Environmental effects on the spatial distribution of swordfish as inferred from data for the Taiwanese distant-water tuna longline fishery in the Pacific Ocean*

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Abstract

Fishery data of swordfish for the Taiwanese distant-water tuna longline fishery and the environmental variables including chlorophyll-a concentration, mixed layer depth, sea surface height, sea surface salinity, sea surface temperature and lunar phase in the Pacific Ocean were collected and analyzed in this study. Generalized additive models were used to model the relationships between environmental variables and catch-rates of swordfish. The effects considered, including the six oceanographic covariates, were all statistically significant in the GAMs, with a very large proportion of deviance explained by latitude. Swordfish CPUE was found to be decreasing with sea surface temperature, mixed layer depth and chlorophyll-a concentration. The nominal and predicted catch-rates showed similar spatial patterns and were high between latitudes 10°N–10°S in the central Pacific Ocean. The forecast ability for the area of high swordfish abundance was further illustrated through the analysis of potential hotspot areas. The results of the hotspot analysis in this study could form the basis for time-area management if there was a wish to reduce catches.

Keywords: spatial distribution, generalized additive model, hot spot analysis.

Introduction

Broadbill swordfish, *Xiphias gladius*, is a large pelagic species in the three oceans, occasionally found in coastal waters, and is widely distributed in the open ocean outside of polar areas. It is considered a highly migratory species, found in temperate or cold waters in summer and returning to warmer waters in fall (Damalas et al. 2007). As one of the larger predators of the oceans, swordfish can grow up to 450 cm fork length and 650 kg in weight.

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Swordfish catch rates were found to increase with latitude and peak at 35–40°N and increase in the vicinity of temperature fronts during the full moon (Bigelow et al. 1999). Several studies have showed that oceanographic effects as well as changes in ocean productivity on the inter-annual variability of swordfish abundance, which uses data derived from satellite remote sensors and commercial catch reports of pelagic fisheries (Seki et al. 2002).

The Taiwanese distant-water tuna longline fishery has operated in the Pacific Ocean since 1963 (Yeh and Sun, 2008). This fleet primarily targets albacore tuna in temperate waters, as well as bigeye and yellowfin tunas in tropical waters in the central Pacific Ocean. Swordfish, and other billfishes and sharks, are incidental catches of this fishery (Sun and Yeh, 1999).

CPUE (i.e. catch per unit of effort) of swordfish for the Taiwanese distant-water tuna longline fishery in the North Pacific Ocean was examined and analyzed Yeh and Sun (2008) for the period of 1995 to 2007, whereas Sun et al. (2009; 2014) developed the swordfish abundance trends using generalized linear models (GLMs) based on a two-stock structure scenario in the North Pacific Ocean, as suggested by Ichinokawa and Brodziak (2008).

The objectives of this study were 1) to examine the relationships between environmental factors and habitat preference of swordfish in the Pacific Ocean using fishery catch and effort data and multi-sensor satellite-based remotely sensed environmental variables, and 2) to identify the habitat characteristics of the areas of highest relative abundance for the Pacific swordfish, which could provide basic scientific information for management of this important marine resource.

Materials and methods

Fishery data

Task II data of the Taiwanese distant-water tuna longline fishery in the Pacific Ocean, including swordfish catch (in number of fish caught) and fishing effort (in number of hooks employed) for 2009-2015 at 5˚ spatial resolution were obtained from the Oversea Fisheries Development Council (OFDC) of Taiwan. This data set contains information on time (year and month) and location (latitude and longitude), but was aggregated by month and by 5˚ grid cell. Data for 2015 were used for model validation. The CPUE of swordfish is expressed as the number of fish caught per 1000 hooks for the longline fishery in this study.

Environmental data

The environmental variables used in this study as independent explanatory variables were chlorophyll-a concentration (CHL), mixed layer depth (MLD), sea surface height (SSH), sea surface salinity (SSS), sea surface temperature (SST) and lunar phase (Lunar). Environmental data were averaged to 5°×5° grids to match the scale of the fishery data, which were sourced from NOAA and NASA and summarized in Table 1.

Statistical model

Generalized additive models (GAMs; Hastie and Tibshirani 1990) are a standard and commonly used approach for modeling the relationships between environmental variables and catch-rates of swordfish (Bigelow et al. 1999). GAMs are extensions of generalized linear models (GLMs), which are often used to predict spatial distribution of species abundance because they deal well with nonlinear relationships between covariates and the response variable (Guisan et al. 2002).

An underlying assumption of a GAM is that functions of the predictors are additive and smooth, and can be non-linear. Year, month, latitude, longitude and six environmental covariates (CHL, MLD, SSH, SSS, SST and Lunar) were considered for inclusion in the model to analyze catch rate data, which can be written as:

SWO ~ Year + Month + Latitude + Longitude + CHL + MLD + SSH + SSS + SST + Lunar

where SWO is the nominal CPUE of swordfish, with a constant added;
Year is the factor for year;
Month is the factor for month;
Latitude and Longitude are the factors for geographic location; and
CHL, MLD, SSH, SSS, SST and Lunar are environmental effects.

Diagnostic plots (i.e., distribution of residuals and quantile-quantile (Q-Q) plot) were used to assess the assumed distribution of log-normal errors. The deviance analysis, the χ^2 test, and AIC (Akaike Information Criterion) values between models developed in stepwise were also used to examine the model fits.

Results and discussion

The main fishing grounds for Taiwanese tuna longline fishery are in temperate waters targeting albacore and in tropical areas targeting bigeye and yellowfin tunas based on the data for 2009-2015, with negligible spatial changes among the seasons (Fig. 1). However, most swordfish were caught in tropical waters of central Pacific Ocean for this fishery (Fig. 2), and accordingly high nominal CPUEs of swordfish occur in the equatorial Pacific Ocean without seasonal patterns (Fig. 3). The spatial distributions by season for oceanographic and environmental variables of CHL, MLD, SSH, SSS, SST and Lunar were showed in Figs. 4-8 as examples.

The assumption of log-normality was considered to be suitable to model the CPUE data of swordfish in the Pacific Ocean for the Taiwanese distant-water tuna longline fishery, as showed in the residual distribution and Q-Q plot as evidence (Fig. 9). There is no evidence for heteroscedacity from the plots of residuals against the values for each environmental covariate (Fig. 9). Therefore, the spatial habitat model for swordfish developed in this study was consequently based on the lognormal error distribution.

The effects considered in the GAMs, including year, season, geographic locations and their two-way interaction, as well as all the six oceanographic covariates, were all statistically significant based on the χ^2 test ($p < 0.05$) and the lower AIC values (Table 2). The deviance explained by the models that were used to model the swordfish CPUE data of the Taiwanese tuna longline fleets varied. It should be noted that a very large proportion of deviance was explained by latitude for the spatial distribution of swordfish, while only a small proportion of deviance was explained by oceanographic variables (Table 2).

Partial plots in log-space for latitude, longitude and environmental effects of sea surface height, sea surface salinity, mixed layer depth, sea surface temperature, chlorophyll-a concentration and lunar phase from the GAM developed for modeling swordfish CPUE data were showed in Fig. 10. Among the partial plots, swordfish CPUE or abundance was found to be decreasing with sea surface temperature (SST), mixed layer depth (MLD) and chlorophyll-a concentration (CHL), but opposite trends were showed for salinity (Fig. 10).

The distributions of nominal CPUE (averaged over 2009-2015) and the predicted catch rates of swordfish showed similar spatial patterns for all the four seasons (Fig. 11). The nominal and predicted catch-rates were high between latitudes 10°N–10°S in the central Pacific Ocean. The habitat model of swordfish was further validated by predicting the density distribution for the recent year of 2015 and overlapped with nominal CPUE data for the same year of 2015, which showed consistent results in spatial patterns without substantial seasonal variation (Fig. 12).

The forecast ability of the area for high swordfish abundance (fishing ground) was further illustrated through the analysis of potential hotspot areas (Fig. 13). Environmental effects have been demonstrated as primary variables to predict the spatial distribution of swordfish in this study. Fisheries management measures such as protected areas could be developed based on the spatial distribution predicted by the habitat model.

This kind of time-area closures has been shown to be a useful tool to reduce fishing mortality, especially for bycatch species, without significant impacts on catches of target species. The results of the hotspot analysis in this study could form the basis for time-area management if there was a wish to potentially reduce catches of the bycatch swordfish for the pelagic longline fisheries.

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Table 1. Summary of available fishery data and remote sensing oceanographic variables at spatial resolution of five degree in this study. DWLL: Taiwanese distant-water tuna longline fishery. CHL: chlorophyll concentration; MLD: mixed layer depth; SSH: sea surface height; SSS: sea surface salinity; SST: sea surface temperature; Lunar: lunar phase.

Parameter	Description	Unit
Fishery data	2009-2015	
Taiwanese DWLL	Taiwanese distant-water longline fishery	
Remote sensing data	2009-2015	
CHL	Sea surface chlorophyll-a concentration	mg/m^3
MLD	Ocean mixed layer thickness	meter
SSH	Sea surface elevation	meter
SSS	Sea surface salinity	psu
SST	Potential temperature	°C
Lunar	lunar phase [Hawaii-Aleutian standard time]	

Table 2. Deviance table for the model selected to analyze monthly fishery and remote sensing oceanographic data at five degree spatial resolution for swordfish caught in the Taiwanese distant-water tuna longline fishery in the Pacific Ocean.

Predictor	Residual D.F.	Residual Dev.	Deviance	P-value	R^2	AIC
NULL	5854	7024				17686
+Year	5849	6931	93	<0.001	0.013	17617
+Month	5838	6853	78	<0.001	0.024	17573
+Latitude	5834	5199	1654	<0.001	0.260	15964
+Longitude	5830	4940	259	<0.001	0.297	15672
+Longitude:Latitude	5819	4543	397	<0.001	0.353	15204
+MLD	5815	4530	13	0.002	0.355	15195
+SST	5813	4520	10	0.003	0.356	15188
+CHL	5811	4516	4	0.031	0.357	15185
+SSS	5807	4490	26	<0.001	0.361	15159
+SSH	5803	4466	25	<0.001	0.364	15136
+Lunar	5799	4458	7	0.038	0.365	15133

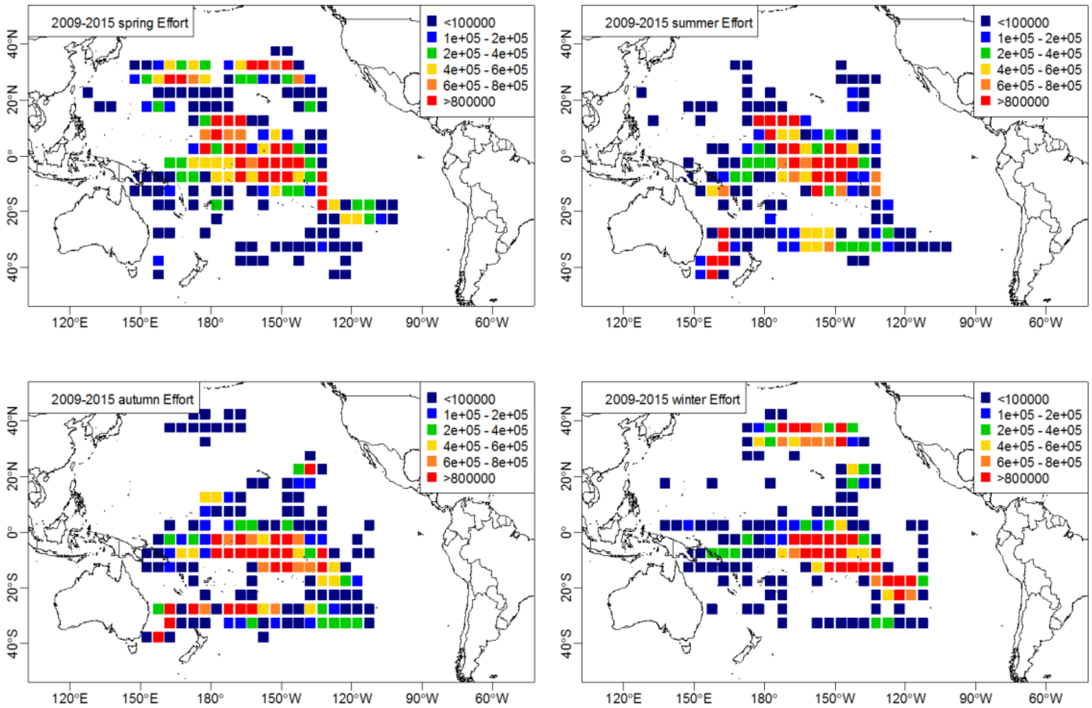

Fig. 1. Distributions of fishing effort in hooks for the Taiwanese distant-water tuna longline fishery in the Pacific Ocean for 2009-2015 by season.

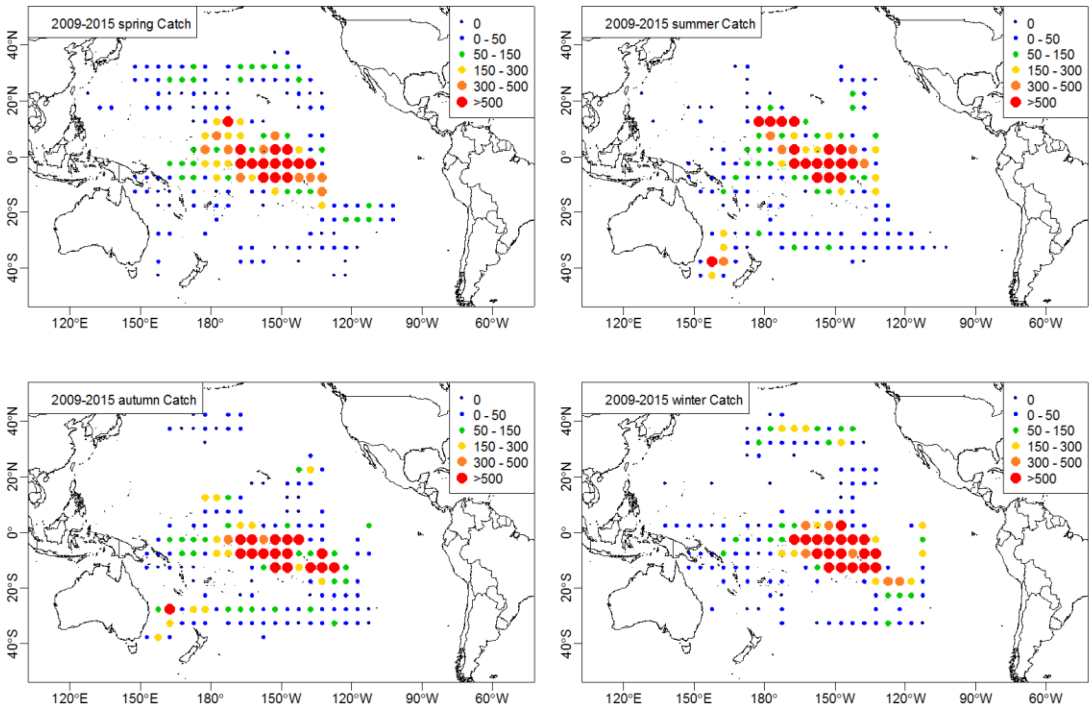

Fig. 2. Distributions of swordfish catch (in number) in the Taiwanese distant-water tuna longline fishery in the Pacific Ocean for 2009-2015 by season.

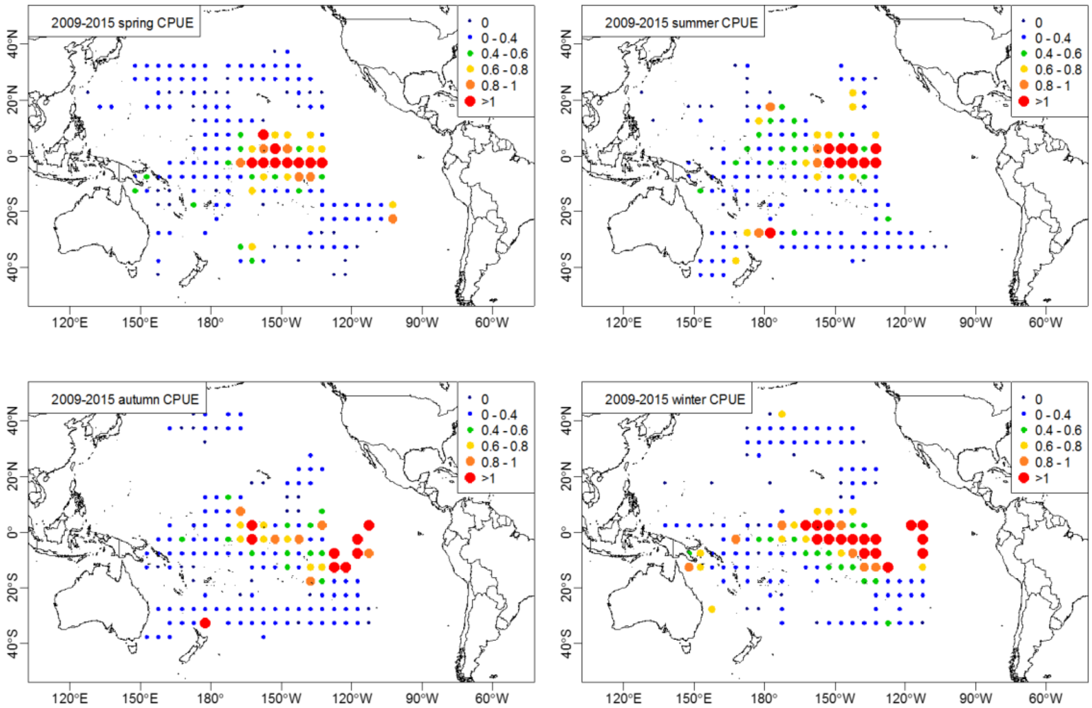

Fig. 3. Distributions of nominal CPUE for swordfish caught in the Taiwanese distant-water tuna longline fishery in the Pacific Ocean for 2009-2015 by season.

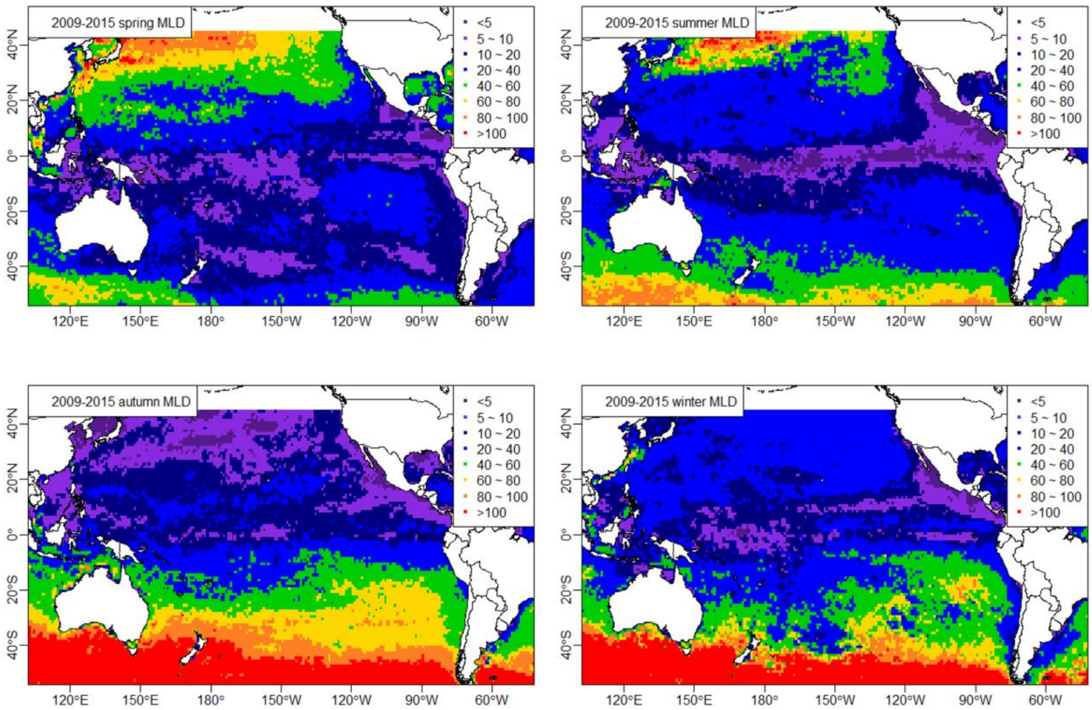

Fig. 4. Distributions of mixed layer depth (MLD) in the Pacific Ocean based on remote sensing data for 2009-2015 by season.

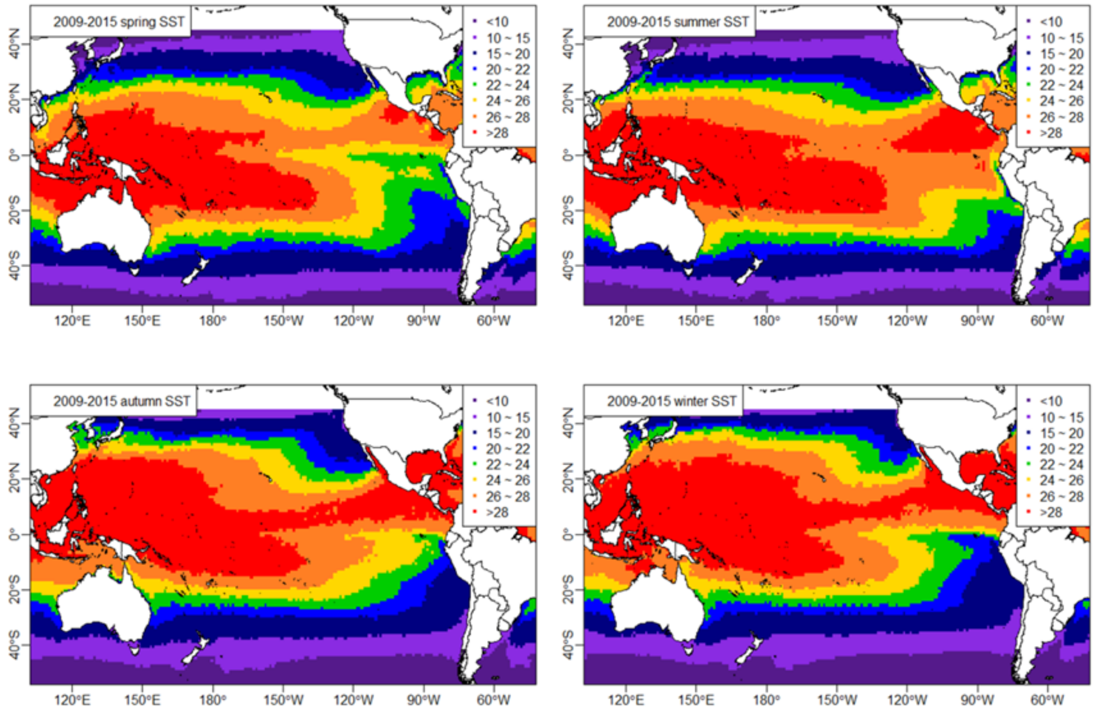

Fig. 5. Distributions of sea surface temperature (SST) in the Pacific Ocean based on remote sensing data for 2009-2015 by season.

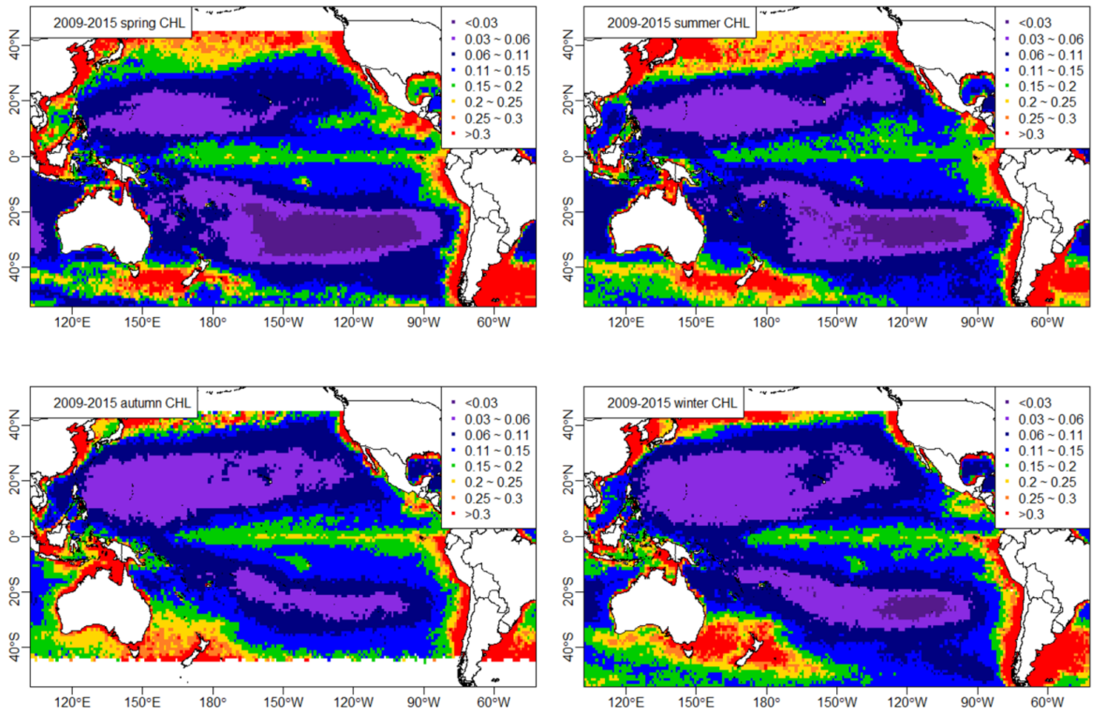

Fig. 6. Distributions of chlorophyll-a concentration (CHL) in the Pacific Ocean based on remote sensing data for 2009-2015 by season.

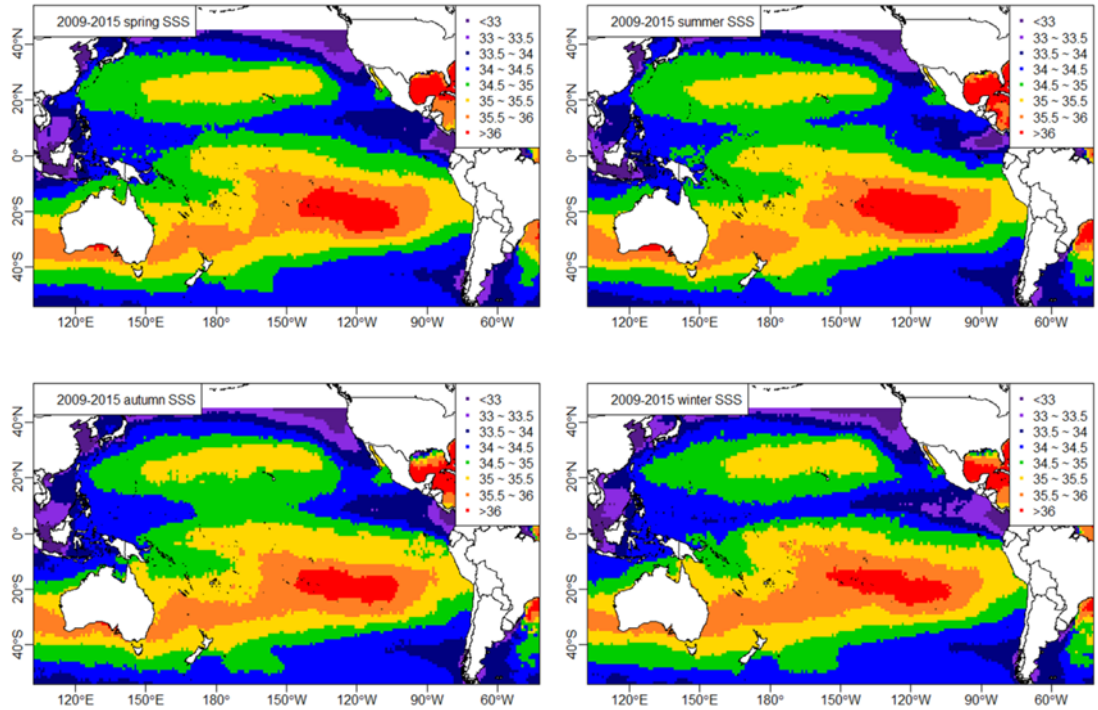

Fig. 7. Distributions of sea surface salinity (SSS) in the Pacific Ocean based on remote sensing data for 2009-2015 by season.

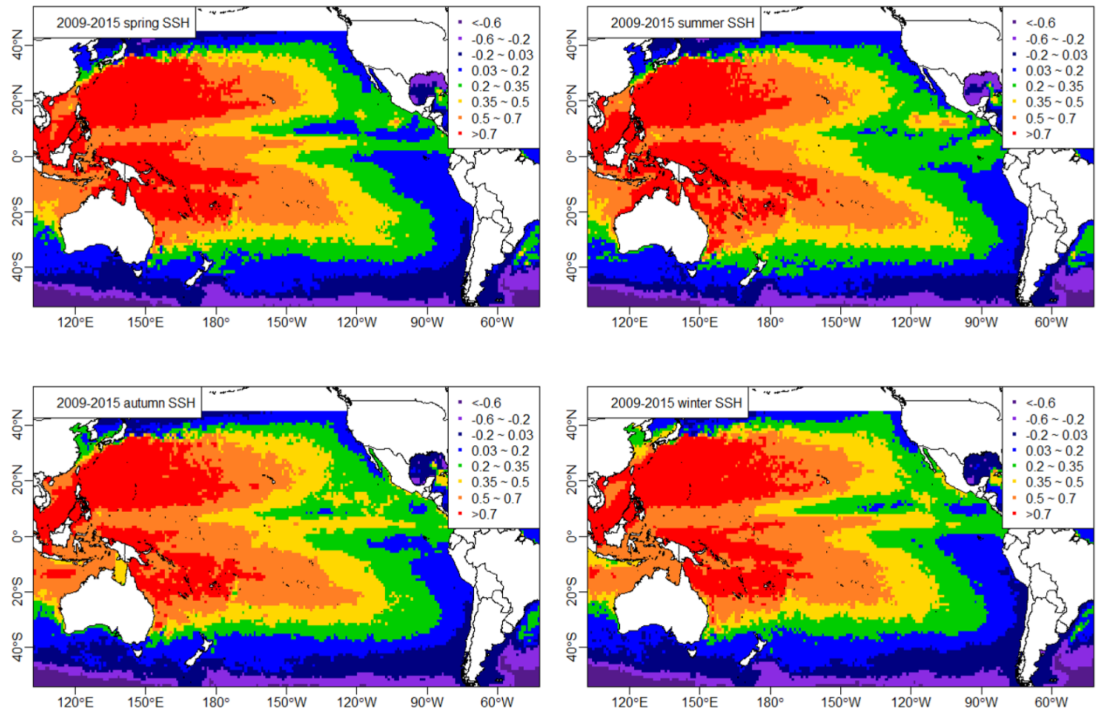

Fig. 8. Distributions of sea surface height (SSH) in the Pacific Ocean based on remote sensing data for 2009-2015 by season.

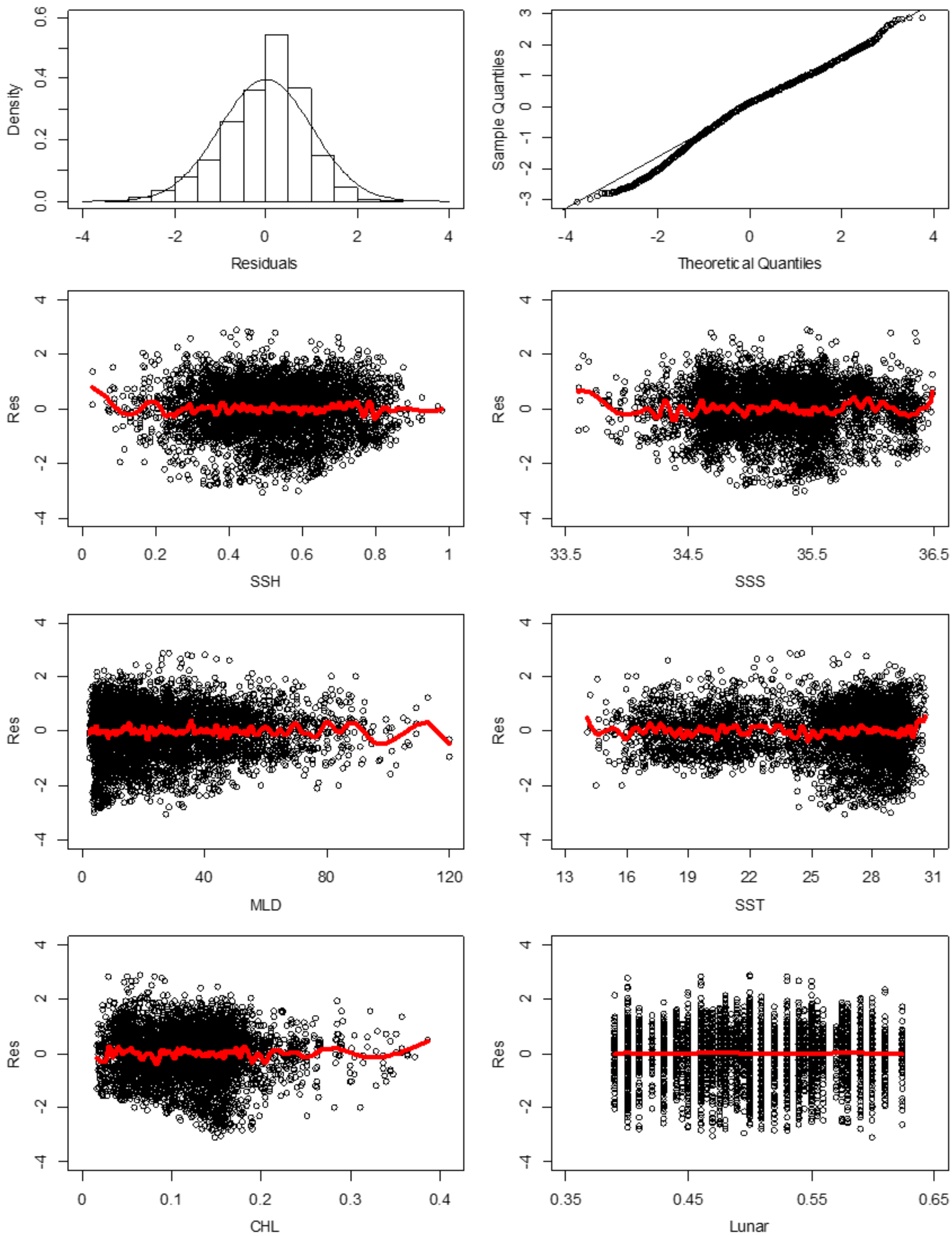

Fig. 9. Diagnostic analysis (residual distributions and Q-Q plots) for the GAM model selected to model the swordfish CPUE for the Taiwanese distant-water tuna longline fishery in the Pacific Ocean.

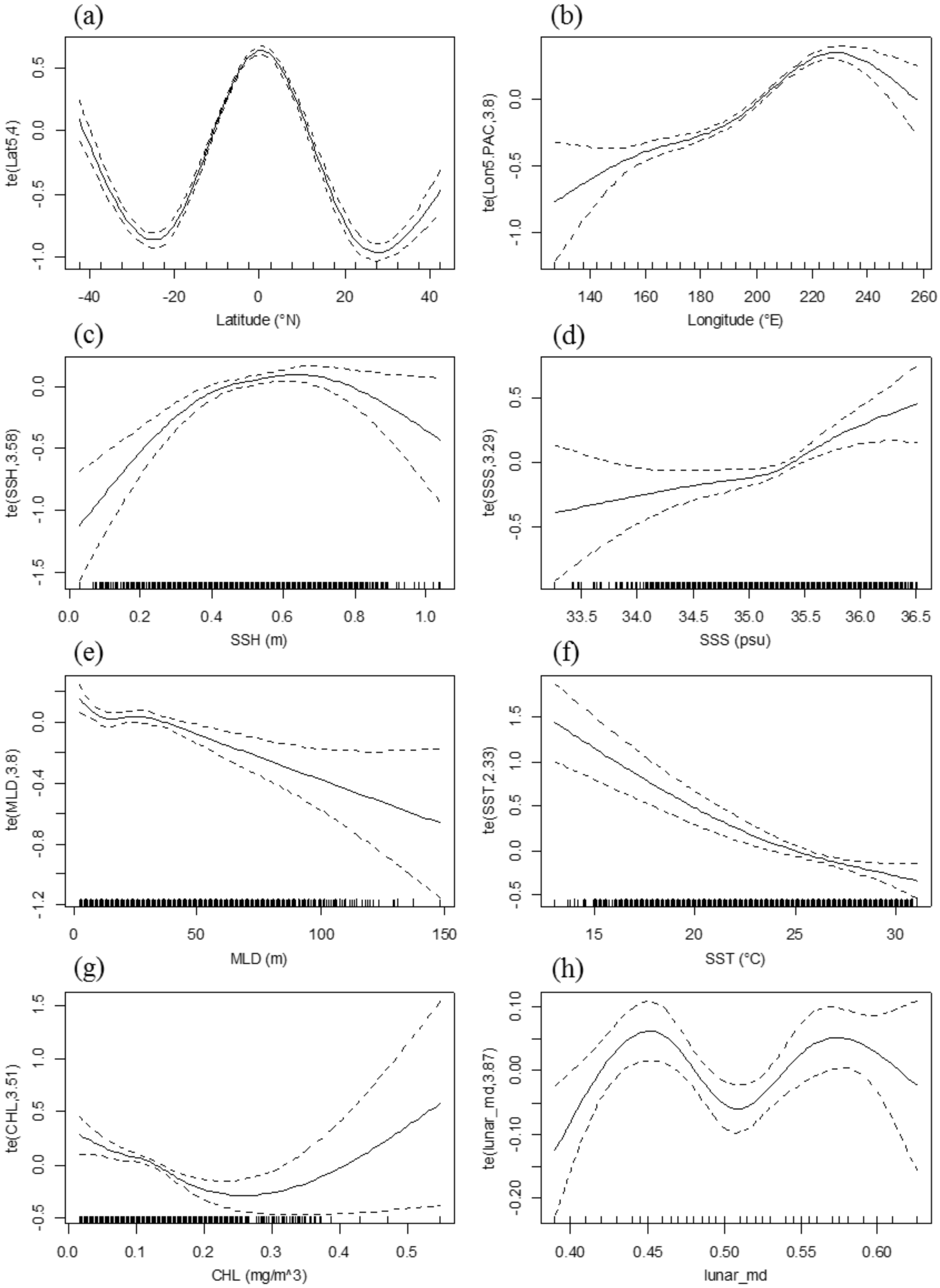

Fig. 10. Partial plots in log-space for (a) latitude, (b) longitude, (c) sea surface height, (d) sea surface salinity, (e) mixed layer depth, (f) sea surface temperature, (g) chlorophyll-a concentration and (h) lunar phase from the GAM developed to model swordfish CPUE for the Taiwanese longline fleet in the Pacific Ocean.

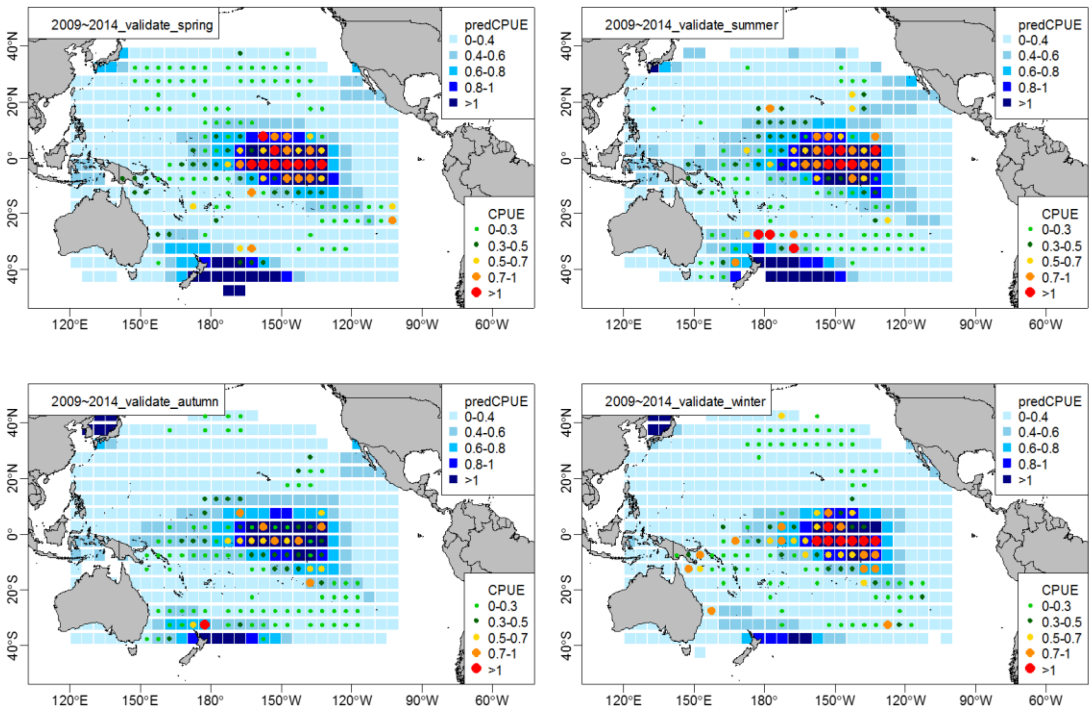

Fig. 11. Distributions of nominal CPUE (solid circles) and predicted values (squares) based on GAM averaged over 2009-2014 for swordfish in the Pacific Ocean.

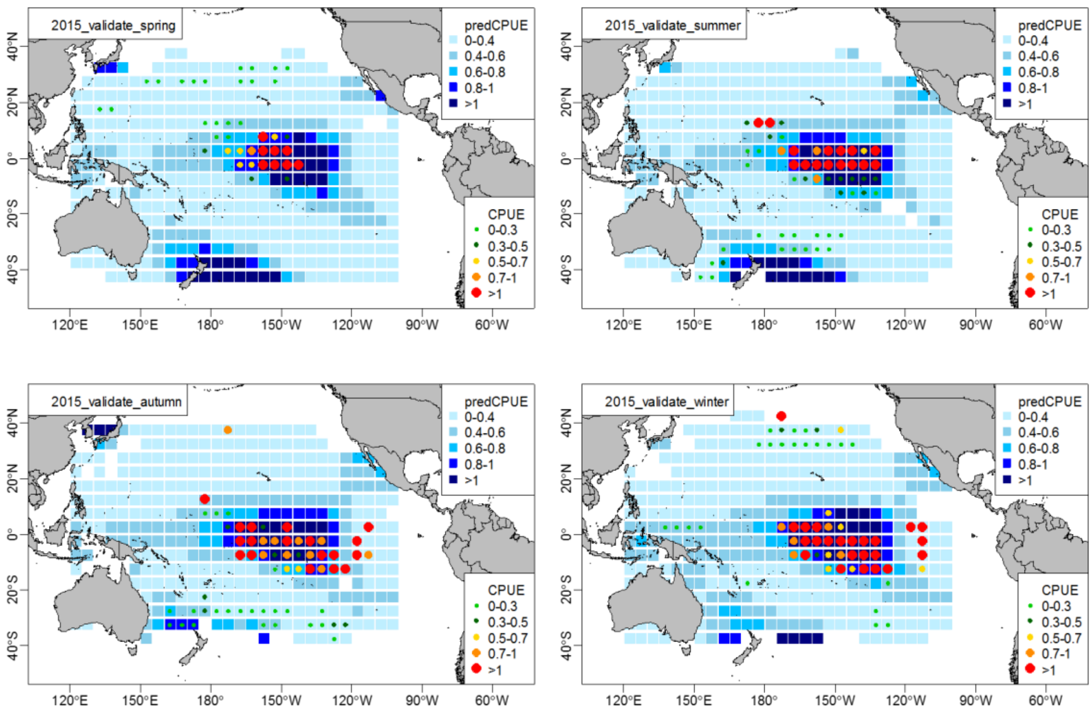

Fig. 12. Distributions of nominal CPUE (solid circles) and predicted values (squares) based on GAM averaged over 2015 for swordfish in the Pacific Ocean.

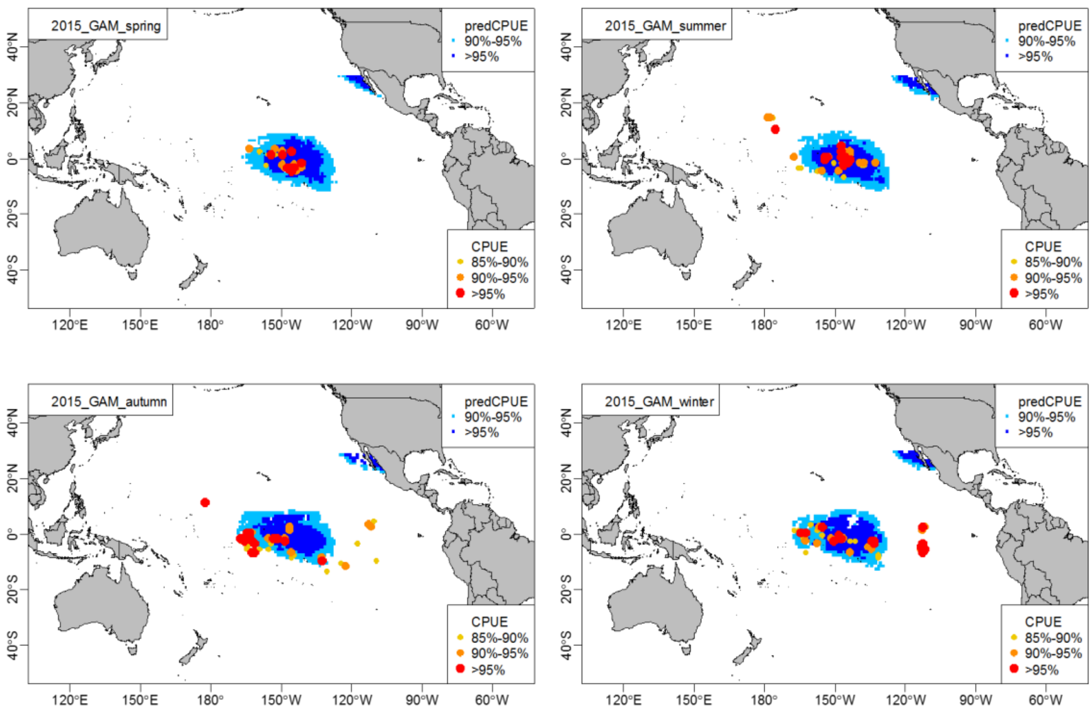

Fig. 13. Hot spot analysis for higher nominal CPUE and predicted values from the GAM for swordfish in the Pacific Ocean for 2015.