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Spatial and Temporal Distribution Patterns of Bigeye Tuna (*Thunnus obesus*) in the Indian Ocean

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Pei-Fen Lee, I-Ching Chen, and Wann-Nian Tzeng (2005) Spatial and temporal distribution patterns of bigeye tuna (*Thunnus obesus*) in the Indian Ocean. *Zoological Studies* **44**(2): 260-270. The spatial and temporal distribution patterns of bigeye tuna (*Thunnus obesus*) in the Indian Ocean were studied based on catch data of Taiwanese longline fishery during the period 1985~1999. We used a geographic information system (GIS) to compile a fishery database to statistically explore the catch per unit effort (CPUE), mean weight distribution, and the relationship between distribution and environmental factors. Results indicated that bigeye tuna were mainly distributed in tropical waters between 10°N and 15°S, although some scattered instances of high catches appeared outside this range. Sea surface temperature (SST) was the optimal environmental factor for predictions of monthly CPUE, but not for the mean weight index which showed a broader pattern. The monthly mean weight index was not correlated with monthly CPUE except in Dec. and Jan. CPUE hotspots generally occurred between 10°N and 15°S, but hotspots for mean weight index were concentrated in the west of this geographical range. Temporal trends of the CPUE and mean weight indices showed regional differences. Most of the monthly mean CPUE values in the 5 ecoregions showed no significant temporal trends, while the mean weight index showed an increasing pattern. The distributional patterns shown by the CPUE and weight indices of bigeye tuna in the Indian Ocean were similar to those in the Pacific Ocean. Given the current population status and the increasing fishing intensity to meet public demand, conservation measures must be considered to ensure a sustainable fishery. http://www.sinica.edu.tw/zool/zoolstud/44.2/260.pdf

Key words: GIS, SST, CPUE, Mean weight index, Trend.

The Indian Ocean has 4 dominant tuna species, i.e., albacore (*Thunnus alalunga*), bigeye tuna (*T. obesus*), yellowfin tuna (*T. albacares*), and skipjack tuna (*Katsuwonus pelamis*), and each of them has a distinct distribution pattern (Anonymous 2004). Among them, bigeye tuna is the most economically valuable (Fonteneau et al. 2004). Accounting for about 18.8% of the global bigeye tuna production, Indian ocean is the 3rd largest supplier to world markets (FAO 1997). Japan, Taiwan, and Korea are the major fishing countries. Based on FAO catch statistics between 1955 and 2001, Taiwan took the lead of total catch of bigeye tuna in the Indian ocean (approximately 29.0%).

Information regarding when and where tuna occur is critical for resource management and fishery practices. Bigeye tuna are widely distributed among the 3 major oceans between 45°N and 40°S except the Mediterranean Sea, especially in tropical waters (Laevastu and Rossa 1962, Kikawa and Ferraro 1966, Collette and Nauen 1983, Carocci and Majkowski 1996, Fonteneau et al. 2004). Despite of the abundant literatures regarding bigeye tuna resources in the Indian Ocean (e.g., Kikawa and Ferraro 1966, Hsu 1994, Wu and Chen 1994, Petit et al. 1995, Fonteneau and Pallarés 2004, Fonteneau et al. 2004), studies on

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detailed distribution patterns are still scanty (Anonymous 2003). Mohri and Nishida (1999a b) found that mature fish are dominant in tropics, while the young are located in middle latitudes.

Longline fishery of bigeye tuna is strongly affected by the depth of the fishing gear (Hanamoto 1987): deeper longlines in the water column tend to be more effective. Therefore, the variation in the depth of longlines as well as the tuna-preferred habitat could be used to standardize longline catch per unit effort (CPUE) data in order to provide an unbiased estimate of bigeye tuna's relative abundance. A habitat-based model that applies this concept to estimate effective longline effort and standardized CPUE for bigeye tuna caught by Japanese longliners in the Pacific Ocean has been developed by Bigelow et al. (2002).

Serious conservation issues have been concerned regarding the impacts caused by advanced fishing techniques applied to catch bigeye tuna of industrial fishing (Fonteneau 2001, Bigelow et al. 2002, Myers and Worm 2003, Fonteneau and Pallarés 2004). For example, applications of fish aggregating devices (FADs) by purse seiners have greatly increased catches of juvenile (Fonteneau and Pallarés 2004). The use of super-cold storage by Taiwanese longliners also allows fishermen to target bigeye and eventually increase the total catch (Okamoto et al. 2004). Although there is yet proof of overfishing in bigeye tuna stocks, the negative prospects of overfishing are worrisome (Fonteneau et al. 2004). Our concern is supported by a study on bigeye tuna resources in the Indian Ocean (Nishida et al. 2002), which recommended reducing the current total catch by 20% to ensure future sustainable yields.

In this study, we analyzed spatial and temporal distribution patterns of bigeye tuna in the Indian Ocean based on catch data recorded by the Taiwanese longline fleet from 1985 to 1999. In addition, we delineated monthly spatial distributions of the CPUE and mean weight indices, derived hotspots (or good fishing zones). Furthermore, comparisons of the temporal trends of these indices between 2 periods: 1985~1990 and 1993~1999 were conducted for better understanding of the population trends of bigeye tuna.

MATERIALS AND METHODS

Study area

Our study area is bounded by longitude 25°E to 125°E and latitude 30°N to 50°S in the Indian Ocean (Fig. 1), where bigeye tuna are considered a unit stock based on genetic evidence (Appleyard et al. 2002).

The Indian Ocean is relatively unique compared to other oceans because of its small area in the northern hemisphere and prevailing seasonal monsoons. During the summer in the northern hemisphere, the Intertropical Convergence Zone (ICZ) moves north, and the southeast trade winds move across the equator, creating southwestern

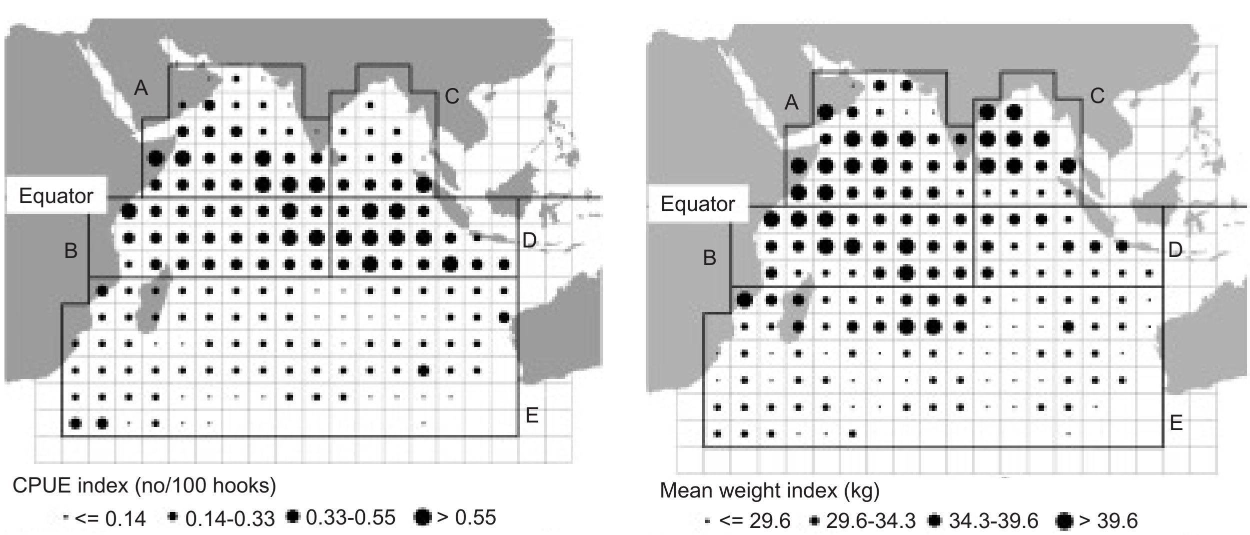

Fig. 1. Spatial distribution of Taiwanese bigeye longline fishery CPUE (left) and mean weight (right) indexes in the Indian Ocean (mean value of 1985-1999). A 5° by 5° grid cell system for recording tuna catch data in the Indian Ocean were used. The ecoregion classification that roughly corresponds to the FAO convention was used to subdivide the catch data for regional analyses.

trade winds (i.e., the SW monsoon) (Wyrtki 1973). During the winter period in the northern hemisphere, the ICZ moves to approximately 20°S and the northeastern trade winds expand their influence to this region (i.e., the NE monsoon). These patterns rotate every 6-mo. The SW monsoon lasts from June to Oct., while the NE monsoon lasts from Dec. to Apr., with May and Nov. being inter-monsoon periods. Because of these patterns, the circulation of the monsoon-induced surface currents to the north of 10°S dramatically change with the season (Tomczak and Godfrey 1994). The drastic changes in the circulation create a distinct zone with a subtropical gyre and subsequent corresponding environmental characteristics. These large-scale seasonal changes of circulation affect the strength of upwelling, surface water temperature, salinity, dissolved oxygen (DO), and the distribution of phytoplankton (Tomczak and Godfrey 1994).

Fishery data

The bigeye catch data of the Taiwanese longline fishery in the Indian Ocean have been collected by the Oversea Fisheries Development Council of Taiwan since 1967. The catch data, including monthly hook numbers, catch numbers, and weights of dominant tuna species, were referenced geographically into 5° grids of latitude and longitude. During the tabulated history of this fishery, there have been changes in target species and fishing methods (Chang 2003, Okamoto et al. 2004). Taiwanese longline vessels were expanded to the whole Indian Ocean after 1973 and adopted "conventional longlining" targeting bigeye tuna. "Deep longlining" was introduced to the Indian Ocean during the mid-1980s and targeted bigeye tuna and yellowfin tuna. Therefore, our analyses are limited to data from 1985 to 1999 because this was the period when bigeye tuna became the major target species of the Taiwanese longline fleet (Wang 2001, Chang 2003, Okamoto et al. 2004). We used a geographic information system (GIS), i.e., ArcGIS 8.3 (ESRI 2002) to construct the fishery and environmental databases.

The use of 5° grids is a conventional method to deal with tuna catch data. Due to the geographic projection, sizes of 5° grids in higher latitudes are smaller than those closer to the tropics. This might lead to the amount of fishing effort decreasing in higher latitudes, eventually affecting the statistical reliability of the data. Since our data were standardized by the CPUE and mean weight indices (see below), this bias was negligible.

Environmental data

Environmental data were collected from NASA's web site and the National Oceanographic Data Center-Ocean Climate Laboratory (NODC/OCL). Sea surface temperature (SST) data from 1985 to 1999 were obtained from the Advanced Very High Resolution Radiometer (AVHRR) carried aboard NOAA-series polar-orbiting satellites. Subsurface data, including temperature, salinity, and DO to a depth of nearly 400 m, were obtained from the World Ocean Database 1998 (WOD98) issued by NODC/OCL (Conkwright et al. 1998). These data are in a resolution of 1° square. For comparison with the fishery data, all oceanographic factors were averaged into monthly 5° squares.

Data analysis

Although bigeye tuna were the major target species for the Taiwanese longline fleet after 1985, our data were mixed with catches of other species. We followed the method proposed by Wang et al. (2001) to extract records specifically targeting bigeye tuna. For each grid, we determined 2 characteristics of distribution: CPUE (catch in numbers per unit of effort, total catches/100 hooks) and mean weight (kg/individual, total weight/total catches). Because the data were spatially scattered and not evenly distributed, we combined all of the data based on year and month. To investigate monthly distribution patterns, we calculated the mean CPUE and weight indices for all years in all grids. ArcGIS was used to create average CPUE and mean weight index distribution maps. Monthly distribution maps were produced to explore temporal patterns. We then identified the peak abundance regions, i.e., hotspots or good fishing zones. The hotspots were defined as regions that have cumulative higher CPUE values or weight records exceeding a certain threshold. To determine this value, we pooled monthly data and calculated the grand mean and its standard deviation. The threshold is equal to the grand mean + (0.5 x standard deviation). Since this value is close to the 3rd quartile of the pooled data, we thus selected the 3rd quartile (Q3) (CPUE = 0.55, weight = 39.6 kg) as the threshold. All monthly peak abundance maps were then summed to create the hotspot maps.

We characterized the hotspots by overlaying water temperature, DO, and salinity layers at various vertical depths onto the hotspot maps. The ranges and mean values of water temperature, DO, and salinity in a particular month were summarized. Coefficients of variation (CVs) were calculated. To investigate regional differences, spatial regions were divided into 5 ecoregions according to FAO conventions (Fig. 1). Basically this division separates the western and eastern parts of the ocean and accounts for the latitudinal differences.

To explore temporal trends, our analysis of the total catch showed a bimodal pattern with a transition in the years between 1991 and 1992 (Chang 2003, Anonymous 2004). Therefore, the catch data were grouped into 2 periods: 1985~1990 and 1993~1999. All subsequent analyses were based on 5 regions and 2 periods. We used analysis of variance (ANOVA) to test if there were significant differences in the CPUE and mean weight indices among regions and between these 2 periods. Tukey's studentized range test was then applied when significant differences were found. Statistical analyses were performed using SAS (Cary, NC, USA) and SYSTAT for Windows (Richmond, CA, USA).

RESULTS

Spatial distribution

The monthly mean CPUE (total catches/100 hooks) per 5° square was 0.33 (SD = 0.18, n = 173) with a range of from 0.05 to 0.81. The overall spatial distribution of the mean CPUE over 15 years of catches by Taiwanese longliners indicated that bigeye tuna were mainly concentrated in waters between 10°N and 15°S, roughly corresponding to the lower halves of regions A and C and the entire regions of B and D (Fig. 1). Most of the CPUE indices in these regions were greater than the mean value, while those outside these regions were smaller.

Values of the mean weight index showed a slightly different pattern (Fig. 1). The overall mean weight was 34.3 kg (SD = 8.8) with a range of between 6.5 and 88.7 kg. Most of the high values

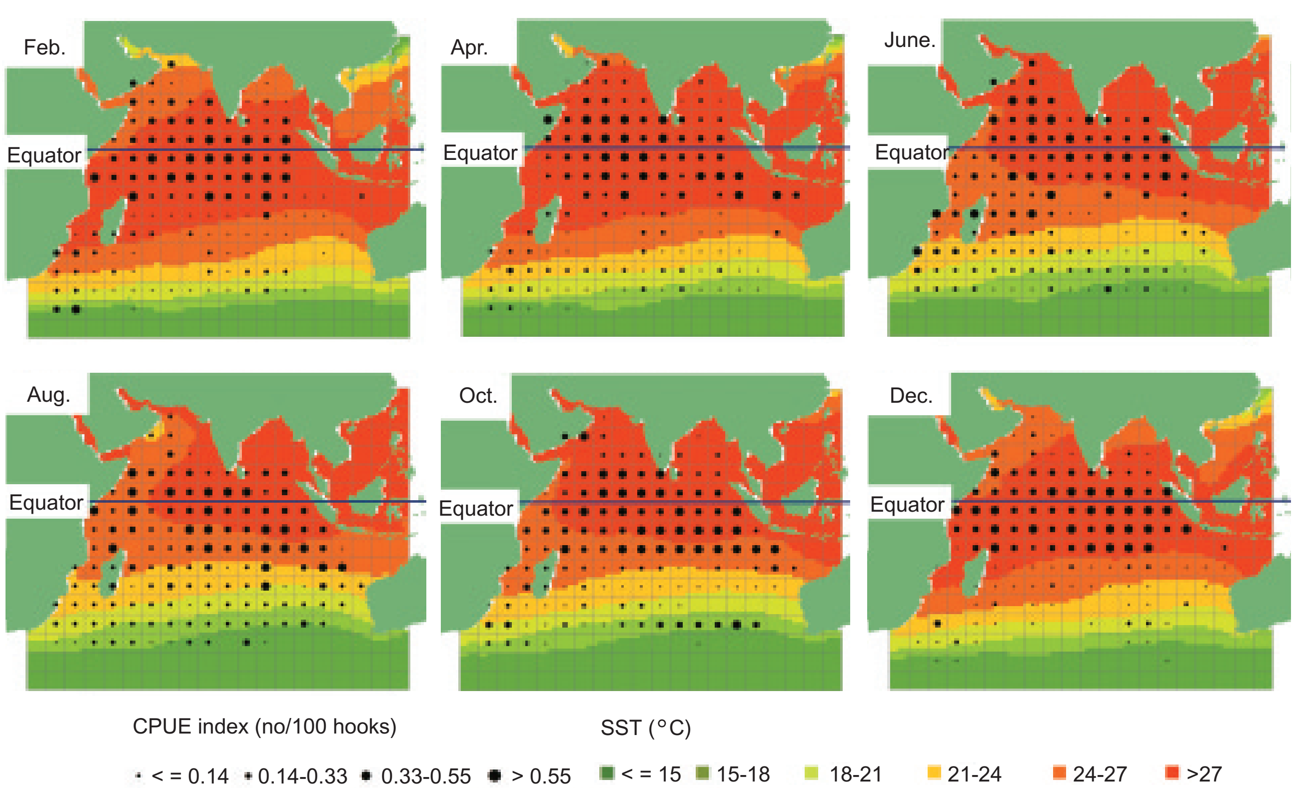

Fig. 2. Bimonthly CPUE distribution of bigeye tuna from the Taiwanese longline fishery in the Indian Ocean and its relationship to sea surface temperature (SST).

occurred in the western and northern parts of the ocean and were not constrained to the equatorial regions where CPUEs were relatively higher. These differences were obvious in the northern hemisphere. Despite some high values of the mean weight index in the waters between 10°N and 15°S, the correlation between the CPUE and mean weight indices was not significant ($p > 0.05$).

The monthly CPUE distribution maps detail the spatial and temporal patterns (Fig. 2). For each monthly map, high CPUE values were distributed in the regions between 10°N and 15°S, although some variations existed. From Dec. to Apr. (corresponding to the NE monsoon), high CPUE values occurred in the regions where the SSTs were all greater than 27°C. During the SW monsoon (between June and October), high CPUE values were rather scattered and extended to areas with SSTs of > 24°C. As these SSTs changed due to changes in the system of currents, the high-catch areas shifted in a reflection of this pattern. In addition, the high-CPUE areas (≥ Q3) were reduced as the high SST areas shrunk between June and Aug.

The maps of monthly mean weight distribution also show seasonal trends (Fig. 3). Most of the high values were located in the western part of the ocean with some extending to the eastern part. Also, the high values were not constrained to waters between 10°N and 15°S. Some scattered high values were evident outside these latitudes in all months except Jan. and Dec. In these 2 months, the CPUE and mean weight indices were highly correlated ($p < 0.001$, $r = 0.13$ for Jan. and $r = 0.15$ for Dec.), while none of the rest of the time did these show any significant relationship.

Hotspots

The hotspot maps for the CPUE and mean weight indices were centered on the equator (Fig. 4). For CPUE, the waters between 10°N and 15°S were the hotspots where most of the high catches occurred. These areas clearly indicate locations of highly productive fishing grounds in the Indian Ocean. In contrast, hotspots for the mean weight index occurred in the same latitudes, but only in the western part (Fig. 4). By comparing the spatial distribution of hotspots for the CPUE and mean weight indices, it is evident that the hotspot locations for the mean weight index was more concentrated and consistent than those for CPUE.

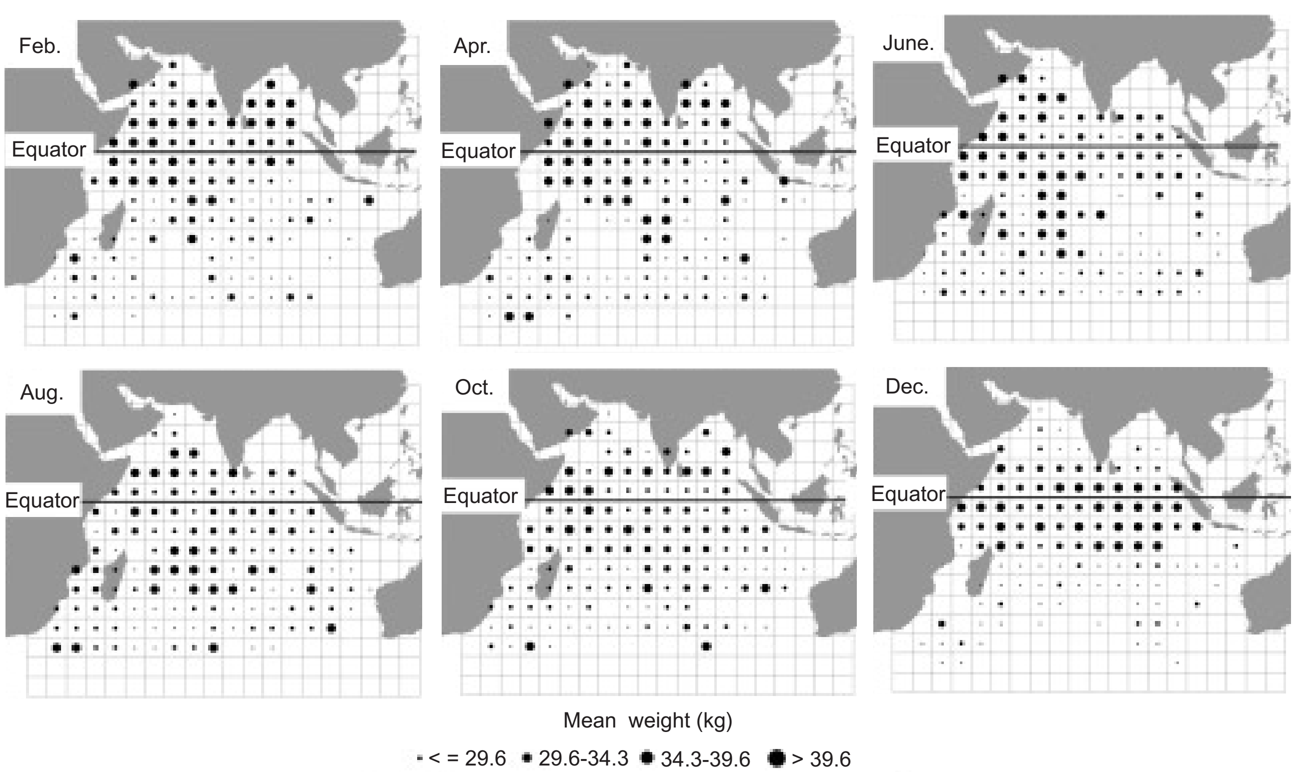

Fig. 3. Bimonthly mean weight index distribution of bigeye tuna from the Taiwanese longline fishery in the Indian Ocean.

Environmental factors (mean temperature, DO, and salinity) where the CPUE hotspots occurred showed certain characteristics (Fig. 5). The pattern for water temperature was relatively stable (CV = 0.022~0.088), from 27~29°C at the surface to 10~12°C at 400 m deep with a thermocline occurring at around 100 m deep. In contrast, DO values were highly variable with higher values above 100 m in depth (CV = 0.11~0.32). Salinity values were relatively variable in the upper layers and relatively stable in the deeper layers (CV = 0.003~0.010). Results for the mean weight index hotspots showed a similar pattern, but with less variation.

Temporal trends

Since there were spatial differences in values for the CPUE and mean weight indices (Fig. 1), we subdivided these indices into 5 regions to explore their temporal trends. The 5 regions showed distinct temporal trends for the CPUE (Fig. 6) and

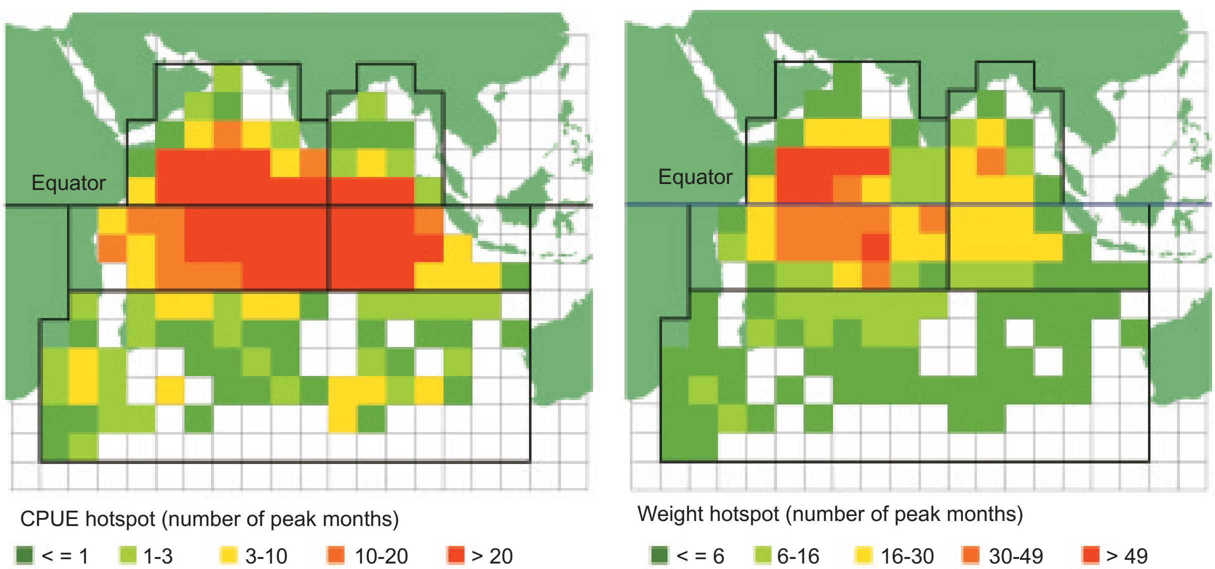

Fig. 4. Hotspots for CPUE (left) and mean weight (right) indexes based on Taiwanese longline fishery data from 1985 to 1999.

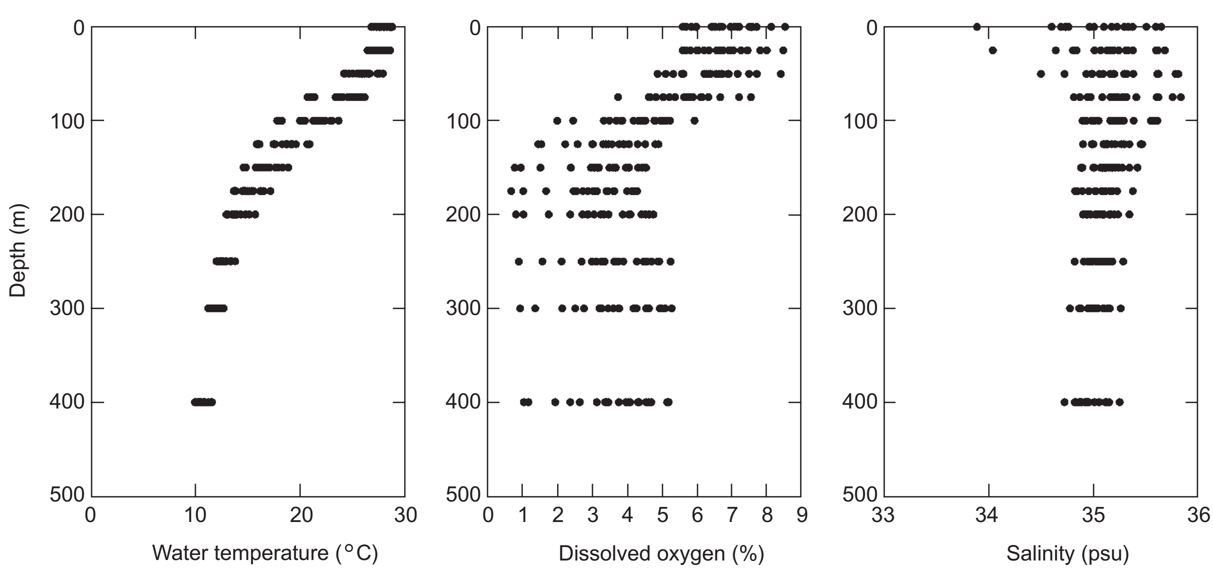

Fig. 5. Distribution of water temperature (°C), dissolved oxygen (DO, %) and salinity (psu) of CPUE hotspots at various vertical depths.

mean weight (Fig. 7) indices. Despite an increase in the total catch during the study period, the temporal CPUE trends appeared relatively stable among the 5 regions, and no declining trends were evident (Fig. 6). The CPUE means significantly differed among the 5 regions ($F = 143.9$, df = 4, 850, $p < 0.001$). Tukey's studentized range tests indicated that the mean CPUE was the highest in region D (0.58 ± 0.24), followed by regions A (0.52 ± 0.81) and B (0.52 ± 0.22), region C (0.39 ± 0.18), and region E (0.15 ± 0.09).

The mean weight index values (Fig. 7) among the 5 regions also significantly differed ($F = 59.2$, df = 4, 850, $p < 0.001$). In contrast to CPUE, Tukey's studentized range tests showed that there were no significant differences in mean weight among regions A (37.8 ± 4.8), B (37.5 ± 4.0), and C (37.1 ± 7.7), while values of these regions and regions D (36.0 ± 4.8) and E (30.6 ± 4.2) significantly differed.

To evaluate temporal differences, we separated the data into 2 periods: 1985~1990 and 1992~1999. Although most of the CPUE trends were stable, we found that region E showed a slightly increasing pattern ($p < 0.001$) (Table 1). In contrast, all regions, except region E, showed an increasing trend for the mean weight index ($p < 0.05$). Both periods showed similar patterns in CPUE differences, and 3 groups could be identified. CPUE indices were higher in regions A, B, and D than in region C and region E (Table 1). For the mean weight index, regional comparisons only distinguished 2 groups: regions A, B, C, and D, and region E.

DISCUSSION

For bigeye tuna, SST was the optimal environmental variable for predicting monthly CPUE in the Indian Ocean. In contrast, the monthly mean weight index showed a broader pattern, and SST was not a good indicator. CPUE hotspots occurred in waters between 10°N and 15°S, which is similar to their distributions in the Pacific (Lu et al. 2001) and Atlantic Oceans (Vannuccini 2003), and to that reported earlier for the Indian Ocean (Mohri and Nishida 1999a b, Bo 2003, Fonteneau et al. 2004). However, mean weight hotspots only occurred in the western portion of these same latitudes. The western tropical regions were reported to be a high-catch zone for bigeye tuna (Okamoto and Miyabe 1999, Fonteneau 2001, Vannuccini 2003, Fonteneau et al. 2004). Our data support this assessment. Temporal trends of the CPUE and mean weight indices showed regional differences. Most of the monthly CPUE values in the 5 ecoregions showed no significant changes, but most of the monthly mean weight index values showed increasing trends.

Table 1. Temporal trends of CPUE and mean weight indexes for bigeye tuna at five regions of the Indian Ocean based Taiwanese longline fishery data between 1985 and 1999

	Region A		Region B		Region C		Region D		Region E	
	1985-1990	1993-1999	1985-1990	1993-1999	1985-1990	1993-1999	1985-1990	1993-1999	1985-1990	1993-1999
n	72	84	70	84	66	75	66	73	72	84
CPUE index										
Mean	0.53	0.54	0.51	0.51	0.42	0.38	0.59	0.58	0.12	0.20
SD	0.20	0.16	0.17	0.15	0.13	0.21	0.20	0.23	0.05	0.09
Period comparison	NS		NS		NS		NS		$p < 0.001$	
Regional difference in period 1985-1990	F=97.2, df=4, 341, $p < 0.001$		3 groups-ABD, C, E							
Regional difference in period 1993-1999	F=66.5, df=4, 295, $p < 0.001$		3 groups-ABD, C, E							
Mean weight index										
Mean	36.2	38.6	35.4	38.9	35.8	38.5	34.7	36.3	31.1	30.2
SD	4.1	4.8	2.6	4.0	7.5	7.9	3.5	4.6	3.8	3.1
Period	$p = 0.001$		$p = 0.042$		$p < 0.001$		$p = 0.032$		NS	
Regional difference in period 1985-1990	F=14.2, df=4, 341, $p < 0.001$		2 groups-ABCD, E							
Regional difference in period 1993-1999	F=43.7, df=4, 395, $p < 0.001$		2 groups-ABCD, E							

NS: non-significant

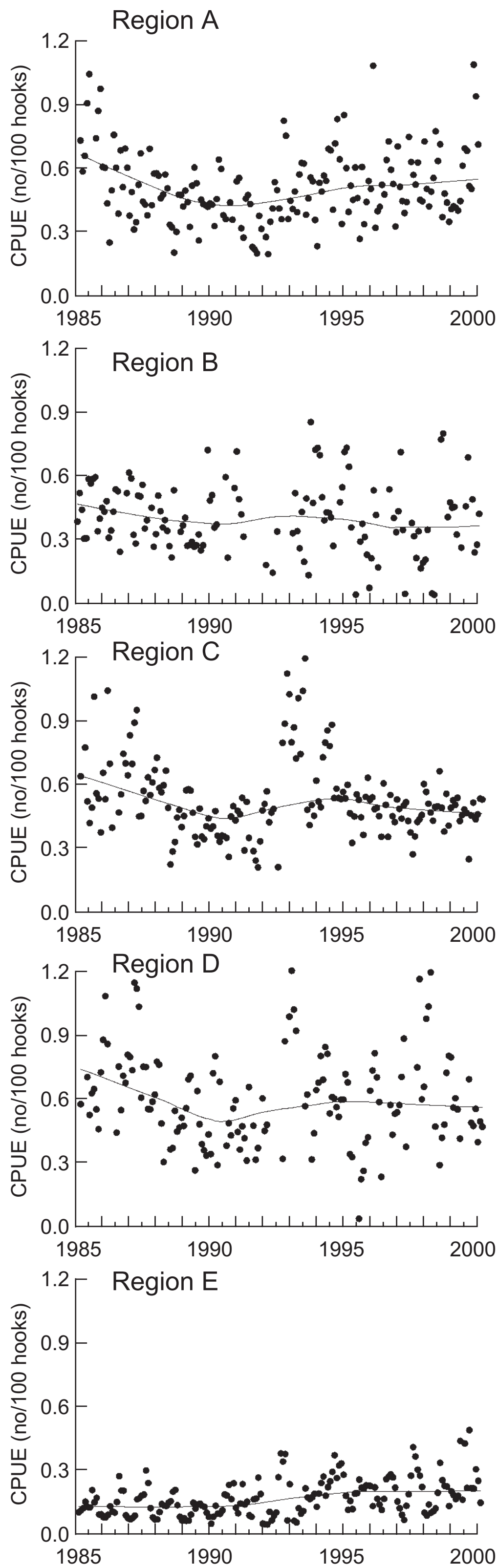

Fig. 6. Monthly trend of CPUE in the five ecoregions of the Indian Ocean based on Taiwanese longline fishery data from 1985 to 1999. The lines were smoothed by the lowess (locally weighted regression scatter plot smoothing) method.

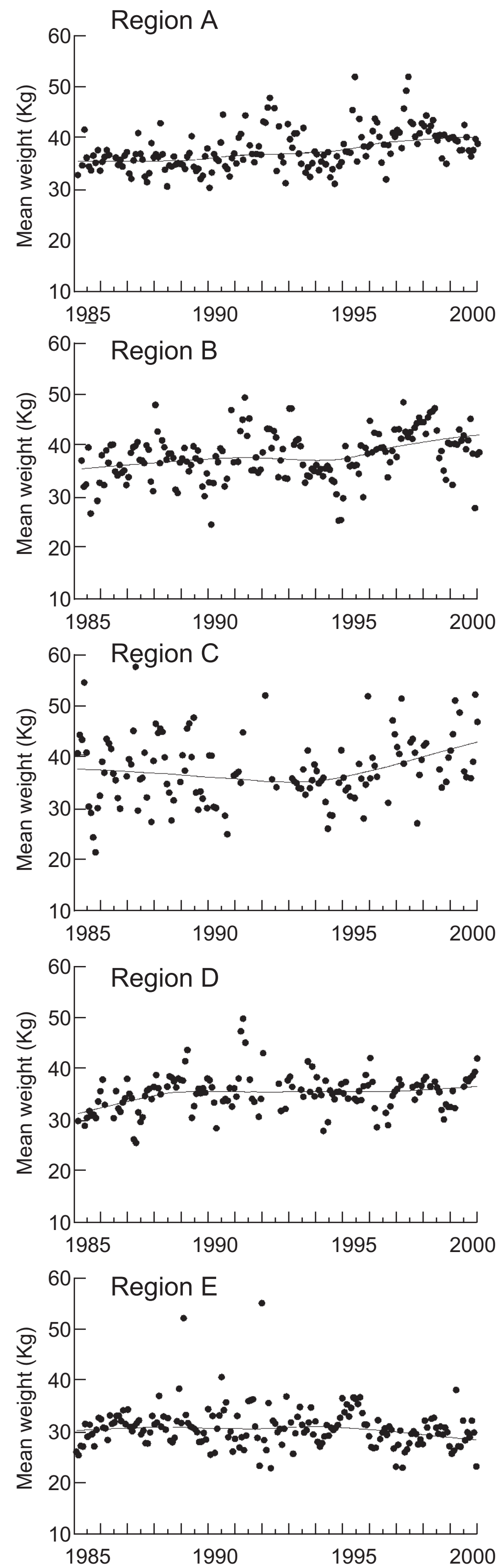

Fig. 7. Monthly trend of mean weight index in the five ecoregions of the Indian Ocean based on Taiwanese longline fishery data from 1985 to 1999. The lines were smoothed by the lowess method.

This pattern supports the observation that larger-sized individuals have been caught in recent years (Fonteneau et al. 2004).

Monthly CPUE distribution patterns roughly coincided with waters with higher SSTs. Monthly mean SST values of ≥ 27°C were important in determining the higher-catch area based on CPUE. A similar result was found by Mohri and Nishida (1999a) and Bo (2003) based on Japanese longline data. Therefore, all changes in CPUE were related to the seasonal monsoon patterns in the Indian Ocean (Bo 2003). Using data with a finer resolution, Bo (2003) also suggested that some subsurface parameters be considered. Using water temperature, salinity, and DO at various depths to correlate the CPUE with a 1°-square dataset, Bo (2003) found some highly correlated results. We were unable to perform a similar analysis due to limitations on data resolution.

CPUE and mean weight were used as abundance indices in this study to compare regional differences and temporal trends. Both indices showed some similarities and differences. For example, monthly CPUE and mean weight indices were significantly correlated in Dec. and Jan., but showed no correlation in other months. This indicates that these 2 indexes provide different but complementary information. In studying albacore in the Indian Ocean, Chen et al. (2005) successfully applied this index to separate the distribution patterns between mature and immature stages. Since the mean weight index is independent of CPUE, it may provide additional important information for resource management. Although there were no significant differences in CPUE values between the 2 time periods (1985~1990 and 1993~1999) for regions A~D used in this study, the mean weight index showed a significant increase. The exact reasons of this increase could not be determined. One of the possibilities is refinements in fishing techniques that greatly enhanced the harvests (Bigelow et al. 2002). The vertical range of bigeye tuna can extend to as deep as 600 m (Hanamoto 1987, Brill and Lutcavage 2001). These zones are not exploited by using standard catching methods. When techniques are improved to explore deeper in the sea, fleets can catch larger fish. Therefore, we suggest that future fishery studies apply this index to supplement CPUE and total catch information for inferring fishery statistics.

The spatial and temporal scales of tuna data used in this study may limit exploitation of these patterns in greater detail. However, our results suggest some insights into the distribution patterns of bigeye tuna in the Indian Ocean. For example, we found that the hotspots for the mean weight index were more concentrated than those for CPUE, which indicates that those highly productive fishing grounds are not always where the largest individuals are caught. These results improve our current knowledge of tuna's distribution. They also provide information for fishery vessels on where and when to catch these resources more efficiently. More importantly, these results provide a scientific foundation on ways to maintain sustainable yields in the future. More information, such as age structure, migration pattern, recruitment variability, and reliable forecast of abundance classes, would greatly help when setting quota prior to each fishing year. Conservation protocols can also be appropriately scaled.

Our results showed an increase in numbers of larger tuna caught in tropical regions in recent years. This means that more adults with reproductive capacity are being depleted. In addition, the increase in juveniles caught using FADs by purse seiners and the steady increase catch by longliners (Fonteneau and Pallares 2004, Fonteneau et al. 2004) will definitely affect future populations in the Indian Ocean. It is important to take action to conserve the species by reducing the total catch, especially that of the purse seine fishery (Shono et al. 2004), and to set up marine protected areas in the tropical western region between 10°N and 15°S in the Indian Ocean (Fonteneau 2001).

Many uncertainties about this heavily exploited species remain (Fonteneau et al. 2004). Further studies should try to differentiate the impacts of different catching methods on CPUE values and to model predicted distributions by incorporating a greater number of suitable environmental variables, such as variables at various depths in the ocean where bigeye tuna occur (e.g., Bo 2003). In our analyses, to overcome the deficiency in our data, they were aggregated over 15 yr to reflect monthly distribution patterns. However, this treatment may be so general as to ignore the effects of large-scale changes, such as El Niño, and inter-annual variations under the current climate change trend. Detailed distribution data from Japan, Korea, and Taiwan may be pooled to yield yearly and monthly distribution patterns (see Fonteneau et al. 2004 for example). In addition, the distribution of food resources for tuna may be an important and direct factor that will contribute to our understanding. No data were available at the time of this writing to explore these relationships (Caddy and Rodhouse 1998). Finally, studies of the impacts of climate variability (e.g., regime shifts) on the dynamics of these top marine predator populations should be the central focus of future research.

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