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# Following tagged Yellowfin tuna along the east coast of India explains its feeding behavior: a case study in the Bay of Bengal

by

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**Abstract (100 words)**

Horizontal movement of pelagic fish predator, Yellowfin (*Thunnus albacares*) tuna, in the oceanic waters of Bay of Bengal has been decoded. Pop-up Satellite Archival Tags (PSATs) were attached to adult tunas to study their distribution and migration. For this, environmental satellite data were matched with the tag locations to understand and characterize habitats of this species. A sub-set of the tag data was selected corresponding to the maximum resident time of tuna indicated by a high density data points. The tagged tuna spent 60 to 70% of its time in the waters having surface temperature within 28$^o$ to 29.5$^o$C and sea surface height anomaly within+5 to +12 cm. The tag positions were located on the satellite images; chlorophyll, sea surface temperature, zooplankton and sea surface height anomaly. The two conditions, specific range of temperature and prey abundance, were found necessary for aggregation of tuna.

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**Abstract**

Horizontal movement of pelagic fish predator, Yellowfin (*Thunnus albacares*) tuna, in the oceanic waters of Bay of Bengal has been decoded. Pop-up Satellite Archival Tags (PSATs) were attached to adult tunas to study their distribution and migration. PSATs were used as instruments to investigate temperature preferences and feeding habits of yellowfin tuna. For this, environmental satellite data were matched with the tag locations to understand and characterize habitats of this species. The tagging operation was performed midway in February 2013 and the tags were tracked for three months. A sub-set of the tag data was selected corresponding to the maximum resident time of tuna indicated by a high density data points. The tagged tuna spent 60 to 70% of its time in the waters having surface temperature within 28$^{o}$ to 29.5$^{o}$C and sea surface height anomaly within+5 to +12 cm. The tag positions were located on the satellite images; chlorophyll, sea surface temperature, zooplankton (MODIS-Aqua) and sea surface height anomaly (TOPEX). Time series of SSH anomaly images revealed a pair of eddies, warm core and cold core, at the site of release and in vicinity. The tagged tuna was found to remain strongly connected with these features. It repeatedly re-visited warm core and cold core eddies, which were up to 60 kilometers apart, to exploit the abundant prey. Sea surface temperature, chlorophyll and zooplankton images indicated that the two conditions, specific range of temperature and prey abundance, should be simultaneously satisfied for aggregation of tuna. Tagged Yellowfin appeared to be moving in and out of the eddies to find the waters where both these conditions were satisfied.

Keywords PSAT tagging, Yellowfin tuna, Bay of Bengal, habitat preference, environmental parameters

## Introduction

Tropical tunas are highly migratory apex predators of the open ocean, with a spatiotemporal distribution strongly related to the environment (Lehodey *et al.*, 1997). It is one of the least exploited resources of the Indian seas accounting for hardly 2% of the total marine fish catch of India, despite the ever increasing demand for tuna resources in the global market fetching high economic returns and foreign exchange (Anrose et al., 2013, Koya et al. 2012, Prathibha Rohit et al. 2011). In view of this, a technique was developed at Indian National Centre for Ocean Information Services (INCOIS) for generating specific forecasts to explore tunas using remote sensing data. Targeting tuna catches in the oceanic waters could partially reduce fishing efforts in the coastal waters there by helping sustainable fishery. However, the environmental preference for each species of tuna is different and requires a detailed study to improve the existing techniques of exploration. More than 200 thousands tropical species of tuna (yellowfin, skipjack and bigeye tunas) were tagged and released in the Indian Ocean as a part of IOTC (Indian Ocean Tuna Commission) programme. The results of the analyses have provided new insights on the biology, the population dynamic and status of the main tuna species (http://www.iotc.org/science/tagging-symposium). PSATs have been used to track movements of large pelagic fishes including tuna and shark and to study their habitat preferences (Gunn et al 2003, Wilson et al. 2005, Sims 2010, Bruno et al. 2014). Chugey et al. (2010) have studied fine-scale movements of swordfish using PSAT technology and correlated these movements with the fisheries of the region off Southern California. They have mentioned average horizontal distance traveled for all swordfish as 30 ± 43 km. In order to understand the species-specific tendency, six tagging experiments were conducted in the Bay of Bengal and Arabian Sea by a group of scientists of this Centre and Fishery Survey of India. The main target was Yellowfin tuna. This species of tuna is found in pelagic waters of tropical and subtropical oceans worldwide. A potentially rich stable fishing ground of Yellowfin tuna has been reported in the off shore waters of east coast of India (Prathibha Rohit and K. Rammohan, 2009). Pop-up satellite archival tags (PSATs) were used for tagging tuna and the data were subsequently used to track movements of tuna and to identify zones of maximum resident times. These tags employ light based geo locations, which uses the length of the day and a noon time calculation to estimate the tags location while underwater. They transmit the data on depth, temperature and light via satellite. The data from archival and pop-up tags have provided valuable insights into the relationships between tuna distribution pattern and environment. In particular, temperature, salinity, oxygen, and prey availability have been shown to affect local tuna abundances, diving behavior, horizontal movements, and migration schemes from local to meso-sacle and basin-scale (Block *et al.*, 1997; Brill *et al.*, 1999, Maury *et al.*, 2001, Zainuddin *et al.*, 2008). Within the oligotrophic tropical waters of the open ocean, tunas constantly swim in search of prey concentrations to fulfill their high energetic requirements (Stequert and Marsac, 1989). Hence, the study of correspondence between tuna tag locations and hydrological structures like upwellings, eddies and frontal zones enhances knowledge of tuna's aggregation pattern for feeding. Royer et al. (2004) and Polovina et al. (2005) have reported that satellite-tagged tuna and turtles have both been shown to track ocean fronts. Fiedler and Bernard (1987) also found that skipjack tuna aggregated on the warm edge of waters near cold and productive water masses off southern California. The majority of tuna tracking studies are found to deal with movement pattern, link resident time with prey availability and understanding depth and temperature preference. Here we report synergistic use of the tag data and satellite data to explain the tuna's aggregation pattern. It was noticed that the yellowfin remained in the same feeding ground for three months and it preferred to feed in the areas rich in prey while avoiding unfavorable water temperatures. This improved sensing of predator-prey association can be applied to specific forecasting approach for exploration of tunas.

## Materials and methods

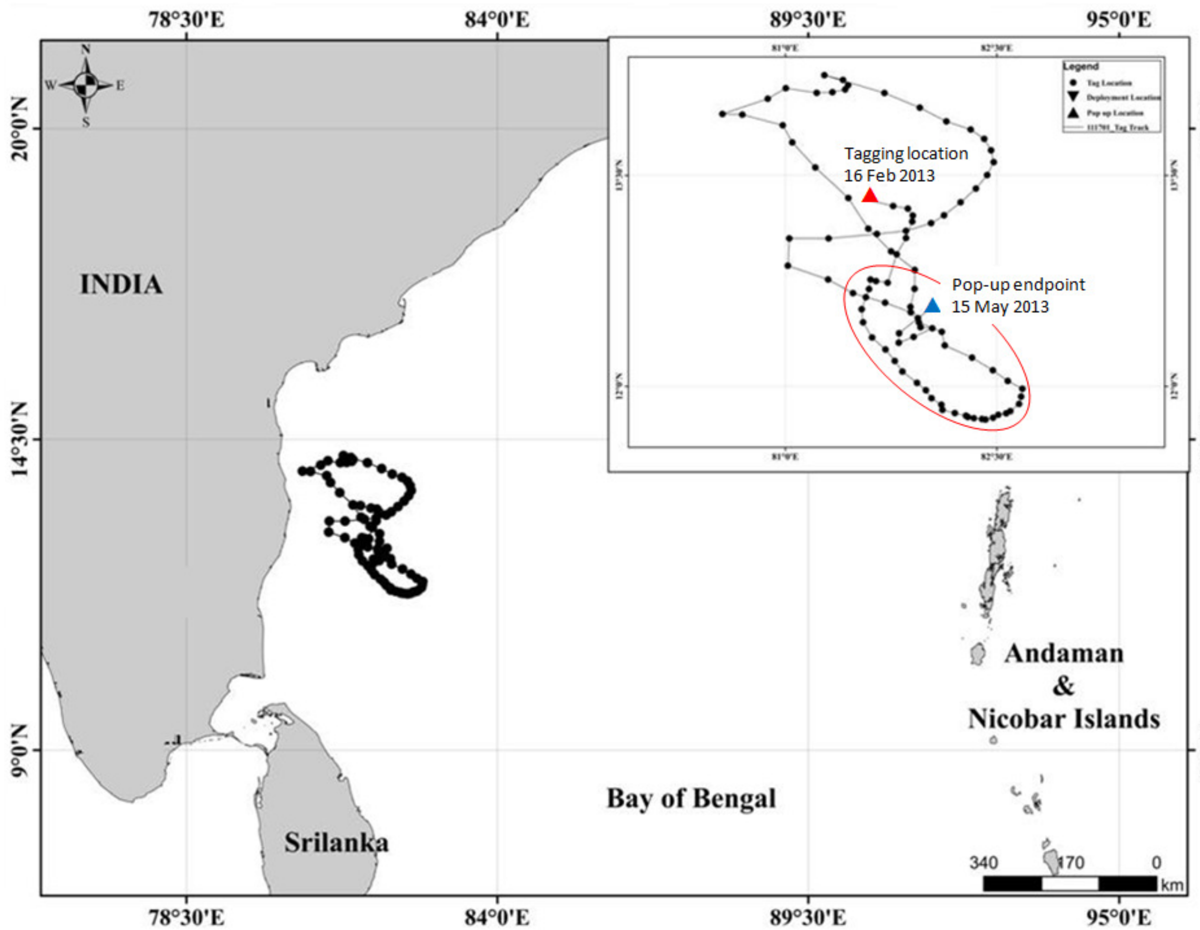
The data analyzed in this paper came from X-Tag (Microwave Telemetry) light-based Pop-up Satellite Archival Tags. An X-Tag records light levels at two-minute intervals while in data collection mode. The three electronic sensors measure ambient water temp, depth of tag and ambient light. A proprietary algorithm is applied to the light-level records in order to estimate daily sunrise and sunset times. These time estimates become part of the transmitted data set, which facilitate computation of the tag locations. Longitude is calculated from the time of local noon, halfway between sunrise and sunset and latitude is calculated from the length of day. These raw light-based locations were further processed by Collecte Localisation Satellite (CLS) using the "Track & Loc" software based on the geolocation method described in Royer and Lutcavage (2009). "Most Probable Tracks" were estimated using Ensemble Kalman Filter (ENKF). In addition to this, CLS used the expectation maximization (EM) algorithm for estimating various biases. With this, the position estimates were significantly improved for the purpose of for reconstructing large scale horizontal movements of tuna. The estimated latitude and longitude points were obtained at the best accurate to 70 kms. Daily chlorophyll and sea surface temperature (SST) images from MODIS data were downloaded using NASA's OceanColor Web. These images were used to retrieve chlorophyll concentrations corresponding to the tag locations. Zooplankton was developed using particulate organic carbon and SST from MODIS data and the split algorithm (Dwivedi et al. 2016). Weekly products of sea surface height anomaly were downloaded from APDRC (Asia-Pacific Data Research Center) site.

## Results and discussion

From the six tagging operations, the tagging data for the tuna tagged on 16 February 2013 at 13.32°N, 81.58°E in the Bay of Bengal revealed congestion of points and retention of tuna for three months in a specific area (12°-15°N, 81°-83°E). Locations of the track and the sticking pattern can be seen in Figure 1. The area surrounds a pair of warm core eddy (WCE) and cold core eddy (CCE) and implies that the tuna remained tied up for a long time to exploit the feeding ground.

Influence of poor accuracy of the tag locations on the study:

The study on feeding behavior involves whether tunas prefer edges or centers of eddies and it involves




resolving tuna's locations at a scale of the order of tens of kilometers. In this context, discussion on

Figure 1 Reference map for the Yellowfin tagging operation and its path in the Bay of Bengal

accuracy of the tag locations is relevant. Locations from PSAT tags have been determined using light the levels. Sources of error in geo location include natural variability in ambient light levels such as light attenuation, turbidity, clock error and shark diving behavior (Musyl et al., 2001). In view of this, the tag locations were re-analyzed using the filtering techniques as mentioned earlier in this paper. It was not possible to resolve the small-scale horizontal movements of the Yellowfin on daily basis due to poor accuracy of the tag's light-based geo locations. However, this was not a preventing factor for studying its feeding behavior in view of the fact that it is not always necessary to track the fish from day to day for this reason. The entire period of 90 transmission days was divided in eight event, the each representing a time slot of several days. With this, the displacements involved from event to event were found to be greater than 70 km, that is larger than the best error rate of the X-tag's geo locations.

It was observed that the Yellowfin shuttled between cold core eddy and warm core eddy in vicinity during the entire period of data transmission. Hence, it would be worthwhile to discuss the basics of distribution of biological productivity across the eddies and temperature preference of Yellowfin before describing the event based feeding behavior.

Spatial profile of chlorophyll and SST along a segment crossing the two eddies is shown in Figure 2.

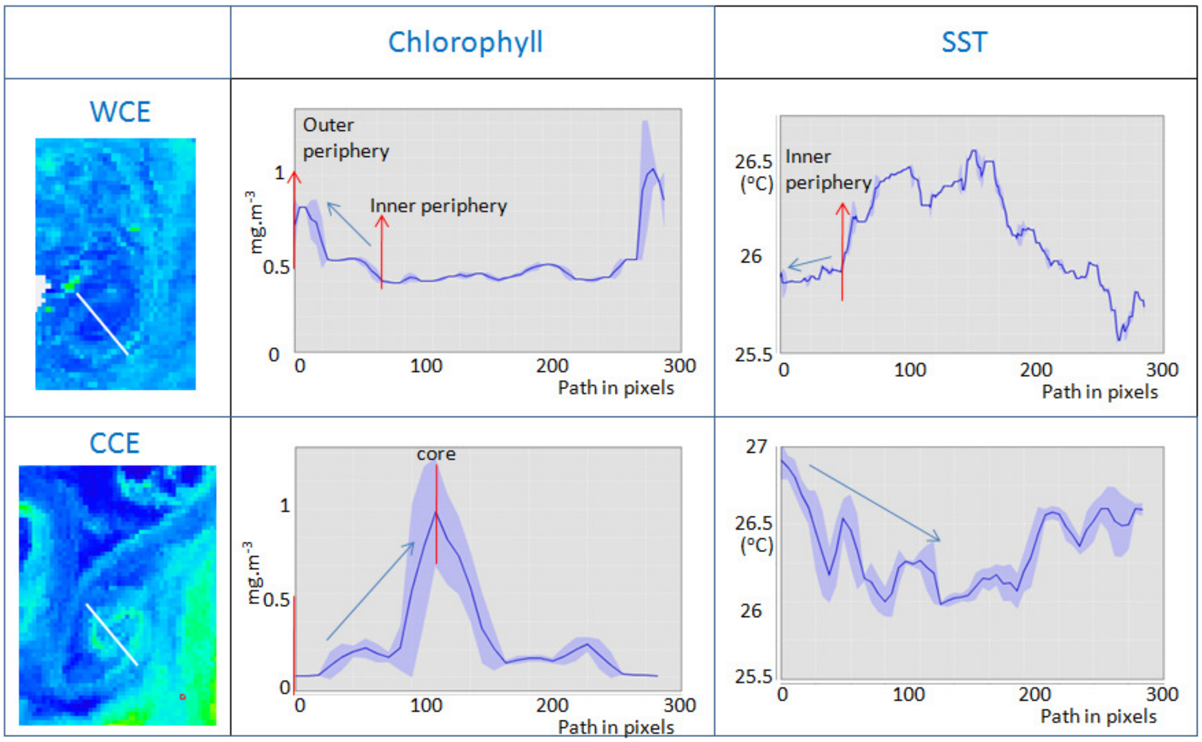



Figure 2 Spatial profile of chlorophyll and SST along a segment crossing WCE and CCE

Relatively low chlorophyll and high SST can be seen at the core of the warm core eddy as expected. In addition to this, within the peripheral are of warm core eddy, chlorophyll is seen increasing from inner periphery to outer periphery and reverse is the pattern for SST. In case of cold core eddy, the spatial profile of chlorophyll and SST is as expected, chlorophyll (SST) can be seen increasing (decreasing) from outer edge to the core.

SSHa was plotted against SST for the tag locations as shown in Figure 3(A). The two parameters can be seen correlated as shown with the trend line. A plot showing Yellowfin's temperature preference in Figure 3(B) shows that the fish spent maximum time in the waters at specific temperatures; 28.5°-29°C (optimum) and at 28-29.5°C as the favored range. SSHa-SST plot reveals +5 to +12 cm as the most preferred SSHa corresponding to this range of temperature. Tuna is reported to have preference for specific temperature to conserve energy. Yellowfin tunas prefer warm waters in the mixed layer and deep diving is occasional (Block et al. 1997).

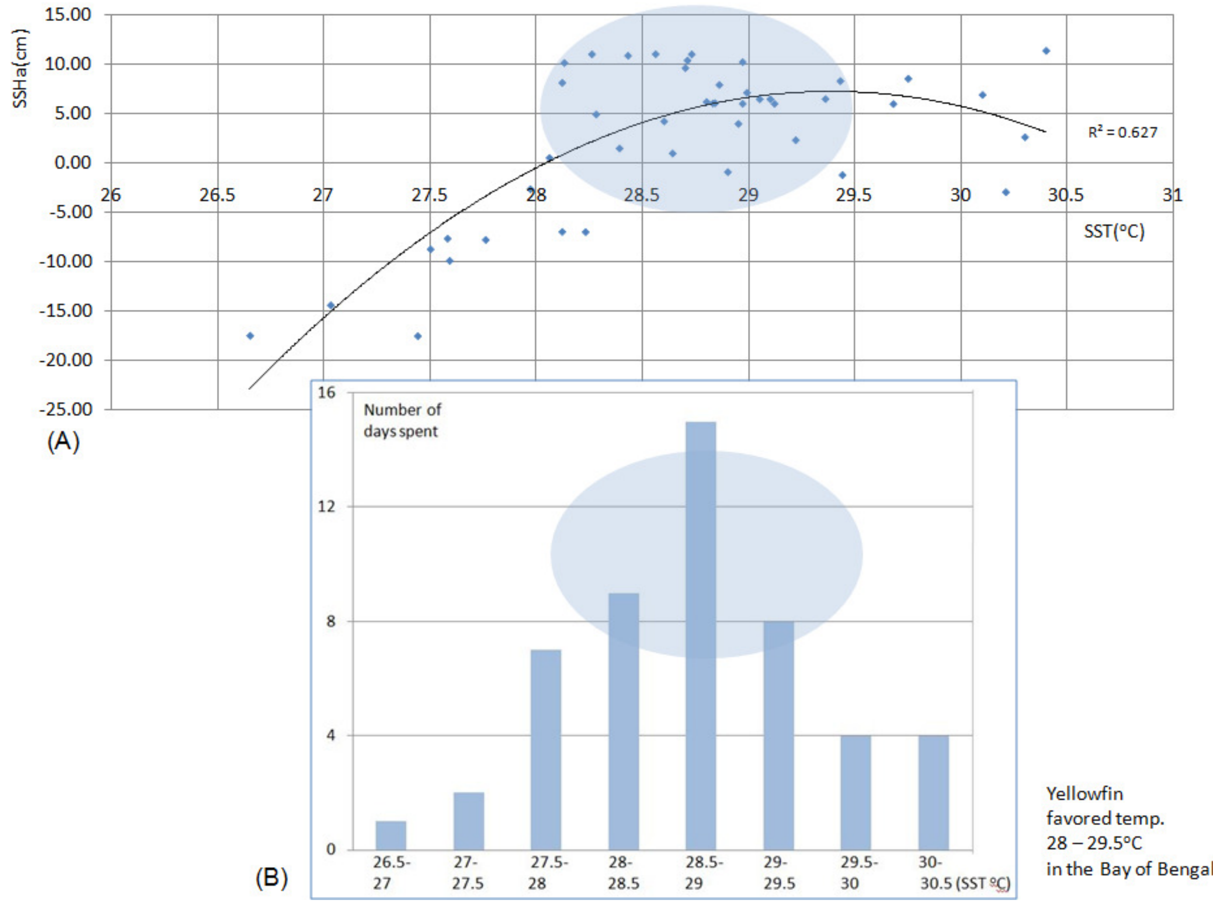



Figure 3 (A) Plot of SSHa versus SST for the tag locations (B) Yellowfin's temperature preference

Event-based movement of Yellowfin:

This part of the section describes eight events that caused changes in distribution of tuna with the help of Table 1 and Figure 4. The figure is split into six segments as indicated at the top. Tuna was found to be shuttling between a pair of stable warm core and cold core eddies according to compliance with the favorable conditions as discussed below.

1. Event: Release of tagged tuna on 16 February

1.1 Release was within CCE;

1.2 It remained within CCE during the initial period (16-20 February 2013)

It can be seen from Table 1 that all the tag locations during this initial period are within cold core eddy indicated by negative SSH (sea surface height) anomaly. Tunas when not spawning move to explore areas of food abundance . In this case study, the release site happened to be in the interior of the eddy and hence, did not have to travel much to locate the feeding ground. Date-wise information on of prey availability (chlorophyll, zooplankton) and water temperature (SST) and SSHa is presented in Figure 4.

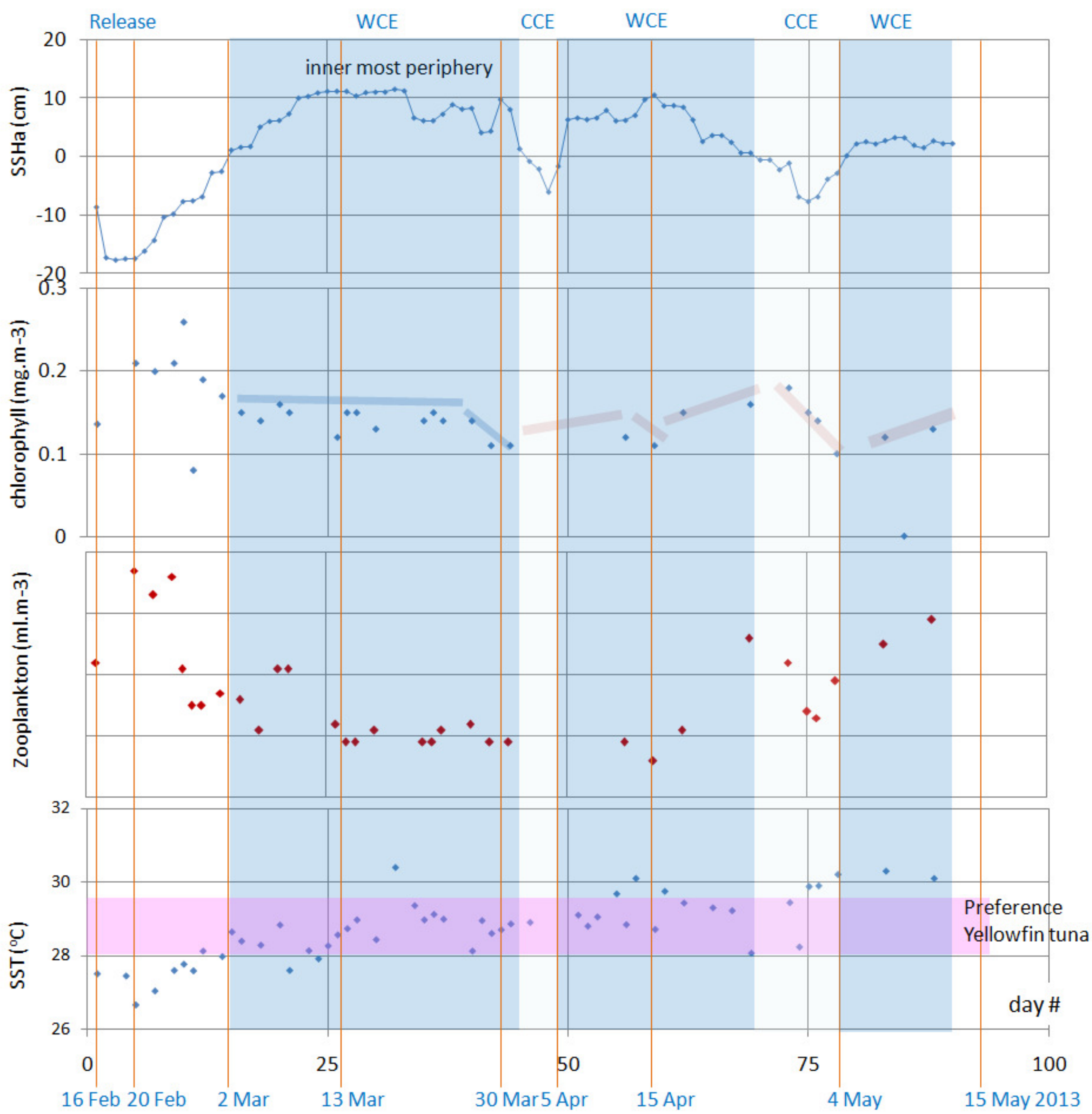



Figure 4 Temporal variations in SSHa, chlorophyll, zooplankton and SST during the data transmission

Yellowfin tuna showed a preference for chlorophyll concentration > 0.2 $mg.m^{-3}$ and zooplankton (normalized displacement volume) > 0.4 $ml.m^{-3}$ and it helped understanding its spatial and temporal distribution. This considered high enough to develop food the chain required to support tuna. Crustaceans especially pelagic crabs and shrimps form the major component of the diet for YFT. Pelagic fishes and squids form the next important component of the food item (Silas et al. (1985), Pon Siraimeetan (1985) and John and Sudarshan (1993)). Pelagic crabs feed on zooplankton and diatom blooms. Thus the food chain for Yellowfin tuna can be visualized as chlorophyll → zooplankton → Crabs and shripms+Pelagic fish and sqids → tuna. Therefore, it is pertinent to consider chlorophyll and zooplankton as an index of prey for tunas. Though prey was available in sufficient quantity at the location of release, temperature declined significantly (27.4$^{o}$C) on the fourth day after the release. This is not suitable for tuna and it may be the reason for tuna leaving CCE.

2. Event: Tagged tuna left CCE and arrived at WCE (21 February - 2 March)

It can be seen from Table 1 that distance travelled by Yellowfin in this process is 85 kms and greater than the geo location error (70 kms). SSHa changed from (-16.3 cm) on 21 February to (+0.9 cm) on 2 March. Sufficient prey was available and temperatures were within the preferred range or close to it at tag locations during this period as indicated in Figure 4.

3. Tagged tuna moved from outer periphery of WCE to inner periphery (3-13 March 2013)

It moved a distance of 84 kms during this period and SSHa changed from (+1.5) to (+11) cms (Table 1). Distance travelled is greater than the location error and the fish moving in the waters of higher magnitude of positive SSH anomaly indicates penetration of the eddy to inner periphery. Moreover, the Table includes a plot showing temporal variations in SSHa during 3-13 March. Consistent increase in positive anomaly is confirmation of movement of tuna in interior of eddy. Sources of positional errors are random in view of sensing of the attenuated light from the tag being at depths and/or in turbid waters. Therefore observation of consistency in anomaly pattern justifies the event. As regards the prey, Figure 4 reveals zooplankton in abundance ( > 0.4 $ml.m^{-3}$) though chlorophyll is on lower side. All the tuna positions are observed in the waters of favorable temperatures (Figure 4). Tuna appears to adjust between feeding in the rich area and avoiding unfavorable temperatures.

4. Tuna remained at inner periphery of WCE for a long time (10-30 March 2013)

It was a three weeks time and covered 82 kms while feeding and to settle for prey and optimum temperatures. SSHa plot in Table 1 shows nearly constant and high positive anomaly during initial period of ten days indicated tuna being located at inner periphery of WCE. In the latter half, SSHa slightly decreased, however, still remained positive. It indicates that the tuna moved towards outer side of the periphery. It can be seen from Figure 2 that chlorophyll increases from inner to outer periphery. Hence, a probable reason for tuna's outward movement may be to pick up higher concentration of prey. Either the prey was used up at inner periphery (could not be checked due to satellite data gap) or the eddy turned weak forcing tuna to move outward. A ratio of maximum SSH anomaly (cm) and eddy radius (pixels), which s indicator of its strength and rotational geostrophic speed, was computed for 12 March (initial period at inner periphery) and 22 March (later period at mid periphery). This was 0.35 and 0.22 respectively and it points at weakening of WCE during later period after 20 March. Over all, Yellowfin remained within WCE at inner and central periphery. High resident time of tuna in the WCE eddy environment is an indication of preference of tuna in the stable feeding ground. Fishing in the areas like this could yield high hooking rates. Availability of food in abundance at the primary and secondary level was inferred from MODIS. It provides a necessary condition for rapid evolution of the food web. As the eddy persisted for a long period of time, the developed food chain is sustained and the probability of accumulation of tuna in a large number increases.

5. Tuna moved out of WCE (30 March - 5 April)

It covered 87 kms after moving out of WCE and till 5 April. SSHa changed, (+9.7) to (-1.8) during this period indicating tuna's movement from WCE to CCE. The SSHa plot in Table 1 reveals increasing pattern of negative anomaly with time, which indicates that tuna is penetrating CCE. Though temperature is within the favorable threshold the area was not rich in prey abundance (chlorophyll < 0.2 $mg.m^{-3}$and zooplankton < 0.4 $ml.m^{-3}$. Hence tuna did not stay long in these waters.

6. Tuna re-entered WCR (5-15 April)

Tuna moved 113 kms during this period. Change in SSHa from (-1.8) to (+10.4) cm is confirmation of its entry to WCR. SSHa pattern in Table 1 shows that tuna was stable initially (SSHa 6-7 cm) and it penetrated WCE at latter stage as reflected by increase in positive anomaly. This is the time when decline in prey and increased SST out of threshold can be observed in Figure 4.

7. Tuna left WCE and entered CCE again (16 April - 4 May)

In this process of switch over, it travelled a distance of 112 kms and SSHa changed from +8.6 to -3 cm (SSHa plot in Table 1). Chlorophyll and zooplankton were sufficiently high and temperature within the threshold (Fugure 4). In later part of this slot, decline in prey is observed and this probably caused displacement of tuna after 4 May.

8. Tuna entered WCE (4-15 May)

Distance moved during this period is 80 km. SSHa changed from (-3) to (+2.1) during this period, which indicates that the tuna moved from CCE to WCE (Table 1). Tuna remained at outer periphery during this period indicated by small magnitude of +ve SSHa. Figure4 reveals that there was high concentration of chlorophyll and zooplankton during this period, however the waters were slightly warmer than the threshold.

## Conclusion

PSATs appear to be instrumental for study of migration of Yellowfin for feeding. The feeding behavior observed in this case study can be used for improved exploration of tuna. Event to event monitoring of Yellowfin was attempted, which involved splitting of the tag data in eight time slots running over 90 days period. With this, distances available for interpretation of the migration pattern were larger than the error in geo location.

Extensive residency of Yellowfin was noticed within the eddy environ. Residency time is subject to realization of two conditions, availability of prey in abundance and specific temperature. The tuna was observed to leave the feeding ground even if any one of the two conditions became unfavorable.

WCE

Yellowfin was found to remain along the inner periphery when the eddy was active and then moved outward to find more prey when it turned weak.

CCE

Yellowfin remained in outer area initially to avoid turbulence and unfavorable temperature at the core. It penetrated inward to find more prey when the eddy became weak.

The tuna was found moving in and out of WCE and CCE, it means; the statement that it remains at periphery of WCE and core of CCE, is imprecise. It locates favorable temperature first, and then within the favorable temperature positions where the prey is abundant. These two conditions continuously change with time according to strength of the eddy.

## Acknowledgment

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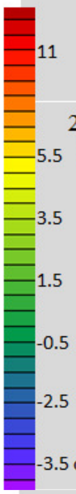
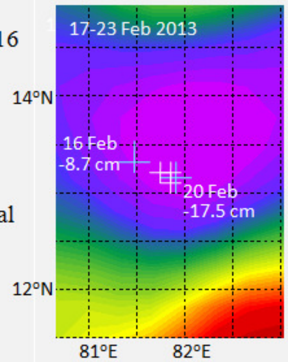
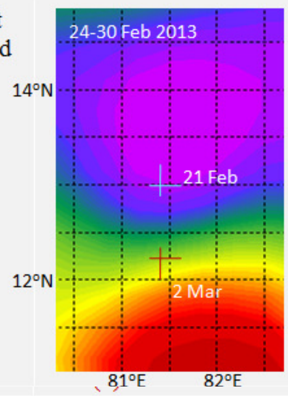
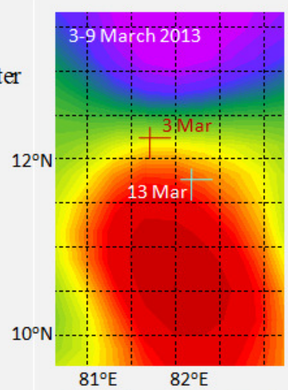
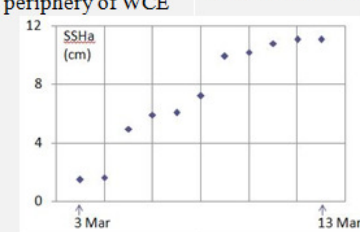
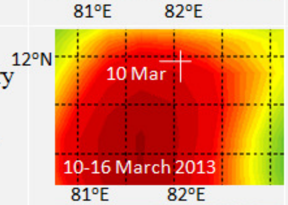
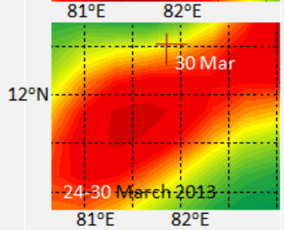
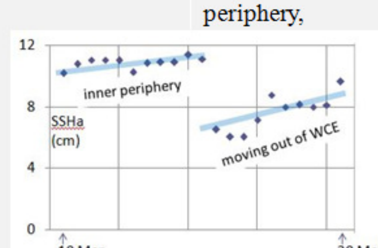
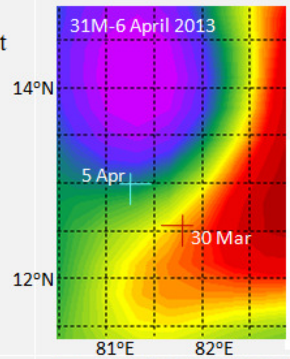
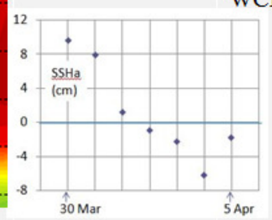
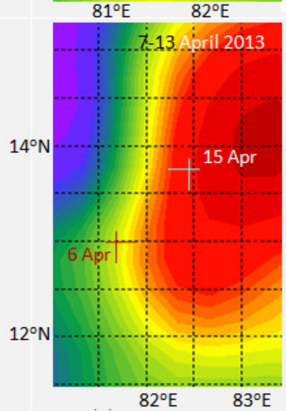
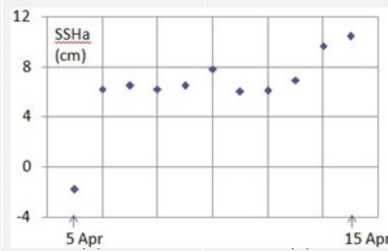
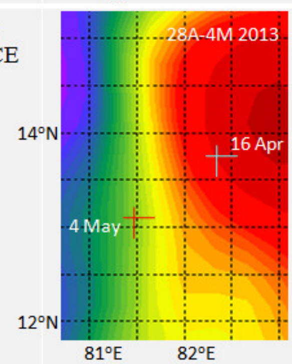
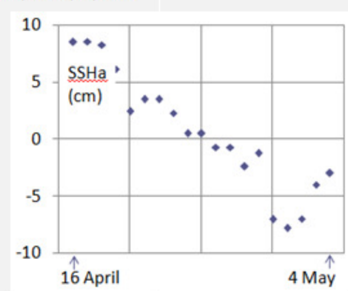
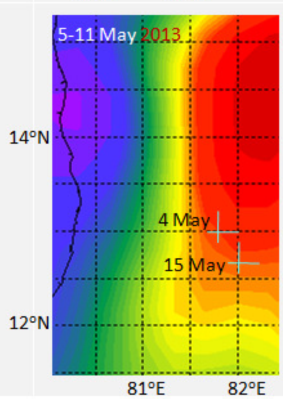
Table 1 Description of Yellowfin events with reference to distance moved & SSHa .... continued on next page




| Period (1) | Event (2) | Illustration TOPEX weekly SSHa (cm) (3) | Distance moved (deg.) during the specified period (4) | Change in SSHa (cm) during the specified period (5) | Remark (6) |
|---|---|---|---|---|---|
| 16-20 February 2013 | i. Release of tagged tuna on 16 February was within CCE;<br><br>ii. It remained within CCE during this initial period |  | All the points are within CCE ,<br><br>it indicates that the release was actually within CCE | SSHa changed from (-8.7) 16 Feb to (-17.5) cm 20 Feb. | Observed –ve anomaly from 16-20 Feb confirms that release of tuna as well as its initial period was within CCE |
| 21F-2M 2013 | Tagged tuna left CCE and arrived at WCE |  | Distance moved during this period 85 kms > location error | SSHa changed from (-16.3) 21 Feb to (+0.9) cm 6 Mar.<br><br>It confirms that tuna left CCE and moved towards the WCE seen in vicinity | uncertainty of tag location does not affect the study of movement pattern |
| 3-13 March 2013 | Tagged tuna moved from outer periphery of WCE to inner periphery |  | Distance moved during this period = 84 kms | SSHa changed, (+1.5) to (+11) cm indicating tuna's movement from outer to inner periphery of WCE<br> | Increasing pattern of +ve anomaly with time is an indication of penetration WCE |
| 10-30 March 2013 | Tuna remained at inner periphery of WCE till 20 March and then moved out, however, still within WCE (indicated by +ve SSHa of smaller magnitude) |  | Distance moved during this period = 82 kms<br><br>SSHa:<br>min: 4.<br>max: 11.4<br>average: 9.<br>SD: 2.4 cm | SSHa remained positive and almost constant<br> | Positive SSHa of high value indicates, tuna is located at inner periphery, |

| Period<br><br>(1) | Event<br><br>(2) | Illustration TOPEX weekly SSHa (cm)<br><br>(3) | Distance moved (deg.) during the specified period<br><br>(4) | Change in SSHa (cm) during the specified period<br><br>(5) | Remark<br><br>(6) |
|---|---|---|---|---|---|
| 30M-5A 2013 | Tuna moved out of WCE |  | Distance moved during this period = 87 kms<br> | SSHa changed, (+9.7) to(-1.8) cm indicating tuna's movement from WCE to CCE | SSHa switching over from (+) to (-) shows tuna's entry to CCE<br><br>(-) anomaly increasing with time indicates, tuna is penetrating CCE |
| 5-15 April 2013 | Tuna re-entered WCE |  | Distance moved during this period = 113 kms<br> | SSHa changed from (-1.8) to (+10.4) cm. | SSHa pattern shows that tuna penetrated WCE, up to inner periphery |
| 16A-4 M 2013 | Tuna left WCE and entered CCE again |  | Distance moved during this period = 112 kms | SSHa changed , (+8.6) to (-3) cm<br> | |
| 4-15 May 2013 | Tuna entered WCE |  | Distance moved during this period = 80 kms | SSHa changed from (-3) to (+2.1) meaning the tuna moved from CCE to WCE | |