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Evaluating habitat suitability and relative abundance of skipjack (*Katsuwonus pelamis*) in the Western and Central Pacific during various El Niño events

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The changes in skipjack (*Katsuwonus pelamis*) resources in the Western and Central Pacific Ocean (WCPO) region are subject to not only fishing activities but also the profound impacts of El Niño. Previous studies have suggested that there are two different types of El Niño events, which differentially influence currents, upwelling, chlorophyll concentrations, and temperature in the tropical Pacific Ocean. The comprehensive interaction mechanism between the skipjack stock and El Niño events remains unclear. Thus, an understanding of the differences in the effects between the two types of El Niño is urgently needed to protect skipjack resources. This study analyzed fisheries data and oceanographic conditions for the period of 1996–2012 to construct a habitat suitability index (HSI) model and conduct catch per unit effort (CPUE) standardization to a) identify skipjack habitat and determine relative abundance, b) compare habitat suitability and relative abundance between different types of El Niño events, and c) understand the effects of the two different types of El Niño on skipjack. The results demonstrate that 1) the arithmetic mean model (AMM) was found to be the optimal HSI model for skipjack in the WCPO region and for different El Niño events; 2) the factors of time, location and fishing method should be considered in the CPUE standardization before their application in the estimation of relative abundance; 3) Central Pacific El Niño events (CP El Niño) and Eastern Pacific El Niño events (EP El Niño) were found to have negative effects on skipjack, and relatively higher vulnerability values were found to be associated with the simultaneous occurrence of the two types of El Niño (such simultaneous occurrences may account for significant historical El Niño events); 4) in terms of the consequences of the different types of El Niño events, CP El Niño events tend to exert more negative influence on relative abundance than EP El Niño events can do; and 5) spatial factors tend to exert more influence than temporal factors in the relative abundance assessment. This study enhances our understanding of the consequences of different El Niño events. In addition, the findings may help inform researchers and policy makers in future resource assessment and management.

1. Introduction

El Niño is a prominent climatic phenomenon with global climatic effects, including increases in seawater temperature and changes in regional rainfall patterns (Chiodi and Harrison, 2013). A prominent consequence of El Niño is its effects on fishery resources in the Pacific Ocean, such as the temporary collapse of Peruvian anchovy stocks (Cahuin et al., 2015) and the altered fishing effort distribution of skipjack tuna in the Pacific (Kumar et al., 2014). During El Niño, a band of warm ocean water develops in the central and east-central equatorial Pacific, leading to water temperature variations in the Central Pacific thermocline and changes in the mixed layer (Lehodey, 2001). These changes might be the major causes of the decline in fishery resources in the region.

Skipjack (*Katsuwonus pelamis*) is a commercially important fish species for food and trade worldwide. Humans catch approximately

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1.4 million tons of tuna per year, which accounts for more than 70% of its global stock (FAO, 2011). In addition to the effects of fishing on tuna populations, recent studies have found that tuna population dynamics might be influenced by El Niño events (Lehodey et al., 1997). Lehodey et al. (2008) discovered that significant spatial shifts in skipjack populations are associated with large zonal displacements of the warm pool due to El Niño events. In addition, the relationships between El Niño indexes and tuna abundance (Lima and Naya, 2011) or spatial distribution (Wang et al., 2014) have been studied. However, the comprehensive interaction mechanism between skipjack tuna stocks and environmental factors during El Niño events remains unclear. Furthermore, updated models that allow more realistic analyses are urgently needed in fishery management.

Recent studies have revealed that El Niño might be much more complex than previously thought. Two different types of El Niño events have been identified in the Pacific region (Ashok et al., 2007; Kao and Yu, 2009; Kug et al., 2010; Yeh et al., 2009). The Eastern Pacific El Niño event (EP El Niño) is a well-known phenomenon in which the temperature of sea surface waters in the South American coastal region increases and unusually warm surface water spreads from east to west in the central Pacific Ocean region. The newly discovered Central Pacific El Niño event (CP El Niño), also known as El Niño Modoki, involves an anomalously warm region in the central equatorial Pacific and relatively cool regions in the eastern and western equatorial Pacific. Under CP El Niño conditions, an anomalous sea surface temperature increase appears in the central Pacific Ocean (Wang and Wu, 2013) and has significant impacts on the surrounding ocean currents, upwelling, water temperatures, chlorophyll concentrations, and habitats for migratory pelagic fishes, among other factors.

In this era of climate change, it is important to understand how the two different types of El Niño events impact skipjack stocks. This study aims to associate the skipjack resources with environmental parameters derived from remote sensing database to conduct habitat suitability index modeling and assessment, to reveal the potential consequences of the two types of El Niño events and to provide fishery management suggestions for the future.

2. Materials and methods

2.1. Study area and data

The study areas are illustrated in Fig. 1 and were chosen for two reasons. First, as stated above, the Western and Central Pacific Ocean (WCPO) is the major skipjack resource region and the primary arena for global skipjack fishing. Thus, this study focuses on the WCPO region. Second, as indicated in Fig. 1(A), there are 4 major current systems in the equatorial Pacific, namely the North Equatorial Current (NEC), the North Equatorial Countercurrent (NECC), the northern branch of the South Equatorial Current (SECn) and the southern branch of the South Equatorial Current (SECs), which greatly influence the marine systems in the WCPO region. Studies have shown that these systems exhibit significant circulation differences in various El Niño scenarios, which profoundly impact the temperature of sea surface waters in the region (Wang and Wu, 2013; Yeh et al., 2009). Thus, the equatorial Pacific was selected for habitat analysis due to the complex environmental background (see Fig. 1(B)).

This study used multi-source data from common and public accessible databases. Daily fishery data of Taiwanese purse seiners for the period of 1996–2012 were collected from the Overseas Fishery Development Council (R.O.C.). These data were geo-referenced and grouped into units of $1 \times 1^{\circ}$ (latitude $\times$ longitude). This is a high-resolution catch dataset that can provide more subtle information for modeling the habitat suitability index. Monthly fishery data of pole-and-line and purse seiners were also obtained from the South Pacific Commission (SPC). The spatial resolution of the data was set to $5 \times 5^{\circ}$ (latitude $\times$ longitude), which covers the majority of global fishery activities in the region of WCPO. These data were employed to analyze the relative abundance index. Environmental data for the period of 1996–2012 were obtained from NOAA Earth System Research Laboratory (NOAA-ESRL, http://www.esrl.noaa.gov/). The environmental parameters consisted of the monthly mean of sea surface temperature (SST), sea surface salinity (SSS), subsurface temperature at various depths (i.e., 25-m depth (T25), 45-m depth (T45), 65-m depth (T65), 85-m depth (T85), 105-m depth (T105), and mixed layer depth (MLD)), and east-west current velocity (EWCV). Two types of El Niño events were categorized by SST data from NOAA's Extended Reconstructed Sea Surface Temperature (ERSST) V3b dataset (Smith and Reynolds, 2003). In addition, the strength of each El Niño event was defined by Golden Gate Weather Services (GGWS) data.

2.2. Habitat suitability index analysis

The habitat suitability index (HSI) was adopted in this study to understand and analyze the impacts of El Niño events on the habitat suitability of skipjack. However, prior to HSI analysis, it is necessary to understand the relationship between a single habitat variable (HV) and skipjack. Then, the suitability index (SI) could be applied to reveal the interactions among various HVs. In free skipjack schools, abundance above a particular threshold implies better SI. Thus, the analysis of suitability quantifies the environmental preferences of skipjack tuna in terms of HVs. The fishing effort of purse seiners is better correlated with the fish habitat suitability than the catch per unit effort (CPUE) (Yen et al., 2012a). Therefore, the SI value was defined as the frequency distribution of fishing effort[2] for each class interval, which was divided by the maximum frequency value to yield a relative frequency distribution. The equation is defined as follows:

$$SI_{HV} = e^{\alpha(HV+\beta)^2} \tag{1}$$

where HV refers to a habitat variable (e.g., SST, SSS or MLD), and α and β are solved with a least squares estimate to minimize the residuals between the observed and predicted SI values (Yen et al., 2012a).

Based on remote sensing data, the HSI can be applied to identify whether areas are suitable habitat for tuna (Yen et al., 2012a). It is a univariate variable with a value between 0 and 1. By adopting results from four commonly applied empirical models, i.e., the Arithmetic Mean Model (AMM) (Yen et al., 2012a), Geometric Mean Model (GMM) (Tian et al., 2009), Continued Product Model (CPM) (Grebenkov et al., 2006), and Minimum Model (MIN) (Van der Lee et al., 2006), different SIs are integrated to discuss the synergistic effects of various environmental factors on skipjack. Note that each model has its own suitability. To improve the accuracy of the modeling performed in this study, Taiwanese purse seiner data from the period of 1996–2012 were adopted as observations. The Person's correlation coefficient (r) between the observations and the outputs of these four HSI models was used to identify the best fitting HSI model.

[2] **Fishing effort** refers to the amount of fishing gear of a specific type used on the fishing grounds over a given unit of time. It is usually a measurement of the amount of fishing. The monthly data with the $1 \times 1^{\circ}$ grid resolution was employed for this analysis.