Spatial and temporal distributions of bigeye tuna (*Thunnus obesus*) catches affected by oceanographic condition and ocean climate variability in the eastern Indian Ocean off Java

(東部インド洋ジャワ島沖合における海況および気候変動とメバチマグロ漁獲量の時空間分布)

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1. Introduction

Bigeye tuna (*Thunnus obesus*) is a commercially targeted species and represents one of the most valuable species of longline fisheries in the eastern Indian Ocean (EIO) off Java. It is a highly migratory species that is distributed between 40°N and 40°S in all 3 major oceans, except in the southwestern sector of the Atlantic. In the upper water column at night, bigeye tuna prefer a thermal range of 22-26°C. The main depth range of fishing for bigeye tuna in the Indian Ocean is 161–280 m, although they can inhabit the 0–100 m depth range during the night.

The El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are two dominant modes of climate variations in the tropical Pacific and Indian Oceans with significant impacts to the ocean climate variability of several parts of the world. Therefore, for sustainable management of bigeye tuna resources in the EIO off Java, understanding the effects of ocean climate variability on catch distribution is essential. The ultimate goal of this study was to investigate how bigeye tuna catch distribution both spatially and temporally affected by oceanographic condition and ocean climate variability in the EIO off Java.

2. Materials and Methods

The study area was located in the EIO, south of Java, spanning between 6–16°S and 104–126°E.The oceanographic condition of the EIO off Java is affected by the confluence regions of the Indonesian Throughflow (ITF), the South Java Current (SJC), the Indian Ocean Kelvin Waves (IOKWs), Rossby waves propagation and the South Equatorial Current (SEC). Those ITF and IOKWs have strong inter-annual signal related to ENSO and the SJC also affects the surrounding area on seasonal time scales. Besides the enlisted dominant physical features, the region is also the location where the onset of IOD is generated. This study utilized bigeye tuna catch data, conductivity temperature and depth (CTD), mixed layer data set of argo float (MLD) and remotely sensed data. In this study, the bigeye tuna catch and satellite remotely sensed data were analyzed for the 12 years datasets from January 1997-December 2008 and emphasized the differences of climate conditions during strong (1997), moderate (2002), and weak (2006) El Niño, positive phase IOD (2003), strong (1999) La Niña, and normal year (2005) events. Remotely-derived environmental variables included sea surface height anomaly (SSHA) (AVISO), sea surface temperature (SST) (NOAA/AVHRR), Chlorophyll-*a* (Chl-*a*) (SeaWiFS), eddy kinetic energy (EKE) (AVISO) and wind direction and speed (NOAA derived from NCEP/NCAR reanalysis). The empirical orthogonal function (EOF) was performed to obtain a more detail structure of the spatial-temporal ocean variability together with wavelet spectrum analysis to highlight the dominant scales of the variability and its periodicity. Further analysis was undertaken with a generalized additive model (GAM) to examine the relationship between oceanographic conditions and catch rates of bigeye tuna. The catchability of bigeye tuna catch was computed for all months during 1997-2008. The catchability coefficient was defined as the proportion of available fish in the population that would be caught by a unit of fishing effort.

3. Results and discussion

3.1 Spatial and temporal variability of oceanographic factors in the EIO off Java

The first EOF modes of Chl-*a*, SSHA and SST accounted for 42.8%, 36.5%, and 27.4% of total variance, corresponded with interannual signal for all the first modes, respectively. The spatial patterns of the first and second EOF modes of SSHA, SST and Chl-*a* gave a very typical cold water of SSHA, low SST and high Chl-*a* concentration located along the southern coast of Indonesian archipelago and warm water of SSHA, high SST and much less Chl-*a* concentration in the offshore region to make frontal areas along the latitudinal line around 10–12ºS. The frontal areas seemed to reveal the confluence region of IOKW and SJC that meet with the outflow of ITF and SEC. The cold water, low SST and high Chl-*a* concentrations occurrence along the southern coast of Indonesian archipelago were likely a manifestation of El Niño and positive phase of IOD events, and upwelling evidence as shown on the first and second EOF modes, respectively. Those typical spatial patterns are consistent with the oceanographic conditions during September–November 1997 of strong El Niño event.

3.2 Habitat distributions of the bigeye tuna catches in the EIO off Java

The HR has the peak season from June-August that corresponded with preconditioning less energetic of current in April to May, warm SSHA during May and decrease to be much less warm after June following favorable condition with cold SST in June to August and high Chl-*a* concentrations in July to September.

HRs changed spatially around 10-16°S and 105-120°E, but they were mostly located on the confluence regions where ITF, westward Rossby wave propagation, and SEC meet in the most frequent bigeye tuna catch in the offshore region around 12-16°S and 110-118°E. The results of the GAM showed all explanatory variables used in the models to be statistically highly significant (*P*<0.0001) and explained 26.6%, 5.42%, 3.31% and 1.26% of the deviance explained in the single parameter models for Chl-*a*, SST, SSHA and EKE, respectively. The GAM results showed that bigeye tuna distributions in the study area were largely influenced by Chl-*a* and SST. This implies that upwelling event and remote forcing from the Pacific to the Indian Oceans by the ITF have a large impact on bigeye tuna catches.

3.3 Ocean climate variability impacts on the hotspots of bigeye tuna in the EIO off Java

Changes in oceanographic conditions during ENSO and positive phase of IOD events resulted in perceivable variations in bigeye tuna catches, with an increasing HR during El Niño and positive phase of IOD events. The La Niña event was less favorable for bigeye tuna catches. The averaged HR of 0.71 (0.43) was recorded during El Niño (La Niña) and 0.6 (0.3) during southeast (northwest) monsoon. Further analysis indicated that the peak season of bigeye tuna catch during southeast monsoon varied from year to year under different regional climatic condition. HR had significant increment during El Niño (1997-1998, 2002 and 2006) and positive phase of IOD (2003) compared to during La Niña (1999) and normal year (2005) events. This inferred that different ocean climate events might cause different oceanographic condition favorable to bigeye catch in the study area.

The spatial prediction of bigeye tuna catch during moderate (June 2002) and weak El Niño (June 2006), and positive phase of IOD (June 2003) showed high potential catches with averaged HR of 1 located mostly along the southern coast of Indonesian archipelago and averaged HR of 0.6 in the offshore around confluence region at 11–16ºS and 110–118ºE. This result is in contrast during the La Niña in June 1999 where predicted hotspots with averaged HR of 0.8 only distributed at the narrow zone in the coastal areas of 8-9ºS and 110-115ºE.

The higher value of catchability coefficients occurred during El Niño and positive phase of IOD events, in May 1997, June 1998, June-July 2002, June 2003, and May-June 2006 coinciding with HRs of 0.94, 0.83, 1.66-1.41, 0.86, and 0.46-0.51, respectively. It was interesting to note here that the high catchability coefficient during 2006 El Niño did not follow the increasing HR value in that period (0.46-0.51 HR), because most catches were made in the areas with less potential habitat of bigeye tuna catches. This dislocating fishing catch of bigeye tuna caused the HR during 2006 El Niño was much less than expected. I found that there were many potential fishing locations that were not used optimally. This inefficient use reduced the total catch to much less than the level that was expected during the El Niño.

4. Further consideration and conclusions

This study has shown how remotely sensed and in situ data together with the GAM, EOF and wavelet analysis could be used to monitor the ocean climate variability during ENSO and IOD as well as seasonal changes affect on different oceanographic conditions. The present study has reached the result as pre mentioned and need to be addressed for further important steps as follow: (i) to provide the information of hotspots of bigeye tuna with GIS tool and to distribute the hotspots map under automatic system displayed through internet connection; (ii) to develop a more accurate prediction system not only increase the capability of GAM but also improve and assimilate the such kind of SINTEX-F model (ENSO and IOD prediction from JAMSTEC); (iii) to develop habitat suitability model that sensitive to the climate variability; (iv) to apply the existing remote sensing infrastructures, oceanographic near real time data available through GEOSS (Global Earth Observation System of Systems) program; (v) there are some interesting highlights need to be explored more such the ITF and the upwelling Rossby waves propagation that have been strongly influenced the oceanographic conditions in the EIO off Java. Further study of this present needs to be addressed in the future.

This study has shown the effects of ENSO and positive phase of IOD induced oceanographic conditions on bigeye tuna catch distribution in the EIO off Java. EOF analysis provides evidence for the existence of the El Niño and positive phase of IOD which clearly induced certain oceanographic conditions in the EIO off Java, with the dominant features being negative SSHA, cold SST and high Chl-*a* concentration along the southern coast of Java. The GAM using four predictor variables may facilitate identification of areas with potentially high bigeye tuna catches in the EIO off Java. These results further emphasize that EOF and wavelet analysis combined with GAM could be applied to identify hotspot areas with highly potential bigeye tuna catches in the EIO off Java. Thus, these results would benefit the tuna fishery-management to reduce risks and increase economic capital as well as envisage better social decisions.