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Forecasting models for tuna fishery with aerospatial remote sensing

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Abstract. Tropical tuna movements can be observed from space. We must deduce them by models based on tuna behaviour. To find high concentrations of tunas, we have to find areas with high density of tuna forage. The knowledge of the surface thermal signature of fertilizing processes of water masses is possible using satellite infrared radiometers. We can estimate forage production, and thereby predict tuna distribution. A forecasting model using the concept of the hydrological history of water masses provides a way to find high concentration of tuna. However a new way of investigation is with expert diagnostic systems.

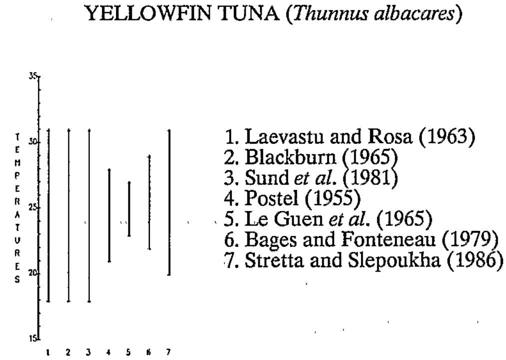
1. Introduction

Sea surface temperature (SST) is the target of numerous investigations in order to describe the oceanic environment and tuna distribution. Laevastu and Rosa (1963) give thermal limits for yellowfin (*Thunnus albacares*) from 18° to 31° with a fishery optimum between 21° and 24°C (figure 1). For skipjack (*Katsuwonus pelamis*) and for big eye (*Thunnus obesus*) these authors give respectively a thermal interval from 17° to 28°C and from 11° to 28°C with a fishery optimum respectively between 20° and 22°C and between 18° and 22°C (figure 1). Blackburn (1965), Nakamura (1969), Evans *et al.* (1981), and Sund *et al.* (1981) point out that the maximum abundances are for yellowfin between 20° and 30°C, for skipjack between 20° and 29°C; for big eye the maximum abundance depends on the fishing gear used.

In the Tropical Atlantic Ocean, yellowfin and skipjack tuna are caught in water where sea surface temperature is between 22° and 29°C (Stretta and Slepoukha 1986). This interval is very close to the interval measured in the Tropical Atlantic. However, 69 per cent of the set containing yellowfin and 62 per cent of the set containing skipjack take place in waters with a temperature higher than 25°C. The distribution of tuna catches in the Tropical Atlantic ocean in relation to sea surface temperature also depends on seasons and geographical areas. For instance, off Cape Lopez (Gabon) in summer, tuna are caught from 23° to 25°C, and off Ghana the main part of the catches during winter are made between 27° to 29°C (Stretta 1988 a). This illustrates that the sea surface temperature measured on the day of the catch is not a good parameter and is not the main environmental parameter to consider. For tuna environmental studies, we have to consider also the content of dissolved oxygen, the depth of the thermocline, the gradient inside the thermocline etc. Inside the limits of environmental and of physiological parameters, tuna forage will induce tuna distribution (Blackburn 1965, Sund *et al.* 1981, Stretta 1988).

2. A proposed model for tuna fishing

If a fishing strategy is the way to direct a fleet to the fishing ground, until recent years this strategy was limited by the choice of seasonal and traditional fishing ground. With aerial remote sensing, it has been possible to build an operational fishing tactic to direct the fishing boats to the fishing ground. With our knowledge about tuna environment it would now be possible to build a long-term fishing



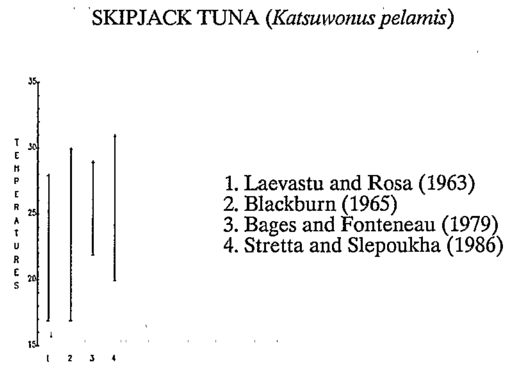


Figure 1. Thermal interval for yellowfin and skipjack tuna as observed by Stretta and Petit (1989 a).

strategy. A forecasting model is necessary to enable rational exploitation of fish stocks, despite the competition between fleets and the laws relating to the exploitation of exclusive economic areas. It will also help to give an answer to the question asked by fishermen as to where the fish are located.

To give an answer to this question while we know that tuna movements cannot be observed in the open ocean from space, we must deduce tuna movements by models based on tuna behaviour.

3. Present models for tuna fishery

3.1. *A forecasting model for tuna fishery*

If we know roughly the direct relationship between tuna and environmental parameters it is possible to use the inverse of this relationship to deduce the presence of tunas from environmental parameters.

By accepting the hypothesis that tuna forage will induce tuna distribution inside the limits of environmental and physiological parameters, if we can find areas with high density of tuna forage, then we shall find high concentrations of tuna. This concept involves finding areas of high productivity with a high density of tuna preys.

To illustrate the hypothesis that tuna forage induces tuna distribution Valiela (1984), writes that the annual consumption of fish by bluefin tuna (*Thunnus thynnus thynnus*) in the North Sea during 1952 has been roughly estimated at

210 000–256 000 tons with 150 000–180 000 tons of herring. In 1952, the stock of herring was about 140 000 tons, so Valiela calculates that consumption of herring by tuna could have removed the entire stock of herring, and that in this case the food web has been affected by fishing fleet.

If we accept the hypothesis that tuna forage induces tuna distribution, Stretta (1988) points out three problems:

(1) The tropical epipelagic water masses under steady conditions like the typical tropical structure (TTS) defined by Herbland and Voituriez (1977) are relatively poor (Le Borgne 1977);
(2) The migrating fauna are not a major food source for tuna (Roger and Grandperrin 1976);
(3) The bioenergetic needs of tuna are important and well described (Kitchell *et al.* 1978, Olson and Boggs 1986).

In tropical waters the question asked by Kitchell *et al.* (1978) arising from this paradoxical situation is: how can tuna schools inhabit such an unproductive environment? That means that (i) tuna prey are concentrated in patches and (ii) tuna have a fantastic ability to find and to harvest these patches of preys.

From bibliographical analysis (Stretta 1986), we know that:
(*a*) Tuna have a wide spectrum of prey;
(*b*) Tuna are active and opportunistic feeders (Stretta 1986);
(*c*) Tuna feed in daytime with their eyes in the epipelagic layer of the ocean.
(*d*) For tuna the limiting factor is the ability to eat and to assimilate the available prey.

3.2. *The praxeological analysis*

To find high concentrations of tuna, we must find areas with high densities of tuna forage. If tropical waters are poor under steady conditions, a high productivity inside the TTS is the result of an ecological imbalance (or ecological 'catastrophe'). A high productivity is the result of an enrichment processing in the water masses. There are two kind of enrichment processing in the tropical Atlantic. One relates to the quasi geostrophic systems, like domes and equatorial thermal ridge and to nongeostrophic systems like equatorial divergence and coastal upwellings (Herbland *et al.* 1983). The other is a system inside the ocean well known by fishermen as the sea mounts. Boehlert and Genin (1987) point out, there is an enrichment of the water masses near a sea mount.

All these enrichment systems have a common point, namely, the emergence of the thermocline into the euphotic layer (or only in the euphotic layer). The layers inside (or below) the thermocline reach the surface when there is a decrease in the sea surface temperature. However, if these layers inside the thermocline do not reach the surface they assist in the formation of thermal domes or equatorial thermal ridges.

The ecosystems where tuna feed are associated with enrichment systems resulting from the movement of the thermocline at the surface or in the surface layer, like frontal areas (Dufour and Stretta 1973), equatorial upwelling (Le Borgne 1977, Voituriez and Herbland 1982) and thermal domes (Voituriez and Dandonneau 1974).

If the arrival of the cold water at the surface of the sea is an indication of the beginning of the enrichment process, the question arises as to how the maturation of the water mass follows. Following a drogue in the mauritanian upwelling, Herbland *et al.* (1973) show that the increase of SST is correlated to the increase of phytoplankton and zooplankton biomasses. In the equatorial upwelling Roger (1982) shows that the biomass of tuna forage is $1165\,\mathrm{mg\,m^{-2}}$ (dry weight) and $311\,\mathrm{mg\,m^{-2}}$ in the TTS. The delay between the beginning of the enrichment process and the presence of tuna forage has been estimated as about 4–6 weeks (Stretta and Slepoukha 1983 a, b, Mendelsshon and Roy 1986). In the Canary islands González Ramos (1989) showed that a month before the beginning of skipjack catches in May, the SST in April is cold (18°C) and the chlorophyll concentration is high (0·4 μg/l against 0.12 μg/l in March). But according to Stretta and Petit (1989 a) the question thus arises as to whether SST is a good way to follow the maturation of water masses.

Then a high concentration of tuna can be theoretically approached by searching for a decrease of SST in the open ocean then following a regular increasing of the SST. These two phenomena represent the thermal signature of fertilizing and maturation processes in the sea. They lead us to consider a new concept in tuna ecology, that of the concept of the hydrological history of waters masses.

This thermal indication can be detected by an aircraft or satellite equipped with an infrared radiometer for measuring SST. For sea mounts, whilst the thermocline does not reach the surface, it is possible to detect by SPOT a change in the direction of the swell (see Petit (1990)).

Analysing the SST evolution during five fishing seasons off Gabon (West Africa) and off the Ivory Coast (West Africa), (Stretta 1977, Stretta and Petit 1989 b, Stretta *et al.* 1990 b) we have constructed what we have called an Ideal Thermal Scenario (ITS) or a 'theoretical thermal scenario' to point out the events (and their duration) which are necessary to obtain favourable conditions for tuna fishery. This ITS built with an empirical analysis could be like this (figure 2):

(1) the arrival at the surface of cold waters from an upwelling;
(2) maturation of these waters during four weeks;
(3) thermal stabilization during two weeks;
(4) favourable conditions for tuna.

But if we choose the SST as an indication of the maturation of water masses, we have the difficulty of monitoring that process. We have taken up an increase of SST of about 1°C each week to follow the maturation process inside the water masses (Stretta and Petit 1989 a). It is necessary to be sure that the schematization of the tuna ecosystem has reached maximum because with only SST we have to follow during time and space a series of events from enrichment to tuna forage.

The most simple model will be to follow along the time/space scale of the SST and to point out the area where the probability of finding forage organisms for tunas is supposed to be high. The model will consist of comparing the thermal scenario of a water mass to the ITS.

The praxeological analysis we have developed (Stretta 1989, 1990) is the analysis of the evolution of events during time and the comparison to an ideal evolution. The first version of this new paradigm is rough and the solutions obtained are not ideal. On the other hand this kind of analysis has the advantage to be close to reality but without mathematical elegance (von Bertalanffy 1968).

3.3. *The forecasting model: PREVI-PECHE*

With the concept of the praxeological analysis of the hydrological history of water masses from METEOSAT-2 and the NOAA meteorological satellites (GOSSTCOMP

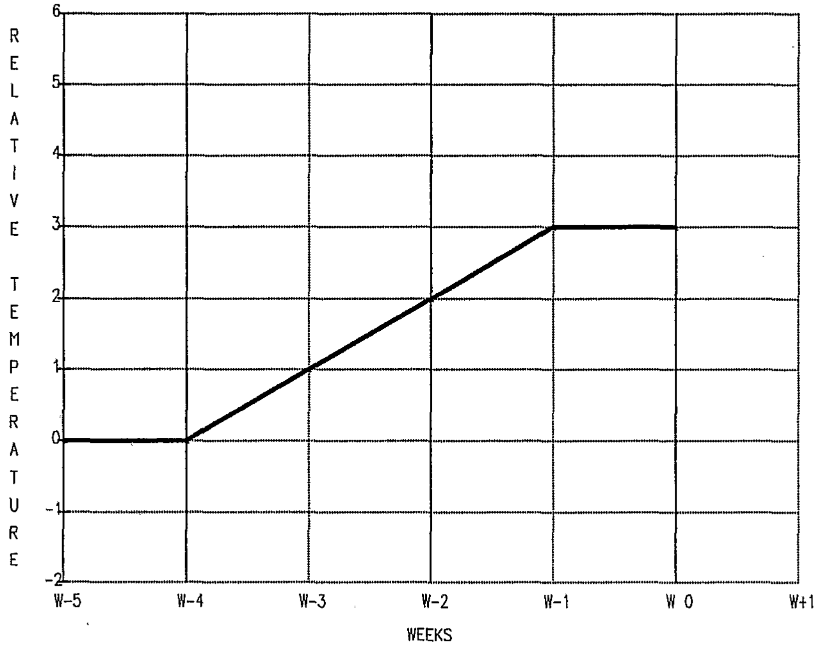


Figure 2. The Ideal Thermal Scenario (ITS) from Stretta and Petit (1989 a). Enrichment from week W−5 to week W−4. Maturation from week W−4 to week W−1. Stabilization of isotherms from week W−1 to week W0.

products) data, a forecasting model called PREVI-PECHE (Stretta 1989, Stretta and Petit 1989 a) was developed in the tropical Atlantic ocean from 20°N to 10°S and from African coasts to 50°W. For this model, the space step chosen was an elementary area with 2° in latitude and 5° in longitude. Each area has a surface of 36 000 sq. miles. The time step chosen was those of the SST map from satellite: a week.

For each area, we compute the following potentialities.

3.3.1. *The historical fishing potentiality* (*HFP*).

HFP results from comparison between the SST historical value from the month before we do the forecasting bulletin and the coldest SST value reached in the area. The SST historical values are taken from an atlas (Hastenrath and Lamb 1977, Merle 1978). If the coldest SST value reached in the area is higher than 25°C, we consider that the area has a very low probability to receive an enrichment by infra-thermoclinal waters. On the other hand, the HFP is maximum if the coldest SST value is below 25°C and if this value appears one month before the forecasting bulletin is done.

3.3.2. *The coming fishing potentiality* (*CFP*)

When we receive an SST map from NOAA (GOSSTCOMP) or from METEOSAT satellites, we are into week W0. After digitization of the map, we compare the evolution of the SST during four weeks before week W0 to the ITS by a series of five tests. The comparison is done from week W − 5 to week W0 (cf. figure 2).

3.3.3. *The area fishing potentiality* (*AFP*)

When we receive an SST map, for each elementary area, we calculate the HFP, we build the thermal scenario and we compare it to the ITS to get the CFP. Then the AFP is the sum of the HFP and the CFP.

Depending on the number of successful tests, the area is declared either: 'highly favourable', or 'favourable', or 'not very favourable', or 'not favourable to tuna fishing operations' for the two next weeks, W + 1 and W + 2 (Stretta and Slepoukha 1983 a, b).

The forecasting model PREVI-PECHE has been presented and described by Stretta and Petit (1989 a).

From February 1982 to June 1985 we have given 82 forecasting bulletins to help French and Ivorian tuna fleets in finding areas of tuna concentration. The comparison between the fisheries and the forecasting bulletin for the validation of the model are not yet completed.

4. Future models for tuna fishery

If PREVI-PECHE is the result of a praxeological analysis of a tuna fishery, there now exists a new way for modelling knowledge, namely the expert diagnostic systems (EDS). The EDS is based on empirical methods built over heuristic knowledge. These methods are able to find the best result but not the optimum result.

An EDS is composed with two elements, a data knowledge base (DKB) for the knowledge of the expert and an inference motor. In a DKB the elements are independent and with no order and a modification of one element has no dramatic donsequences for the process.

The aim of an EDS is to model the behaviour of an expert in front of specific problems while we have no algorithm to solve these problems. If the EDS specific problems while we have no algorithm to solve these problems. If the EDS records the specialized knowledge of an expert in this database, then we must face the problem of the choice of the expert. We can choose between the fishery biologist and the fisherman. The first solution certainly gives priority to the environmental remotely-sensed data, the second solution gives priority to tuna behaviour. The response is probably an EDS mixing both solutions. The EDS have the particularity to use symbolical knowledge while the classical models use numerical data.

There are five steps to build an EDS (Chatain and Dussauchoy 1987):

–identification of the problem,
–the determination of the main concepts and the relations between these concepts,
–the organization of the concepts,
–the realization of the EDS and the first tests,
–the validation.

One of the main difficulties (or perhaps a limit) in the development of an EDS, is to extract the knowledge when we are involved in biological processes.

To realize such a kind of forecasting model and to get it operational, a European scientific association is necessary. This association is possible and suitable between European countries involved in tuna fishing. These countries would be Spain, Portugal, Italy and France. Tuna fishing takes place in the Mediterranean by Italian and French fleets; in the intertropical belt of the Atlantic Ocean by Portuguese, Spanish and French fleets; and in the Indian Ocean by Spanish and French fleets. Several African countries who are planning to develop their own tuna fisheries in the Atlanta and Indian oceans could also be invited to cooperate with this European scientific association.

5. Conclusions

The classical studies on tuna environment began in the Gulf of Guinea with the beginning of commercial fishery at the end of the sixties. During the seventies these studies introduced aerial then spatial remote-sensing methods. These original studies gave the first steps towards a fishing strategy during the eighties.

In the future, the possibilities and the characteristics of the new sensors (passive and active), the development of EDS, and a strong-willed European scientific association could be the way forward for the future development of tuna fisheries.

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