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APPLICATION OF SATELLITE MICROWAVE REMOTE SENSING DATA TO SIMULATE MIGRATION PATTERN OF ALBACORE TUNA

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Abstract. To simulate migration pattern of albacore tuna in the western North Pacific Ocean during the winter period, a kinesis model driven by high accuracy of sea surface temperature (SST) maps was used. The SST data were derived from the Tropical Rainfall Measuring Mission/TRMM Microwave Imager (TRMM/TMI). Simulations showed that albacore tuna aggregated in areas of thermal preference indicated by contour line of 20°C SST. Results are compared with empirical observation maps of albacore tuna fishing locations determined from longline fishing operation during the same time periods. Albacore tuna distributions along thermal fronts generating from Simulations were fairly consistent with fishing data especially during November-January, although seasonal variations in surface temperature ranges occupied suggest that additional oceanographic factors are involved particularly during February-March. Simulations and empirical data had similar temperature distributions at approximately 18-21°C and one-sample Kolmogorov-Smirnov test reinforced the result performance. These results suggest that kinesis model driven by satellite microwave remote sensing is one of effective mechanisms for describing migration pattern of tuna in the open ocean environment.

Keywords: *Kinesis model, Microwave remote sensing, SST, Albacore tuna, Migration pattern*

1. Introduction

Satellite remote sensing has proved an important source of information in studying dynamics of tuna migration pattern in relation to preferred oceanographic conditions (Polovina et al., 2001; Zainuddin et al., 2004). Microwave remote sensing has the advantage over optical remote sensing in that it enables to gather information in all weather conditions without any restriction by cloud or rain (Wenz et al., 2000). This is an advantage that is not possible with the visible and/or infrared remote sensing. Therefore, to investigate tuna migration in relation to their environments, microwave remote sensing plays a substantial role mainly in collecting large number of sampling data and producing clear image. With these particular capabilities, the accuracy of research would significantly be improved. Albacore (*Thunnus alalunga)*, is a highly migratory tuna that supports important commercial fisheries such as longline and trolling fisheries operating in the western North Pacific Ocean. The distribution, migration and abundance of the fish are markedly influenced by oceanographic conditions such oceanic fronts, eddy fields and upwelling regions (Laurs et al., 1984; Polovina et al., 2001; Zainuddin, 2011). Using microwave sensor such as TMI and AMSR-E, dynamics of commercially pelagic fish such as albacore tuna as well as the oceanographic phenomena can continuously and systematically be assessed (Zainuddin et al., 2004;2006; Lan et al., 2012).

Temperature influences fish species at different stages of their life cycles, for example during spawning, and influencing distribution, aggregation, migration and schooling behaviour of juvenile and adults (e.g., Laevastu and Hayes, 1981; Sund et al., 1981). Although sea surface temperature (SST) can influence the geographical range of marine species, the observed association of albacore with ocean thermal structures cannot be explained by temperature per se, but involve also other behavioural mechanisms linked with feeding activity (Laurs et al., 1984). Thus the importance of sea surface temperature for operational fisheries oceanography is due mainly to the fact that it can be used as an (indirect) indicator of areas of fish forage concentration, that are also potential favorable zones for fish aggregation and migration (Santos, 2000).

Humston *et al.* (2000) simulated the Atlantic bluefin tuna schools using kinesis model with NOAA/AVHRR SST single map as a stimulus. For studying the pelagic fish migration in a wide ocean environment, it is important to use serial maps to observe the fish movement. Therefore, the objective of this study was to simulate albacore migration pattern based on the most preferred oceanographic condition in the series SST maps derived from satellite remote sensing within the study area.

2. Sea Surface Temperature and Fishery Data

Tropical Rainfall Measuring Mission (TRMM)/ TRMM Microwave Imager (TMI) was used to

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study SST. This study used monthly mean (composite images from the original daily data) SST data sets, extending from approximately 40ºS to 40ºN at a pixel resolution of 0.25º (about 25 km) for both latitude and longitude obtained from JAXA/EORC database (TMI SST version 2.0). The TMI SSTs have been shown to agree well with SSTs measured with buoys and ships observations in the mean difference of about less than 0.1 ºC (Bhat et al., 2004). The root mean square (rms) difference of the observations is about 0.6ºC (Wentz et al., 2000). This sensor (TMI) has a full suite of channels ranging from 10.7 to 85 GHz and represents a satellite microwave sensor that is capable of accurately measuring SST under nearly all weather conditions (Wentz et al., 2000). Hence, we look at the new insights that can be gained from TMI data to aid our understanding of tuna distribution and migration in the western North Pacific Ocean. Since the spatial resolution of TRMM/TMI is 25 km, the SST images were resampled onto 9 km grid by constructing a program using the Interactive Data Language (IDL) software package. The resampled images were conducted to match with maximum swimming speed of albacore and time step used in the model.

The fishery data consisted of daily geo-referenced fishing position and catch per unit effort (CPUE). The daily data were compiled into monthly resolution for the period of winter term (November 1998-March 1999) obtained from the Japan Fisheries Information and Service Center (JAFIC). We compiled the data to match with satellite data resolution.

3. Methods

This study used two types of data sets, satellite and longline fishery data sets. Parameters of model were resulted from the analysis of fishing performance, SST satellite data and reference data as well. These parameters were then used to simulate tuna migration pattern by contructing a program in IDL. We examined the simulation results using statistical test (one sample Kolmogorov-Smirnov test-empirical cumulative distribution function/ECDF) to get the reliable migration pattern map (Figure 1).

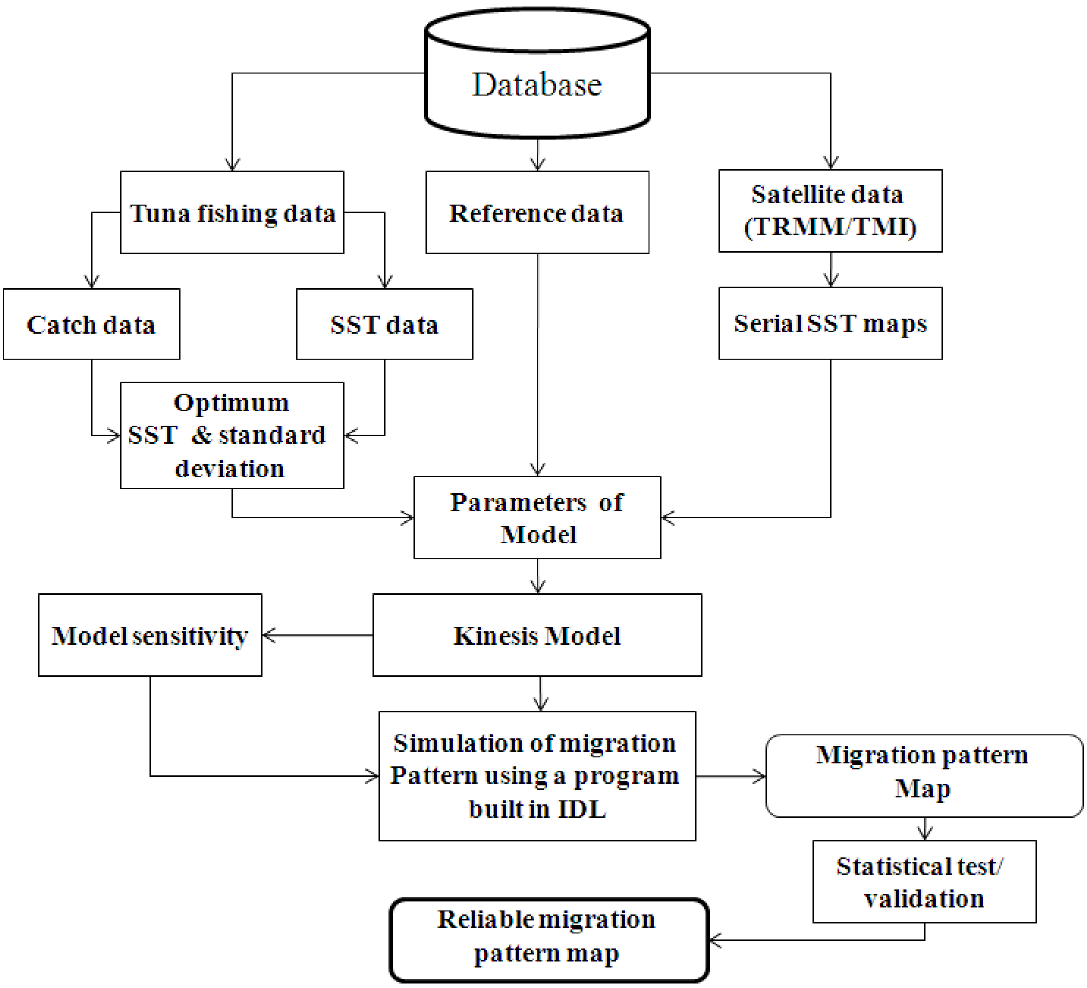

Figure 1. Flow chart analysis for studying tuna migration pattern using kinesis model simulation.

3.1 Kinesis Model

Kinesis is a non-directional, behavioural response to external stimuli driven by inherent awareness of preferred oceanographic conditions (Humston et al., 2000). This model was developed based on two types of fish behavioural responses. They are orthokinesis response in which the fish change their speed, turning frequency, and klinokinesis which indicates the average angle of turns depending on the intensity of stimulus in their surroundings (Humston et al., 2000). This model assumes only that albacore tuna have a sense of their ambient SST conditions as well as `inherent knowledge' of preferred ambient states, and can adjust their behaviour and spatial position accordingly.

A kinesis model driven by high-accuracy of TRMM/TMI SST was used to simulate albacore tuna movement (migration) in the study area during winter (November-March 1998-1999). The results of this simulation will be compared with fishing data and environmental features. Monthly SST data were used to generate simulation using the following algorithms (Humston et al., 2000):

$$|\varepsilon| = \sqrt{(\phi^2 / 2)} \quad (1)$$

$$V(t) = f(V_{t-1}) + g(\varepsilon) \quad (2)$$

$$S_t = V(t)\, x\, \delta \quad (3)$$

$$f(V_{t-1}) = V_{t-1}\, x\, H_1\left[e^{(-0.5)[(T-T_0)/\sigma]^2} \right] \quad (4)$$

$$g(\varepsilon) = \varepsilon\, x\left[1 - \left(H_2 e^{(-0.5)[(T-T_0)/\sigma]^2} \right) \right] \quad (5)$$

where Φ is maximum swimming velocity; ε is distributed normally random component; $V(t)$ is total velocity of an individual fish at time t; V_{t-1} is total velocity of an individual fish at time t-1; g(ε) define the relative contributions of each x or y component given the difference between immediate and optimal ambient temperature values; S_t is the distance of an individual fish movement at time t; H_1 is height of Gaussian curve in $f(V_{t-1})$; H_2 is height of Gaussian curve in $g(\varepsilon)$; σ is variance parameter which control width of Gaussian curves; T is ambient temperature during time step; T_0 is an optimal temperature for albacore in the study area; and δ is time step length.

3.2 Model Design

To examine the performance of model simulation and investigate the potential mechanisms affecting spatio-temporal distributions of albacore, two types of simulations were run using the series algorithms (Equations 1-5). The first set of model (model sensitivity) was used to examine model performance, and the second series of model (migration model) was used to simulate migration route for albacore during the peak season (winter period) in the study area.

3.3 Model Sensitivity

The first step for simulating migration pattern of tuna was to test the model sensitivity using a simple method of fish response in a single dimension. This simulation step aimed to produce the best time step for the simulation of tuna migration route. The model was run in Cartesian plane, using position along the X-axis (X_o=0 km as a target) as the stimulus parameter. Maximum swimming speed of albacore was set to 6.6 km h^{-1} and was then adjusted to 36 km h^{-1} to match with data resolution (Laurs et al., 1977; Zainuddin, 2006) for two model runs, indicating the search velocity of this species outside the preferred range. Following Humston et al. (2000), model run was initialized by uniformly distribution of fish along the X-axis (-50,50). Each fish was assigned a random velocity for initial time step and then run by 1000 individuals for the periods of 30-416 days, sufficient time for the system to attain equilibrium (Humston et al., 2000) using the IDL. The periods were obtained by considering the coverage of study area (model domain), time step and fish swimming speed.

3.4 Simulation of Migration Patterns

The second model run was generated to simulate dynamic movements of 500 albacore in the study area using TRMM/TMI SST maps as the stimulus. The number of 500 fish was selected by trial for simulation. One different from Humston's approach that used static condition of SST map (only a single map), this study attempted to simulate spatial movement and migration of albacore using dynamic maps of SST with monthly and eight days temporal resolutions during winter period. In all simulations, T_o was set at 20°C with σ =1.6, reflecting the optimum SST for albacore in the study area (Zainuddin et al., 2004). The widths of Gaussian functions for deterministic (H_1) and stochastic (random) components (H_2) were set at 0.7 and 0.9, respectively. Albacore movements were simulated for 5 months (winter period) using monthly data. The starting position of fish on the SST map in November for monthly simulation was determined using random function in the IDL, and the model was run up to 82 days, allowing fish to disperse preferentially throughout the model domain. From the time period, we could also see that the high density of fish concentrated near optimum SST. The next step simulation was run up to one month in every month from December to March using all monthly images of SST as the stimulus. Final positions of fish in each period were visualized/ mapped out using the Generic Mapping Tools (GMT) software package and were compared with positions of albacore fishing ground obtained from the JAFIC database.

4. Results and Discussion

This study selected the TMI SST data for generating simulation of migration route, since the microwave sensor is capable of measuring SST through clouds so that the satellite instrument can produce a clear image. Considering this point, it has been assumed that the SST data set represents the real variability of surface temperature of fishing ground in relation to the availability of albacore tuna. Our preliminary study indicted that the relationship between TMI SST and fishing ground SST for albacore tuna was statistically significant ($P< 0.001$, $R^2=0.85$). Therefore, the accuracy of TMI data used to simulate albacore tuna migration has significantly been improved. Applying the optimum SST for albacore aggregation, i.e. 20 ºC isotherms a target indicator, some patterns of migration route were illuminated using the kinesis model in winter period. The different point from the Humston *et al.* (2000) model is that this study used the dynamic map of serial SST images as the stimulus. As a result, the application of kinesis model on the sequence of SST maps (November-March) can be used to track migration route for the fish with monthly temporal resolution.

Model results from sensitivity analysis are shown in Figure 2. Using a time step of 0.25 h, the model produced excellent aggregation over the specified range of target value (X=0). Number of fish around the target position increased with the shorter time step. As time step increased, the effectiveness of the kinesis model was reduced. Using longer time step, the model resulted no significant aggregation of fish near the target position. After examining sensitivity analysis, the best time step for migration model was 0.25 h (the shortest one). This finding was consistent with the result obtained by previous study i.e. Humston et al. (2000). The short time steps are needed since stimulus levels are only considered at the starting and ending positions of a fish movement during a time step (Humston et al., 2000). Therefore, it becomes more realistic that fish would respond the changes in stimulus over their environment even small spatial and temporal scales. All parameter values of albacore kinesis model are shown in Table 1.

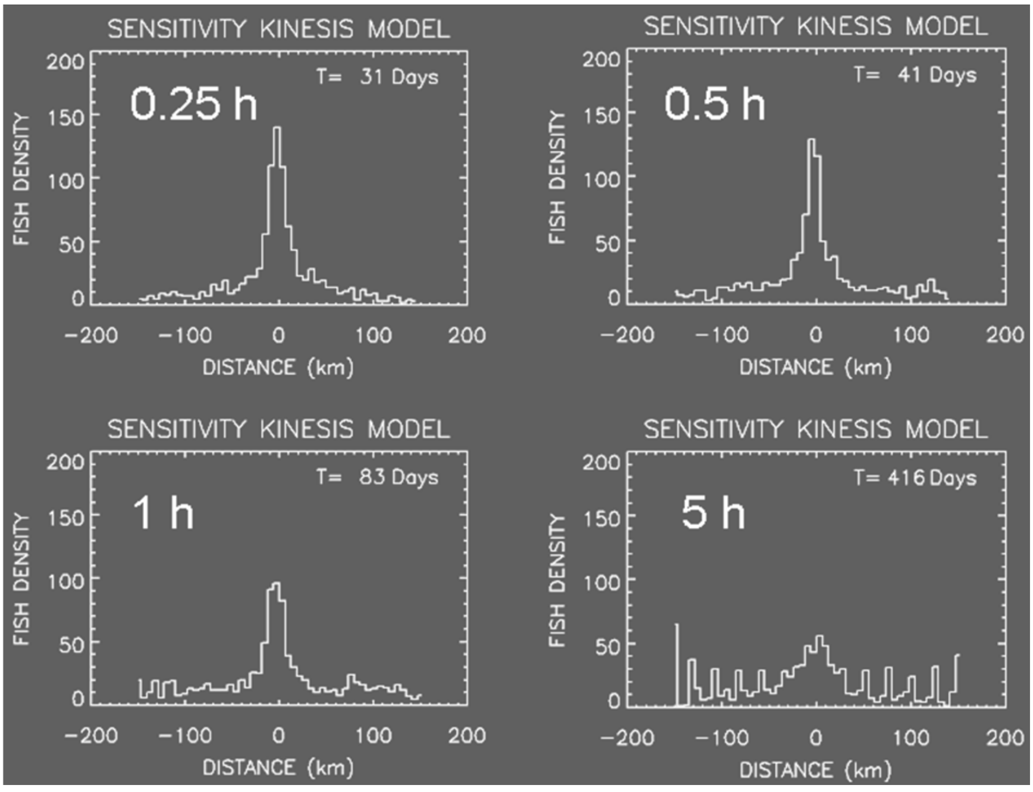

Figure 2. Results of sensitivity analysis of kinesis model using different time steps parametrized to δ = 0.25, 0.5, 1 and 5 h. (h=hour).

Table 1. Parameter values of albacore tuna spatial movements model used for running simulation

Symbol	Description	Value	Unit	Reference
T	Ambient SST during timestep	Spatially variable	°C	TRMM/TMI
To	Optimal SST	20	°C	Zainuddin et al. (2004)
σ	wide of Gaussian curve	1.6	Dimensionless	Zainuddin et al. (2004)
Φ	Maximum sustained swimming speed	6.6	Km h^{-1}	Laurs et al. (1977)
δ	timestep length	0.25	h	
H_1	Height of Gaussian curve in $f(V_{t-1})$	0.9	Dimensionless	
H_2	Height of Gaussian curve in g(ε)	0.7	Dimensionless	

Individual tuna positions at the start and end of runs are represented on colour-coded maps of SST, and the corresponding water temperature occupied by fish at the same time period are shown as histograms (Figure. 3). The area of SST occupied by albacore at the start of model runs generally ranged from 17 ºC to 28 ºC. The spatial fish movements tended to randomly distribute over the entire study area. However, histograms of SST in relation to fish concentration at the end of model runs indicate highest concentrations of fish in surface waters of 20°C with many fish evenly distributed between 20°C and 24°C. At the final position, the fish clearly aggregated in the specific area around 35ºN by following the preferred environmental indicator of about 20°C SST. These results reflect that at the start of model runs, random component dominates the fish movements. As they encounter less favorable areas, the fish movements become more disperse. In contrast, when the fish find preferable area, they have a tendency to aggregate.

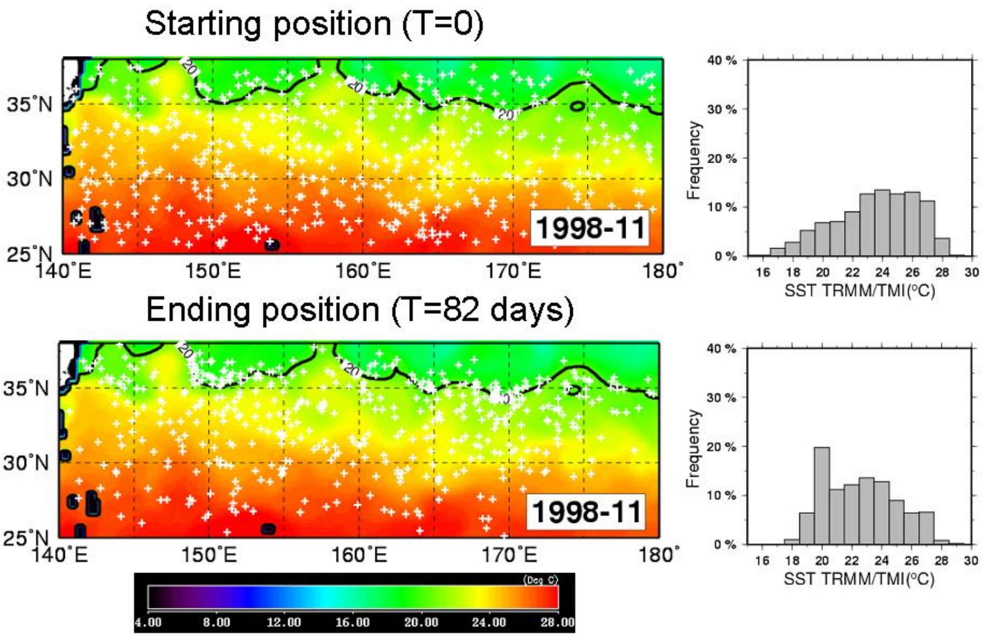

Figure 3. Spatial distribution plot of albacore at starting position (random distribution) (top) and at the ending position (first model run) (bottom) with each histogram frequency of TRMM/TMI SST around the fish distribution in November 1998.

The map of spatial distribution of albacore derived from simulation is similar to that of fishing data (Figure 4). At the running model monthly from November 1998 to March 1999 (a single winter period), fish tended to concentrate near the center of the thermal front indicated by 20ºC. The highest densities of fishing data which were mostly consistent with the model run, occur during November-December. During January-March, fish distributed in areas of 18 – 20 ºC, northern part of optimum temperature of the model. In this period, from the model, it is obvious, fish consistently occurred near the target temperature.

The north and southward tuna migrations for albacore are important bio-ecological phenomena in the study area. Migratory behaviour (i.e. active migration toward spawning ground) is important biological aspect of the fish, whereas the response or reaction of the species to ambient temperature (their environmental conditions) is also important ecological aspect of tuna. This study has demonstrated how albacore migrate from northern to southern area during November-March. The movement of albacore southward during the period can be tracked clearly by the model (Figure 4). Most fish occupied eastern area of 160 °E. In November the fish occurred near 35 °N and moved down to the south at 34 °N and 32 °N in December and January, respectively. In February-March the fish concentrated near 30 °N. It is most likely that this species respond to the progression of seasonal warming during their southward migration. The fish tend to occupy the area of favorable SST, approximately vary between 18 and 21 ºC, which might be linked to the movement of forage fish. The serial maps showed that the fish most likely search for optimum temperature (thermal front) during their north-south migration.

This study found that the high CPUEs were obtained in substantial number in November-January when the fish seem to concentrate in close proximity to the front (Figure 4). However, during February-March, albacore tends to occur in water of 18-19 ºC and the fish aggregations produced by the model consistently occurs near the 20 ºC isotherm. As a consequence, albacore were found mainly in northern part of the fish concentrations resulting from the model. To resolve this problem (i.e. discrepancy between model and field data), this study recommends the use of multi-parameter environmental stimulus such as SST and chlorophyll-a, a good oceanographic indicator to detect tuna migration route (Polovina et al., 2001), together into the simulation model using monthly basis data. Overall, the model can illustrate the southward migration pattern for albacore, which probably corresponds to the movement of albacore prey such as Pacific saury and squid to the south during summer-fall (Sinclair, 1991; Kimura et al., 1997). The movements of prey abundance influence the behavior of tuna migration (Polovina, 1996). Some aspects of the dynamic albacore forage have been described using the movement of the 20 ºC isotherm as a hot spot surrogate for simulation model. Therefore, modelling migration as a kinesis behaviour is appropriate in that it assumes the simplest powers of sensory perception and cognitive ability (i.e. memory of past events) on the part of the fish (Humston et al., 2000).

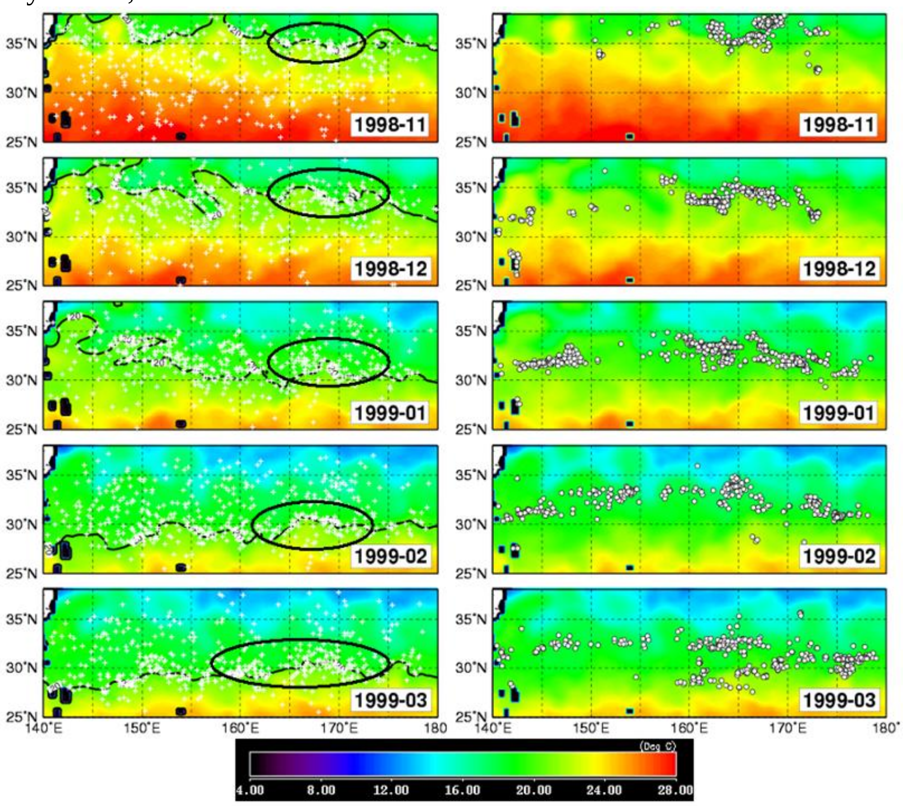

Figure 4. Spatial distribution of albacore displayed as observation data (right) and the result of kinesis model (left) for tracking migration pattern of albacore in winter period (November 1998-March 1999) with contour line resolution of 1 degree (black line).

The histograms of SST in relation to the fish density at the end of model runs in all months indicated that the highest concentrations of fish were found in water of 18.5 - 21.5 ºC and tended to be centered at 20 ºC (Figure 5). These are very similar to SST in the area of high catch of fishing ground (Figure 5). Both these histograms (Figure 5, a and b) are consistent with the favorable range of SST as illustrated in the preferred oceanographic condition for albacore produced by the ECDF and histogram of high catch data (Figure 6). Using SST satellite data as stimulus, this model performed reasonable spatial distribution of albacore around the optimum temperature. During five months of simulation (November-March), this model produced SST with no significant difference of the two modes when compared to the longline fishing positions (Figure 4) using one sample Kolmogorov-Smirnov test ($P < 0.05$) (Figure 6). This analysis indicates that the SST distribution produced by model matchs with the one resulted from empirical data (Figures 4 and 6).

Despite this simulation model could not explain completely north-south migration of albacore, the model can track effectively the dynamics of the optimum SST isotherm. This environmental indicator probably corresponds to the high productive tuna habitat (frontal zones). Albacore appeared to utilize some part of the isotherm for north-south migration and most likely the species respond to many environmental cues simultaneously including directional orientation such as searching food within favorable habitat. To produce the innovative and more realistic approach, this study suggests the development of simulation model using a number of optimum oceanographic conditions (SST, Chl-a and current velocity) as stimulus factors and the use of input data (serial satellite images) with finer spatial and temporal resolution.

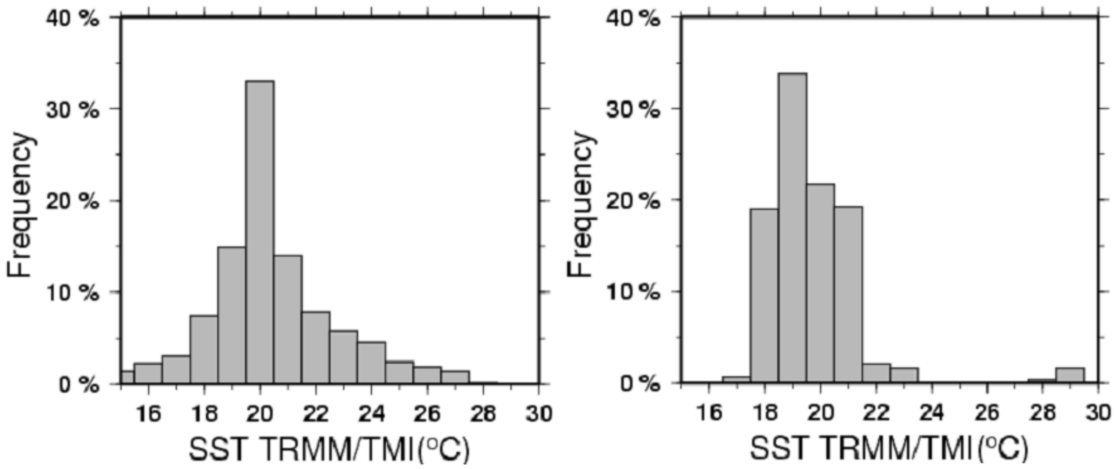

Figure 5. Sea surface temperature in relation to frequency of fish distribution produced by kinesis model (left) and fishing area (right) during winter term (November 1998-March 1999).

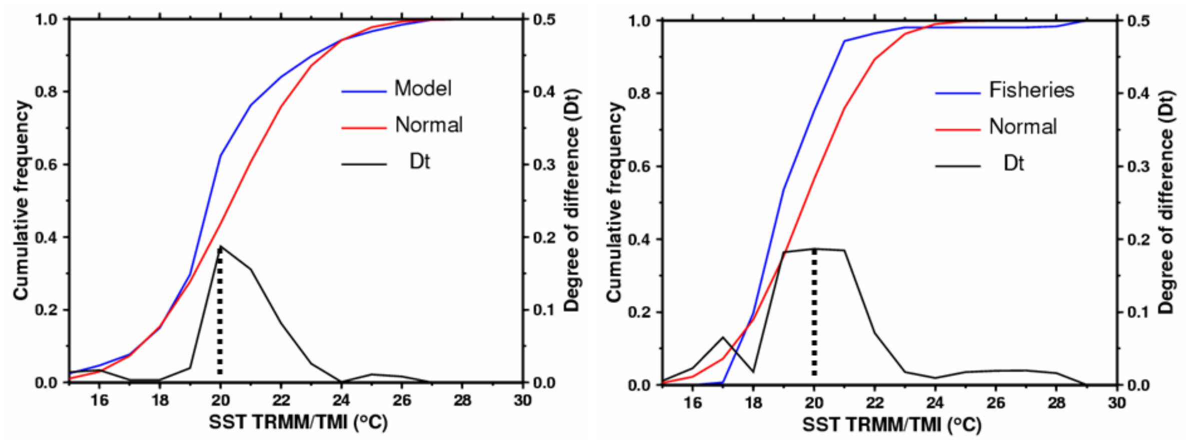

Figure 6. Distribution of Sea surface temperature cumulative frequency produced by kinesis model (left) and fishing area (right) using one-sample Kologorov Smirnov test during winter term (November 1998-March 1999).

5. Conclusions

The general agreement of simulations of kinesis behaviour with observed albacore tuna spatial distributions presents an effective alternative in studying fish migration models. The kinesis model can explain some important behaviours of tuna migration during a single winter period (November- March 1998-1999) using 20 °C isotherm as a main indicator of thermal front. Albacore concentrated near the front during north-south migration in the study area and fairly consistent with empirical data particularly during December-January. This study also suggested that additional foraging factors are involved with their migration as we can find during February-March.

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