Thesis for the Degree of Master of Fisheries Science

Environmental effect on the skipjack tuna (*Katsuwonus pelamis*) fishery in the Sri Lankan waters

by

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Pukyong National University

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스리랑카 가다랑어 어업에 대한 해양환경의 영향

Advisor: Prof. Suam Kim

by

Mahadurage Ishara Gimhan Rathnasuriya

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Abstract

Skipjack tuna (*Katsuwonus pelamis*) is one of most important species in Sri Lankan waters and this species and fisheries show highly sensitive to their environmental changes. This study shows variation of skipjack tuna abundance in Sri Lankan waters in relation to changing environmental parameters. Nine year satellite derived environmental parameters (sea surface temperature (SST), sea surface chlorophyll (SSC) and sea surface height (SSH) and offshore skipjack tuna catch and effort data were obtained. Results of the analysis showed that skipjack tuna showed seasonal variations in their abundance with environmental parameters. An empirical cumulative distribution function (ECDF) approach identified that high catch per unit effort (CPUE) of skipjack tuna occurred when SST ranged from 28 to 29.5 ^{o}C, SSC concentration ranged from 0.05 to 0.5 mg/m^3 and SSH ranged from 80 to 90 cm. Cross correlation functions (CCF) results of the average SST with CPUE were positive and significant, with positive time lag of 2 months during the study period. CCFs of the average SSC with the CPUE were positive and significant, with positive time lag of 6 months. These results showed SST and SSC are important environmental parameters affecting on abundance of skipjack tuna resources in Sri Lankan waters.

1. Introduction

1.1 Fisheries in Sri Lankan Waters

The Marine fisheries in Sri Lankan plays a vital role by providing livelihoods for coastal communities and providing more than 50% of animal protein requirement for people in the country. Marine fisheries sector shows increase trend of its share for the Gross Domestic Production (GDP) of the country in 2012 (Statistics MFARD, 2013). The Marine fisheries mainly consist with two sub sectors, coastal and offshore fisheries with total production of 445,930 metric tons (MT) in 2013.

Before 1980 the marine fisheries activities mainly concentrated within the coastal belt and the production was reached their optimum levels (Maldeniya and Amarasooriya, 1998). Since 1960 there had been many attempts by the government to develop the offshore fisheries. Introduction of new nylon nets, fibre-reinforced plastic (FRP) boats and craft motorization were helped to develop the fisheries production in both coastal and offshore sectors. The marine production of Sri Lanka mainly comprised with coastal species (such as clupeids, large pelagic tuna, carangids) before introduction of multiday boats and advance technologies to fisheries sector. Later offshore pelagic species have shown significant increasing trend in total marine production. Offshore fish production is mainly comprised with tropical tuna and tuna-like species such as yellowfin tuna (*Thunnus albacares),* bigeye tuna (*Thunnus obsesus*), skipjack tuna (*Katsuwonu spelamis*), kawakawa (*Enthynnus affinis*)*,* frigate tuna (*Auxis thazard*), bullet tuna (*Auxis rochei*), bill fish, sharks and seer fish. Estimated large pelagic fishery production in 2012 was 105,240 MT and tuna catch represents 66,840 MT (63%). Large pelagic catch is dominated by skipjack tuna by representing 24 % to total while yellow fin tuna takes second place (Jayasooriya and H.M.U.Bandara, 2013).

A marine fishery of Sri Lanka is comprised with multiple crafts and has been evolved over the last decades with technological improvements. Approximately 53,590 fishing vessel are operating at present in the marine fishery of Sri Lanka (Statistics MFARD, 2013). Of which 90 % are engaged in coastal fisheries activities which target multispecies according to seasonal variations. Offshore fishing crafts represents rest of 9 % with rapid increasing over the past decade to target large pelagic fisheries with special attention on tropical tuna species.

1.2 Skipjack Tuna Species

Skipjack tuna (*Katsuwonus pelamis*) is a medium size perciform pelagic fish belonging to scombridae family. It is a tropical highly migratory tuna species mainly found in warm waters (sea surface temperature between 24 and 32 °C) of the Atlantic, Pacific, and Indian Ocean. Also a small percentage of catch comes from temperate waters between 18 and 24 °C (e.g., in New Zealand and Azores). It inhabits upper mixed layers of ocean and form both free schools and schools associated with floating objects (ISSF, 2014 , Collette and Nauen, 1983).

Skipjack tuna mainly feeds on fish, crustaceans and mollusks such as cephalopods. Also it plays an important role as prey species for large pelagic fishes and sharks. It commonly reaches fork lengths up to 80 cm (31 in) and a weight of 8–10 kg and the estimated potential lifespan ranges between 8 and 12 years (Wikipedia, 2015).

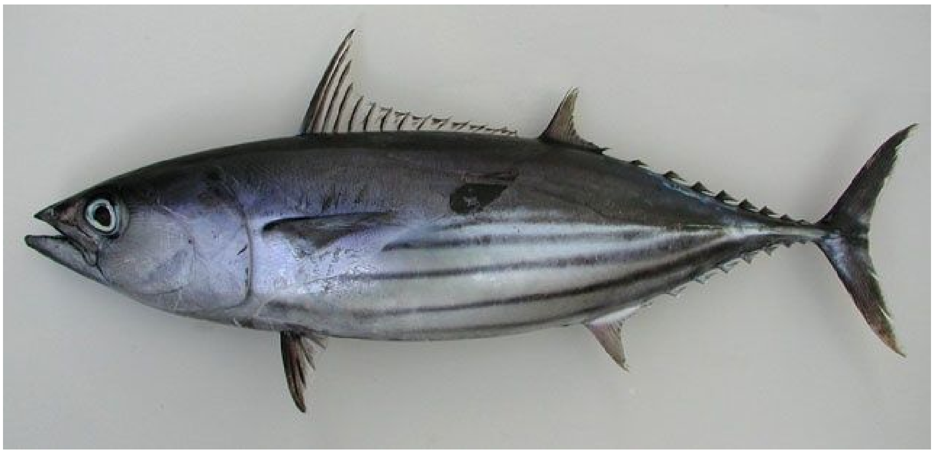

Figure 1. Skipjack tuna (*Katsuwonus pelamis*). (Source of picture: http://www.fishbase.org (by Fujiwara, S)).

Skipjack tuna believe to be as resilience species at current fishing pressure due to high fecundity, spawning throughout the year, rapid growth rate and short life span (AsiaPacific-FishWatch, 2015, Adam, 2010). It is difficult to assess the stock status, due to its high and variable productivity and its continuous re-location and variable recruitment that make growth estimates difficult. According to recent stock assessments, skipjack tuna resources in the Western and Central Pacific and Indian oceans are stated as not overfished (ISSF, 2014).

1.3 World’s Skipjack Tuna Fishery

Skipjack tuna is one of the main commercial species in the world. According to the fishery statistics, skipjack tuna was world's second-most important capture fish species in 2009 (ISSF, 2014 , Wikipedia, 2015). Also it contributes more than one half of the total world catch of principal market species of tuna.

Skipjack resources is caught by local fishers and/ or foreign licensed vessels using many different fishing gears, from traditional to industrial and recreational, including purse-seine, pole-and-line, ring nets, hand lines, troll and gillnets. The industrial scale exploitation of skipjack fisheries started in the early 1960s within Eastern Pacific Ocean and the Atlantic Ocean, and it progressively expanded to the Western Pacific Ocean in the 1970s and to the Indian Ocean in the 1980s (Dueri et al., 2014).

There are 5 stocks of skipjack tuna worldwide, Eastern Atlantic, Western Atlantic, Eastern Pacific, Western Pacific and Indian Ocean. All skipjack tuna resources are managed by regional tuna fisheries management organizations (RFMOs) and by national governments (ISSF, 2014) to achieve sustainable utilization of tuna resources with current fishing pressure and climate impacts.

1.4 Skipjack Tuna Fishery in Sri Lanka

Tunas have contributed significant amount of total fish landing in recent decades in Sri Lanka. Especially in recent years tuna represented more than 50% of total landings in large pelagic fish production. The fishery has undergone changes in craft and gear over the last four to five decades. Almost 5000 boats are currently engage in tuna fishing activities, among them about 600 are categorized as single day boats operated in coastal areas and rest of the boats are multiday fishing vessels where operated in deep sea areas within and out of EEZ areas. Multiday fishing vessels mainly target large size tuna species such as yellow fin tuna (*Thunnus albacares),* big eye tuna (*Thunnus obsesus*), skipjack tuna (*Katsuwonu spelamis*) and single day boats and other coastal fishing crafts targets skipjack tuna and other small tuna varieties (kawakawa (*Enthynnus affinis*)*,* frigate tuna (*Auxis thazard*) and bullet tuna (*Auxis rochei*)).

Fishing gears used in tuna fisheries in Sri Lanka consists gillnet, long line, troll line and pole and line. Relative importance of the different type of fishing gears has changed throughout the past few decades with introduction of new technologies to the fishery. Troll lines and pole-and-line were dominant during 1960s, but gill net became major fishing gear in tuna fisheries since 1970s (Joseph and Moyiadeen, 1986). During last decade long line became important fishing gear to promote of quality fish production for cater the rapidly developing export market (Jayasooriya and H.M.U.Bandara, 2013). At present condition large mesh gill net and long line are widely used while gill net cum long line combination contributes to more than 75 % of the total tuna fishing effort in the country (Jayasooriya and H.M.U.Bandara, 2013).

Skipjack tuna plays a vital role in marine fishery production in Sri Lanka since early development of fishery (Amarasiri and Joseph, 1986, Haputhantri, 2014). It maintains highest catch which landed from both coastal and offshore large pelagic fishery over the past decades. The estimated skipjack tuna production in 2013 was 25,759 MT which is 54 % reduction in total production compare to 2012 (NARA, 2014). Out of total skipjack tuna production in 2013, 96 % of catch originate from offshore fishery operations while coastal fishery represents 4 %.

Skipjack tuna annual production over the past decades showed clear increasing trend up to 2010 with highest production of 66,910 MT in 2010. Subsequently production follows a declining trend up to present.

Gillnets alone or in combination with other gears, are the main fishing gear used in skipjack tuna fisheries in Sri Lanka. The troll lines, hand lines, ring net and purse seines are the other gear combinations that frequently carried out with gillnet cum longline operations (IOTC, 2006, Dayaratne and Maldeniya, 1995). Pole line fishery has being seasonally practiced for targeting coastal inhabit skipjack tuna in south and east coast of Sri Lanka (Maldeniya and Amarasooriya, 1998). According to the large pelagic production data during 2012 and 2013, it is clear that 68 %, 14 %, 11 % and 7 % of skipjack tuna comes from large mesh gillnet, ring net operations, hand line and tuna long line respectively (Jayasooriya and H.M.U.Bandara, 2013). Gillnet fishery runs throughout the year, with effort being considerably more during the southwest monsoon period of May to October (Amarasiri and Joseph, 1986). Specially, skipjack tuna pole-and-line fishery only operates in southern part of Sri Lanka during November to March. Studies revealed that offshore skipjack tuna production increased from January to July and then it decreased and remained more or less steady level during the rest of period (IOTC, 2006).

Statistics on skipjack tuna production clearly showed highest production in the southern statistical zone of Sri Lanka while minimum in the north-western statistical zone. The peak skipjack production period in southern (southwest, south and southeast statistical zones) and western coast (west and northwest statistical zones) was in July and June respectively while it was September in northeast statistical zone (IOTC, 2006).

1.5 Climate of Sri Lanka

Sri Lanka is located in the Indian Ocean, southeast of India, between 5°55' and 9°51' N latitude, and 79°41' and 81°53' E longitude (Wikepedia, 2015). Country has tropical climate with two main weather periods, i.e., south-west monsoon and north-east monsoon. The south-west monsoon takes place from May to August, which brings rains to the southern and western coastal regions, and the central hill country. The north-east monsoon takes place from October to January, which brings rain to the north and east of the island. This is weaker and shorter-lived than the southwest monsoon. There is also an inter-monsoon period in October and November when rain and thunderstorms can occur in many parts of the country (De Bruin et al., 1994).

Large scale oceanic-currents around Sri Lanka are governed by the monsoonal wind patterns and temperature changes in region. Currents of the east of the island are strongest during the north-east monsoon (November-March), and follow a gyre which changes from clockwise to anti-clockwise and back again during the course of the year. Currents in the south of the island flow eastwards from about May to about October, and westwards for the remainder of the year. In general the currents off the east coast are stronger than those off the west coast, while those off the southern coast are among the strongest (De Bruin et al., 1994).

1.6 Climate Change Effects on Ocean Fisheries

Climate change has been part of the natural order of our planet; as a consequence of excessive greenhouse gas (GHG) emissions from fossil fuel combustion in energy generation, transport and industry, deforestation and intensive agriculture amplified these changes over the last decades. It is now clearly recognized that climate change as one of the greatest threats facing mankind today (Williams and Rota, 2011).

Future impacts of climate change on marine ecosystem and fisheries are increasing concerns due to its high uncertainty in capture fisheries. Furthermore demographic growth and rising incomes are expected to boost the demand for fish products and further increase the pressure on marine resources (Garcia and Rosenberg, 2010). Changes in climate is expected to affect the marine environment by modifying the physical and chemical properties of seawater (temperature, salinity, currents, vertical stratification, oxygen concentration) and result in changes of primary production of the global ocean. It is known evident that all these changes are tied with the dynamics of many marine fish stocks (Lehodey et al., 2006, Brander, 2010, Drinkwater et al., 2010).

1.6.1 Direct Effect of Climate Change on the Oceanic Fisheries

It is proved that many marine organisms are likely to respond to projected changes in water temperature, dissolved oxygen (O_2), ocean currents and ocean acidification to optimize their use of energy for growth, movement, predation and reproduction (Pörtner, 2002, Pörtner, 2006). These direct effect of climate change mainly affect on the physiological performance of an individual fish (Lehodey et al., 2011) significant effect on the distribution of both oceanic and coastal fish populations (Bell et al., 2010).

Effect of Sea Surface Temperature

Sea surface temperature (SST) is first and most important factor which climate change can directly affect the important biological processes of fish including growth, reproduction, swimming ability and behavior. Also each species of fish has a limited range of SST which helps to maintain their optimum physiological activities.

It is clearly proved that tuna species have shown their vertical and horizontal distribution as a results of the changes in SST though they have specialized anatomy (i.e. a vascular counter-current heat exchanger) allowing them to sustain muscle temperature which help to increasing both their physiological performance and temperature range which they can live (Barrett and Hester, 1964, Carey and Teal, 1966, Neill et al., 1976). This adaptation allows extending feeding habitat of the adult tuna to the reach deep forage layers (Musyl et al., 2003) or more productive temperate surface layers. Also the sensitivity of the different life stages of each tuna species to SST can be varied due to their physiological differences. Especially larval and juvenile tuna are more sensitive to temperature and wide their thermal habitat as they become younger.

SST changes have both negative and positive consequences on skipjack tuna resources which are varied among the oceanic region. According to the RCP 8.5 scenario temperature will increase up to 33 - 34 ^{0}C in the equatorial zone and particularly in the warm pool of the Western Pacific ocean water which exceeds the temperature tolerance of skipjack tuna ranges between 20 and 32 ^{0}C (Dueri et al., 2014) and affects negatively on their survival/ distribution. Also, effects will occur in the Eastern Pacific and Western Atlantic oceans. Nevertheless, increased stratification and strong vertical temperature gradients of water column due to higher SST may limit vertical distribution of skipjack tuna.

Ocean warming may have effects on the changes of spawning location and the success of year-class skipjack tuna due to their phenological adaptations such as shifting of spawning grounds from tropical to subtropical waters and early spawning seasons (Lehodey et al., 2011). As a result of changes in spawning patterns may have possible changes in larval distribution, survival and recruitment.

Dissolved oxygen (DO) is a fundamental and limiting factor for fish metabolism and determines growth and activity levels (Brett, 1979), and which is closely related with both biotic and abiotic factors/ processes of the ocean system (biological production, temperature, salinity, ocean circulations and mixing). The performance of oceanic fish species related to availability of DO is complex beyond their basic maintenance functions (Lehodey et al., 2011) and limitation with their thermal envelope (Pörtner and Knust, 2007).

Recent studies have proved consistently decreasing trend of DO in all major ocean basins (Joos et al., 2011) as a result of larger-scale processes occurring at higher latitudes. Specifically, the increasing temperature and thermal stratification of the ocean at higher latitudes are lead to decreased transfer of oxygen from atmosphere to ocean, resulting in lower concentrations of O_2 in deeper water in the tropics (Schmittner et al., 2008, Bopp et al., 2002, Matear and Hirst, 2003).

Detectable reductions in DO in local areas in all oceans are highly variable. In the Japan/East Sea study showed that a large long-term decrease in the oceanic O_2 concentration of more than 20µmol kg^{-1} since the mid-1950s (Kim et al., 2000). In Pacific studies showed that major westward expansion of O_2 minimum waters in the Eastern Pacific basin over the past 50 years and some future prediction scenarios showed considerable decrease O_2 in deep layers of the tropical Pacific Ocean (Borgne et al., 2011). Substantial reductions in DO are also reported for the eastern South Pacific above 3000 m (Shaffer et al., 2000), the Indian Ocean (Bindoff and Mcdougall, 2000), the North Atlantic (Garcia et al., 1998, Pahlow and Riebesell, 2000), and the Southern Ocean (Matear et al., 2000).

The DO reduction in ocean basins can have significant consequences for ecosystem as well as current tuna distribution pattern. Marine fish are highly sensitive to the availability of DO, as a result of low DO levels in deeper waters, organisms cannot maintain their metabolic rate and swim when O_2 decreases to 1 mg/l or less (Heath, 1995). Some species have adaptations to low O_2 level while some cannot, especially many of the organisms in the food web including tuna cannot live in anoxic conditions for long periods.

Sensitivity of tuna fish species to the availability of O_2 in subsurface waters highly varies among the tropical tuna species, while have greater impact on species that swim regularly between the surface and subsurface (yellowfin tuna and albacore tuna) and to deep layers (bigeye tuna). Skipjack tuna have low tolerance level for the ambient O_2 concentration compare to other tropical tuna species (yellowfin, albacore and bigeye tuna). However, there is a limited impact of reduced subsurface O_2 on Skipjack tuna inhabiting the surface layers (Lehodey et al., 2011) due to no significant reduction of O_2 in surface layers in tropical water habitats. In other hand, the decrease in O_2 concentrations in surface and subsurface waters at mid to high latitudes that occur as the ocean warms may limit the extension of tuna habitat into more temperature areas. These overall changes in habitat compression for tuna species have significantly affect the catchability of tuna (BRILL, 1994) and lead high uncertainty of future tuna resources in tropical waters.

1.6.2 Indirect Effect of Climate Change on the Oceanic Fisheries

Climate changes have significant indirect effects on the ocean fisheries by changing their ecosystem process. Reduction and altering of global ocean primary productivity and consequences of these changes on food webs in the oceans are concerned as priority in indirect effects of global warming. Nevertheless, changes in ocean salinity are an indirect and important indicator which is potentially sensitive of a number of climate change processes such as precipitation, evaporation, river runoff and ice melt (Martinez et al., 2009). Salinity changes have significant effects on both fish physiological processes and recruitment process, and a consequence, salinity changes lead the abundance and distribution of marine fish resources.

Effect of Sea Surface Salinity

Ocean salinity plays a critical role in water circulation and cycle patterns which are powered by disparities in both temperature and salinity. Studies revealed that combined effect of temperature and salinity changes due to climate changes have changed density of the ocean surface and lead to change vertical stratification, surface mixing and general circulation patterns (Martinez et al., 2009). Ocean salinity is an important abiotic factor which allows the marine organisms to maintain optimum physiological activities while seasonal and long term salinity changes in different water layers have significant effects on their abundance and distribution (Ojaveer and Kalejs, 2005).

Salinity changes over the past decades are varied across the oceans. In general, near surface waters in the more evaporative regions showed an increased salinity in almost all ocean basins, but high latitudes a decreasing trend due to greater precipitation, higher runoff, ice melting and advection (NASA, 2015). The Atlantic has been getting saltier in upper 500 m layers between 15°S and 42°N region including the North Atlantic subtropical gyre while the Pacific has been getting fresher with the exception of the South

Pacific subtropical gyre between 8°S and 32°S and above 300 m where there is an increase in salinity (Boyer et al., 2005). The Indian Ocean is generally increasing its salinity in the upper layers while freshening can be observed in the South Indian Gyre (Bindoff et al., 2007). However, the seasonal salinity variation in surface waters is mainly governed by river inflow (primarily from Bay of Bengal), influx of fresh water in the Indonesian Through Flow and the influx of saltier waters from the Red Sea and Persian Gulf with monsoonal patterns.

Tuna distribution and abundance showed relationship of the direct and indirect effects of salinity changes. According to Francis Rougerie and Jacques Chabbane (1983), there is a strong correlation between salinity of surface waters and tuna catch (yellowfin and skipjack tuna) in the Pacific Ocean. Studies proved that low salinity is a good predictor for the tuna habitat prediction in many oceans (Maury et al., 2001, Rougerie and Chabbane, 1983) in seasonal scale. As surface water salinity in Indian Ocean is highly related with monsoonal wind pattern and fresh water discharges to Eastern Indian Ocean, surface water salinity can be used as a key environmental factor to predict seasonal tuna distribution and abundance while long term changes can be important for predict their vulnerability to climate change impacts.

Effect of Ocean Productivity

Climate change impact on the changes in ocean productivity play a vital role in the ocean fisheries as it is a key component for food webs in oceans. Most of high primary production ocean occurs where nutrients, such as nitrogen, phosphorus and silicon, are transported to surface waters from the deeper layers of the ocean through water mass movements (Borgne et al., 2011). It is proved that the strong variations in the supply of nutrients have been observed as a result of climate variability throughout the past decades (Martinez et al., 2009, Behrenfeld et al., 2006), by occurrence of ocean stratification throughout the various ocean regions.

Oceanic fisheries are acutely sensitive to alterations in primary productivity (Lehodey et al., 2011). These reductions of primary production, as well as mismatch of primary productivity with higher tropic levels lead to change in all the food-web structures, as an ultimately results it affects overall reduction in fish production. The changes of productivity in lower level of food web have direct impact on the distribution and abundance of tuna in different ocean basins. For example, high skipjack tuna catch in the Pacific Ocean during the 1998 as a respond to the strong ENSO events of 1997–1998; this event clearly demonstrated the sensitivity of the link between high primary production and tuna recruitment (Lehodey et al., 2011).

However, large gap in knowledge remain, particularly the implications of climate change for the large and complex food-web that supports tuna populations and their fisheries in local oceanic regions where regional and local management can apply.

1.7 Objective of the study

Skipjack tuna is a species which is more susceptible to environmental changes. Studies of skipjack tuna spatial and temporal abundance relevant to environmental parameters are important to identify tuna resource availability and their potential changes with relevant to climate changes. This study focused to identify skipjack tuna abundance in Sri Lankan waters with special reference to the sea surface temperature (SST), sea surface chlorophyll (SSC) and sea surface height (SSH) during the study period of 2005 to 2013.

2. Materials and Methods

2.1 Tuna Fishery Data

Skipjack tuna fisheries catch and effort data from offshore boats were collected from the large pelagic database (PELAGOS) manage by National Aquatic Resources Research and Development Agency (NARA) of Sri Lanka for the study period of January 2005 to December 2013. This database is based on the port sampling programme is conducted by NARA to collect sound catch, effort and biological data of large pelagic fish (Haputhanthri, 2014).

The catch and effort data from the offshore boats in southern and western part of landing sites of Sri Lanka were used as a proxy for the abundance and availability of the skipjack tuna in Southern Sri Lankan ocean waters mainly targeted by large pelagic fishing activities. The selected offshore boats category was consist of two main boat groups operating in offshore tuna activities, UN2B (IMUL 1, 8.8-9.8m length, 40 HP) and UN3A (IMUL 2, 12.2-15.5m length, 60 HP) respectively. These catch and effort data were standardized by calculating catch per unit effort (CPUE – weight by kg per day per single boat landing) values for all the landings during the study period. Then average CPUE for each month for the whole area was calculated.

2.2 Environmental Data

Monthly average sea surface temperature (SST) and sea surface temperature anomaly (SSTA) data for the study period were obtained from satellite data for the study area (0^{o} N, 6.5^{o} N to 76^{o} E, 85.6^{o} E) (Fig. 2) with $1/4^{o}$ spatial resolution and one month temporal resolution. SST and SSTA data were extracted as blended products from two sensors, Advanced Microwave Scanning Radiometer (AMSR) and Advanced Very High Resolution Radiometer (AVHRR) on the NASA Earth Observing System satellites (ftp://eclipse.ncdc.noaa.gov).

Monthly average sea surface chlorophyll (SSC) concentration (mg/m3) data for the study period were obtained using the Globcolor data project (http://hermes.acri.fr/) satellite data for the study area. The SSC are generated from four satellite sensors based on the Weight Averaging (AVW) and GSM model technique (Maritorena and Siegel, 2005). Monthly average sea surface height (SSH – Absolute Dynamic Topography) (cm) data for the area were obtained from the AVISO data project (ftp://ftp.aviso.altimetry.fr/).

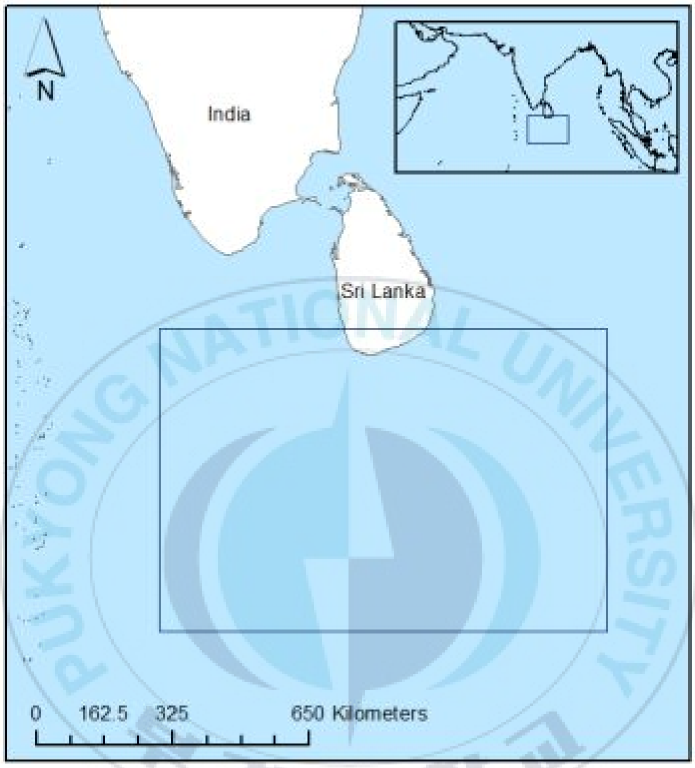

Figure 2. Map of the study area

2.3 Statistical Methods

Scatter plot function was used to identify the relationship between skipjack tuna average CPUE and environmental parameters, i.e. SST, SSC and SSH.

Graphical illustrations were used to identify the seasonal and inter-annual variations of the average monthly CPUE and environmental parameters for each year during the study period. As the seasonal variations of all environmental parameters and average CPUE were very similar, average monthly values of the parameters were pooled for all years during the study period.

The associations between skipjack tuna CPUE and satellite-based SST, SSC, and SSH were explored using an empirical cumulative distribution function (ECDF) approach. In this analysis three functions (Perry and Smith, 1994; Andrade and Garcia, 1999, Rajapaksha et al., 2013) were used as follows:

$$f(t) = \frac{1}{n}\sum_{i=1}^{n} l(x_i)$$

With the indication function:

$$l\,(X_i) = \begin{cases} 1\; if\; X_i \leq 1 \\ 0\; otherwise \end{cases}$$

$$g(t) = \frac{1}{n}\sum_{i=1}^{n} \left(\frac{y_i}{\bar{y}}\right) l(x_i)$$

$$D(t) = max|f(t) - g(t)|$$

where *f(t)* is empirical cumulative frequency distribution function, *g(t)* is CPUE-weighted cumulative distribution function, $l(x_i)$ is indication function and *D(t)* is the absolute value of the difference between the two curves *f(t)* and *g(t)* at any point *t* and assessed by the standard Kolmogorov-Smirnov test. *n* is the number of fishing activities, x_i the measurement for satellite-derived oceanographic variables in a fishing activity *i*, *t* an index ranking the ordered observations from the lowest to highest value of the oceanographic variables, y_i is the CPUE obtained in a fishing activity *i* and $\bar{y}$ the estimated mean of CPUE for all fishing activities. The maximum value of *D(t)* represents specific values of the oceanographic variables at which the highest CPUE can be obtained.

Cross-correlation function (CCF) was used to identify the sensitivity and the responsiveness of the state to the environmental factors pressure. In here monthly average data of CPUE and environmental parameters were converted to stationary by using first order differencing before the CCF analysis.

3. Results

3.1 Direct Comparison between Fishery and Environmental Parameters

Results shows skipjack tuna fishing occurred in areas and periods where SST ranged between 27.5 °C to 30.5 °C. However, most of the fishing activities were concentrated in the waters where SST varied between 28.0 to 29.5 °C (Fig. 3). Also the CPUE data distribution in relation to SST showed a positive skew (+0.60).

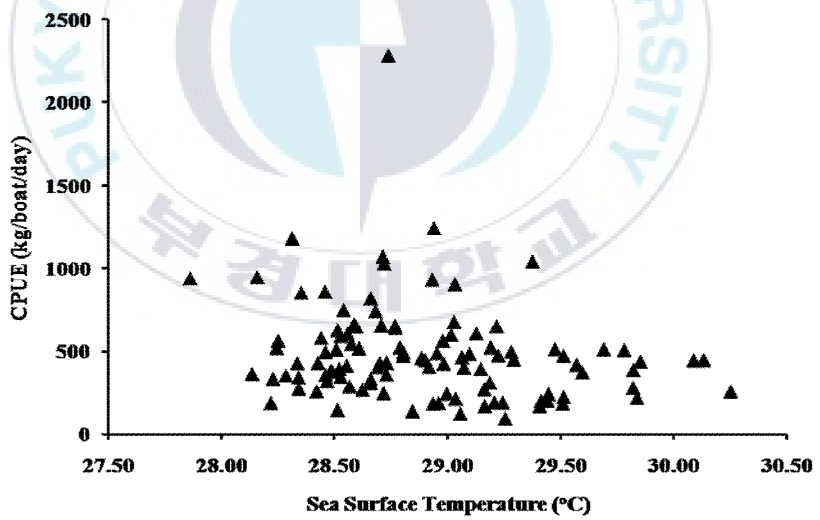

Figure 3. Scatterplot of CPUE of skipjack tuna in relation sea surface temperature of Sri Lankan waters

Sea surface chlorophyll concentration were ranged between 0.05 to 0.50 mg/m^3 within the fishing grounds of the skipjack tuna and most fishing concentrated waters where SSC 0.10 to o.20 mg/m^3 (Fig. 4). The CPUE data distribution in relation to SSC showed positive skew (+1.22).

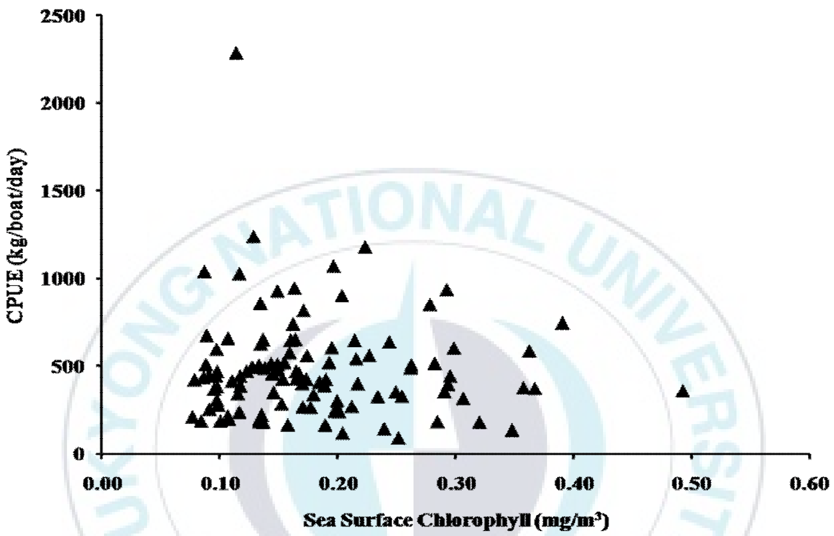

Figure 4. Scatterplot of CPUE of skipjack tuna in relation sea surface chlorophyll of Sri Lankan waters

Sea surface height varied from 73 to 93 cm where skipjack tuna fishing were occurred and catches are concentrated within 80 to 90 cm (Fig. 5). The

CPUE data distribution in relation to SSH showed negatively skewed (-0.52).

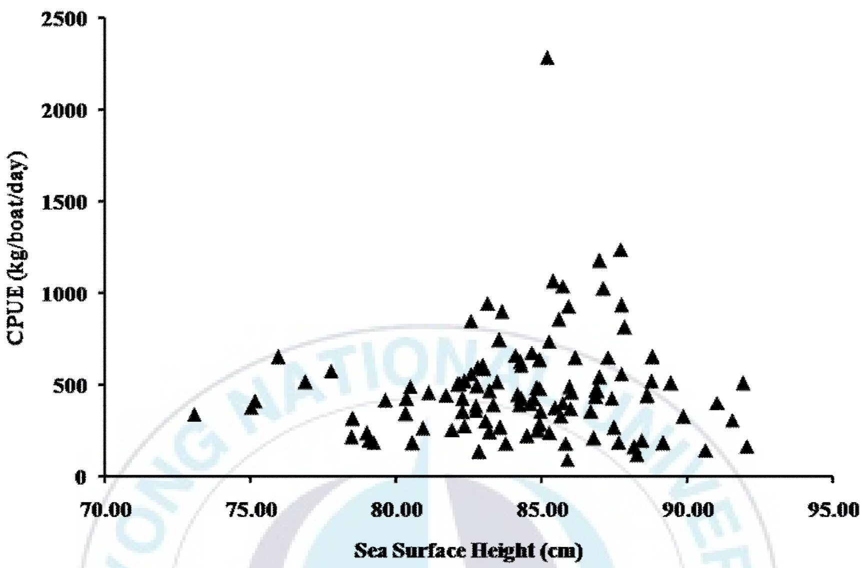

Figure 5. Scatterplot of CPUE of skipjack tuna in relation sea surface height of Sri Lankan waters

3.2 Seasonal Variations

Temporal variability of SST and SSC throughout years was very similar, so average values of the parameters pooled to show general pattern. During March to June average monthly SST maintained above 29.0 ^{o}C with highest recorded SST in April. Rest of months maintained lower SST presence between 28.5 to 29.0 °C (Fig. 6).

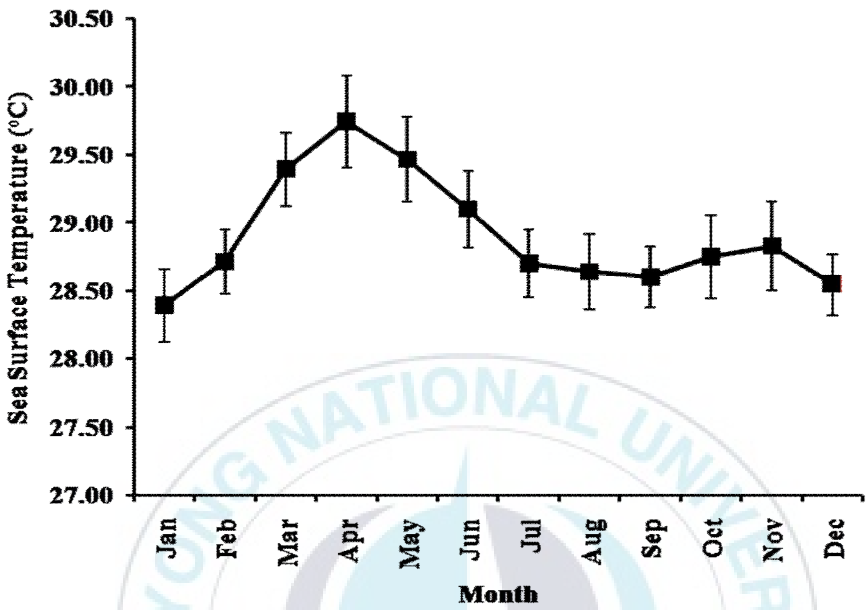

Figure 6. Average temporal variability of sea surface temperature

Average monthly SSC variation (Fig. 7) shows inverse pattern of the average monthly SST. Pearson Correlation results showed significant ($p <$ 0.01) negative correlation (r = -0.56) between SST and SSC during the period.

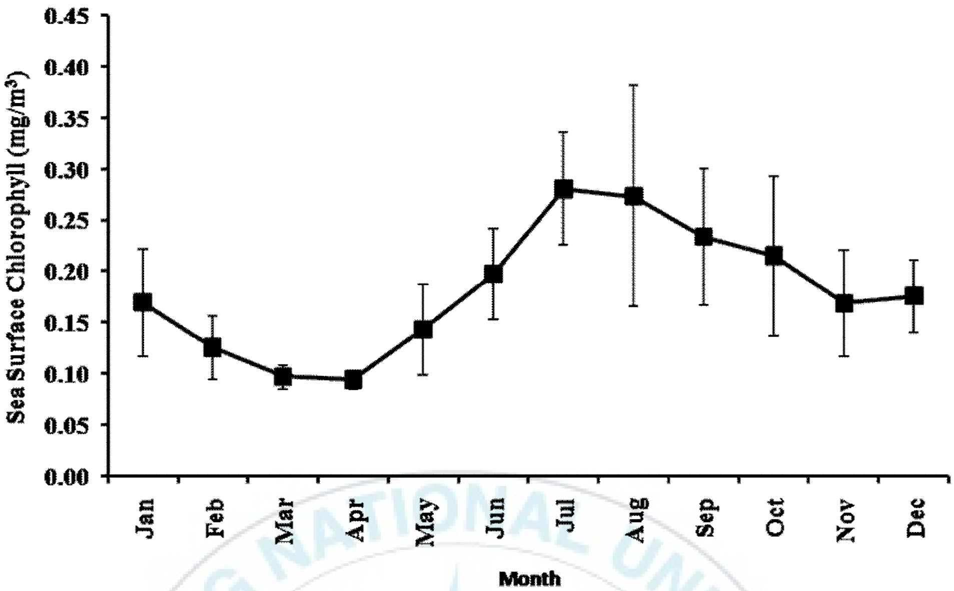

Figure 7. Average temporal variability of sea surface chlorophyll

3.3 Empirical Cumulative Distribution Function

The empirical cumulative density function (ECDF) results showed a significant (p < 0.01) association between CPUE of skipjack tuna and environmental variables (SST, SSC & SSH). The SSC showed a strongest significant association ranging from 0.05 to 0.5 mg/m^3 where highest CPUE can be obtained (Fig. 8b). The SSH showed the lower significant association with CPUE where highest ranging from 80 to 90 cm (Fig. 8c). The lowest association was observed in SST ranging from 28 to 29.5 ^{o}C (Fig. 8a).

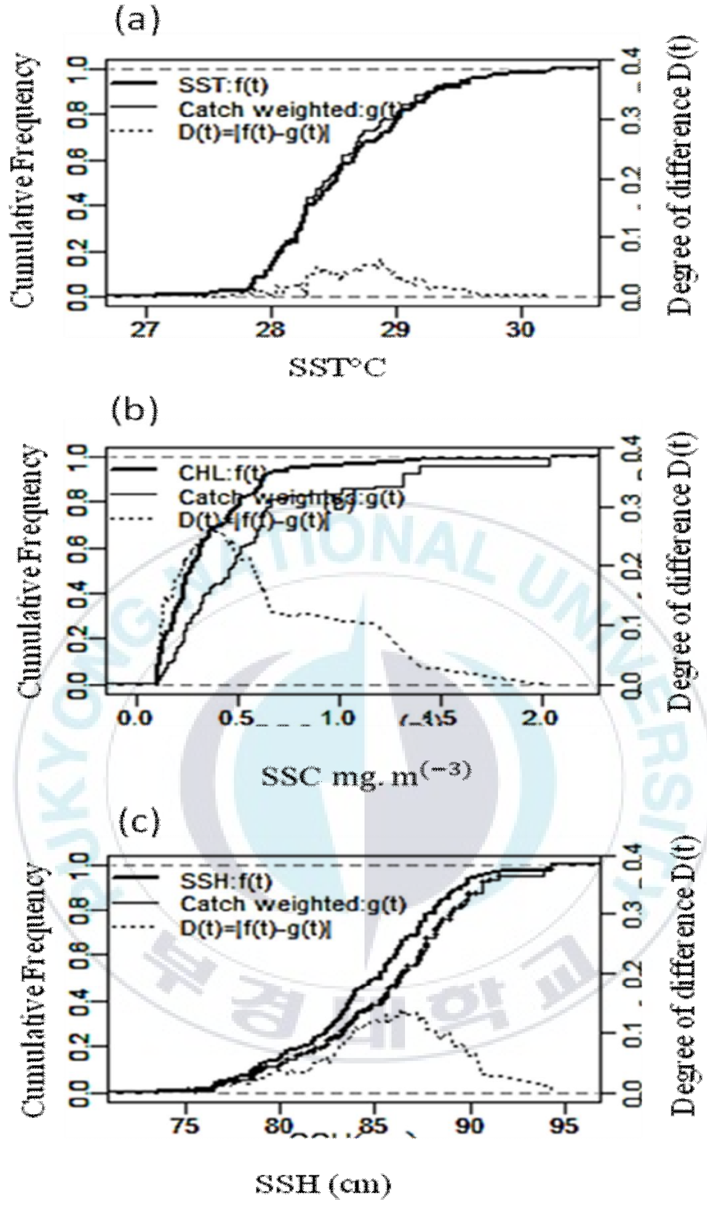

Figure 8. Empirical cumulative distribution frequencies of SST (a), SSC (b) and SSH (c) superimposed of skipjack tuna catch weighted SST, SSC and SSH. The dashed-lines show degree of differences of two curves.

3.4 Cross-correlation Function Analysis

The cross-correlation between environmental parameters, SST, SSC and SSH were analyzed with CPUE and fish catch to identify nature of the relationship and how they are correlated in time. CCFs of the average SST with CPUE were positive and significant, with positive time lag of 2 months during the study period. CCFs of the average SST with catch were positive and significant, with positive time lag of 2 months (Fig.9a & 9b). Positive relationship of SST with positive time lag indicates increase of the state of temperature leads to higher CPUE and higher catches of skipjack tuna.

CCFs of the average SSC with the CPUE were positive and significant, with positive time lag of 6 months. Positive relationship clearly shows that how primary productivity influences the fish abundance in the waters and time lag of the positive signal (Fig. 9c & 9d).

Results of CCFs of the SSH with catch were negative and significant, with positive time lag. Negative relationship indicates increase of the SSH with season lead to decrease the abundance of fish with positive time lag (Fig. 9e & 9f).

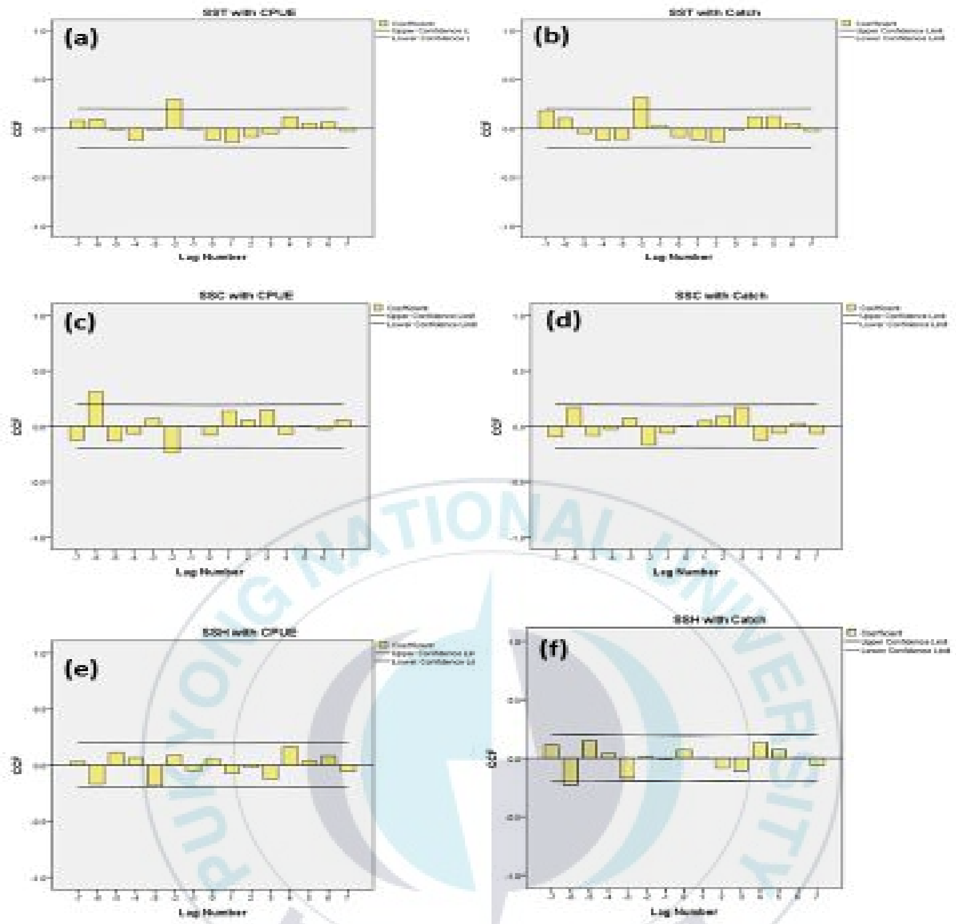

Figure 9. Cross-correlation coefficients (CCF) of skipjack tuna CPUE and catch data with selected environmental variables. (a) skipjack tuna CPUE with sea surface temperature (b) skipjack tuna catch with sea surface temperature (c) skipjack tuna CPUE with sea surface chlorophyll (d) skipjack tuna catch with sea surface chlorophyll (e) skipjack tuna CPUE with sea surface height (f) skipjack tuna CPUE with sea surface height. Vertical bars denote the CCF and two horizontal lines denotes confidence threshold for a $\alpha = 0.05$

4. Discussion

4.1 Direct Comparison between Fishery and Environmental Parameters

Long term skipjack tuna CPUE and environmental parameters showed seasonal and inter-annual fluctuations throughout the study period. The fishing activities were spread out within the sea surface temperature ranging from 27 to 30.5 ^{o}C which is presence within known SST range for skipjack tuna distribution in the tropical waters (Leheody, 2011 book CC, Dueri et al, 2013). The lower positive skewed CPUE distribution in relation to SST showed highest possible fishing activities occurred within mid range of observed SST (28.0 to 29.5 ^{o}C).

Sea surface chlorophyll concentration were ranged between 0.05 to 0.50 mg/m^3 within the fishing grounds of the skipjack tuna and most fishing concentrated waters where SSC 0.10 to 0.20 mg/m^3. These highest possible fishing activities overlaps within the higher positive skewed SSC and lower positive skewed SST showed negative relationship between these 2 parameters on the skipjack abundance in these waters. It proved the significant negative ($r = -0.56$, $p < 0.01$) correlation between SST and SSC in the waters where fishing occurs.

The fishing activities occurred within the SSH from 73 to 93 cm, while more activities concentrated from 80 to 90 cm. This high sea state occurs during the 1st half of the South-west monsoon pattern where high SST and lower level of SSC presence. These optimum conditions lead to higher abundance of skipjack tuna in the waters. This result proved that gillnet fishery for tuna runs throughout the year, with effort being considerably more during the southwest monsoon period of May to October (Amarasiri and Joseph, 1986).

4.2 Empirical Cumulative Distribution Function

The empirical cumulative density function (ECDF) results showed a significant ($p < 0.01$) association between CPUE of skipjack tuna and environmental variables (SST, SSC & SSH). The SSC showed a strongest significant association ranging from 0.05 to 0.5 mg/m^3 where highest CPUE can be obtained. It inferred preferred ranges of skipjack tuna in Sri Lankan waters, corresponded to SST between 28 to 29.5 ^{o}C, SSC between 0.05 to 0.5 mg/m^3 and SSH between 80 to 90 cm.

4.3 Cross-correlation Function Analysis

CCFs results of the average SST with CPUE and catch were positive and significant, with positive time lag of 2 months during the study period. The positive relationship between SST and skipjack tuna abundance with short time lag can be explained by the seasonal distribution and migration pattern changes within the region.

CCFs of the average SSC with the CPUE were positive and significant, with positive time lag of 6 months. This result indicates the higher SSC state leads the food abundance in the area with positive time lag where skipjack tuna attracts. This time lag of the tuna abundance responds overlap within the high temperature 1st inter monsoon season within the study area. These both SST and SSC CCFs results shows that most seasonal abundance of skipjack tuna occurrence seasons overlaps within inter monsoonal and monsoonal period within this region.

Offshore tuna fishing sector in Sri Lanka began in 80's and expanded with influx of technological improvement to the industry throughout last decades. At present it is fastest growing subsector in fisheries with promising future demand. Skipjack tuna plays vital role with highest portion of production which accounts 63 % of total oceanic landings (Haputhanthri, 2014). Importance of environmental parameters on the abundance of tuna species is essential to understand potential fishing grounds, seasons and ongoing climate change processes in the region. The specific information on fisheries and environmental parameters are crucial for clear understanding of relationships which can be applied for future management in fisheries.

This study focused on; to identify skipjack tuna abundance in Sri Lankan waters with special reference to the sea surface temperature (SST), sea surface chlorophyll (SSC) and sea surface height (SSH). The analyzed results showed significant clear seasonal variations in the SST and SSC in Sri Lankan waters. These seasonal variations overlap within the optimum SST requirements for skipjack tuna abundance.

The highest CPUE of skipjack tuna correspondents to the narrow SST between 28 to 29.5 ^{o}C, SSC ranging from 0.05 to 0.5 mg/m^3 and SSH between 80 to 90 cm. As skipjack tuna inhabits in surface waters this combination of the environmental parameters can be used to predict the time and area of higher abundance of skipjack tuna in Sri Lankan waters. Furthermore future studies of regional skipjack tuna stock distribution and their migration pattern in this region can be undertaken to provide much more detailed explanation of the seasonal abundance in Sri Lankan waters.

The offshore tuna fishery in Sri Lanka mainly targeted on both yellowfin and skipjack tuna fishery and use both long-line and gill net during their fishery operations. The gear operations of can be highly varied within single trip which result the complexity of catch data in offshore tuna fisheries. These results emphasized the importance of the specific data collection procedures in tuna fisheries to identify environmental effects and long term climate change impacts on skipjack tuna resources in Sri Lankan waters.

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