on water density and salinity may be more significant for low trophic production in the Oyashio area than in the PDO-related mixed layer depth.

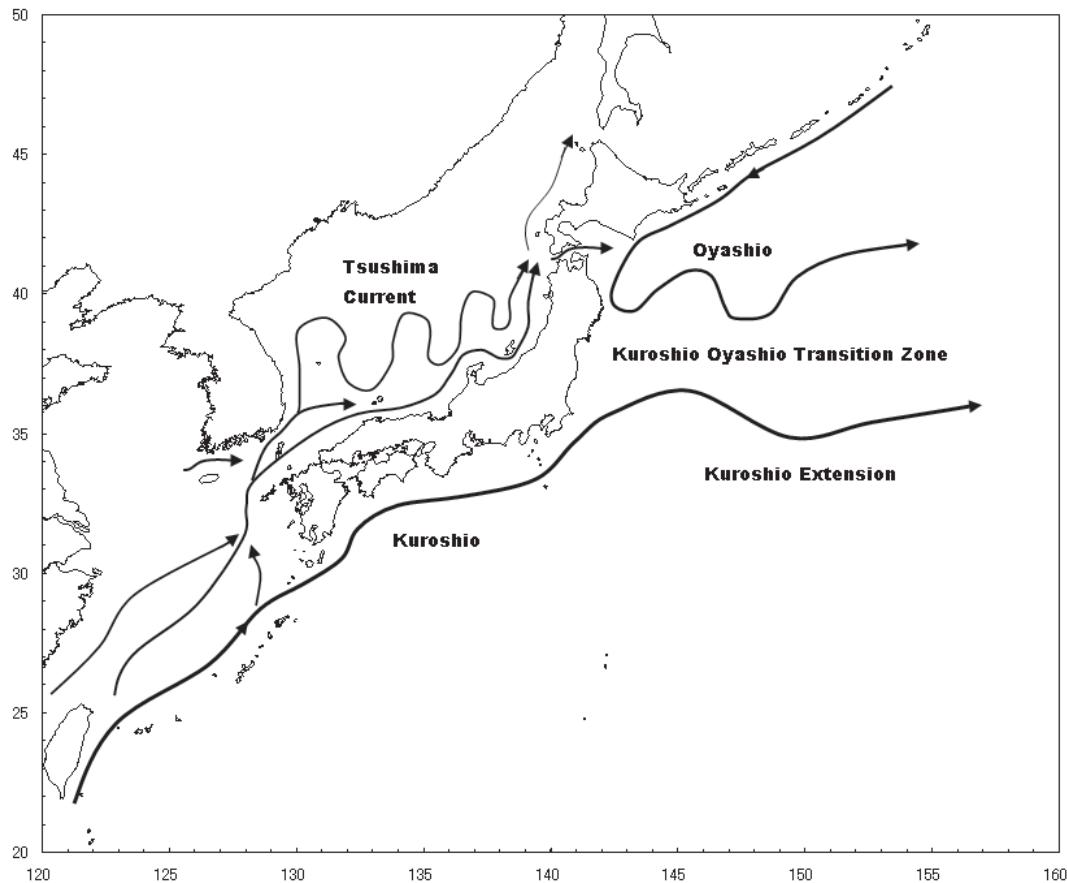
If winds are reduced by future warming of the ocean, the primary production in the seas around Japan may be reduced because of reduced vertical mixing in winter. Warming could also reduce the nutrient supply to the subarctic gyre and thus decrease primary production in the Oyashio region. However, variation in zooplankton biomass off Sanriku had a positive correlation with sea surface temperature (SST) and sunshine at Nemuro and a negative correlation with sea level pressure at Nemuro in the Oyashio (Fig. 20, Tomosada and Odate, 1995). Thus, higher SST and stormier conditions would improve productivity, although low zooplankton biomass in the Oyashio, Kuroshio and transition waters during the 1980s may have been caused by mass predation by Japanese sardine (Taniguchi, 1999). In general, the impacts of climate and ocean changes vary among areas and species, and the impacts are poorly understood, but it is clear that climate and ocean conditions are major influences in the production of fishes in the seas around Japan.



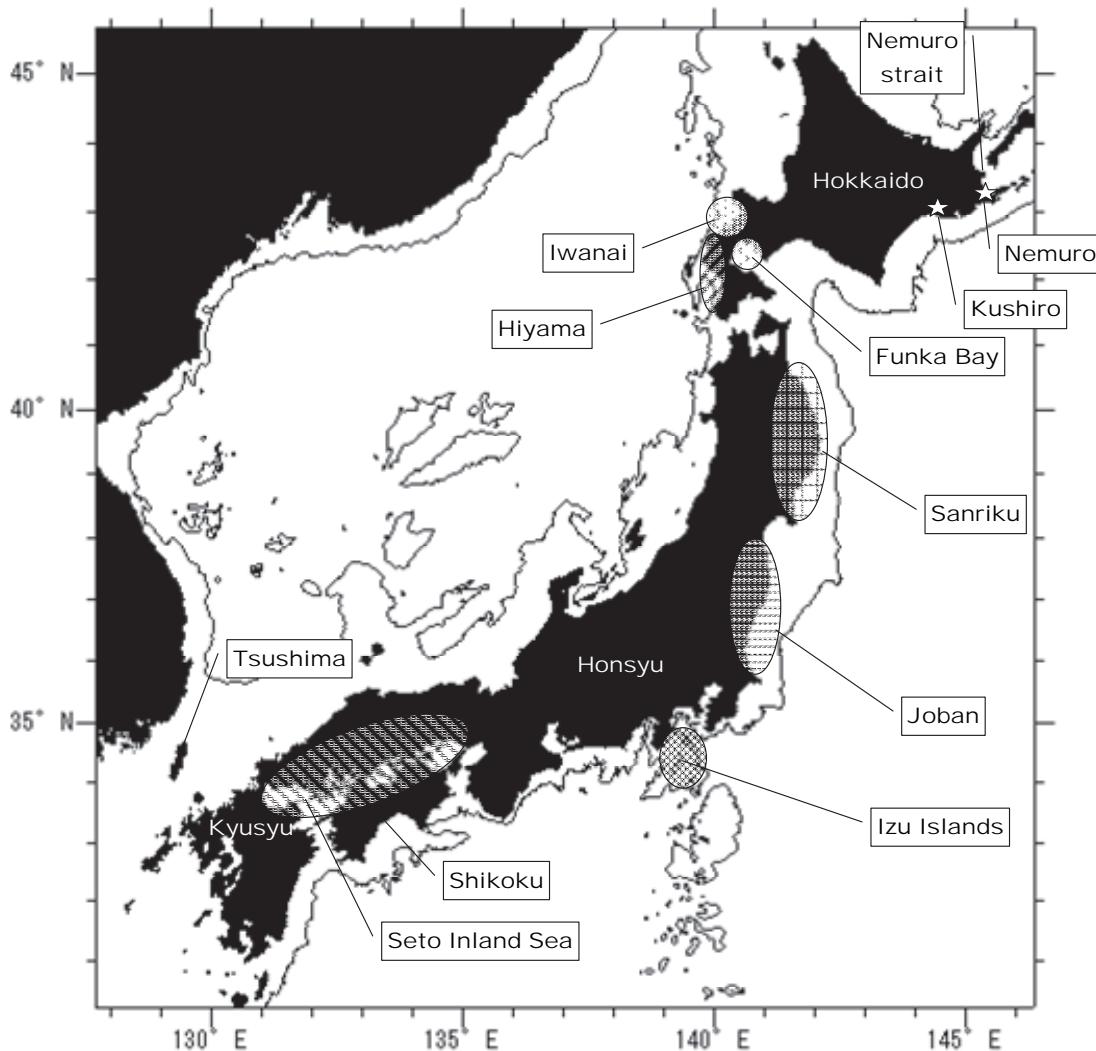
**Fig. 17** Total marine catch by Japan from 1950 to 2002 (FAO data).



**Fig. 18** Japanese sardine and anchovy catch by Japan from 1950 to 2002 (FAO data).



**Fig. 19** Major ocean current systems around Japan.



**Fig. 20** Map showing key locations (cross-hatched ovals, and stars) and islands mentioned in the text, and 1000 m isobath around Japan.

## Key Species in the Fishery

In our report, a stock is considered to be an aggregation of individuals that are fished as one unit. The definition does not imply that there are genetic differences among stocks. A population is a large aggregation of individuals or stocks that have discrete migration patterns, spawning areas and/or spawning seasons, although there may be migrations of individuals among populations. In this study we consider the impacts of climate and climate change on nine species (Table 10) that represented approximately 58 to 80% of the total catch between 1980 and 2000. Biomass and indices of production rates of selected stocks are shown in Figs. 21–24.

## Chub mackerel (*Scomber japonicus*)

### Biology

Chub mackerel mature mostly at an age of 2 years and a fork length of 32 cm (Yatsu *et al.*, 2002; Watanabe and Yatsu, 2004). Spawning occurs during winter and spring in the area around the Izu Islands (Fig. 20), East China Sea and southern Japan Sea. The Oyashio Current is a major feeding and rearing area in the Pacific Ocean. The fisheries for chub mackerel target a wide range of size, including immature fish, which have been heavily fished since the 1990s. They feed on zooplankton, squids and fishes, particularly anchovy.

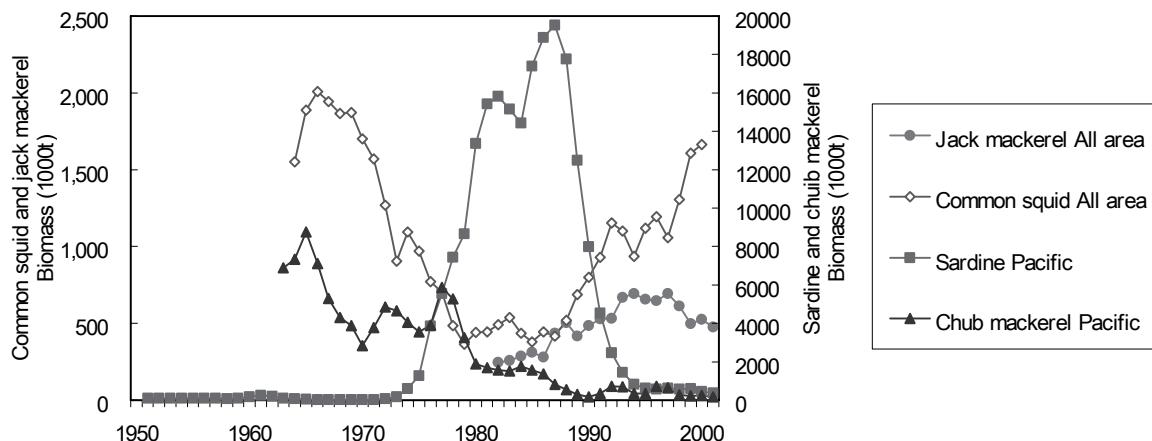
**Table 10** Catches of key species and their combined percentage of the total catch in t (FAO).

	1980	1985	1990	1995	2000
Chub mackerel	1,300,994	771,764	272,477	469,447	346,220
Jack mackerel	56,177	158,073	227,837	317,993	249,040
Japanese sardine	2,197,744	3,866,928	3,678,229	661,391	149,616
Anchovy	150,604	205,824	311,427	251,958	381,020
Alaska (walleye) pollock	1,552,429	1,533,179	871,408	338,507	300,001
Chum salmon	87,713	167,960	207,989	249,982	151,123
Pacific saury	187,155	245,944	308,271	273,510	216,471
Common squid*	330,464	132,519	209,390	290,273	337,285
Neon flying squid**	552,722	462,044	549,410	435,772	28,271
Total	6,416,002	7,544,235	6,636,438	3,288,833	2,159,047
% of all species	75.42%	79.50%	80.19%	69.83%	57.81%

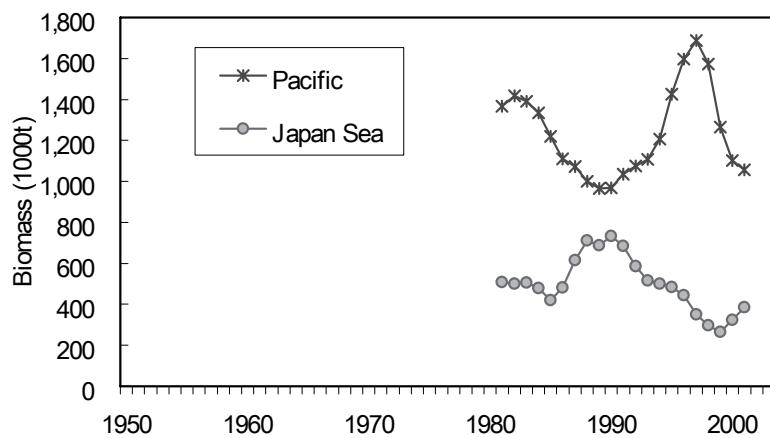
Source: FAO.

\* referred to as "Japanese flying squid" in FAO statistics,

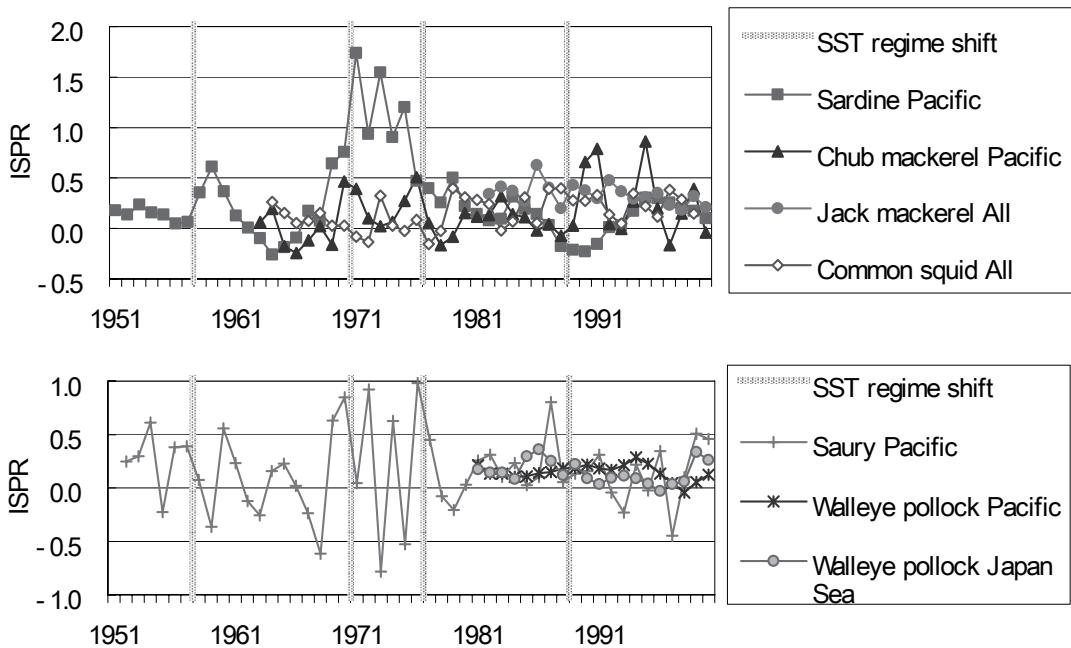
\*\* after Yatsu *et al.* (2000)



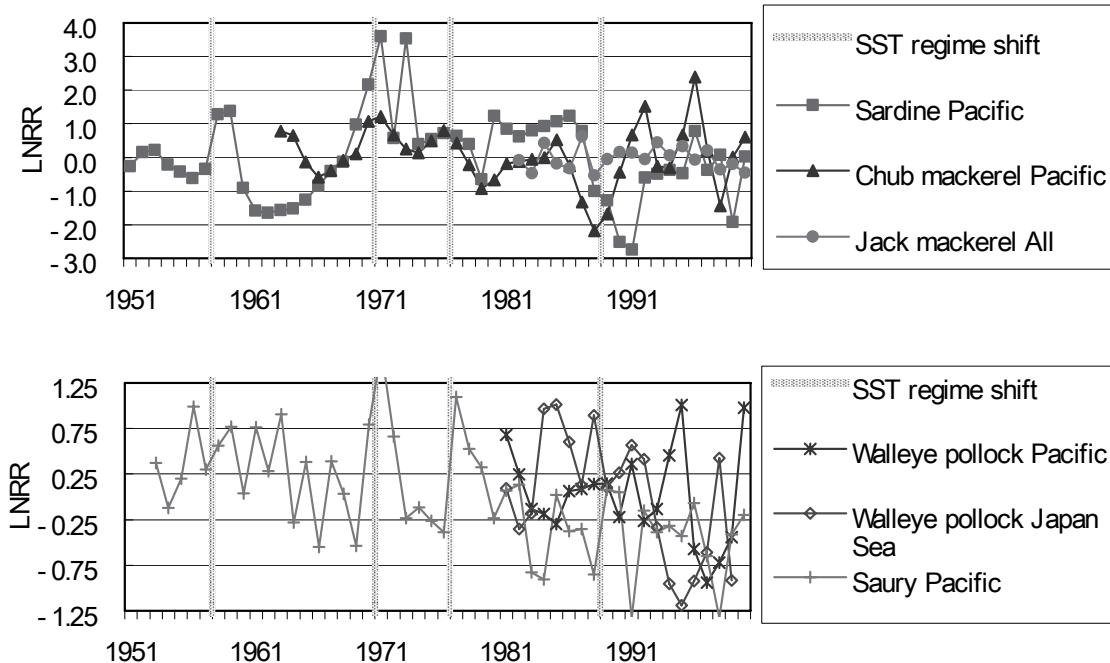
**Fig. 21** Biomass of Japanese sardine (Pacific stock), chub mackerel (Pacific stock), jack mackerel (two stocks combined) and common squid (two stocks combined).



**Fig. 22** Biomass of the Pacific stock and the northern Japan Sea stock of walleye pollock.



**Fig. 23** Trajectories of instant surplus production rates (ISPR) of seven stocks around Japan. Years of SST (sea surface temperature) regime shifts follow Yasunaka and Hanawa (2002).



**Fig. 24** Trajectories of logarithm of recruitment number residuals from Ricker curves (LNRR) of six fish stocks around Japan.

## Fishery

Two stocks, the Tsushima Current stock and the Pacific stock, contribute to the catch. The Tsushima Current stock is distributed in the East China Sea, Yellow Sea, Bohai Sea, and the Japan Sea (Fig. 19). The Pacific stock is distributed along the Pacific coast of Japan and east to the Central North Pacific Ocean, including inside of the Exclusive Economic Zone (EEZ) of Russia (Belyaev and Ivanov, 1987). Migration between the Pacific stock and the Tsushima Current stock has been reported, but is believed to be rare.

### Climate and ocean effects

Productivity of the Pacific stock was high in the early 1970s (Figs. 23 and 24) and catches were high in the 1980s when the PDO was generally negative (Table 11). The productivity tends to be similar to

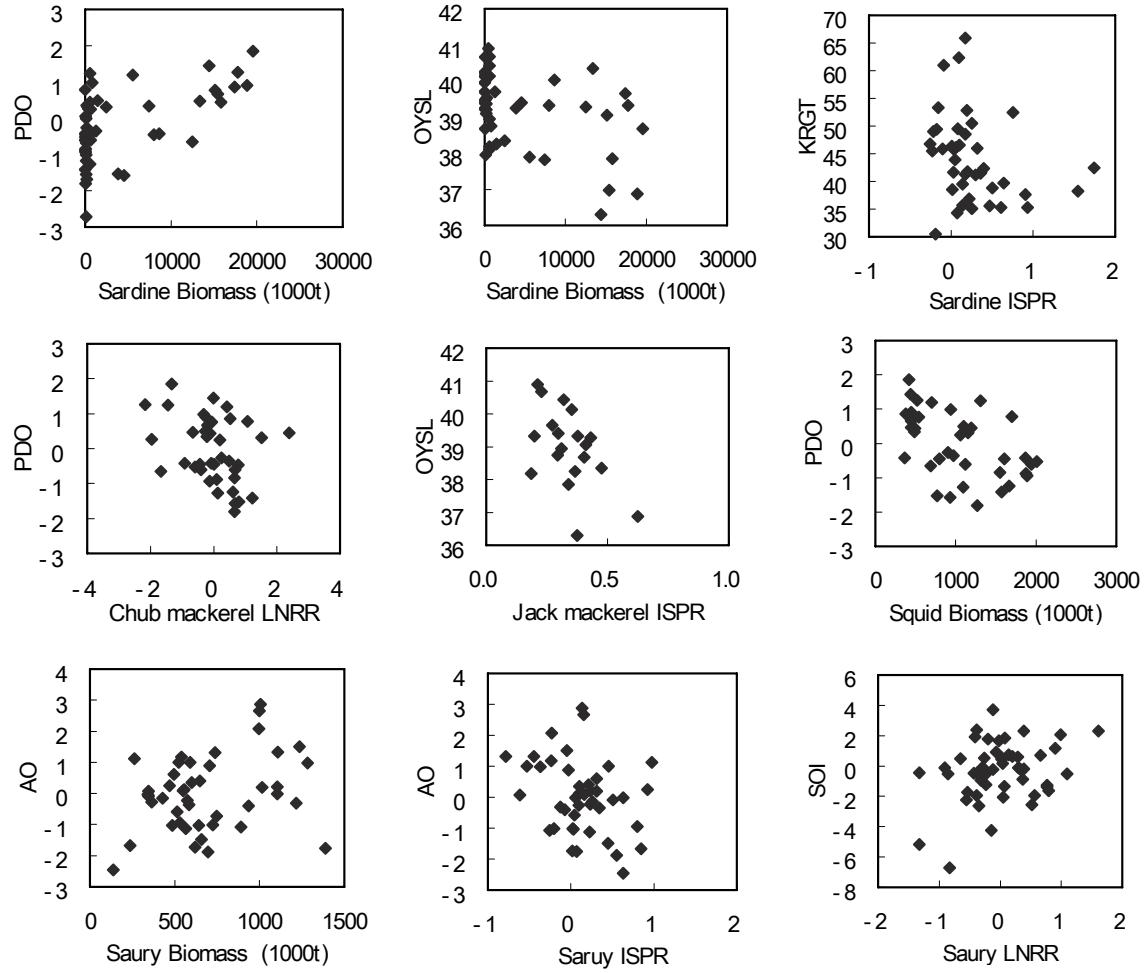
that of the Japanese sardine and Pacific saury. After the 1989 regime shift, chub mackerel did not recover, possibly as a consequence of the extensive fishing effort, especially for immature fish (Yatsu *et al.*, 2002). Productivity of the Pacific stock was negatively related to the PDO without a lag (Fig. 25). The biomass of the Pacific stock of chub mackerel appears to be negatively related to PDO with a 1-year lag (Fig. 26) and SST of the northern Izu Islands in winter within the Kuroshio, which suggests that there is a relationship between SST and spawning success (Yatsu *et al.*, 2005). There was a distinct reduction in production (and catch) following the 1977 regime shift of the PDO to a positive state indicating that decadal-scale variability affects recruitment. Sardine biomass also negatively affected the reproductive success of the Pacific stock of chub mackerel due to possible competition for prey during the larval stage (Yatsu *et al.*, 2005).

**Table 11** Chub mackerel catches (t).

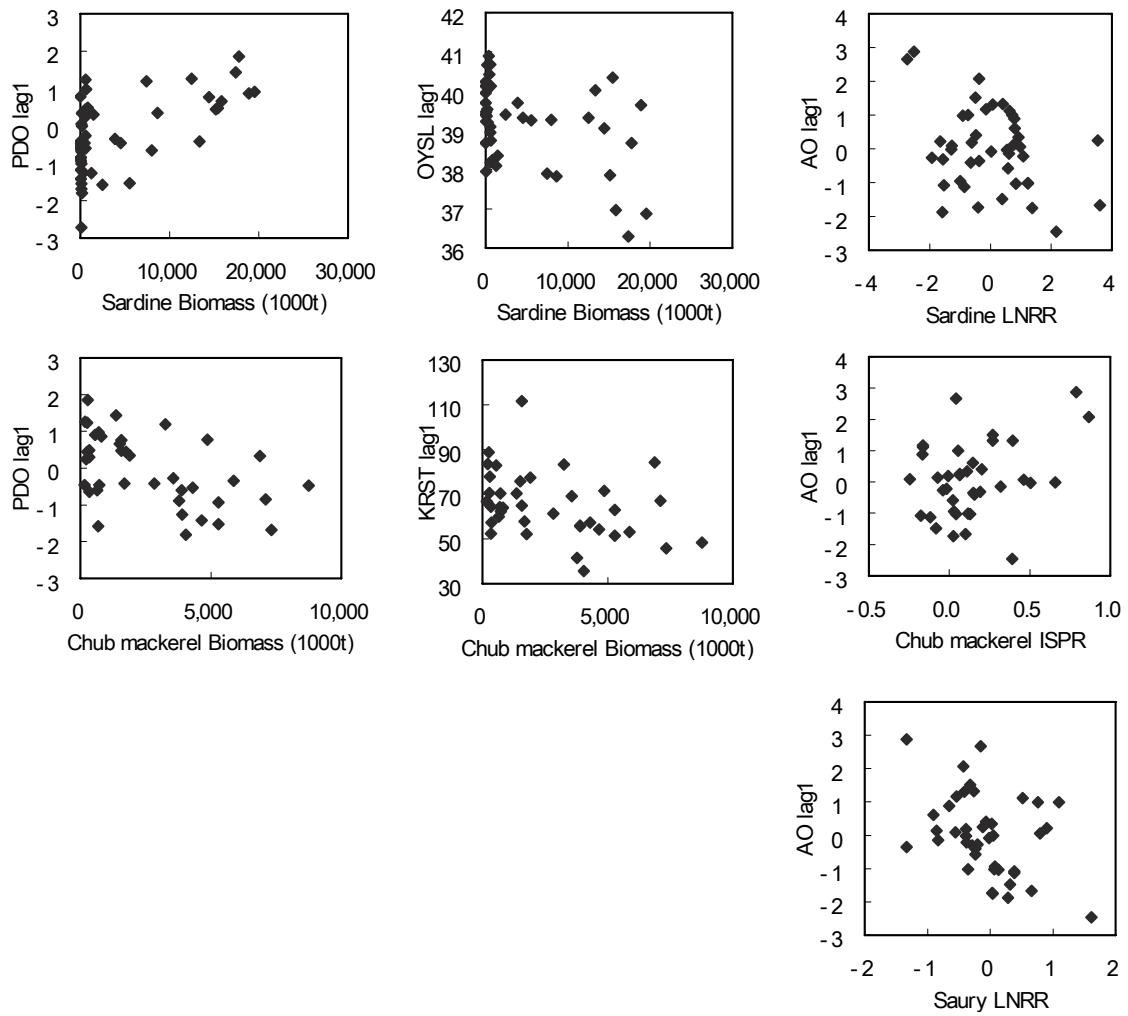
Year	Catch (FAO)	Catch, Tsushima Current stock	Catch, Pacific stock
1980	1,300,994	504,000	617,000
1981	907,589	470,000	393,000
1982	717,513	402,000	293,000
1983	804,479	408,000	353,000
1984	813,262 <sup>1</sup>	353,000	527,000
1985	717,764	305,000	403,000
1986	944,350	344,000	587,000
1987	700,686	329,000	299,000
1988	646,196 <sup>1</sup>	411,000	248,000
1989	526,270 <sup>1</sup>	414,000	121,000
1990	272,477	207,000	20,000
1991	253,991	220,000	24,000
1992	266,609 <sup>1</sup>	234,000	88,000
1993	664,298 <sup>1</sup>	373,000	401,000
1994	633,062	503,000	119,000
1995	469,447 <sup>1</sup>	364,000	152,000
1996	760,430 <sup>1</sup>	740,000	261,000
1997	848,967	337,000	343,000
1998	511,238	297,000	111,000
1999	381,866	242,000	61,000
2000	346,220	200,000	89,000

<sup>1</sup> FAO catch is smaller than sum of the two stocks.

Source of catch by stock: FAJ (2004a)



**Fig. 25** Statistically significant relationships between productivity of stocks and environmental variables with no time lag. KRGIT: Kuroshio geostrophic transport across 134°E in winter, OYSL: southern limit of the coastal branch of the Oyashio Current (adopted from Yatsu *et al.*, 2005).



**Fig. 26** Statistically significant relationships between productivity of stocks and environmental variables with a 1-year time lag. KRST: Kuroshio Sverdrup transport along 30°N in winter, OYSL: southern limit of the coastal branch of the Oyashio Current (adopted from Yatsu *et al.*, 2005).

### Jack mackerel (*Trachurus japonicus*)

#### Biology

Jack mackerel mature at age 1 at a fork length of about 20 cm. Maximum age is 5 years and maximum size is about 45 cm. They tend to change their habitat from pelagic to near-bottom as they grow. Jack mackerel are basically zooplankton feeders.

#### Fishery

Purse seines and set nets are the major methods of fishing. Total catches mostly increased in the late 1980s and remained high until 1999 (Table 12).

Two stocks have been recognized for stock assessments: the Pacific stock and the Tsushima Current stock. The Pacific stock is distributed along the Pacific coast of Japan at about 145°E longitude and north to about 40°N latitude. The Tsushima Current stock is distributed in the East China Sea and southern Japan Sea.

Several tagging experiments and biological surveys have been conducted to study stock structure. Earlier, the Tsushima Current stock was divided into more than three stocks, but now it is treated as a single stock for assessments. It is believed that both stocks overlap at the southern coast of Japan off Kyushu Island and have common spawning grounds in the East China Sea. A new research project

**Table 12** Jack mackerel catches (t).

Year	Catch (FAO)	Tsushima Current stock, Japan	Tsushima Current stock, Korea	Tsushima Current stock, Total	Pacific stock, Japan
1980	56,177	39,000	1,000	40,000	11,000
1981	66,044	46,000	6,000	52,000	12,000
1982	108,754	87,000	11,000	98,000	13,000
1983	134,535	103,000	12,000	115,000	18,000
1984	139,435	111,000	7,000	118,000	17,000
1985	158,073	132,000	16,000	148,000	14,000
1986	114,581	68,000	7,000	75,000	37,000
1987	186,979	139,000	14,000	153,000	37,000
1988	234,225	184,000	40,000	224,000	30,000
1989	188,111	140,000	23,000	163,000	33,000
1990	227,837	170,000	17,000	187,000	42,000
1991	228,894	153,000	16,000	169,000	61,000
1992	230,573	153,000	28,000	181,000	62,000
1993	318,403	226,000	38,000	264,000	79,000
1994	332,264	235,000	38,000	273,000	80,000
1995	317,993	231,000	12,000	243,000	70,000
1996	334,275	195,000	15,000	210,000	80,000
1997	326,668	233,000	23,000	256,000	76,000
1998	314,723	224,000	22,000	246,000	60,000
1999	214,129	141,000	14,000	155,000	48,000
2000	249,040	147,000	20,000	167,000	56,000
2001	217,742	—	—	—	—
2002	199,495	—	—	—	—

Source of catch by stock: FAJ (2004a)

on jack mackerel is using population genetics methods and models of larval transport to help determine the degree of overlapping distributions. The Tsushima Current stock extends into the Korean and Chinese waters beyond the Japanese EEZ.

Both stocks have separate spawning grounds along the coast, but the common spawning area is in the East China Sea, located from 25° to 30°N. The SST range at the spawning grounds is from 15° to 26°C (optimum 16°–17°C). The SST in the fishing area is from 24° to 29°C.

#### Climate and ocean effects

The biomass of jack mackerel (both stocks combined) is positively correlated with winter SSTs of the Japan Sea, East China Sea and Pacific coast of southern Japan. On the other hand, jack mackerel productivity and recruitment improved when the spring SST was lower in the East China Sea where

major spawning occurs (Sassa and Konishi, 2002). Productivity appears to have been affected by the 1988/89 regime shift (Figs. 23 and 24), although earlier shifts did not appear to have major impacts. There seems to be a negative relationship with PDO, in which the periods of positive PDO resulted in reduced productivity. Thus, in the 1980s, catches were less than in the 1990s (Table 12).

#### Japanese sardine (*Sardinops melanostictus*)

##### Biology

Japanese sardines mature at 17 cm in standard body length and the first age of maturation is 1 year during a low stock period and 3 years during a high stock period (Morimoto, 1998). The species is recruited to the fishery at the age of about 6 months when commercial fisheries harvest Japanese sardines in the size range of 11 to 24 cm. However, post-larvae individuals (whitebait or shirasu) are also fished

during high stock abundance periods. Maximum age is about 7 years and maximum lengths are approximately 25 cm. Prey of sardine includes both zooplankton and phytoplankton, the latter of which is seldom utilized by other fishes.

Two stocks of Japanese sardine have been recognized. The Pacific stock and the Tsushima Current stock are distinguished by their distributions and migration patterns. The Pacific stock is distributed along the Pacific coast of Japan and east to 180° longitude during high abundance periods. In periods of low abundance, only juveniles migrate into the Central North Pacific. The western boundary of the Pacific stock coincides with the spawning areas from the eastern coast to Kyushu Island (Fig. 20) to northern Japan at high abundances. In low abundances, the spawning area of the Pacific stock is the southern coast of Shikoku Island and central Japan. Feeding areas are mainly in the Oyashio and Kuroshio–Oyashio Transition Zone (KOTZ) in the summer and autumn. The Pacific stock occurs in the EEZ of Russia and outside of the EEZ of Japan. The Tsushima Current stock is distributed in the East China Sea and the Japan Sea. The major spawning area is in the East China Sea and the southern part of the Japan Sea during the high stock period, but it shrinks to the East China Sea during the low abundance. The northern limit of their migration also shrinks from the Sakhalin waters and Okhotsk Sea to the southern part of the Japan Sea (Hiyama, 1998). There are no apparent genetic differences between the two stocks (Okazaki *et al.*, 1996).

### Fishery

Japanese sardines have a long history of large fluctuations in abundance (Table 13, Figs. 18 and 21). Kawasaki (1983) was the first to recognize that the fluctuations in sardine abundance were synchronous with sardine populations off the Pacific coast of North America and Chile. Off Japan, the catches in the 1960s were about 10,000 t annually. In the mid-1970s the catches by Japan (and abundances) increased dramatically to about 4 million t per year in the mid-1980s. In the early 1990s, catches (and abundances) decreased quickly to levels of less than 200,000 t in 2000 (Table 13).

### Climate and ocean effects

The large fluctuations in abundance have been shown to relate to large-scale climate changes and not to unique local environmental conditions or to fishing (Figs. 25 and 26; Kawasaki, 1983). Large-scale or global climate change causes a strengthening or weakening of winds and ocean currents off the coast of Japan which affects the upwelling of nutrients and plankton production and larvae transportation (Kasai *et al.*, 1997). There is a relationship between the winter SST or subsurface temperature in the rearing area of juvenile sardines and their survival for both stocks (Hiyama *et al.*, 1995; Ebisawa and Kinoshita, 1998; Noto and Yasuda, 1999). The ocean conditions, in turn, are related to direct atmospheric forcing on a decadal scale, as identified by the PDO and the boundaries of the Oyashio and Kuroshio Currents (Yatsu *et al.*, 2005).

There are a number of studies on the impact of ocean conditions on the population dynamics of the Japanese sardine, as the fishery is important economically and socially to the Japanese people. Watanabe *et al.* (1995) showed that mortality after the end of the first-feeding stage, *i.e.*, from post-larva to age 1, controlled year-class strength. Hiyama *et al.* (1995) reported that both density-dependent effects and winter temperature of the western Japan Sea at 50 m depth are responsible for the reproductive success of the Tsushima Current stock. On the basis of a numerical model, Kasai *et al.* (1997) concluded that strong year classes of sardine can be formed by intensive transport of larvae to the Kuroshio Extension and by good survival in the KOTZ where nutrient supply is affected by the strength of the Oyashio. This conclusion was supported by Ebisawa and Kinoshita (1998) who detected a negative correlation between reproductive success of the Pacific stock and Oyashio expansion (represented by an area of SST < 10°C) in the Joban area (Fig. 20). Thus, the more southern intrusion of the Oyashio coastal branch would enhance zooplankton production in the nursery ground of the KOTZ which supports survival of juveniles derived from spawning grounds formed offshore of Shikoku and Kyushu beyond the Kuroshio axis. Noto and Yasuda (1999) showed that low SST in the southern

**Table 13** Japanese sardine catches and estimated biomass (t).

Year	Catch (FAO)	Catch, Pacific stock	Catch, Tsushima stock
1980	2,197,744	1,679,000	—
1981	3,089,311	2,460,000	—
1982	3,289,954	3,037,000	—
1983	3,745,148	3,495,000	—
1984	4,179,426	3,786,000	—
1985	3,866,928	3,356,000	—
1986	4,209,513	3,766,000	—
1987	4,362,025	3,314,000	—
1988	4,488,411	3,446,000	—
1989	4,098,989	2,849,000	1,586,000
1990	3,678,229	2,525,000	1,521,000
1991	3,010,498	1,948,000	1,294,000
1992	2,223,766	1,151,000	989,000
1993	1,713,687	729,000	923,000
1994	1,188,848	416,000	765,000
1995	661,391	262,000	340,000
1996	319,354	153,000	143,000
1997	284,054	230,000	37,000
1998	167,073	136,000	32,000
1999	351,207	295,000	54,000
2000	149,616	130,000	15,000

Source of catch by stock: FAJ (2004a)

region of the Kuroshio Extension improved food production for larval sardines and resulted in improved year-class strength of the Pacific stock. When the southern region of the Kuroshio Extension is favorable for sardine survival, they are able to expand their adult distribution and their spawning areas. A low SST is an index of mixed layer depth (Polovina *et al.*, 1995). In subtropical waters, including the Kuroshio, deeper mixing layers contain more nutrients in the spring and thus more productive habitat for juvenile sardines. Conversely, warmer SSTs reduce productive habitat, and were shown to be related to high larval mortality. If unfavorable conditions persist for more than 7 years, the life span of the Japanese sardine, the population that migrates over a wide area would collapse. Recent studies revealed that SST directly affects growth rates of larvae and juveniles, hence early survival rates (Takahashi *et al.*, 2004; Takasuka *et al.*, 2004). The coastal population would remain, but would be small as the coastal habitat suitable for production is limited. Noto and Yasuda (1999)

suggested that the abrupt increase in SST in 1988 in the southern region of the Kuroshio Extension indicated a close relationship between decadal-scale climate changes and ocean changes, and the dramatic fluctuations in abundance.

### Anchovy (*Engraulis japonicus*)

#### Biology

Anchovy mature at a standard body length of about 6 cm in coastal waters and at about 10 cm in offshore and oceanic waters. Age and growth of Japanese anchovy are controversial, and growth may greatly fluctuate, depending on prey conditions and migration routes. Annual rings in scales suggest slower growth (10 cm at 1 year, 14 cm at about 2 years) in contrast to much faster growth estimated by daily increments in otoliths (the age of 12 to 13 cm fish was 263 to 295 days) (Mitani, 2001). Recruitment into the fishery occurs at about the age of a few months (whitebait or shirasu) and the

maximum age is about 3 years at a length of 14 cm, according to traditional age estimation with scales. Anchovy are zooplankton feeders.

### *Fishery*

Three stocks are recognized for stock assessment: the Pacific stock, the Seto Inland Sea stock, and the Tsushima Current stock. The boundaries among stocks are not always clear, especially during periods of large abundances as mixing and exchange sometimes occur, depending on their densities. The Tsushima Current stock expands into the Russian, Korean, and Chinese waters, beyond the EEZ of Japan. The Pacific stock is also distributed in Russian EEZ when the stock is abundant.

Anchovy catches averaged 185,691 t between 1980 and 1989, then increased to 311,427 t in 1990, and remained high in the 1990s, averaging 317,290 t between 1990 and 2000 (Table 14). The major fisheries use purse seines and set nets; whitebait or shirasu are harvested by seine nets (a small-scale

midwater trawl). The spawning stock biomass was estimated using the procedures of virtual population analysis (VPA) and egg census surveys (FAJ, 2004a) for 1996 to 2000, and shows a major increase beginning in 1998.

### *Climate and ocean effects*

In general, there is an alternating pattern of abundance between anchovy and sardine (Fig. 18). In the 1950s and 1960s, anchovy abundance was large when sardine abundance was small. This pattern switched in the late 1970s and 1980s, reversing again in the 1990s. Recent studies revealed that optimum SST on early growth rates of anchovy are higher than sardine, thus decadal shifts in SST may explain the alternation of sardine and anchovy through selective survival of larger or faster-growing individuals (Takahashi *et al.*, 2004; Takasuka *et al.*, 2004, 2007). It is apparent that the impacts of climate–ocean conditions are opposite for sardines and anchovies.

**Table 14** Anchovy catches (t).

Year	Catch (FAO)	Tsushima Current stock, Japan <sup>1</sup> only	Pacific stock	Seto Island Sea stock
1980	150,604	—	—	40,000
1981	160,468	—	—	68,000
1982	197,453	—	—	76,000
1983	207,601	—	—	81,000
1984	224,069	—	—	75,000
1985	205,824	—	—	100,000
1986	210,630	—	66,000	93,000
1987	140,509	—	63,000	36,000
1988	177,492	—	68,000	58,000
1989	182,258	—	88,000	40,000
1990	311,427	—	234,000	32,000
1991	328,870	76,000	207,000	42,000
1992	300,892	84,000	186,000	27,000
1993	194,511	68,000	101,000	25,000
1994	188,034	57,000	110,000	21,000
1995	251,958	95,000	140,000	23,000
1996	345,517	114,000	210,000	20,000
1997	233,113	78,000	134,000	20,000
1998	470,616	140,000	304,000	17,000
1999	484,230	143,000	313,000	23,000
2000	381,020	128,000	210,000	34,000

<sup>1</sup> data exists for Korea, and China, Taiwan; source of catch by stock: FAJ (2004a)

## Walleye pollock (*Theragra chalcogramma*)

### Biology

Walleye pollock are distributed throughout the water column to the bottom. They mature at about age 3 and 32 cm in standard body length (Keizo Yabuki, Hokkaido National Fisheries Research Institute, unpublished data). There is debate about maximum ages, but there is some agreement that walleye pollock can live up to 33 years (King and McFarlane, 2003). There is a spawning migration from overwintering areas to distinct spawning areas, mainly in Nemuro Strait (Fig. 20), Funka Bay (the Pacific stock) and coastal areas of western Hokkaido and Sakhalin (the North Japan Sea stock). However, the spawning area of the latter stock may have shrunk to the Hiyama and Iwanai districts (Fig. 20), southwestern Hokkaido, in response to stock decline. Eggs and larvae are pelagic and only loosely associated with a particular bottom area. Walleye pollock consume a wide variety of prey, including krill, squids, fishes and demersal crustaceans. Cannibalism is common.

### Fishery

Four stocks have been recognized for stock assessments around Japan: the North Japan Sea stock, the Kitami (Okhotsk Sea) stock, the Nemuro stock, and the Pacific stock (Tsiji, 1989). This separation is based on information relating to spatial distribution, tagging, age and growth data, morphometric characteristics, and ecological considerations. The North Japan Sea stock is distributed in the northeastern area of the Japan Sea. The Kitami, or Okhotsk Sea, stock is distributed in the southwestern part of the Okhotsk Sea. The Nemuro stock is found during the spawning season in Nemuro Strait. The Pacific stock is distributed along the Pacific coast of the northeastern part of Honshu, Hokkaido, and south Kuril Islands. Tagging studies carried out in the past 40 years have indicated that fish normally migrate among these four stocks (Yoshida, 1982). Biochemical studies have not revealed genetic differences among the four stocks (Iwata, 1975). All stocks, except the Nemuro stock, have two or more spawning grounds. The stability of the spawning stock units and the characteristics of a stock change with the environment and population abundances (Kyushin *et al.*, 1961; Tsiji, 1978). There are also walleye pollock that are pelagic during the feeding period and spawn with a variety of stocks (Ogata, 1956; Yoshida, 1982). All stocks are

also distributed within the Russian EEZ. Catch statistics indicate a constant decline in catch since 1980 (Table 15). However, biomass estimates (Fig. 22) indicate that there was an increase in the 1980s in the North Japan Sea stock, but a decrease in the Pacific stock.

### Climate and ocean effects

Figures 23 and 24 show that there is no relationship between walleye pollock productivity and regime shifts, although there were decadal-scale fluctuations in estimated biomass. The productivity of the North Japan Sea stock is positively related to SST in the spawning grounds in the winter. The productivity of the Pacific stock is positively related to SST of southern Hokkaido in winter and spring. It appears that ocean conditions affect productivity and result in trends that are approximately decadal; however, there is no clear relationship with standard large-scale indices of climate. In the Pacific stock, strong year classes were produced in 1981, 1991, 1994, 1995 and 2000 (FAJ, 2004a). Strong year classes of the North Japan Sea stock were observed in 1984, 1985, 1986 and 1988 (FAJ, 2004a). Mechanistic linkages between occurrences of strong year class and environmental conditions remain unknown.

## Chum salmon (*Oncorhynchus keta*)

### Biology

Chum salmon are anadromous. In Japan, virtually all chum salmon are reared in hatcheries and released after a short rearing period following hatching. In the ocean, the fry remain in coastal areas for several months before they move offshore (Urawa, 2000; Yatsu and Kaeriyama, 2005). The catch of chum salmon in Japanese fisheries consists mainly of fish produced in Japan. New information indicates that Japanese-produced chum salmon spend their first marine year in the southern Okhotsk Sea. In the fall, the juveniles move into the northern North Pacific and the Bering Sea where most remain for 3 to 5 years. Maturing chum salmon begin their return migration about April–May and arrive at the rivers where they were released about August–September. All chum salmon die after spawning, although natural spawning rarely occurs in Japan. Chum salmon are basically zooplankton feeders.

**Table 15** Walleye pollock catches (t).

Year	Catch (FAO)	Pacific stock	North Japan Sea stock
1980	1,552,429		—
1981	1,595,302	294,765	—
1982	1,570,373	246,506	—
1983	1,434,430	279,916	—
1984	1,604,929	283,354	—
1985	1,533,179	274,466	117,468
1986	1,421,802	206,541	79,942
1987	1,312,510	236,513	83,510
1988	1,259,095	221,344	120,644
1989	1,153,750	196,721	130,583
1990	871,408	166,001	128,417
1991	540,946	166,901	128,391
1992	498,756	159,028	127,012
1993	382,308	145,315	75,531
1994	379,351	141,724	64,777
1995	338,507	146,632	65,005
1996	331,163	112,661	80,746
1997	338,785	164,989	70,846
1998	315,987	190,360	56,320
1999	382,385	245,151	51,617
2000	300,001	209,900	41,847
2001	241,881	129,982	45,615
2002	213,254	110,377	60,074

Source of catch by stock: FAJ (2004a)

### Fishery

Since the 1970s, the high seas salmon fishery has declined and in recent years has been confined to the Russian EEZ (Table 16). Thus, the recent chum salmon catch is mainly from the coastal set net fishery around Hokkaido and northern Honshu. There is a relationship between size and age at maturity and abundance of chum salmon (Kaeriyama, 1989).

### Climate and ocean effects

There are natural fluctuations in Pacific salmon abundance that are related to fluctuations in large-scale climate indices and to regime shifts (Beamish

and Bouillon, 1993; Yatsu and Kaeriyama, 2005). It is generally accepted now that the early assumptions that climate and ocean impacts on survival followed a random model are not correct. However, the mechanisms that result in trends in production are poorly understood. It is known that coastal environments are important. For example, Saito (2002) detected positive correlations between marine survival rates and coastal SST in particular areas of Hokkaido and northern Honshu. There is not a good relationship between PDO and catch for chum salmon produced in Japan (Kaeriyama, 2004; Yatsu and Kaeriyama, 2005). Thus, marine survival of Japanese chum salmon is correlated more with the coastal environment than with the PDO or Aleutian Low Pressure Index.

**Table 16** Chum salmon catches (t).

Year	Catch (FAO)	Catch (NPAFC*)
1980	87,713	96,800
1981	112,361	120,800
1982	102,654	111,80
1983	125,196	133,50
1984	127,712	136,30
1985	167,960	176,70
1986	142,081	157,52
1987	136,641	146,60
1988	149,369	159,20
1989	169,245	181,03
1990	207,989	222,88
1991	191,596	197,58
1992	149,540	137,20
1993	195,892	187,86
1994	205,647	191,52
1995	249,982	231,05
1996	280,855	266,15
1997	250,837	237,35
1998	190,553	178,54
1999	171,182	158,30
2000	151,123	139,93

\* North Pacific Anadromous Fish Commission

### Pacific saury (*Cololabis saira*)

#### Biology

Pacific saury have a life span of 2 years or less. The age of the first maturation is at about 6 months. Their maximum size is 34 cm in body length. Pacific saury are zooplankton feeders.

#### Fishery

Two stocks occur around Japan. The Northwestern Pacific stock occurs in the northwestern Pacific from the Pacific coast off Japan to 170°E (Odate, 1977). The Japan Sea stock occurs in the Japan Sea. Most catches of Pacific saury in Japan are made from the Northwestern Pacific stock (Table 17). Catches from the Japan Sea stock are much smaller than those from the Pacific Ocean. The distribution is very broad and includes the EEZ waters of Russia, Korea, and Japan. Gong *et al.* (1983) reported that Pacific saury remain in the southern region of the Japan Sea and the East China Sea in winter. The Northwestern Pacific stock spawns mainly in winter throughout the subtropical waters, including the Kuroshio and Kuroshio Extension, much wider areas than

previously assumed. They also spawn in spring and autumn in the KOTZ. Baytaluk and Davydova (2001) reported that large numbers of larvae were found in the central Pacific Ocean in spring. In this report we consider that the two stocks are geographically divided, consistent with Odate (1977) who suggested that the Central Pacific stock occurs in the central part of the North Pacific Ocean separately from the Northwestern Pacific stock. However, Nagasawa *et al.* (1988) stated that separation of the Northwestern Pacific stock and the Central Pacific stock is doubtful, based on the parasite studies. Accordingly, it is possible that there is only one stock ranging from the northwestern Pacific to the central part of the North Pacific.

Pacific saury are fished using stick-held dip-nets. Drift gill net fisheries and set net fisheries are used locally or seasonally, but account for less than 5% of the catch. The fishery for the Northwestern Pacific stock averaged 280,000 t from 1980 to 2000 (Table 15). There is no apparent trend in catches.

#### Climate and ocean effects

The optimum SST range for hatching is from 14° to 20°C. The lower limit of the distribution in the feeding grounds is about 4°C. The optimum SST range in the feeding grounds located in the subarctic waters, including the Oyashio, is from 8° to 12°C.

Ebisawa and Snow (1999) reported that SST of the Kuroshio (southeast of Honshu) in winter is positively correlated with the catch per unit effort (CPUE) of the Pacific saury stick-held dip-net fishery. The CPUE of large-sized saury in this fishery is related to SST in the winter of the previous 2 years. Kurita (2001) reported that the abundance of zooplankton in the feeding areas (the Oyashio waters) affected the condition of Pacific saury, which may influence the success of the spawning. However, an actual relationship between zooplankton abundance and the success of spawning has not been reported. Tian *et al.* (2002) stated that the occurrence of El Niño and MOI (Monsoon Index) positively affected the abundance of Pacific saury (especially for large-sized fish). Productivity is significantly related to the Southern Oscillation Index (SOI), but does not appear to be related to the PDO (Figs. 23 and 24) and thus, to regime shifts. The clear relationship to SST in the Kuroshio and Kuroshio Extension in winter and in their spawning area indicates that climate-related changes in the ocean will affect the production of Pacific saury.

**Table 17** Pacific saury catches (t) by country.

Catch (FAO)	Japan	Russia	Korea	Taiwan	Northwestern Pacific stock total	
1980	187,155	192,449	38,579	—	231,028	
1981	160,319	159,304	31,716	—	191,020	
1982	206,958	192,883	23,439	—	216,322	
1983	239,658	232,560	7,800	—	240,360	
1984	209,974	223,769	0	—	223,769	
1985	245,944	259,247	7,500	—	266,747	
1986	217,229	225,718	11,700	—	237,418	
1987	197,084	210,249	23,400	—	233,649	
1988	291,575	287,927	50,300	1,960	350,176	
1989	246,821	246,713	68,500	3,236	335,980	
1990	308,271	310,592	61,850	17,612	398,624	
1991	303,567	298,935	46,461	25,135	381,311	
1992	265,884	258,717	44,016	33,708	359,471	
1993	277,461	273,702	48,022	40,154	373,338	
1994	261,587	250,704	23,846	32,280	319,380	
1995	273,510	272,901	24,115	30,996	341,784	
1996	229,227	231,238	9,726	18,729	267,980	
1997	290,812	285,438	6,525	50,227	364,077	
1998	144,983	140,110	5,097	13,926	23,000	182,133
1999	141,011	134,937	5,050	18,036	—	158,023
2000	216,471	211,883	16,345	—	—	228,228
2001	—	266,344	—	—	—	266,344

Source of catch by stock: FAJ (2004a)

### Common squid (*Todarodes pacificus*)

#### Biology

Common squid is a coastal/offshore species with a life span of approximately 1 year and a maximum mantle length of 27 cm (Murata, 1990). Although this species is abundant in the entire area of the Japan Sea, it is confined to coastal and offshore waters in the Pacific Ocean. They change their prey from zooplankton to small fishes and squids as they grow.

#### Fishery

Off Japan, an autumn cohort and a winter cohort are recognized for management purposes. The autumn cohort consists of squid hatched from October to December in the East China Sea and the southern Japan Sea (Murata, 1990). The autumn cohort migrates to its feeding area around the northern Japan Sea and returns to its spawning grounds via the Japan Sea. Extensive tagging studies have identified the

migration pattern, and para-larval distribution indicates that the spawning area is in the East China Sea and southern Japan Sea. The winter cohort is composed of squid that hatch during December to February in the East China Sea. Tagging studies have shown that these young squid migrate to their feeding grounds around Hokkaido mainly via the northwestern Pacific (Murata, 1990). Most of the winter cohorts return to their spawning grounds through the Japan Sea. In general, the two cohorts have distinct hatching periods, season-specific body sizes, and migration patterns. However, the separation is not perfect because of overlapping length distributions. Thus, the portioning of catches using mean mantle length in the summer is not exact (Kidokoro, 2002). In addition to Japan, the stocks are fished by Korea and China using jigs, trawls, purse seines, and set nets. Proportions of catch by Japan and Korea in recent years are more than 90% (Table 18). CPUE of commercial and research jig fishing can be used as a proxy of stock abundance. The biomass of common squid was high in the 1960s, declined in the 1970s, and remained at

low levels through to the early 1990s when it increased substantially (Fig. 21).

#### *Climate and ocean effects*

In general, warmer temperature conditions around Japanese waters are favorable for common squid (Sakurai *et al.*, 2000). The area that is suitable for spawning for both stocks is considered to be a major factor affecting abundance (Sakurai *et al.*, 2000). Hatchlings are abundant in SSTs of 17° to 23°C. This temperature range, and ocean conditions favorable for pre-spawning behaviour and post-spawning retention of eggs within a mid-water layer, are important for year-class survival (Sakurai *et al.*, 2000).

The biomass of common squid increased in the mid-1980s (Fig. 21). Productivity is positively correlated with winter SST along the Kuroshio path and its southern areas. Abundance is negatively correlated to the PDO without a lag (Fig. 25). Common squid and jack mackerel productivity and biomass trends are similar and roughly opposite to Japanese sardine (Figs. 26 and 27).

#### **Neon flying squid (*Ommastrephes bartrami*)**

##### *Biology*

Neon flying squid is an oceanic species that has a life span of slightly longer than 1 year and that grows to a size of 60 cm mantle length in females and 45 cm in males (Yatsu *et al.*, 1998). They are voracious predators of small fishes and squids.

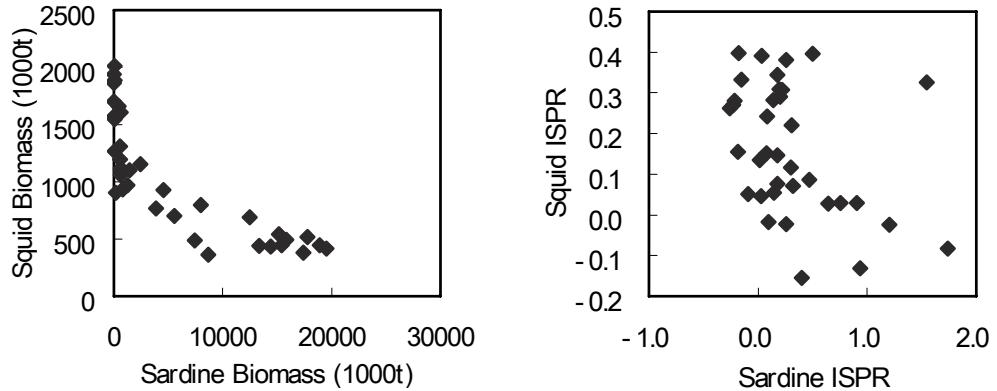
##### *Fishery*

Two cohorts are recognized. The winter–spring cohort and the autumn cohort have distinct hatching periods, body sizes, and migration patterns (Yatsu *et al.*, 1998). The winter–spring cohort has been the target of the traditional jig fishery in the northwestern Pacific, west of 160°E. The autumn cohort is distributed mainly in the central and eastern North Pacific. This cohort was the target of the international driftnet fishery beginning in 1978 and ending in 1992 by international agreement. A new jig fishery on this cohort started in the mid-1990s throughout the western and central North Pacific.

**Table 18** Common squid catches (t).

Year	Catch <sup>1</sup>	Japan and Korea total	Autumn cohort, Japan	Autumn cohort, Korea	Winter cohort, Japan	Winter cohort, Korea
1980	405,420	379,258	176,853	37,469	153,914	11,022
1981	290,381	248,029	134,366	29,962	66,948	16,753
1982	274,206	236,662	130,867	38,360	51,870	15,565
1983	245,855	229,264	135,327	25,908	56,650	11,379
1984	286,501	218,129	116,720	25,017	61,799	14,593
1985	214,275	174,285	103,719	30,548	27,687	12,331
1986	141,457	130,573	55,430	23,265	37,928	13,950
1987	262,025	249,485	144,017	43,580	44,538	17,350
1988	227,786	200,172	108,976	31,915	41,670	17,611
1989	319,790	277,205	146,221	41,767	65,098	24,119
1990	321,459	285,474	134,794	45,462	75,386	29,832
1991	402,976	355,623	130,359	66,914	115,361	42,989
1992	545,209	531,002	154,830	72,712	236,380	67,080
1993	548,365	530,156	148,048	131,471	165,940	84,697
1994	504,425	483,917	128,121	128,597	166,224	60,975
1995	513,413	497,352	128,135	125,558	168,320	75,339
1996	715,908	696,630	176,916	139,259	267,095	113,360
1997	603,367	590,574	139,821	138,714	225,793	86,246
1998	378,605	344,504	108,089	102,990	73,401	60,024
1999	497,887	478,196	140,482	160,140	98,917	78,657
2000	570,427	564,960	104,157	152,677	234,493	73,633

<sup>1</sup> All nations' catch for "Japanese flying squid" from FAO statistics; source of catch by stock: FAJ (2004a)



**Fig. 27** Relationships between sardine and common squid biomass and productivity (adopted from Yatsu *et al.*, 2005).

Tagging surveys were not successful in providing information about the stock structure. However, a study of helminth parasites identified a central North Pacific and an eastern North Pacific stock within the autumn cohort (Nagasaki *et al.*, 1998). The autumn cohort is now fished by Japan, China, and probably Korea and Taiwan. Recent catch data by all countries may be incomplete. CPUE from research driftnet studies in the early summer can be used as a proxy of the abundance of the Central North Pacific stock within the autumn cohort (Yatsu *et al.*, 2000).

Prior to the moratorium on driftnet fishing in 1992, catches by all countries increased steadily from the early 1970s to 300,000–350,000 t in the early 1980s. Since 1993, Japanese annual catches have ranged between 15,000 and 85,000 t (Table 19).

#### *Climate and ocean effects*

The SST at the spawning grounds ranges from 22° to 26°C, as indicated by para-larval distribution (Yatsu *et al.*, 2000). SST at the feeding grounds ranges from 10° to 25°C, with the densest concentrations of squid occurring at temperatures between 15° and 22°C (Yatsu *et al.*, 1993). SST should be an important factor affecting the spawning, survival, and growth of para-larvae, hence stock abundance (Yatsu *et al.*, 2000). Zooplankton mean density in the Central North Pacific (Sugimoto and Tadokoro, 1998) is significantly negatively correlated to the research driftnet CPUE ( $r = -0.57$ ,  $P < 0.05$ ,  $df = 14$ ). SSTs in the hatching and nursery areas (30°–36°N, 170°–150°W from October to March) and during pre-recruitment (30°–36°N, 170°–150°W from January to June) had some positive relationship

to abundance after the moratorium on driftnet fishing in 1992 (Yatsu *et al.*, 2000).

#### **Possible Greenhouse Gas-induced Changes in the Climate and Ocean Environment**

It is now recognized that natural changes in climate have major impacts on the abundance of marine fish. However, while there is a great amount of evidence that climate affects fish, the mechanisms that cause the fluctuations in abundances are not well understood. We know that major climate events associated with ENSO (El Niño–Southern Oscillation) regimes, regime shifts, and 50- to 70-year climate trends are reflected in the population dynamics of most fishes. Unfortunately, we are not yet able to forecast accurately how global warming will have an impact on these natural climate fluctuations. Potential impacts will change the strength and direction of ocean currents which will affect the larvae transportation and availability of nutrients which, in turn, will affect the food of fishes.

In particular, the food for larval and juvenile fish in their first ocean year appears to be critical for their survival over the first marine winter and for their recruitment into commercial fisheries because survival rates are extremely low during larval and juvenile stages. Ocean temperatures will change and, in most ecosystems, will warm. Warmer temperatures affect metabolic functions of fish as well as their behaviour, food, and predators. Although we cannot predict accurately how the ocean ecosystems will change, we are improving our understanding and are able to make informed

**Table 19** Japanese neon flying squid catches (t) by country and fishery.

Year	Total catch	Jig catch, Japan	Driftnet catch, Japan	Driftnet catch, Korea	Jig and driftnet, Taiwan	Jig catch, China
1980	198,000	70,000	122,000	0	6,000	0
1981	175,000	57,000	103,000	0	15,000	0
1982	242,000	58,000	159,000	0	25,000	0
1983	322,000	45,000	216,000	38,000	23,000	0
1984	230,000	29,000	124,000	49,000	28,000	0
1985	342,000	51,000	198,000	71,000	22,000	0
1986	248,000	23,000	152,000	59,000	14,000	0
1987	332,000	21,000	208,000	84,000	19,000	0
1988	285,000	16,000	158,000	101,000	10,000	0
1989	351,000	16,000	171,000	134,000	30,000	0
1990	360,000	34,000	188,000	124,000	14,000	0
1991	196,000	13,000	102,000	69,000	12,000	0
1992	177,000	2,000	100,000	61,000	10,000	4,000
1993	—	15,000	0	—	—	13,000
1994	—	71,000	0	—	—	17,000
1995	—	60,000	0	—	—	69,000
1996	—	58,000	0	—	—	74,000
1997	—	63,000	0	—	—	60,000
1998	—	85,000	0	—	—	—
1999	—	26,000	0	—	—	—
2000	—	28,000	0	—	—	—

Source of catch by stock: FAJ (2004b)

speculation. If we recognize that changes will occur and that our understanding of the impacts is imperfect, it becomes evident that our management of the fisheries is critical. Overfishing at the beginning of a prolonged trend of poor ocean productivity could reduce a stock to such levels that literally could take centuries to recover.

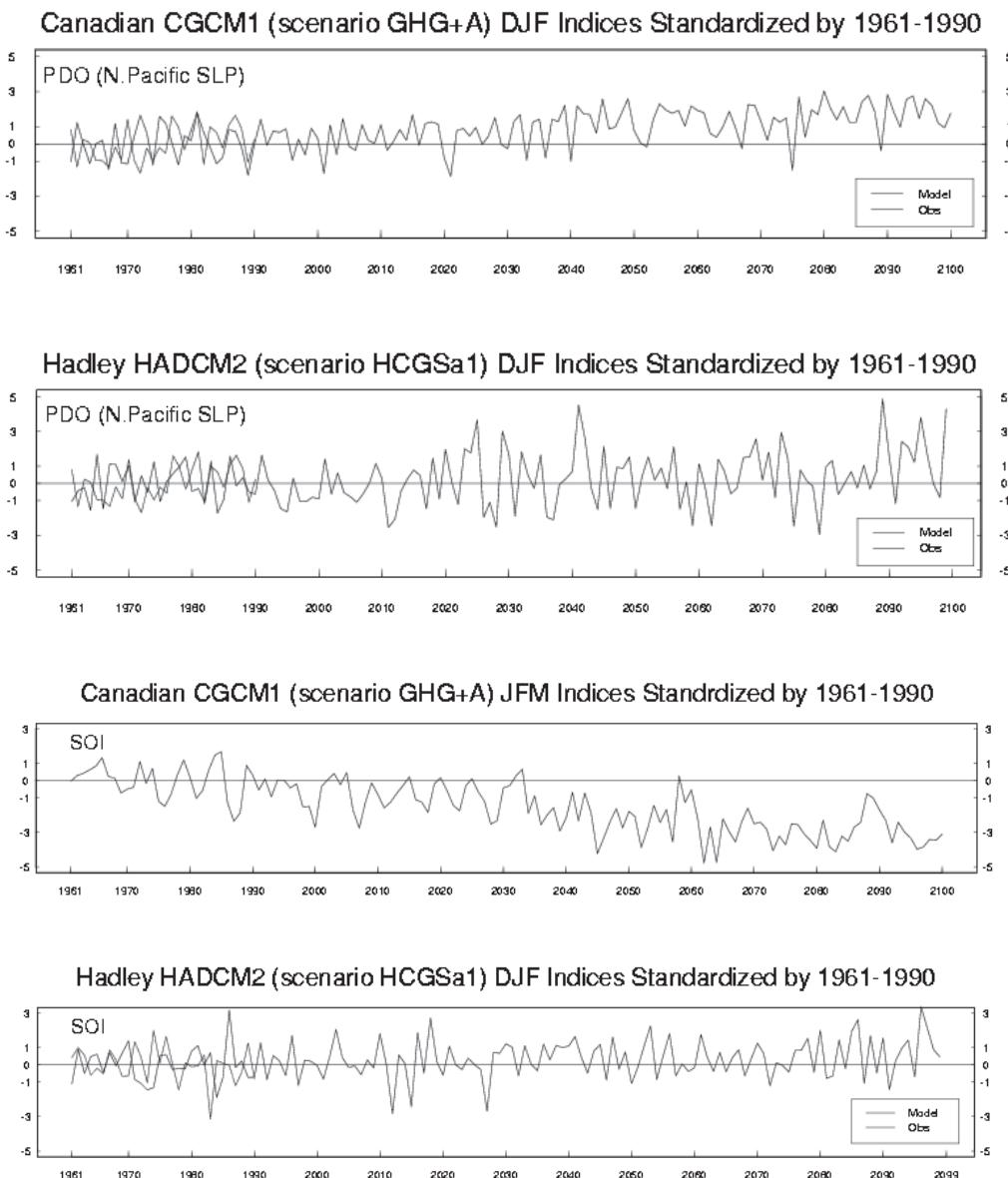
Changes in the climate and ocean environment over and around Japan as a result of global warming can only be approximated (Nishioka and Harasawa, 1998). At the time of a doubling of CO<sub>2</sub> (relative to 1990 levels) it is estimated that air temperature would increase between 1.0° and 2.5°C. Sea level rises on the coast of the Japan Sea would be 10 to 20 cm higher and about 15 cm higher along the Pacific Ocean and Okhotsk Sea coasts. Along the coast of the Japan Sea, the SST increase would be 1.6°C, 1.2° to 1.6°C along the Pacific coast, and 1.8°C along the coast of the Okhotsk Sea. The strength of the Kuroshio Current depends on the changes in the subtropical Pacific gyres. If the temperature difference between higher and lower latitudes is

reduced, trade winds and westerly winds are estimated to weaken. As a consequence, the strength of the Oyashio and Kuroshio would weaken, and the mixed layer depth would become shallower, reducing plankton production. There seems little doubt that global warming will change the path of the Kuroshio and the structure of the Oyashio and the Transition area. However, there is another interpretation in which global warming impacts on the gyres in the subarctic Pacific could result in more periods of stormy winters similar to the conditions from 1977 to 1989 (Mote *et al.*, 1999).

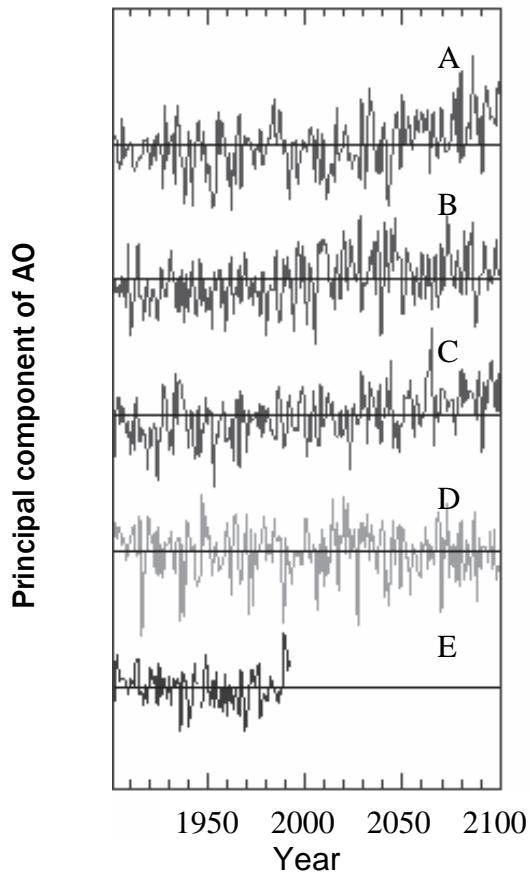
According to Mote *et al.* (1999), over the next 100 years there will be a trend of increasingly positive PDO or stormy periods according to two major GCM models, the UK Hadley Centre model and the Canadian Climate Centre model (Fig. 28; Beamish and Noakes, 2002). Also, the above two models predict an increase in the Arctic Oscillation (AO) in the next century (Fig. 29), though the two scenarios forecast SOI differently. Assessment of greenhouse gas effects on fisheries is difficult because of the

unexpected ecosystem dynamics, even though some species in the Japanese fisheries have simpler life histories than species such as Pacific salmon (Mote *et al.*, 1999; Beamish and Noakes, 2002). Climate effects will result in different impacts, depending on ecosystem structure – species types of prey, predators, competitors, and changes in their associations. It is important to preserve the natural buffering characteristics of individual stocks (Shuter

*et al.*, 2002). For example, diverse age structure, genetic diversity, migration pathways, and multiple habitats are essential for mitigating unexpected climate changes. Although small pelagics around Japan are genetically uniform (Okazaki *et al.*, 1996), their natural buffering capacity will not be easily lost because of their adaptability (Kuroda, 1991; McFarlane *et al.*, 2002).



**Fig. 28** Observed and predicted PDO (Pacific Decadal Oscillation) and SOI (Southern Oscillation Index) under the two major models (Canadian Climate Centre CGCM1 and Hadley HADCM2) from 1961 to 2100 (adopted from <http://www.usgcrp.gov/usgcrp/nacc/background/scenarios/indices.html>, with permission).



**Fig. 29** Simulated and actual Arctic Oscillation (AO) time series (November–April averages). A–C: three independent climate change simulations; D: control simulation; E: observed (adopted from Fyfe *et al.*, 1999; <http://www.usgcrp.gov/usgcrp/nacc/background/scenarios/indices.html>, with permission).

Ono *et al.* (2002) detected a decreasing trend in primary production in the Oyashio during the 1970–1993 period. If this trend continues, production of small pelagics and other predatory species will decrease in both the Kuroshio and Oyashio areas. This is because most of the small pelagic fishes around the Pacific coast of Japan utilize the productive Oyashio area as feeding grounds during spring–autumn. Shifts in the geographic range of sardine populations corresponding to temperature changes will not result in a collapse of stocks because their behaviour is flexible (*e.g.*, the spawning ground for sardine shifted considerably around Japan; Kuroda, 1991), and they have sustained themselves during changing temperatures over evolutionary time.

Some of the observed shifts in biological productivity of sardine, chub mackerel and common

squid correspond to regime shifts in SST (1957/58, 1970/71, 1976/77, 1988/89; Yasunaka and Hanawa, 2002), and in PDO (Figs. 23–26). Biological productivity of Pacific saury, jack mackerel and walleye pollock were not evidently related to regime shifts; however, decadal and inter-annual fluctuations were observed. For Pacific saury, this is probably because of the correlation of productivity with ENSO (Fig. 25; Tian *et al.*, 2002). Since biomass and productivity of sardine and common squid are negatively correlated (Fig. 27), there might be an inter-species competition in addition to unknown linkages to PDO variability. It should also be remembered that an increase in biomass is a result of accumulation of enhanced productivity over time and that biological productivity may be decreased by increased biomass known as the density-dependent effect.

The 1970/71 regime shift resulted in extremely high production rates for sardine and chub mackerel. The well known 1976/77 regime shift was detected in the productivity and recruitment of chub mackerel, and possibly Pacific saury, but did not seem to affect sardine. Yatsu and Kidokoro (2001) found coherent shifts in body size and intrinsic population growth rate of common squid in 1976/77 and around 1986. The 1989 regime shift, when the AO shifted to a positive phase, affected sardine and chub mackerel productivity and recruitment, production–biomass relations (Yatsu *et al.*, 2003), and possibly jack mackerel recruitment.

In general, peaks in biomass lag up to a decade from the SST regime shifts, probably because of the time required for biomass accumulation in response to shifts in the stock-specific production rates and fishing mortality. Recruitment corresponds more closely with the SST regime shifts than with productivity, indicating early survival is the most sensitive stage in species life history to oceanographic changes. Yatsu *et al.* (2003) argued that productivity is less sensitive to environmental variability than to recruitment, as production is the composite of recruitment, individual growth and natural mortality over a broad range of ages. Even if these relationships between the PDO and AO were determined accurately, prediction of sardine and chub mackerel populations is difficult because the positive PDO and AO have a contradicting relationship to sardine and chub mackerel productivity. Jack mackerel will increase, as its production is negatively related to the Oyashio

southern limit, which has a negative relationship with the PDO (Fig. 25), and geographic distribution is confined to central and southern Japan, *i.e.*, jack mackerel seem independent of Oyashio productivity. Under the decreasing scenario of Oyashio productivity, the Pacific saury production rate will decrease.

## Possible Impacts of Climate Change on Fish Populations and Fisheries

A summary of linkages between stock trends and environmental conditions for different species is provided in Table 20.

### Chub mackerel

There is clear evidence that climate, and climate shifts, affect the production of chub mackerel. There also is evidence that overfishing of immature fish affects the ability of the population to respond to periods of favourable environmental conditions. It is apparent that future changes in climate will have an impact on production. Warming of the spawning areas in the winter will have a negative impact, as will more intense and frequent periods of extreme winter storminess (more intense Aleutian Lows and a positive PDO).

### Jack mackerel

Jack mackerel may increase in abundance as their productivity is negatively related to the southern limit of the Oyashio, which has a negative relationship with the PDO.

### Japanese sardine

In the Tsushima Current stock, reproductive success is negatively affected by winter temperature in the southwestern Japan Sea (Hiyama *et al.*, 1995). A similar effect of winter temperature is also known in the Pacific stock (Ebisawa and Kinoshita, 1998; Noto and Yasuda, 1999). The impacts of global warming induced climate change on Japanese sardine will relate to impacts on the dynamics of the western gyres, including the Kuroshio, Kuroshio Extension and Oyashio, and the structure of the Transition area. If the impact results in more intense and more extreme winter Aleutian Lows, and thus periods of positive PDO, then sardine abundance would continue to fluctuate, perhaps with all-time record

highs of abundance. However, other models suggest that winds will be reduced, and this could result in periods of increased stability, reduced plankton productivity, and low sardine survival, typical of the period from the late 1940s to the mid-1970s.

### Anchovy

The production of anchovy is opposite to that of Japanese sardine and this relationship is expected to continue. Therefore, a key to understanding the impacts of climate change on anchovy is to look at the behaviour of sardine. There is not a good relationship between PDO and other major ocean-climate indices and production, but there are persistent trends in production that change quickly to opposite trends, indicating that climate and ocean conditions are important. A key to the understanding of the impacts is the response of major atmospheric circulation patterns in the winter to increased greenhouse gas production. If winds are reduced, anchovy production may be generally increased as sardine production is reduced. The opposite would occur if there are more frequent periods of intense Aleutian Lows.

### Walleye pollock

There is no relationship between walleye pollock productivity or catch and the PDO, but there are decadal-scale fluctuations. This indicates that climate effects are important and that there is a persistence in climate-related impacts on walleye pollock. They are at the southern limit of their range around Japan and a warming of the ocean would reduce their productivity. Because walleye pollock are also relatively long-lived (maximum ages of about 30 years), there is a resiliency in the population to prolonged unfavourable ocean conditions if the stocks are not overfished. This resiliency could ensure that the stocks are maintained, and even enhanced, during the periods when naturally cold ocean conditions occur.

### Chum salmon

Chum salmon are virtually all produced in hatcheries and the number of fry produced has been maintained at about 2 billion in recent years. This means that egg-to-fry survival is independent of climate impacts, either directly in fresh water or indirectly in the regulation of the number of eggs produced (as would occur in naturally spawning stocks).

However, there will be an impact on chum salmon in the ocean during the early marine rearing period. In general, Pacific salmon at their southern range in the ocean are expected to have reduced marine survival and thus, reduced production as a consequence of the warming of the sea surface and the reduction in

plankton preferred by juveniles. A reduction in food reduces carrying capacity and reduces production either by increased predation mortality or by reduced growth in the early marine period, and a subsequent reduced ability to survive harsh environmental conditions in the first marine winter.

**Table 20** Summary of linkages between stock trend and environmental conditions in major stocks.

	<b>Biomass trend</b>	<b>Production/ recruitment trend</b>	<b>Environmental links (excluding SST)</b>	<b>SST link</b>	<b>Regime effect</b>
Chub mackerel	Similar biomass trend to sardine up to 1988, then there is overfishing	Recruitment is similar to saury	<ul style="list-style-type: none"> <li>- Positive PDO and negative AO increase abundance,</li> <li>- Positive AO increases recruitment,</li> <li>- More Kuroshio transport reduces biomass</li> </ul>	Warm winter SST in Kuroshio reduces recruitment	There is a regime effect
Jack mackerel	Similar biomass trends to common squid		More production with more southern Oyashio	Warm spring SST in East China Sea is related to biomass but reduces recruitment	There seems to be no regime effect but biomass trajectory is similar to that of common squid
Japanese sardine	Opposite response to common squid and jack mackerel	Production opposite to common squid	<ul style="list-style-type: none"> <li>- Positive PDO and negative AO increase abundance,</li> <li>- More southern Oyashio increases abundance,</li> <li>- More Kuroshio transport reduces production</li> </ul>	High winter SST in Kuroshio Extension reduces recruitment	There is a regime effect
Walleye pollock	Decadal fluctuations are evident	There are sporadic occurrences of strong year classes			There is no regime effect but decadal-scale fluctuations occur
Pacific saury		Recruitment similar to chub mackerel	<ul style="list-style-type: none"> <li>- Positive SOI increases productivity,</li> <li>- Positive AO decreases productivity with lag of 1 year</li> </ul>	Warm winter SST in Kuroshio reduces recruitment	There is no regime effect but there is a relationship with SOI and inter-annual fluctuations
Common squid	<ul style="list-style-type: none"> <li>- Similar biomass trends to jack mackerel,</li> <li>- Opposite response to sardine</li> </ul>	Production opposite to sardine	Positive PDO reduces biomass, as in 1977–1990		There is a regime effect

SST = sea surface temperature, PDO = Pacific Decadal Oscillation, AO = Arctic Oscillation, SOI = Southern Oscillation Index

### **Pacific saury**

The abundance trend of Pacific saury is related more to ENSO than to the PDO, suggesting that it is necessary to understand how global warming will change the pattern of ENSO to understand the impacts on Pacific saury. Warm surface waters in the Kuroshio and subtropical waters south of Shikoku and Kyushu are associated with reduced recruitment. Thus Pacific saury may be less abundant under a global warming scenario.

### **Common squid**

Common squid should respond to greenhouse gas-induced climate change in a manner similar to jack mackerel, and opposite to Japanese sardine. If jack mackerel abundance increases because its

productivity is negatively related to the Oyashio southern limit, which is negatively related to PDO, then common squid should also increase in a decadal fashion. Common squid were reduced in abundance during the 1980s when the PDO was positive and the Aleutian Low was strong. If there are more frequent periods of intense Aleutian Lows, there may be more frequent periods of reduced abundance of common squid. Because common squid live only for 1 year, their abundance trends change quickly.

### **Neon flying squid**

There is no apparent relationship to the PDO. There is a relationship between SST and abundance which indicates that warmer surface waters may be more productive for neon flying squid.

## References

- Baytalyuk A.A. and Davydova, S.V. 2001. Proceedings of Japan-Russia cooperative meeting on ecology and population dynamics of Pacific saury, chub mackerel, Japanese sardine, Japanese anchovy, squids, and walleye pollock. Fisheries Agency of Japan, 103 pp.
- Beamish, R.J. and Bouillon, D.R. 1993. Pacific salmon production trends in relation to climate. *Can. J. Fish. Aquat. Sci.* **50**: 1002–1016.
- Beamish, R.J. and Noakes, D.J. 2002. The role of climate in the past, present, and future of Pacific salmon fisheries off the west coast of Canada. pp. 231–244 in *Fisheries in a Changing Climate*, edited by N.A. McGinn, American Fisheries Society Symposium 32, Bethesda, Maryland.
- Belayev, V.A. and Ivanov, A.N. 1987. Dynamic processes in the fish community of the North-west Pacific. pp. 179–193. in *Ecosystem Dynamics of the Kuroshio-Oyashio Transition Region*, edited by M. Terazaki et al., University of Tokyo.
- Chiba, S., Ono, T., Tadokoro, K., Midorikawa, T. and Saino, T. 2004. Increased stratification and decreased lower trophic level productivity in the Oyashio region of the North Pacific: A 30-year retrospective study. *J. Oceanogr.* **60**: 149–162.
- Ebisawa, Y. and Snow, N. 1999. Influence of variation of the Kuroshio water on catch fluctuations of saury, *Cololabis saira*, in the waters off northeastern Japan. *Bull. Ibaraki Fish. Exper. Station* **37**: 29–36. (in Japanese)
- Ebisawa, Y. and Kinoshita, T. 1998. Relationship of surface water temperature in Boso-Sanriku area sea and recruitment per spawning biomass of the Japanese sardine. *Bull. Ibaraki Fish. Exper. Station* **36**: 49–55. (in Japanese)
- FAJ (Fisheries Agency of Japan and Fisheries Research Agency of Japan). 2004a. Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2004/2005) part 1. Fisheries Agency of Japan and Fisheries Research Agency, 449 pp. (in Japanese)
- FAJ (Fisheries Agency of Japan and Fisheries Research Agency of Japan). 2004b. The current status of international fishery stocks (summarized edition FY 2004). Fisheries Agency of Japan and Fisheries Research Agency, 138 pp.
- Fyfe, J.C., Boer, G.J. and Flato, G.M. 1999. The Arctic and Antarctic Oscillations and their projected changes under global warming. *Geophys. Res. Lett.* **26**: 1601–1604.
- Gong, Y., Hirano, T. and Zhang, C. I. 1983. On the migration of Pacific saury in relation to oceanographic conditions off Korea. *Bull. Japanese Soc. Fish. Oceanogr.* **44**: 51–75.
- Hiyama, Y. 1998. Migration range and growth rate in the Tsushima Current area. pp. 35–44 in *Stock Fluctuations and Ecological Changes of the Japanese Sardine*, edited by Y. Watanabe, and T. Wada, Koseisya-Koseikaku Co., Tokyo. (in Japanese)
- Hiyama, Y., Nishida, H. and Goto, T. 1995. Interannual fluctuations in recruitment and growth of the Sardine, *Sardinops melanostictus*, in the Sea of Japan and adjacent waters. *Res. Pop. Ecol.* **37**: 177–183.
- Iwata, M. 1975. Population genetics of the breeding groups of walleye pollock (*Theragra chalcogramma*) based on tetrazolium oxidase polymorphism. Science Report of Hokkaido Fisheries Experimental Station 17, pp. 1–9. (in Japanese)
- Kasai, A., Sugimoto, T. and Nakata, H. 1997. The dependence of yearly recruitment of Japanese sardine *Sardinops melanosticus* on survival in the Kuroshio-Oyashio transition region. *Fish. Sci.* **63**: 372–377.
- Kaeriyama, M. 1989. Aspects of salmon ranching in Japan. *Physiological Ecology of Japan*, Special Volume 1, pp. 625–638.
- Kaeriyama, M. 2004. Evaluation of carrying capacity of Pacific salmon in the North Pacific Ocean for ecosystem-based sustainable conservation management. N. Pac. Anadr. Fish Comm. Tech. Rep. 5, pp. 1–4.
- Kawasaki, T. 1983. Why do some pelagic fishes have wide fluctuations in their numbers? FAO Fish. Rep. 291, pp. 1065–1080.
- Kidokoro, H. 2002. Fluctuations in body size and abundance of Japanese common squid (*Todarodes pacificus*) in the Sea of Japan. GLOBEC Rep. 15, 42 pp.
- King, J.R. and McFarlane, G.A. 2003. Marine fish life history strategies: applications to fishery management. *Fish. Mgmt. Ecol.* **10**: 249–264.
- Kurita, Y. 2001. Annual report on “comprehensive study of the variation of the oceanic environment and fish populations in the North-western Pacific”. Fisheries Agency of Japan, 64 pp.
- Kuroda, K. 1991. Studies on the recruitment process focusing on the early life history of the Japanese sardine, *Sardinops melanostictus* (Schlegel). *Bull. Nat. Res. Inst. Fish. Sci.* **3**: 25–278.
- Kyushin, K., Kinoshita, T. and Hayashi, K. 1961. On the population of Alaska pollock in the Pacific

- coastal area west of Cape Erimo of Hokkaido. "Hokusushi geppou" **18**: 14–20. (in Japanese)
- McFarlane, G.A., Smith, P.E., Baumgartner, T.R. and Hunter, J.R. 2002. Climate variability and Pacific sardine populations and fisheries. American Fisheries Symposium 32, pp. 195–214.
- Mitani, S. 2001. Growth of Japanese anchovy. *Nippon Suisan Gakkaishi* **67**: 1131–1132. (in Japanese)
- Morimoto, H. 1998. Maturation. pp. 45–53, in Stock Fluctuations and Ecological Changes of the Japanese Sardine, edited by Y. Watanabe and T. Wada, Koseisya-Koseikaku Co., Tokyo. (in Japanese)
- Mote, P., Canning, D., Fluharty, D., Francis, R., Franklin, J., Hamlet, A., Hersman, M., Holmberg, M., Gray-Ideker, K., Keeton, W.S., Lettenmaier, D., Leung, R., Mantua, N., Miles, E., Noble, B., Parandvash, H., Peterson, D.W., Snover, A. and Willard, S. 1999. Impact of climate variability and change in the Pacific Northwest. JISAO/SMA Climate Impact Group, Univ. Washington, 109 pp.
- Murata, M. 1990. Oceanic resources of squids. *Mar. Behav. Physiol.* **18**: 19–71.
- Nagasawa, K., Imai, Y. and Ishida, K. 1988. Long-term changes in the population size and geographical distribution of *Pennella* sp. (Copepoda) on the saury, *Cololabis saira*, in the western North Pacific and adjacent waters. *Hydrobiologia* **167/168**: 571–577.
- Nagasawa, K., Mori, J. and Okamura, H. 1998. Parasites as biological tags of stock of neon flying squid (*Ommastrephes bartramii*) in the North Pacific Ocean. pp. 49–64 in Large Pelagic Squids, edited by T. Okutani, Japan Marine Fishery Resources Research Center, Tokyo.
- Nakata, K., Koyama, S. and Matsukawa, Y. 2001. Interannual variation in spring biomass and gut content composition of copepods in the Kuroshio current, 1971–89. *Fish. Oceanogr.* **10**: 329–341.
- Nishioka, S. and Harasawa, H. 1998. Global Warming the Potential Impacts on Japan, Springer.
- Noto, M. and Yasuda, I. 1999. Population decline of the Japanese sardine, *Sardinops melanostictus*, in relation to sea surface temperature in the Kuroshio Extension. *Can. J. Fish. Aquat. Sci.* **56**: 973–983.
- Ogata, T. 1956. On distribution of Pacific saury in the North Pacific Ocean. *Res. Bull. Japan Sea Regulatory Fish. Res. Lab.* **4**: 93–139.
- Odate, S. 1977. On distribution of Pacific saury in the North Pacific Ocean. Research Contribution. Contribution No. 92 from the Research Institute of North Pacific Fisheries, Faculty of Fisheries, Hokkaido University, Hakodate Japan, pp. 353–381. (in Japanese)
- Okazaki, T., Kobayashi, T. and Uozumi, Y. 1996. Genetic relationships of pilchards (genus *Sardinops*) with anti-tropical distributions. *Mar. Biol.* **126**: 585–590.
- Ono, T., Tadokoro, K., Midorikawa, T., Nishioka, J. and Saino, T. 2002. Multi-decadal decrease of net community production in western subarctic North Pacific. *Geophys. Res. Lett.* **29**: 10.1029/2001 GL014332.
- Polovina, J.J., Mitchum, G.T. and Evans, G.T. 1995. Decadal and basin-scale variation in mixed layer depth and the impact on biological production in the central and North Pacific, 1960–88. *Deep-Sea Res. I* **42**: 1701–1716.
- Saito, T. 2002. Factors affecting survival of hatchery-reared chum salmon in Japan. N. Pac. Anadr. Fish Comm. Tech. Rep. 4, pp. 37–38.
- Sakurai, Y., Kiyofuji, H., Saito, S., Goto, T. and Hiyama, Y. 2000. Changes in inferred spawning areas of *Todarodes pacificus* (Cephalopoda: Ommastrephidae) due to changing environmental conditions. *ICES J. Mar. Sci.* **57**: 24–30.
- Salanthe, E.P. 2006. Influences of a shift in North Pacific storm tracks on western North American precipitation under global warming. *Geophys. Res. Lett.* **33**: L19820, doi:10.1029/2006GL026882.
- Sassa, C. and Konishi, Y. 2002. Distribution and transportation of jack mackerel larvae in the East China Sea. *Kaiyo Mon. Spec. Issue* **31**: 92–98. (in Japanese)
- Shuter, B.J., Carline, R.F. and McGinn, N.A.. 2002. An overview of the symposium. pp. xiii–xix in Fisheries in a Changing Climate, Edited by N.A. McGinn, American Fisheries Society Symposium 32.
- Sugimoto, T. and Tadokoro, K. 1998. Interdecadal variations of plankton biomass and physical environment in the North Pacific. *Fish. Oceanogr.* **7**: 289–299.
- Takahashi M., Nishida H. and Yatsu, A. 2004. Preliminary study of growth of larval and early juvenile Japanese sardine in the Kuroshio-Oyashio transition region. PICES 13th Annual Meeting, p. 231. (Abstract)
- Takasuka A., Oozeki Y., Aoki I., Kimura R., Kubota H. and Yamakawa T. 2004. Differential optimal temperatures for growth of larval anchovy and sardine: A potential mechanism for regime shifts? PICES 13th Annual Meeting, p. 27. (Abstract)
- Takasuka, A., Oozeki, Y. and Aoki, I. 2007. Optimal growth temperature hypothesis: Why do anchovy flourish and sardine collapse or vice versa under the same ocean regime? *Can. J. Fish. Aquat. Sci.* **64**: 768–776.
- Taniguchi, A. 1999. Difference in the structure of the lower trophic levels of pelagic ecosystems in the eastern and western subarctic Pacific. *Prog. Oceanogr.* **43**: 289–315.

- Tian Y., Akamine, T. and Suda, M. 2002. Variations in the abundance of Pacific saury (*Cololabis saira*) from the northwestern Pacific in relation to oceanic-climate changes. *Fish. Res.* **60**: 439–454.
- Tomosada, A. and Odate, K. 1995. Long-term variability in zooplankton biomass and environment. “Umi-to-Sora” **71**: 1–7. (in Japanese)
- Tsuji, S. 1978. General remarks on the populations of Alaska pollock (*Theragra chalcogramma* (Pallas)) in waters of Hokkaido. “Hokusushi geppou” **35**: 1–57. (in Japanese)
- Tsuji, S. 1989. Alaska pollock population, *Theragra chalcogramma*, of Japan and its adjacent waters I: Japanese fisheries and population studies. *Mar. Behav. Physiol.* **16**: 61–107.
- Urawa, S. 2000. Migration of Japanese chum salmon and future studies. *National Salmon Resources Center News* **5**: 3–9. (in Japanese).
- Watanabe, C. and Yatsu, A. 2004. Effects of density-dependence and sea surface temperature on interannual variation in length-at-age of chub mackerel (*Scomber japonicus*) in the Kuroshio-Oyashio area during 1970–1997. *Fish. Bull. U.S.* **102**: 196–206.
- Watanabe, Y., Zenitani, H. and Kimura, R. 1995. Population decline of the Japanese sardine *Sardinops melanostictus* owing to recruitment failures. *Can. J. Fish. Aquat. Sci.* **52**: 1609–1616.
- Yasunaka, S. and Hanawa, K. 2002. Regime shifts found in the northern hemisphere SST field. *J. Meteorol. Soc. Japan* **80**: 119–135.
- Yatsu, A. and Kidokoro, H. 2002. Coherent low frequency variability in biomass and in body size of Japanese common squid, *Todarodes pacificus*, during 1964–2000. PICES 11th Annual Meeting, p. 89. (Abstract)
- Yatsu, A. and Kaeriyama, M. 2005. Linkages between coastal and open ocean habitats and dynamics of Japanese stocks of chum salmon and Japanese sardine. *Deep-Sea Res. II* **52**: 727–737.
- Yatsu, A., Hiramatsu, K. and Hayase, S. 1993. Outline of Japanese squid driftnet fishery with notes on the bycatch. *Bull. Int. Nat. N. Pac. Fish. Comm.* **53**: 5–24.
- Yatsu, A., Tanaka, H. and Mori, J. 1998. Population structure of the neon flying squid, *Ommastrephes bartramii*, in the North Pacific Ocean. pp. 31–48 in Large Pelagic Squids, edited by T. Okutani, Japan Marine Fishery Resources Research Center, Tokyo.
- Yatsu, A., Watanabe, T., Mori, J., Nagasawa, K., Ishida, Y., Meguro, T., Kamei, Y. and Sakurai, Y. 2000. Interannual variability in stock abundance of the neon flying squid, *Ommastrephes bartrami*, in the North Pacific Ocean during 1979–1998: impact of driftnet fishing and oceanographic conditions. *Fish. Oceanogr.* **9**: 163–170.
- Yatsu, A., Mitani, T., Watanabe, C., Nishida, H., Kawabata, A. and Matsuda, H. 2002 Current stock status and management of chub mackerel, *Scomber japonicus*, along the Pacific coast of Japan - an example of allowable biological catch determination. *Fish. Sci.* **68**(suppl. 1): 93–96.
- Yatsu, A., Watanabe, T., Ishida, M., Sugisaki, H. and Jacobson, L.D. 2003. DRAFT: Reproductive success variability of the Pacific stocks of Japanese sardine, *Sardinops melanostictus*, and chub mackerel, *Scomber japonicus*: Possible processes and management strategy. GLOBEC Special Contribution 6, pp. 109–126.
- Yatsu, A., Watanabe, T., Ishida, M., Sugisaki, H. and Jacobson, L.D. 2005. Environmental effects on recruitment and productivity of Japanese sardine *Sardinops melanostictus* and chub mackerel *Scomber japonicus* with recommendations for management. *Fish. Oceanogr.* **14**: 163–278.
- Yoshida, H. 1982. On the results of tagging experiments of Alaska pollock around Hokkaido. “Gyogyo shigen kenkyu kaigi kita-nihon sokou bukai-ho” **15**: 70–81. (in Japanese)