Fisheries Research 166 (2015) 67–79

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Environmental variations on swordfish (*Xiphias gladius*) catch rates in the Indian Ocean

Kuo-Wei Lan[a,b], Ming-An Lee[a,b,*], Sheng-Ping Wang[a,b], Zhao-Yang Chen[c]

[a] Department of Environmental Biology Fisheries Science, National Taiwan Ocean University, 2 Pei-Ning Rd., Keelung 20224, Taiwan, ROC
[b] Center of Excellence for Oceans, National Taiwan Ocean University, 2 Pei-Ning Rd., Keelung 20224, Taiwan, ROC
[c] Taiwan Fisheries Sustainable Development Association, 5 Huangang St., Zhongzheng Dist., Keelung City 20224, Taiwan, ROC

ARTICLE INFO

Article history:
Received 21 March 2014
Received in revised form 14 August 2014
Accepted 14 August 2014
Handling Editor A.E. Punt
Available online 6 September 2014

Keywords:
Swordfish
Environmental variables
Longline fisheries
Generalized additive models

ABSTRACT

The environmental processes associated with the climatic oscillations that drive variability in swordfish catch rates are largely unexplored. This study used generalized additive models fitted to longline fishery data to investigate relationships between environmental variables and catch rates to understand the processes influencing swordfish distributions in the Indian Ocean. The catch rates and distribution of swordfish in the Indian Ocean were sensitive to climatic and environmental variation. The environmental effects differ between the northwest and southwest Indian Ocean. The predicted relative abundance reveals a notable increase along the western coast of the northwest Indian Ocean during nominal Indian Ocean Dipole and negative Southern Indian Ocean Dipole (IOSD) events, and is related to the changes in net primary production and shallow mixed layer depth. The predicted relative abundances also show that the distribution of lower sea surface temperature and sea surface height deviation surrounding Madagascar increased during negative IOSD events in the southwest Indian Ocean.

1. Introduction

Swordfish (*Xiphias gladius*) are a type of billfish (Xiphiidae), which are highly migratory in tropical and temperate waters worldwide. They range from northern coastal state waters to 50° S in the Indian Ocean (IOTC, 2011) and exhibit sexual dimorphism in maximal size, growth rates, and age at maturity; females reach larger sizes, grow more rapidly, and mature later than males do (Poisson and Fauvel, 2009). Genetic studies of the stock structure of swordfish in the Indian Ocean have failed to reveal spatial heterogeneity, and one pan-ocean stock has been assumed for stock assessment purposes (Chow and Takeyama, 2000). Muths et al. (2009) indicated that swordfish in the southwest region potentially constitute a subpopulation distinct from that in the rest of the Indian Ocean. Swordfish are relatively long-lived, mature relatively late in life, and exhibit sexual dimorphism, which causes them to be vulnerable to overexploitation (Poisson and Fauvel, 2009).

Catches of swordfish in the Indian Ocean were first recorded by the Japanese in the early 1950s as a bycatch in tuna longline fisheries. The majority of swordfish are caught by longline fisheries in the Indian Ocean, particularly by Taiwanese seasonal targeting fisheries and Japanese longline fisheries (as bycatch), which have the longest period of catch data series (Wang and Nishida, 2009). Taiwanese longline fisheries in the Indian Ocean changed fishing operations in the late 1980s and the early 1990s, but have been relatively stable thereafter (Wang and Nishida, 2011). Since the early 1990s, Taiwan has been the dominant swordfish catching fleet in the Indian Ocean (41–70% of the total catch). Taiwanese longliners, particularly in the southwestern and equatorial western Indian Ocean, target swordfish by using shallow longlines at night (IOTC, 2011). Catch rates (defined as catch per unit effort, CPUE) of the swordfish longline fisheries indicate that declines in swordfish abundance occurred from the early 1990s to the mid-2000s, with the most severe declines occurring in the southwest region (Wang and Nishida, 2011). In recent years, catch rates have stabilized or slightly increased.

Swordfish are not gregarious, although densities increase in areas of oceanic fronts and seamounts (Poisson and Fauvel, 2009). Biophysical and oceanographic environmental factors, including sea surface temperature (SST) (Nakamura, 1986; Bigelow et al., 1999), sea surface height (Guyomard et al., 2004; Tserpes et al., 2008), mixed layer depth (MLD) (Chang et al., 2013) and net primary production related to forage (prey) (Guyomard et al., 2004; Chang et al., 2013), play crucial roles in controlling the distribution and

* Corresponding author at: Department of Environmental Biology Fisheries Science, National Taiwan Ocean University, 2 Pei-Ning Rd., Keelung 20224, Taiwan, ROC. Tel.: +886 2 24622192x5032; fax: +886 2 24634419.
E-mail addresses: malee@mail.ntou.edu.tw, malee@ntou.edu.tw (M.-A. Lee).

http://dx.doi.org/10.1016/j.fishres.2014.08.010

catch rate of swordfish. Swordfish move to warmer waters to spawn and overwinter, and to cooler, temperate waters to feed (Nakamura, 1986; Takahashi et al., 2003). Both the sex ratio and size distribution of swordfish have been observed to vary seasonally, suggesting that swordfish exhibit synchronized sex- and size-related movements (Poisson and Fauvel, 2009). Swordfish also exhibit daily vertical movements. They spend the day feeding in deeper waters and then rise toward the surface at night (Takahashi et al., 2003; Abascal et al., 2010). In addition, climatic oscillations, anomalies, and changes clearly affect numerous ecological processes in marine ecosystems, affecting the catch rates and the distribution of pelagic species (Stenseth et al., 2004; Lan et al., 2013; Tian et al., 2013).

The Indian Ocean Dipole (IOD) is in a positive phase when an anomalous upwelling occurs along the Sumatra-Java coast, enhancing cooling of SSTs in the eastern tropical Indian Ocean. As a result of warmer SSTs and a deeper thermocline in the west, surface primary productivity decreases in the west and increases in the east in association with upwelling and a shallower thermocline (Saji et al., 1999; Marsac, 2008). Dipole mode events in the subtropical southern Indian Ocean region have been determined to be linked with the strengthening and weakening of the Mascarene High. The Indian Ocean subtropical dipole (IOSD) has been remarkably accurately simulated in coupled ocean-atmosphere general circulation models (Behera and Yamagata, 2001; Suzuki et al., 2004). In a positive IOSD event, the resultant stronger winds off the coast of Australia cause cooling of SSTs in the southeastern region, mainly through increased evaporation. Conversely, reduced evaporation caused by reduced wind speed allows an increased influx from the atmosphere, thus warming the southwestern region. In addition, the dipole phenomena in the tropical and subtropical Indian Ocean are independent phenomena with no causal relation to any atmospheric and oceanic interaction (Saji et al., 1999; Behera and Yamagata, 2001; Suzuki et al., 2004). Variations in population abundances and distributions of pelagic tuna species have been observed to be linked to large-scale climate phenomena of IOD in the Indian Ocean (Marsac, 2008; Lan et al., 2013). However, the relationship between swordfish catch rates and large-scale climate phenomena (IOD and IOSD) is unclear and has not yet been examined in this region.

Understanding the effects of environmental conditions on fish catch rates is an essential step toward ecosystem-based management of fisheries, which is increasingly becoming a standard approach in management policy (Pikitch et al., 2004; Su et al., 2011). Models of catch rates that incorporate relevant environmental variables can be used to infer possible responses in the distribution of highly migratory species. The purpose of this study was to investigate relationships between environmental variation and catch rates to identify the underlying processes influencing swordfish catch rates and their distribution in the Indian Ocean, and thereby predict distribution. These functional relationships can be used to evaluate the impacts of climate variability on the spatial pattern and vulnerability of swordfish.

2. Data and methods

2.1. Swordfish fishery data

The fishery data were compiled from logbooks of the Taiwanese longline fleets in the Indian Ocean, provided by the Overseas Fisheries Development Council of Taiwan. Data from 1998 to 2011 were used for analysis, because satellite-based NPP data were not available before 1998. The fishery data included fishing effort (number of hooks), fishing date, and catch in number of swordfish. The catch and effort data were aggregated by year, month and $5^\circ \times 5^\circ$ spatial grid. Monthly nominal catch rate was calculated as the number

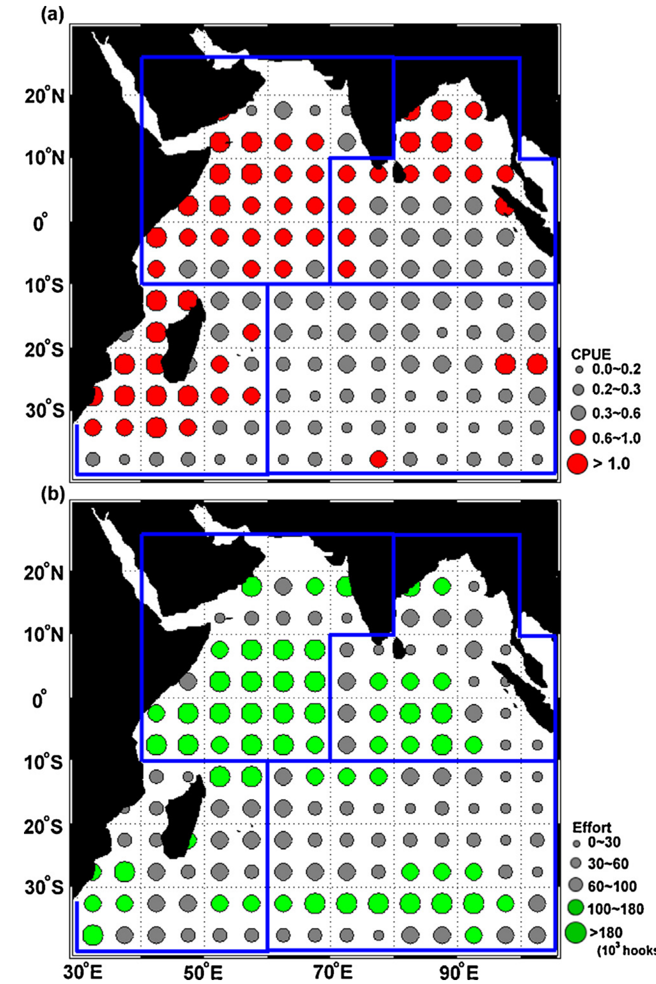

Fig. 1. Spatial distribution of (a) catch rates (number of fish caught per 1000 hooks) and (b) fishing effort of swordfish for 1998–2011. The blue lines separate the Indian Ocean into 4 subareas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of fish captured per 1000 hooks (fish/10^3 hooks). The fishery data were allocated to four subareas (northwest (NW), southwest (SW), northeast (NE), and southeast (SE)) of the Indian Ocean which have been used for swordfish assessment since 2008 (Wang and Nishida, 2009; Fig. 1).

2.2. Environmental variables and dipole modular index

Monthly environmental variables for the period January 1998–December 2011 were sourced as follows: (1) SST pathfinder monthly composites fields with a 4-km spatial resolution were obtained from the National Oceanographic Data Center (http://www.nodc.noaa.gov/); (2) NPP monthly SeaWiFS based estimates with 9-km resolution were obtained from Oregon State University's Ocean Productivity website (http://oceancolor.gsfc.nasa.gov/). These estimates are based on the Vertically Generalized Production Model developed by Behrenfeld and Falkowski (1997), which is the standard algorithm for NPP estimation; (3) sea surface height deviation (SSHD) was obtained from the Archiving, Validation, and Interpretation of Satellite Oceanographic data program with 0.25-degree resolution; and (4) MLD data with a one-degree spatial resolution were downloaded from the European Centre for Medium Range Weather Forecast Ocean Analysis System (http://www.ecmwf.int/). The environmental variables were then