Mapping of potential fishing zones in support of fisheries management in West Africa

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ABSTRACT

The distribution pattern of three tuna species *viz*. Skipjack (*Katsuwonus pelamis*), Yellowfin (*Thunnus albacares*) and Bigeye (*Thunnus obesus*) and key environmental factors were analyzed to develop potential fishing zone (PFZ) maps to support fisheries resource management in West Africa. The PFZ maps were developed from a Generalized Additive Model built from a binomial distribution with a probit link function. Inputs into the model were presence- absence data generated from tuna catch records from Ghana as well as sea surface temperature (SST), sea surface heights (SSH), geostrophic currents (UV) and salinity (SSS) datasets covering latitudes 10°S to 40°N and longitudes 35°W to 15°E in the period 2014-2015. Results from the analyses showed a non-linear response pattern with varying relationships among the environmental factors. The major fishing grounds identified from the outputs of the predictive model corresponded with regions where SST was between 21 and 28.5 °C, SSH above 0.05 m, geostrophic current speed above 0.25 m/s and SSS levels above 33.5 ppt. High tuna distribution was consistent with the major upwelling regions, suggesting that the dynamics of the upper ocean may account for the observed spatial pattern. Outputs from the model can provide a quick overview of the possible areas where tuna is likely to aggregate and the potential fishing grounds where monitoring and surveillance need to be intensified.

Keywords: Tuna; Generalized Additive Model; Potential fishing zone maps; fisheries management, Guinea Current

Introduction

Tropical tunas occupy the warm upper oceanic waters, with temperatures between 20-30°C (Holland *et al.,* 1990). In the eastern equatorial Atlantic, the optimal oceanographic conditions support high abundance of tuna. There are many fishing companies operating in the high seas targeting mainly Skipjack (*Katsuwonus pelamis*), Yellowfin (*Thunnus albacares*) and Bigeye (*Thunnus obesus*) tuna in the region.

The tuna industry of West Africa makes a considerable contribution to food security and provides economic benefits. The region serves as an important spawning ground and migratory path (Fromentin and Powers, 2005), and catch information from surface gears indicate that the eastern equatorial Atlantic is a major nursery ground for tuna (Mensah and Quaatey, 2002). Trends in catch over many decades in the major tuna fishing countries in West Africa show a steady increase, from about 1,000 tonnes in the 1960s to over 80,000 tonnes in 2000 (Miyabe and Nakano, 2004). The increased catch is not only a result of the high occurrence of tuna species but can also be attributed to increased fishing pressure from the tuna fisheries industry. This can result in the collapse of the tuna fishery, hence the need to adopt management measures for sustainable exploitation of the resource in line with current trends in global climate change.

Current increases in sea surface temperature associated with global climate change and the increasing fishing pressure are expected to affect fish stocks (IPCC, 2007).

Generally, warming climate will increase stratification of the upper ocean, which will reduce nutrient regeneration for increased plankton growth. This may affect migration, feeding behaviour and spawning, and in the long term, the existence of marine living organisms. Even more threatening is the irreversible impact of overfishing of many ecosystems which affects not only the balance of life in the oceans, but also the social and economic well-being of coastal communities. Adopting conservation methods for effective management of the tuna fisheries requires an in-depth understanding of the impact of changes in the habitat of fish (Holland *et al.,* 1990). Such changes have been observed to affect foraging behaviour and migratory patterns of pelagic fishes (Gutenkunst *et al*. 2007).

The eastern tropical Atlantic is the spawning ground for these tunas (Mensah and Quaatey, 2002). They are known to undertake large-scale migration over long distances, often staying outside the Exclusive Economic Zones of countries in West Africa (Blackburn and Williams, 1975), which makes them vulnerable to illegal fishing practices. There is high incidence of illegal fishing activities in the Gulf of Guinea (Nunoo *et al.,* 2015). For instance, the unselective fishing of juveniles and small tunas by purse seiners through the use of fish aggregating device (FAD) and other sophisticated equipment like sonars, radio buoys, echo sounder, fish finder, etc. appear to make this fisheries unsustainable (Adinortey *et al.,* 2014). This, coupled with weak enforcement of fishing and maritime laws, makes marine living resources vulnerable and likely to be overfished. This raises concerns about management approaches that need to be adopted for sustainable harvesting of such commercially important fish species. Currently, many coastal states including developing countries have adopted electronic vessel monitoring systems (VMS) in their fisheries management strategies. These include the use of Automatic Identification System data to provide near-real time traffic, navigation and vessel information for fisheries application (Natale *et al.,* 2015).

This systems can be implemented at national to regional scale to effectively identify the major fishing grounds and monitor the activities of fishing vessels in those areas. This, when implemented operationally, can provide near real-time and forecasts of fishing grounds to fisheries managers and other national agencies such as the coast guards and the navy.

Methodology

Tuna catch data from 2014 to 2015 were obtained from logbooks of purse-seine tuna fleets, courtesy of the Fisheries Scientific Surveys Division of the Fisheries Commission of Ghana. The data comprised tuna catches (in tonnes) for three dominant species in the eastern equatorial Atlantic, the geographic coordinates where they were fished, and the dates of each catch. In our analysis, monthly catch-per-unit effort (CPUE) were calculated from the total weight of tuna caught and the number of fishing days in the month.

Four environmental parameters, i.e. sea surface temperatures (SST), sea surface heights (SSH), geostrophic currents (UV components) and salinity (SSS) datasets with a spatial resolution of 9 km over a spatial extent of 10°S to 40°N and 35°W to 15°E in the Atlantic Ocean were extracted from the global Mercator Ocean products for the same period. Monthly variations in the environmental parameters were analyzed to ascertain any potential impact on the distribution of tuna in the eastern equatorial Atlantic in a predictive model.

Construction of Generalized Additive Model (GAM)

A spatial predicting tool for empirically estimating the distribution of fish was constructed from a generalized additive model. Predictors for the model were SST, SSH, geostrophic current and SSS. A presence/absence variable was constructed from the tuna data by assigning a value of 1 to every grid from which any of the three tuna species was caught and a value of 0 to every grid with no catch. The presence-absence tuna data followed a binomial distribution. Consequently, the GAM used a binomial distribution as the family associated with a probit link function. The GAM was implemented in R data analysis statistical package (version 0.97.551) as:

$$\mathbf{y \sim \alpha + s(SST) + s(SSH) + s(Currents) + s(SSS) + \varepsilon}$$

where y is the response variable, α is a constant and ε is the error term; s is the spline smooth function of the predictors.

Results

Tuna abundance

The trend in tuna catch data for the study period shows monthly variation in abundance of tuna in the eastern tropical Atlantic (Figure 1). There is considerable reduction in abundance during January to March. A closed season is enforced each year between February and March in the equatorial Atlantic on tuna vessels flagged to Ghana. The Fisheries Enforcement Unit (FEU) of the Monitoring, Control and Surveillance (MCS) Division of the Fisheries Commission has the national mandate to ensure sustainable fisheries management. The FEU is equipped with electronic monitoring systems that can track all fishing vessels participating in the vessel monitoring programme. The catch composition from the logbook records indicates that Skipjack was the dominant species, accounting for about 59% of the weight of tuna landings in Ghana (Figure 2). The two other common species, Bigeye and Yellowfin accounted for 15% and 27% of the landing, respectively.

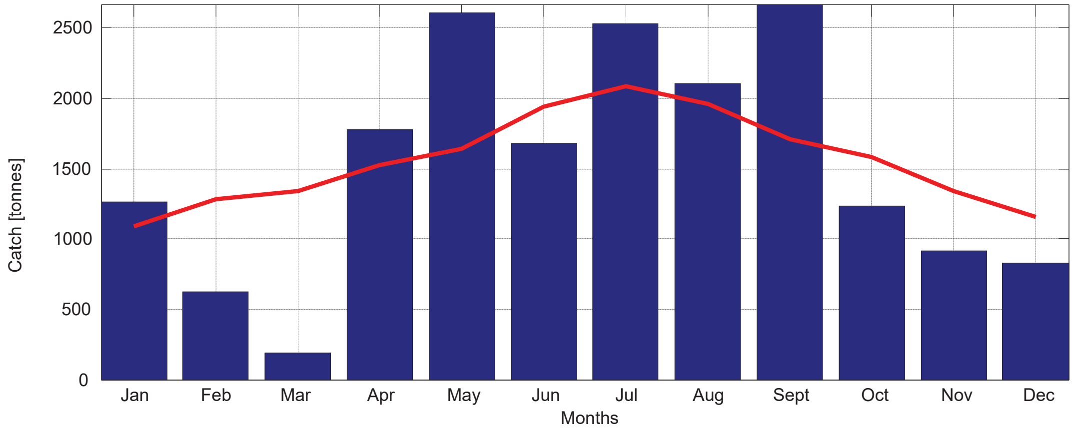


Fig. 1: Catch per unit effort (weight in tonnes/number of fishing days – blue bars) and average catch (tonnes – red line) for Skipjack, Yellowfin and Bigeye tuna in the eastern equatorial Atlantic. (The values are averages for each month for the two years, 2014 and 2015).

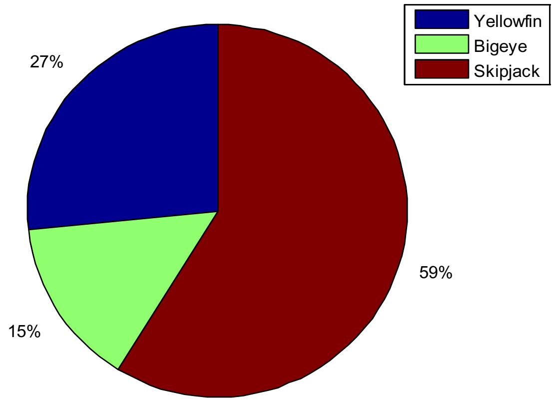


Fig. 2: Percentage composition of Skipjack, Yellowfin and Bigeye tuna in the eastern equatorial Atlantic from 2014 to 2015.

Fishing effort also varied at a trend similar to the observed seasonal trend in abundance during the study period. High catch per unit effort (CPUE) was recorded from May to September. During periods of reduced fishing intensity the percentage distribution of Skipjack increased slightly, which may suggest it was a response to reduced effort coupled with improved biological productivity within the region. Tuna abundance for all the three species peaked during September/October which is the end of the major upwelling season.

Seasonal variability of oceanographic conditions

Monthly variability of catch and oceanographic conditions (SST, SSS, current velocity and SSH) between 2014 and 2015 closely followed a seasonal pattern (Figure 3a-d). High tuna catch was found in June to September where SST was coldest (Figure 3a), SSS was at its peak (Figure 3b), velocity of surface currents in the equatorial Atlantic was highest (Figure 3c) and SSH showed negative anomalies (Figure 3d). The peaks of catch occurred during the periods when the seasonal upwelling (upward flow of cold nutrient-rich bottom water) had intensified. SST during that period was at its minimum, and ranged between 25.5 and 26.5°C. Low catches were recorded during months when SST exceeded 27.5‰. In the Guinea Current region, salinity levels were lower in January but steadily increased in April, and remained dense from June till August, after which they began to dip (Figure 3b). Salinity ranged between 34 and 35°C in the Guinea Current region during the study period. The trend in surface current velocities showed that the Guinea Current experienced minimum current velocities from January to April and from October to November (Figure 3c). Maximum velocities were observed from May to August, a period which has a strong connection with increased wind speeds during the upwelling season.

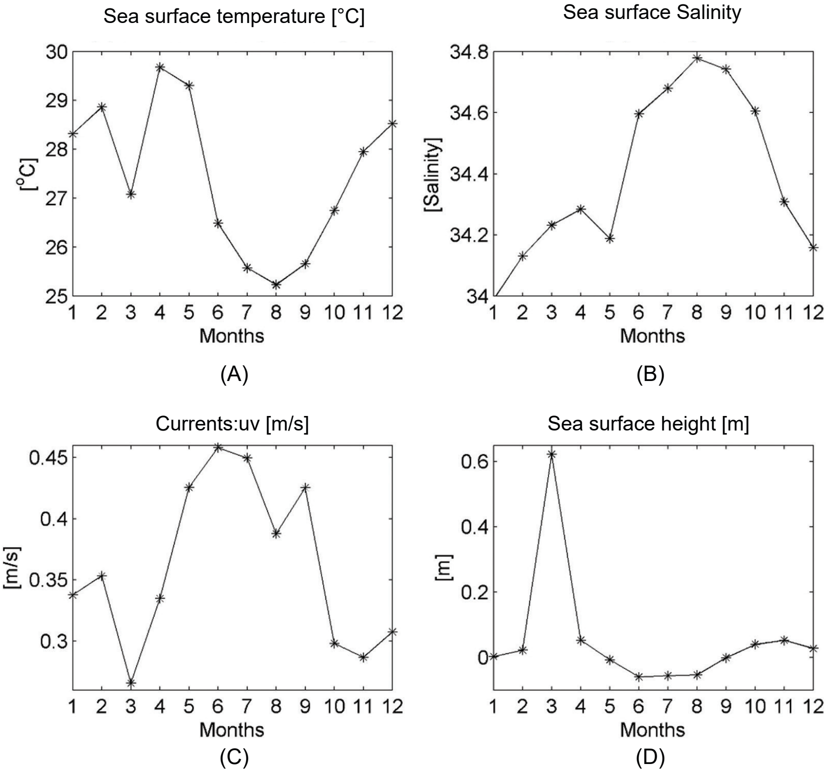


Fig. 3: Monthly variation in (A) sea surface temperature (B) sea surface salinity (C) currents and (D) sea surface height from tuna catch locations. (The values are averages for each month for the two years, 2014 and 2015).

Preferred oceanographic conditions from tuna catch data

Generalized Additive Model (GAM) analyses using SST, SSS, surface current velocity and SSH as predictors yielded a significant reduction in the residual deviance using a $\chi 2$ test (Table 1). When the four predictors were used alone, SST had the lowest AIC. Subsequently, SSH, currents and SSS were added to the model, which further reduced the AIC and residual deviance. This indicates that the strong combined effect of these environmental parameters influenced tuna distribution in the eastern equatorial Atlantic. Among all the relationships shown in Table1, predictor variables of Model 7 were significantly non-linear ($\chi 2$-tests: $p < 2.2*10-16$) with the least residual deviance value.

Table 1: Analysis of deviance of three-variable GAM of presence-absence data of tuna catch. (Changes in AIC and residual difference, degrees of freedom and associated significance from a Chi-square test)

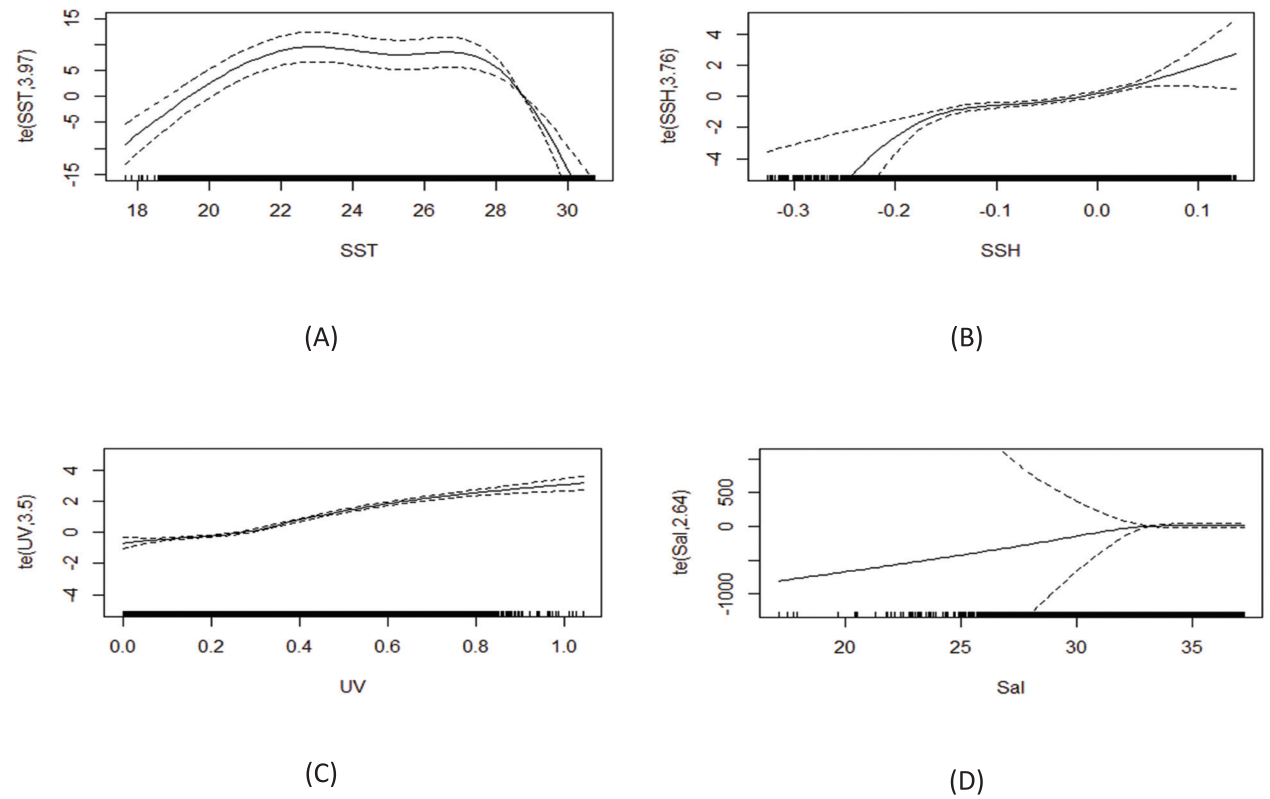
Model	AIC	Residual deviance	χ^2 p-value
1. Occurrence ~ SST	3404.6	3782.1	<<0.00001
2. Occurrence ~ Current velocity	3416.9	3774.8	<<0.00001
3. Occurrence ~ SSH	4062.9	4623.3	<<0.0001
4. Occurrence ~ SSS	4289.3	4933.9	<<0.0001
5. Occurrence ~ SST + SSH	3263.2	3615.9	<<0.00001
6. Occurrence ~ SST + SSH + Currents	2105.9	2014.9	<<0.00001
7. Occurrence ~ SST + SSH + Currents + SSS	2100.0	1981.3	<<0.00001

Temperature had a predominant influence on tuna distribution. It had the lowest residual deviance when compared with SSH, currents and SSS. The loess plot revealed a non-linear response pattern with a strong positive relationship between temperature and tuna distribution from about 21˚C to 28.5˚C (Figure 4a-d). From the plot, temperatures between 22.2˚C and 27.6˚C provided the best thermal condition that influenced tuna aggregation.

Sea surface height data revealed that the tunas were mostly concentrated in regions with surface height anomalies above -0.03 m but not exceeding 0.05 m (Figure 4b). These SSH were observed in the shelf regions off Ghana, the equatorial region and northern parts of the Guinea Current. Ocean surface heights for these ranges were predominantly observed from July to September and associated with increased primary productivity.

The loess plot showed that surface current velocities associated with tuna catch distribution occurred in regions of the ocean with current speeds above 0.28 m/s (Figure 4c). The plot further indicates that there is almost a direct linear relationship with current speed and the abundance of tuna. Spatially, most regions of the Guinea Current often do not have magnitude of surface currents exceeding 0.4 m/s except during the upwelling season from July to September.

In the eastern equatorial Atlantic, salinity levels recorded from the tuna catch position did not exceed 35 ppt (Figure 4d), which was relatively low compared to the coastal waters. However, the regions off the northern coast of Gambia and the upwelling regions in the Gulf of Guinea had relatively high salinity levels almost all year round.



(A) (B)

(C) (D)

Fig. 4: Loess plots of (A) sea surface temperature (B) sea surface height (C) currents (D) sea surface salinity used in the Generalized additive model (GAM). (Dashed lines indicate 95% confidence intervals. The relative density of data points is shown by the inner ticks on the x-axis)

An output from the GAM using SST, SSH, surface currents and SSS as inputs ensures fisheries managers can now forecast potential fishing zones (PFZ) with some degree of certainty. Figure 5 shows a forecast product that indicates that the optimal conditions conducive for fishes to aggregate were in the equatorial regions and north of latitude 6°S which are the major upwelling regions. Low probability of tuna occurrences was observed in the coastal waters with riverine discharge from the Niger and Congo rivers, as well as regions traversed by the westward flowing North Equatorial Counter Current (NECC). Changes in the spatial distribution of tuna are expected to vary with processes that drive phytoplankton growth and changes in riverine discharge and current flow systems in the region.

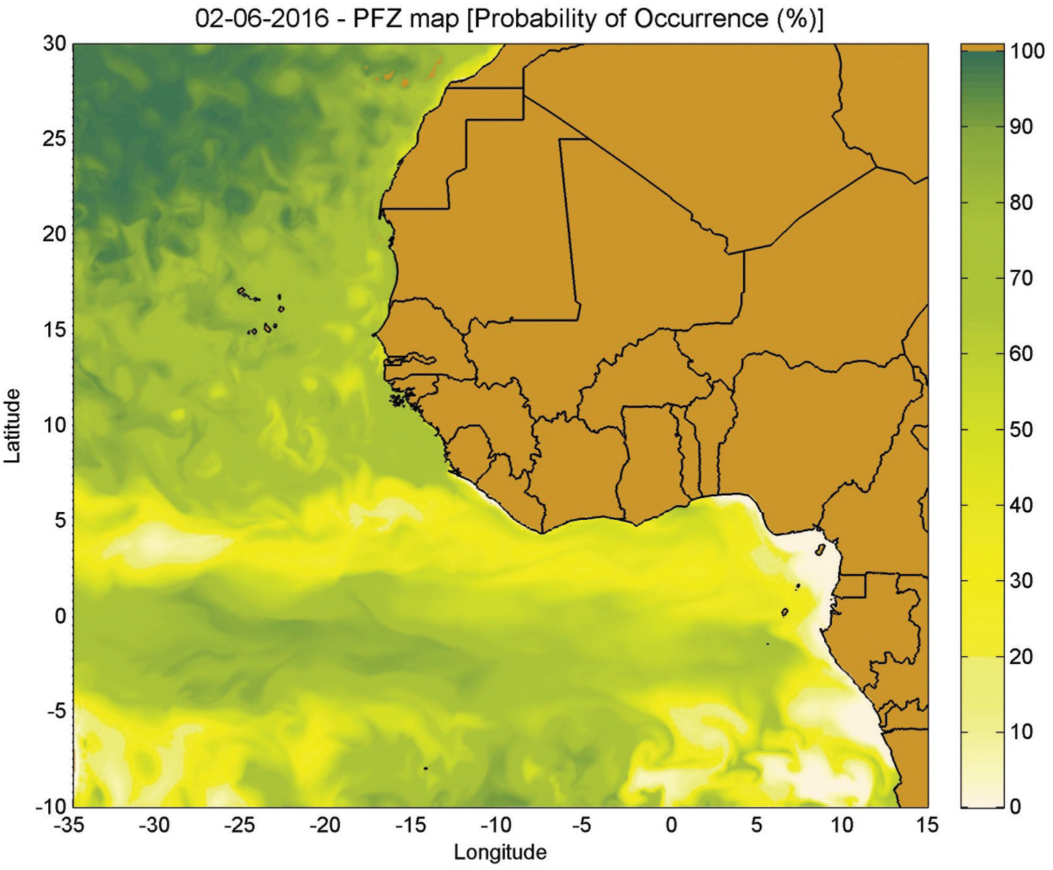


Fig. 5: Potential fishing zone map derived from Generalized additive model (GAM) with oceanographic parameters (sea surface temperature, sea surface height, sea surface currents and sea surface salinity) as inputs. The scale (0-100) gives an indication of favourable conditions that promote fish aggregation.

Discussion

Tuna catches in the Gulf of Guinea largely occur in two major upwelling areas, i.e. off the shelf waters of Ghana and Cote d'Ivoire, and within the equatorial waters. In the Gulf of Guinea, the seasonal upwelling which peaks during July to September ensures an abundance of plankton (Wiafe *et al.,* 2008) that is preyed on by small pelagics, especially *Sardinella,* which are in turn preyed on by large pelagics (Koranteng, 2002). These biological interactions in the Gulf of Guinea increase food availability for large pelagics, which explains the rise in tuna abundance. Sardines have been observed to be an important component of the diet of juvenile Pacific Bluefin tuna, *Thunnus thynnus orientalis,* in the productive waters off Japan (Baillif, 1991; Polovinia, 1996). It was observed in this study that an increase in tuna catch occurred after the upwelling season. During this period in the equatorial Atlantic, there is a slight rise in temperature. Increased temperature after upwelling may have improved temperature preference for tropical tuna. The sub(surface) vertical movements bring nutrients and subsequent local enrichment that enhance phytoplankton growth with a corresponding increase in zooplankton (McGlade *et al.*, 2002) and small pelagics which are the preferred tuna prey (Sevchenko, 1996). Results of PICOLO I and II experiments in the tropical Atlantic indicate increased zooplankton biomass (copepod) is associated with increased Chl-a concentrations and decreased SST during periods of increased upwelling (Champalbert and Pagano, 2002).

The low abundance of Bluefin can be attributed to the conservation efforts being implemented by the regional fisheries management organizations (e.g. International Commission for the Conservation of Atlantic Tunas - ICCAT) mandated to ensure the sustainable use of the resource. These management strategies specifically target Bluefin, which prohibits fishing in the East Atlantic by large-scale baitboats and trolls. These industrial fishing fleets in recent years are permitted to fish from 1 July to 31 October. Again, fishing vessels flagged to Ghana are prohibited from fishing from January to February, further reducing fishing efforts and catch during those periods.

Fishing effort of tuna followed a seasonal pattern similar to tuna abundance in the eastern Atlantic. There is intense fishing during the period of the year when upwelling intensifies resulting in high phytoplankton abundance and its associated cold surface temperatures. Changes in temperatures have also been observed to affect fish activity and distribution. Studies of temperature effect on metabolic rate and swimming speed of Pacific Bluefin tuna suggest there is reduced metabolism and activity during intermediate ambient temperatures and considerably high metabolism at very low or high temperatures (Blank *et al.,* 2007). There is also the tendency for tuna to vertically migrate in response to changing temperature in the upper ocean surface (Kitigawa *et al.,* 2000). Copepods, the dominant zooplankton, peak in numbers during the upwelling season (Wiafe *et al.,* 2008), and are the preferred prey of *Sardinella spp.* (Koranteng and McGlade, 2001). Increased primary and secondary production, inadvertently, will result in food availability for tuna in the equatorial and shelf regions in the Gulf of Guinea. During this period there is intense fishing by both the artisanal and industrial fisheries for small pelagics and high value commercial species including tuna. The warming of the Guinea Current large marine ecosystem peaks in January to May. This creates a highly stratified conditions with a deep and strong thermocline which locks the nutrient-rich water at deeper depths.

The GAM analyses revealed strong environmental influence on the distribution of tropical Atlantic tuna. The optimal range for the four parameters associated with fish catch locations which were observed are also linked to the intensification of the upwelling in the Gulf of Guinea. This strong connection between the distribution of the tuna and upwelling gives credence to the huge importance that regional and international fisheries management bodies attach to fishing activities in that area. The output from this model will be useful for monitoring the temporal and spatial changes in the upper ocean and their influence on tuna distribution. A reliable and timely generation of this habitat mapping information will further enhance the sustainable management of tuna resources. Inference made from the forecast PFZs can ensure that activities of fishing fleets that target Atlantic tuna can be predicted to identify areas which are likely to be targeted for fishing. Hence, monitoring and surveillance patrols can be planned based on hotspots identified from the PFZ maps.

High AIC and residual deviance observed during the initial setup of the GAM with only SST, SSH, SSS and surface currents clearly indicates that the distribution of tuna, like many other fishes, responds better to a suite of environmental parameters. However, the lowest AIC or residual deviance for surface temperature, when compared with surface height, salinity and currents, further indicates its major role in fish assemblages in the major upwelling centres. Walsh and Kleiber (2001) noted the importance of temperature on tuna based on the physiological impact and ecological influence on the species. Temperature exerts a strong effect on energetic demands of endothermic species, and it influences biological production in marine ecosystems. Regions in the Guinea current LME with high tuna distribution are the upwelling centres off the shelves of Ghana-Cote d'Ivoire and the equatorial Atlantic which have moderate to low surface temperatures, negative SSH anomalies, relatively high surface currents and low salinity. Wexler *et al.* (2011) provides various thermal preferences for survival, development and growth of Pacific Yellowfin tuna larvae. For instance, yolk sac and first-feeding Yellowfin larvae exhibited lethal limits for their survival at temperatures less than 21°C and greater than 33°C. These figures are within observed thermal ranges in the eastern equatorial Atlantic, supporting studies that indicate the area is a spawning and nursery area.

Conclusions

The spatial distribution of tuna followed the cold tongue of water that emanated from the southwestern coast of Africa, which moved westward along the equator. This has a persistent connection with the upwelling regions of the west coast of Africa. Tuna catch locations were in less warmer waters with relatively less thermal variation. Those areas in the Gulf of Guinea are also highly productive, especially during the upwelling seasons. Outputs from the model can provide a quick outlook of the possible areas where tuna is likely to aggregate and the potential fishing area where monitoring and surveillance needs to be intensified.

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