Migration of Young Bluefin Tuna, *Thunnus orientalis* Temminck et Schlegel, through Archival Tagging Experiments and Its Relation with Oceanographic Conditions in the Western North Pacific

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A total of 105 young bluefin tuna with archival tags was released in the Tsushima Strait (between the East China Sea and the Japan Sea) in winters of 1995 and 1996. Of 24 fish recaptured, five moved to the North Pacific and spent there more than one year, and their migration patterns were analyzed in relation to oceanographic conditions observed by satellites. The fish preferred warm water around 18℃ in the upper layer in the western North Pacific. They showed clockwise migration patterns closely related with the ocean structure in and around the Kuroshio-Oyashio Inter-frontal Zone. The fish moved westward in spring in and around the Kuroshio Extension, northward in summer in the warm water spread from the crest of the Kuroshio Extension, eastward in fall along the south of the Oyashio front, and southward in early winter to the Kuroshio Extension. It is likely that their migration routes are related with changes of chlorophyll-*a* concentration as well as ocean currents.

Key words: bluefin tuna, migration, Pacific, oceanographic condition, archival tag, remote sensing

Introduction

Most of Japanese northern bluefin tuna catches are obtained by purse seine fisheries which target both immature and mature fish in the western North Pacific and the Japan Sea. Longline fishery also harvests pre-spawning and spawning adults in the waters off southern Japan and the eastern Taiwan in spring. Trollers mainly operate in the northeastern East China Sea (hereafter ECS), and catch a large amount of young bluefin tuna in winter. Based on the seasonal changes in the fishing grounds and fish size caught by various fisheries around Japan, the migration patterns of bluefin tuna in the Pacific Ocean were previously studied by Yamanaka (1982). Bayliff *et al*. (1991) and Yonemori (1989) also hypothesized the migration of bluefin tuna in the Pacific by using data from tags. But these authors could not appear the annual migration patterns of bluefin tuna throughout a year.

The western North Pacific is one of three most famous fishing grounds in world, encountering the warm current Kuroshio and the cold current Oyashio. The relationships between fish migration and ocean current in this area were discussed for Japanese sardine (Inagake 1987), skipjack tuna (Kawai and Sasaki 1962) and saury (Tomosada and Inagake 1986), but not for bluefin tuna. Yamanaka *et al*. (1969) suggested that bluefin tuna change the water mass according with their growth. However, their discussion was limited to the comparison of the tuna distribution and water mass and did not refer to the relationship between the tuna migration and oceanic current.

Recently, archival tags, which estimate geographical positions from change of light level, are commonly used, and enable us to get continuous time-series data with longer duration and higher resolution. They have been deployed for southern bluefin tuna (Gunn, pers. comm.) and Atlantic bluefin tuna (Block *et al*. 1998). Itoh *et al*. (unpublished) showed various migration patterns of young bluefin tuna, including the trans-Pacific migration, using the archival tags. Kitagawa *et al*. (2000) found that spatial and seasonal changes in vertical structure of ambient water temperature have a great effect on the vertical distribution and movement of the young bluefin tuna in the East China Sea using archival tag data. On the other hand, global oceanographic conditions have been detected using satellite data in recent years. These satellite data are useful to analyze relationships between oceanographic conditions and basin-scale migration routes detected by archival tags.

In this paper, we describe the migration routes of the young bluefin tuna in the western North Pacific with relation to oceanic conditions, based on five tag data from the fish which spent there more than one year, and discuss the effect of oceanic currents on their migrations.

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Materials and Methods

Tag data

Tagging surveys were conducted in December 1995 and November 1996 in the Tsushima Strait, connecting ECS and the Japan Sea. Fish were caught by trolling and individually tagged. An archival tag (Northwest Marine Technology, Inc. U.S.*) was inserted into the abdominal cavity of fish on board and was released immediately after tagged. A total of 105 bluefin tuna ranging from 45 to 78 cm in fork length (hereafter FL) was released, and 24 tag recoveries were obtained until May 31, 2000. In this paper, we used data from the tags, #194, #199, #226, #227 and #241, of five fish spent more than one year in the North Pacific. These fish were estimated to be age 0 at release based on their sizes (49-55 cm FL, Yukinawa and Yabuta 1963, Foreman 1996).

Data on daily locations and ambient temperatures at three layers (near the sea surface, 60-63 m and 120-126 m) were retrieved from the tags. Data on pressure and temperature were calibrated before tagged and after recovered. Daily locations were estimated from the time of sunrise and sunset determined from a change in light intensity and stored every day in a tag. In particular, locations of in latitude were adjusted by seeking for the nearest point that showed the same surface water temperature as recorded in a tag along the estimated longitude. The surface water temperature maps, published from the Japan Fisheries Information Service Center, were used for this purpose. Locations of longitude were not adjusted because the data were reliable.

Information on the five bluefin tuna deployed with archival tags and on the data status is summarized in Table 1. Monthly percentage of days with data on location and water temperature is shown in Table 2. Ambient temperature in each of three depth zones were recorded when the fish swam

Table 1. Information on the five recaptured bluefin tuna and the status of sensor used in this study.

Deployment data			Recapture data				Liberty time in day	Depth (m) of water temperature recording			Sensor Status
Fork Length (cm)	Date	Position	Body Size*	Date	Position						
49	14/Dec./1995	34°04' N 129°04' E	61kg BW	20/June/1999	38°39' N	157°10' E	1285	Near surface	62	125	Light intensity records were in trouble from January 1999
54	11/Dec./1995	34°17' N 129°52' E	68kg BW	4/July/1999	40°03' N	152°19' E	1302	Near surface	62	125	No problem through the free
50	10/Dec./1995	33°59' N 129°01' E	65kg BW	16/June/1999	38°43' N	148°38' E	1285	Near surface	60	120	Temperature records were in trouble from May 1996
52	10/Dec./1995	33°59' N 129°01' E	76kg BW	1/May/2000	33°00' N	141°51' E	1635	Near surface	62	124	Temperature records were in trouble from Aug. 1998
55	29/Nov./1996	34°25' N 129°08' E	87.6cm FL	1/Aug./1998	31°48' N	117°18' W	611	Near surface	63	126	No problem through the free

* FL: Fork length BW: Whole body weight

Table 2. Monthly percentages of available ambient temperature and locations, obtained by archival tags.

Year	Month	#194				#199				#226				#227				#241			
		Ambient temperature			Location	Ambient temperature			Location	Ambient temperature			Location	Ambient temperature			Location	Ambient temperature			Location
		surface	62m	125m	estimated	surface	62m	125m	estimated	surface	60m	120m	estimate	surface	62m	124m	estimated	surface	63m	126m	estimated
1995	Dec	100.0	100.0	33.3	100.0	100.0	100.0	-	90.5	100.0	100.0	63.6	95.5	100.0	100.0	68.2	95.5				
1996	Jan	100.0	100.0	90.3	96.8	100.0	100.0	16.1	96.8	100.0	100.0	90.3	100.0	100.0	100.0	93.5	90.3				
	Feb	100.0	100.0	27.6	93.1	100.0	100.0	31.0	96.6	100.0	100.0	93.1	89.7	100.0	100.0	69.0	100.0				
	Mar	100.0	100.0	12.9	93.5	100.0	100.0	22.6	77.4	100.0	100.0	35.5	96.8	100.0	100.0	48.4	90.3				
	Apr	100.0	100.0	26.7	86.7	100.0	100.0	33.3	90.0	100.0	100.0	10.0	93.3	100.0	90.0	40.0	93.3				
	May	100.0	96.8	-	100.0	100.0	96.8	48.4	87.1	9.7	12.9	-	6.5	100.0	100.0	32.3	96.8				
	Jun	100.0	90.0	6.7	100.0	100.0	43.3	13.3	100.0	-	-	-	-	100.0	90.0	16.7	96.7				
	Jul	100.0	87.1	-	93.5	100.0	45.2	12.9	93.5	-	-	-	-	100.0	71.0	45.2	100.0				
	Aug	100.0	93.5	25.8	45.2	100.0	51.6	3.2	100.0	-	-	-	-	100.0	58.1	25.8	96.8				
	Sep	100.0	30.0	10.0	76.7	100.0	63.3	16.7	90.0	-	-	-	-	100.0	20.0	3.3	100.0				
	Oct	100.0	93.5	54.8	45.2	100.0	96.8	48.4	80.6	-	-	-	-	100.0	22.6	9.7	100.0				
	Nov	100.0	100.0	-	90.0	100.0	96.7	53.3	93.3	-	-	-	-	100.0	80.0	3.3	96.7	100.0	100.0	-	-
	Dec	100.0	96.8	12.9	74.2	100.0	80.6	35.5	87.1	-	-	-	-	100.0	100.0	6.5	100.0	100.0	96.8	3.2	96.8
1997	Jan	100.0	100.0	-	100.0	100.0	96.8	90.3	74.2	-	-	-	-	100.0	100.0	12.9	100.0	100.0	100.0	25.8	83.9
	Feb	100.0	100.0	96.4	82.1	100.0	100.0	92.9	75.0	-	-	-	-	100.0	78.6	7.1	96.4	100.0	100.0	7.1	85.7
	Mar	100.0	100.0	87.1	58.1	100.0	96.8	93.5	71.0	-	-	-	-	100.0	100.0	51.6	93.5	100.0	96.8	51.6	25.8
	Apr	100.0	93.3	76.7	76.7	100.0	100.0	90.0	76.7	-	-	-	-	100.0	100.0	16.7	100.0	100.0	100.0	63.3	90.0
	May	100.0	80.6	32.3	93.5	100.0	90.3	67.7	90.3	-	-	-	-	100.0	90.3	9.7	100.0	100.0	71.0	45.2	83.9
	Jun	100.0	100.0	46.7	80.0	100.0	83.3	53.3	80.0	-	-	-	-	100.0	73.3	46.7	96.7	100.0	43.3	36.7	93.3
	Jul	100.0	35.5	9.7	96.8	100.0	64.5	25.8	93.5	-	-	-	-	100.0	51.6	22.6	100.0	100.0	32.3	16.1	90.3
	Aug	100.0	12.9	3.2	100.0	100.0	9.7	9.7	100.0	-	-	-	-	100.0	87.1	35.5	96.8	100.0	-	3.2	96.8
	Sep	100.0	20.0	-	100.0	100.0	26.7	13.3	96.7	-	-	-	-	100.0	56.7	26.7	90.0	100.0	23.3	13.3	30.0
	Oct	100.0	19.4	6.5	100.0	100.0	29.0	3.2	90.3	-	-	-	-	100.0	83.9	48.4	71.0	100.0	35.5	12.9	93.5
	Nov	100.0	66.7	16.7	86.7	100.0	96.7	60.0	73.3	-	-	-	-	100.0	83.3	56.7	86.7	100.0	93.3	23.3	93.3
	Dec	100.0	80.6	19.4	93.5	100.0	100.0	25.8	87.1	-	-	-	-	100.0	96.8	22.6	80.6	100.0	100.0	32.3	96.8
1998	Jan	100.0	93.5	67.7	54.8	100.0	100.0	61.3	90.3	-	-	-	-	100.0	100.0	67.7	83.9	100.0	100.0	61.3	93.5
	Feb	100.0	100.0	92.9	32.1	100.0	96.4	60.7	82.1	-	-	-	-	100.0	100.0	75.0	100.0	100.0	100.0	14.3	78.6
	Mar	100.0	100.0	96.8	54.8	100.0	96.8	77.4	64.5	-	-	-	-	100.0	100.0	58.1	96.8	100.0	100.0	12.9	29.0
	Apr	100.0	90.0	46.7	80.0	100.0	100.0	93.3	70.0	-	-	-	-	100.0	100.0	86.7	80.0	100.0	100.0	46.7	100.0
	May	100.0	100.0	74.2	67.7	100.0	93.5	45.2	87.1	-	-	-	-	100.0	93.5	54.8	90.3	100.0	71.0	35.5	96.8
	Jun	100.0	73.3	16.7	86.7	100.0	76.7	36.7	83.3	-	-	-	-	100.0	100.0	73.3	86.7	100.0	70.0	50.0	100.0
	Jul	100.0	41.9	16.1	93.5	100.0	58.1	16.1	93.5	-	-	-	-	100.0	96.8	90.3	93.5	100.0	96.8	77.4	83.9
	Aug	100.0	9.7	6.5	96.8	100.0	22.6	-	96.8	-	-	-	-	100.0	64.5	41.9	64.5	100.0	100.0	-	-
	Sep	100.0	3.3	3.3	100.0	100.0	16.7	3.3	96.7	-	-	-	-	-	-	-	-				
	Oct	100.0	45.2	9.7	80.6	100.0	51.6	32.3	61.3	-	-	-	-	-	-	-	-				
	Nov	100.0	73.3	23.3	90.0	100.0	93.3	80.0	50.0	-	-	-	-	-	-	-	-				
	Dec	100.0	100.0	54.8	67.7	100.0	100.0	38.7	87.1	-	-	-	-	-	-	-	-				
1999	Jan	100.0	96.8	67.7	22.6	100.0	100.0	64.5	90.3	-	-	-	-	-	-	-	-				
	Feb	100.0	92.9	64.3	-	100.0	92.9	71.4	67.9	-	-	-	-	-	-	-	-				
	Mar	100.0	100.0	100.0	-	100.0	100.0	93.5	80.6	-	-	-	-	-	-	-	-				
	Apr	100.0	100.0	100.0	-	100.0	93.3	100.0	63.3	-	-	-	-	-	-	-	-				
	May	100.0	96.8	54.8	-	100.0	100.0	90.3	48.4	-	-	-	-	-	-	-	-				
	Jun	66.7	63.3	46.7	-	100.0	90.0	46.7	80.0	-	-	-	-	-	-	-	-				
	Jul					75.0	25.0	-	75.0					-	-	-	-				

"-" represents that no daily data should be obtained during each liberty time.

* Present patent is held by lotck Engineering Inc., Canada.

Table 3. Definition of water masses and currents.

Target characteristics	Extraction method
Kuroshio Axis	15～16.5℃ isotherm at 200 m (Kawai, 1969)
Kuroshio Extension Axis	14℃ isotherm at 200 m (Kawai, 1969)
Warm-core ring	Temperature front at 200 m
Oyashio front	5 ℃ isotherm at 100 m
Original Oyashio Water	Water with temperature colder than 2 ℃ (Kawai, 1972)
Warm water spred from the Kuroshio Extension	Area with T>10 ℃ at 100 m and T<14 ℃ at 200 m

in those depth zones. Data from tag #194 was in trouble for geographical positions after January 1999. Geographical positions from tags #226 and #227 could not be adjusted after May 1996 and August 1998, respectively, because ambient temperatures were not recorded.

Satellite remote sensing data

Three kinds of satellite remote sensing data, sea surface height (SSH), sea surface temperature (SST) and sea surface chlorophyll-***a*** concentration (SSC), were used from the NASA and the Colorado Center for Astrodynamics Research to get oceanographic conditions around the tagged fish.

The NASA distributes weekly global gridded MCSST (the multichannel sea surface temperature) images derived from the NOAA AVHRR. We composed several weekly nighttime MCSST images into a near monthly MCSST image, which was used in this paper.

The NASA also distributes the standard mapped images of chlorophyll-***a*** (hereafter Chl-***a***) concentration derived from the SeaWiFS. We interpolated daily Chl-***a*** images to fill cloudy pixels considering spatial decorrelation scale of 50 km and temporal of 2 days. Then, a monthly Chl-***a*** image composed from the interpolated daily images was used in this paper.

The Colorado Center for Astrodynamics Research distributes the semimonthly sea surface height image derived from TOPEX/Poseidon and ERS-2. We used the image of middle of each month with depth of no motion at 1000 m.

Data on SSH and SST range from December 1995 to July 1999, and those on SSC from September 1997 to July 1999.

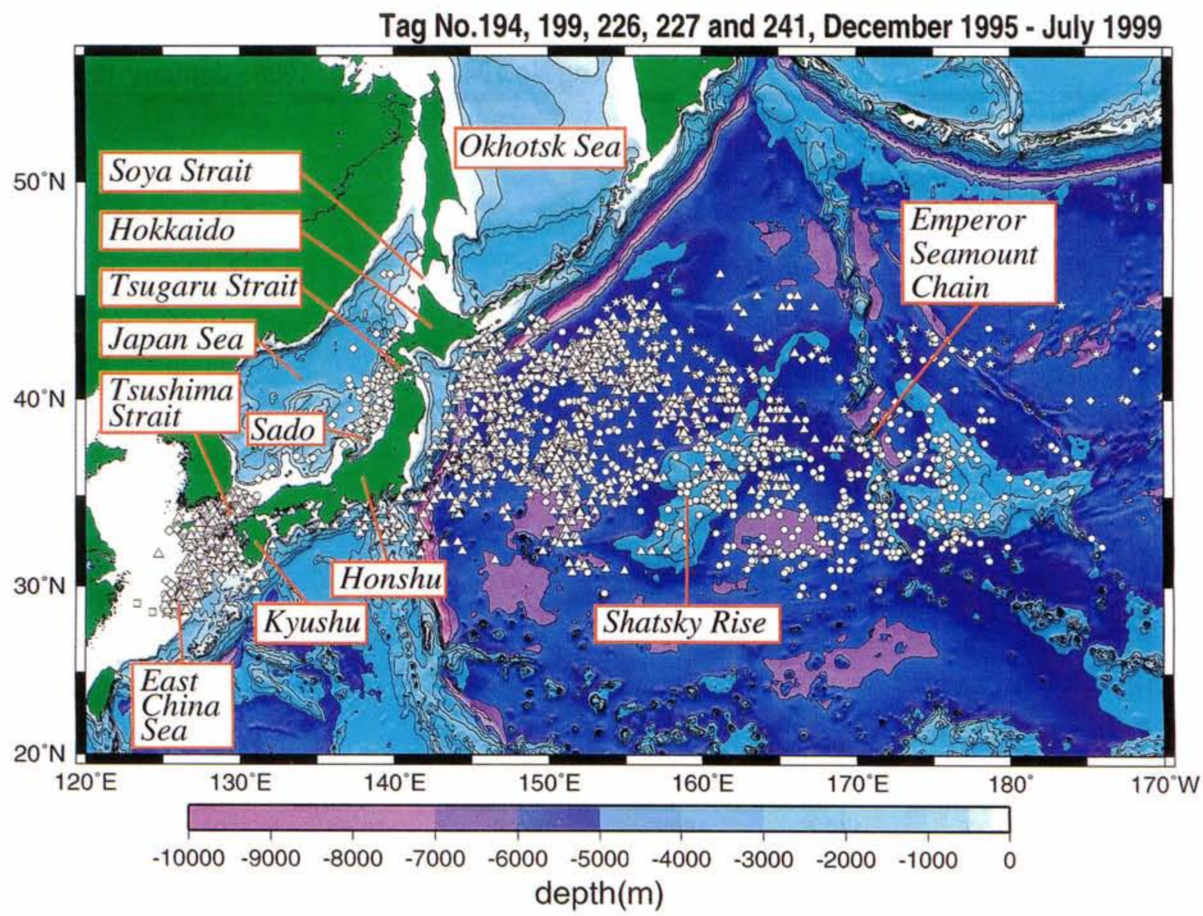


Fig. 1. Daily locations of five bluefin tuna from December 1995 to July 1999 with bottom topography. △, #194; ○, #199; □, #226; ◇, #227; ☆, #241.

Temperature map

To identify oceanographic conditions, water temperatures at 100 and 200 m in depths were also used with maps on SSH and SST detected by satellite remote sensing. 100 m and 200 m temperature maps using in this paper were printed in ***the Monthly Ocean Report***, which was published by the Climate and Marine Department, Japan Meteorological Agency. The definition of each water mass and axis of each current using in this paper are listed in Table 3.

Migration of Young Bluefin Tuna Related to Oceanic Conditions in the western North Pacific

Figure 1 shows all daily locations of five bluefin tunas with the sea bottom topography. The five recaptured fish were distributed mainly in the following five areas: 1) the Tsushima Strait to the shelf edge of ECS, 2) along around 145°E line and around 150°E line of 35-40°N in the Pacific in summer where the first and second crests of Kuroshio Extension (hereafter KE) usually exist respectively, 3) 40-42°N line in fall where is the Oyashio front and/or the Subarctic Boundary, 4) around the Shatsky Rise and the Emperor Seamount Chain in late fall, and 5) around KE in winter and spring.

Figure 2 shows the daily locations of each fish. Of them, one fish (#226) were not estimated the daily locations after May 1996. Figure 3 shows the schematic diagram of their migration. In ECS, all five fish usually stayed in the northeastern area through a half of one year after release, but sometimes migrated to southern waters along the shelf edge near the Kuroshio from January to June. When they left ECS, there were two routes; one was the path to the Pacific Ocean along the Kuroshio beyond the southern coast of Kyushu (#194 in March and #241 in May), and another was the path to the Japan Sea (#199 from June to November and #227 from June to August). When the two fish left the Japan Sea to the Pacific Ocean, there were two paths; one was through the Tsugaru Strait (#199 in November) and another was through the Soya Strait and Okhotsk Sea (#227 in August).

They arrived in the western North Pacific Ocean, the most of fish showed clockwise annual migration patterns (Fig. 3). From May to August, they migrated northward along around 145°E line or around 150°E line where the warm water usually spread from the first or second crest of KE. They then reached to the Oyashio front, and migrated eastward along the front and/or the Subarctic Boundary from August to October. There fish migrated southward to the waters near the Shatsky Rise and the Emperor Seamount Chain in November, and moved southward into KE in December. They were distributed in and around KE during winter and early spring, and they concentrated again around the first or second crest of KE in May.

Monthly maps of SST, SSH and SSC with daily locations of all five tunas are shown in Figs.

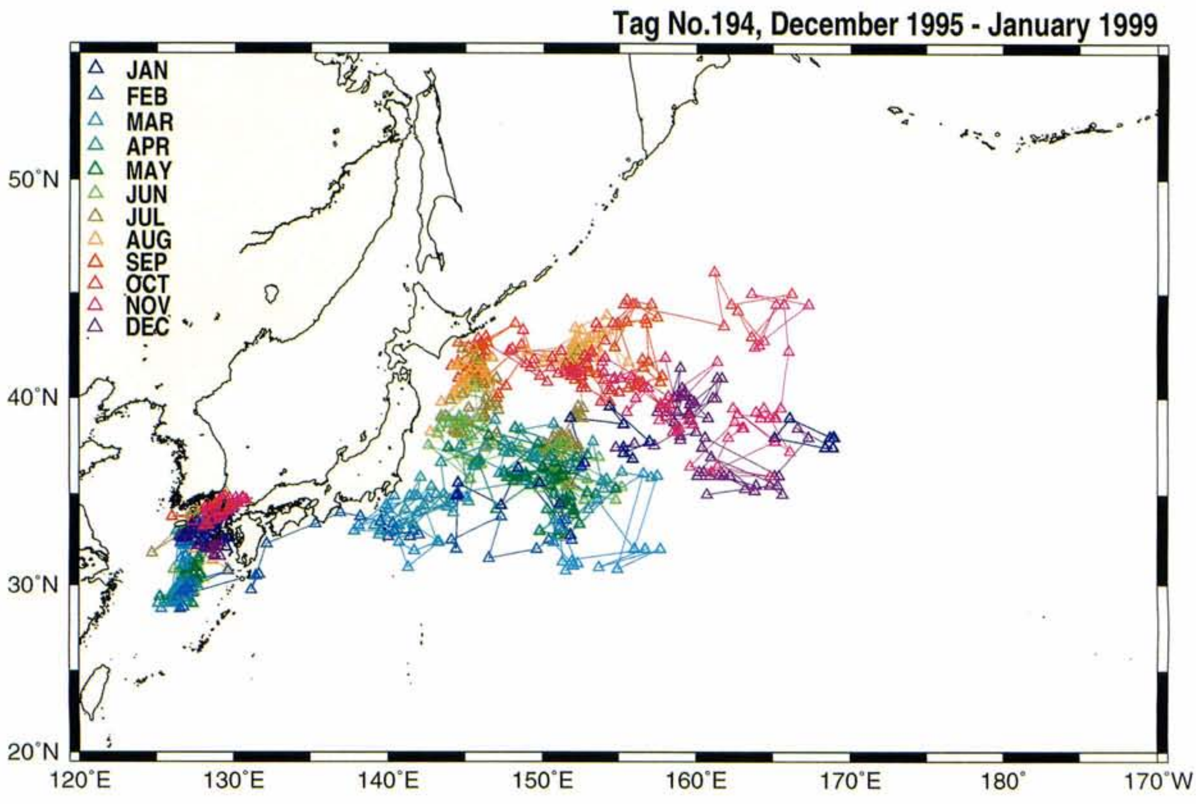
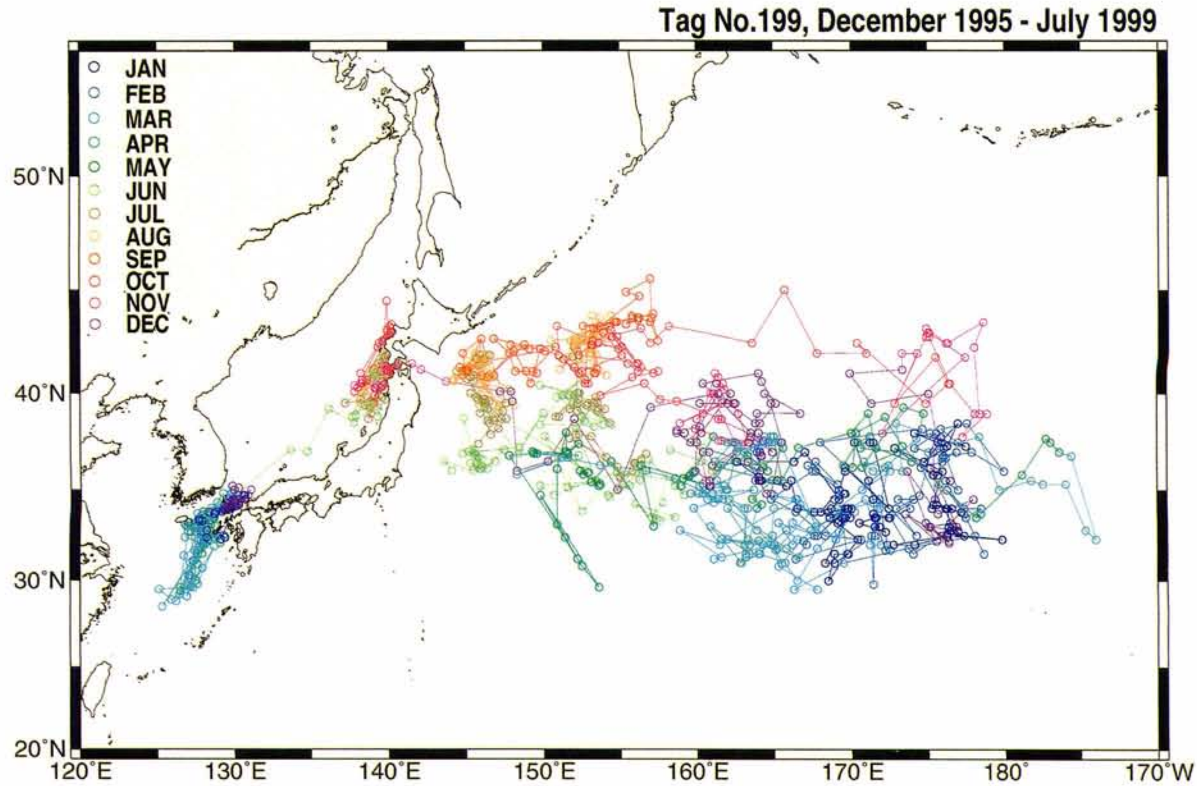


Fig. 2. Daily locations of each bluefin tuna from December 1995 to July 1999. The mark was distinguished by 12 colors corresponding to each month from January to December.



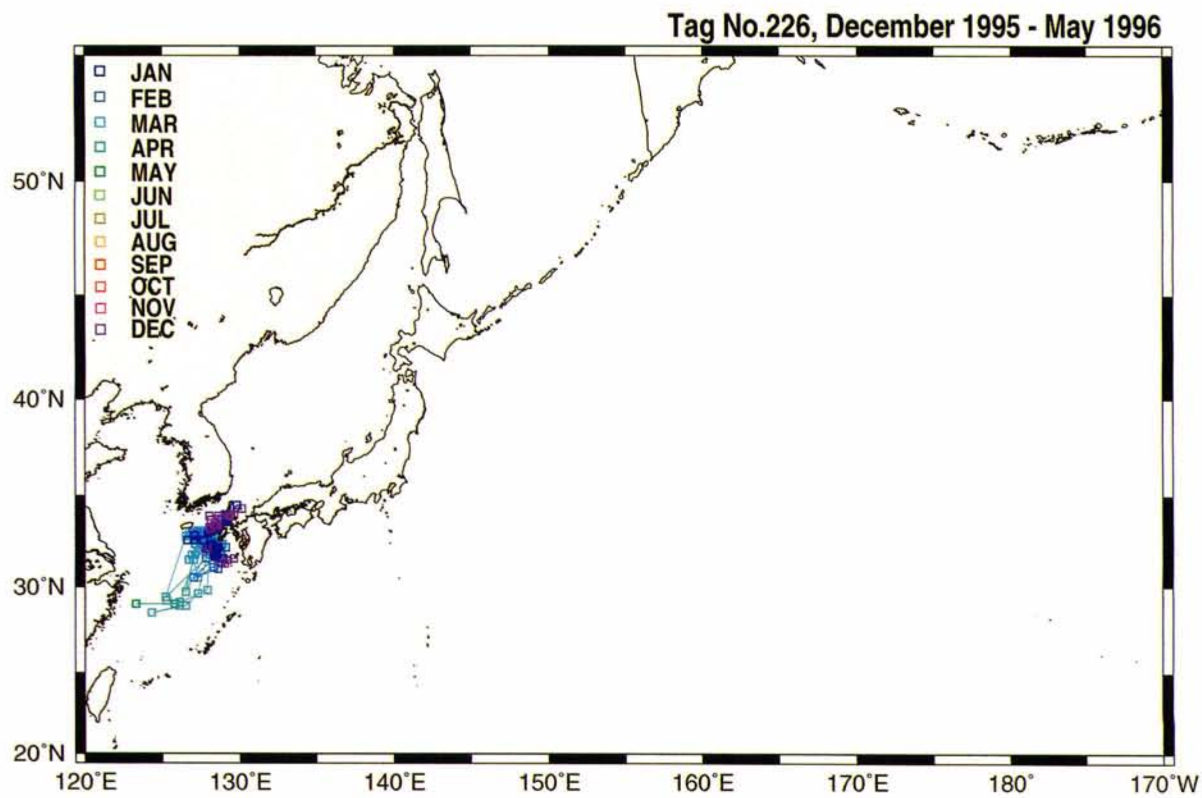
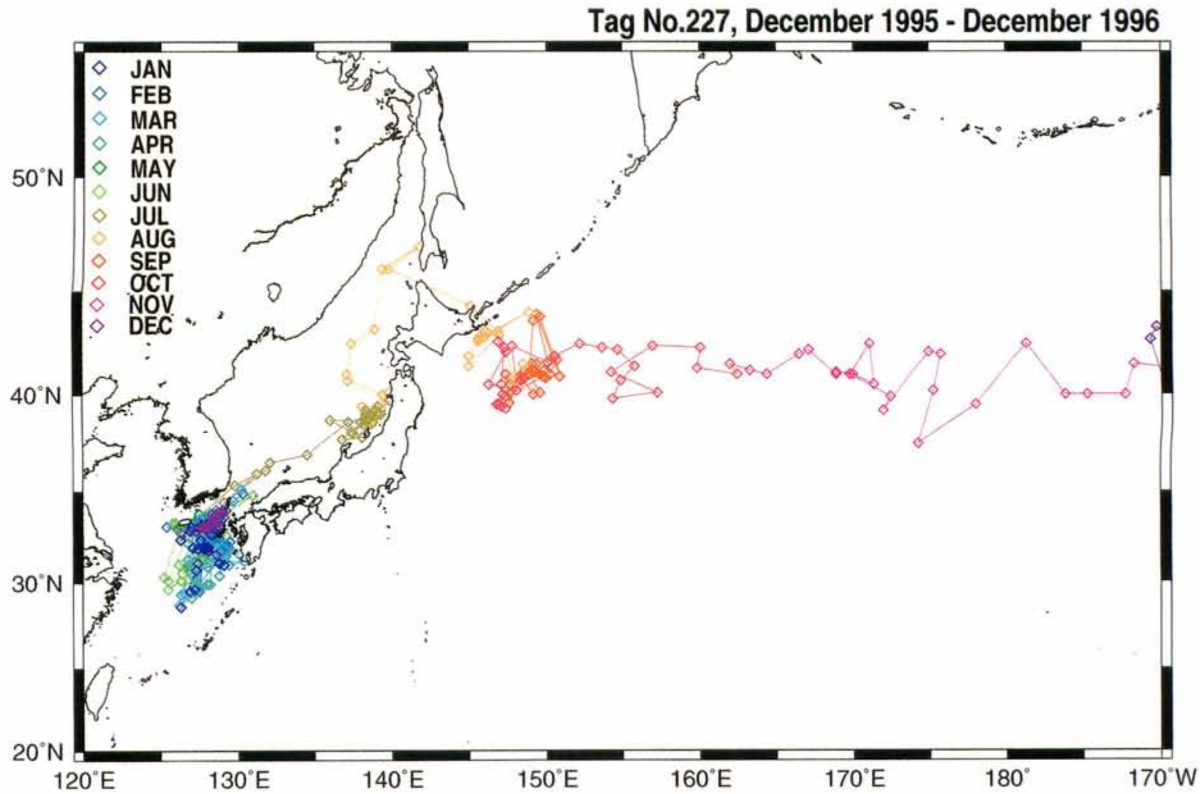
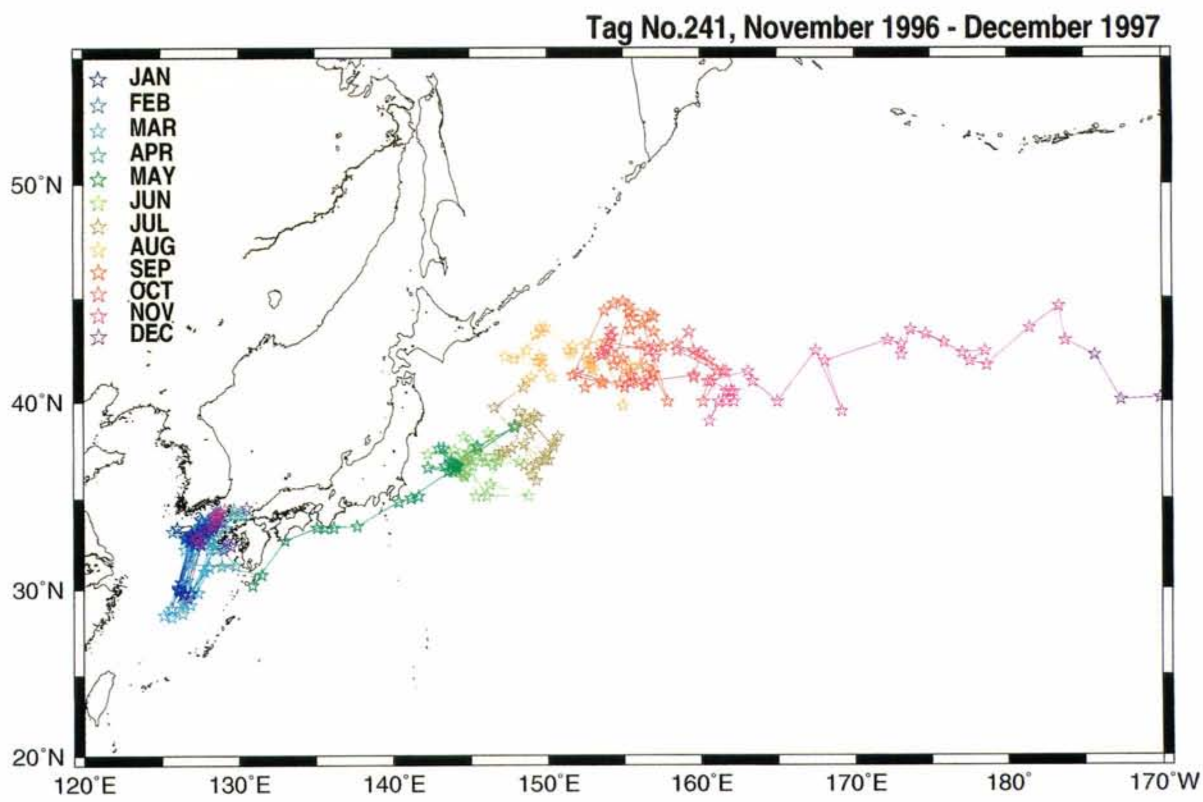


Fig. 2. Continued.





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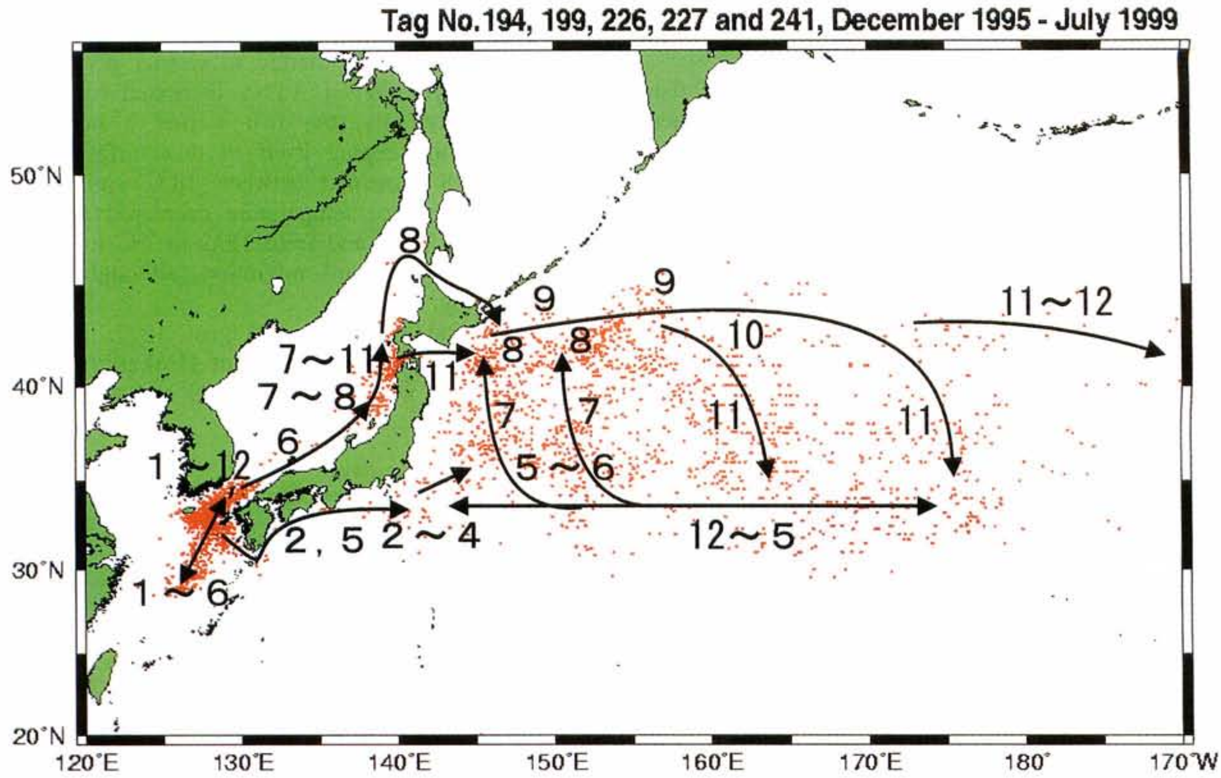


Fig. 3. Schematic diagram of migratory paths of bluefin tuna found by five archival tags in this study. Red dots show the daily locations of each bluefin tuna. The numeral denotes the month when the fish was usually distributed.

4a-4k. Figure 5 indicates daily changes of ambient temperatures at three layers (see Table 1) and latitude of fish locations. The detailed migration pattern of each is described with a relation to oceanographic conditions and the topography between a release and a recapture.

#194 fish (indicated by the triangle symbol in the Fig. 2 and Figs. 4a-4k)

#194 fish stayed in ECS during the first thirteen months from late December 1995 to early February 1997 (Figs. 4a-4d). The fish was usually distributed in the northeastern area of ECS, but it migrated southward in the winter season. From December 1995 to March 1996, the fish migrated to southern waters along the shelf edge of ECS (around 29-30° N, see Figs. 1, 2 and 4a). The ambient temperatures at three layers (hereafter ATs) decreased gradually from 18℃ in December to 15℃ in the end of January due to a winter cooling and vertical mixing, and ATs of 15℃ usually continued until March. When the fish moved southward to the Kuroshio (temperature at 100 m depth of the Kuroshio was 18-21℃ in ECS in February) in early February, ATs increased to 17℃, but it decreased again to 15℃ with a little northward shift of the fish. The fish stayed in the southern area till May 1996.

The fish moved northward in mid-June, then usually stayed in the northeastern area of the ECS from July to November 1996. The ambient temperature of near sea surface (hereafter ATNS) increased from 17.0℃ in early May to 29.6℃ in mid-August, although the ambient temperature at the depth of 62 m (hereafter AT62) remained around 13 -15℃ from May to late September 1996. When the fish showed a little southward movement to the west of Kyushu in late August, AT62 increased around 19℃ (Fig. 5). The ambient temperature at the depth of 125 m (hereafter AT125) was sometimes observed around 14-15℃ from April to August. AT62 increased to 17-22℃ in October-November 1996, although AT125 increased slightly to around 16℃.

AT125, which recorded a few times in the northern area, increased to around 18℃ in mid-December 1996, because ATs converged almost the same value due to a winter vertical mixing of waters. When ATs decreased to 16.0℃ in the end of January 1997, the fish moved suddenly southward to the Kuroshio southwest of Kyushu from the northeastern area of the ECS in early February 1997 (Figs. 4d and 5). ATNS and AT62 then recovered to 18-21℃ but AT125 was still around 17℃ (Fig. 5). The fish showed active vertical movement to the deeper layer than 125 m in the Kuroshio after February, because AT125 higher than 18℃ were recorded continuously. The fish moved eastward rapidly to the Pacific Ocean beyond the south of Kyusyu in mid-February, and then still moved along the Kuroshio, judging from the AT125 of 13-18℃. Then, the fish arrived within February and stayed in the Kuroshio near the Izu Islands until mid-April

1997. ATs were around 18-19℃ from the later half of February to late March according to development of vertical mixing.

In the later half of April 1997, the fish migrated northward from the Izu Islands area, then ATs shifted from around 18℃ to 14-15℃. The fish migrated through the Kuroshio warm-core ring in the first crest of KE as shown in Inagake and Saitoh (1998). SSH map in Fig. 4e shows that spreading of the warm water was restricted on the first crest of KE but was prominent from the second crest between April and July. The fish returned southeastward along the warm water spread from the second crest of KE in May. ATNS increased to 19 ℃ and AT125 were sometimes observed around 13-14℃(Fig. 5). This reducing the number of AT125 indicated that the fish started to restrict diving into subsurface layer. When ATNS increased to around 21℃ in early July, the fish started a northward migration with keeping itself in this surface warm water (ATNS remained between 18℃ and 22℃). However subsurface temperature decreased from 16 ℃ to 9℃ in AT62 and from 12℃ to 7℃ in AT125 according to northward migration, although ATNS remained (Fig. 5).

From end of July to August 1997, the fish reached the Oyashio front east of Hokkaido (around 42°N, 152°E), where both of #199 and #241 were,

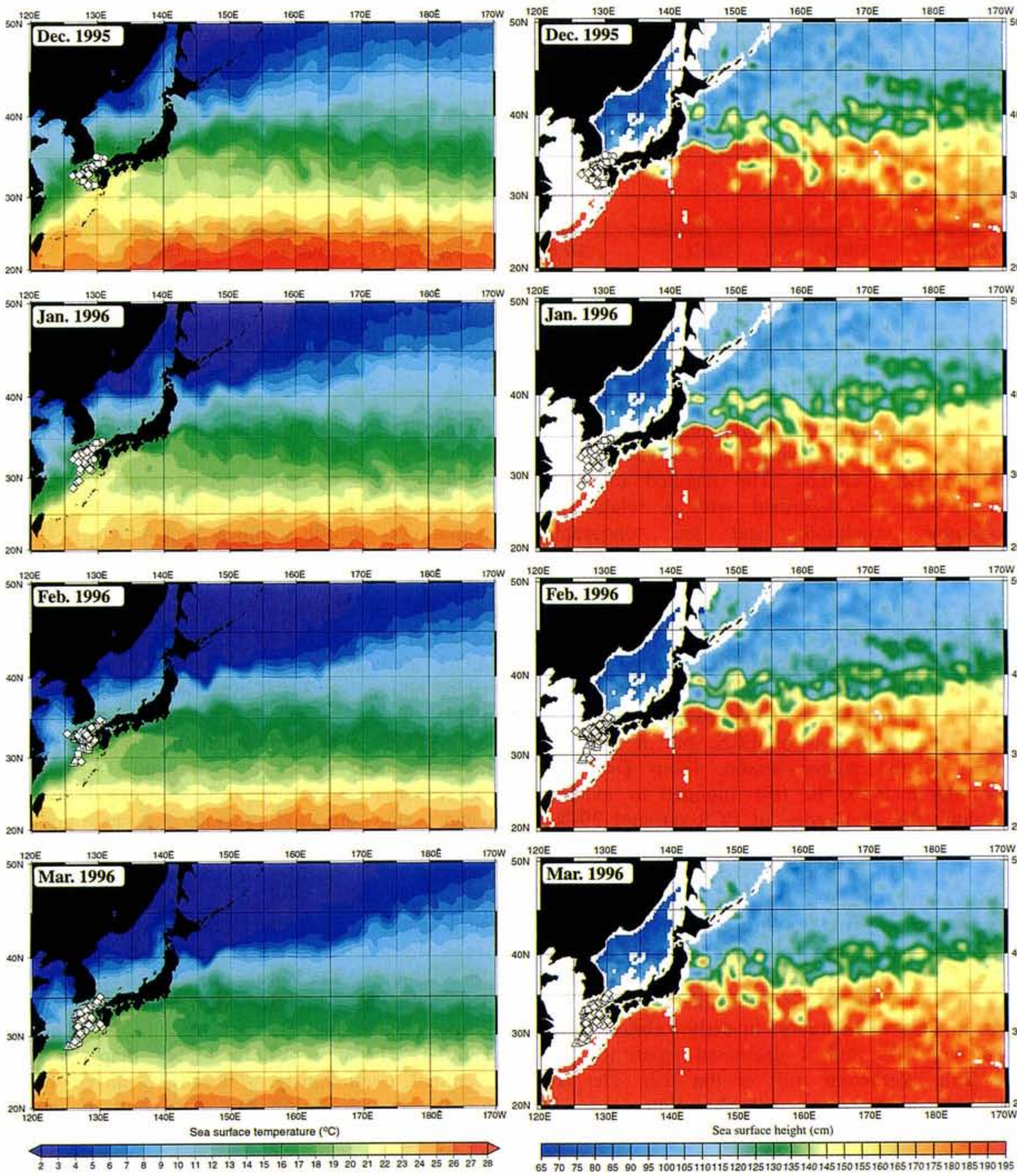


Fig. 4a. Monthly horizontal distributions of sea surface temperature, sea surface height referred from 1000 m with daily locations of each bluefin tuna by month from December 1995 to March 1996.
△, #194; ○, #199; □, #226; ◇, #227.

and then these fish moved northeastward along the Oyashio front from August to September (Fig. 4f). In this period, the fish sometimes rushed into cold water (colder than 5℃) deeper than 125 m depth, which was probably near the core of the Original Oyashio Water (Kawai 1972), because the coldest temperature recorded was 2.2℃ at 62 m depth (Table 3). The SSC and SSH maps (Fig. 4f) show that they concentrated at the southern edge of the high Chl-*a* concentration and the northern edge of the high SSH area around 42-43°N, assumed to be the Oyashio front, in September. In October, the fish remained almost the same area as it was in September, and kept itself mostly in the surface layer with the exception of a few days having dived into 62 m or 125 m layer where the temperature was between 5.9℃ and 10℃ (Fig. 5).

The fish separated from other two fish after end of October 1997 and moved to east-southeastward, then reached northwestern waters of the Shatsky Rise in December where Chl-*a* still remained in a higher concentration (Fig. 4g). ATNS increased from 14-15℃ in late October to 18℃ in the first half of November due to the southward migration, although the fish still kept inactive in vertical movement from July to October (Fig. 5). ATNS and AT125 in late November decreased to 12-14℃ and to 6-7℃, respectively, due to a winter cooling. But ATNS and AT125 in December fluctuated between 10℃ and 16℃, and between 6℃ and 14℃, respectively (Fig. 5),

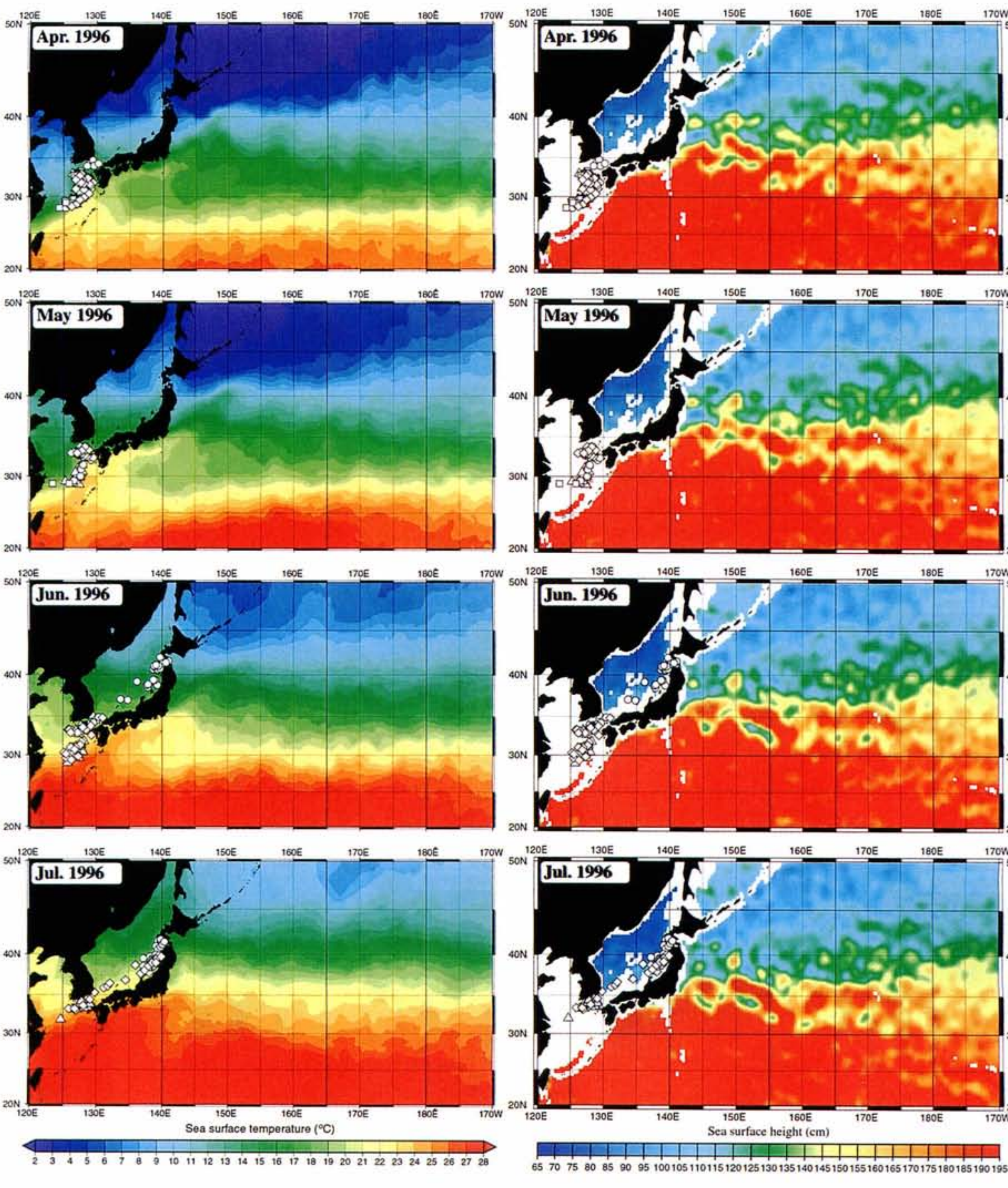


Fig. 4b. Same as Fig. 4a, but for April 1996 to July 1996. △, #194; ○, #199; □, #226; ◇, #227.

which suggested that the fish was distributed several meso-scale eddies and ridge of the warm water spread from KE (Figs. 4f and 4g).

ATs converged and decreased to around 10-13 ℃ in late December 1997 (Fig. 5), due to a development of winter vertical mixing. High concentration area of Chl-*a* disappeared around the fish in January 1998 (Fig. 4g). With a little northward shift (ATs decreasing from 15℃ to 12℃ in early January), the fish traveled widely west-southwestward beyond KE (ATs increased to 20℃).

SSH and SSC maps in February 1998 (Fig. 4g) shows that the fish was distributed in the warm waters out of a couple of cold rings in 35°N, 150°E and 32°N, 153°E in the subtropical region south of KE, where was a litter higher Chl-*a* concentration area. ATs decreased to 18℃ from 20℃ due to a winter cooling. In March, the fish moved eastward through the warm waters spread from the third crest and the forth crest of KE to the west of the Shatsky Rise where the higher Chl-*a* concentration area appeared. ATs decreased to 12℃ at the end of March (Fig. 5).

In early and middle April 1998, the fish migrated to the first crest of KE (Fig. 4h). ATNS and AT125 fluctuated between 11℃ and 16℃, and between 9℃ and 12℃, respectively, then ATs converged and increased to around 16-17℃ in late April. It is suggested that the fish moved westward within the warm water spread from offshore crests of KE to the first crest of KE, and arrived the first crest of KE area in late April which temperature at

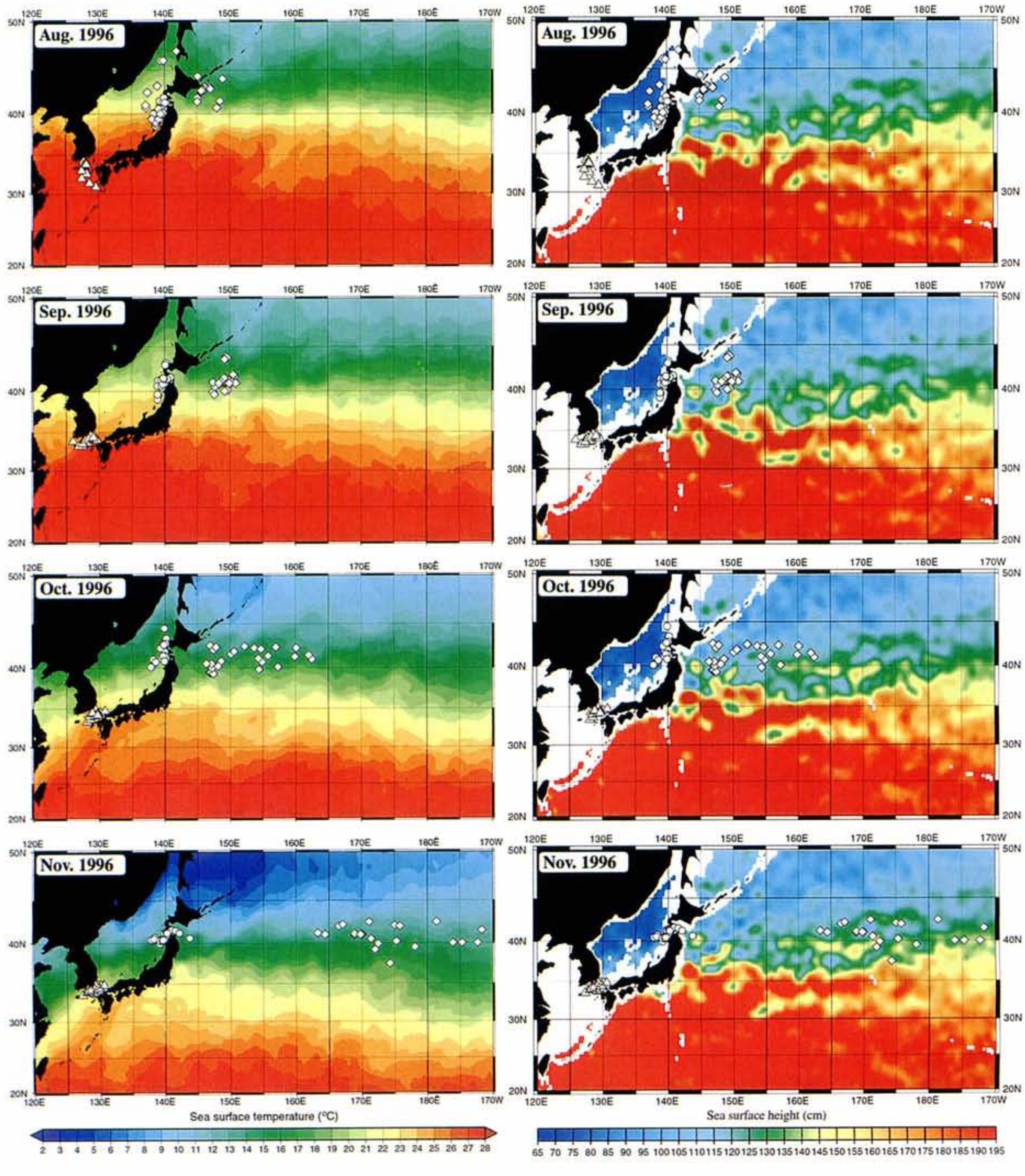


Fig. 4c. Same as Fig. 4a, but for August 1996 to November 1996.
△, #194; ○, #199; ◇, #227; ☆, #241.

the depth of 100 m was around 17℃, almost the same value of AT125. The spring bloom occurred around the fish in early and middle April 1998 (SSC map in Fig. 4h).

In May 1998, the fish migrated eastward along the first and second crests of KE around 36°N line where the southern edge of the high Chl-*a* concentration area was found (Fig. 4h). ATs increased from 16℃ to 20℃ from late April to early May, and then ATNS decreased to 16-17℃ with a little movement to the northern area of the second crest of KE. The fish returned to the north of KE in mid-May, where the vertical temperature gradient gradually developed, therefore ATNS increased to 18-19℃ but AT125 decreased 11℃ of (Fig. 5). There was no typical meandering of KE between 145°E and 155°E from May to July 1998, in contrast to 1997 when the warm water spreading from the second crest appeared around 150°E and the fish migrated northward along this warm water (Fig. 4e).

In June 1998, the fish moved westward again to the first crest of KE, and encountered with #199 fish (Fig. 4h). After then these fish migrated together for five months (Figs. 4h-4i). In May and June, an existence of the warm water spread from the first crest of KE and the Kuroshio warm-core ring, which was recognized in May and was observed to join with KE in June by *the Monthly Ocean Report* (Japan Meteorological Agency 1998). ATNS decreased once to 15.3℃ in early June but soon increased to 18-20℃ (Fig. 5) reflecting a rapid

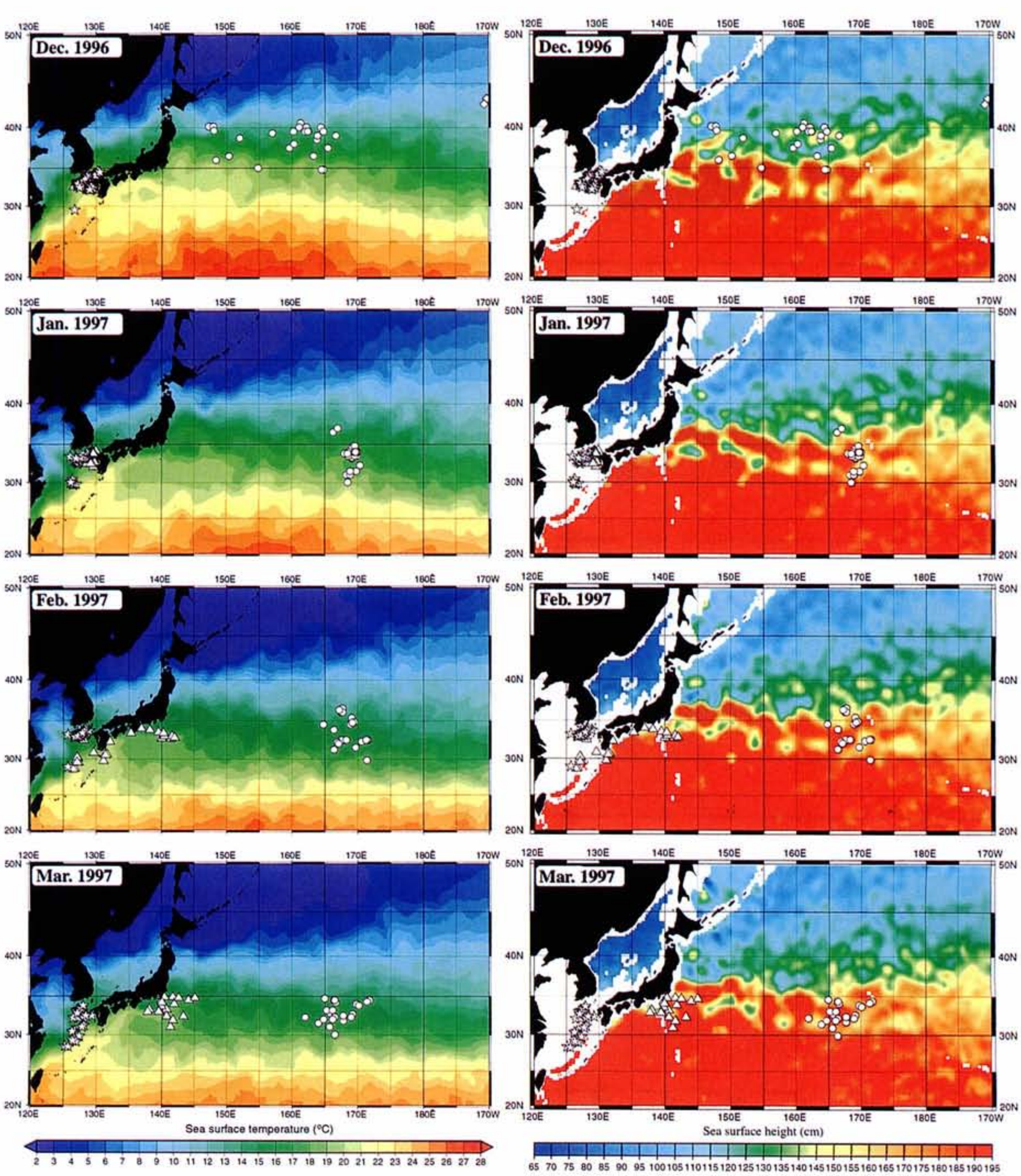


Fig. 4d. Same as Fig. 4a, but for December 1996 to March 1997.
△, #194; ○, #199; ☆, #241.

seasonal warming in spite of a movement forward north. But AT125 which were occasionally recorded, remained around 6-8℃ (Fig. 5), which indicates that the fish dived close to the Oyashio water.

From July to August 1998, the fish shifted northward along the warm water spread from the first crest and a couple of the Kuroshio warm-core rings (Figs. 4h and 4i) where was near the Oyashio first Intrusion (Japan Meteorological Agency 1998). Then, they arrived to the southeast of Hokkaido, where they came in contact with the Oyashio front (Fig. 4i). The southern limit of the high Chl-*a* concentration area shifted northward from May to August, and two fish seemed to chase the high Chl-*a* concentration area in their northward migrations. Their ATNS were 19-20℃. But their AT62 and AT125 colder than 5℃ were sometimes observed (Fig. 5), which shows that they sometimes rushed into the cold water near the Original Oyashio Water southeast of Hokkaido in summer.

In September 1998 (Fig. 4h), this fish and #199 fish showed a little eastward movement near the Kuroshio warm-core ring around 41°N, 145°E (Japan Meteorological Agency 1998), southeast of Hokkaido. The fish stayed within a surface layer (ATNS was 18-20℃), judging from the facts that only three days AT125 (3-4℃) and four days AT62 (3-14℃) was observed in two months of August and September (Fig. 5).

In October 1998, these fish moved east-

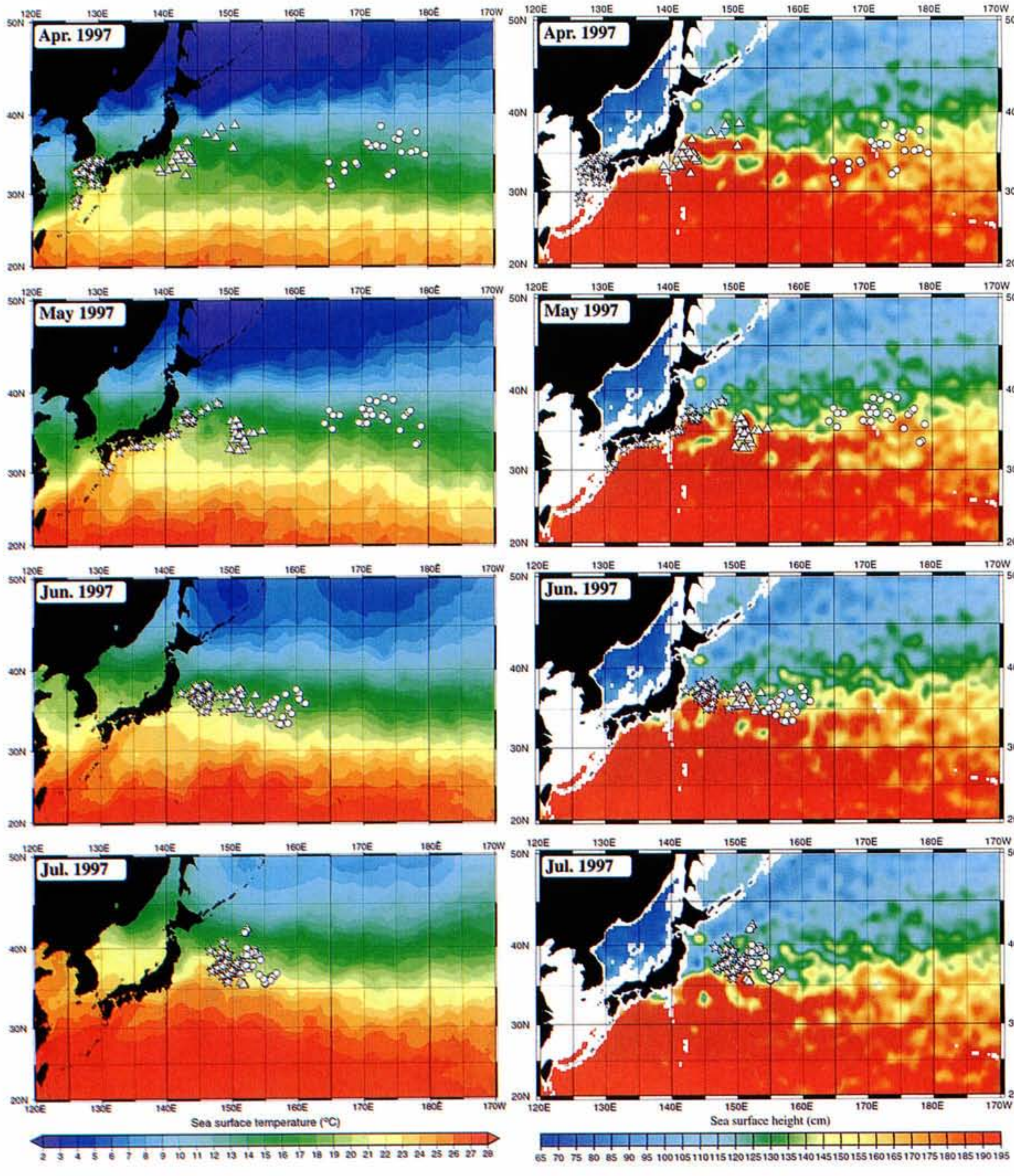


Fig. 4e. Same as Fig. 4a, but for April 1997 to July 1997. △, #194; ○, #199; ☆, #241.

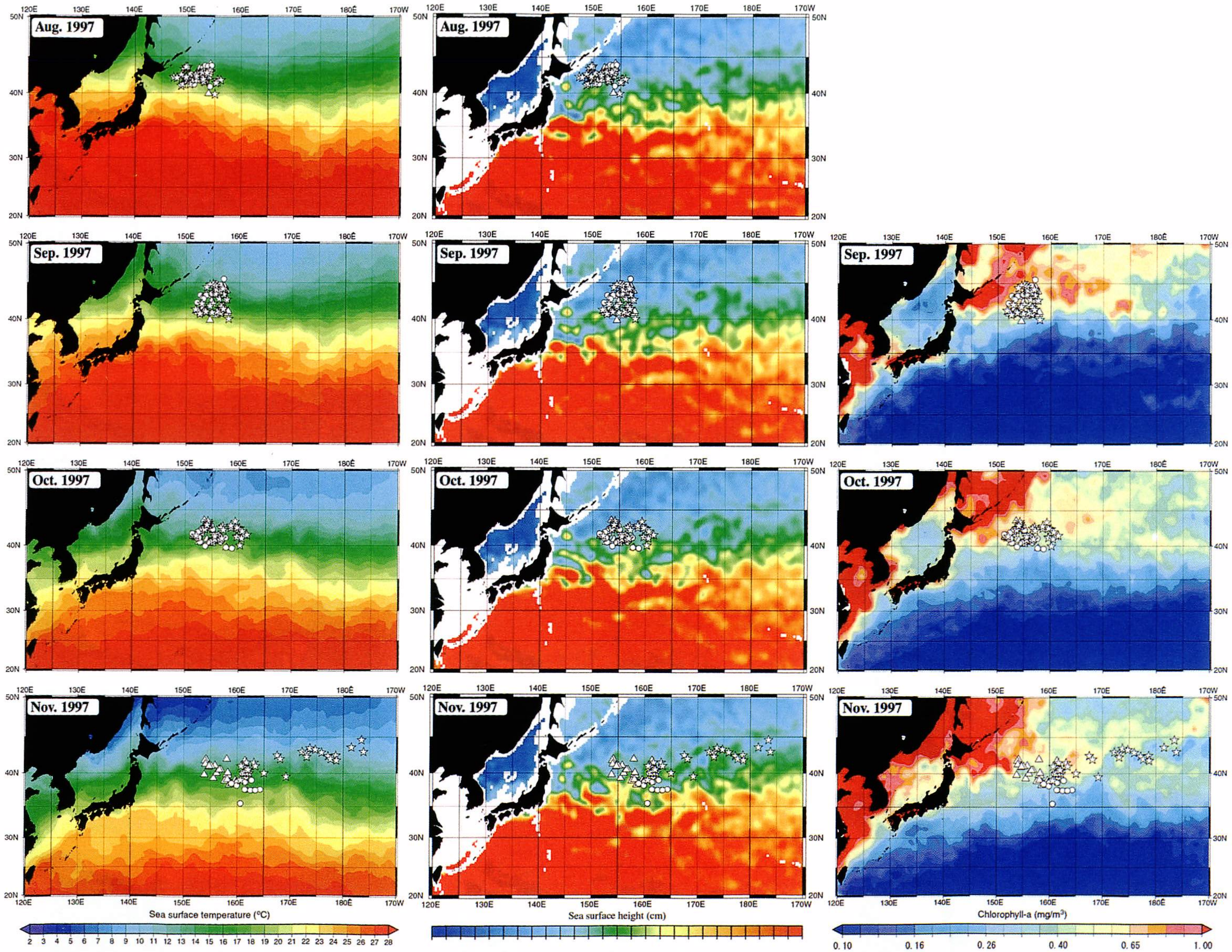


Fig. 4f. Same as Fig. 4a, but for August 1997 to November 1997, adding horizontal distributions of chlorophyll-*a* concentration. △, #194; ○, #199; ☆, #241.

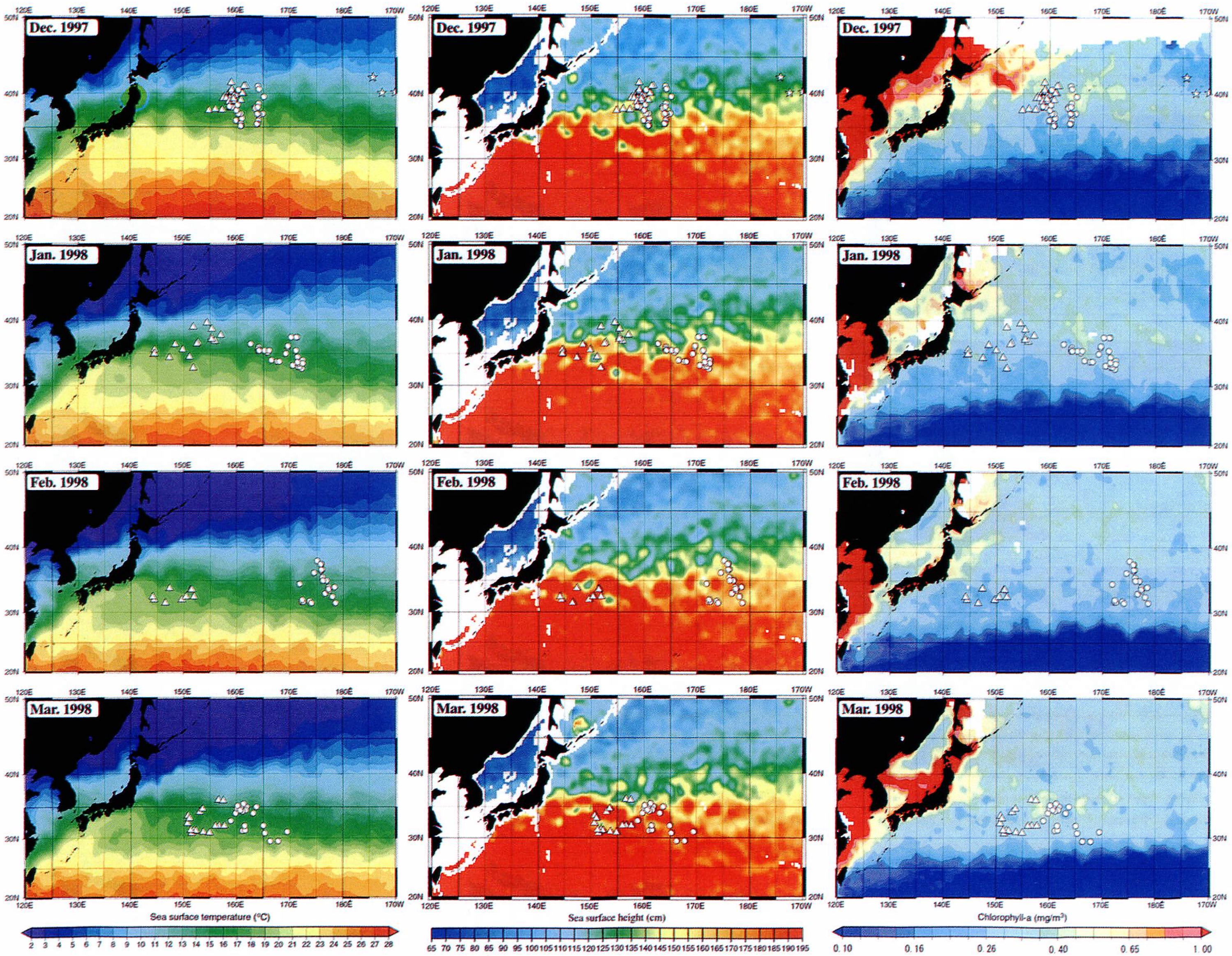


Fig. 4g. Same as Fig. 4f, but for December 1997 to March 1998.
△, #194; ○, #199; ☆, #241.

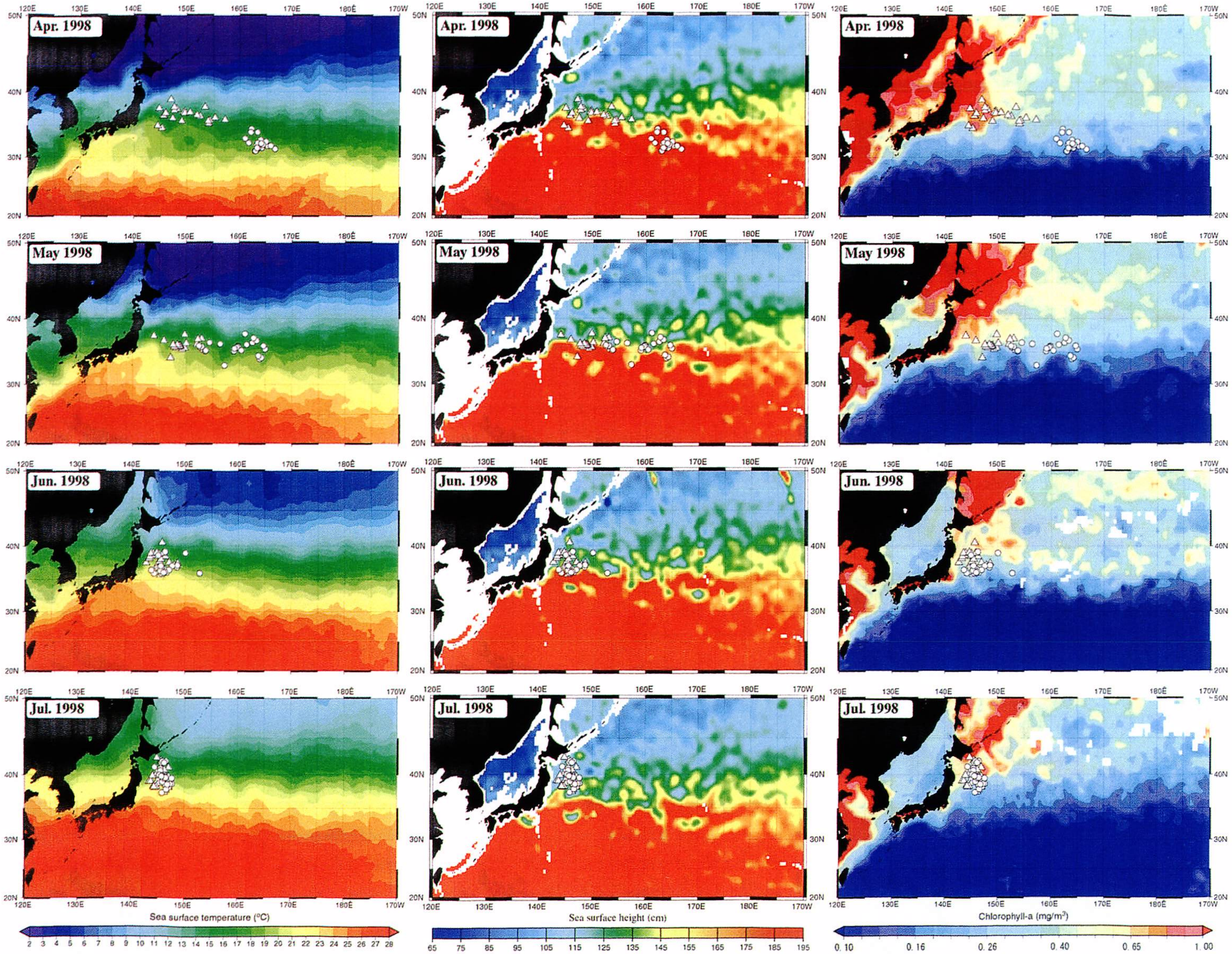


Fig. 4h. Same as Fig. 4f, but for April 1998 to July 1998.
△, #194; ○, #199.

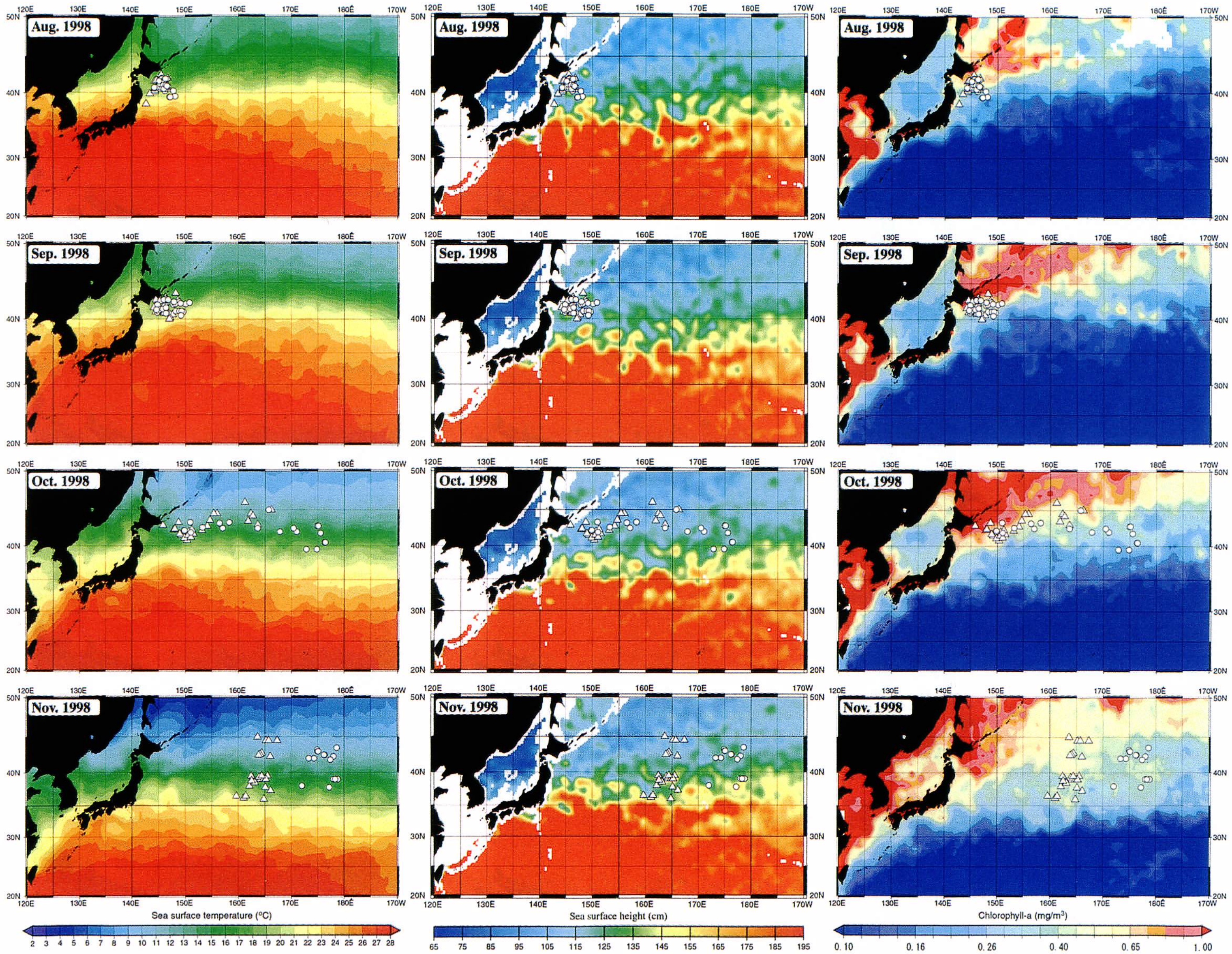


Fig. 4i. Same as Fig. 4f, but for August 1998 to November 1998.
△, #194; ○, #199.

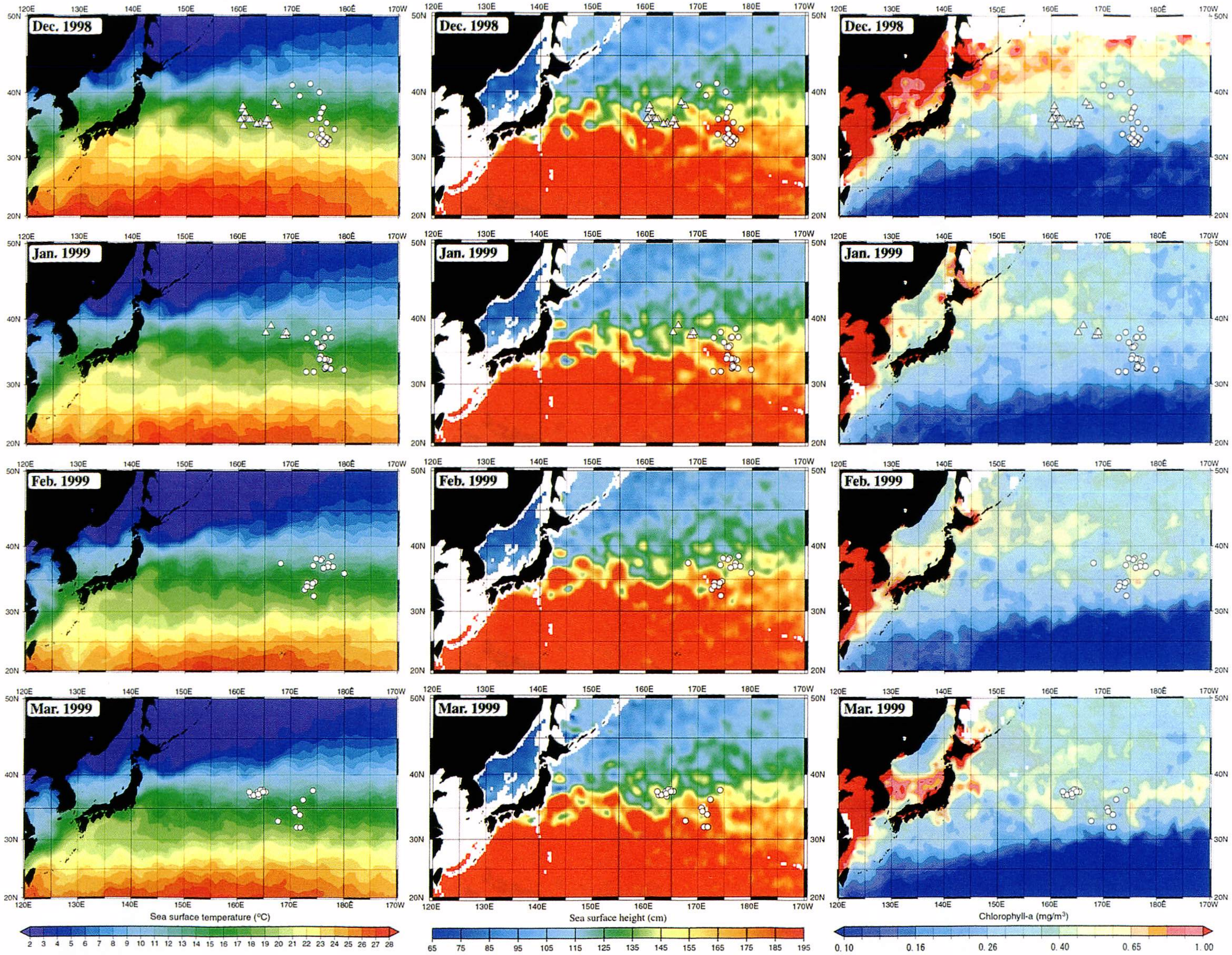


Fig. 4j. Same as Fig. 4f, but for December 1998 to March 1999.
△, #194; ○, #199.

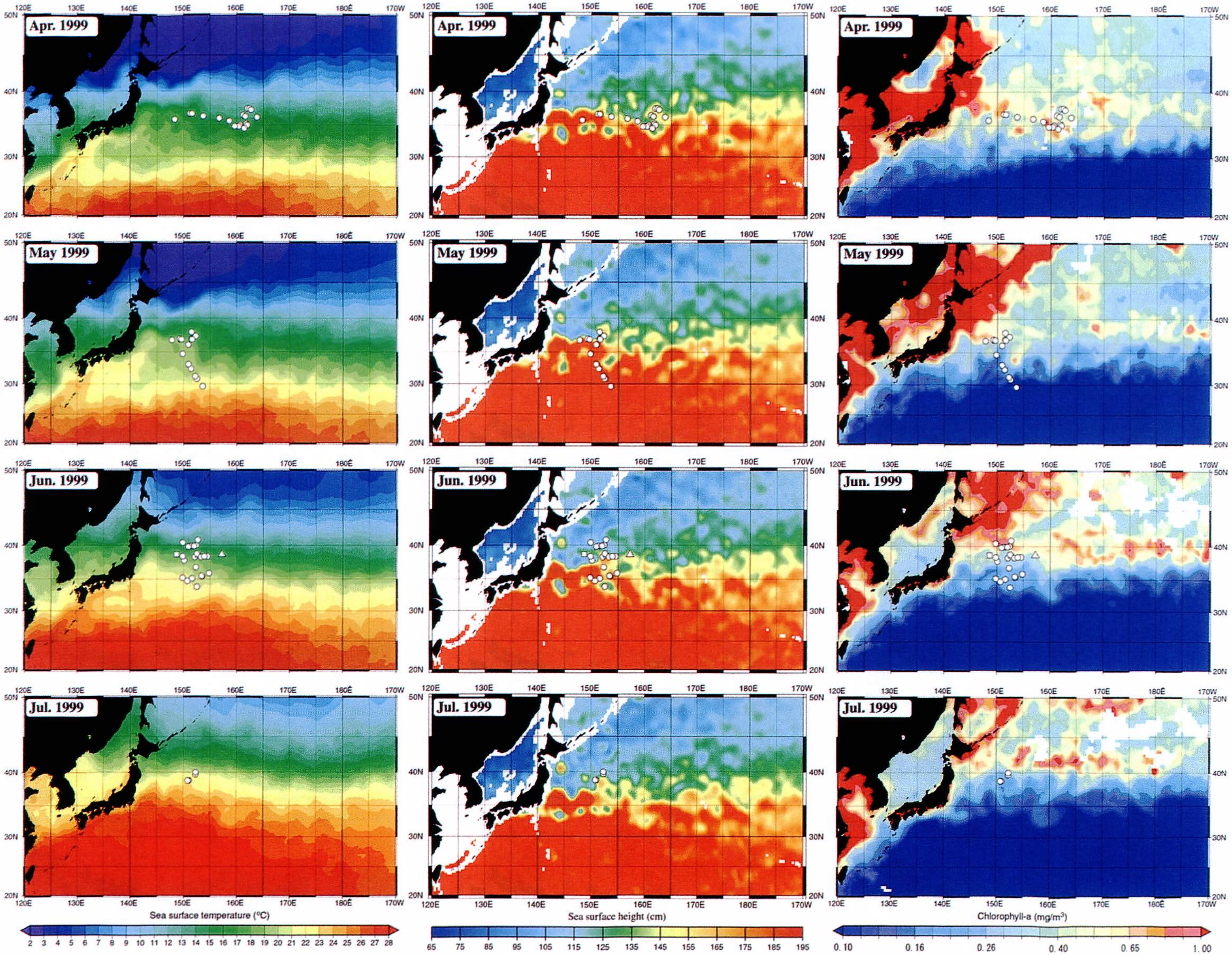


Fig. 4k. Same as Fig. 4f, but for April 1999 to July 1999.
○, #199.

northeastward along the southern edge of the high Chl-*a* concentration area of the Oyashio (Fig. 4i), which was suggested by AT125 observing around 5-6℃ (Fig. 5). Then the fish arrived to the water around 45° N, 165° E, but #199 reached far east to the Emperor Seamount Chain in early November (Fig. 4i). The high Chl-*a* concentration area around the fish shifted northward in early November (Fig. 4i) and ATNS of the fish decreased to 11℃ from 18-20℃ in September (Fig. 5). The fish rapidly turned southward and reached the northern area of KE in early December through a couple of the Kuroshio warm core-rings (around 39° N, 165° E and 40° N, 160° E) around the Shatsky Rise (Fig. 4j). After this southward shift, ATNS and AT62 recovered to 18℃ and AT125 also did to 15℃ from

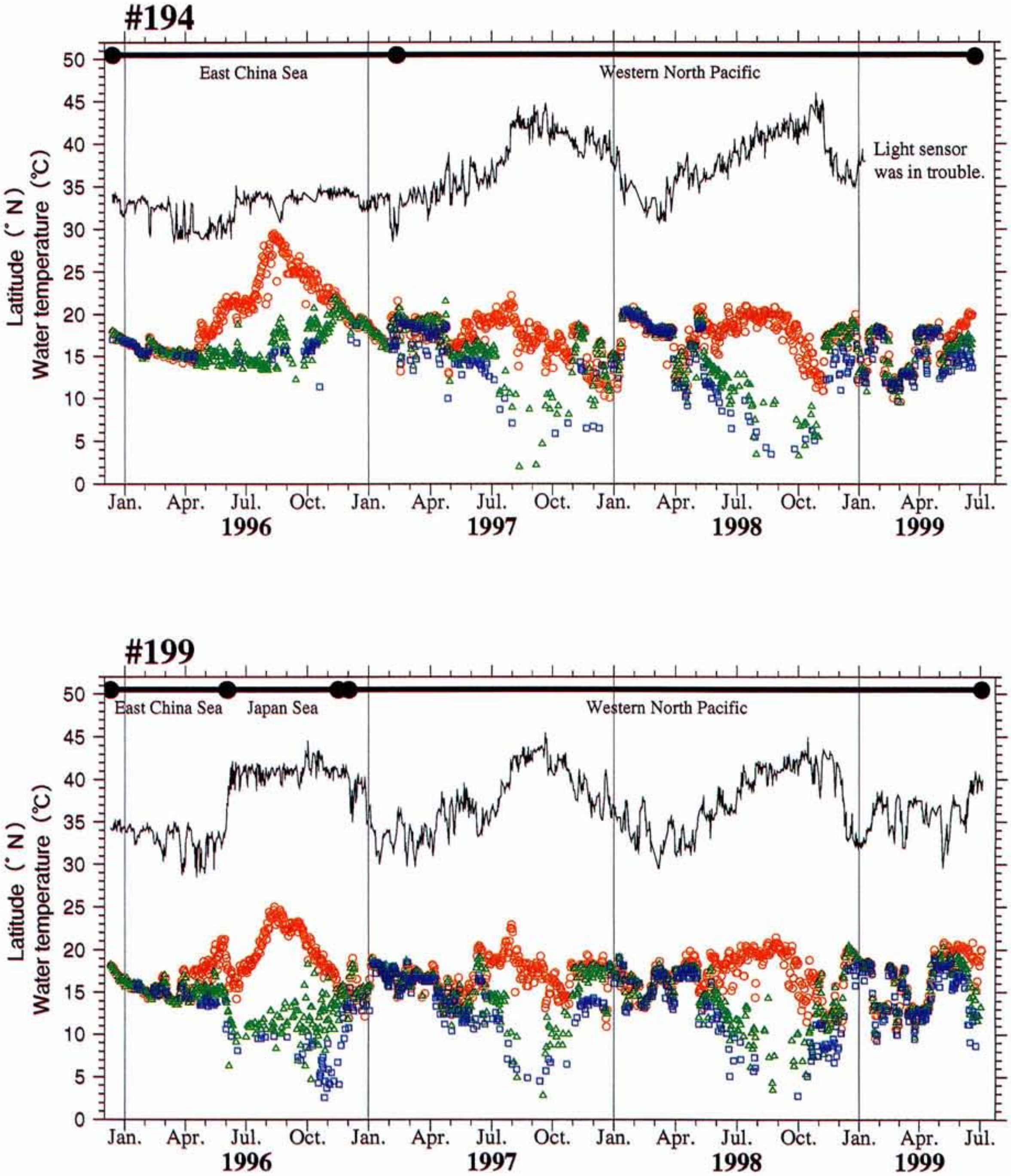
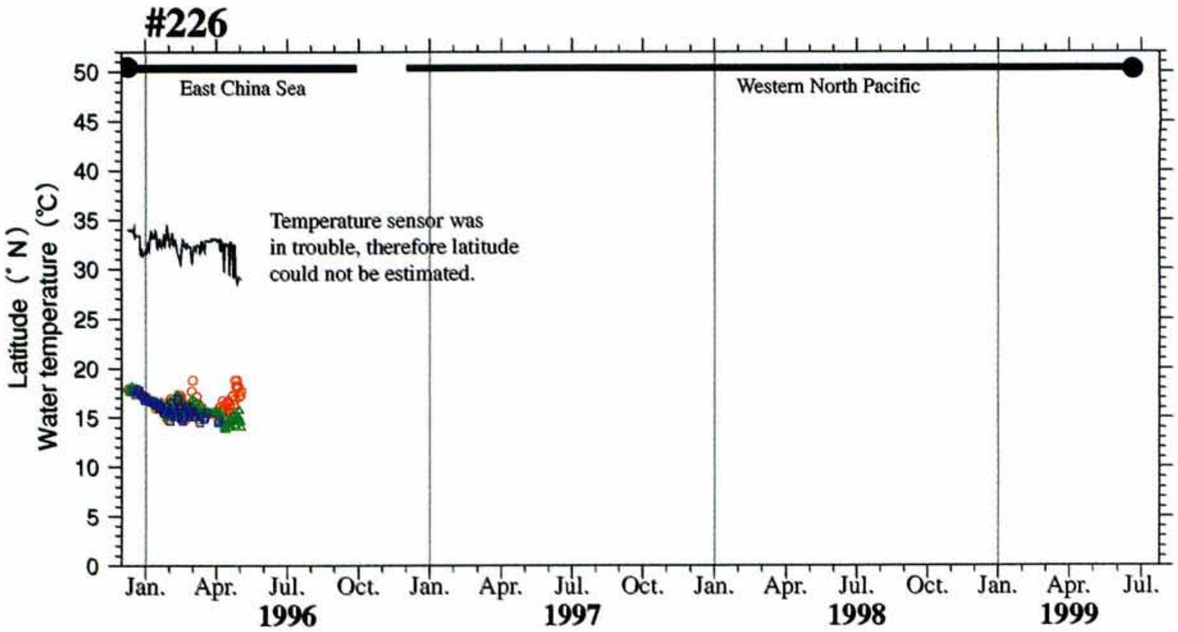


Fig. 5. Time series of ambient temperatures at three layers and of each fish's positions in latitude (black thin line) with habitat area (upper thick line). Red circle denotes the ambient temperature at near sea surface. Green triangle denotes the ambient temperature at the depth of 62 m for #194, #199 and #227, 60 m for #226, and 63 m for #241. Blue square denotes the ambient temperature at the depth of 125 m for #194 and #199, 120 m for #226, 124 m for #227, and 126 m for #241.

5-6℃ in late November. This southward migration route was a little higher concentration area of Chl-*a* as well as warm area.

From December 1998 to January 1999, the fish gradually moved eastward from the Shatsky Rise area to the west of the Emperor Seamount Chain along the northern area of KE (Fig. 4j). ATNS decreased to 12℃ and ATs converged in the end of December (Fig. 5) due to an active winter convection.

Because the light intensity records were in trouble after middle of January 1999, the migration routes of the fish was unknown a half of year before it was recaptured on 20 June 1999 at 38°39'N, 157°10'E in the warm water spread from the third crest of KE. But, temperature data could help us to suggest the distribution area of the fish from January to June 1999 (Fig. 5). ATs increased 18℃ from 12-13℃ in January, and then decreased to 11℃ in late February. It was suggested that the fish moved southward into the subtropical area south of KE in January, and then moved to northern water of KE. ATs increased to 18℃ in April, then decreased to 13-14℃ in the first half of May (Fig. 5). It was suggested that the fish stayed in KE area in April and moved northward into the warm water spread from the third crest of KE. ATNS increased to 20℃ due to a summer warming although AT125



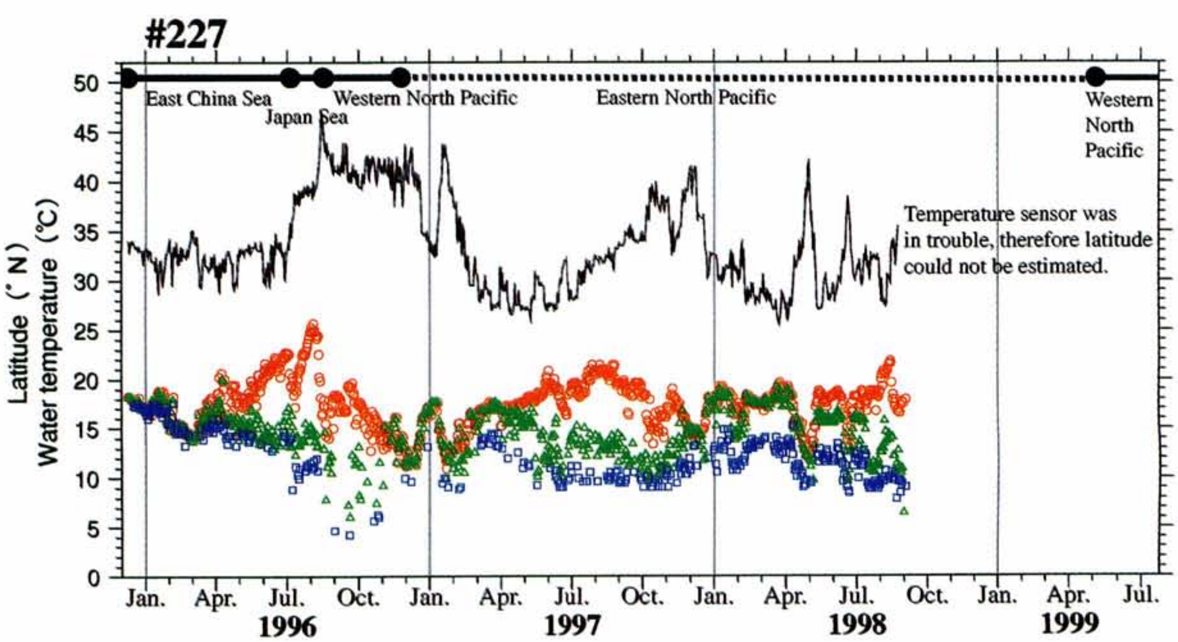


Fig. 5. Continued.

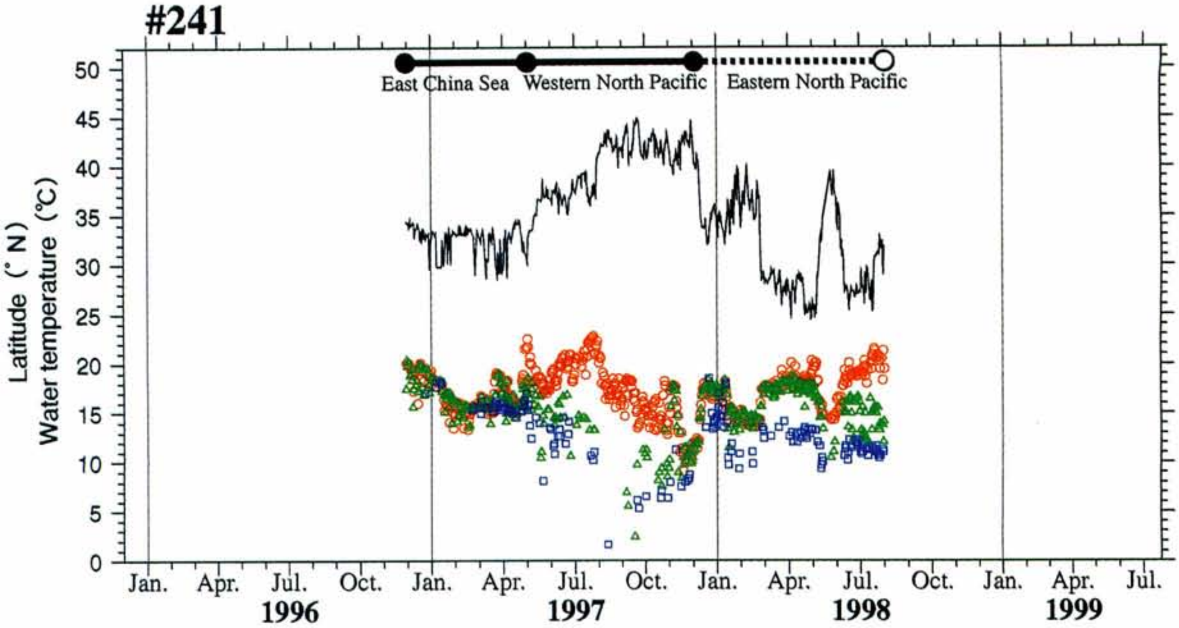


Fig. 5. Continued.

remained constant around 14-15℃ in June. It can be presumed that the fish stayed in the warm water spread from the third crest of KE from May to June before recapture.

#199 fish (indicated by the circle symbol in the Fig. 2 and Figs. 4a-4k)

#199 fish stayed in ECS during six months from late December 1995 to beginning of June 1996 (Figs. 4a and 4b). The fish was usually distributed in the northeastern area of the ECS but it showed north-south movement several times from February to May (Figs. 4a, 4b and 5). ATs of the fish changed several times between 14℃ and 17℃ according to north-south movements (Fig. 5).

In the first half of June 1996, the fish moved northward into the Japan Sea (Fig. 4b). ATNS rapidly decreased from 21℃ in late May in ECS to 15℃ in mid-June in the Japan Sea, and AT62 and AT125 decreased from 15℃ to 10℃ during this northward movement (Fig. 5). The fish may move along the Tsushima Current, because temperature at 100 m depth of the Tsushima Current was around 10℃ (Japan Meteorological Agency 1996), which corresponded to mostly AT62 and AT125.

The fish spend five months in the area west of the Tsugaru Strait from July to mid-November 1996, and then the fish moved eastward to the Pacific Ocean through the Tsugaru Strait (Fig. 4c). In the west of the Strait, ATNS gradually increased to 25 ℃ in mid-August, and then decreased to 15℃ in late November (Fig. 5). The fish should stay near the Tsushima Current, because AT62 was usually between 8 and 13℃. AT125 became to observe between 2℃ and 9℃ from middle of October. It suggested that the fish tried active vertical movement around the Tsushima Current in fall before the eastward migration to the Pacific Ocean.

In later half of November after passing the Tsugaru Strait, ATs converged around 15℃ (Fig. 5) which was the same temperature of the Tsugaru Warm Current in late November 1996 (Japan Meteorological Agency 1996). Then the fish rapidly moved southeastward to 155°E line in early December. ATs increased to 18-19 ℃ (Fig. 5), the fish should have passed the offshore Kuroshio warm-core ring, because temperature at 100 m depth of the warm-core ring was around 18℃ (Japan Meteorological Agency 1996). In the middle and late December, ATs was usually 15℃ (Fig. 5) in the offshore area between 157°E and 168°E along 40° N, where a train of warm-core rings was observed on SSH map (Figs. 4d). ATs decreased to 12-13℃ in late December, and then the fish migrated southward and stayed into the subtropical waters south of KE near the Emperor Seamount Chain from January to March. ATs recovered around 18℃ in early January 1997, and then ATs fluctuated between 14℃ and 18℃ to March (Fig. 5). SSH map in Fig. 4d shows there were several cyclonic and anti-cyclonic eddies around the fish.

In April 1997, the fish moved northeastward from the Emperor Seamount Chain to the date line along the warm water spread from KE (Fig. 4e). ATs rapidly decreased from 17℃ down to 12-13℃ in April, then the fish turned southward to the northern area of KE and ATs recovered to 16℃ (Fig. 5). Although the fish seems to try turning again to the northern area from habitat water, ATs decreased the 12-13℃ again, then the fish moved westward and arrived in the warm water spread from the second crest of KE (152-153°E) in the mid-July, where the fish encountered #194 and #241 fish (Figs. 4e). AT125 was almost stable around 11-12 ℃ during May to mid-July, but ATNS increased from 13-15℃ in May to 19℃ in late June due to a seasonal warming (Fig. 5). AT125 sometimes increased to 14-17℃, which indicated that the fish was distributed mainly in the warm water spread from KE with being sometimes closely to KE.

In early July to the beginning of August 1997, the fish migrated northward through mainly the surface layer of the warm water spread from the second crest of KE (Figs. 4e-4f). ATNS increased to 22℃ because of seasonal warming, but AT62 and AT125 decreased to 6℃ (Fig. 5).

In August 1997 (Fig. 4f), the fish concentrated near the Oyashio (around 42°N, 152°E) with #194 and #241 fish, and they moved northeastward along the Oyashio front during September. From August to mid-September, AT62 and AT125 were observed only five days in each layer with a cold temperature (2.8 - 4.9℃), and ATNS decreased to 13℃ from 20 ℃ (Fig. 5). The fish moved a little southward (from 45°N to 41°N) from late September to early October, ATNS increased to 17℃. ATNS decreased down to 14℃ in late October due to a seasonal cooling. Then the fish started east-southeastward movement to the Shatsky Rise, and ATNS recovered to 18℃ in the end of October. Frequency of AT62 observation increased and AT62 was around 8-12℃ during the movement, which the thicker warm water may permit the fish to migrate into deeper waters.

The fish stayed in the water above the Shatsky Rise until early December. And then the fish was distributed in the warm water spread from the forth crest of KE around 160°E and near the high concentration area of Chl-*a* (Fig. 4g). ATNS and AT62 were around 18℃ and AT125 was around 13 -14℃ in December except for three days in late December. When the fish moved a little northward, ATs decreased to 11-13℃ (Fig. 5). At the end of December, ATs converged on 17-18℃, as a result of the development of vertical mixing in upper layer.

In January to mid February 1998 (Fig. 4g), the fish moved eastward beyond the fifth crest of KE (around 170°E) from the southern edge of the higher Chl-*a* concentration area to the date line area where not so high concentration of Chl-*a* was observed. The fish returned to the eastern edge of a warm water spread from the forth crest of KE (around 163 °E) in March, where the high Chl-*a* concentration appeared and #194 also migrated in. ATs fluctuated from around 18℃ to around 13℃ from January to March, because the fish may travel meanderingly between KE and the warm water spread from KE (Fig. 5).

In April 1998, #199 fish showed a small southeastward movement into the forth crest of KE (around 163°E) nearby the Shatsky Rise where was lower Chl-*a* concentration, but this movement made its ATs recover to 18℃ from 13-16℃ in late March (Fig. 4h).

In May 1998, the fish moved westward through the warm water spread from the third and forth crests of KE (Fig. 4h) which temperature at 100 m depth was 17-18℃ (Japan Meteorological Agency 1998). #199 fish were distributed zonally (east-west) between the first and forth crests of KE from 144° E to 165°E around 36°N line as well as #194 fish. It is likely that this is caused by no typical meandering of KE from the first to third crests in 1998, which compared with ones in 1997 and in 1999. ATNS changed from 18℃ to 13℃ with northward and southward movements as well AT125 fluctuated between 11℃ and 17℃ (Fig. 5).

In June 1998, the fish caught up with #194 fish in the first crest of KE (Fig. 4h). After then their migration to the Oyashio front was already described in the previous section of #199 fish. In early October (Fig. 4i), the fish started its eastward migration little earlier than when #194 fish did. ATs of these fish showed no difference before this eastward migration (Fig. 5). #199 fish may leave from the high Chl-*a* concentration area of the Oyashio in late October, although #194 fish still remained. In November, the fish reached to the waters around the Emperor Seamount Chain, but #194 fish stayed near the Shatsky Rise. ATNS of the fish was warmer (14-17℃) than #194's (11-14 ℃). AT125 increased to 7-11℃ in late October, but AT62 and AT125 of #194 fish were still 5-6℃ (Fig. 5).

In November 1998, #199 fish was distributed in the higher Chl-*a* concentration area appeared in the eastern area of the Emperor Seamount Chain (40°N, 178°E: Fig. 4i). ATNS decreased from 17℃ to 11-12℃ and AT125 decreased from 11℃ to 7-8℃. The decrease in ATs was caused by a little northward movement of the fish.

In early December 1998, the fish moved southward in the east of the Emperor Seamount Chain where was a little concentration of Chl-*a* although high concentration was still observed in northern area (Fig. 4j). ATNS and AT62 recovered to 19-20℃ and AT125 increased to 17-18℃ (Fig. 5). It is likely that the fish rushed into KE, because AT125 corresponded to the temperature of KE at 100 m (17-18℃, Japan Meteorological Agency 1999).

The fish, then, stayed in KE area until mid-January 1999 (Fig. 4j) and ATs was around 18℃. After then the fish moved northward in late January, ATs decreased to 10-13℃. In February, the fish moved to the higher concentration area appeared along KE east of the Emperor Seamount Chain (Fig. 4j). ATs fluctuated between 12℃ and 18℃ (Fig. 5), due to north-south movements.

From late February to April 1999, the fish migrated westward almost along KE (Figs. 4j and 4k). ATs fluctuated between 12℃ and 19℃ (Fig. 5), which indicated that the fish traveled between KE and the warm water spread from KE. The spring bloom occurred along the migration route in this period.

In the first half of May 1999, the fish moved southeastward along the second crest of KE, and ATs recovering to 18-20℃ (Figs. 4k and 5). From late May to July, the fish was mainly distributed northward in the warm water spread from the second crest of KE, corresponding with the spring bloom occurred. ATNS remained around 18℃ but AT62 and AT125 decreased to around 10℃ after the second half of June. Finally, the fish was recaptured by a purse seiner near the northern limit of the warm water (40° 03'N, 152° 19'E) in 4 July 1999.

#226 fish (indicated by the square symbol in the Fig. 2 and Figs. 4a-4k)

#226 fish was released in the Tsushima Strait (33° 59'N, 129° 52'E) on 10 December 1995. The temperature records of this fish were in trouble from May 1996. Therefore daily positions were estimated during only first five months. The fish was usually distributed in the northeastern area of the ECS with a few times of north-south shift during first five months after released (Fig. 2). ATs were higher in south and lower in north (Fig. 5).

Longitudinal positions of the fish were still useful after May 1996. The change of longitude showed that the fish stayed in ECS in all of first ten months until September 1996 (Fig. 6). After that, the fish migrated into the Pacific Ocean east of 145° E in December 1996. The fish shifted westward from 150° E to 140° E in March 1997, then rapidly returned to around 160° E in mid-April. And then, the fish stayed in the area between 150° E and 160° E until December 1997 with a gradual eastward shift similar to those observed in #194 fish (Fig. 6). The fish stayed mainly around 160° E, which is the same longitude as the Shatsky Rise, from December 1997 to February 1998. The fish moved eastward to 170° E in March-April 1998, and turned westward to the 150° E from mid-April to June (Fig. 6). The fish

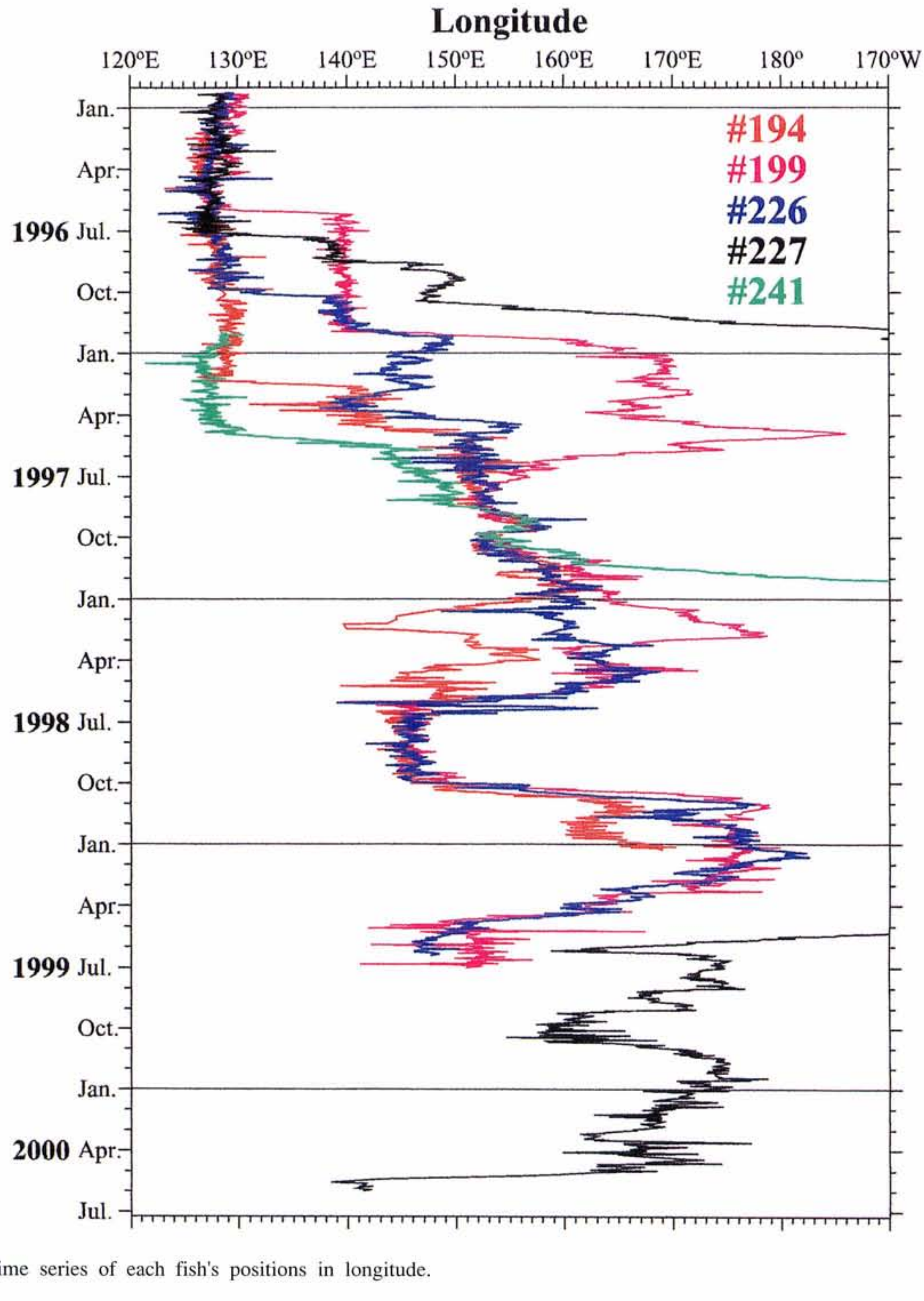


Fig. 6. Time series of each fish's positions in longitude.

stayed in 145-150°E until September. In October 1998, the fish moved eastward rapidly to 170-180° E, and stayed until January 1999. The fish moved westward and reached the 148°E area in June. The change of longitude of the fish after June 1998 corresponded to ones #194 and #199 fish, which suggested that the #226 fish migrated together with these fish in this period. At last, the fish was recaptured at 38°43'N, 148°38'E near the location where #199 fish stayed in June 1999.

#227 fish (indicated by the diamond symbol in the Fig. 2 and Figs. 4a-4k)

#227 fish has the records of the longest liberty time and distance among all recaptured fish attached archival tags as of 31 May 2000, and the fish showed a round trip of trans-Pacific migrations, going from the Japanese waters to the water off the North America and returned to Japan. In this paper, the migration of the fish is described in the western North Pacific.

The fish was released in the Tsushima Strait (33°59'N, 129°52'E) on 10 December 1995, which was the same as the time and place for #226 fish. The temperature records of the fish were in trouble from the end of August 1998. #227 stayed in ECS during seven months until early July 1996 after release. The fish was mainly distributed in the northeastern area of the ECS and it showed several north-south shifts, like as other fish (Figs. 2 and 5). ATs of the fish fluctuated between 14℃ and 18℃ during north-south shifts (Fig. 5).

The fish started to move northward to the Japan Sea in the second half of June 1996 (Fig. 5), when ATNS increased up to 22℃. The fish was distributed in the Japan Sea from mid-July to early August. AT124 decreased to 11℃ from 14-15℃ in ECS (Fig. 5). It is likely that the fish migrated northward along the Tsushima Current, because AT124 was coincident with temperature at 100 m depth of the Current (10℃, Japan Meteorological Agency 1996). The fish stopped by near Sado Island (38°N, 138°E) from mid-July to early August (Fig. 2), and ATNS of the fish increased to 25℃ there (Fig. 5). After then the fish started again northward migration, and moved to the Pacific Ocean through the Soya Strait. It may take a few days that the fish passed the Okhotsk Sea (Fig. 2). The fish was distributed in the surface layer off southeast of Hokkaido in the later half of August, because AT124 was not observed. ATNS decreased to 14℃ in late August (Fig. 5), it was the same SST value as the first Oyashio Intrusion (Japan Meteorological Agency 1996). The fish might cross the Oyashio front off east of Hokkaido.

In late August to mid-October 1996, the fish stayed around 41°N, 147°E (Fig. 2), where was the Kuroshio warm-core ring near the Oyashio front (Fig. 4c, Japan Meteorological Agency 1996). ATNS fluctuated between 14℃ and 19℃, and AT124 was observed only twice and were around 4℃ (Fig. 5). It is likely that the fish traveled around the Oyashio front and the Kuroshio warm-core ring. The fish started trans-Pacific migration toward the west coast of the North America in mid-October 1996 (Fig. 2). The trans-Pacific migration route was consistent with the northern ridge of higher SSH around 40°N (green area in SSH map of Fig. 4c), which was assumed to correspond to the Subarctic Boundary with eastward current.

The fish was recaptured in the Northwest Pacific in late May 2000. Unfortunately, we could not describe a detailed migration from the North American coast to Japanese waters, because the temperature records were not available during this migration. The change of longitude (Fig. 6) showed that the fish left the North American coast in early April 1999 and reached in early June at 160°E (the same longitude of the Shatsky Rise). And then, the longitude of the fish was between 160°E and 180° E to early May 2000. The fish was recaptured at 33°00'N, 141°51'E east of Izu Islands at 31 May 2000, after the fish moved westward from 160°E area.

#241 fish (indicated by the star symbol in the Fig. 2 and Figs. 4a-4k)

#241 fish, which is another example of trans-Pacific migrations, was released in the Tsushima Strait (34°25'N, 129°08'E) on 29 November 1996. The fish stayed in ECS five months after release (Fig. 2). The fish stayed mainly in the northeastern area of the ECS with several north-south movements. ATs decreased from 20℃ in November 1996 to 15-16℃ in mid-January 1997 and became stable around 16℃ until mid-March 1997 (Fig. 5). ATs remained nevertheless southward movements. But in late March to early April 1997, when the fish showed the southward movement, ATNS increased to 17-18℃ (Fig. 5) due to a spring warming. After returning to around Tsushima Strait with decreasing of ATs to 15-16℃ on the second half of April, the fish moved southward rapidly to the south of Kyushu Island in April to May, then ATNS and AT126 increased to 22.8℃ and 17.0℃, respectively. It is likely that the fish moved into the Kuroshio because AT126 was almost the same as temperature at 100 m depth of the Kuroshio main axis (18℃: Japan Meteorological Agency 1997).

After the fish reached the Kuroshio, the fish continued to move eastward along the south coast of Japan (Fig. 2). ATNS decreased gradually to 17℃ during this migration, although AT126 decreased to 13-14℃ suddenly after arriving in the Pacific Ocean. The fish may move along the inshore side of the Kuroshio front. The fish immediately arrived in the warm waters spread from the first and second crests of KE in May, which were different from migration routes of #194 fish with staying around Izu Islands (Fig. 2).

In June 1997, the fish stayed in the warm water spread from KE. ATNS fluctuated between 20℃ and 18℃ and AT126 changed from 13-14℃ to 10-11℃, which maybe caused by a little northward excursion. The fish moved eastward to the northern area of the second crest in July, and then encountered with the other two fish (#194 and #199). The warm water spreading of the second crest was more prominent than one of the first crest (Fig. 4e).

#241 fish started northward migration in late July 1997 and ATNS increased to 22℃ (Fig. 5). A group of three fish (#194, #199 and #241) was distributed at the northern edge of the warm water spread from KE from August to the first half of October. Their distribution area was at the southern edge of the highest Chl-*a* concentration area in the Oyashio region along the northern edge of the high SSH area around 40° N (Fig. 4f). They were distributed in the upper layer during August to October, because AT63 and AT126 were observed at ten and five days in this period, respectively. The fish rushed into the cold water during this period near the Original Oyashio Water, judging from two data of temperature under 5℃ in the AT63 and AT126 (Fig. 5). ATNS fluctuated between 13.3℃ and 20.9℃ (Fig. 5), showing a wide movement in and around the warm water.

The fish started trans-Pacific migration from mid-October 1997 (Fig. 2). The migration routes corresponded to the northern edge of the high SSH and to the southern ridge of the high Chl-*a* concentration zone around 42-43° N (green area in SSH map of Fig. 4f). The fish should migrate along the Subarctic Boundary with an eastward current. ATNS increased from 13℃ in late October to 17℃ in early November. The fish reached around the date line in the end of November, and ATNS decreased to 10℃ (Fig. 5). Accompanying this cooling of ATNS and vanishing the high Chl-*a* concentration, the fish departed from the northern edge of the high SSH and moved southward (Fig. 4g). ATNS increased to 18℃ in mid-December around 170° W (Fig. 5). The fish was recaptured at 31° 48'N, 117° 18'W, west of the US on 1 August 1998.

Discussion

We described migration patterns of young bluefin tuna with relation to oceanographic conditions detected by satellite data. Estimation of daily positions in this paper is the same way described in Itoh *et al.* (unpublished). We considered that the accuracy of daily positions is good enough to discuss the large-scale migration of fish.

All five bluefin tuna in this paper were mainly distributed along the coast of Japan during a half of one year after release. The possible migration paths of young bluefin tuna along Japanese coast were suggested by the conventional tagging surveys (Bayliff *et al.* 1991, Yonemori 1989). In the offshore waters, #194, #199 and maybe #226 fish showed clockwise annual migration patterns closely related the oceanographic conditions. The fish moved westward in spring around the Kuroshio Extension, northward in summer in the warm water spread from the crest of the Kuroshio Extension, eastward in fall along the south of the Oyashio front and the Subarctic Boundary, and southward in early winter to the Kuroshio Extension. Uehara (1962) showed that the fishing ground of skipjack tuna moved along the Kuroshio in the waters south of Japan, and Kawai and Sasaki (1962) showed that skipjack tuna were distributed along a strong current of the secondary Kuroshio front and jut out northward in summer. It is likely that young bluefin tuna utilized the eastward currents of the Tsushima Current, Kuroshio, Oyashio front and Subarctic Boundary in their each eastward migration except for their westward migration around KE in spring. It is known in the water east of Hokkaido that the Japanese sardine utilized the currents in its northward and southward migration periods (Inagake 1987), and the saury moved to Hokkaido coast along the subarctic front against its current in a southward migration period (Tomosada and Inagake 1986). These fishes have a possibility to have a selective migration system for an oceanic current in their each migration period.

Two fish (#241 and #227) showed trans-Pacific migration. #241 fish distributed together with moved #226 and #194 fish, before the fish started the trans-Pacific migration. There was no typical difference for their locations and ATs among these fish before they separated each other. In this paper, we could not find out the reasons why some bluefin tuna selected the trans-Pacific migration and other fish did staying in the western North Pacific from the point of view of oceanic conditions. Potential mechanisms to control the migration roots as well as the timing of onset of migration might include small-scale oceanographic conditions, carrying capacity, their individual characteristics for migration activity, and other biological factor.

The northward migration routes were located in the first crest of KE in 1998 summer. In the period, a typical meandering at the second crest was not observed, but the prominent northward spreading of the warm water and a couple of the Kuroshio warm-core rings existed in the northern area of the first crest. In contrast, the fish migrated northward in the second crest in 1997 and 1999 when the northward spreading of the warm water from the second crest was prominent but the warm water spreading was restricted in the northern area of the first crest. It is likely that young bluefin tuna searched the warm waters over 21-22℃ near surface along KE from April to June and then they started the northward migration.

Histogram of ATs recorded by five tags is shown in Fig. 7. They were mainly distributed in the waters of 14-19℃, which dominated 65% of all data obtained, throughout the whole area and all season (Fig. 7a). Higher temperatures were recorded during the distribution in ECS (Fig. 7b) in spring to fall, KE in spring and Japan Sea (Fig. 5). Only #194 fish experienced ATs higher than 25℃ in ECS (Fig. 5). Lower temperatures than 10℃ were recorded when they dived into deeper waters around the Oyashio front and the Subarctic Boundary between summer and fall (Figs. 5 and 7c). Kitagawa *et al.* (2000) and Itoh *et al.* (unpublished) stated that young bluefin tuna preferred 14 - 21℃. Uda (1960) stated that bluefin tuna preferred the sea surface temperature 12 - 21℃. It is suggested that their preferring temperature did not change so much with a growth during age 0 to 4 and older, but that the mode of ATs shifted from 15℃ in ECS at age 0 and 1 to 17℃ in the western North Pacific during age 1 to 4 (Fig. 7b and c).

There were some phenomena suggesting that their migrations were induced by changes of ATs.

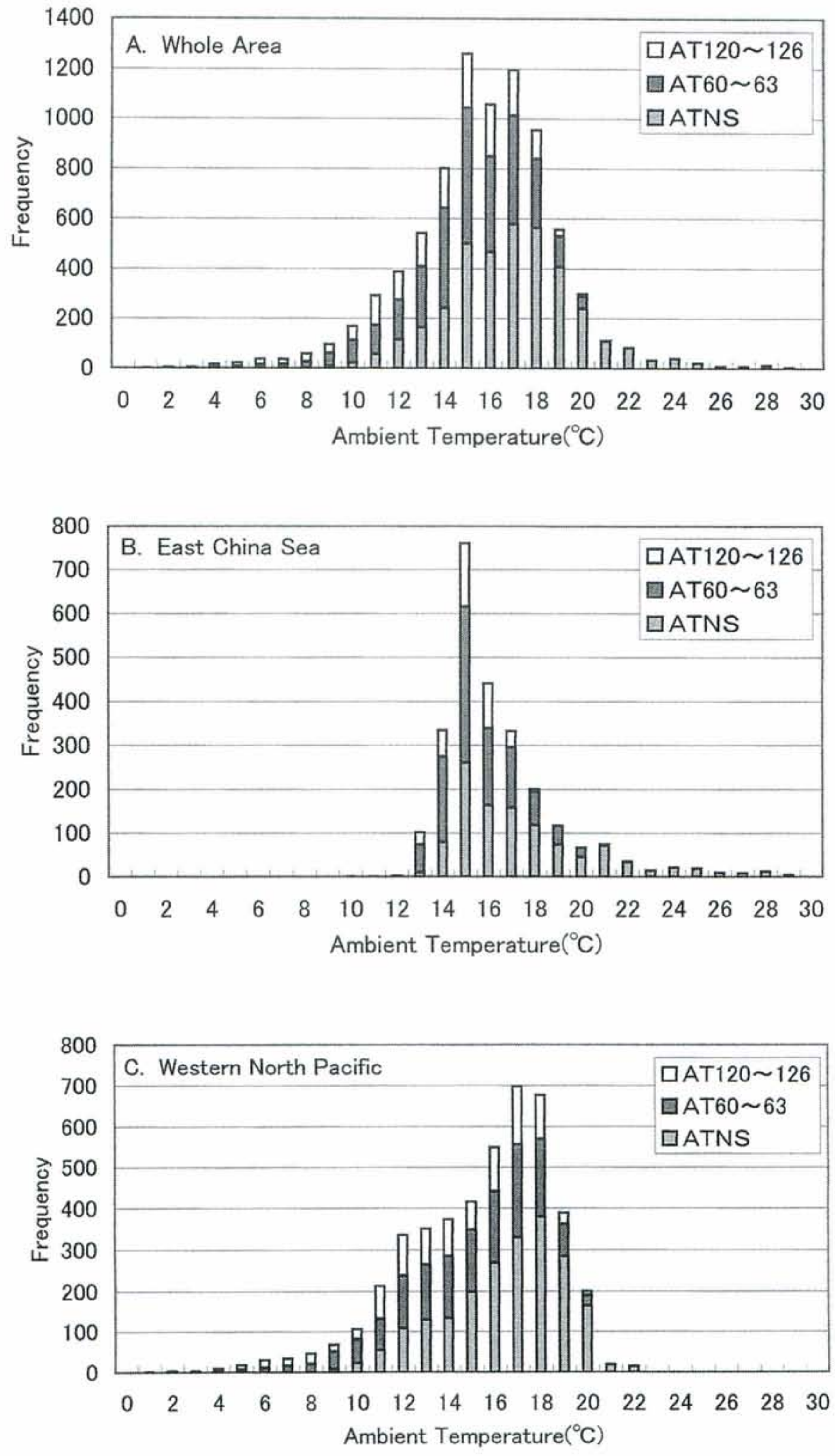


Fig. 7. Histogram of ambient temperature recorded by five tags.
A: In whole area, B: In the East China Sea, C: In the western North Pacific.
Each frequency was calculated by the ambient temperature at the near sea surface (white stick), at the depth of 60m for #226, 62 m for #194, #199 and #227, and 63 m for #241 (dark gray stick), at the depth of 120 m for #226, 124 m for #227, 125 m for #194 and #199, and 126 m for #241 (light grey stick).

In ECS, the fish were distributed mainly in the northeastern area of the ECS with a few or several southward shifts along the shelf edge of ECS from January to May. These southward shifts were induced by the winter cooling under 15℃ at the surface layer and ATs recovered over 17-18℃ (Fig. 5).

It was February for #194 and the end of April for #241 that fish moved to the Pacific Ocean from the ECS. On the other hand, it was June that #199 and #227 fish moved to the Japan Sea. Former two fish moved during southward shifts avoiding cooler water in the northern area. Latter two fish may miss to move to the Pacific during southward shifts. As temperature in the southern area gradually increased, they hardly moved the warmer southern area and tended to stay in the northern area around Tsushima Islands. As temperature in the area increases in summer, the fish may move to the Japan Sea for the purpose of avoiding warmer waters. There may be young bluefin tuna bearing with warm water in the northern area, like #194.

In the western North Pacific, there were similar behavior in related to ambient water temperatures. When #194 and #199 fish moved along the Oyashio front, ATNS decreased to 13-15℃ during fall. After that they started to move to the water north of the Shatsky Rise and their ATNS recovered to 18℃. On the other hand, when ATNS during the migration along KE in spring increased over 20℃, the fish started to move northward to the Oyashio front through the crest of KE and then ATNS decreased down to around 18℃. However, although ATNS of #194 fish reached close to 30℃, the fish occurred to stay in ECS throughout a year and its ATNS recorded close to 30℃ during that summer.

Young bluefin tuna sometimes utilized the higher Chl-*a* concentration area during the clockwise migration as well as keeping their preferring ATs. Oyashio front in summer corresponded to higher Chl-*a* concentration area within the preferring ATNS. In the Shatsky Rise and Emperor Seamount Chain waters in winter, a little higher Chl-*a* concentration often appeared. In early spring, spring blooms occurred along KE. In May to August the fish moved to northward along the crest of KE with the northward shift of spring blooms. Higher Chl-*a* concentration areas are associated with their preys, anchovy, squids and so on (Watanabe 1960, Yokota *et al.* 1961, Pinkas 1971). Their migration routes depended on oceanic conditions as well as other factors such as food condition and predators.

We regarded that young bluefin tuna should have a capability to select its habitat waters throughout the year instinctively selecting the efficient utilization of current with maintenance of their habitat temperature and making the use of the abundance area of prey. The bluefin tuna might have gotten this migration system in the long evolution process.

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Appendix Table 1. Abbreviation using in this paper.

ATNT	Ambient temperatures at the near sea surface observed by tag sensors
AT60	Ambient temperature at the depth of 60m observed by the tag sensor #226
AT62	Ambient temperature at the depth of 62m observed by the tag sensors, #194, #199 and #227
AT63	Ambient temperature at the depth of 63m observed by the tag sensor #241
AT120	Ambient temperature at the depth of 120m observed by the tag sensor #226
AT124	Ambient temperature at the depth of 124m observed by the tag sensor #227
AT125	Ambient temperature at the depth of 125m observed by the tag sensor #194 and #199
AT126	Ambient temperature at the depth of 126m observed by the tag sensor #241
ATs	Ambient temperatures at three layers observed by the tag sensor
Chl-*a*	Chlorophyll-*a*
ECS	The East China Sea
FL	Fork length
KE	The Kuroshio Extension
MCSST	Multichannel sea surface temperature
SSC	Sea surface chlorophyll-*a*
SSH	Sea surface height
SST	Sea surface temperature

北西太平洋における記録型標識を用いたクロマグロ幼魚の回遊と海洋環境

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摘　要

1995年、1996年の冬季に対馬海峡で記録型標識を装着、放流したクロマグロ幼魚105個体のうち、これまでに24個体を回収した。そのうち、放流後1年以上を太平洋で過ごしたと思われる5個体の標識データから、それらの回遊経路を人工衛星から観測された海洋構造と対比した。この結果、北西太平洋では春季に黒潮続流域を西進、夏季に三陸沖を黒潮分派に沿って北上、秋季に親潮前線に沿って東進、冬季に日付変更線付近の黒潮続流域に向かって南下、という海洋構造に応じた時計回りの回遊パターンが認められた。また、生息水温の昇温・降温にともない、クロマグロ幼魚が表層水温18℃前後の水塊へと移動する傾向が認められた。さらに春季ブルームの消長などクロロフィル*a*高密度域の推移も本種の回遊経路に影響を及ぼしていることが示唆された。

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