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Environmental influences on seasonal movement patterns and regional fidelity of striped marlin *Kajikia audax* in the Pacific Ocean

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ABSTRACT

Striped marlin is a highly mobile species distributed throughout the Pacific Ocean. They are less migratory than other billfish species and show considerable variation in spatial distribution as a consequence of habitat preference. The spatial patterns and habitat characteristics of striped marlin in the Pacific Ocean were examined using generalized linear and additive models fitted to fishery-dependent catch-per-unit-effort and satellite-based environmental data. Of the oceanographic variables considered in the analyses, sea surface temperature (SST) explained the largest proportion of the deviance, and is considered the best predictor of the spatial distribution of this species. Results from the models showed that preferred habitats of striped marlin were non-contiguous in the Pacific Ocean, and there was a seasonal movement of preferred habitat within each region that could be related to the changes in SST. Stock assessments and management for striped marlin should be conducted regionally as this species exhibits some level of regional site fidelity. Information from tagging experiments for each region is needed to further improve the understanding of movement patterns and thus enhance the ability to better define the habitat ranges and stock boundaries for this species.

1. Introduction

Striped marlin *Kajikia audax* (Philippi 1887) (Collette et al., 2006), is a commercially important species caught primarily as bycatch in longline fisheries targeting tunas, and is occasionally targeted in coastal drift-net and harpoon fisheries off Japan for the high-grade sashimi and frozen filet market (Piner et al., 2013). This species also forms the basis for important recreational fisheries off Hawaii, California, Mexico, Ecuador, New Zealand, Australia, and East Africa (Bromhead et al., 2004). It is the most studied of the billfish species (family: Istiophoridae), owing to its economic importance (Molony, 2008).

Striped marlin is an epi-pelagic, highly mobile species distributed throughout tropical, subtropical, and temperate oceanic waters of the Pacific and Indian Oceans (Ueyanagi, 1964). Some individuals have been found occasionally in the Atlantic Ocean near the Cape of Good Hope (South Africa) during the austral summer (Penrith and Cram, 1974), but these are regarded as stragglers from the Indian Ocean (Graves and McDowell, 1995). In the Pacific Ocean, the spatial distribution of striped marlin has been inferred from commercial longline catch-rates and conventional tagging data, and has been characterized as a horseshoe-like pattern, primarily between 20 and 30° north and south of the equator in the central Pacific Ocean, with a continuous distribution across the equator along the west coast of Central America (Squire and Suzuki, 1990).

Temperature is one of the most important environmental factors determining the spatial distribution of striped marlin in the Pacific Ocean. For example, Howard and Ueyanagi (1965) proposed that the 20–25 °C sea surface temperature (SST) isotherms formed the boundary for striped marlin in the western Pacific Ocean. Highest catch-rates of striped marlin in the recreational fishery off California and Mexico were found between 22 and 24 °C SST (Ortega-Garcia et al., 2003), and between 23 and 26 °C SST for the longline fisheries in the western and central North Pacific Ocean (Lien et al., 2014). Bromhead et al. (2004) found that catch-rates of striped marlin were high in waters between 22 and 26 °C off the east coast of Australia based on data from longline fisheries.

Similar to blue marlin (*Makaira nigricans*), striped marlin spend the majority of their time in the mixed layer (i.e., upper 90 m of the water column), with occasional dives for feeding, particularly during daytime (e.g., Brill et al., 1993; Domeier et al., 2003; Sippel et al., 2011). Holts and Bedford (1990) found that the thermocline

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may restrict the vertical movement of striped marlin, and inferred that the depth of the thermocline would influence catch-rates of this species. Prince et al. (2010) and Stramma et al. (2012) found, based on direct measurement of vertical movement, that a shallow thermocline (ca. 25–50 m) above a barrier of cold hypoxic water in the eastern tropical Pacific Ocean restricts the depth distribution of high oxygen demand pelagic species such as marlins. These studies highlight the importance of oceanographic factors on the distribution of striped marlin.

Several stock structure hypotheses have been proposed for striped marlin in the Pacific Ocean. For example, Shomura (1980) hypothesized a single panmictic population, while Kamimura and Honma (1958) proposed a hypothesis of northern–southern Pacific stocks based on the differences in morphometric and meristic characters, and spatially and temporally distinct spawning grounds. Kume and Joseph (1969) reported the range of movements of some tagged individuals as evidence that fish in the southern and northern East Pacific Ocean likely comprise a single population. However, McDowell and Graves (2008) suggested multiple genetic stocks of striped marlin in the Pacific Ocean, including a North Pacific stock (Japan, Taiwan, Hawaii, and California), a southwest Pacific stock (Australia), and two stocks in the eastern Pacific Ocean (Mexico and Ecuador) based on significant genetic differentiation among these regions. In contrast, Purcell and Edmands (2011) proposed a single genetic stock in the eastern Pacific Ocean (Mexico to Central America) based on the analyses with more representative samples of the species' range, i.e., 1199 specimens collected across the Pacific Ocean.

This study aimed to examine the relationships between environmental factors and habitat preferences of striped marlin for various regions of the Pacific Ocean using fishery data from pelagic longline operations and multi-sensor satellite-based remotely-sensed oceanographic variables, and to use these relationships to identify the habitat ranges and possible seasonal movement patterns. This is first study that has used environmental data to enhance the ability to better validate the assumed stocks of striped marlin and their boundaries, and thus provides basic information necessary for accurate assessments and effective management arrangements of this species.

2. Materials and methods

2.1. Data used

Fishery data on time and location of operations, fishing effort in the number of hooks deployed, and number of fish caught by the Taiwanese distant-water longline fishery in the Pacific Ocean, aggregated by month and 5° × 5° grid cell, were obtained from the Overseas Fisheries Development Council of Taiwan (http://www.ofdc.org.tw/). CPUE (catch-per-unit-effort) was expressed as the number of fish caught per 1000 hooks. Fishery data for 1998–2012 were used for the analyses because data for some of the satellite-based oceanographic variables are not available before 1998 and because fishery data for the entire Pacific basin only became available when the Taiwanese longline fishery started to fish bigeye tuna (*Thunnus obesus*) in the tropical Pacific Ocean, in addition to albacore (*Thunnus alalunga*) in temperate waters (Fig. 1).

The environmental variables that are likely to be useful predictors of striped marlin distribution were: sea surface temperature (SST), mixed layer depth (MLD), chlorophyll-*a* concentration (CHL), and sea surface height (SSH), which were sourced as follows:

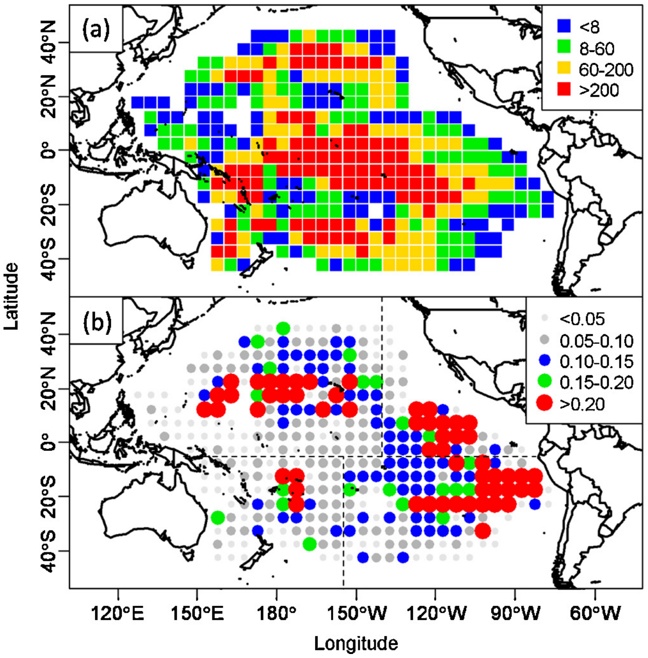

Fig. 1. Distributions of (a) fishing effort (10^5 hooks) for the Taiwanese distant-water tuna longline fishery in the Pacific Ocean and (b) nominal CPUE (number of fish caught per 1000 hooks) of striped marlin for 1998–2012.

(1) Monthly averaged SST for 1998–2012 from the gridded Pathfinder AVHRR daytime dataset (v5, http://www.podaac.jpl.nasa.gov);
(2) Monthly MLD data (defined as the depth at which there is a 0.5° decrease in temperature from the value at the sea surface) from the outputs of TOPS model for 1998–2012 (http://orca.science.oregonstate.edu/);
(3) Monthly CHL data for 1998–2012 from the MODIS Aqua Ocean Color dataset (http://oceancolor.gsfc.nasa.gov); and
(4) Monthly SSH data from the AVISO dataset of delay merged-mission satellite altimetry data products for 1998–2012 (http://www.aviso.oceanobs.com).

The environmental data were averaged to 5° × 5° grids to match the spatial scale of the fishery catch and effort data. Catch-effort observations for a few month by grid combinations were excluded from the analyses because environmental data were missing.

2.2. Modeling approach

Generalized linear models (GLMs) and generalized additive models (GAMs) are commonly used approaches that have been applied extensively in ecological modeling and fisheries research (Maunder and Punt, 2004). First introduced by Nelder and Wedderburn (1972), GLMs have been used to standardize catch-rates since the 1980s, by assuming a linear relationship between a link function of the expected response variable and multiple explanatory variables. GAMs are extensions of GLMs (Hastie and Tibshirani, 1990), but replace the linear functions of explanatory variables with additive and smooth functions. Advantages and disadvantages using GLMs and GAMs for analyzing catch and effort data are discussed by Guisan et al. (2002) and Maunder and Punt (2004).

Eight covariates were considered for inclusion in the GLMs and GAMs: SST, MLD, CHL, SSH, year, month, latitude, and longitude. Spatial and temporal factors were included in the model because oceanographic variables are not the sole determinant of habitat for