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EVALUATION AND IMPROVEMENTS OF A SATELLITE BASED FORECAST SYSTEM FOR SRI LANKAN YELLOWFIN TUNA FISHERY

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ABSTRACT

The relationship between yellowfin tuna (*Thunnus albacares*) catches in the Northeast Indian Ocean, by Sri Lankan long-line fleets, and oceanographic variables obtained from remote sensing satellites was studied to improve a forecasting system for the fishery. Sea surface temperature (AMSRE, AVHRR), chlorophyll-*a* concentration (MODIS), sea surface height (TOPEX/Poseidon) were analyzed in relation to catch data expressed as catch per unit of effort (CPUE), which was calculated as the number of fish caught by 100 hooks. Splitting the yellowfin fishing areas into three regions, NW, NE and SW, the spatial and temporal variability of oceanographic parameters were determined in relation to CPUE. An existing fishery forecasting system that was based on satellite data was evaluated with updated fishery and satellite data. The results indicate that highest CPUEs corresponded with areas of SST 28.0–30.0 ^{o}C, CHL 0.05–0.4 mg m^{3}, and SSH 200-220 cm during the study period. Slight variations of these parameters were observed with time in different fishing areas considered. The CPUE varies between 0.07–14.0 and the mean CPUE was 1.3 during the year 2008. However, the fishery is highly affected in NW fishing area during SW monsoon while other two areas were not influenced by monsoons. To identify the functional relationships between the environmental variables and CPUE, generalized additive model (GAM) was applied. The areas of highest CPUEs predicted by the model were consistent with the potential habitats on the prediction and observation data. Sea surface temperature and chlorophyll-*a* concentration were statistically significant within predicted ranges while sea surface height showed a flat relationship. These parameters seem to be important in controlling yellowfin tuna distribution in the region.

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ABBREVIATIONS

AMSR-E	Advance Microvawe Scanning Radiometer-Earth observing system)
AVHRR	Advance Very High Resolution Radiometer
CHL	Chlophyll_*a*
CPUE	Catch Per Unit of Effort (per 100 hooks)
EEZ	Exclusive Economic Zone
gsfc	Goddard Space Flight Center
HDF	Hierarchical data Format
ICEIDA	ICElandic International Development Agency
IOTC	Indian Ocean Tuna Commission
MFAR	Ministry of Fisheries and Aquatic Resources
MIL	Marine Information Laboratory
MODIS	MODerate resolution Imaging Spectroradiometer
NARA	National Aquatic Resources Research and Development Agency
NASA	National Aeronautics and Space Administration
netCDF	Network Compatible Data Format
RADAR	RAdio Distance And Ranging
SSH	Sea Surface Height
SST	Sea Surface Temperature
WPTT	Working Party on Tropical Tunas
GAM	Generalized Additive Model

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1 INTRODUCTION

Sri Lanka is an island in the Indian Ocean (06 ºN, 80 ºE) with sovereign rights over 200 nautical miles (517,064 km^2) of Exclusive Economic Zone (EEZ). Fishing takes place all around the island and in international waters. However limited fishing operations take place in international waters of the Arabian Sea. The fishing industry contributes 2.6% (MFAR 2009) to the Gross National Production (GNP).

The estimated total fish production in 2008 was 350,000 t of which 48% is from coastal waters (57,000 km^2) while 38% from offshore fishery (470,000 km^2 EEZ plus international waters). The rest, 14% is from inland fisheries and aquaculture (MFAR 2009). The local consumption is 90% of the total production and the rest is exported.

Coastal fishery within the continental shelf (< 200 m depth) is multispecies and multi-gear consisting small pelagic, demersal and coral reef fishes. There are localized fishing activities for shrimp, sea cucumber and crabs (Samaranayake 2003). The fishery plays an important role in terms of income generation, employments, foreign exchange and the provision of animal protein for the population (Sydnes and Normann 2003, Sugunan 1997).

The coastal fishery generally can be considered above its optimal level of exploitation. The potential for further expansion of coastal fishery in Sri Lanka is then limited (Haputhantri 2004). In the early 1980s fishermen were encouraged by the government to engage in an offshore fishery with subsidies. Today over 3000 vessels are engaged in offshore fishing activities (MFAR, 2009). Tuna species such as skipjack, yellowfin, and bigeye are dominant in the offshore fishery (Dissanayake 2005). Billfishes (sail fish, marlin and sword fish) and sharks are by-catches of tuna long-line and gillnets.

Yellowfin tuna is known to be highly migratory and widely distributed (Zagaglila *et al.* 2004). The wide distribution of yellowfin tuna means that search for this resource is time consuming and costly. The search can be made more efficient and less costly by predicting the areas where fish aggregate in space and time.

Satellite derived information has been used by several countries such as USA and Japan to predict potential fishing zones for several fish species (Stretta 1991, Power and May 1991, Podestá *et al.* 1993, de Rosa and Maury 1998, Bigelow *et al.* 1999).

In 2008, a fishery forecasting system for yellowfin tuna was developed in Sri Lanka based on catch records and satellite derived oceanographic data from 2006–2007. The oceanographic parameters such as sea surface temperature, sea surface chlorophyll concentration and dynamic sea surface heights were used. The forecasting system was tested in 2008/09 and showed encouraging results.

Only two years of fishery and oceanographic data was used to determine forecasting parameters and the spatial and temporal variability of the forecasting parameters of yellowfin catches have not been properly understood. As the Sri Lankan long-line fishery stretches over a large area, the spatial variability of forecasting parameters is significant. Therefore, a limited part of potential fishing areas has been forecasted and the accuracy levels remain unresolved. The forecasting system requires improvements by continued data matching and further analyses of fishery and environmental data. This study was undertaken to improve the accuracy of the existing fishery forecasting system in Sri Lanka. The main objectives of the study were then to analyze spatial and temporal variation of oceanographic parameters in relation to yellowfin tuna catches by Sri Lankan long-lines to improve the existing forecast system for yellowfin tuna fishery.

2 OVERVIEW OF THE STUDY

2.1 Yellowfin tuna fishery in the Indian Ocean

The yellowfin tuna (*Thunus albacares*) is a major target species of the tuna fishery in the Indian Ocean (Somvanshi 2002, Nootmorn *et al*. 2005). Fishing gears used in this fishery are purse seines, long-lines and gillnets. Hand-lines pole-and-line is also used in the small-scale coastal fishery. Yellowfin tuna is fished throughout the Indian Ocean, with the majority of the catches being taken in western equatorial waters. Japan, Taiwan and China engage in large-scale fishery while small-scale long-liners engage from Indonesia and Sri Lanka (Zhu *et al.* 2006).

Total annual average catches of yellowfin tuna in the Indian Ocean are shown in Figure 1. The average catches were around 30,000 t from 1959 to 1982 and most catches were by long-lines. From there, the yellowfin tuna catches were gradually increased with the introduction of purse seines and more effort from long-liners into the fishery. The average catches then increase up to 330,000 t around 1993 and stable until 2007 with a peak of 500,000 t in 2004. Fishing effort by gillnets and line fishing has been increased from 1992.

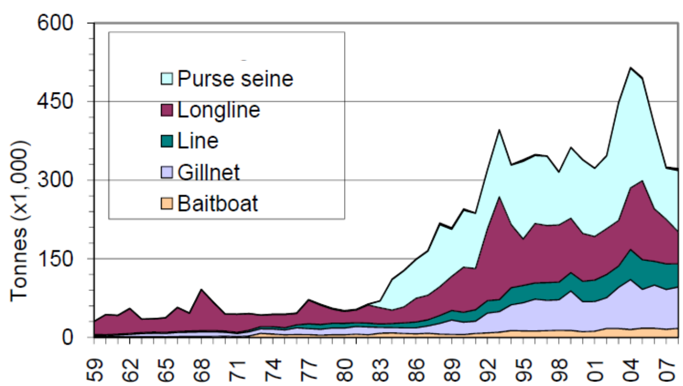


Figure 1: Annual catches of yellowfin tuna in the Indian Ocean by gear from 1959 to 2008 (IOTC 2009).

2.2 Yellowfin tuna fishery by Sri Lankan long-liners

The average tuna production is ~70,000 t of which the yellowfin tuna was 20,000 t (~29%) during 2003-2009 (Figure 2). There is a significant drop in total tuna catches in 2005. However Yellowfin catches gradually increased from 18,000 t in 2003 to 23,000 t in 2009. Chilled yellowfin tuna has become a lucrative export venture and much attention has been paid to quality management in terms of proper handling and storage. Shashimi and loins are the major yellowfin export products to Japan and EU markets.

Long-lines and gillnets are the main fishing gears used by which 95% fishing effort on yellowfin tuna catches (Dissanayake 2008). Trolling-lines and hand-lines are minor gears used during calm sea conditions. About twenty well-equipped vessels operate deep long-lines (>100 m) and entire catch is exported (Leonard 2003). The number of hooks in long-lines varies from 200-600 while industrial long-liners use more than 1000 hooks. The average hooking depth varies from 70 m to 100 m (Leonard, 2003). Long–lines are becoming more popular since the fish caught is of higher quality than in gillnets.

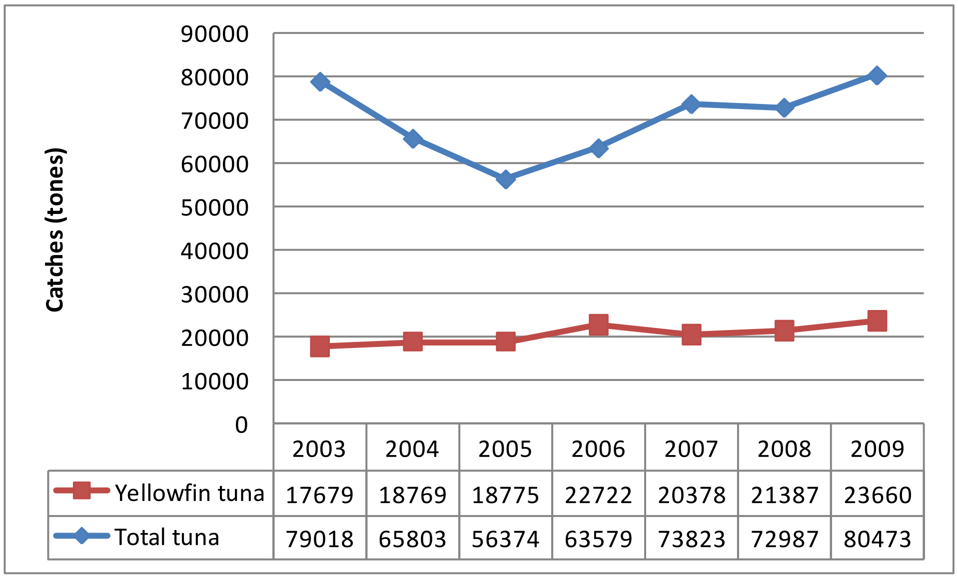


Figure 2: Yellowfin tuna contribution to the total tuna catches during 2003-2009 in Sri Lanka (Source: PELAGOS database, NARA).

2.3 Oceanographic influences on yellowfin tuna

Many oceanographic factors may influence the density and distribution of yellowfin tuna. These factors include sea surface temperature (SST), chlorophyll_*a* concentration, sea surface height, salinity, dissolved oxygen concentration, and thermocline depth (Romena, 2000).

2.3.1 Temperature

The ocean surface is heated by solar radiation. The heating effect of solar radiation is confined to the ocean surface where more than 90% of the infrared part of the spectrum is being absorbed. Mixing of the ocean surface layer by winds (esp. monsoon in the Indian Ocean) transfers the heat down to hundreds of meters. This creates a mixed layer of water of almost uniform temperature. Below the mixed layer at depths of about 70-100 m at 68-74 ^{o}E (Figure **3**a) the temperature decreases rapidly. The steepest temperature gradient is known as the thermocline. Yellowfin tuna have been found relatively high density around the thermocline in high seas of the Indian Ocean (Block *et al.* 1997).

Temperature is one of the most important physical properties influencing the distribution of marine species (Lalli and Parsons 1997). It exerts an influence on many physical, chemical and biological events. Temperature controls the biological processes such as metabolism and growth. Water temperature partly determines the concentration of dissolved gasses such as oxygen and carbon dioxide, which are profoundly linked to biological processes.

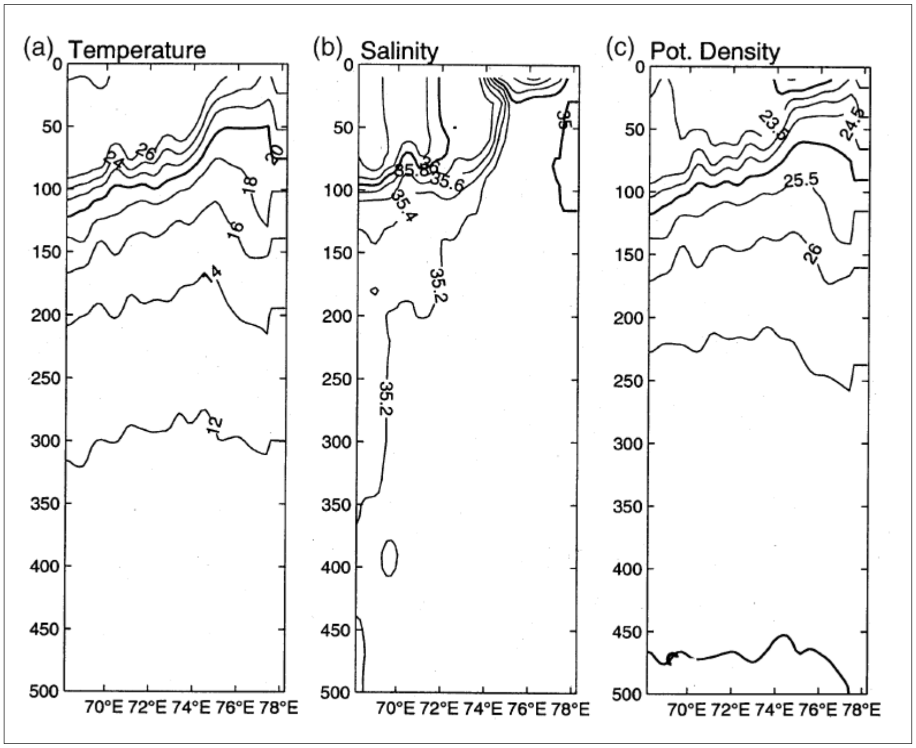


Figure 3: Section off the west Indian coast along 8°N during the summer monsoon showing a) potential temperature b) salinity c) potential density (Schott and Julian 2001).

Temperature influences the yellowfin tuna at different stages of its life cycle, for example spawning, growth and survival of the eggs and larvae. Temperature also influences the distribution, aggregation, migration and schooling behavior of juveniles and adults (Sund *et al.* 1981). Relative abundance of yellowfin tuna increases near the equator within temperature limits between 18–31 °C (Stretta 1991). In the tropical Atlantic most of the catches of this species occurs within temperature range between 22–29 °C and preferentially above 25 °C. According to Zagaglia (2004), there was no distinct temperature preference of yellowfin tuna and he suggested the flat relationship between SST and CPUE in the temperature range of 26–28.5 °C. However, SST is the most widely used ocean environmental parameter to predict yellowfin tuna aggregations and this may be due to several reasons. The temperature is an indicator of important ocean processes such as upwelling, advection and some mesoscale dynamic features including fronts and eddies. Temperature is also the oceanographic parameter that has been most successfully measured using remote sensing technology (Brill 1994).

Oceanographic parameters such as SST obtained from satellite images can potentially be used to identify good fishing grounds (Santos 2000; Yamanaka *et al.* 1988). Satellite sensors (AVHRR, AMSRE, MODIS) are useful to study thermal fronts, eddies and upwelling that influence the distribution of fish species. Argo floats are capable of determining the thermocline depth that is causing the vertical distribution of yellowfin tuna. Oceanographic and fishery data could be used to identify environmental changes and their impact on migration and distribution of yellowfin tuna (Santos 2000).

2.3.2 Chlorophyll

Primary productivity is proportional to the chlorophyll_*a* concentration in the surface layer of the ocean. Chlorophyll can be used as an alternative parameter to the productivity in waters where optical properties are basically determined by phytoplankton (Stewart 1985). Laurs *et al.* (1984) and Zagaglia *et al.* (2004) have found an inverse relationship between chlorophyll and yellowfin CPUE. Yellowfin tuna are visual predators and clear water would help to increase their success of foraging. The main food of yellowfin tuna is flying fish. The flying fish are zooplankton feeders, which are particularly abundant in chlorophyll fronts. This phenomenon has been used to explain high abundance of yellowfin tuna observed in chlorophyll fronts (Brill and Lutcavage 2001).

Upwelling is an oceanographic phenomenon that brings nutrient-rich deeper waters to the surface. The upwelled water is colder than the surface and can be detected from satellite derived SST images. The nutrients fertilize phytoplankton, which is eaten by zooplankton in the mixed layer. Small fish eats zooplankton and larger fish in the food web in turn eats those. As a result, upwelling regions are productive supporting the world's major fisheries (Bidigare *et.al.*,2009).

Surface phytoplankton pigment concentrations have been estimated using remote sensing ocean color sensors from CZCS sensor onboard NIMBUS–7 operational from 1979–1986 (Abbott and Chelton 1991). New generations of ocean color sensors have permitted the measurement of phytoplankton pigment concentrations with increased accuracy (Santos 2000).

2.3.3 Currents

Indian Ocean circulation is predominantly driven by monsoon winds north of about 10 ^{o}S latitude while south of 10 ^{o}S circulation is predominantly driven by Trade winds (Friedrich and Julian 2001). The monsoon circulation is influenced by fresh-water fluxes in some locations such as the Bay of Bengal and by heat in some locations. Typical circulation patterns during the southwest monsoon (May–September) are shown in Figure **4** and during the northeast monsoon (December–March) are shown in Figure **5**.

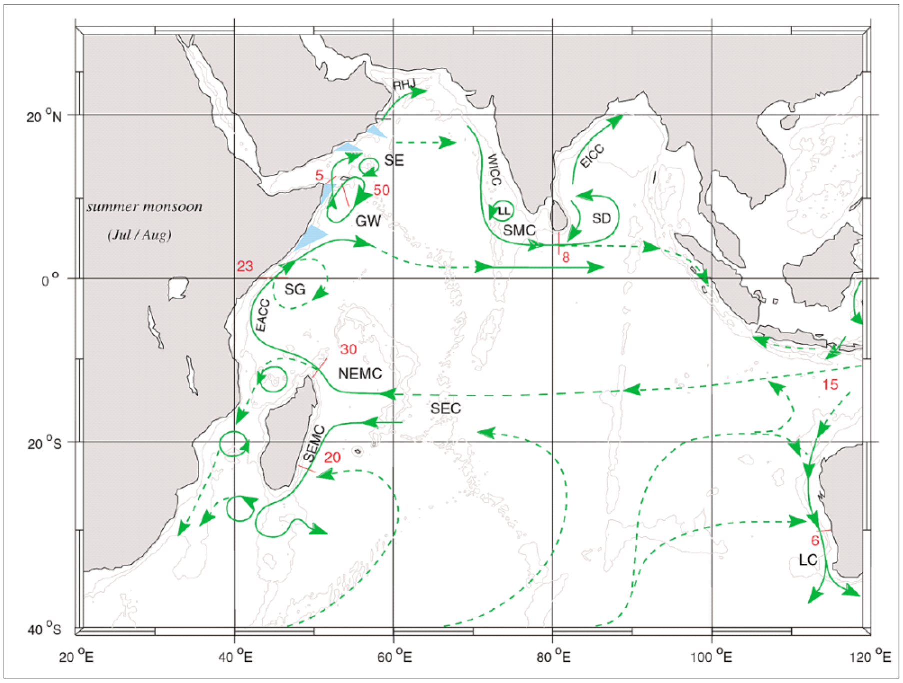


Figure 4: A schematic representations of identified current branches during the southwest monsoon. Current branches indicated (see also Figure 5) are the South Equatorial Current (SEC), South Equatorial Countercurrent (SECC), Northeast and Southeast Madagascar Current (NEMC and SEMC), East African Coast Current (EACC), Somali Current (SC), Southern Gyre (SG) and Great Whirl (GW) and associated upwelling wedges, Socotra Eddy (SE), Ras al Hadd Jet (RHJ) and upwelling wedges off Oman, West Indian Coast Current (WICC), Laccadive High and Low (LH and LL), East Indian Coast Current (EICC), Southwest and Northeast Monsoon Current (SMC and NMC), South Java Current (JC) and Leeuwin Current (LC). Source: Friedrich and Julian 2001.

During the northern winter (winter monsoon), winds are directed away from the Asian continent, causing southwesterly wind stresses over the Bay of Bengal and the Arabian Sea. During the northern summer, (summer monsoon) wind blows southwesterly over both basins. Mixing of upper layer of the ocean is highly variable. The thermocline fluctuates between 100-150 m depths.

Tuna migration is basically associated with ocean currents. They migrate to find rich feeding grounds where they can grow and buildup energy store as fat. Then they return to their specific spawning grounds and this cycle continues every year (Nishida, 1992). Nishida (1992) proposed two major stocks of yellowfin tunas in the Indian Ocean, a western and an eastern stock, with an area of overlap between about 70–90 ^{o}E. Morita and Koto (1971) suggested that there is a movement of yellowfin tuna from the equatorial western Indian Ocean, through the southern Maldives and up past Sri Lanka into the Bay of Bengal every year between October and March. If this is the case, it is possible that the juvenile yellowfin caught off the west coast of Sri Lanka come from the western stock, while those caught off the east coast of the Sri Lanka could come from the eastern stock.

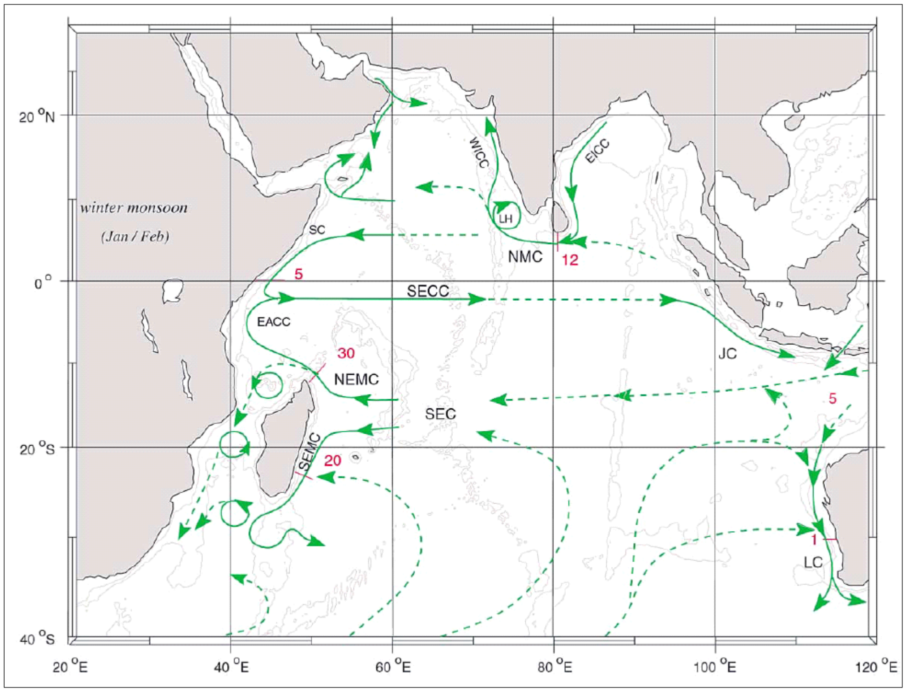


Figure 5: As in Figure 4 but showing reversal current pattern during the Northeast monsoon (December - March). Source: Friedrich and Julian 2001.

Sea surface height measurements provide insights into ocean currents, sea level rise and ocean tides. Height differences cause water to flow due to pressure gradients. Ocean currents transport water around the globe, lift cold water from the sea floor to the surface (upwelling), and pull warm water away from the equator towards the poles. The ocean currents move water and mix with nutrients a rich continental shelf water that is brought from landmasses. Various types of movements affect the distribution of nutrients available to phytoplankton and hence influence the biological productivity. Therefore the ocean circulation influences the geographical distribution of pelagic and benthic marine species (Lalli and Parsons 1997).

The abundance and distribution of yellowfin tuna is related to convergent (downwelling) and divergent (upwelling) characters in the ocean. Yellowfin tuna is aggregated in divergent areas (Power and May 1991; Podesta *et al.* 1993; Andrade and Garcia 1999). The aggregation of yellowfin tuna has also been related to upwelling oceanographic features and to oceanic currents systems (Laurs and Lynn 1977; Power and May 1991). Sea surface height differences in the ocean tends to flow the water from high to low regions contributing to form the ocean currents. Therefore a significant relationship between the yellowfin tuna abundance and SSH anomaly was evident (Zagaglia *et al*., 2004).

2.4 Existing fishery forecasting system in Sri Lanka

One of the primary concerns of the Ministry of Fisheries and Aquatic Resources (MFAR) of Sri Lanka is to promote the offshore fishery in order to relieve the fishing pressure of the coastal resources and to increase the annual production. The research institute of the MFAR the National Aquatic Resources Research and Development Agency (NARA) started preliminary studies to develop a fishery forecasting system in 2001. However, major developments took place with a capacity building project called "Development of Satellite Based Fishery Forecasting System for Sri Lanka" which was launched in 2007. The Icelandic International Development Agency (ICEIDA) supported the project. Under this project the Marine Information Laboratory (MIL) was established. The MIL consists of facilities and staff who have been trained to acquire and process satellite data for fish forecasting.

Systematic fishery data collection began in 2006 from vessel skippers who maintained their personal fishing logs. Numerous fishery records were gathered but a considerable part of these records had to be discarded due to incomplete information. A standardized way of data recording was made with the introduction of logbooks in 2007.

The existing forecasting system for yellofin tuna long-line fishery is based on catch data from 2006–2007 matched with satellite derived data on sea surface temperature (SST), sea surface chlorophyll (CHL) and sea surface height (SSH). The most favorable ranges of SST, CHL and SSH for higher catches were determined and used as forecasting parameters for yellowfin tuna as described in this section.

Chlorophyll data from MODIS (MODerate resolution Imaging Spectroradiometer) sensor onboard MODIS–Aqua satellite and distributed by NASA gfsc in HDF format was downloaded (open source). Level–3 mapped data (MODIS 2010) in 4 km resolution 3–day composites was used to generate monthly composites. Sea surface temperature data from AMSR–E (Advanced Microwave Scanning Radiometer of the Earth Observing System) on Aqua platform was downloaded (AMSR 2010). The spatial resolution of the data was 1/3 degrees in latitude and longitude. Gridded absolute dynamic height of the sea surface (SSH) data from TOPEX/Poseidon and ERS altimetric data products were downloaded (AVISO 2010). Spatial resolution of 3-day composites data (netCDF) was 1/3 degree.

Availability of satellite data in the tropical region is limited by the frequent presence of clouds. This hampers the use of images for deriving oceanographic information. Two options have been used to avoid cloud contamination in satellite images. SST data obtained with inactive microwave sensors and SSH obtained from active microwave (RADAR) sensors. Both these sensor techniques penetrate clouds to a variable degree. Chlorophyll is determined by ocean colour sensors (visible near infrared) that are unable to penetrate clouds. Increased data coverage is obtained by averaging (composition) of several successive images (Figure **6**) over time from ocean colour satellite images. The averaging time period must be within the range of variability of oceanographic parameters within the region. Satellite data averaged over 3–days for SST and SSH while Chlorophyll averaged over 30-days were used to match with fishery data of 3–day intervals. All the satellite data in similar periods of 3-day intervals were processed using Marine Explorer GIS (ESL 2010) software to extract SST, CHL and SSH values in fishing locations.

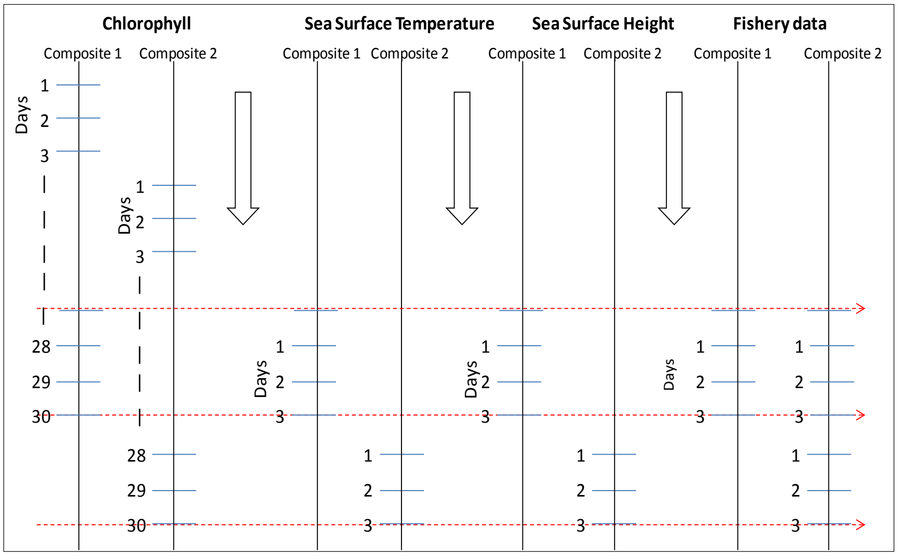
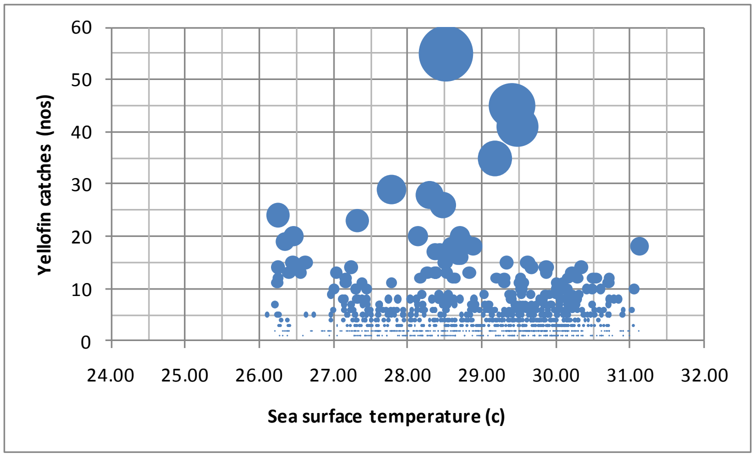


Figure 6: Sketch diagram showing composites of satellite and fishery data for data matchups. In the left 30-day chlorophyll (composite-1) updating every 3-day (composit-2) and similarly for SST, SSH.

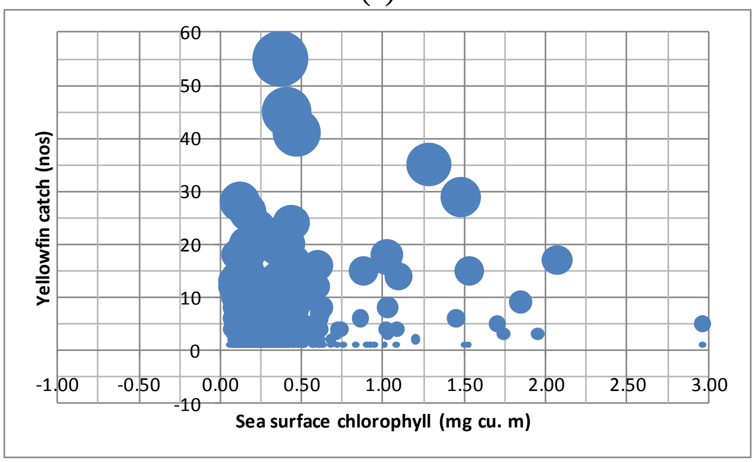
The fishery forecasting parameters (SST, CHL and SSH) have been set visually according to the ranges that corresponded to highest catches (Figure **7**) excluding outliers. Table **1** shows the set values as favorable ranges (forecasting parameters) used in order to forecast yellowfin tuna fishing grounds using satellite derived oceanographic data.

The application of the forecasting parameters to satellite images is tricky. The set ranges need to be adjusted depending on the set range spread on the images. For instance, applying only favorable range of SST (27.0–28.5 ^{o}C) might indicate a vast area, which is meaningless as a forecast. In this situation, the set value was narrowed down towards the value where the maximum CPUEs occurred. Similar procedure was adopted for the other parameters such as chlorophyll and sea surface heights (Table **1**).

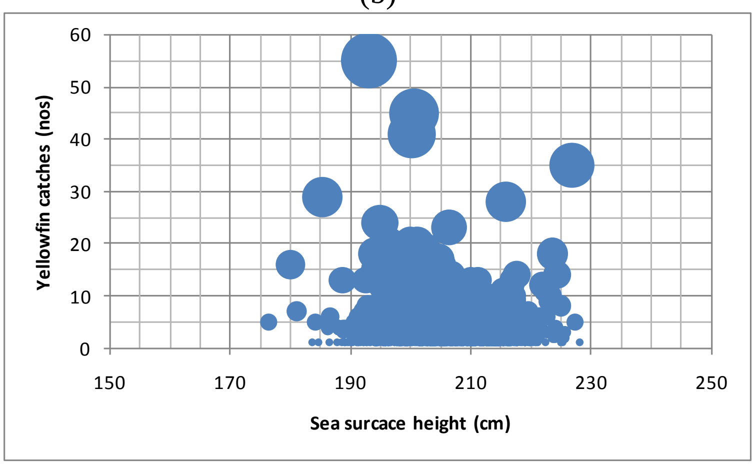
However, there are some situations where there is no overlap of predictable conditions or value for the parameters used in the prediction. This can occur due to different time scales of environmental responses. For example, SST response to wind mixing is more rapid than the response of SSH or chlorophyll. Therefore, the overall understanding of the oceanography in the region and the fishery is important. Near real time information from the fishers (feedback) is useful in this process. Radio communication can play an important role in this regard.



(a)



(b)



(c)

Figure 7: Yellowfin tuna catch by Sri Lankan long-lines against (a) Sea surface temperature (b) sea surface chlorophyll_a and (c) sea surface height (2006–2007).

Table 1: Favourable ranges of forecasting parameters for yellowfin tuna in the existing fishery forecasting system.

Parameter	**Range**	**Units**
Sea surface temperature	27.0–28.5	Degree Celsius (ºC)
Chlorophyll	0.2–0.5	Milligram per cubic meter (mg m^{-3})
Seas surface height (reference to Geoid)	190–210	Centimeter (cm)

As the Sri Lankan long-line fishery stretches over a large area, the spatial variability of forecasting parameters is significant. Yellowfin tuna is considered to be associated with thermocline, which is variable in time and space. Therefore it is derivable to include thermocline information into the forecasting system. The forecasting system is based on few parameters (SST, CHL and SSH) and requires further improvements. Continued data matching and further analyses of fishery and environmental data can make improvements.

Statistical analyses are required to set up precise confidence intervals for forecasting parameters. Evaluating the stability of the parameters is an important factor to ensure the accuracy of the forecast. Therefore, continuous fishery data collection and matchup with oceanographic parameters is proposed for a considerable period of time.

Weekly forecasts were validated with a selected group of fishermen in 2008 and the results were encouraging (Figure **8**). However, validation of forests has only been done for a short time period. Spatial and temporal variability of the forecasting parameters have not been properly understood. Therefore, the accuracy levels remain unresolved.

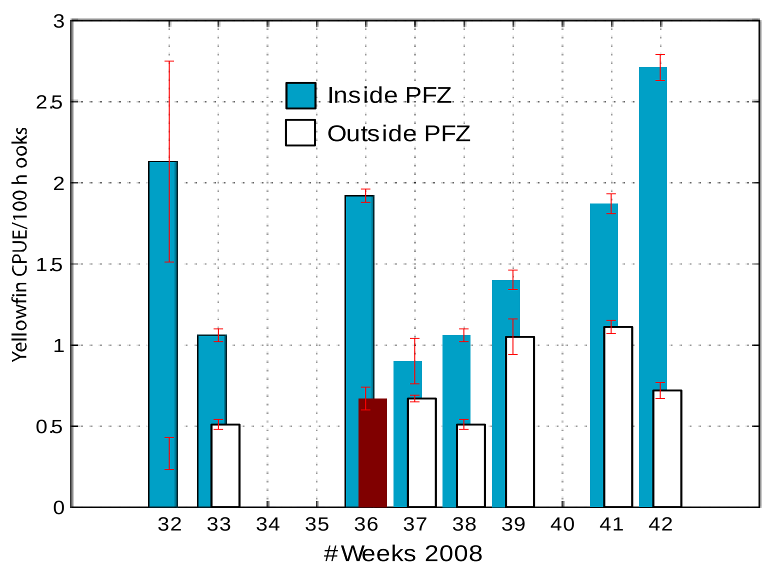


Figure 8: Validation results of fish forecasts showing high CPUEs within predicted fishing zones compared to outside areas.

3 METHODOLOGY

3.1 Study area

The study area is the northeast part of the Indian Ocean between latitude from 00–20 ^{o}N and longitude from 070–090 ^{o}E (Figure **9**). The area is highly productive and extensive seasonal fishing operations are taking place. The oceanography of the area is driven by the southwest and northeast monsoon.

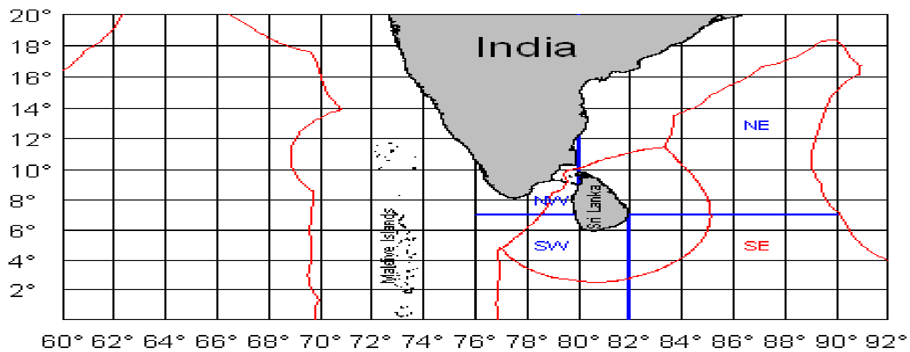


Figure 9: Geographical location of the study area showing three fishing areas; northwest (NW), northeast (NE) and southwest (SW) of Sri Lanka long-line fishery.

Fishing activities for yellowfin tuna take place in NW, SW and NE areas except SE as shown in Figure **9**. Therefore, the SE is considered as a non-fishing area by Sri Lankan long-liners. Hooking depths in NW and NE are relatively shallow (45–65 m) while in southwest they are comparatively deep (70–130 m). Weight of individual yellowfin tuna caught in the NE is on average about twice as high as in the NW where it is 20 kg. Based on this, it is thought that there are two distinct stocks in these areas.

Monsoon currents in either side of the country are influenced by the shadow effect of the island and this mainly influences on coastal fishery. However, the long-line fishery in the NW is significantly influenced by the reflected waves by the Indian continent causing rough sea conditions during the southwest monsoon. Taking the fishery and oceanography, the study area is divided into three regions and the fishery data analyses are consequently performed according to the divisions namely northwest (NW), southwest (SW) and northeast (NE).

3.2 Long-line data

Fishery data used in this study was collected from logbooks of the Sri Lankan long-line fleets. The logbook is designed to collect standardized information for research. The information consists of position of the long-line set, the species, number of hooks and the number of individual fish caught in each fishing operation. The data from 2006–2008 are stored in a mySQL database where query is sent to extract the required datasets for analyses. Catch per unit of effort (CPUE) measured as number of fish caught per 100 hooks was used as a relative index of abundance. The number of fishing trips, positive catches and zero catch records is summarized in Table **2**.

Table 2: Data summary of the long-line fleets used in this study.

	2006	2007	2008
Number of fishing trips	301	489	712
Total positions	3316	5039	7804
Positive catches	1355	2299	4870
Zero catches	1961	2740	2934

The length of long-lines is 10–15 miles, but they tend to drift during the deployed periods (4–6 hrs) due to ocean currents. However, the long-line data fall within the minimum resolution of satellite data (1/3^{o}) used in this study. Therefore, CPUE in 1/3^{o} latitude x 1/3^{o} longitude degree grids, integrated to 3–days of fishing activity for the 2006–2007 data matchups and 5–days of fishing activity is used in the 2008 data matching assuming that SST, CHL and SSH are no significantly vary within five day periods.

Depth adjustments of long–lines are limited in the Sri Lankan fisheries (Figure **10**) of which 90% are hand operated. The average depth of hooks varies between 45 m (buoyed hooks) and 65 m (middle hook) in shallow long–lines and 70 m and 130 m in deep long–lines. Shallow long–lines are used in the NW and NE areas and deep long–lines in the SW. Distance between buoys in shallow long–line is ~300 m and in deeper long–line is ~550 m. There are three to five branch lines between two buoys and the number of buoys is 50-100 per long-line.

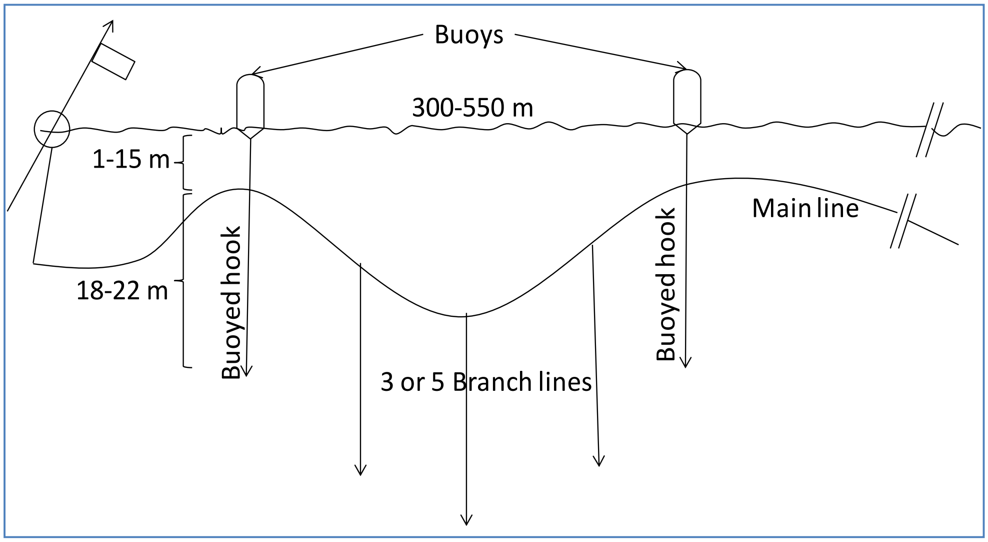


Figure 10: Schematic illustration of a Sri Lankan surface long-line.

3.3 Remote sensing data

3.3.1 Sea surface temperature

Daily SST data calculated from two satellite sensors (merged product) AMSR-E (2006–2007) and AMSR–AVHRR (2008) were used. The AMSR–E data were on 1/3 latitude/longitude degree grids and AMSRE–AVHRR blended data were on 1/4 degree grids. The grid resolution of blended data were converted into 1/3 latitude/longitude degree grids. The blended multiple satellite data products fill the data gaps in both time and space. The data are available in netCDF format (Unidata [2010]: AMSRE-AVHRR [2010]:). The SST data were averaged over three–day (2006–2007) and five–day (2008) periods in 1/3 degree latitude/longitude grids to coincide with fishery data which were similarly gridded and averaged. The gridded SST and the fishery data were then matched up (see chapter 3.4.2) extracting the SST for particular CPUEs for each five-day interval for statistical analyses.

3.3.2 Chlorophyll

Three-day composites of chlorophyll data from the MODIS (MODIS [2010]) sensor onboard Aqua satellite were used to matchup with fishery data in 2006–2007 as described in section 2.4. Three day compositing was not adequate to remove cloud contaminated pixels in the CHL image. The minimum period of composting to remove cloudy pixels was found to be at least one month. Therefore, monthly chlorophyll images were generated in 3–day steps (Figure **6**) and then matched with catch data. In situations where monthly chlorophyll composites remained cloudy, Kriging interpolation technique was used to fill the data gaps. Data analyses were done separately in three fishery sub divisions (NW, SW and NE) to understand the spatial variability. Chlorophyll data have not been matched up with fishery data for 2008.

3.3.3 Sea surface height

The daily SSH data calculated from information collected by the TOPEX and Poseidon altimeter satellite sensors and distributed by AVISO in netCDF format were used. Daily data were averaged over three-day (2006–2007) and five-day (2008) periods in 1/3 degree latitude /longitude grids. The data (AVISO 2010) were matched up with synchronized periodical fishery data. Spatial and temporal variability of SSH in relation to yellowfin abundance in 2008 were done and compared with the matchup results in 2007.

3.4 Data analyses

3.4.1 Fishery data

An initial display of monthly CPUEs from all fishing areas in 2008 showed variations over the year. The amount of data in the data set was not adequate enough to show a good pattern. Then the data for three months intervals were combined to show the CPUE distribution. The data combination into three-month periods was carried out considering the monsoon periods of the study area. The seasonal monsoon winds affect the oceanography differently in different fishing areas. Therefore the CPUE data for the three fishing areas were analyzed separately for temporal variability.

Long-lines catches depend not only on the ocean environmental parameters but also some other factors such as time of fishing, bait and hooking depth. Therefore, environmental analyses of yellowfin fishery were done discarding zero catches from the dataset.

The statistical significance of the CPUE in time (months and 3-month period) and space (NW, NE and SW) was calculated using Analysis of Variance (ANOVA). The statistical analysis was performed using R software (version 2.10.1).

3.4.2 Match up data

Fishery data from Sri Lanka long-line catches were matched up with satellite derived SST, CHL and SSH for analyses. CPUE was averaged over 3–day intervals (2006–2007) and in 5–day intervals (2008). Data matching procedure is described in chapter 2.4.

Fisheries information was stored in a structural database in mySQL where SQL (Structured Query Language) statements can be sent to call necessary data for analyses. R software has a facility to communicate with databases via SQL.

Figure 11 shows a schematic representation of data preparation and analyses. Sea surface temperature, chlorophyll and sea surface heights were analyzed in relation to CPUE to understand the space and time variability for yellowfin tuna abundance.

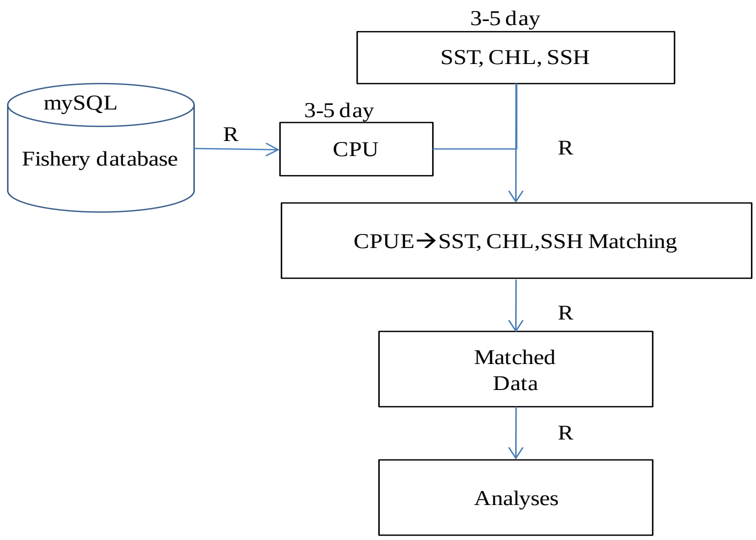


Figure 11: A schematic representation of data preparation and analyses using R software.

The relationship between CPUE and different oceanographic parameters was computed and favorable range of each oceanographic parameter was estimated by applying Generalized Additive Model (GAM). The GAM is a non-parametric generalization of multiple linear regressions, which is less restrictive in assumptions of the underlying statistical data distribution (Hastie and Tibshirani 1990). The GAM was used to determine the nature of the relationship between CPUE and the environmental variables. The three environmental variables (SST and CHL and SSH) were included in the GAM for the data 2006–2008.

$$CPUE = s(SST) + s(CHL) + s(SSH)$$

where, *SST: Sea surface temperature*
CHL: Chlorophyll
SSH: Sea surface height
And s(.) is a spline smoothing function of variables

4 RESULTS

4.1 Fishery data analysis

Monthly average CPUE of yellowfin tuna fishery for all fishing areas was fluctuated in between 0.6 and 5.5 while the mean was around 1.3 over the year (Figure **12**a, Table **4**). The highest mothly average of CPUE was 5.5 in the SW and the lowest 0.87 in the NW. However the difference in mean CPUE among the areas was not statistically significant (df = 2, P>0.05, Table **3**). The changes in CPUE between months were statistically significant (df =11, P< 0.001, Table **3**). CPUEs are more fluctuates in the NW during the year (Figure **12**b) compare to the other two areas. Box-plots (Figure **12**c) show the CPUE distribution in the three fishing areas. In the NE CPUE is slightly higher compare to other two fishing areas.

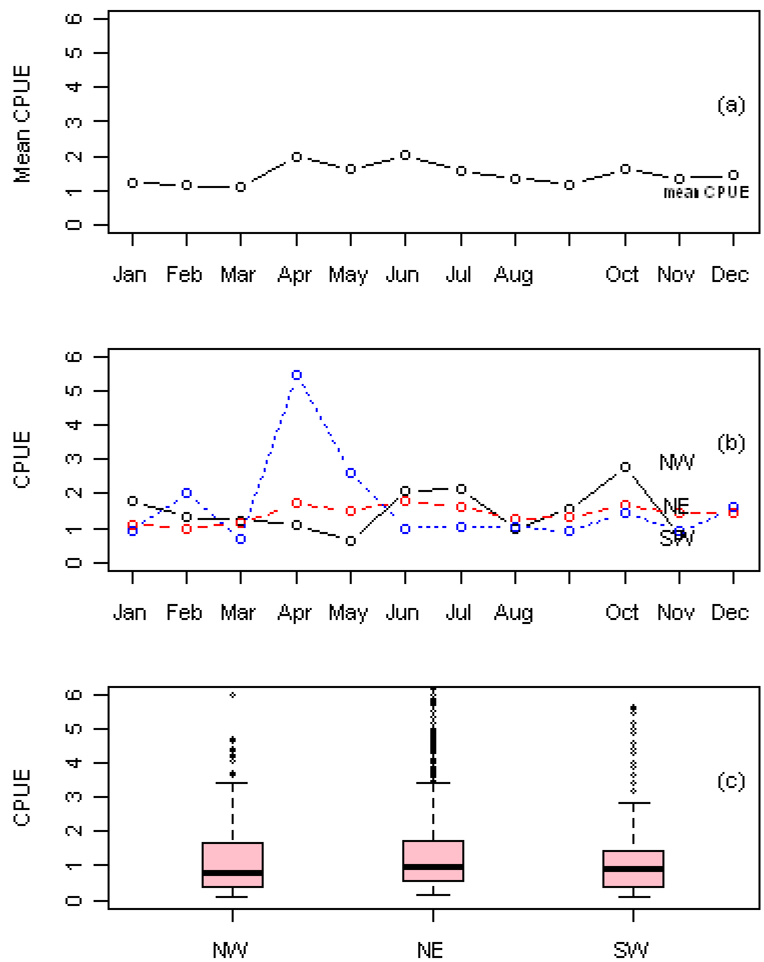


Figure 12: Temporal variability of (a) mean CPUE of yellowfin tuna fishery (b) mean CPUE in the three fishing areas and (c) Box and Whisker plot of yellowfin CPUE in three fishing areas (2008).

Temporal differences in CPUEs among three areas were computed (Table **4**). CPUE was somewhat higher in the NE throughout the year. No pattern is apparent in CPUE among months or years. It is possible that tuna distribution is more affected by local oceanographic conditions than seasonal changes. However the length of the catch data series available is not long enough to confirm this beyond doubt.

Table 3: Analysis of Variance Output for the spatial and temporal differences, (A) area and (M) month.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
factor(A)	2	4.72	2.3621	2.4564	0.08672 .
factor(M)	11	73.73	6.7023	6.9701	4.639e-11 ***
Residuals	530	509.64	0.9616		

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 4: Temporal variations of yellowfin CPUE in NW, NE and SW fishing areas (2008).

Month	**CPUE (NW) ± SD**	**CPUE (NE) ± SD**	**CPUE (SW) ± SD**	**Stat. Signif.**
Jan	1.80±1.83	1.11±0.90	0.93±0.83	0.003528 **
Feb	1.32±2.26	0.98±0.77	2.02±1.78	0.01123 *
Mar	1.22±1.02	1.14±1.22	0.69±0.37	0.2038
Apr	1.10±1.55	1.71±2.43	5.48±12.50	0.001581 **
May	0.62± NA	1.50±2.03	2.61±4.57	0.1198
Jun	NA± NA	1.80±2.18	1.00±0.52	0.1595
Jul	2.09±3.39	1.64±1.99	1.05±1.55	0.1595
Aug	2.16±2.11	1.27±1.11	1.05±0.65	0.08268 .
Sep	0.98±0.66	1.31±1.28	0.90±0.69	0.1394
Oct	1.54±1.55	1.69±2.51	1.43±1.19	0.8085
Nov	2.77±2.30	1.44±1.34	0.89±0.98	0.09373 .
Dec	0.81±1.14	1.42±1.55	1.62±1.30	0.7014

Mean CPUEs were highly variable over the year in the NW (Figure 4.2a) and the fishery was highly affected by southwest monsoon. Reasonable catches exist after the monsoon and low CPUE during the SW monsoon compared to the other two areas. Catches were more stable in the NE area and SW throughout the year and not affected by monsoons (Figure 4.2b; Figure 4.2c).

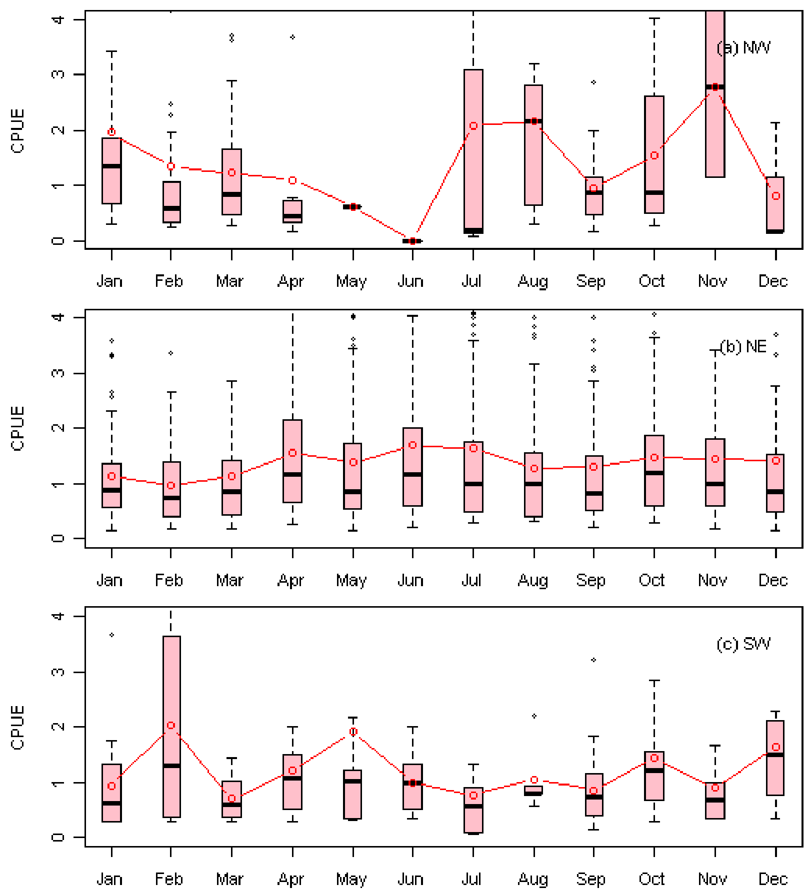
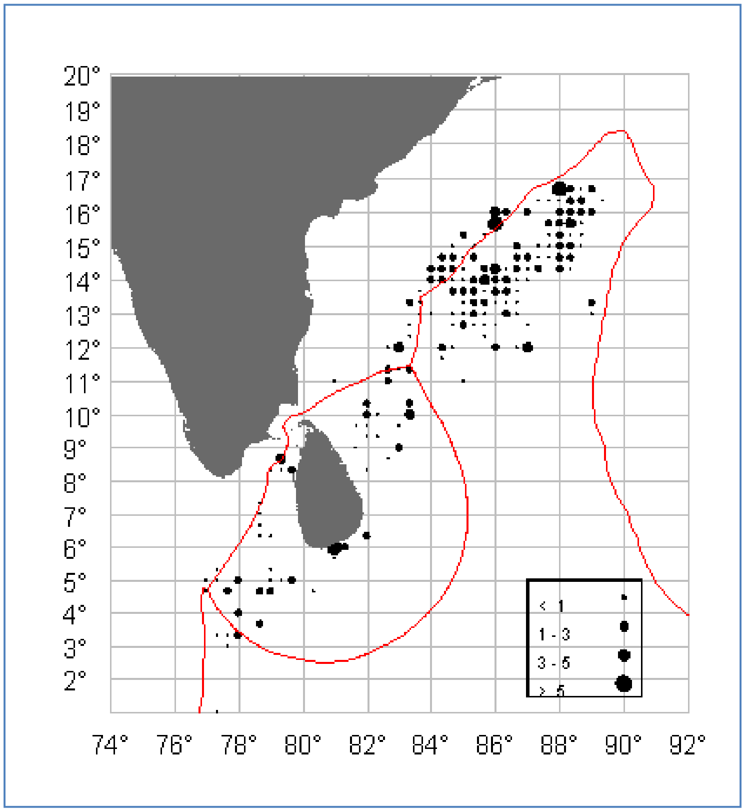


Figure 13: Temporal variations of mean CPUE (dotline) in (a) NW, (b) NE and (c) SW fishing areas (2008). The box plots show the inter quintile ranges (25%-75%) and the dashed line show the upper and lower fences while points indicates the outliers.

The results reveal that there is variability in the abundance and distribution of yellowfin tuna in space and time. The CPUE distribution (Figure **14**) shows that there is a slight shift in the higher CPUE towards northeast in the time from February to June. This shift might be related to slow movements towards the main food during the period. But Figure **15** and Figure **16** which shows average distribution over a three-month periods reveals that the shift within the year is very unclear and that demonstrates that little seasonality is seen from the data which can either because the data series are too short or there is no seasonality to be found at all.



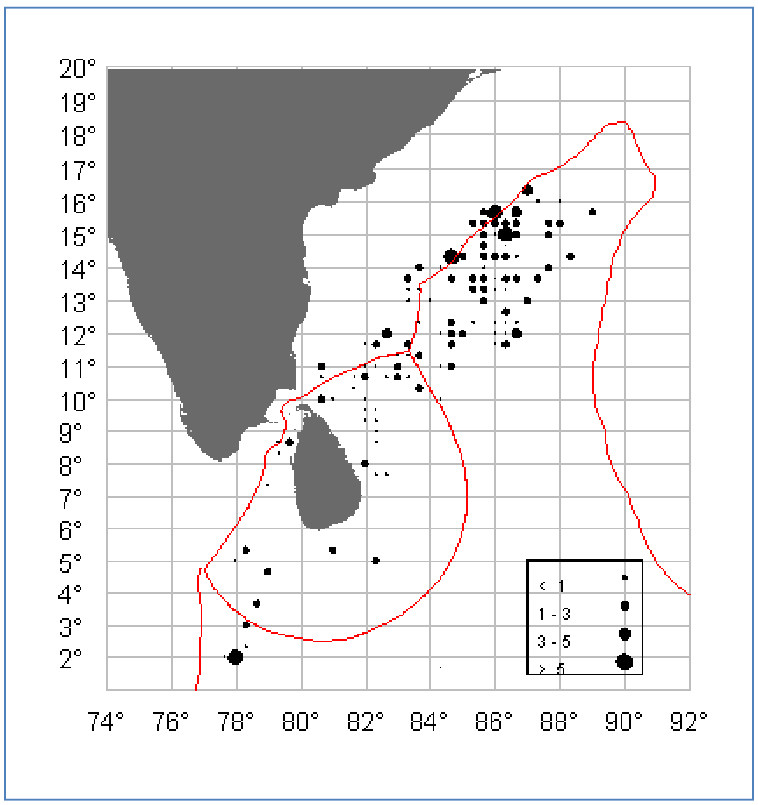


Figure 14: CPUE distributions of yellowfin tuna in February (upper) and June (lower) at 1/3° latitude 1/3° longitude grids in 2008.

The combined CPUE over three-month intervals is summarized in Table 5. The lowest catch was recorded from July–September in the SW. The CPUE was significantly higher from April to June ($P<0.01$) in SW than the other areas while it reported higher CPUE in from January to March too.

Table 5: CPUE averaged over 3-months periods in NW, NE, SW fishing areas.

Season	CPUE (NW)	CPUE (NE)	CPUE (SW)	Statistical Significant
Jan - March	1.38± 1.73	1.38± 1.71	1.59± 3.79	0.3110
April - June	1.06± 1.49	1.66± 2.22	3.12± 7.83	0.004012 **
July - Sep	1.40± 1.54	1.42± 1.56	0.97± 1.04	0.1370
Oct - Dec	1.55± 1.55	1.54± 1.93	1.32± 1.17	0.6811

4.2 Preferred oceanographic conditions for yellowfin tuna

4.2.1 Sea Surface Temperature

The variability of SST where catches took place in the three different areas is shown Figure **17**a. Slight differences in the temperature preference of yellowfin tuna were noted depending on the areas. The temperatures of yellowfin tuna catches in the NW are lower than the other two areas. Wider temperature range for yellowfin tuna catches was observed in NE (28.1–29.6 ^{o}C) than in the NW (27.8–28.7 ^{o}C) and SW (28.6–29.4 ^{o}C). High CPUEs were observed in comparatively higher temperatures in the NE than in other areas. However, the observed preference temperatures for yellowfin tuna in all study areas are within 27–30 ^{o}C in the existing forecasting system. Yellowfin tuna catches occurred in areas where SST ranged from 26–31 ^{o}C, but most of the catches were obtained in areas where SST varied primarily between 28–30 ^{o}C (Figure 17c). The CPUE in fishing grounds tended to be centered at 29 ^{o}C sea surface temperature. Therefore, the SST 27–30^{o}C range could be considered as the most favorable range for yellowfin tuna abundance while this has a temporal variability.

Temporal differences of SST with respect to CPUEs within each area were compared (Table 6). In the NW the highest CPUEs were observed from July to March (Table **6**) where temperatures range from 26.8–28.7 ^{o}C. The highest CPUEs were reported from April to October in NE and the temperature range was within 28.4–30 ^{o}C during this period. The temperature fluctuated in a narrow range (28.6–29.6 ^{o}C) in the SW where the high catches were evident in 28.7 to 29.4 ^{o}C.

Therefore, it is reasonable to conclude that the favorable temperature ranges for yellowfin tuna remains within the range (27–30 ^{o}C) although there are differences over months within areas (Figure **18**).

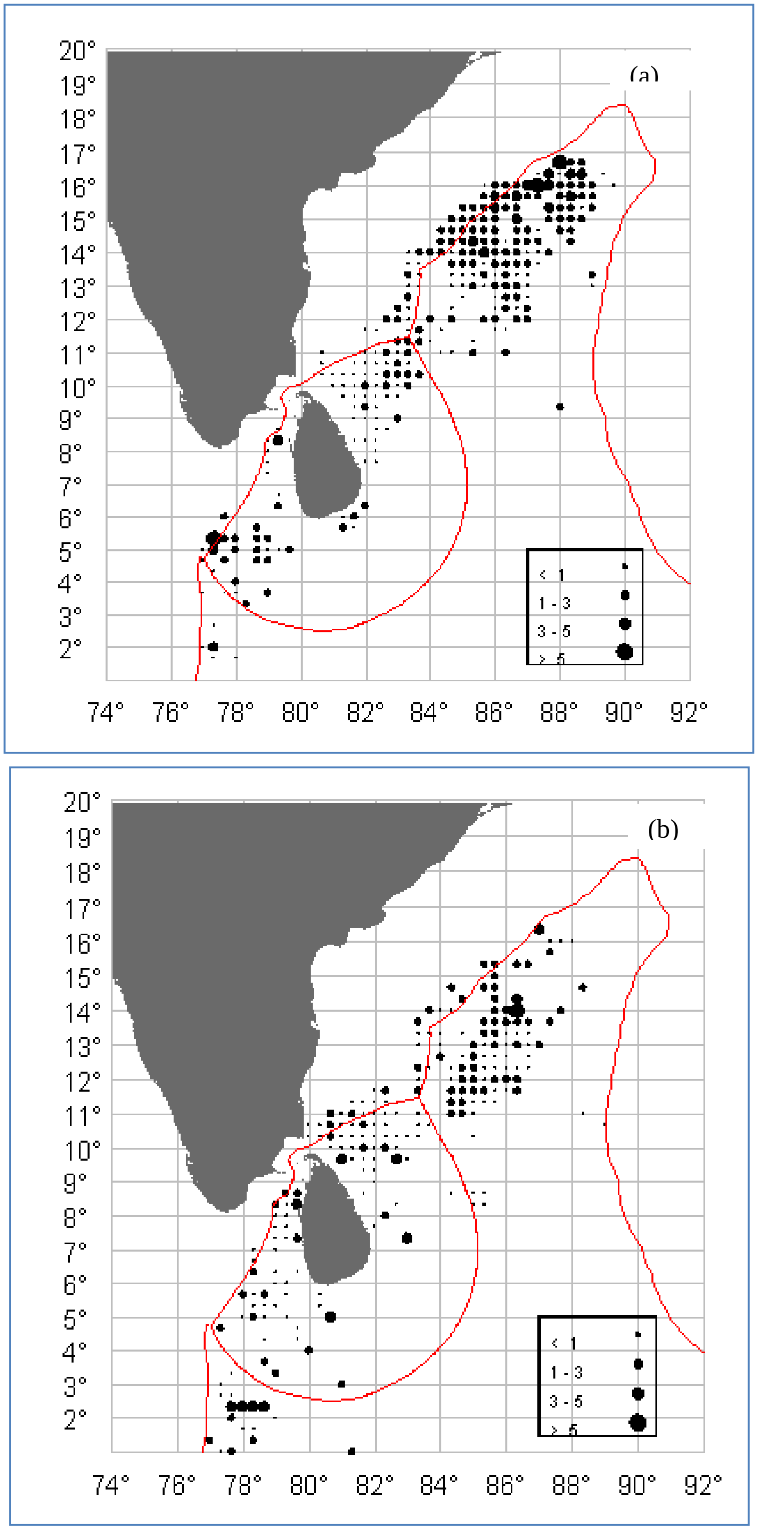


Figure 15: Seasonal CPUE distributions of yellowfin tuna from Jan-March (a) and April-June (b) at 1/3^{o} latitude 1/3^{o} longitude grids (2008).

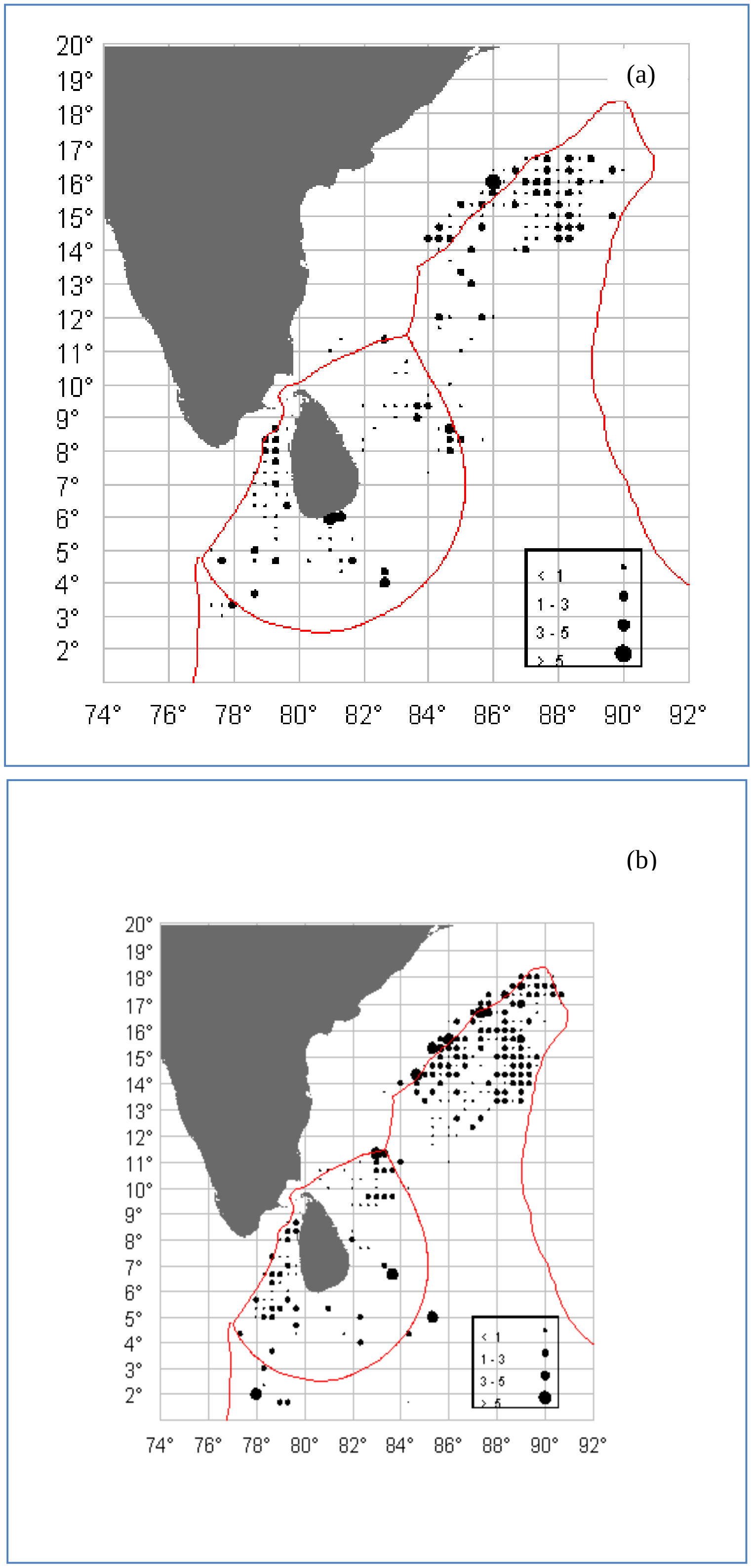


Figure 16: Seasonal CPUE distributions of yellowfin tuna from July-September (a) and October-December (b) at 1/3o latitude 1/3o longitude grids (2008).

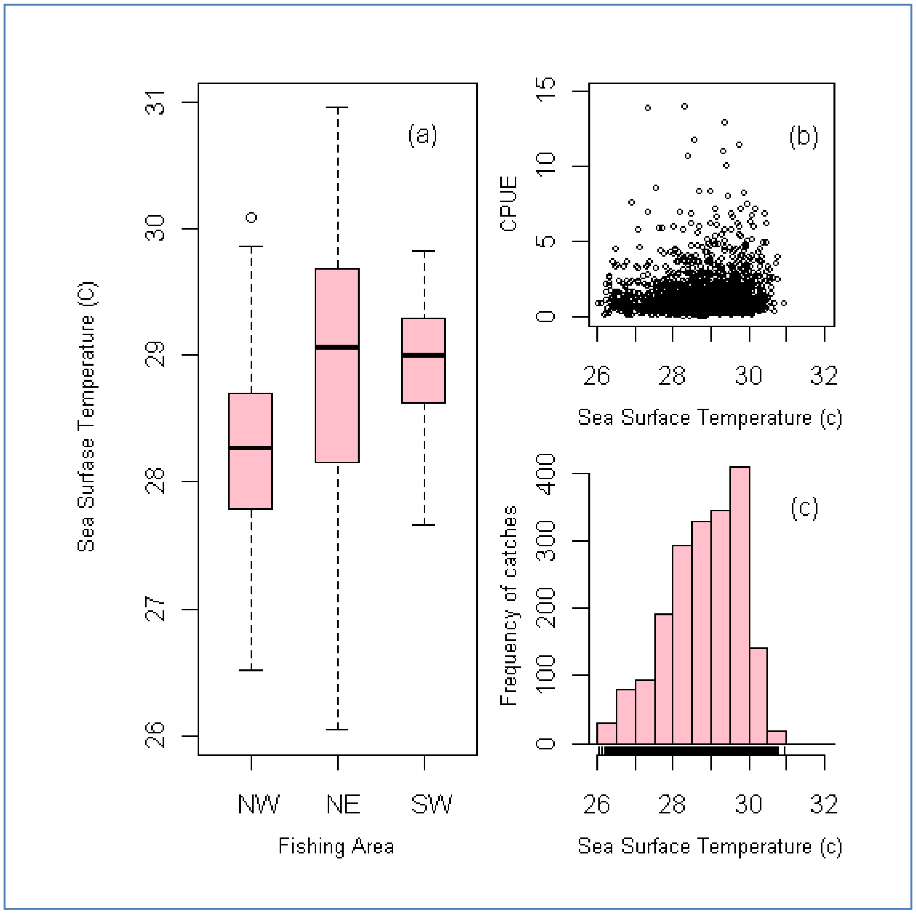


Figure 17: (a) Box and whisker plot of SST ranges of yellowfin tuna catches in three fishing areas (NW, NE, SW) (b) Scatter plot of CPUE against SST and (c) Histogram of SST at yellowfin tuna catches by Sri Lankan long-lines in 2008.

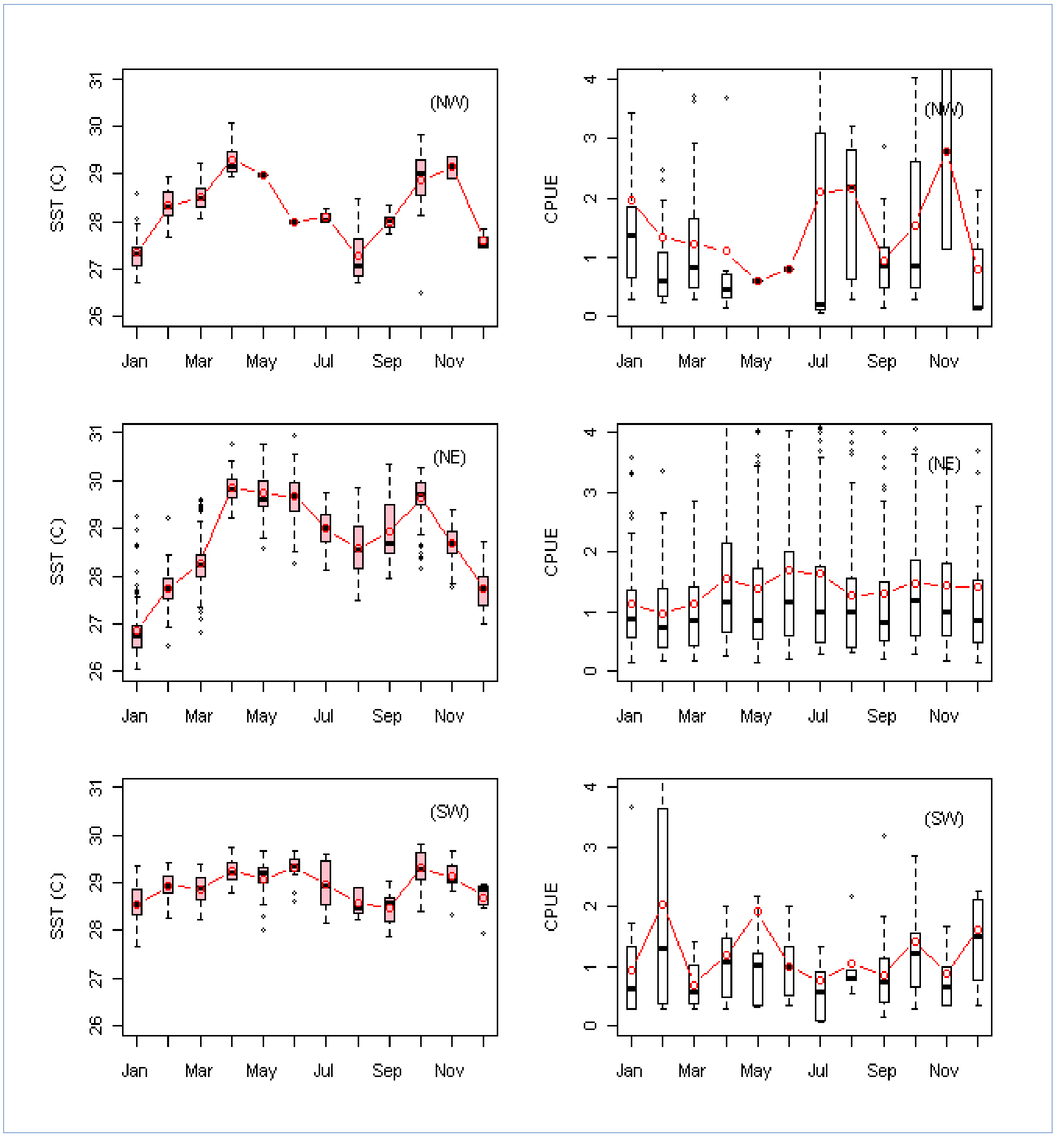


Figure 18: Monthly mean SST (left) and monthly mean CPUE (right) of yellofin tuna catches (2008) in three fishing areas. Box-plots show the inner quintile ranges (data distributed within 25-75%) with the median.

The monthly SST distribution and the distribution of favorable temperature range for yellowfin tuna in the NE in June (Figure **19**) shows the favorable temperature range in the particular month. Favorable temperature in the NE widely spread means that the favorable area is larger. The solid histogram is the SST distribution of yellowfin tuna, which is populated around the mean favorable SST. The results clearly indicate that the distribution of yellowfin tuna were comparatively narrow when compared to the SST distribution in the area. Therefore SST can be successfully used to forecast the high-density areas of this species.

Table 6: Temporal variation of the most favourable mean temperatures and corresponding CPUEs of yellowfin tuna in three fishing areas (2008).

Month	SST (NW) ±SD	CPUE (NW) ±SD	SST (NE) ± SD	CPUE (NE) ± SD	SST (SW) ± SD	CPUE (SW) ±SD
Jan.	27.35±0.39	1.80±1.83	26.86±0.55	1.11±0.90	28.55±0.45	0.93±0.83
Feb.	28.33±0.34	1.32±2.26	27.75±0.35	0.98±0.77	28.94±0.29	2.02±1.78
Mar.	28.50±0.30	1.22±1.02	28.27±0.50	1.14±1.22	28.88±0.32	0.69±0.37
Apr.	29.31±0.39	1.10±1.55	29.84±0.30	1.71±2.43	29.25±0.25	5.48±12.50
May	28.98± NA	0.62± NA	29.74±0.42	1.50±2.03	29.08±0.41	2.61±4.57
Jun.	NA	NA± NA	29.67±0.46	1.80±2.18	29.32±0.29	1.00±0.52
Jul.	28.10±0.16	2.09±3.39	28.99±0.39	1.64±1.99	28.96±0.49	1.05±1.55
Aug.	27.30±0.56	2.16±2.11	28.57±0.56	1.27±1.11	28.57±0.31	1.05±0.65
Sep.	28.00±0.16	0.98±0.66	28.93±0.57	1.31±1.28	28.48±0.33	0.90±0.69
Oct.	28.88±0.65	1.54±1.55	29.63±0.43	1.69±2.51	29.31±0.36	1.43±1.19
Nov.	29.14±0.32	2.77±2.30	28.69±0.36	1.44±1.34	29.14±0.32	0.89±0.98
Dec	27.60±0.22	0.81±1.14	27.73±0.40	1.42±1.55	28.70±0.29	1.62±1.30

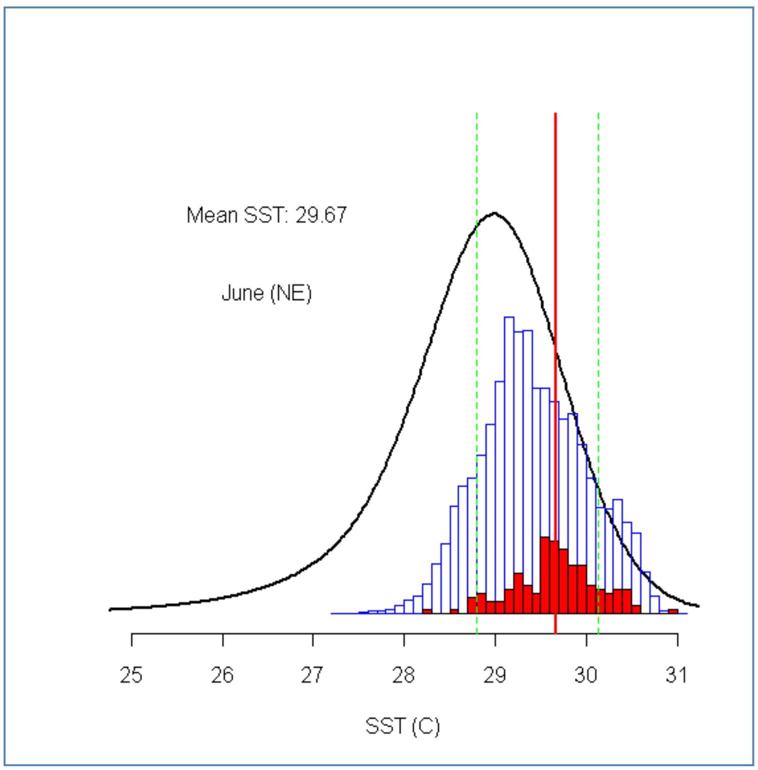


Figure 19: Histograms showing SST distribution of NE fishing area and solid vertical line is the mean favourable SST in June with two dashed lines showing the standard deviations. The solid curve shows the SST distribution in the NE throughout the year (2008).

The monthly average CPUE with respect to different temperature ranges in space and time clearly highlight the slightly different temperature preference of yellowfin tuna in different areas and time (Figure 20). The CPUE distribution within favorable temperature range is not clearly shown in these monthly average maps.

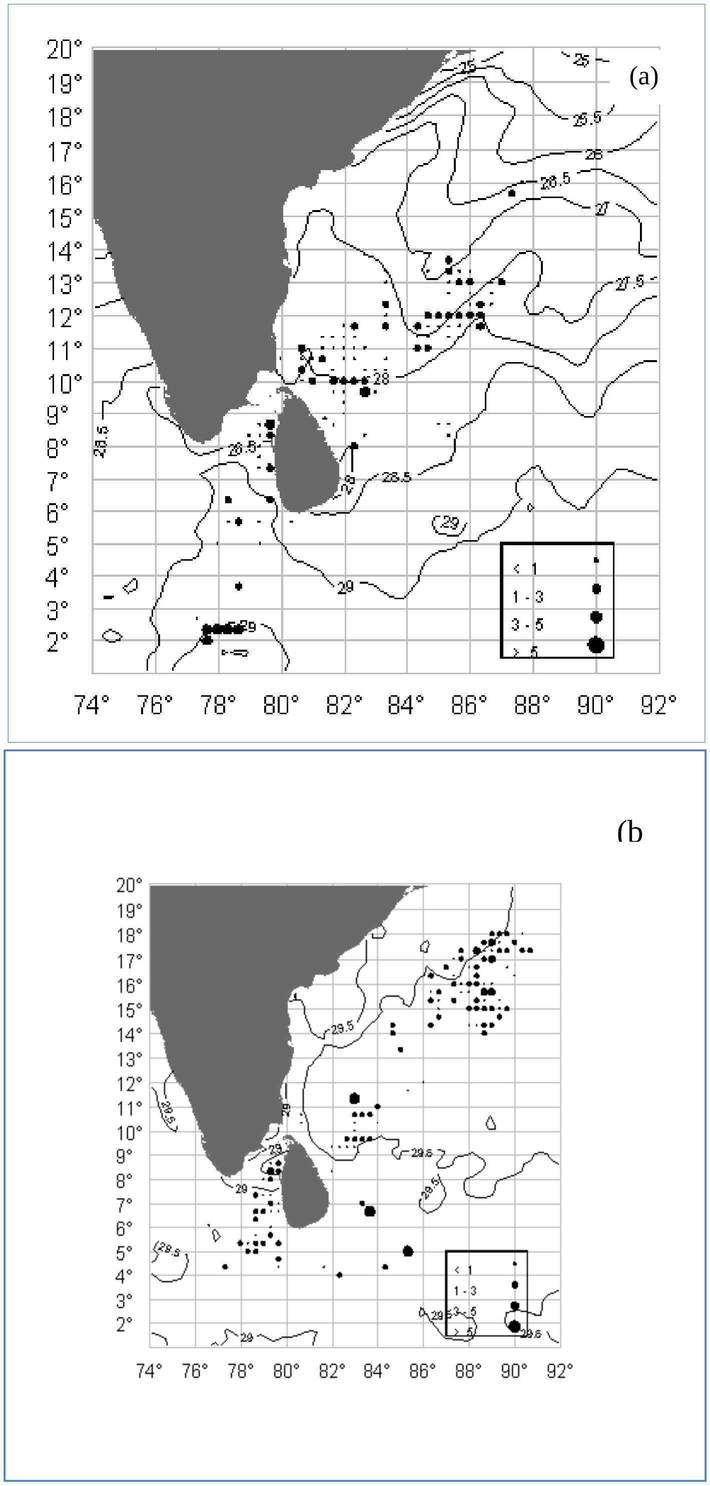


Figure 20: Seasonal CPUE distributions of yellowfin tuna in relation to sea surface temperature (a) February and (b) October 2008.

4.2.2 Sea Surface Height

The frequency distribution of CPUE weighted sea surface height follows a Gaussian distribution (Figure **21**). Distribution of high CPUEs in relation to SSH indicated that yellowfin tuna were found in areas where sea surface height ranged from 185 cm to 235 cm. Most of the fish were obtained from the waters where SSH varied from 200 cm to 220 cm (210 cm ± 10 cm) and this can be used as the favorable SSH range for yellowfin tuna. Temporal difference of SSH in each area is shown in Figure 22 and summarized in

Table 7**. SSH is showed a significant difference in temporally and spatially (p<0.001,**

Table **7**). SSH of NE area was comparatively higher and varied over a wide range than other two fishing areas.

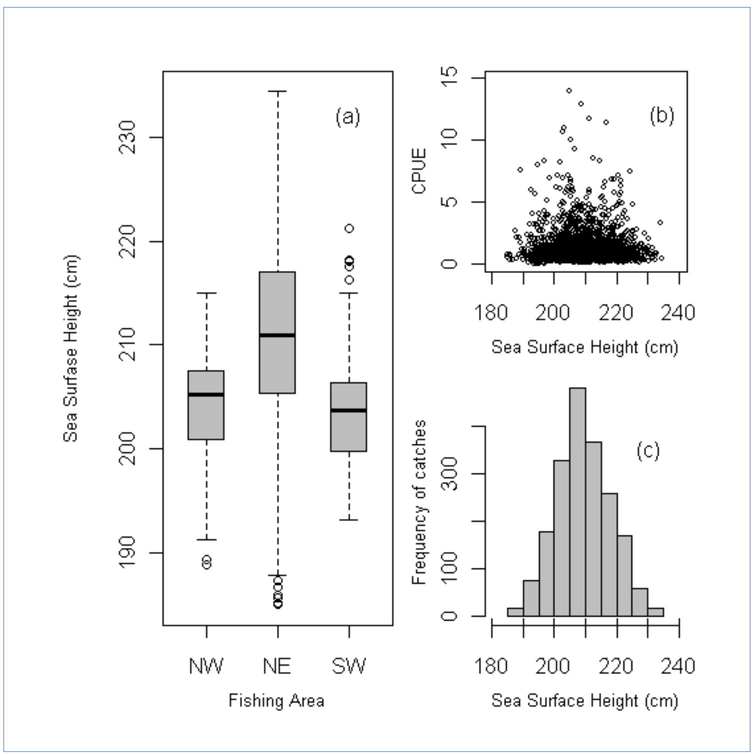


Figure 21: Box and whisker plot of SSH ranges of yellowfin tuna catches in three fishing areas (NW, NE, SW). (b) Scatter plot of CPUE against SSH and (c) frequency distribution SSH of yellowfin tuna catches by Sri Lankan long-lines in 2008.

The CPUE and SSH in the three different areas in SW and NW, the SSH fluctuated within a narrow range while it fluctuated widely in the NE (Figure **21**). In the NW and SW the high CPUEs were associated with the comparatively lower SSH range (206–208) compared to the NE range (210–216). Higher and more variability of SSH in the NE may be due complex oceanographic condition in the Bay of Bengal. The monthly average CPUE with and SSH in space and time are shown in (Figure **23**). This clearly indicates SSH preference of yellowfin tuna in fishing areas.

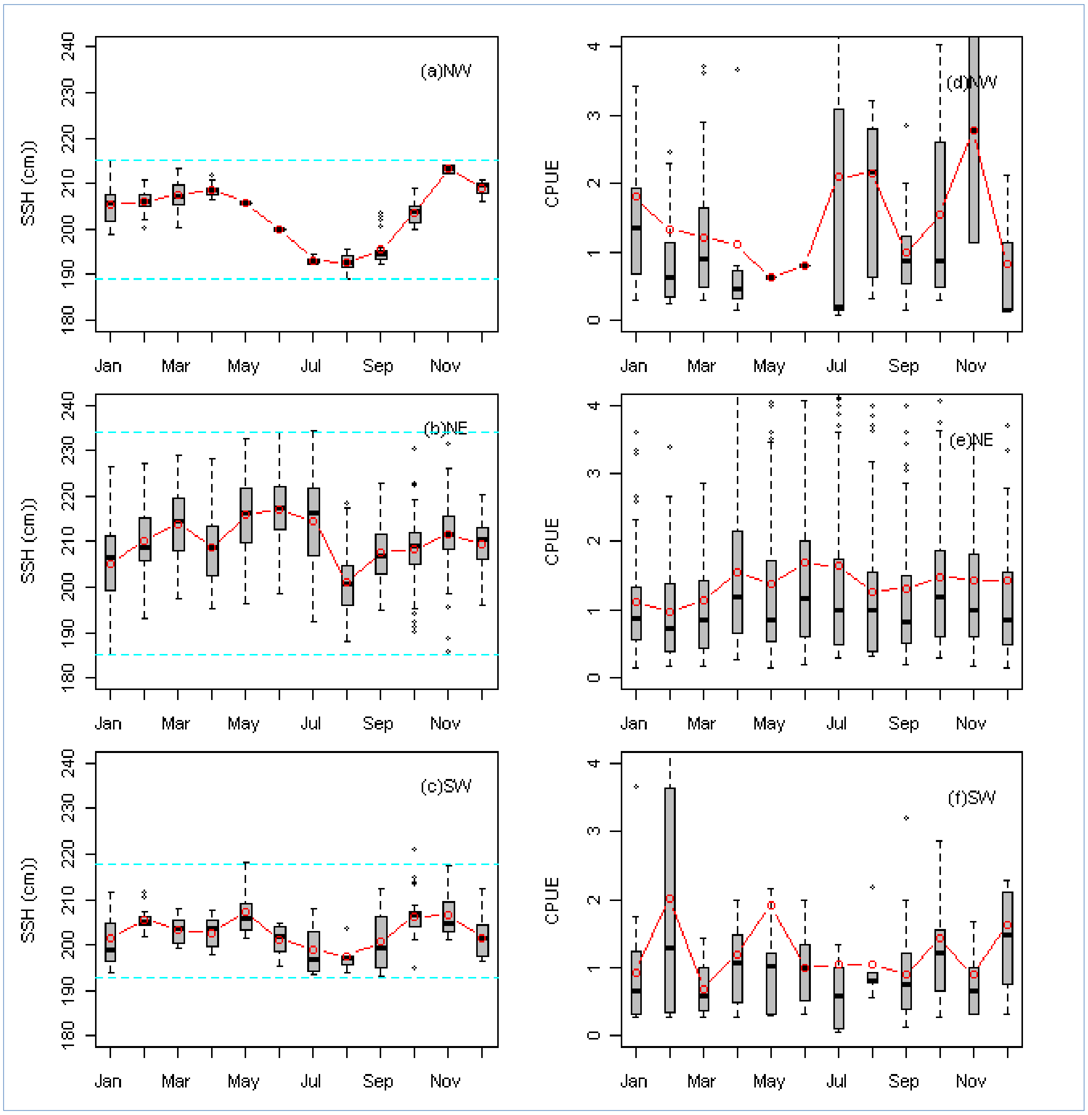


Figure 22: Monthly mean SSH (left-dotted line) and monthly mean CPUE (right–dotted line) of yellofin tuna catches (2008) in three fishing areas. Box and Whisker plots show the inner quintiles ranges median.

Table 7: Temporal variability of the SSH and CPUEs of yellowfin tuna in the three areas (2008)

Month	SSH (NW) ±SD	CPUE (NW) ±SD	SSH (NE) ±SD	CPUE (NE) ±SD	SSH (SW) ±SD	CPUE (SW) ±SD
Jan.	206.41 ± 3.55	1.80±1.83	205.25 ± 8.27	1.11±0.90	201.38 ± 6.04	0.93±0.83
Feb.	206.03 ± 2.29	1.32±2.26	210.21 ± 7.16	0.98±0.77	205.75 ± 2.75	2.02±1.78
Mar.	207.54 ± 2.71	1.22±1.02	214.09 ± 7.42	1.14±1.22	203.32 ± 2.66	0.69±0.37
Apr.	208.71 ± 1.62	1.10±1.55	208.51 ± 7.44	1.71±2.43	202.40 ± 3.09	5.48±12.50
May	205.82 ± NA	0.62± NA	216.11 ± 8.08	1.50±2.03	207.48 ± 5.42	2.61±4.57
Jun.	193.53 ± 1.29	NA± NA	216.78 ± 6.86	1.80±2.18	201.28 ± 3.08	1.00±0.52
Jul.	NA	2.09±3.39	215.35 ± 10.2	1.64±1.99	199.61 ± 4.87	1.05±1.55
Aug.	192.94 ±1.99	2.16±2.11	200.97 ± 7.33	1.27±1.11	197.68 ± 3.60	1.05±0.65
Sep.	195.42 ±3.22	0.98±0.66	207.51 ± 6.74	1.31±1.28	200.71 ± 6.37	0.90±0.69
Oct.	203. 60 ±2.67	1.54±1.55	208.27 ± 6.72	1.69±2.51	206.07 ± 3.74	1.43±1.19
Nov.	214.17 ±2.31	2.77±2.30	211.83 ± 7.25	1.44±1.34	206.09 ± 4.29	0.89±0.98
Dec	208.81 ±2.48	0.81±1.14	209.39 ± 5.35	1.42±1.55	201.98 ± 4.67	1.62±1.30

4.2.3 Chlorophyll

The frequency of high CPUE of yellowfin tuna in relation to CHL is not normally distributed (Figure **24**b). The fishing was occurred in areas where CHL varied from 0.05–0.8 mg m^3. However, yellowfin tuna catches were mostly taken in fishing grounds where CHL ranged from 0.05–0.25 mg m^3. CPUE is negatively correlated with CHL.

CHL concentrations showed a significant difference in temporally and spatially ($p<0.0001$). SSC of NE area was comparatively lower and fluctuated with relatively narrow range compared to the other two fishing areas. Temporal difference of SSH within each area is summarized in Table 8.

The oceanographic parameters, such as SST and SSH, favorable for yellowfin tuna in three fishing grounds in 2007-2008 were compared (Figure **25**). The parameters show slight variations, which may be due to temporal extreme oceanographic conditions caused by monsoons. However, the parameters are reasonably consistent within two years compared and can be used to forecast potential areas for yellofin tuna.

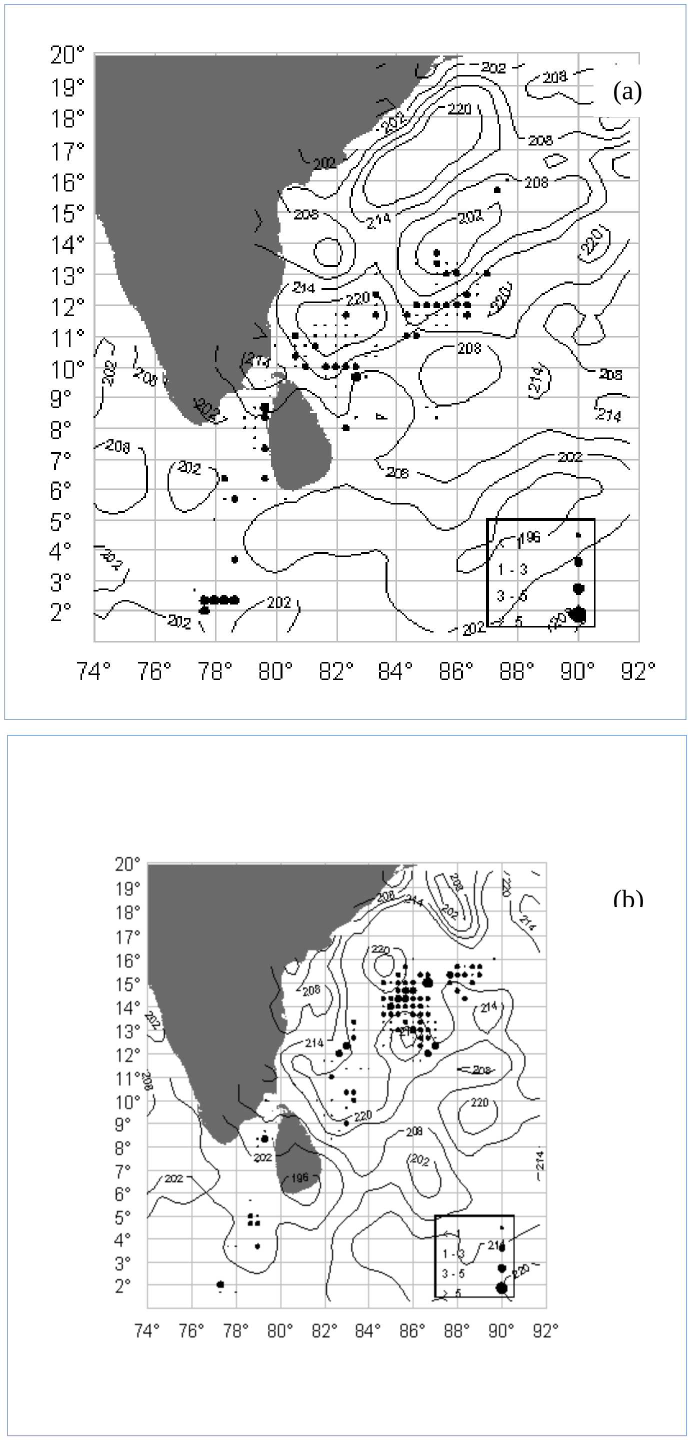


Figure 23: Seasonal CPUE distributions of yellowfin tuna February (a) and April (b) in relation to sea surface height (2008).

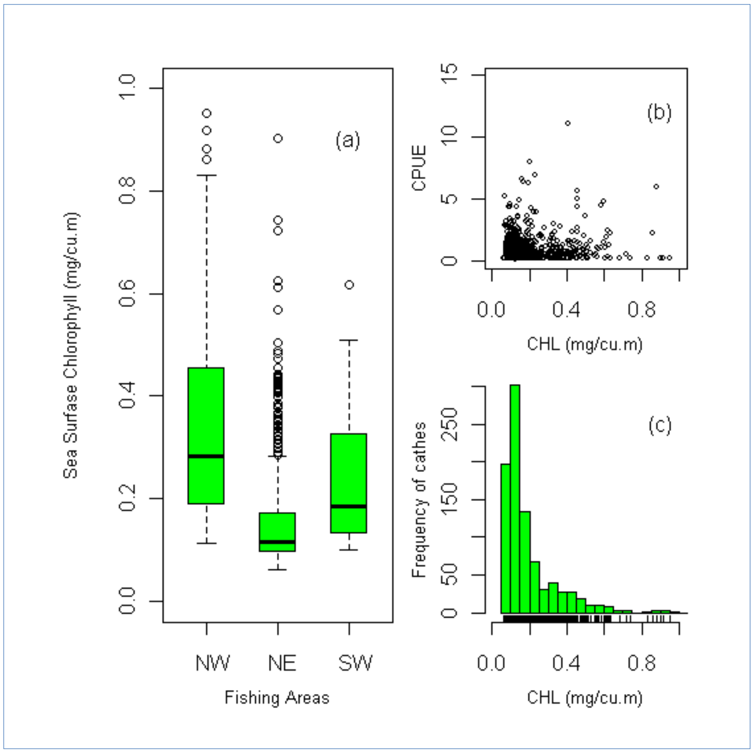


Figure 24: (a) Box and whisker plot of CHL ranges of yellowfin tuna catches in three fishing areas (NW, NE, SW) (b) Scatter plot of CPUE against CHL and (c) frequency distribution CHL of yellowfin tuna catches by Sri Lankan long-lines in 2006–2007.

Table 8: Temporal variability of CHL and CPUEs of yellowfin tuna in the three fishing areas (2007).

Month	CHL (NW)	CPUE (NW)	CHL (NE)	CPUE (NE)	CHL (SW)	CPUE (SW)
Jan.	0.25±0.11	0.85±0.57	0.29±0.13	1.45±1.88	NA	NA
Feb.	0.37±0.18	0.44±0.25	0.25±0.10	0.83±0.74	0.32±0.01	0.27±0.05
Mar.	0.30±0.20	1.33±1.85	0.15±0.07	0.80±0.67	0.15±0.04	0.99±0.56
Apr.	0.24±0.25	0.94±1.11	0.11±0.02	0.82±0.61	0.18±0.13	0.70±0.51
May	0.17±0.06	1.14±0.50	0.10±0.06	1.41±1.00	0.13±0.01	1.24±0.70
Jun.	NA	NA	0.09±0.01	0.75±0.55	NA	NA
Jul.	0.29±0.01	0.31±0.01	0.13±0.05	0.77±0.75	NA	NA
Aug.	NA	NA	0.34±0.28	0.90±0.38	0.25±0.01	0.40±0.02
Sep.	0.32± 0.02	4.91±5.85	0.26±0.07	0.54±0.40	0.15±0.04	0.89±0.59
Oct.	0.42±0.13	1.52±1.46	0.25±0.04	0.73±0.54	0.37±0.09	0.85±0.71
Nov.	0.35±0.15	1.59±1.66	0.30±0.21	3.32±4.43	0.22±0.12	0.86±0.55
Dec	0.22±0.12	1.50±2.00	0.26±0.17	1.06±1.67	0.16±0.01	1.62±0.01

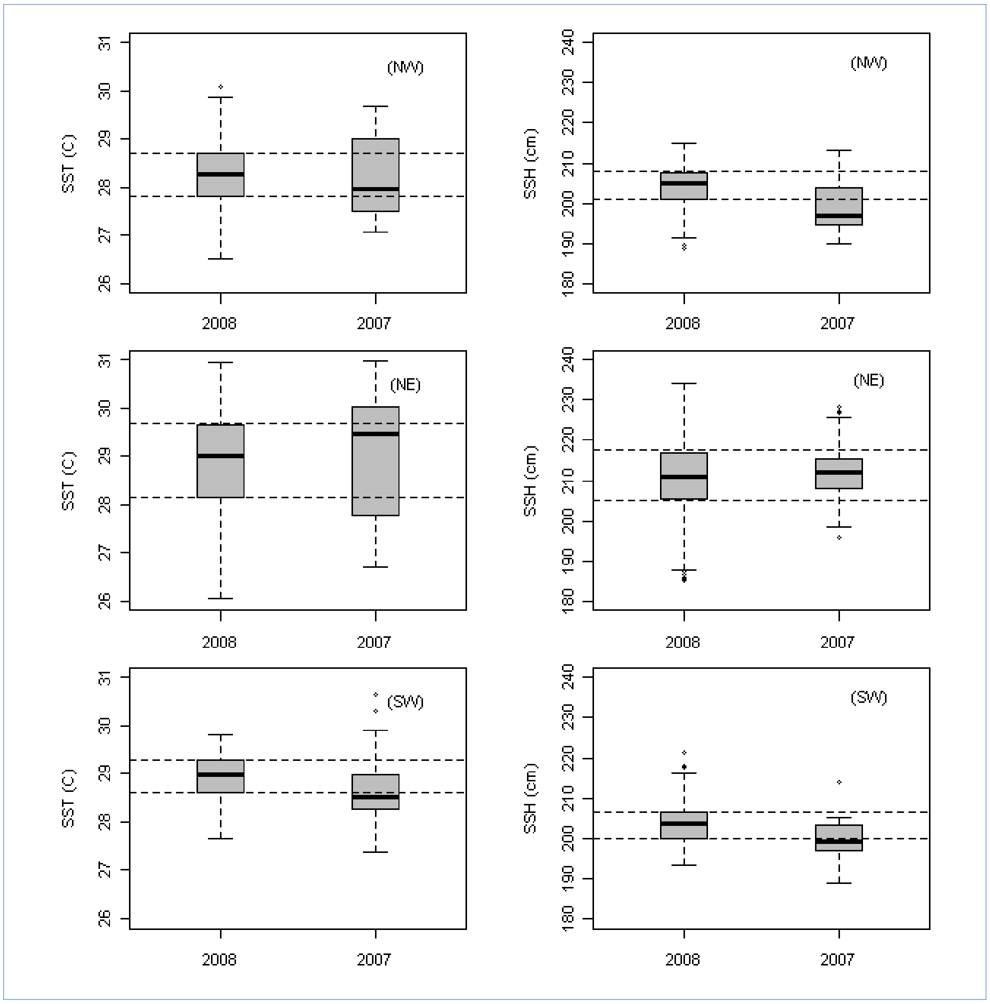


Figure 25: Comparison of forecasting parameters determined from 2008 with 2007 fishery and oceanographic data. Sea surface temperature (left) and Sea surface height (right), the dashed horizontal lines show the most favourable ranges estimated in 2008 for yellowfin tuna.

To optimize the predicted ranges of these parameters, Generalized Additive Model (GAM) was applied. The relationship between yellowfin tuna CPUE and all three variables SST and CHL was highly significant (Table 9) when it applies the GAM. GAM analysis also clearly indicated that yellowfin tuna catches were found in strong association with environmental SST of about 28–30^{0}C, CHL of about 0.05–0.4 mg m^{3} and SSH of about 200 to 220 cm (Figure **26**). These results were consistent with the output producing from the distribution map and high catch histogram analyses.

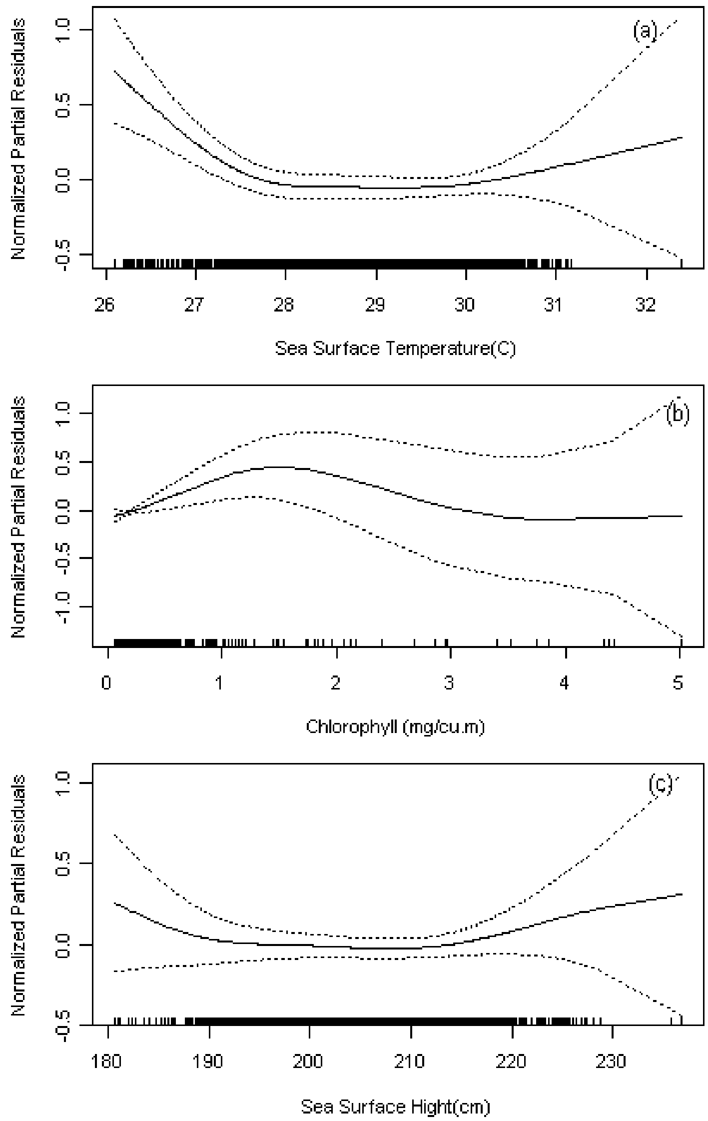


Figure 26: Generalised additive model (GAM) derived effect of oceanographic variables (a) AMSRE-AVHRR SST (b) MODIS CHL and (c) AVISO SSH on yellowfin CPUE. Tick marks (rug) at abscissa axis represent the observed data points. Solid-line is the explaining function and dashed-line indicate the 95% confidence interval, equivalent to two standard deviations (±2 S.D.)

Table 9: analyses of variance for significant parameters included in the GAM for yellowfin tuna.

Parameter	*F** statistic	*p*-value
Sea surface temperature Chlorophyll_a	9.80	0.00005
concentration	5.09	0.00620
Sea surface height	2.59	0.07504

Based on the results, preferred oceanographic conditions for yellowfin tuna were obtained. The preferred ranges are SST from 28–30 °C, CHL from 0.025–0.25 mg m^3 and SSH 200–220 cm.

5 DISCUSSION

Results in this study indicated that the CUPE ranges from 0.07–14 in yellowfin tuna long line fishery. According to Sivasubramaniam (1985), the catch rates of yellowfin tuna has fluctuated around 80 kg per day. In his study it was not able to focus the CPUE analysis based on the weight due to unavailability of such information in the database. The reported CPUE values in the present study were comparatively lower than the other yellowfin tuna fishery Nations in the Indian Ocean (IOTC 2009). This may be due to inefficient long-lines used by Sri Lankan fleets. Inefficiency of Sri Lankan long-lines occurs due to several reasons. Size of fleets, number of hooks, hooking depths and depth adjustments, suitable baits, onboard technology and the overall knowledge on fishing skills are the limiting factors.

The distribution of yellowfin tuna CPUE in the NW shows seasonality may be associated with the monsoon oceanographic conditions. But CPUE in the NE and SW not shown any seasonality and the catches were more stable throughout the year. The distribution of CPUE gives an insight evidenced on their slight movements by shifting fishing locations in the NE. Migration of yellowfin tuna has previously been explained by Anderson (1988). According to his explanation, yellowfin tuna migrate in the central Indian Ocean in which a broad band of young fish in the equatorial waters moves east and west in phase with the seasonally changing monsoon currents. Morita and Koto (1971) have highlighted the movement of yellowfin tuna from the equatorial western Indian Ocean, through the southern Maldives and NW part of Sri Lanka into the Bay of Bengal every year between October and March. In this study, for instance, migration of yellowfin tuna was not clear. However, shifting of fishing locations was observed within the bay of Bengal. Limited information is available on tuna migration pattern in the Indian Ocean. Limited fishery data was used in this study and long time series of fishery data may provide more precise representation of yellowfin tuna.

The most of the fishing effort of the Sri Lankan long-liners concentrated in NE area. If we consider the CPUE distribution in the NE, it confirms the yellowfin tuna availability throughout the year swimming along the east coast off Sri Lanka to the East Indian coast towards the north of the Bay of Bengal. Then turn down and move along the Andaman Sea to the south. Nishida (1992) proposed two major stocks of yellowfin tunas in the Indian Ocean: a western and an eastern stock. According to his study the margin of two stocks are very close to Sri Lankan EEZ and mixing of stocks can occur within the eastern part of the country. This could be a reason for high CPUEs in the NE throughout the year. If these two stocks migrate towards Sri Lanka in different time of year, it might be a reason for consistent yellowfin tuna catches in the NE.

Although this study used short data set in 2008, the biophysical environmental data have been selected accurately to describe the environment of major yellowfin tuna fishing grounds. The AMSRE–AVHRR blended SST was selected as the AMSRE microwave sensor is capable of measuring SST through clouds. Combinations of SST data with the MODIS CHL and AVISO SSH data have provided favorable conditions for yellowfin tuna. The relationship between yellowfin catch and environments clearly indicates that there are specific times and locations where yellowfin tuna are abundant. In the present study, we describe a highly productive yellowfin habitats are linked to dynamics of physical oceanographic structures.

The results show that the SST influences the abundance and distribution of yellowfin tuna in off NE Indian Ocean. The highest CPUEs correspond to the SST between 27.0–30.0 ^{o}C and there are temporal variations in three areas. According to Stretta (1991), yellowfin tuna prefers warmer waters and the abundance of this species was higher with temperature limits between 18 ^{o}C and 31.0 ^{o}C. It is reported that in the tropical Atlantic, most of the catches of yellowfin tuna occurs with temperatures between 22.0 ^{o}C and 29.0 ^{o}C, and preferentially above 25.0 ^{o}C. The flat relationship was evident in the temperature and distribution of *T. albacares* catches in Brazil coast within the range of 26–28.5 ^{o}C (Zagaglia 2004). By these observations it has been concluded that, the SST values above 28.0 ^{o}C seem to form a pathway of favorable thermal conditions to the migratory movements of *T. albacores* (Zagaglia, 2004). The result of this study is also consistent with the other findings in tropical waters.

Now it is well established that SST is an important predictor of CPUE in the yellowfin tuna longline fishery. View on an ocean scale, SST represented not only the temperature but also the correspondence with latitudes. Studies on albacore tuna in Indian and Pacific Oceans have shown that the favorable SST limits are depended on the season as well as life history stages. So it is better to consider the effect of SST on the different life history stages of yellowfin tuna, which will ensure the higher CPUEs by avoiding young and juvenile in, catches.

Block *et al*. (1997) and Brill *et al*. (1999) found that the depth of the mixed layer is more important than the SST for the abundance of yellowfin tuna. According to their findings, adult *T. albacares* were found inside the mixed layer or immediately below it while juveniles are associated in much shallow areas. It was unable to correlate the mix layer depth (depth of thermocline) and the CPUE during the present study, as time did not permit. The knowledge on the relations between CPUE and thermocline depth can be used to further improve the existing forecasting system in the near future.

The results of this study revealed that 0.3 mg m^{-3} CHL isopleth creates the most productive yellowfin tuna habitat off NE Indian Ocean. The favorable CHL range for the abundance of yellowfin tuna in equatorial Atlantic has been calculated as in the range of 0.2–0.4 mg m^{-3} (Zagaglia 2004). Thus, the results of this study are consistent with other results discussed on the favorable CHL ranges for yellowfin tuna (Zagaglia 2004).. Further, the CHL concentration was inversely related to the CPUE. The inverse correlation could be due to the fact that tuna are visual predators and prefer clear waters (Laurs *et al.* 1984). Although some CHL frontal regions close proximity to the warm waters can be places of high density of tuna (Brill & Lutcavage 2001; Fiedler & Bernard 1987), such well developed CHL fronts were observed in the NE part of our study region and this is another possible reason for the higher aggregation of yellowfin tuna in NE area.

The optimum SSH ranges for the abundance and distribution of yellowfin tuna off East Indian Ocean was estimated 200–220 cm though there are some differences within the areas. The importance of SSH to forecast the yellowfin tuna fishing habitats have been discussed by various authors (Polito *et al.* 2000, Zagaglia 2004). It has been pointed out that the relationship between the SSH and CPUE may vary considerably as SSHA (Sea Surface Height Anomaly) is the result of a complex combination of dynamical and thermodynamic factors, which could affect in opposite ways the concentration of the fishing resources (Zagaglia 2004). However it is difficult to make any comparison with others findings as they have used SSHA.

Based on the results, the favorable oceanographic parameters for yellowfin tuna aggregation off East Indian Ocean were characterized by; SST of 28–30 ºC, CHL of 0.1–0.4 mg m^{-3} and SSH 200–220 cm. These results are very similar to the previous study for yellowfin tuna in relation to SST (Uda 1973) and CHL (Polovina *et al.* 2001). The results obtained from this study can be used to understand the relation between the abundance of yellowfin tuna with respect to some oceanographic parameters such as chlorophyll concentration, SST and SSH. The recent findings and seasonal and temporal variability can be incorporated to improve the excising fishery forecasting system.

The thermocline, current pattern, eddies, wind and bottom topography are considered as other factors that directly affect the distribution and abundance of yellowfin tuna. The effects of the thermocline factor in three fishing areas are to be considered in future studies.

Limited data set (2006–2007 and 2008) was used for the present analysis. The use of long-term time series fishery data will ensure the accuracy and precision of the forecasting parameters.

The satellite measurements can only penetrate few meters into sea surface. Thus the techniques used in defining the potential locations of fish stocks using satellite data may be associated drawbacks as we are unable to focus for the some important parameters such as thermocline depth. Further the resolution of the satellite images is low and the accuracy of the measurements is questionable.

The limitations of the availability of in-situ data may yield some inconsistencies with the results. The habitat preference and the migration pattern of yellowfin tuna were not well documented in the Indian Ocean. So the interpretations are based on the limited information available. The results would have been more realistic if more biological information on yellowfin tuna could be incorporated.

6 CONCLUSIONS AND RECOMMENDATIONS

Based on the results, the favorable oceanographic parameters for yellowfin tuna abundance in the East Indian Ocean could be used to forecast the potential favorable zones considering special and temporal variability. This would help to reduce the time spend for searching and thereby reducing the operational coast. Moreover this would lead to lessen the days at sea, which would ensure the better quality of the fish for exports.

It should be considered that the results provide only the potential favorable areas for yellowfin tuna fishery with several oceanographic parameters. The vertical distribution of yellowfin tuna was not yet properly understood in these regions and many other parameters are influenced the fish abundance. In order to minimize the errors of fish forecast, the support of local fisher folk is essential for research on other parameters, which are not possible to derive from satellites.

Consideration of long-term fishery data and more oceanographic parameters such as vertical temperature, salinity, dissolve oxygen and current patterns are to be incorporated in future studies to improve the forecast system. Besides, the research on habitat preference of yellowfin tuna would also increase the validity of this study.

Due to the high cost of marine research, the use of satellite data in defining environmental variability in the ocean environment has significant economic importance. The experimental fishing based on the forecast and in-situ oceanographic data collection would be much useful to investigate other oceanographic parameters for yellowfin tuna abundance. However, a collaboration of governmental agencies, research institutes and fishing fleets would be a wise decision in terms of sharing the knowledge and cost.

Prediction of favorable fishing zones is useful to make fishery operations more efficiently. Use of the information more effectively, awareness creation and training on navigation, gear technology, and modern equipment to offshore fishers are recommended.

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LIST OF REFERENCES

Abbott, M.R and Chelton, D.B.,(1991). Advances in passive remote sensing of the ocean. *Reviews of Geophysics, Supplement*, 29. 571-589.

Andrade, H.A and Garcia, A.E. (1999). Skipjack tuna in relation to sea surface temperature off the southern Brazilian coast. *Fisheries Oceanography* 8:245-254.

Bidigare R. R., Chai F., Landry M. R., Lukas, R., Hannides C. C. S., Christensen S. J., Karl D. M., Shi L., and Chao Y. (2009) Subtropical ocean ecosystem structure changes forced by North Pacific climate variations. *J. Plankton Res*. 31:1131-1139.

Bigelow, K.A.Boggs, C.H., and He, X. (1999). Environmental effects on swaordfish and blue shark catch rates in the U.S. North Pacific long-line fishery. *Fishery and Oceanography* 8(3): 178-198.

Block B.A., Keen, J.E, Castillo B., Dewar, H. Freund E.V., Marcinek D.J., Brill R.W., Farwell C. (1997). Environmental preferences of yellowfin tuna (*Tunnus albacores*) at the northern extent if its range. *Marine Biology* 130:119-132

Brill, R.W., 1994. A review of temperature and oxygen tolerance studies of tunas pertinent to fisheries oceanography, movements models and stock assessments. *Fish. Oceanogr.*, **3** (3): 204-216.

Brill, R. W., Block, B. A., Boggs, C. H., Bigelow, K. A., Freund, E. V. and Marcinek, D. J. (1999). Horizontal movements and depth distribution of large adult yellowfin tuna (*Thunnus albacares*) near the Hawaiian Islands recorded using ultrasonic telemetry: implications for the physiological ecology of pelagic fishes. *Mar. Biol*. 133, 395–408.

Brill R. W., & Lutcavage, M. E. (2001). Understanding environmental influences on movements and depth distributions of tunas and billfishes can significantly improve population assessments. American Fisheries Society Symposium, 25:179– 198.

De Rosa, A.L. & O. Maury, (1998). Analyse Spatio-Temporelle des Relations Thons-Environnements. Utilisation des données opa et des outils D'Analyse SIG et GAM. ICCAT . SCRS / 97/85. 253-256 pp.

Dissanayake, (2005). Monitoring and assessment of offshore fishery in Sri Lanka. Report submitted for United Nations Fisheries Training programme, Marine Research Institute, Reykjavik, Iceland.

Dissanayake, DCT, Samaraweera EKV and Amarasiri, C. (2008). Fishery and feeding habits of yellowfin tuna (Thunnus albacares) targeted by coastal tuna longlining in the north western and north eastern coasts of Sri Lanka. *Sri Lanka journal of Aquatic Science* 13:1-21.

Fiedler, P. C., & Bernard, H. J. (1987). Tuna aggregation and feeding near fronts observed in satellite imagery. Continental Shelf Research, 7(8):871– 881.

Francis M. (2002). Changes in depth of yellowfin tuna habitat in the Indian Ocean: an historical perspective 1955-2001, IOTC proceedings no. 5 450-458 pp.

Haputhantri, S.S.K. 2004. Assessment of a coastal fishery of Sri Lanka using single species and multi-species approaches. Unpublished Ph.D. dissertation, Institute National Polytechnique de Toulouse, France.

Hastie, T.J. and Tibshirani, R.J. (1990). *Generalized Additive Models* (GAM). New York: Chapman and Hall.

IOTC Secretariat. (2009). Report of the eleventh session of the IOTC working party on tropical tunas IOTC-2009-WPTT 17-20.

Kimura, S., Nakai, M. and Sugimoto, T. (1997). Migration of albacore, Thunnus alalunga, in the North Pacific Ocean in relation to large oceanic phenomena. *Fish. Oceanogr*. 6:51–57.

Lalli, C. M. and Parsons, T. R. (1997). Biological Oceanography an introduction. 2nd edition. Wobun: Butterworth-Heinemann.

Laurs, R. M., & Lynn, R. J. (1977). Seasonal migration of North Pacific albacore, Thunnus alalunga, into North American coastal waters: Distribution, relative abundance, and association with Transition Zone waters. *Fisheries Bulletin*, 75:795-822.

Laurs, R. M., Fiedler, P. C., & Montgomery, D. R. (1984). Albacore tuna catch distributions relative to environmental features observed from satellites. *Deep-Sea Research* 31(9A):1085–1099.

Leonard, L. (2003). *Tuna exporters seek more concessions*. [December, 2005] <http://www.sundayobserver.lk/2003/11/09/bus06.html>

MFAR Ministry of Fisheries (MOF) Sri Lanka (2008). <http://www.fisheries.gov.lk/>

MFAR Ministry of Fisheries (MOF) Sri Lanka (2009). <http://www.fisheries.gov.lk/>

Morita Y. AND T.Koto (1971). Some consideration of the population structure of yellowfin tuna in the Indian Ocean based on long line fishery data. *Bull. Far Seas Fish. Res. Lab*. 4:125-140.

Nishida, T. (1992). Considerations of stock structure of yellowfin tuna (*Tunnus albacores*) in the Indian Ocean based on fishery data. *Fisheries Oceanography* 1(2):143-152.

Nootmorn P, Yakoh A, Kawises K (2005) Reproductive biology of yellowfin tuna in the eastern Indian Ocean. Victoria: Indian Ocean Tuna Commission, 2005.

Podesta, G.P, Browdwr, J.A, Hoey, J.J (1993). Exploring the association between swordfish catch rates and thermal fronts on U.S. long-linegrounds in the in the western North Atlantic. *Cont. Shellf Res.* 13:253-277 .

Polito, P. S., Sato, O. T., and Liu, W. T. (2000). Characterization and validation of the heat storage variability from TOPEX/Poseidon at four oceanographic sites. *Journal of Geophysical Research* 105(7):16911 –16921.

Polovina, J.J., Hovwel, E., Kobayashi, D.R. (2001). The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. *Progress in Oceanography* 49:469-483.

Power, J. H. and May Jr., L. N. (1991). Satellite observed sea surface temperatures and yellowfin tuna catch and effort in the Gulf of Mexico. *Fisheries Bulletin of United States* 89:429– 439.

Ramos, A.G., Santiago, J., Sangra, P. and Canton, M. (1996). An application of satellite-derived sea surface temperature data to the skipjack (*Katsuwonus pelamis* Linnaeus, 1758) and albacore tuna (Thunnus alalunga Bonaterre, 1788) fisheries in the north-east Atlantic. *Int. J. Rem. Sens*. 17:749–759.

Romena, N. A. 2000. Factors affecting distribution of adult yellowfin tuna (*Thunnus albacares*) and its reproductive ecology in the Indian Ocean based on Japanese tuna longline fisheries and survey information. Thesis submitted in partial fulfillment for the degree of Master of Science in Ecological Marine Management. Vrije Universiteit Brussel, Belgium. 87 pp.

Samaranayake, R. A. D. B. (2003). Review of national fisheries situation in Sri Lanka, p. 987-1012. In G. Silvestre, L. Garces, I. Stobutzki, M. Ahmed, R. A. Valmonte-Santos, C. Z. Luna, L. Lachica-Aliño, P. Munro, V. Christensenand D. Pauly (eds.) Assessment, management and future directions for coastal fisheries in Asian Countries. WorldFish Center Conference Proceedings 67.

Santos, A. M. P. (2000). Fisheries oceanography using satellite and airborne remote sensing methods: A review. *Fisheries Research*, *49*:1–20.

Schott F.A. and Julian P. McCreary Jr. 2001. The monsoon circulation of the Indian Ocean. *Progress In Oceanography*, *Vol.* 51, Issue 1, pp 1-123.

Sivasubramaniam, K. (1985). *The tuna fishery in the EEZ s of India, Maldives and Sri Lanka.* BOBP working paper 31:19-42. Rome: Food and Agricultural Organization of the United Nations.

Somvanshi V. (2002) Review of biological aspects of yellowfin tuna (*Thunnus albacares*) from the Indian Ocean. IOTC Proc. 5: 420-426

Sons L.M, Zhang Y., Xu L.X, Jing W.X.X and Wang J.Q (2008). Environmental preferences of long-line for yellowfin tuna (Thunnus albacores) in the tropical high seas of the Indian Ocean. *Fisheries Oceanography* 17:4:239-253

Stewart, R. H. (1985). Methods of satellite oceanography. Scripps institution of oceanography. San Diego, CA7 EUA 360 pp.

Stretta, J. M. (1991). Forecasting models for tuna fishery with aerospatial remote sensing. *International Journal of Remote Sensing* 12(4):771-779.

Sugunan, V.V. 1997. *Fisheries management of small water bodies in seven countries in Africa, Asia and Latin America.* FAO Fisheries Circular 933. Rome: Food and Agricultural Organization of the United Nations.

Sund, P.N., Blackburn, M. and Williams, F. (1981). Tunas and their environment in the Pacific Ocean: a review. *Oceanogr. Mar. Biol. Ann. Rev.* 19:443–512.

Sydnes, A.K and Normam, A.K. (2003). Desk study on the fisheries sector in Sri Lanka. Norwegian College of Fishery Science. Tromsø.

Uda, M. (1973). Pulsative fluctuation of oceanic fronts in association with the tuna fishing grounds and fisheries. *J. Fac. Mar. Sci. Techn. Tokai University* 7:245-265.

Yamanaka, I., Ito, S., Niwa, K., Tanabe, R., Yabuta, Y., & Chikuni, S. (1988). The fisheries forecasting system in Japan for coastal pelagic fish. FAO Fisheries Technical Paper, 301 (72 pp.)

Zagaglia C. R., J. A. Lorenzzetti and J.L. Stech. (2004). Remote sensing data and longline catches of yellowfin tuna (*Thunnus albacares*) in the equatorial Atlantic. *Remote Sensing of Environment* 93:267–281.

Zhu, G.P., Chen, X.J. and Xu, L.X. (2006). Preliminary study on the fishery biology of yellowfin tuna, Tunnas albacares, in the western central Indian Ocean. *Mar. Fish.* 28:25-29.

AVHRR-AMSR. FTP directory. [January 2010]
<ftp://eclipse.ncdc.noaa.gov/pub/OI-daily-v2/NetCDF/2006/AVHRR-AMSR/>

AVISO. Altimetry FTP directory. [January 2010]
<ftp://ftp.cls.fr/pub/oceano/AVISO/SSH/duacs/global/nrt/madt/merged/h/>

ESL. Environmental Simulation Laboratory. [January 2010]
<http://www.esl.co.jp/Sympo/seminar/Marine%20Explorer.pdf>

MODIS Ocean color FTP directory. [January 2010] <ftp://oceans.gsfc.nasa.gov/MODISA/)>

Unidata data service provider. [January 2010]
<http://www.unidata.ucar.edu/software/netcdf/>