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Distribution, body length and abundance of blue shark and shortfin mako in the Northwestern Pacific Ocean based on longline research vessels from 2000 to 2014[1]

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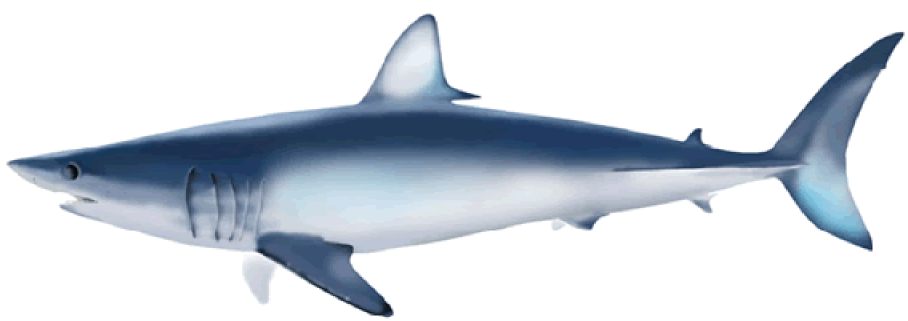

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Abstract

National Research Institute of Far Seas Fisheries has been conducting longline surveys since 2000 using charterd commercial longline vessels in the Northwestern Pacific Ocean. In each year, two cruises conducted in around offshore area of the northeast of Japan in the season from the mid April to the mid June. Each cruise is designed to collect data related to bycatch species such as seabird, sea turtle and sharks, especially tests of effectiveness of variouse seabird mitigation measuers have been its most important objectives. In each longoline set of the survey, on-board scientists collects detailed biological information of species caught such as size and sex.

This study summarize the information of blue shark (*Prionace glauca*) and shortfin mako(*Isurus oxyrinchus*) obtained by the survery cruises conducted in the period between 2000 and 2014. Both shark have eurythermous distribution, and the data indicated that the sea surface temperature of positive catch sites of shortfin mako was warmer than blue shark. The level of nominal catch rate of blue shark were more than 10 times larger than shortfin mako. The standardized catch per unit effort (CPUE) of the both species was calculated using generalized linear model (GLM) with negative binomial errors or delta-lognormal GLM. The standardized CPUE of blue shark peaked in the mid of 2000s, decreased and increased since 2012, and the values of shortfin mako have increased with fluctuations.

Introduction

The subarctic-subtropical transition zone (TZ), which is one of the main oceanic features of the North Pacific (Roden, 1991), provides important habitat for many epipelagic nekton species such as tuna and shark and squid which are highly migratory between subtropical areas and subarctic areas (Mishima, 1981; Kubodera et al., 1983; Pearcy 1991). The blue shark is one of the most wide-ranging of all sharks, being found throughout tropical and temperate seas from about 60˚N to 50˚S latitude (Nakano and Stevens, 2008), and the diets of the species are small pelagic fish, cephalopod, small sharks, cetaceans and seabirds (Campagno, 1984; Clarke et al. 1996; Henderson et al. 2001). The shortfin mako is found throughout temperate and tropical wateres of all oceans from about 50˚N to 50˚S (Campagno, 2001), and the diets of shortfin mako are mainly teleost fish and cephalopods (Stillwell and Kohler, 1982; Stevns, 1984) and elasmobranch fishes (Cliff et al. 1990). As methioned above, oceanic sharks are top predator and play a important roles in the open ocean ecosystem.

Demand to assess the stock status of sharks are increased rapidly in the recent years, but shortage of thier fishery and research data hampered to obtain accurate and precise estimates of thier stock status. This is mainly due to the fact that many of them discarded without recording as due to their relatively lower market values than tunas and billfishes. To overcome this, standardized CPUE of blue shark caught by Japanese longliners is estimated using data processed by the filtering method (Nakano and Clark 2006; Kai et al. 2014). The filtered data was verified through the comparison with longline survey data conducted in the same area and time. (Takahashi et al., 2012), to follow the recommendation of ISC Shark WG that the catch and effort data of sharks caught by commercial vessels needed to be verified using fishery-independent data such as observer and survey ones (ISC, 2012). In the present study, distribution, body sizes and catch rates of blue shark and shortfin mako collected by the longline survery conducted from 2000 and 2014 were analyzed. The surveys were conducted by National Research Institute of Far Seas Fisheries to collect data related to bycatch species such as seabird, sea turtle and sharks, especially tests of effectiveness of variouse seabird mitigation measuers have been its most important objectives, and the estimation of distribution and abundance of sharks in offshore are of northeast Japan have been its secondary objective. (Minami et al., 2006; Sato et al., 2010; Sato et al., 2012). This study outlined the blue shark and shortfin mako shark data obtained by this survey for the benefit of the assessment activities of stocks of both species in the North Pacific. In each year, total from 14 to 55 sets (960 hooks per set) are deployed in the season from the mid April to the mid June, and they widely covers the Kuroshio – Oyashio regression zone from 140 degree East to 160 degree East where commercial longline boats actively caught blue and shortfim mako sharks. The operational style of the survey is design to comparable to those of Japanese offshore surface longliners targeting swordfish and blue shark (Kai et al. 2014)(traditional style of night shallow longline). Because Japanese offshore surface longliners frequently catch shortfin mako shark, the data obtained by this survey expected to represent the dynamics of population of blue and shortfin mako sharks in the offshore area of the northeast Japan.

Materials and Methods

Vessels, sampling gear, survey area and periods

Two Japanese commercial longline fishing vessels (Kurosaki and Taikei-maru No. 2, vessel size is 196 tons for both), were chartered to conduct researches for bycatch species like seabirds, sea turtles as well as sharks (Sato et al., 2010; Satio et al., 2012; Yokota et.al., 2006; Minami et al., 2006). So far in every year, most of cruise days assigned to the experiments of seabird mitigation measures, longline sets fro the stay on other topics such as sea turtle mitigation measure and shark tagging are aslo conducted depend on year. and the detailed contents of research partially changed annually (Fig. 1). Because this research planed to benefit sound operation of Japanese offshore surface longliners, same night shallow sets (4 hooks per basket, Fig. 5) was adopted in the survey, and total of 960 hooks were deployed before sun set (2 - 4 PM) and retrived before sunrise (2 -5 AM). In some year, Combinations of circle and J-type hooks were used in some years. Yokota et al. (2006) concluded that no significant differences of catch rate for blue shark between circle and J-type hook was observed. Therefore, hook type was not incorporated to the GLM model in the present study. The bait of this survey was mainly mackerel (*Scomber* spp.).

In each longline sets, detailed fishing conditions, eg. , time and position of gear setting and retrieving, weather, sea surface temperature, were recorded. In each year, longline sets of two cruises widely covered Kuroshio - Oyashio transition zone in the offshore area of the northeast Japan (25 ˚N to 40 ˚N and 140 ˚E to 150 ˚E) where Japanese offshore surface longliners actively catches blue shark and bycatch of shortfin mako frequently occurred (Fig. 2). Operation sites in 2012 were wider (longitude > 150˚E) than the other years, but we did not use those offshore data in the present study. Operation sites were located in the North Western Pacific Ocean, mainly off northeast area of Japan (Fig. 2), The annual survey was composed of two cruises of approximately 30 days ship time in April - May and May - June respectively (Fig.3). In some years, such as 2011 when the great East Japan earthquake occurred, season of survey changed and number of sets decreased due to problem of charted longline boats, and data of these years were eliminated from the analysis (Fig.3). Data in 2001 and 2011 were deleted from analysis as survey conducted in different area or different season from ones in usual year. Depth recorders (Murayama electric comp., SBT-500) were attached to the base of hook line of the selected branch lines of longline to measure set depth of shallower and deeper hooks.

Measurement of fishes

All hooked sharks were identified to species and the numbers were recorded by onboard researchers, and the body length (precaudal length) was measured to its nearest centimeter. Their sexes were identified though the macroscopic observation of its reproductive organ. When quite large number of blue sharks were caught at single sets (approximately larger than 50 individuals), collection of biological information was limited to first 30 or 40 individuals, but body sizes by species and sex were measured as much as possible.

Model descriptions

A GAM (generalized additive model) approach used to predict binary (presence/absence) of two elasmobranches in the Pacific Ocean (Zuur et al., 2009). We analyzed the presence of shark (blue shark or shortfin mako), and assumed that $Yi \sim B(1,\pi i)$, $var(Yi) = \pi i * (1-\pi i)$ and

$$\text{logit}(\pi i) \sim \alpha + \text{factor(year)} + \text{factor(month)} + \text{factor(lat)} + s(sst)$$

where α is coefficient, lat and *sst* are latitude and the sea surface temperature, respectively. The sea surface temperature was used from satellite data (AVHRR; advanced very high resolution radiometer) at the positions on setting longline. The models were fit using the "mgcv" package in the R version 3.03 environment (R-core team, 2013.Functions s in a thin plate regression spline fit to a given environmental parameter. Un-biased risk estimator (UBRE) and *p*-value was checked. UBRE is essentially scaled AIC, and is used by the cross-validation process to find the optimal amount of smoothing (Zuur, 2012).

Two GLM (generalized linear model) approaches used to predict catch rates shortfin mako, one was negative binomial GLM and the other was delta-lognormal GLM because the 0 catch rates of shortfin mako were around 50% through survey years. In addition, those results were compared with nominal CPUE (number / 1000 hooks). The standardization of blue shark was used negative binomial GLM. The negative binomial models of two sharks were using the "MASS" package in the R following the equation:

$$\text{catch} \sim \text{factor(year)} + \text{factor(area)} + \text{factor(month)} + \text{lat}*\text{sst} + \text{offset(hooks)} + NB$$

where, catch: expected catch in number, hooks: number of hooks, *NB*: negative binomial error distribution with log link function.

The binomial part in delta model was as follows;

$$r_y \sim \text{Bin}(1, p_y)$$

$$\log(p/1-p) = \text{factor(year)} + \text{sst} + \alpha,$$

where r_y is response variable on presence (=1) or absence (=0) of a catch, and p represents probability of the presence of a catch at stratum of year and sst, α is coefficient. The lognormal model part was as follows;

$$\text{lcpue} \sim N(\mu, \sigma^2)$$

$$\mu = \text{factor(year)} + \text{factor(month)} + \text{lat} + \text{sst},$$

where lcpue and lat represents log transformed CPUE (number/hooks), and latitude at setting longline, respectively.

Results

Mean depth of the shallowest and deepest branch line were 47.6±14.2 m (mean± standard deviation) and 76.2±19.3 m, respectively. Fish species caught by longline operation in each year were shown in Table 1, and the most abundant species was blue shark (79.1%; fraction by number). Shortfin mako sharks was third adundant species (2.3 %) and cagut all year analyzed. Salmon shark was also frequently caught (2.2 %) but were l no catch obtained in 2004 and 2005. Billfishes, such as striped marlin (0.7 %) and swordfish (1.3 %) were fewer than above three sharks. Among other species written above, Pelagic stingray (0.8 %), dolphinfish (2.5 %) and lancefish (8.1 %) were often caught. Some of sharks were live-released after the measurements immediately and the fraction of live release of shortfin mako and blue shark through the survey periods was 56% and 90%, respectively.

The range of precaudal length of blue shark and shortfin mako was 39 to 320 cm, 60 to 300 cm, respectively (Fig. 4). Body length of blue shark decreased with increasing the latitude (Fig. 5), and male of blue shark in the southern part of the survey area (< 30 ˚N) was larger than female. Body length of shortfin mako does not show apparent latitudinal trend in both sex and most of them were smaller than 150 cm (Fig. 5).

Blue sharks distributed in the most wide range in terms of sea surface temperature and caught almost all operational points (Fig. 6). Shortfin mako also have eurythermal distribution (Fig. 6), but likely to prefer the warmer waters (> 18 ˚C) then blue shark. The negative cites (Fig. 6 gray points) of shortfin mako were larger than blue shark though the shortfin mako also observed anywhere in the survey area.

The shapes of the functional forms for selected variate (SST) was illustrated in Figure 7. These indicate that the two species displayed non-linear responses to the variate. For instance, the spline function of the variate of blue shark was almost positive. However, the spline function of the SST of shortfin mako was negative over 18˚C.

The yearly trend of nominal and standardized CPUEs of two species were calculated (Fig. 8). The mean CPUE of blue shark (49.46 / 1000 hooks) were higher than shortfin mako (1.50 / 1000 hooks). The nominal and standardized CPUE of blue shark increased until the mid of 2000s, decreased in between 2009 and 2012 and increased in most recet two years (Fig. 8). The nominal and standardized CPUEs of shortfin mako have fluctuated until 2012 and apprently increased in most recent two years..

Discussion

Fishery independent data from appropriately designed surveys are prefered over fishery-dependent data because they do not have many of the biases associated with data from commercial or recreational fisheres due to change fish gear, methods and targeting practices over time (Simpfendorfer et al., 2002). The chartered surveys have been constantly conducted since 2000 in the same season, area, fishing gear and operational style, except in 2001 and 2011. The survey periods were from April to June, and gear and operation of fishing were almost same. In addition, the fishing methods, such as setting time, end time and hpb, were not changed. The survey areas were part of main fishing grounds of blue shark, shortfin mako and salmon shark in the North Pacific Ocean where Japanese offshore surface longline fleet actively targeting swordfish and blue shark (Kai et al. 2014). Every year more than 36 longline sets in average were conducted (Table 1) which widely covered Kuroshio - Oyashio transsition zone in the offshore are of the northeast Japan where Japanese offshore surface longliners caguht large number of blue and shortfin mako sharks. In this surveys, all catches were precisely recorded by on-board scientists and sexed size data of blue and shortfin mako sharks. Considering these facts written above, survey data analyzed in this study believed to posess high quality and enoguh quantitiy information to reveal dynamitc of population of blue and shortfin mako sharks distributed in survey area. As mentioned above, the surveys in the present study was available for estimating the distribution, habitat select and calculating the relative biomass, such as standardized CPUE for sharks.

Turn to biological and ecological characteristics of two species, blue shark and shortfin mako were measured on board, and size distributions were shown in Fig. 4. When length frequency of blue and shortfin mako sharks obtained by this survery were compared with the reproted growth parameter of the north Pacific blue shark (Nakano, 1994) and shortfin mako (Semba et al., 2009; Wells et al., 2013), both two species were caught by the survey from young of year class to young adults. The length frequency of shortfin mako has one notable mode peaked at around 70 cm, which supposed to be that of recruitment.

This indicates that the survey area is overlapping with the main distribution area of thier juvenile, semi-adult and young-adult sharks in offshore area of the northeast Japan. Body length of blue shark in the northern area was smaller than southern area. Nakano (1994) and Nakano and Stevens (2008) reported that distributon of blue shark was segregated by sex and size, and juvenile of blue shark distributted in the northern area in the North Pacific Ocean. As for shortfin mako, no clear releationship between body length and latitude was observed. The ontogenetic shift of distribution of shortfin mako from waters off Japan (<100 cm) to western or southern area was suggested to occur; (≥100 cm) through the analysis of port sampling size data of shortfin mako caught by Japanese offshore surface longliners (Shiozaki et al., 2013). They also reported that the strong evidence on the sexual difference in the distribution pattern and environmental preference was not found in the subtropical area in the northwest and the north central Pacific. The results of the present study support this observation by Shiozaki et al (2013). In the north Pacific, another pupping ground of shortfin mako was suggested to be in the northeastern area (Wells et al. 2013). The relationship of these two pupping ground could be investigated through the north Pacific wide study of fishery data such as size and CPUE analysis. Conclusion of previous and our study was almost same, but it should be conducted the corporative surveys in the eastern side of the North Pacific Ocean.

Distribution pattern of blue shark and shortfin mako was revealed to be partially different in terms of their water temperature preference, and shortfin mako was suggested to habitat in somewhat warmer area than blue shark (Fig. 7). In the survey area, there are mainly two water masses, one was Kuroshio warm current area and the other was Oyashio cold current. Transition zone (Roden 1991) produced by the interaction of Kuroshio Current and Oyashio Current introduce the remarkable oceanographic fronts bounding the transition zone at approximately 32˚N as called "subtropical front" (Zainnuddin et al. 2008). The longline survey which data analyzed in this study covers the western part of the transition zone. According to Nakano (1994), parturition of blue shark occurs in early summer on the nursery ground located 30 ˚N to 40˚N., The results of this study shows that small and middle sized shortfin mako including young or year class widely distribute in the western part of the transition zone. Thus this area considered to have important role for the ecology of stocks of blue and shortfin mako sharks in the north Pacific. Spatiotemporal change of structure and environmental condition of the transition zone can be accounted into the population dynamic studies of these two stocks for the better understanding of their stock status as well as growth and migration mechanisms. Further investigation about relationship among habitat and migration of these two stocks and environmental condition of the transition zone should be accounted for their population dynamic study.

The level of calculated standardized CPUE of blue shark was roughly 30 times higher than shortfin mako. The standardized CPUE of blue shark peaked in the mid 2000s, decreased until 2012, and it turned into rapid increasing trend. Standarized CPUE of shortfin mako shows general increasing trend in the period analyzed except for 2012 when it decreased sharply. Same as blue shark, it shows rapid increasing trend in most recent two years. Observed apparent increasing trend in most recent years could be due to the drastic decrease of fishing pressure in these peroid. Due to the Great East Japan Earthquake, Japanese offshore surface longline fleet, which is one of major longline fleet in the subtropical north Pacific, largely reduced their activity.

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Table 1 Species list and catch Number of fish by species caught by longline survey and number of sets deployed in each year (April, May and June only)

Species	Latin name	2000	2002	2003	2004	2005	2006	2007	2008	2009	2010	2012	2013	2014	Total
Devilray	*Mobula japonica*									2					2
Pelagic stingray	*Pteroplatytrygon violacea*	1	22	16	43	11	11	52	6	24	25		1	2	214
Unknown Rays				2	3				4	1	1	1			12
Blue shark	*Prionace glauca*	896	478	1261	1365	1728	2708	2728	2595	1543	2125	1355	2409	3174	24,365
Shortfin mako	*Isurus oxyrinchus*	12	25	39	55	16	34	63	82	74	47	30	49	124	650
Salmon shark	*Lamna ditropis*	4	1	8			38	93	104	59	62	78	166	59	672
Tiger shark	*Galeocerdo cuvier*				1			1							2
Silky shark	*Carcharhinus falciformis*			1	1	2		1			1				6
Smooth hammerhead	*Sphyrna zygaena*					1									1
Cookie-cutter shark	*Isistius brasiliensis*				1										1
Longfin mako	*Isurus paucus*				1	2	2	2	1	1					9
Bigeye thresher	*Alopias superciliosus*	6	1	7	13	2	2	54	4	7	8	1	4	3	112
Great hammerhead	*Sphyrna mokarran*				1										1
	Zameus squamulosus	1	2								1	4	6		14
Common thresher	*Alopias vulpinus*			3	2	2									7
Oceanic whitetip shark	*Carcharhinus longimanus*				1	1					1				3
Scalloped hammerhead	*Sphyrna lewini*				1										1
Unknown Sharks			4	4	4		1	6		2	1	1			23
Skipjack tuna	*Katsuwonus pelamis*			1			4	1							6
Yellowfin tuna	*Thunnus albacares*		7	9			7	4		2	1				30
Blue marlin	*Makaira mazara*						1	3	1	1	2	1	1	1	11
Bluefin tuna	*Thunnus orientalis*		1	1	3	2	2	1	5				1	3	16
Dolphinfish	*Coryphaena hippurus*		18	54	269	72	122	36	40	30	16	15	19		691
Sailfish	*Istiophorus platypterus*			1											1
Albacore	*Thunnus alalunga*		9	6		17	15	10	12	4	4	4			81
Spearfish	*Tetrapturus angustirostris*				2		1	1							4
Striped marlin	*Kajikia audax*		12	31	14	12	40	26	1	10	26	3	16	4	195
Sunfish	*Mola mola*		1	1	1	2	2			2	1	1	1	2	14
Lancefish	*Alepisaurus ferox*	9	189	167	150	85	194	236	212	218	307	135	191	166	2,259
Swordfish	*Xiphias gladius*		18	41	60	30	40	75	22	21	20	5	10	6	348
Bigeye tuna	*Thunnus obesus*		57	64	9	11	92	66	5	5	3		1	1	314
Sharptail mola	*Masturus lanceolatus*						1				1				2
Opah	*Lampris guttatus*		5	1	1		1	6	26	2	5	4	8	4	63
Total		929	850	1,718	2,001	1,996	3,318	3,465	3,120	2,008	2,658	1,638	2,883	3,549	30,130
Total operation number		31	14	31	29	31	54	55	45	44	41	36	35	30	476
Total hooks number		23,146	13,268	28,580	28,242	28,228	50,751	51,536	43,200	42,240	38,992	34,560	33,600	27,692	444,035

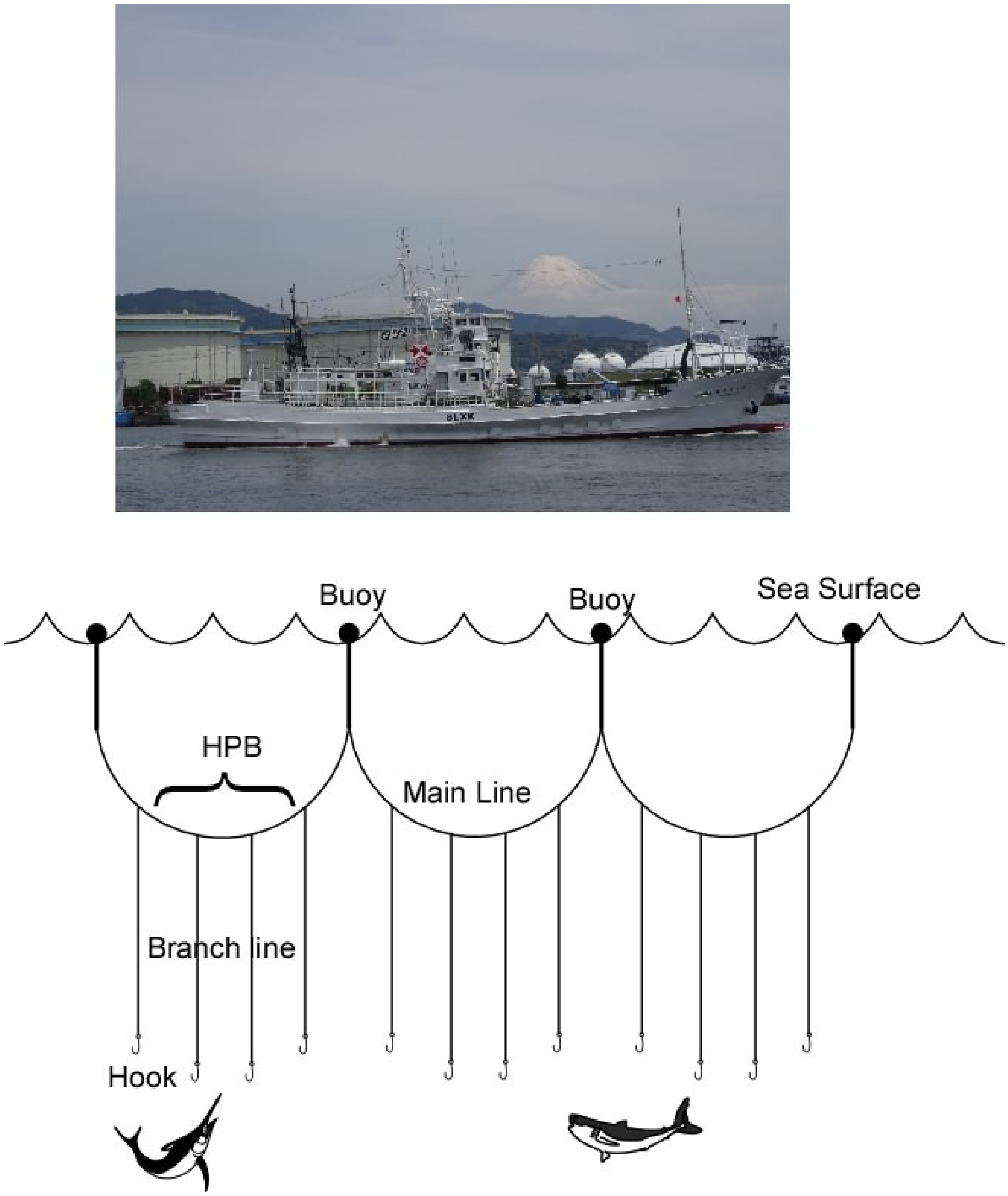


Fig. 1 Photograph of longline vessel (Dai2-Taikei), and typical draw of longline fishing.

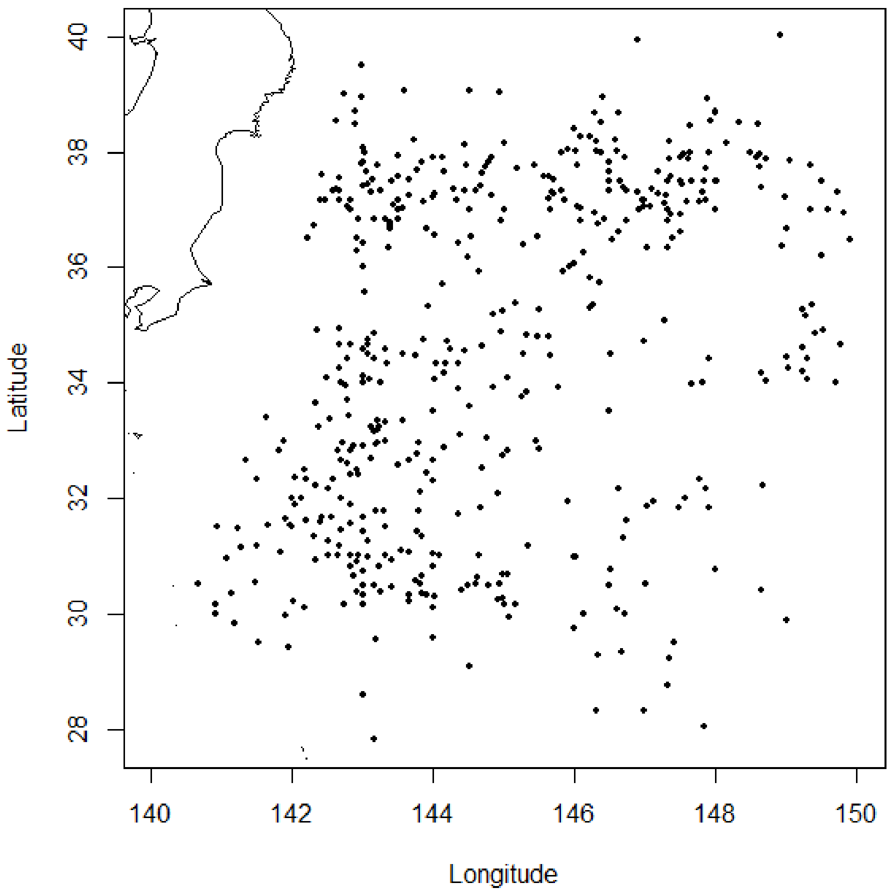


Fig. 2 Operation sites in this surveys.

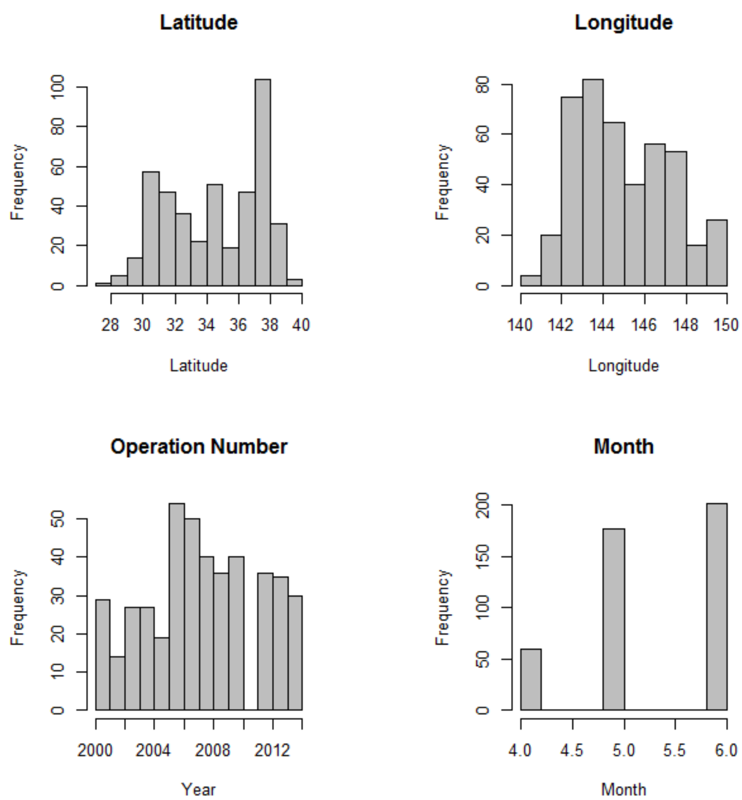


Fig. 3 Operation conditions of latitude (upper left), longitude (upper right), year (lower left) and month (lower right).

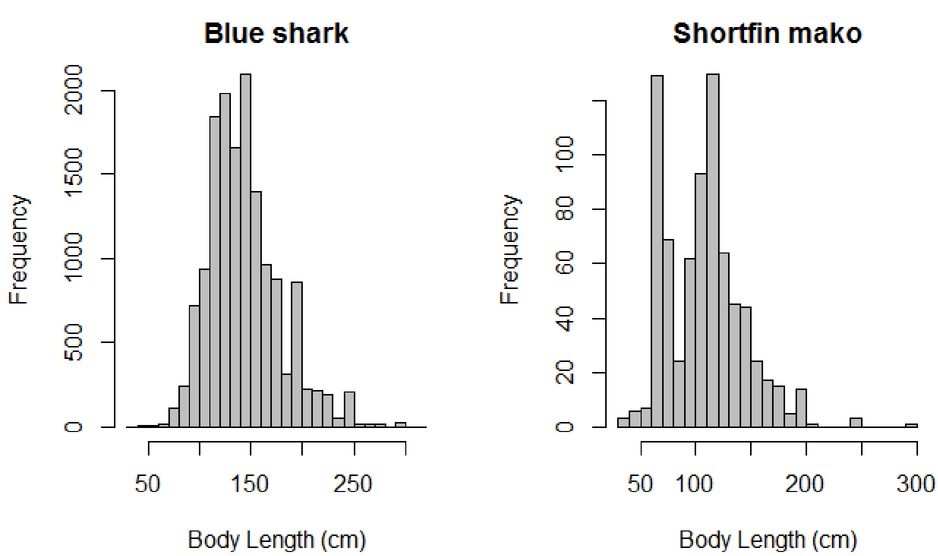


Fig.4 Body length distributions of blue shark and shortfin mako.

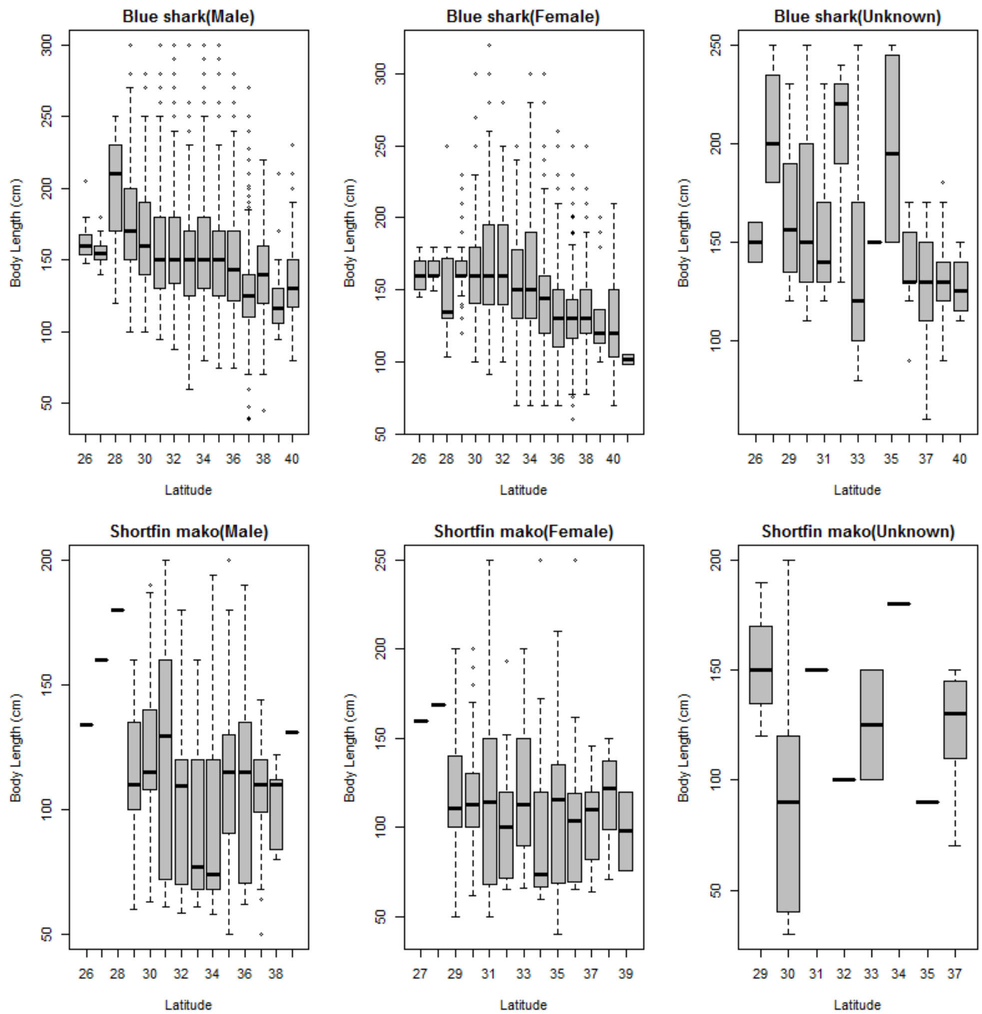


Fig. 5 Boxplot of body length of blue shark and shortfin mako by sex and latitude. Box plots show median values (solid horizontal lines), 50th percentile values (box outline), 90th percentile values (whiskers), and outlier values (open circles).

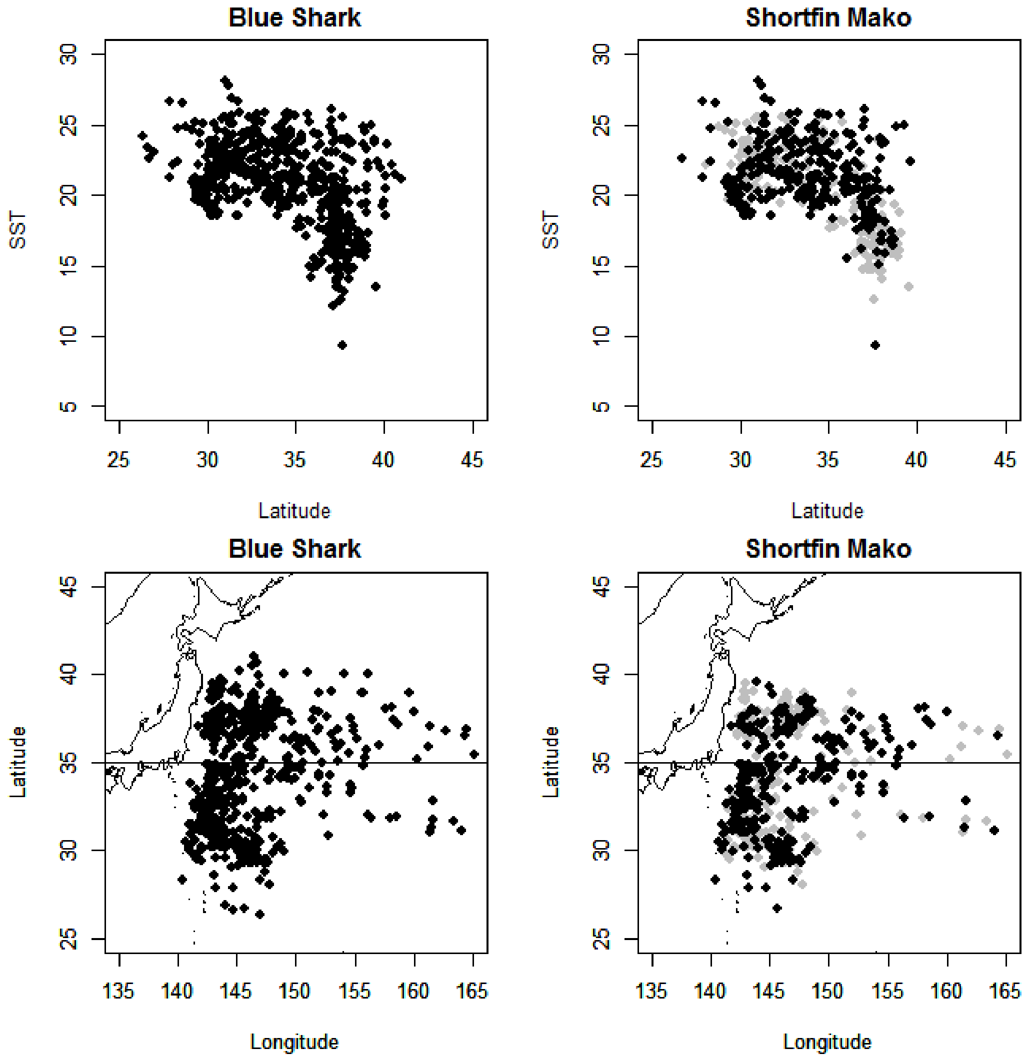


Fig. 6 Relationships between latitude and SST of blue shark (upper left) and shortfin mako (upper right), and horizontal distribution of blue shark (lower left) and shortfin mako (lower right). Black and gray points represent positive and negative catch points, respectively.

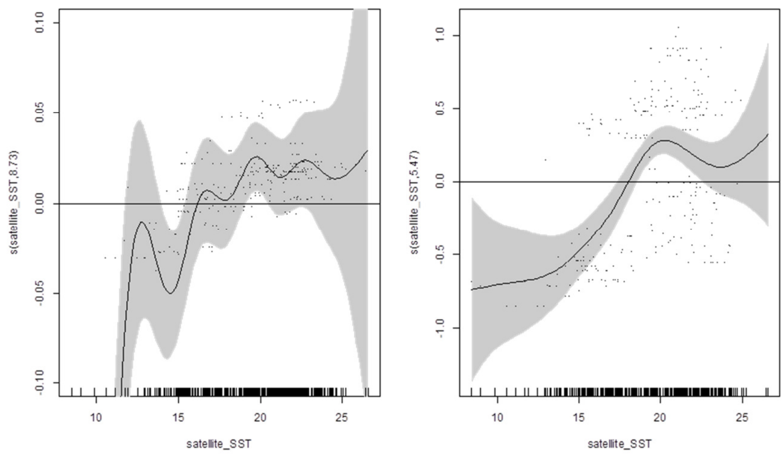


Fig. 7 Smoothed fits of variate (SST) the presence-absence of blue shark (upper panels) and shortfin mako (lower panels). The y-axis represents the spline function. Shade indicates 95% confidence intervals.

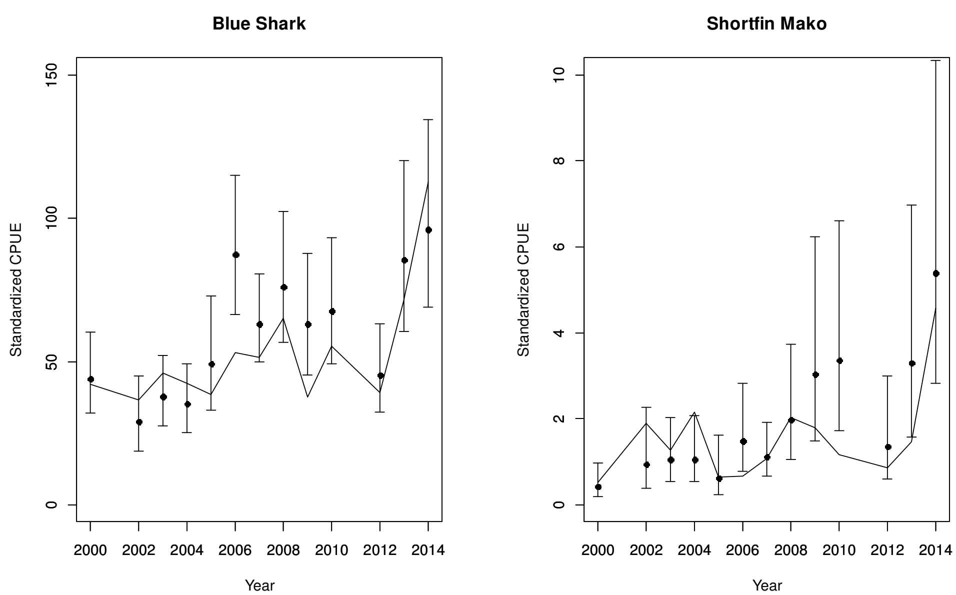
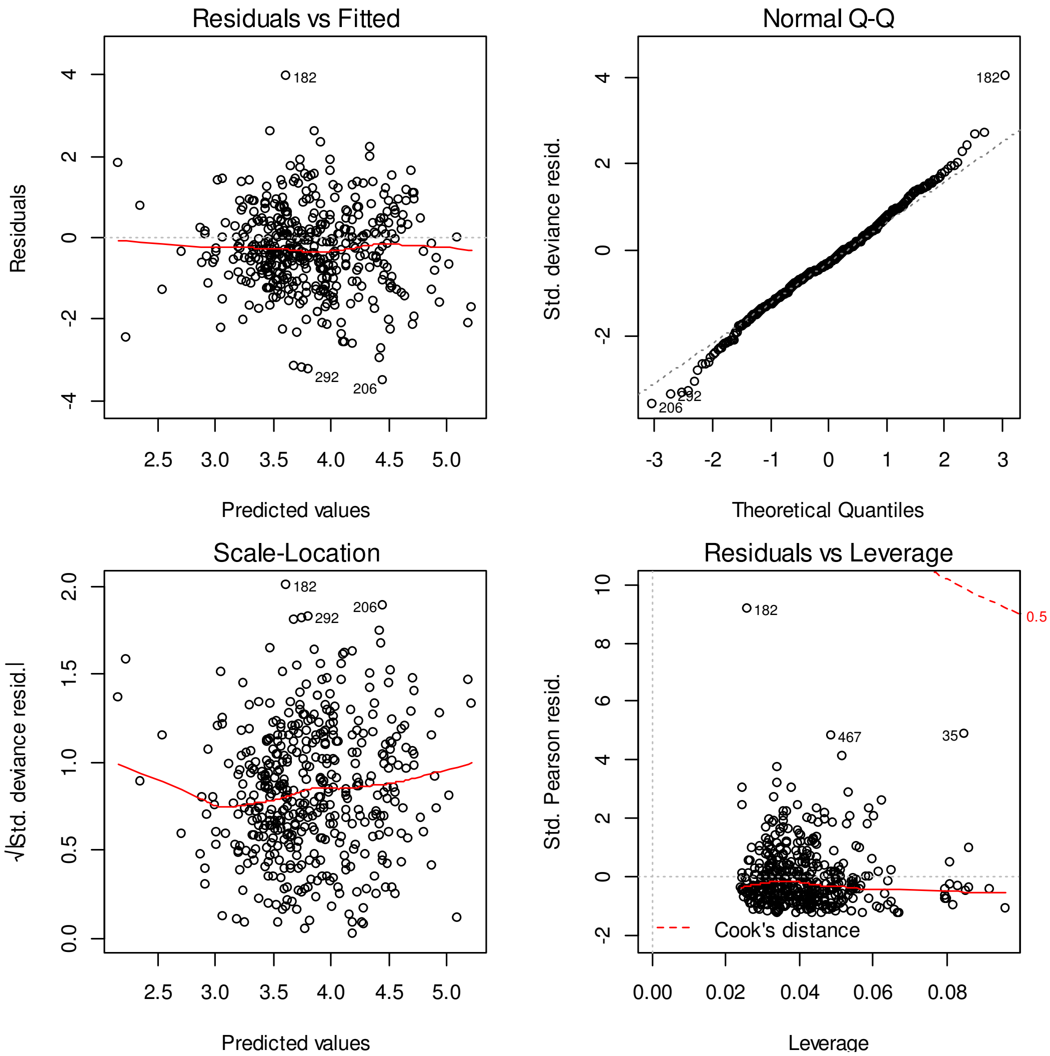


Fig. 8 Standardize CPUE (closed circles) with 95% confidential intervals (vertical bars) and Nominal CPUE (solid lines) of blue shark (left) and shortfin mako (right).

Appendix Figures and Tables

Summary of GLM (blue shark)



Appndiex Fig. 1 Diagnostics of the GLM analysis for CPUE standardization of blue shark during 2000 to 2013.

Blue shark

glm.nb(formula = blue_shrk ~ as.factor(year) + as.factor(month) +
    set_lat + satellite_SST + Vessel + offset(log(hooks)), data = data,
    link = "log", init.theta = 1.515025826)

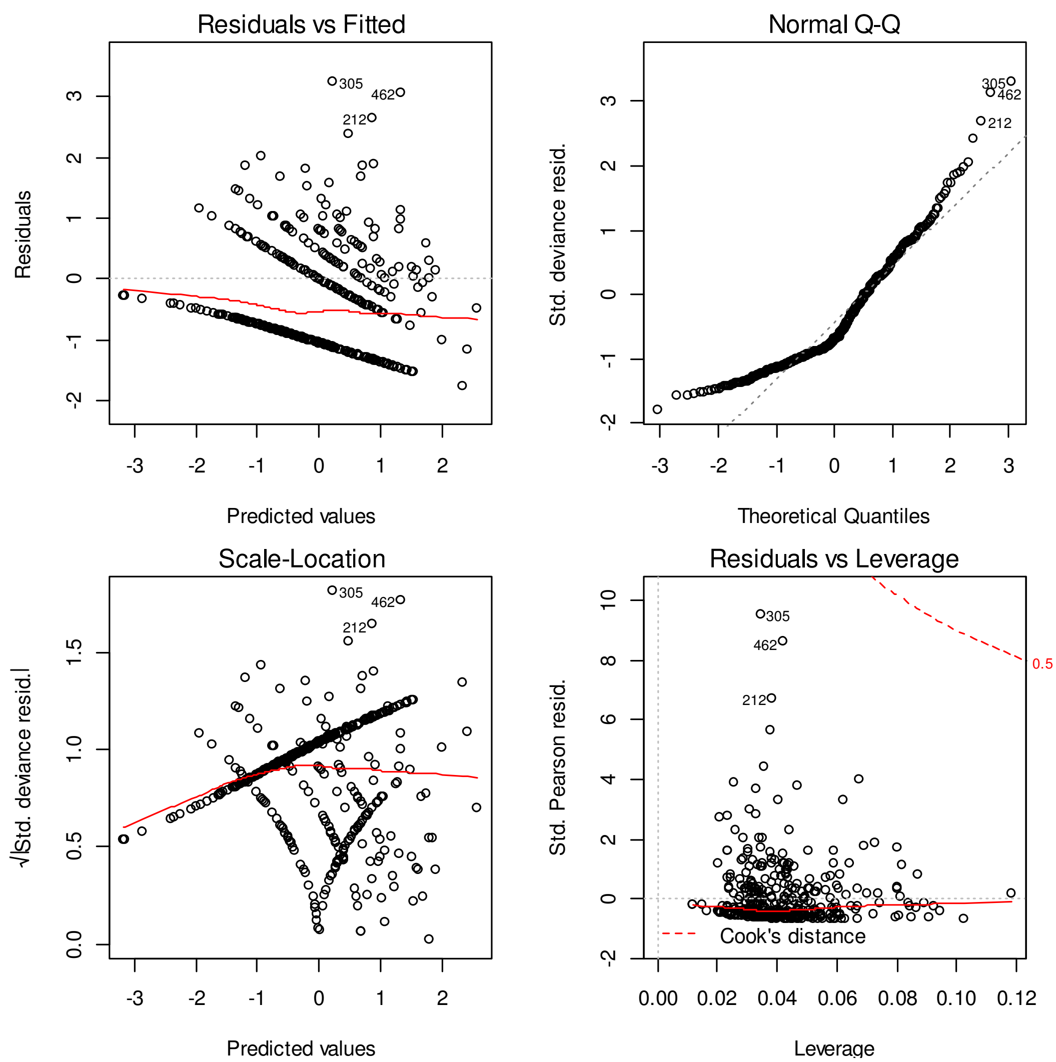
Deviance Residuals:

Min	1Q	Median	3Q	Max
-3.5015	-0.8951	-0.3244	0.3325	3.9776

```
Coefficients:
                      Estimate Std. Error z value Pr(>|z|)
(Intercept)           -10.05788    1.40777  -7.145 9.03e-13 ***
as.factor(year)2002    -0.32570    0.28235  -1.154  0.24869
as.factor(year)2003    -0.10357    0.23702  -0.437  0.66213
as.factor(year)2004    -0.10674    0.24346  -0.438  0.66107
as.factor(year)2005     0.01796    0.25085   0.072  0.94294
as.factor(year)2006     0.47785    0.20854   2.291  0.02194 *
as.factor(year)2007     0.26786    0.20350   1.316  0.18809
as.factor(year)2008     0.36453    0.20943   1.741  0.08175 .
as.factor(year)2009     0.07027    0.21601   0.325  0.74496
as.factor(year)2010     0.21532    0.21682   0.993  0.32068
as.factor(year)2012    -0.17850    0.22283  -0.801  0.42309
as.factor(year)2013     0.20708    0.21789   0.950  0.34190
as.factor(year)2014     0.73288    0.22714   3.227  0.00125 **
as.factor(month)5       0.26818    0.14317   1.873  0.06105 .
as.factor(month)6      -0.13572    0.17213  -0.788  0.43042
set_lat                 0.15708    0.02722   5.770 7.91e-09 ***
satellite_SST           0.06561    0.03020   2.173  0.02982 *
Vessel 第二大慶丸         0.25794    0.12782   2.018  0.04358 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for Negative Binomial(1.515) family taken to be 1)

    Null deviance: 612.87  on 436  degrees of freedom
Residual deviance: 486.54  on 419  degrees of freedom
AIC: 4223.1

Number of Fisher Scoring iterations: 1


              Theta:  1.515
          Std. Err.:  0.100
```

2 x log-likelihood: -4185.109

Summary of GLM with negative binomial error (shortfin mako shark)



Appndiex Fig. 2 Diagnostics of the GLM analysis for CPUE standardization of shortfin mako during 2000 to 2013.

glm.nb(formula = mako ~ as.factor(year) + as.factor(month) +
set_lat + satellite_SST + Vessel + offset(log(hooks)), data = data,
link = "log", init.theta = 0.5027038475)

Deviance Residuals:

Min	1Q	Median	3Q	Max
-1.7584	-1.0043	-0.6969	0.1636	3.2487

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-27.36520	3.17202	-8.627	< 2e-16	***
as.factor(year)2002	0.82213	0.62170	1.322	0.18604	
as.factor(year)2003	1.02192	0.54609	1.871	0.06130	.
as.factor(year)2004	0.96743	0.54707	1.768	0.07700	.
as.factor(year)2005	0.18330	0.61874	0.296	0.76704	
as.factor(year)2006	0.95524	0.52030	1.836	0.06637	.
as.factor(year)2007	0.81757	0.49385	1.656	0.09782	.
as.factor(year)2008	1.21728	0.49879	2.440	0.01467	*
as.factor(year)2009	1.60682	0.51121	3.143	0.00167	**
as.factor(year)2010	1.54873	0.51483	3.008	0.00263	**
as.factor(year)2012	0.91873	0.54795	1.677	0.09361	.
as.factor(year)2013	1.30822	0.51356	2.547	0.01085	*
as.factor(year)2014	2.42257	0.51138	4.737	2.17e-06	***
as.factor(month)5	-0.06990	0.31595	-0.221	0.82492	
as.factor(month)6	-0.96013	0.37553	-2.557	0.01057	*
set_lat	0.33512	0.05974	5.610	2.03e-08	***
satellite_SST	0.42249	0.06695	6.310	2.79e-10	***
Vessel 第二大慶丸	0.38898	0.27718	1.403	0.16051	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(0.5027) family taken to be 1)

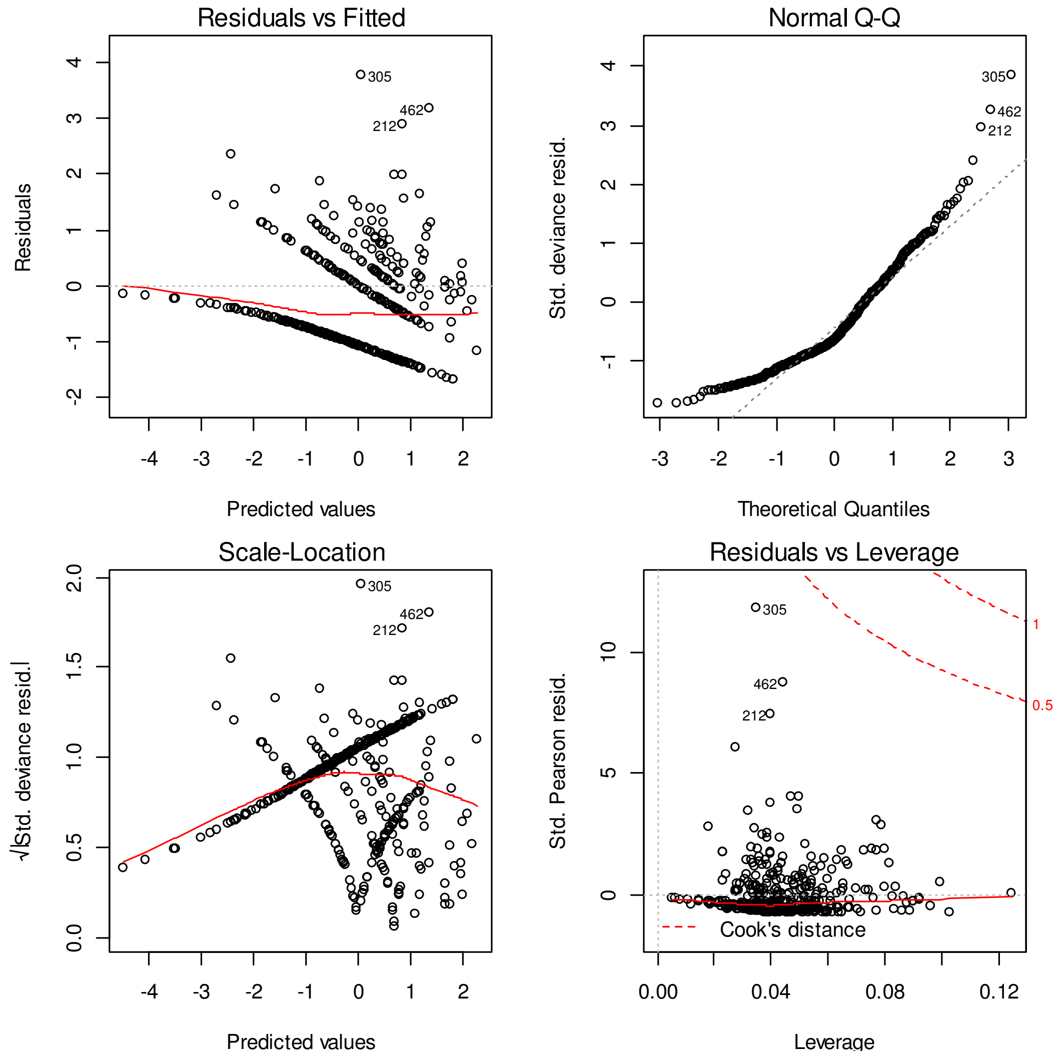
Null deviance: 471.37 on 436 degrees of freedom
Residual deviance: 371.24 on 419 degrees of freedom
AIC: 1270.2

Number of Fisher Scoring iterations: 1

Theta: 0.5027

Std. Err.: 0.0627

2 x log-likelihood: -1232.2130



With interaction (lat*sst) of shortfin mako

glm.nb(formula = mako ~ as.factor(year) + as.factor(month) +
set_lat * satellite_SST + Vessel + offset(log(hooks)), data = data,
link = "log", init.theta = 0.5799958974)

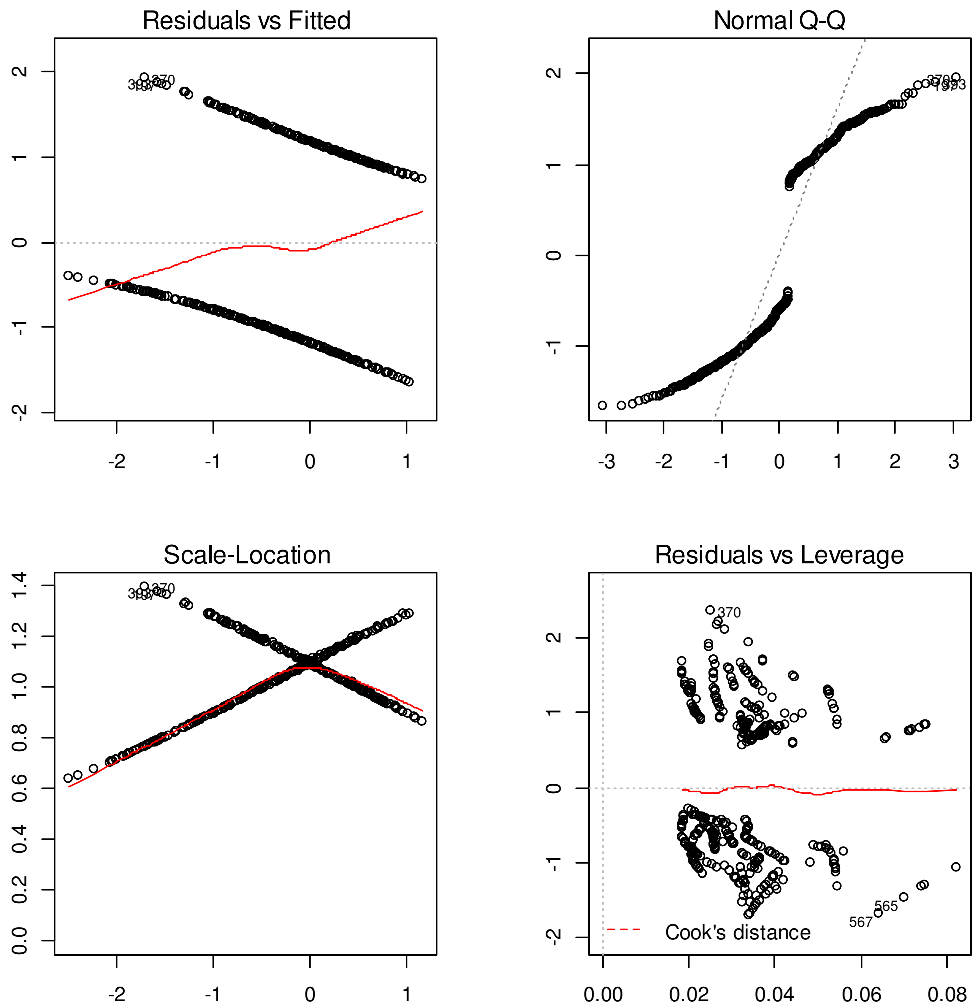
Deviance Residuals:

Min	1Q	Median	3Q	Max
-1.6870	-0.9884	-0.6481	0.1541	3.7846

```
Coefficients:
                      Estimate Std. Error z value Pr(>|z|)
(Intercept)           32.20885   13.63345   2.362 0.018153 *
as.factor(year)2002    0.80214    0.59898   1.339 0.180518
as.factor(year)2003    0.90761    0.52962   1.714 0.086587 .
as.factor(year)2004    0.91250    0.52978   1.722 0.084991 .
as.factor(year)2005    0.38393    0.60525   0.634 0.525862
as.factor(year)2006    1.24820    0.51636   2.417 0.015636 *
as.factor(year)2007    0.98014    0.47900   2.046 0.040736 *
as.factor(year)2008    1.54347    0.48852   3.159 0.001580 **
as.factor(year)2009    1.97099    0.51305   3.842 0.000122 ***
as.factor(year)2010    2.07283    0.50366   4.116 3.86e-05 ***
as.factor(year)2012    1.16064    0.55086   2.107 0.035120 *
as.factor(year)2013    2.05104    0.52428   3.912 9.15e-05 ***
as.factor(year)2014    2.54337    0.49714   5.116 3.12e-07 ***
as.factor(month)5     -0.03620    0.30926  -0.117 0.906831
as.factor(month)6     -0.72287    0.36658  -1.972 0.048616 *
set_lat               -1.35770    0.38222  -3.552 0.000382 ***
satellite_SST         -2.49889    0.66475  -3.759 0.000170 ***
Vessel 第二大慶丸       0.44290    0.26745   1.656 0.097721 .
set_lat:satellite_SST  0.08295    0.01883   4.405 1.06e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(0.58) family taken to be 1)

    Null deviance: 510.01  on 436  degrees of freedom
Residual deviance: 372.87  on 418  degrees of freedom
AIC: 1246.9

Number of Fisher Scoring iterations: 1


              Theta:  0.5800
          Std. Err.:  0.0752
```

2 x log-likelihood: -1206.8860

Summary of delta-lognormal GLM (shortfin mako shark)



Call:

glm(formula = pcatch ~ factor(year) + satellite_SST, family = binomial,
    data = data)

Deviance Residuals:

Min	1Q	Median	3Q	Max
-1.6391	-1.0332	-0.6021	1.1000	1.9306

Coefficients:

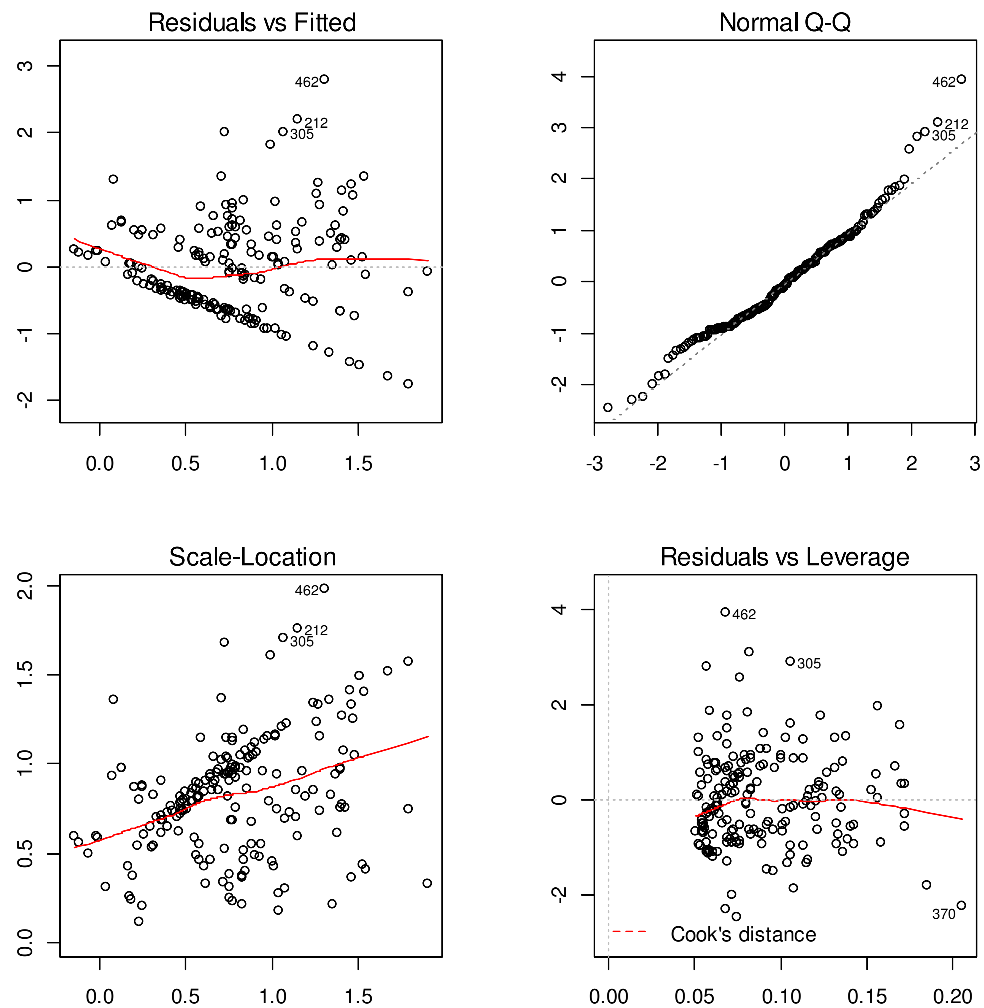
	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-4.33714	0.89406	-4.851	1.23e-06	***
factor(year)2002	1.24417	0.68693	1.811	0.0701	.
factor(year)2003	1.34214	0.56532	2.374	0.0176	*
factor(year)2004	0.98784	0.57537	1.717	0.0860	.
factor(year)2005	0.24857	0.61316	0.405	0.6852	
factor(year)2006	-0.04475	0.49207	-0.091	0.9275	
factor(year)2007	0.37467	0.49104	0.763	0.4455	
factor(year)2008	0.64395	0.51984	1.239	0.2154	
factor(year)2009	0.69440	0.53449	1.299	0.1939	
factor(year)2010	0.31546	0.53684	0.588	0.5568	
factor(year)2012	-0.23071	0.59595	-0.387	0.6987	
factor(year)2013	0.60779	0.54376	1.118	0.2637	
factor(year)2014	1.42530	0.55658	2.561	0.0104	*
satellite_SST	0.18185	0.03920	4.639	3.50e-06	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

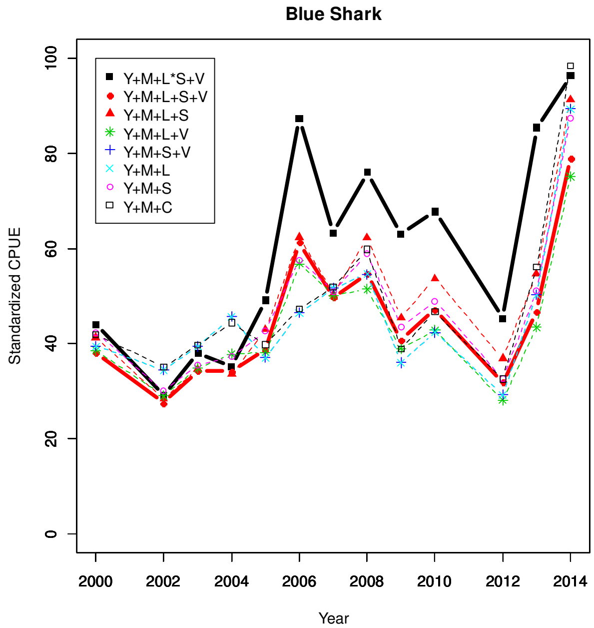
Null deviance: 597.82 on 436 degrees of freedom
Residual deviance: 545.25 on 423 degrees of freedom
AIC: 573.25

Number of Fisher Scoring iterations: 4

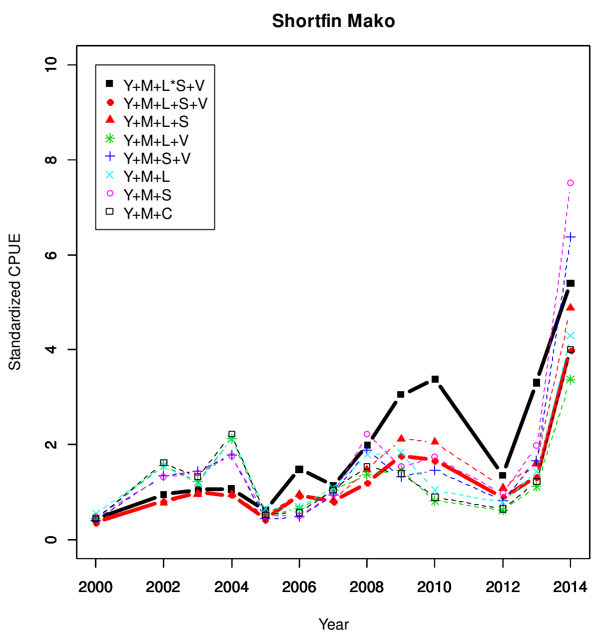



```
Call:
glm(formula = lcpue ~ as.factor(year) + as.factor(month) + set_lat +
    satellite_SST, family = gaussian, data = data[data$mako >
    0, ])

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-1.75170  -0.50313  -0.06655   0.44043   2.79670

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)         -7.44049    2.00770  -3.706 0.000284 ***
```

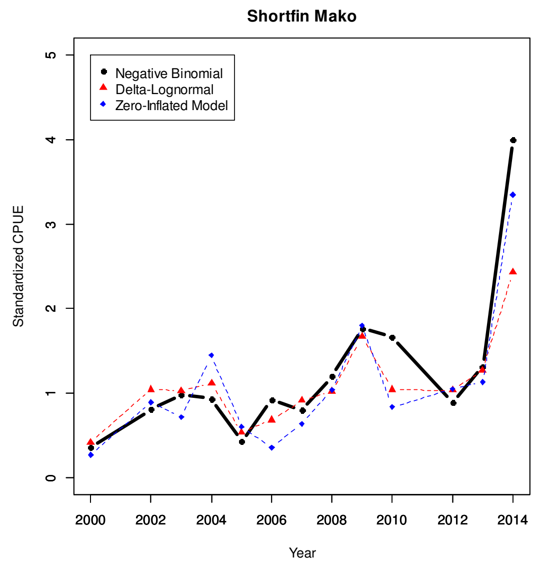
```
as.factor(year)2002   0.28632    0.34725    0.825 0.410773
as.factor(year)2003   0.23947    0.30555    0.784 0.434268
as.factor(year)2004   0.45825    0.30766    1.489 0.138193
as.factor(year)2005   0.10890    0.34629    0.314 0.753543
as.factor(year)2006   0.53195    0.31106    1.710 0.089047 .
as.factor(year)2007   0.56520    0.28680    1.971 0.050365 .
as.factor(year)2008   0.52852    0.30525    1.731 0.085167 .
as.factor(year)2009   0.99358    0.30393    3.269 0.001303 **
as.factor(year)2010   0.73031    0.32624    2.239 0.026469 *
as.factor(year)2012   1.07982    0.37200    2.903 0.004184 **
as.factor(year)2013   0.76403    0.31923    2.393 0.017771 *
as.factor(year)2014   1.07349    0.30930    3.471 0.000656 ***
as.factor(month)5    -0.19685    0.22831   -0.862 0.389770
as.factor(month)6    -0.66058    0.24664   -2.678 0.008117 **
set_lat               0.16414    0.03816    4.301 2.85e-05 ***
satellite_SST         0.12425    0.04331    2.868 0.004641 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for gaussian family taken to be 0.5432025)

    Null deviance: 124.885  on 188  degrees of freedom
Residual deviance:  93.431  on 172  degrees of freedom
AIC: 439.2

Number of Fisher Scoring iterations: 2
```



Appendix figure Comparison of standardized CPUE of blue shark with difference of explanatory variables



Appendix figure Comparison of standardized CPUE of shortfin mako with difference of explanatory variables



Appendix figure Comparison of standardized CPUE of shortfin mako between GLM with negative binomial, delta log-normal and zero inflated model.
Zero-inflated model is as follows;Catch ~ factor(year) + factor(month) + sst + factor(vessel) + offset(log(hooks)) | factor(year) + sst, family=negbin.

Appendix table Model description and AIC value of GLM with negativ binomial errors

Model description (BSH)	AIC	Model description (Mako)	AIC
C~Y+M+L*S+V	4185.8	C~Y+M+L*S+V	1246.9
C~Y+M+L+S+V	4223.1	C~Y+M+L+S+V	1270.2
C~Y+M+L+S	4225.0	C~Y+M+L+S	1270.1
C~Y+M+L+V	4224.8	C~Y+M+L+V	1306.6
C~Y+M+L+V	4250.4	C~Y+M+L+V	1296.4
C~Y+M+L	4227.2	C~Y+M+L	1307.4
C~Y+M+S	4250.1	C~Y+M+S	1295.7
C~Y+M+V	4260.4	C~Y+M+V	1305.7