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Spatial and Temporal Distributions of Sailfish Associated with Environmental Factors in the Northwestern Pacific Ocean

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ABSTRACT

This study applied the generalized additive models (GAMs) to examine the relationship between sailfish catch per unit effort (CPUE) from 1998 to 2004 and environmental variables, which included satellite-derived remote sensing data and other spatio-temporal variables in the marginal seas of the northwestern Pacific Ocean. The results of the stepwise GAMs analysis found less important influences upon sailfish CPUE from chlorophyll-*a* concentration (Chl-*a*) and sea surface height anomaly (SSHA). The final GAMs fitting model was constructed by the spatio-temporal variables, including the year, month, latitude, longitude, sea surface temperature (SST), Pacific decadal oscillation (PDO), southern oscillation index (SOI), and the bathymetry of operational factors. There was a significant relationship (R^2 = 0.52, P < 0.0000) among the predicted values of GAMs analysis and nominal sailfish CPUE. It showed that the relatively high sailfish CPUE was found in June and July and a higher sailfish CPUE between 28 °C and 30 °C SST. The highest value of sailfish CPUE was found in 29 °C SST. These results can benefit to examine progressively the feeding and spawning habitats and its possible migratory route of sailfish in the northwestern Pacific Ocean.

Keywords: sailfish, catch per unit effort, sea surface temperature, chlorophyll-*a* concentration, generalized additive model

INTRODUCTION

Six billfish species were found in the waters around Taiwan, including swordfish, striped marlin, blue marlin, black marlin, sailfish, and small marlin (Chiang, 2004; Ho *et al*., 2005). About its ecological characteristics, the billfish is usually distributed in the water areas with higher temperature and has seasonal migratory patterns. The billfish swims in the surface of epipelagic and oceanic waters and generally remains above the thermocline layer, in water temperatures between 13 °C and 27 °C (FAO, 2003). The billfish can swim from the surface down to a depth of 650 m and is found primarily in the temperate and tropical regions in the ocean (FAO, 2003; Chiang, 2004; Chiang *et al*., 2004). Cephalopods (squid and octopus) and bony fishes are the primary prey of the billfish. Mackerel, skipjack, dolphin fish, and flyingfish are the most commonly taken fishes. Especially, the annual Indo-Pacific sailfish (*Istiophorus platypterus*, hereafter as sailfish) accounts for the largest annual catch, varying from 300 to 1,000 metric tons and is considered one of most valuable fisheries in the waters off eastern Taiwan (FA, 2006).

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Some recent studies have pointed out that sailfish regularly migrate to Taiwan's eastern coastal waters in early summer (Chiang, 2004; Chiang *et al*., 2004). However, little research has been done for the spatial and temporal distributions of sailfish relative to the environmental variables. Additionally, in recent years, the generalized additive models (GAMs) have been extensively used to assess the relative influence of environmental factors (including satellite-derived remote sensing and oceanographic parameters, etc.) on the performance of fishing operations, defined as the nominal catch per unit effort (CPUE) of fish (Venables and Dichmont, 2004; Zagaglia *et al*., 2004; Raventos and Macpherson, 2005; Walsh *et al*., 2005; Zainuddin *et al*., 2006; Damalas *et al*., 2007; Hazin and Erzini, 2007). Among those, Zagaglia *et al*. (2004) investigated the relationship between yellowfin tuna caught in the tropical Atlantic by the northeast Brazilian longline fleet, and environmental variables obtained from multi-sensor satellite data such as sea surface temperature (SST), chlorophyll-*a* concentration (Chl-*a*), sea surface height anomaly (SSHA), and wind velocity by GAMs analysis. The results obtained showed evidence of non-linear relationships between catch yields and environmental data. The largest CPUE of yellowfin tuna in the region seems to be strongly associated with the Intertropical Convergence Zone (ITCZ) position and its temporal variability. Zainuddin *et al*. (2006) also detected ocean hot spots for albacore (*Thunnus alaunga*) using multi-sensor satellite remote sensing images and catch data in the northwestern North Pacific. In addition, Walsh *et al*. (2005) correlated a GAM of blue marlin catch to environmental and operational fishery data. This GAM included nine significant predictors and explained 41.1% of observed deviant blue marlin catches. Additionally, Damalas *et al*. (2007) examined the relative influence of environmental, spatial, temporal and operational factors on swordfish catch rates by the GAMs in the Greek swordfish longline fishery between 1998 and 2004. Moreover, Hazin and Erzini (2007) used the GAMs to relate catch to environmental predictor variables, and their results highlighted the importance of environmental variables for the fishery and for the spatial distribution of different size classes of swordfish.

The objectives of this study are to apply the GAMs statistical analysis to investigate the relationship between sailfish CPUE and environmental variables, which include the information derived from multi-sensor satellite remote sensing data and other spatio-temporal environmental variables in the marginal seas of the northwestern Pacific Ocean.

MATERIALS AND METHODS

1. Data Sets

(1) Sailfish catch data

In this study, the six-year fishery dependent sailfish catch data was collected from the information documented in the logbooks of Taiwanese small-scale tuna longline fishing boats during the 1998 ~ 2004 period, and compiled by the Overseas Fisheries Development Council (OFDC) of Taiwan. The logbooks record the information, including fishery catch (weights and numbers), fishing location (latitude and longitude), and fishing effort (number of hooks). The study area (i.e., the major fishing ground of sailfish longline fishery) is bounded in the adjacent seas of the northwestern Pacific Ocean. It includes the shallower marginal seas (water depth less than 1000 m, i.e., the East China Sea and the South China Sea) and the deeper open ocean (with a water depth of more than 3000 m, i.e., Philippine sea) (Fig. 1).

(2) Satellite-derived environmental factors and climate indices

A. Sea surface temperature (SST)

In this study, the 4 km (spatial resolution of per pixel) AVHRR Pathfinder Version 5.0 SST Project (Pathfinder V5) is a new re-analysis of the AVHRR data stream developed by the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS) and the NOAA National Oceanographic Data Center (NODC). On the PO.DAAC website (http://poet.jpl.nasa.gov/), the monthly AVHRR Pathfinder V5 SST data are archived from 1998 to 2004. Its accuracy is 0.3 to 0.5 °C.

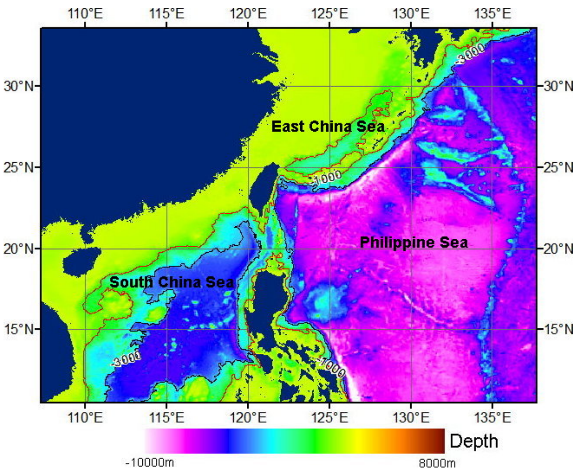

Fig. 1 Map of the study area.

B. Chlorophyll-*a* concentration (Chl-*a*)

SeaWiFS Chl-*a* concentration data were obtained from the NASA OceanColor Website (http://oceancolor.gsfc.nasa.gov). GES-DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni) is designed for visualization and analysis of the Ocean Biology Processing Group (OBPG) SeaWiFS global 0.1 degree (11.1 km) spatial resolution data products. Monthly SeaWiFS Chl-*a* ASCII data from 1998 to 2004 can be generated, which fall within the boundaries of this study area.

C. Sea surface height anomaly (SSHA)

The sea surface height anomalies (SSHA) were derived from JASON-1, TOPEX, ERS-2, ENVISAT and GFO altimeters, processed by the NRL site at the Stennis Space Center, and GTS data were provided by the NOAA/National Ocean Services (http://oceanservices.noaa.gov). Its spatial resolution is 0.25 degrees.

D. Climate indices

The two important climate indices, SOI and PDO index were used to examine their influence in the GAM. The SOI is calculated from the monthly fluctuations in the air pressure difference between Tahiti and Darwin. Sustained negative values of the SOI often indicate El Niño episodes and are accompanied by the sustained warming of the eastern tropical Pacific Ocean. The most recent strong El Niño was in 1997/98. The PDO index is defined as the dominant principal component of North Pacific monthly sea surface temperature variability (poleward of 20° N for the 1900 ~ 1993 periods). Those data were provided by the NOAA/Climate Diagnostics Center (http://www.cdc.noaa.gov).

2. *Generalized Additive Models (GAMs)*

Recently, the GAMs have been usually applied to fit the relationship between the response variable and the explanatory variables (Bigelow *et al.*, 1999; Venables and Ripley, 2002; Huet *et al.*, 2004; Damalas *et al.*, 2007). In the present study, the relationship between the sailfish catch rates, expressed as CPUEs, and environmental variables (multi-sensor satellite data, spatial and temporal operational factors) were analyzed using the GAMs statistical method (Hastie and Tibshirani, 1990). GAMs processing was implemented using S-PLUS statistical software (Insightful Corporation, Seattle). A total of 10 investigated variables were used in the expected model, as follows:

$$\ln(CPUE) = lo(year) + lo(month) + lo(latitude) + lo(longitude) + lo(SST) + lo(Chl\text{-}a) + lo(SSHA) + lo(PDO) + lo(SOI) + lo(bathymetry) + \varepsilon_i,$$

Where ln is a natural log as a link function. Loess smoother (lo), a local regression, was applied as a nonparametric scatterplot smoothing. It is a generalization of running means, which gets a predicted value at each point by fitting a weighted linear regression, where the weights decrease with distance from the point of interest. The final ε is a random error term. In addition, the Akaike information criterion (AIC) was used to find the best of the GAMs.

AIC is defined as follows:

$$AIC = -2\ln(L) + 2K$$

Where L is the likelihood function, the -2ln(L) is replaced to calculate the AIC by the residual deviance here.

RESULTS

1. Geographical Distribution of Sailfish Fishing Effort

Annual spatial distribution of sailfish fishing efforts around the coastal waters of Taiwan and Philippines in 1998 ~ 2004 is shown in Fig. 2. The geographical distribution of the dominant fishing efforts was located in the waters off eastern Taiwan, bounded in the area defined by 19 ~ 26° N and 121 ~ 124° E. The average yearly fishing effort of the longline fishery is more than 100 thousand hooks within a 1 x 1 latitude/longitude grid. The highest catch effort was 563 thousands hook, found in northeastern Taiwan, near the Su-Ao coastal waters, bounded by 24 ~ 25° N and 122 ~ 123° E.

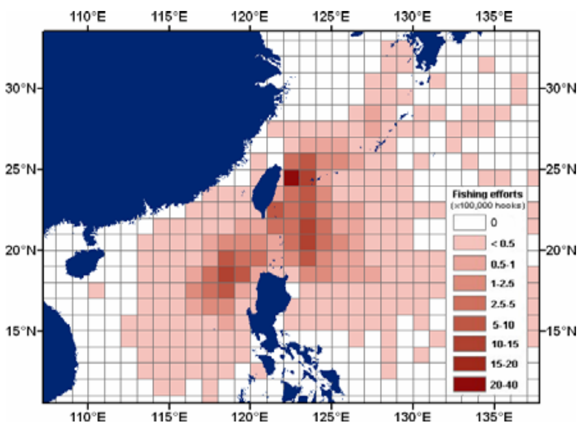

Fig. 2 The yearly mean fishing efforts from 1998 to 2004. The spatial resolution is 1 x 1 latitude/ longitude.

Moreover, the second dominant fishing area was located in the northwestern Philippines Sea, bounded in the area defined by 17 ~ 20° N and 117 ~ 120° E. Its highest catch effort was 278 thousand hooks, bounded by 18 ~ 19° N and 118 ~ 119° E.

2. Geographical Distribution of Sailfish CPUE

All of the 7-year sailfish longline fishery data was summed up to be integrated into a 1 x 1-degree grid layer by ESRI/ArcGIS spatial analyses. A map of the yearly sailfish CPUE from 1998 to 2004 is shown in Fig. 3. The mean CPUE from 1998 to 2004 is 1.3 fish per 1,000 hooks. The higher CPUEs, more than 1.5 fish per 1,000 hooks, occurred in the origin of the Kuroshio warm current near the western side of the Philippine Sea. A few higher CPUEs were found in the northeastern South China Sea close to the coastal water of the Philippines. Additionally, the maximum sailfish CPUE around the Taiwan coastal waters was found in the mainstream of the Kuroshio in the exclusive economic zone (EEZ) of Taiwan. In this spatial grid, bounded by 23 ~ 24° N and 121 ~ 122° E, there was about 2.5 fish per 1,000 hooks for the small longline fishery.

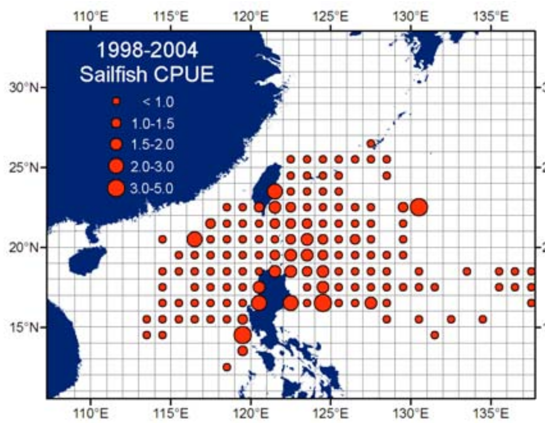

Fig. 3 Average CPUE (numbers of fish per 1,000 hooks) of Taiwan sailfish small longline fishery from 1998 to 2004. The spatial resolution is 1 x 1 latitude/ longitude.

Furthermore, the monthly CPUEs of 7-year sailfish fishing data were also mapped into 1 x 1-degree grid layers, as seen in Fig. 4. It showed that the low CPUE was found in the winter (from December to February of the next year); its average CPUE was 0.75 fish per 1,000 hooks. In contrast, the high CPUE was found in the early summer (in June and July), and its average CPUE was 2.6 fish per 1,000 hooks. The highest CPUE, 2.8 fish per 1,000 hooks, occurred in June. All monthly average CPUEs are tallied in Fig. 5.

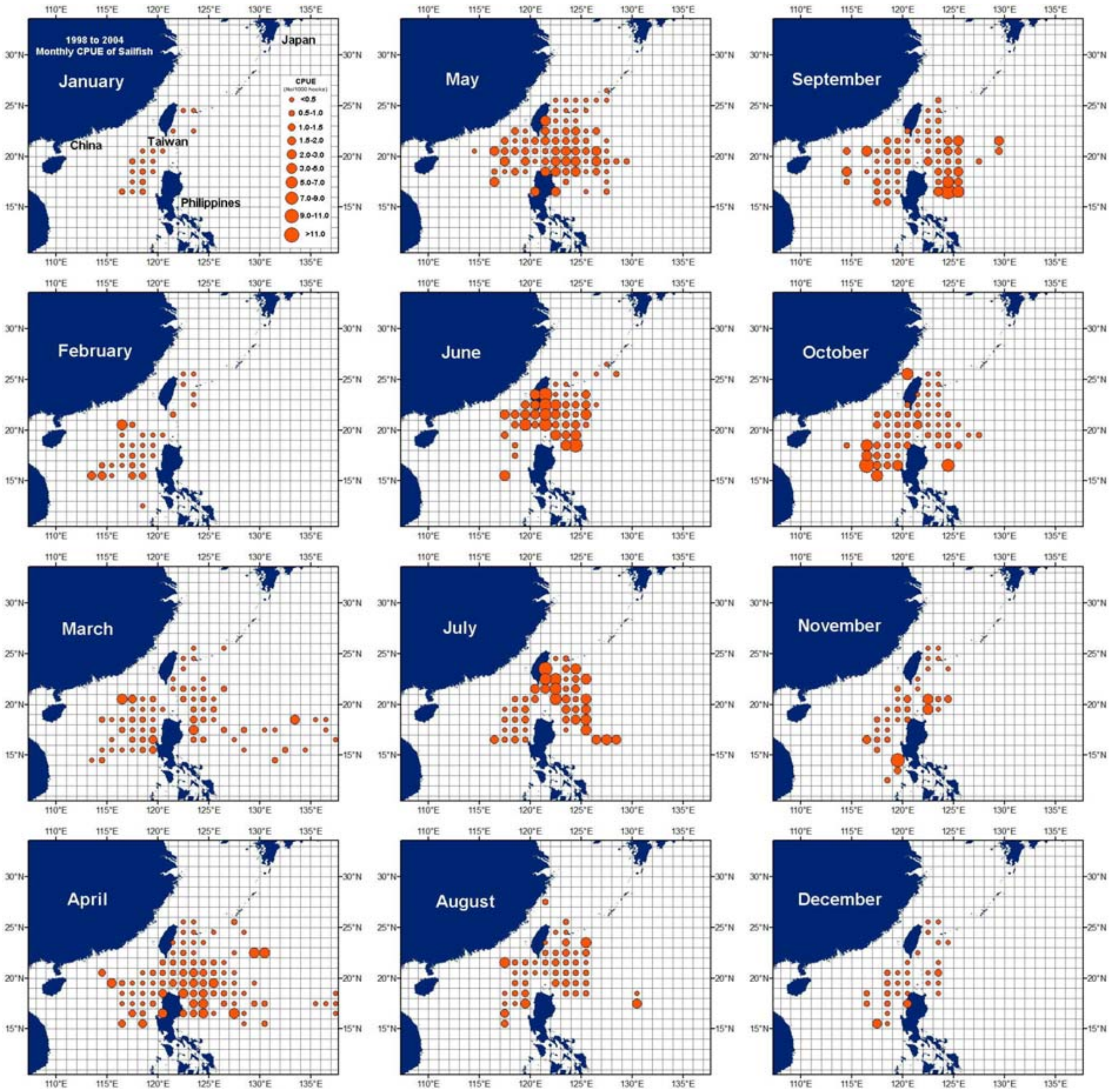

Fig. 4 Monthly mean sailfish CPUE from 1998 to 2004 in the northwestern Pacific Ocean.

3. Satellite-derived Environmental Variables

Additionally, the satellite-derived 7-year average SST (Fig. 6a) and Chl-*a* concentration (Fig. 6b) are used to compare it with the fishing efforts (Fig. 2) and CPUE of sailfish (Fig. 3), we could find that the water temperature of the sailfish fishing ground was limited between 26 to 30 °C. The 26 °C isotherm could be the northern boundary of the major fishing ground. The overall average latitudinal position of 26 °C isotherm was located at about 25° N at the westward side of eastern Taiwan. Only a warm tongue of 26 °C isotherm reached to 27° N as a northeastward intrusion derived from the mainstream of the Kurosho. Moreover, the upper boundary of Chl-*a* concentration of the sailfish fishing ground was about 0.4 mg m^{-3}, nearly corresponding with the 200 m water depth. We could find that the higher sailfish CPUE happened in water of a lower Chl-*a* concentration, the southeastward side (open sea) of the 0.2 mg m^{-3} contour line.

4. GAMs Analysis

The results of the GAMs analysis derived effects of year, month, latitude, and longitude on the

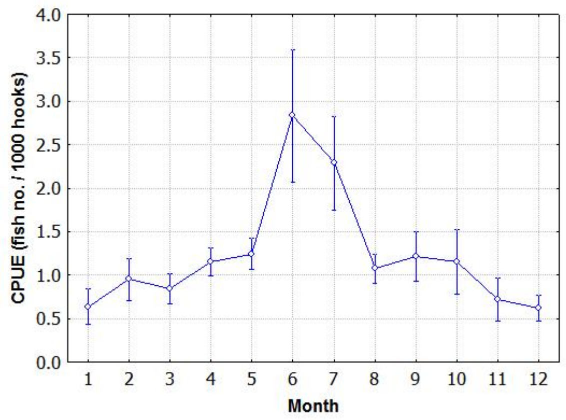

Fig. 5 Monthly variation of sailfish CPUE from 1998 to 2004.

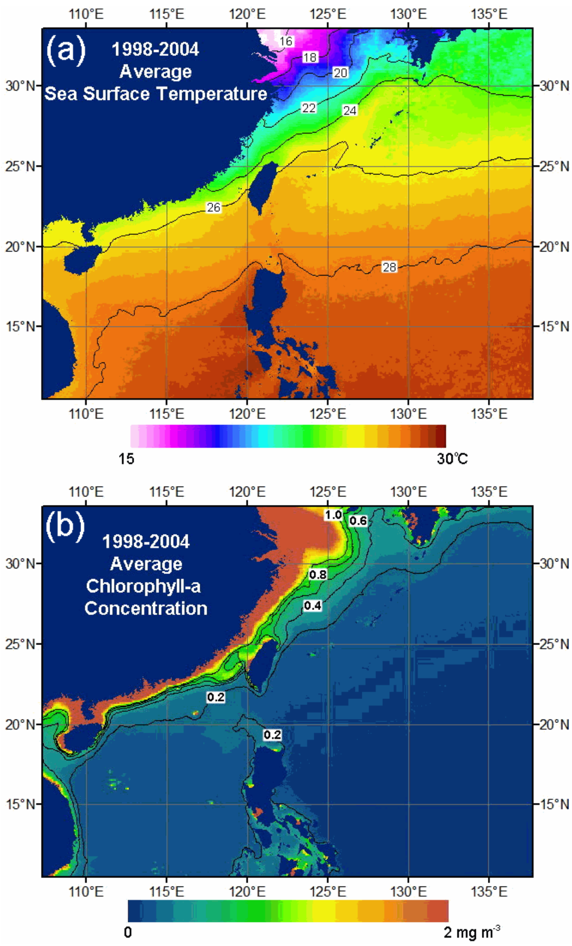

Fig. 6 The average satellite-derived sea surface temperature (a) and chlorophyll-*a* concentration (b) images during 1998 to 2004.

log-transformed sailfish CPUE (ln(CPUE)) are shown in Fig. 7. From the analysis of temporal variations, we find that the relative high sailfish CPUE happened in 1999 and from June to July, monthly. In addition, the lower sailfish CPUE was associated with higher northern latitudes in the spatial variations. And there was no significant correlation between sailfish CPUE and longitudinal variation, only a higher sailfish CPUE was found nearby 125° E.

Furthermore, the results of the GAMs analysis derived the effects of multi-sensor satellite environmental variables, including SST, Chl-*a*, SSHA and water depth as a physical factor, as shown in Fig. 8. Firstly, it showed a higher sailfish CPUE between 28 °C and 30 °C SST. The highest value of sailfish CPUE was found in 29 °C SST. Secondly, a gradual decrease in sailfish CPUE was associated with a gradual Chl-*a* concentration. Regarding the SSHA, there was no significant correlation between SSHA and sailfish CPUE. Moreover, water depth also plays a role in influencing the variations of sailfish CPUE. The higher sailfish CPUE happened from 1000 to 3500 m water depth.

Table 1 is the statistical results of the stepwise GAMs analysis applied to investigate the effects of environmental variables relating to sailfish CPUE. We were able to find less important influences of Chl-*a* and SSHA. Hence, the final fitting model of GAMs analysis was used, as follows:

$$\ln(\mathrm{CPUE}) = \mathrm{lo(year)} + \mathrm{lo(month)} + \mathrm{lo(latitude)} + \mathrm{lo(longitude)} + \mathrm{lo(SST)} + \mathrm{lo(PDO)} + \mathrm{lo(SOI)} + \mathrm{lo(bathymetry)} + \varepsilon_{i,}$$

This above model was applied to calculate the predicted fitting CPUE to compare it with the nominal CPUE in Fig. 9 and Table 2 ($R^2 = 0.52$, $P < 0.0000$).

DISCUSSION

Sailfish is widely distributed in the tropical and temperate waters of the Pacific and Indian oceans (Beardsley *et al.*, 1975). Its geographical range, based on data from longline catches, is approximately 45° to

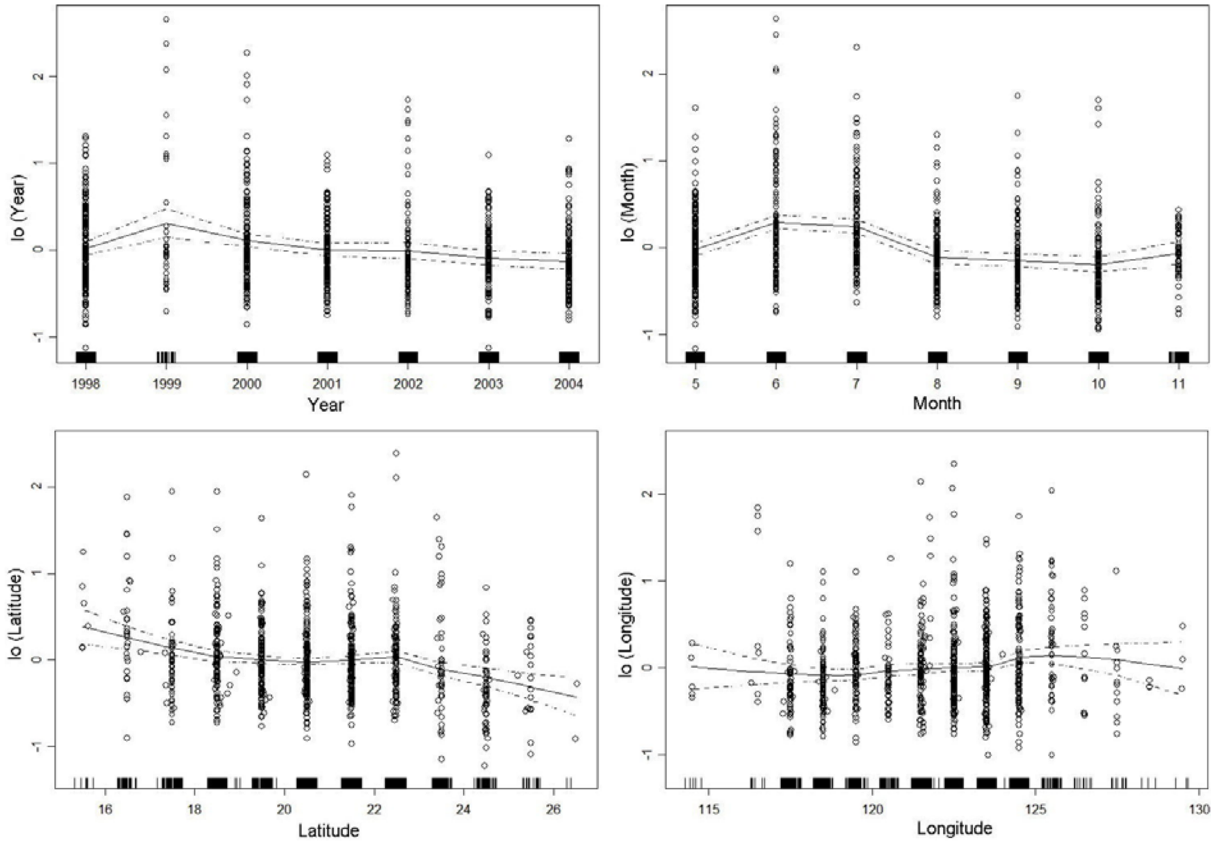

Fig. 7 Generalized additive models (GAMs) derived effect of year, month, latitude, and longitude on the log-transformed sailfish CPUE. Dashed lines indicate 95% confidential intervals. Tick marks on the x-axis show the locations of data points.

Table 1 Stepwise generalized additive model fitting for environmental factors affecting CPUE of the sailfish small longline fishery

Factors	Residual Degrees of Freedom	Residual Deviance	Cumulative Percentage of Deviance explained	Akaike Information Criterion	*F*	Pr(*F*)
Null	886	252.44		252.44		
+Year	880	244.35	3.2%	256.35	1.99	0.078
+Month	874	215.20	14.8%	239.20	15.66	0.000
+Latitude	870	205.82	18.5%	237.82	6.19	0.000
+Longitude	866	200.87	20.4%	240.87	4.49	0.003
+SST	862	196.35	22.2%	245.12	5.65	0.000
+Chl-a	858	195.42	22.6%	251.86	0.70	0.546
+SSHA	853	193.93	23.2%	260.40	1.51	0.196
+PDO	849	192.24	23.8%	266.21	4.06	0.009
+SOI	845	189.57	24.9%	271.12	4.59	0.004
+Bathymetry	842	186.96	25.9%	275.82	3.41	0.022

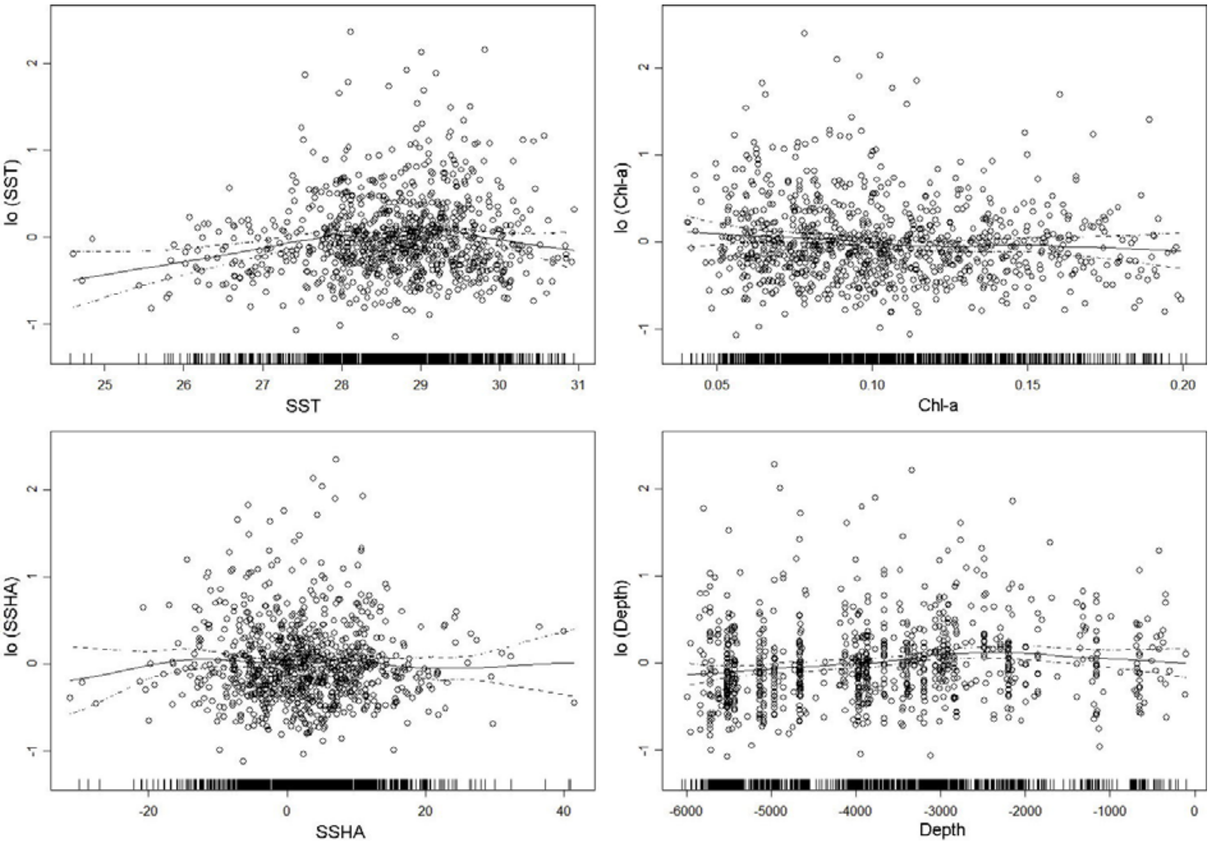

Fig. 8 Generalized additive models (GAMs) derived effect of SST (sea surface temperature), Chl-a (chlorophyll-a concentration), SSHA (sea surface height anomaly), and depth (unit: meter) on the log-transformed sailfish CPUE. Dashed lines indicate 95% confidential intervals. Tick marks on the x-axis show the locations of data points.

Table 2 Analysis of variance for the relationship between ln(CPUE) and derived sailfish CPUE by GAMs fitting model

	Degrees of Freedom	Sum of Squares	Mean Square	*F*	Pr(*F*)
Regression	1	4.6677	4.6677	49.8141	0.0000
Residual	46	4.3103	0.0937		

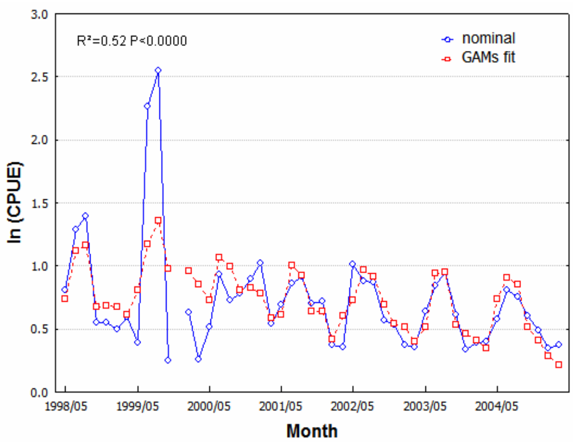

Fig. 9 Comparison of nominal sailfish CPUE of logbooks and predicted CPUE.

50° N in the northwestern Pacific and 35° to 40° S in the southwestern Pacific (Nakamura, 1985). Large numbers of sailfish are usually found in the warm Kuroshio and its branch, the Tsushima Current, in the Sea of Japan, in the East China Sea, and around the Philippines (Nakamura, 1985). Hoolihan (2005) analyzed the sailfish's pop-up satellite archival tag and reported that the sailfish inhabited water depths ranging from 0 m to 61 m and spent about 85% of their time at depths above 10 m, which was correlated with the thermocline barrier. Moreover, sailfish is found to prefer warmer temperatures, ranging from 19.7 °C to 30.1 °C. Ovichinnikov

(1966) also found that the geographic distribution of sailfish was usually related to 28 °C water temperature.

1. Spatial Variables Influence the Sailfish Distributions

Sailfish is a highly migrating species (HMS) and usually shows a strong tendency to inhabit close to the continental coasts. FAO (2003) statistics showed that the largest sailfish fishing ground was located in the Pacific Ocean, with more than 32 ~ 78% production of sailfish realized in the northwestern portion. In this study, the greatest part of accumulative fishing efforts of sailfish small longline fisheries were found close to the exclusive economic zones (EEZs) of Taiwan and the Philippines. The largest fishing ground was found around the offshore area of northeastern Taiwan (Fig. 2). It is located around the largest offshore fishing port, the Su-Ao fishing port, and provides convenient supplies to fish markets. This largest fishing effort is also located at the adjacent turning point of the Kuroshio mainstream, passing from eastern Taiwan to the Okinawa trough. The warmer water of the Kuroshio provides a suitable migratory route and habitat for sailfish. The experiment of the Fisheries Research Institute, deploying an archival pop-up satellite tagging of sailfish, showed a released sailfish from southeastern Taiwan, then the satellite tag was found from the Argos satellite communication system in the waters of northeastern Taiwan (Chiang *et al*., 2009).

The sailfish CPUE (catch rate) is an abundant index of the sailfish small longline fishery. In this study, the higher CPUEs were found within the boundary of the Kuroshio, especially near the eastern Taiwan water (Fig. 3). We had known that the Kuroshio is a warm (higher SST) and nutrient-poor (lower Chl-*a* concentration) western boundary current, similar to the Gulf Stream. The mainstream of the Kuroshio always passes through the water of eastern Taiwan from the northern equatorial current to the southern water of Japan. So, it would play an important hydrographic system in affecting the spatial distribution of sailfish. In the North Atlantic, Mejuto (2003) found that the swordfish adjust their spatio-temporal distribution due to their physiological needs, strongly influenced by the latitudinal position of the path of the Gulf Stream, which in turn corresponds with temperature variations and abundant zooplankton. Generally, the Kuroshio moves close to and sometimes onto the shelf during the wintertime and offshore in the summertime off eastern and northeastern Taiwan (Sun, 1987; Tang *et al*., 2000).

Furthermore, the results of the GAMs analysis, as seen in Fig. 7, show an increasing latitudinal position from 16.5° N to 25.5° N, that is associated with a decreasing sailfish CPUE. In addition, a slight increase was also found with the longitudinal increase from 117.5° E to 125.5° E. So the higher sailfish CPUE could be found in the southern area below 22.5° N and the western area of 125.5° E, within the basin of the Kuroshio in eastern water of Taiwan.

2. Temporal Variables Influence the Sailfish Distributions

The fishing period of sailfish is about from May to November, and the highest CPUE occurred in June (Figs. 4 & 5). During early summer, especially from May to June, sailfish is found predominantly in the landward side of the Kuroshio warm current (Chiang, 2004). According to the analysis of monthly SST images of May to August from 1998 to 2004, the specific 29 °C isotherm moved northwardly, close to the coastal waters of southeastern Taiwan in June (Fig. 10). At this time, it shows the highest sailfish CPUE. From the results of the GAMs analysis, the 29 °C of SST also show the highest sailfish CPUE (Fig. 8). In fact, many studies have suggested that the SST parameters usually are used to examine the relationship with the distributions of tuna species in the past (Andrade and Garcia, 1999; Schick *et al*., 2004; Santos *et al*., 2006; Schaefer *et al*., 2007; Teo *et al*., 2007). Therefore, the satellite-derived SST variability (especially 29 °C isotherm) should be an important environmental index of the spatio-temporal distribution of sailfish around the coastal waters of Taiwan. Monthly variability of sailfish CPUE was also found in the

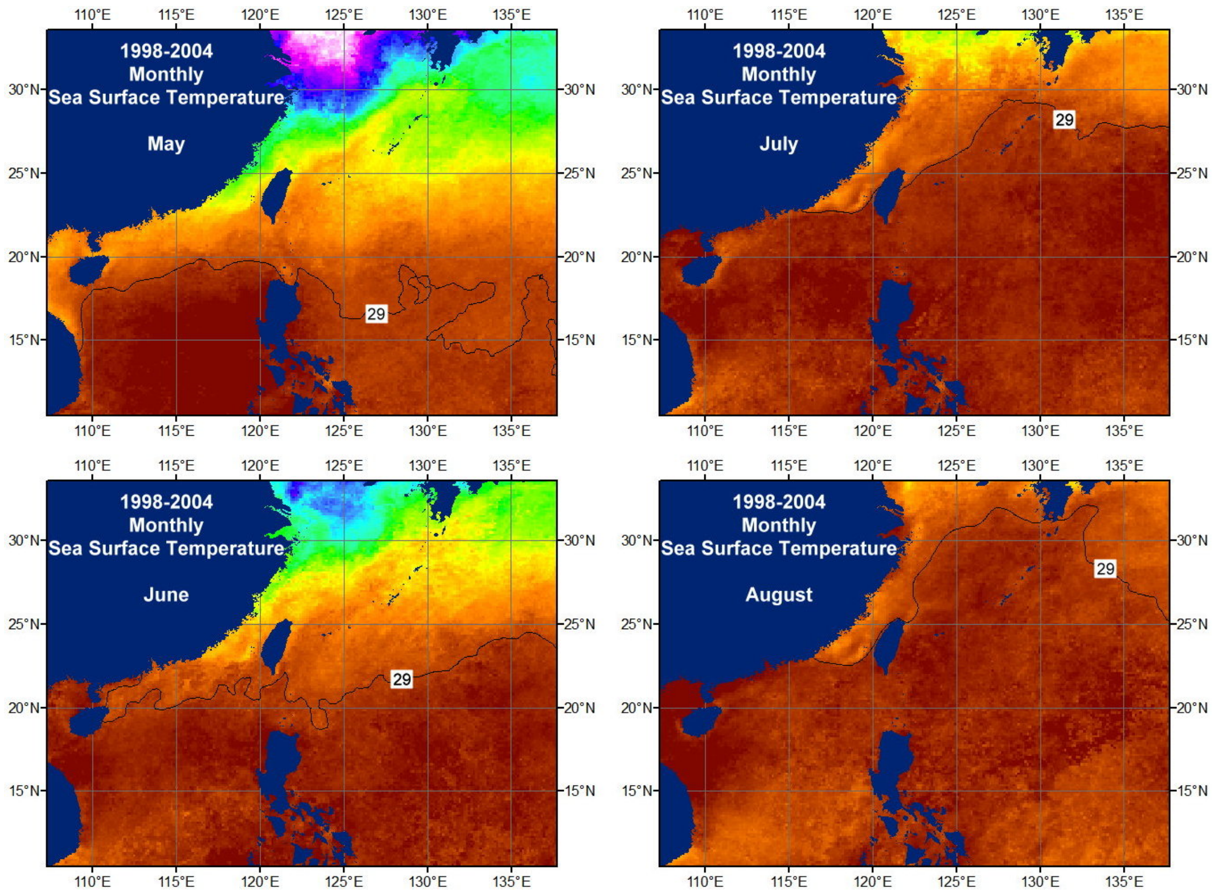

Fig. 10 NOAA/AVHRR monthly sea surface temperature images of May to August during 1998 to 2004.

results of the GAMs analysis (Fig. 7), which showed the higher sailfish CPUE in June and July. In addition, the monthly Chl-*a* concentrations of May to August showed no significant variation, especially within the 0.2 mg m^{-3} contours (Fig. 11).

In this study, we found a good relationship between the GAM predicted and nominal sailfish CPUE ($R^2 = 0.52$, $p < 0.000$) (Fig. 9). Actually, GAM approach is useful in constructing forecasting models by identifying promising relationships with predictor variables and improving abundance forecasts through the incorporation of environmental variables (Wang *et al.*, 2009). Therefore, the prediction with a GAM fitted to sailfish CPUE data will be a useful monitoring technique for the Taiwanese small-scale longline fishery and its result might be considered as important information in fishery management. The GAM approach allowed us to examine the relationship between logbook data and predicted values, to characterize bias in this relationship, and to identify specific patterns to each major sector of the fishery (William *et al.*, 2002).

Regarding the yearly variability of sailfish CPUE, we found a distinct rise in 1999 during La Niña events, which followed the strong 1997/1998 El Niño event. Due to the less variability of the Chl-*a* concentration, we could conclude that the SST should be an important factor to affect sailfish distribution. In this study, we found the sailfish CPUEs rose abruptly in 1999 (Fig. 9). In fact, some studies have analyzed the relationships between the CPUE of tuna or tuna-like species and the ENSO event. Howell and Kobayashi (2006) examined the effects of fishery-based (operational) and oceanographic parameters on bigeye tuna (*Thunnus obesus*) CPUE at Palmyra Atoll in the central Tropical Pacific. They mentioned that there is an increase in bigeye CPUE corresponding to an increase in eastward advection during the winter months of El Niño events. Lehodey *et al.* (2006) reported that fish population variability and fisheries

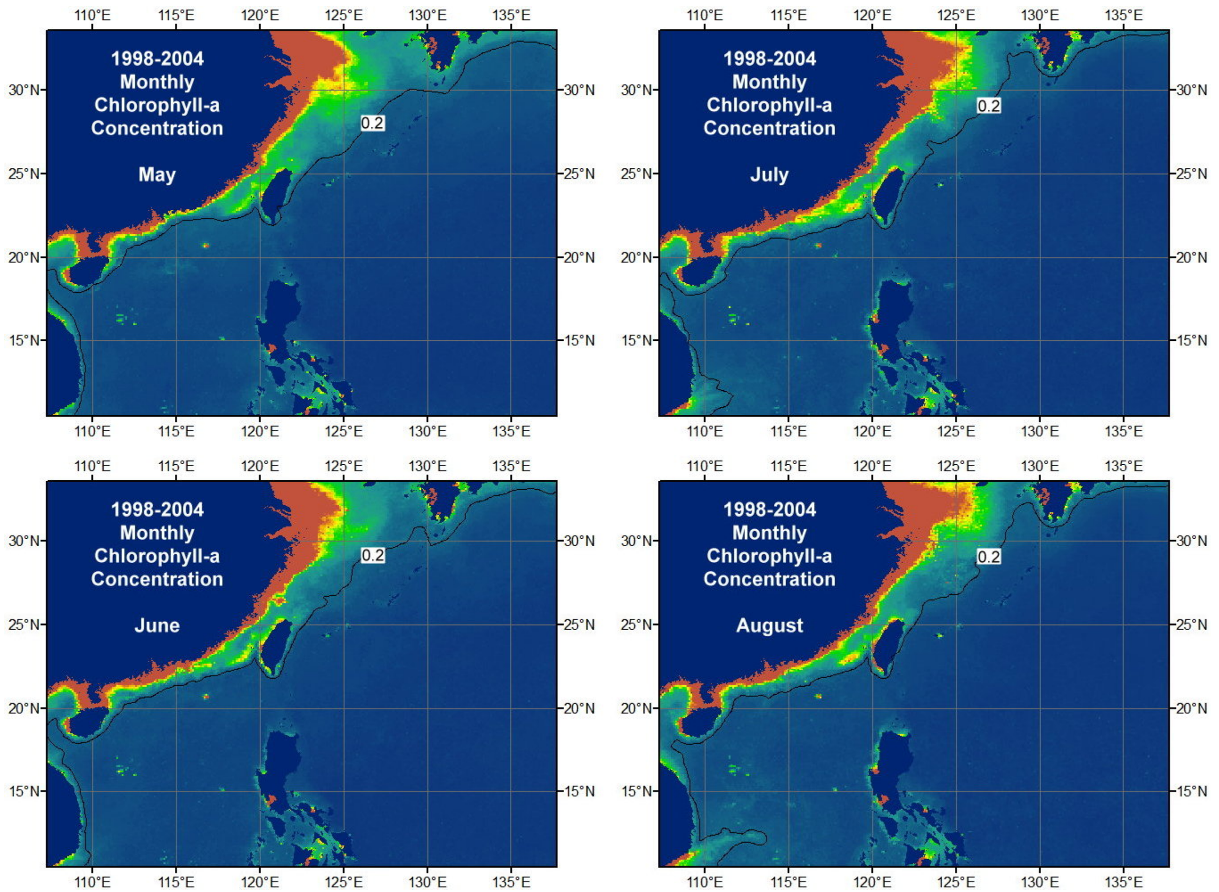

Fig. 11 OrbView-2/SeaWiFS monthly chlorophyll-*a* concentration images of May to August during 1998 to 2004.

activities are closely linked to weather and climate dynamics (ENSO event). And Lehodey *et al*. (2003) also concluded that while tropical tuna species like skipjack and yellowfin had higher recruitments during El Niño events, while the subtropical albacore species (*Thunnus alalunga*) showed the opposite pattern with low recruitment during El Niño and high recruitment during La Niña. Therefore, we need to do a more detailed analysis to explore whether the increasing CPUE was induced and affected in relation to a large-scale ENSO event, especially the La Niño phenomenon in 1999.

3. Effects of Other Environmental Variables

In this study, we also examined how the water depths of fishing grounds affected the spatial distributions of sailfish catch rates. The results showed that all of the small longline fishing effort and its caught sailfishes were located in the deeper water areas, more than 1000 m around the marginal seas of northwestern Pacific Ocean (Figs. 1 ~ 3). Additionally, the GAMs plot (Fig. 8) also indicates a higher abundance of sailfish between 2000 m and 3000 m water depth. Teo *et al*. (2007) found that the breeding areas used by the bluefin tuna were significantly associated with bathymetry, SST, eddy kinetic energy, surface chlorophyll concentration, and surface wind speed. The bluefin tuna exhibited a significant preference for areas with continental slope waters, about 2800 m to 3400 m water depth.

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REFERENCES

Andrade, H. A. and C. A. E. Garcia (1999) Skipjack tuna fishery in relation to sea surface temperature off the southern Brazilian coast. Fish. Oceanogr., 8(4): 245–254.

Beardsley, G. L., N. R. Merrett and W. J. Richards (1975) Synopsis of the biology of the sailfish, *Istiophorus platypterus* (Shaw and Nodder, 1791). *In* Proceedings of the International Billfish Symposium. Part 3. Species Synopses (R. S. Shomura and F. Williams eds.), NOAA Technical Report NMFS SSRF-675: 95-120.

Bigelow, K. A., C. H. Boggs and X. He (1999) Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. Fish. Oceanogr., 8(3): 178–198.

Chiang, W. C., S. C. Fu, T. L. Huang, C. L. Sun, W. Y. Chen, D. C. Liu, W. C. Su and M. K. Musyl (2009) Electric tagging studies of sailfish (*Istiophorus platypterus*) in eastern Taiwan to examine movement patterns, habitat preferences and fisheries interaction. Proceedings of the 60th Annual Tuna Conference: 19.

Chiang, W. C. (2004) Population dynamics and stock assessment of sailfish (*Istiophorus platypterus*) in waters off eastern Taiwan. Ph. D. Thesis, Institute of Oceanography, National Taiwan University, 194 pp.

Chiang, W. C., C. L. Sun, S. Z. Yeh and W. C. Su (2004) Age and growth of sailfish (*Istiophorus platypterus*) in waters off eastern Taiwan. Fish. Bull., 102(2): 251–263.

Damalas, D., P. Megalofonou and M. Apostolopoulou (2007) Environmental, spatial, temporal and operational effects on swordfish (*Xiphias gladius*) catch rates of eastern Mediterranean Sea longline fisheries. Fish. Res., 84: 233–246.

FA (2006) Fisheries statistical yearbook of Taiwan, Kinmen and Matsu area, 2006, Fisheries Agency, 494 pp.

FAO (2003) FAO Yearbook. Fishery Statistics. Capture Production, Vol. 92/1 (2001) FAO Fisheries Series, 63, 627 pp.

Hastie, T. J. and R. J. Tibshirani (1990) Generalized Additive Models (Monographs on Statistics and Applied Probability). New York, Chapman and Hall, 356 pp.

Hazin, H. and K. Erzini (2007) Assessing swordfish distribution in the South Atlantic from spatial predictions. Fish. Res., 90(1-3): 45-55.

Ho, Y. S., W. C. Chiang and W. Y. Chen (2005) Introduction of billfish. FRI Newsletter, 9: 41–44.

Hoolihan, J. P. (2005) Horizontal and vertical movements of sailfish (*Istiophorus platypterus*) in the Arabian Gulf, determined by ultrasonic and pop-up satellite tagging. Mar. Biol., 146: 1015–1029.

Howell, E. A. and D. R. Kobayashi (2006) El Niño effects in the Palmyra Atoll region: oceanographic changes and bigeye tuna (*Thunnus obesus*) catch rate variability. Fish. Oceanogr., 15(6): 477–489.

Huet, S., A. Bouvier, M. A. Poursat and E. Jolivet (2004) Statistical tools for nonlinear regression: a practical guide with S-PLUS and R example (second edition). Springer-Verlag New York, 232 pp.

Lehodey, P., J. Alheit, M. Barange, T. Baumgartner, G. Beaugrand, K. Drinkwater, J. M. Fromentin, S. R. Hare, G. Ottersen, R. I. Perry, C. Roy, C. D. Lingen and F. Werner (2006) Climate Variability, Fish, and Fisheries. J. Clim., 19(20): 5009–5030.

Lehodey, P., F. Chai and J. Hampton (2003) Modeling climate-related variability of tuna populations from a coupled ocean-biogeochemical-populations dynamics model. Fish. Oceanogr., 12(4/5): 483–494.

Mejuto, J., B. García-Cortés and J. M. de la Serna (2003) An overview of the activity of the Spanish surface longline fleet targeting swordfish (*Xiphias gladius)* during 2000, with special reference to the Atlantic Ocean. Col. Vol. Sci. Pap. ICCAT, 55(4): 1485-1494.

Nakamura, I. (1985) FAO species catalogue. Billfishes of the world. Annotated and illustrated catalogue of marlins, sailfishes, spearfishes and swordfishes known to date. FAO Fisheries Synopsis 125(V5), 65 pp.

Ovichinnikov, V. V. (1966) The effect of oceanographic conditions on distribution of the sailfish, *Istiophorus platypterus,* off the west African coast. Oceanogr., 6: 566–567.

Raventos, N. and E. Macpherson (2005) Environmental influences on temporal patterns of settlement in two littoral labrid fishes in the Mediterranean Sea. Estuar. Coast. Shelf Sci., 63: 479–487.

Santos, A. M. P., A. F. G. Fiúza and R. M. Laurs (2006) Influence of SST on catches of swordfish and tuna in the Portuguese domestic longline fishery. Int. J. Remote Sens., 27(15): 3131–3152.

Schaefer, K. M., D. W. Fuller and B. A. Block (2007) Movements, behavior, and habitat utilization of yellowfin tuna (*Thunnus albacares*) in the northeastern Pacific Ocean, ascertained through archival tag data. Mar. Biol., 152: 503–525.

Schick, R. S., J. Goldstein and M. E. Lutcavage (2004) Bluefin tuna (*Thunnus thynnus*) distribution in relation to sea surface temperature fronts in the Gulf of Maine (1994–96). Fish. Oceanogr., 13(4): 225–238.

Sun, X. (1987) Analysis of surface path of the Kuroshio in the East China Sea. In Essays on the Investigation of Kuroshio, Ocean Press, Beijing, 1–14.

Tang, T. Y., J. H. Tai and Y. J. Yang (2000) The flow pattern north of Taiwan and the migration of the Kuroshio. Cont. Shelf Res., 20: 349–371.

Teo, S. L. H., A. M. Boustany and B. A. Block (2007) Oceanographic preferences of Atlantic bluefin tuna, *Thunnus thynnus*, on their Gulf of Mexico breeding grounds. Mar. Biol., 152: 1105–1119.

Venables, W. N. and B. D. Ripley (2002) Modern applied statistics with S (fourth edition). Springer-Verlag New York. 495pp.

Venables, W. N. and C. M. Dichmont (2004) GLMs, GAMs and GLMMs: an overview of theory for applications in fisheries research. Fish. Res., 70: 319–337.

Walsh, W. A., R. Y. Ito, K. E. Kawamoto and M. McCracken (2005) Analysis of logbook accuracy for blue marlin (*Makaira nigricans*) in the Hawaii-based longline fishery with a generalized additive model and commercial scales data. Fish. Res., 75: 175–192.

Wang S., G. Morishima, R. Sharma, and L. Gilbertson (2009) The use of generalized additive models for forecasting the abundance of Queets River coho salmon. N. Am. J. Fish. Manage. 29: 423–433

William A. W., K. Pierre, and M. Marti (2002) Comparison of logbook reports of incidental blue shark catch rates by Hawaii-based longline vessels to fishery observer data by application of a generalized additive model. Fish. Res., 58: 79-94.

Zagaglia, C. R., J. A. Lorenzzetti and J. L. Stech (2004) Remote sensing data and longline catches of yellowfin tuna (*Thunnus albacares*) in the equatorial Atlantic. Fish. Res., 84: 233–246.

Zainuddin, M., H. Kiyofuji, K. Saitoh and S. I. Saitoh (2006) Using multi-sensor satellite remote sensing and catch data to detect ocean hot spots for albacore (*Thunnus alalunga*) in the northwestern North Pacific. Deep Sea Res. Part II, 53(3/4): 419–431.

西北太平洋海域海洋環境因子對雨傘旗魚時空分布之影響研究

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摘　要

本研究利用廣義加法模式 (GAM) 探討 1998 至 2004 年台灣小型鮪延繩釣雨傘旗魚 (sailfish) 的時空分布特性及其與海洋環境因子之相關性。其中，海洋環境因子包含衛星遙測海面水溫、海洋水色及海面高度等影像資料。利用廣義加法模式逐步分析結果顯示，影響雨傘旗魚棲息分布的最主要海洋環境因子是海面水溫，至於海洋水色及海面高度影響並不顯著。此外，雨傘旗魚的時空分布，也受時間變數中的年別及月別參數，及空間變數中的作業海域經度、緯度與作業水深等影響，並發現也與大尺度氣候變遷指標，如 PDO 及 SOI 等指數有相關性。其中，本研究結果發現雨傘旗魚主要漁期發生於每年 5 至 11 月份，其中 6 及 7 月份是主要盛漁期。另外，雨傘旗魚的主要漁獲海面水溫介於 28 ~ 30 °C，其中最高單位努力漁獲量則發生於海面水溫 29 °C 海域。此外，本研究利用廣義加法模式建立之雨傘旗魚單位努力漁獲量與海洋環境因子之關係式，推算結果也與名目單位努力漁獲量，呈現顯著高度相關 ($R^2 = 0.52$, $p<0.000$)。

關鍵詞：雨傘旗魚、單位努力漁獲量、海面水溫、海洋水色、廣義加法模式

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