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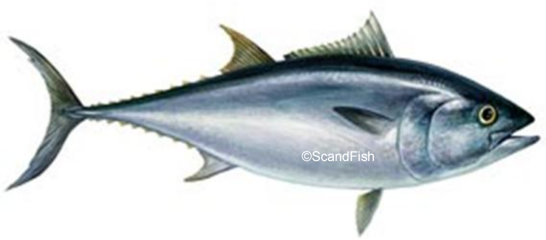
Environmental analysis of Bluefin Tuna: Identifying its preferred habitat in the Mediterranean Sea



Thunnus thynnus

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Rationale

Bluefin tuna (BFT) populations (Atlantic, Pacific and southern species) have declined alarmingly over the past few decades mainly driven by the demand for sushi and sashimi. There are two populations of Atlantic bluefin tuna. The smaller western stock classified as critically endangered has declined by nearly 90% since the 1970s, fishers now witnessing catches that are under 10% of the quota (Safina and Klinger 2008). The larger eastern stock, which spawns in the Mediterranean Sea, have been overexploited since the 1950s or 1960s in the North Sea or North-west Atlantic, and since the 1980s in the central and eastern Mediterranean (Fromentin 2008). The biomass of adults (spawning stock biomass) is now (2006) at its lowest on record, ca. 40% of late 1950s' biomasses (MacKenzie et al. 2008). Both populations are classified as *Critically Endangered*, i.e. 90% decline in adult biomass within three generations (IUCN[1] criterion). MacKenzie et al. 2008 predict that the adult population in 2011 will likely be 75% lower relative to 2005 and that quotas in some intervening years will allow the fishery to capture legally all of the adult fish.

Purse seine nets are currently responsible for 60-80% of the bluefin tuna catch in the Mediterranean. The fleets operate particularly in the Tyrrhenian Sea, Ligurian Sea, the Strait of Sicily, the Aegean Sea and more recently in the Gulf of Sirte, the waters off Egypt and the Sea of Marmara. Most of the catch is destined for fattening in cages. WWF estimates that catches in 2004 were around 1.5 times higher than the annual quota, one third being illegal. As of July 2006, the farms' total capacity was 55,300 Metric tonnes (Mt) to be compared with the annual eastern bluefin tuna quota of 32,000 Mt. The practice of transferring live tuna at sea to tug boats for transportation to the farms also renders difficult to keep track of how many tuna were caught by who and where, and what size they were.

Currently, controls at sea are performed by Member States (MS) in coordination with the Community Fisheries Control Agency (CFCA) and the European Commission – Joint Research Centre (EC-JRC) for regional campaigns using the Vessel Detection System (VDS). Mostly guided by the positioning of fishing vessels (Vessel Monitoring System, VMS), team-members of the FISHREG Action at the JRC order and process satellite-derived radar and optical high-resolution images of the sea surface (of 100*100 km^2) to identify non-reported fishing vessels and tug boats pulling cages. This method for targeting the control assumes that vessels practicing illegal, unreported and unregulated (IUU) fishing have their VMS active or are nearby the fleets fishing legally. However, there are known means to manipulate VMS data on board and some might just deactivate their positioning system, especially during fishing closure. Considering the importance of BFT IUU fishing, non-positioned fishing vessels are most probably operating in the high seas of the Mediterranean Sea.

A VMS-independent mean is thus required to ensure the control is partial and spots most of the BFT habitats together with IUU fishing. The BFT preferred habitat mapping from satellite-derived environmental data allows focusing part of the control on areas where the resource most likely is, and thus where fishing fleets could be. In addition, some fishermen use elaborated charts based on satellite-derived environmental data to track tuna schools (e.g. http://www.geoeye.com/CorpSite/products/solutions/seastar/products-services.aspx). It is therefore anticipated that the BFT habitat mapping is likely to highlight areas where IUU fishing vessels are. The habitat mapping can also be used to explain vessel movements and to refine catch estimates using VMS.

[1] International Union for Conservation of Nature

Objectives

The objective is to identify the preferred habitat of bluefin tuna in the Mediterranean Sea from environmental data to:

- Contribute to guide the control of the fishing fleet by VDS in complement of VMS in the frame of the fight against IUU fishing,
- explain vessel movements,
- improve catch estimates using VMS,
- increase the knowledge on BFT migration, population structure and further refine the stock assessment.

The current knowledge of this highly migratory fish is still relatively low. The structure in metapopulations and the current stock assessment method are questioned (Fromentin and Powers 2005) especially regarding the large bias induced if migratory aspects are included (Fromentin and Kell 2007). Electronic tagging was used lately to show mixing of BFT populations (spawning in the Gulf of Mexico or in the Mediterranean Sea, Block et al. 2005) and natal homing in the Western Atlantic Ocean (Rooker et al. 2008). A recent attempt to develop a full foodweb modelling up to tuna species was performed (Lehodey et al. 2008; Senina et al. 2008), however the coarse spatial and temporal resolutions and the foodweb complexity limit their application at present.

For all these research efforts, the habitat mapping can provide an independent and complementary source of information for validation or refinements at high spatial and temporal scales. The habitat mapping could efficiently contribute in particular to the identification of the main migration routes and their variability which are largely unknown (Fromentin 2008). The relationship between sea surface temperature or habitat mapping and the extensive trap data (Addis et al. 2008) is able to reveal the trigger(s) of BFT migration as traps are passive and fixed fishing gears from which a migrating tuna flux can be derived. The important capacity of BFT to cover large distances to seek the best feeding and spawning grounds in a changing environment remains most probably its best asset against overfishing.

Relevant background knowledge on BFT and its habitat

The environmental data used are derived from satellite remote sensing and are freely available online, both Near Real Time (NRT) and for the last decade (Sep. 1997 – now). Since the area of interest is the Mediterranean Sea, which is well known as a BFT spawning ground, the study focuses on tunas above 10kg having two specific behaviours: feeding and spawning. Adult BFT are not mature in the Mediterranean Sea below the weight of about 20kg and 3 years of age (~100 kg and 7 years in the Western Atlantic Ocean for unknown reason). At the age of 4 and 30 kg (actual minimum catch size), 50% of the Mediterranean population is mature and 100% is mature above 50 kg. The habitat mapping includes favourable areas of immature BFT (feeding behaviour) and mature BFT (feeding and spawning behaviours).

The focus is given on the fishing season which has been reduced these last years to the spawning season (May to July). In 2008 the fishing season has been reduced to six months (from July 1st to December 31st) and to two months in 2009 (April 15th to June 15th). Spawning sites appear to be concentrated mostly around the Balearic Islands, the Tyrrhenian Sea and the southern central and eastern Mediterranean Sea. The spawning frequency being estimated to 1.2 days (Medina et al. 2002), the tuna schools are assumed to search for the ideal spawning environment most of the spawning season (~2-3 months) and hunt for fish occasionally. These highly migratory fishes can travel several thousands of kilometres each year in the Eastern and Western Atlantic Ocean and must search for the spawning grounds (the Mediterranean Sea and the Gulf of Mexico, Block et al. 2005) several weeks or months in advance. The increasing temperature is most probably the major trigger of the migration. One could also hypothesize BFT could trace the high-salinity Mediterranean Intermediate Water originating from the Eastern Mediterranean basin while diving down to 900 m in the Atlantic Ocean. BFT is assumed to seek continuously either the feeding grounds or the spawning grounds from May to July. After the spawning season, only the feeding behaviour is assumed.

These two behaviours differ significantly since they correspond to distinct biological requirements. In order to optimize recruitment, the BFT spawning shoal seeks the best potential conditions for the larvae's development. These conditions are primarily low turbulence and a significant abundance of small zooplankton, mainly copepods and copepoda nauplii on which larvae feed (Uotani et al. 1990, Fromentin and Powers 2005). High temperature traces efficiently low turbulence levels as the surface temperature integrates the degree of mixing with subsurface waters. Larvae sampling and spawning observation in captivity reveal that spawning occurs only for water temperature above 20^{o}C with higher rates above 24^{o}C (García et al. 2005; Schaefer 2001). Mesotrophic conditions on the other hand can be identified by medium-low chlorophyll content (~0.05-0.15 mg m^{-3}).

The multi-annual mean maps of chlorophyll-a and SST (Figures 1 and Figure 2) for the month of June show that known spawning areas (red and green circles) are located in the warmest waters that contain chlorophyll-a in the range 0.05 to 0.15 mg m^{-3}. From these elements, we could foresee that **the 'spawning habitat criterion' may include a regional maximum of temperature (or a 30 days increase of temperature above a given threshold as shown in the example below with a minimum temperature of 20^{o}C) <u>and</u> the range of chlorophyll from 0.05 to 0.15 mg Chla m^{-3}.** Figure 3 shows the distribution of the spawning habitat criterion from multi-annual data presented in figures 1 and 2. This first simple comparison is promising since this criterion highlights the main spawning areas but also other recently identified areas in the Gulf of Sirte (off Libya) and along the coast of the Levantine Sea and other reported areas (Sea of Marmara, Ligurian Sea and Adriatic Sea).

On the opposite, feeding BFT seeks schools of forage fish (e.g. herring) regardless the turbulence level at the vicinity of thermal (Humston et al. 2000) and chlorophyll fronts (Royer et al. 2004, Santoleri 2006; Schick and Lutcavage 2009) characterized by a high temporal stability (efficient energy transfer along the food web) or capacity of retention (edge of counter clock-wise warm eddies, Teo et al. 2007). BFT hunt by sight, therefore they also stay where chlorophyll concentrations are below ~0.50 mg m^{-3} (Royer et al. 2004). **The 'feeding habitat criterion' may thus include the distance from thermal fronts (below ~15 km,** Royer et al. 2004, Schick et al. 2004**) <u>and</u> the distance from chlorophyll fronts (below 10 km,** Royer et al. 2004**) <u>and</u> a chlorophyll content comprised between 0.05 and 0.40 mg Chla m^{-3}** (Royer et al. 2004). Such criterion of BFT feeding habitat could also be called criterion of forage fish habitat as it traces the main BFT preys. Figures 4 and 5 show preliminary maps of the feeding habitat for May and June 2007 using the above criterion. A brief description of the feeding habitat processing is given in Annex 2. Figures 6, 7 and 8 present the May-June-July 2007 maps for the spawning criteria. It appears from this first result that spawning and feeding grounds are different and the variability of both habitats is high in space and time although few regions seem to be recurrently more favourable for feeding than others (e.g., Ligurian Sea, off the Italian coast in the Adriatic Sea). **Spawning generally occurs first in the Eastern Mediterranean Sea and spreads during two to three months towards west following the heating of surface waters**. The fishing pressure became higher on the eastern basin than on the western basin because of the anticipated closure these last years from late July to July 1st (and June 16th in 2008 for EU vessels). **Since** there is some evidence from tagging experiments that **BFT is organized in meta populations with relatively independent eastern and western populations in the Mediterranean Sea, the increase of fishing effort on the eastern stock will lead to a high risk of collapse** while the western stock is submitted to a decreasing fishing pressure. In the western Mediterranean Sea on the opposite, different source of observations (traps, industrial and recreational fisheries, scientists) converge to show that, although the fraction of large to small BFT has decreased, the populations of small individuals seem to fairly maintain and maybe increase. This statement may also result of the fisheries' closure for most of the spawning period in the Western Mediterranean Sea since 2007.

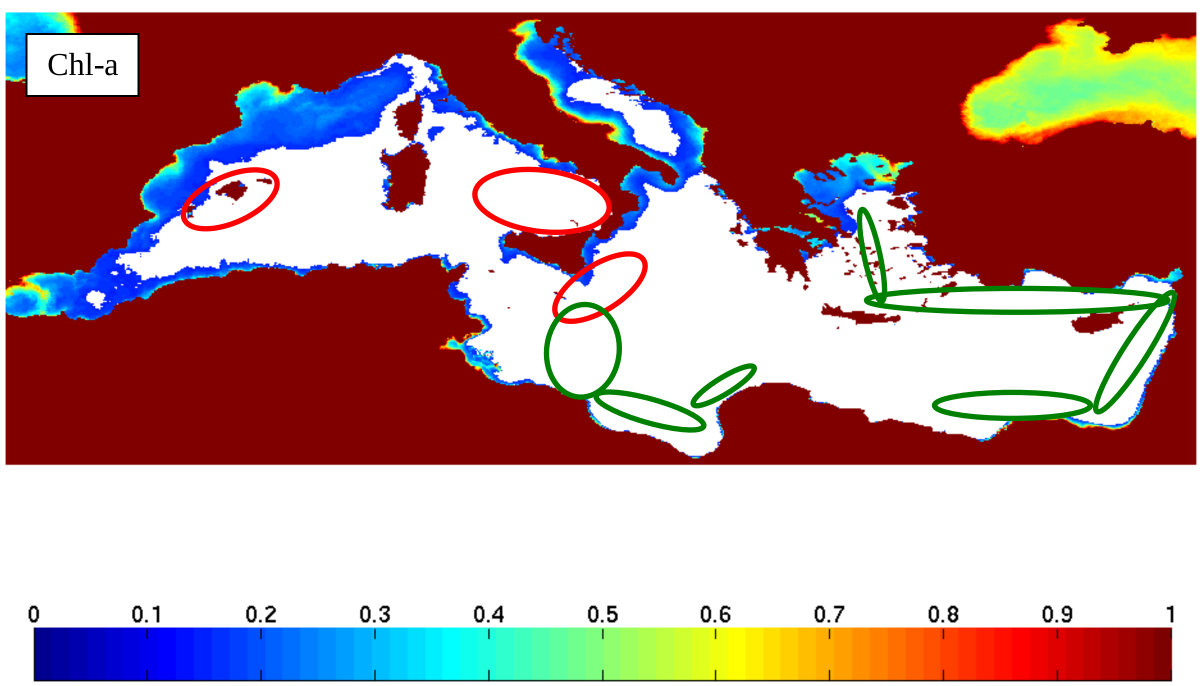

Figure 1: Satellite-derived surface chlorophyll-a concentration for June (mean 2003-2007, MODIS-Aqua, http://oceancolor.gsfc.nasa.gov/cgi/l3, white highlights the range 0.05-0.15 mg m^{-3}). Red circles show the major BFT spawning areas (Ravier and Fromentin 2004 from Mather et al. 1995) and green circles are more recently discovered spawning areas (EU Commission Scientific, Technical and Economic Committee for Fisheries, STECF 2006, and Fishing Industry).

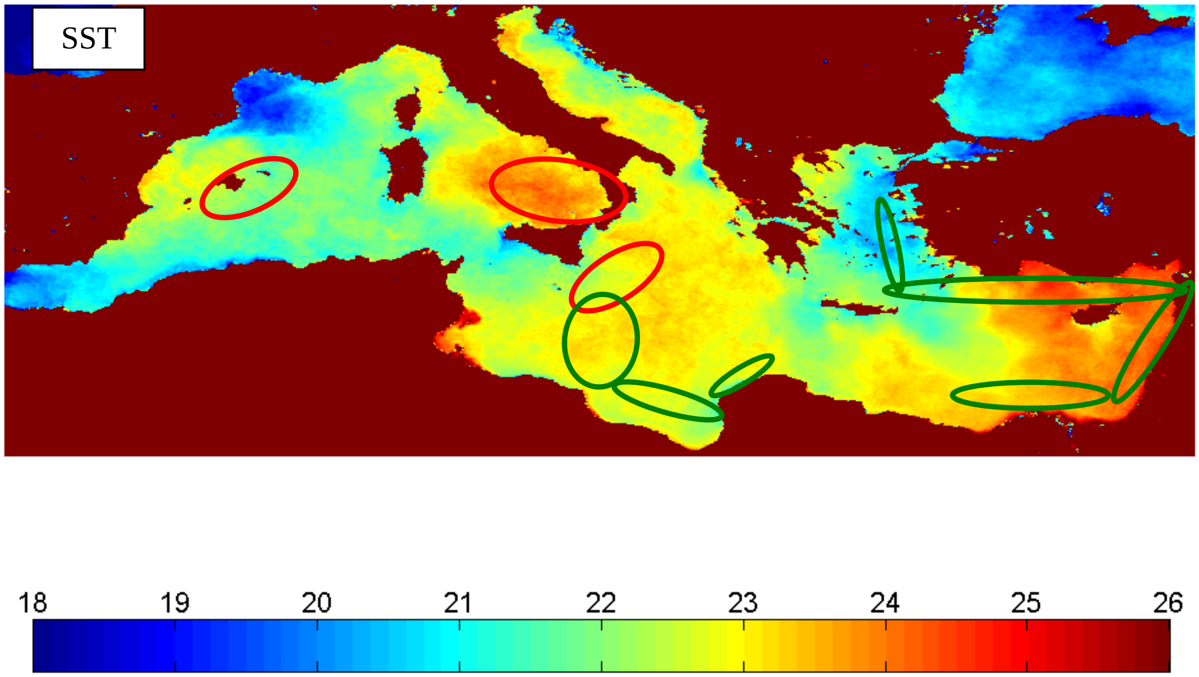

Figure 2: Satellite-derived sea surface temperature for June (mean 2003-2005, MODIS-Aqua, http://oceancolor.gsfc.nasa.gov/cgi/l3). Red circles show the major BFT spawning areas (Ravier and Fromentin 2004 from Mather et al. 1995) and green circles are more recently discovered spawning areas (EU Commission Scientific, Technical and Economic Committee for Fisheries, STECF 2006, and Fishing Industry).

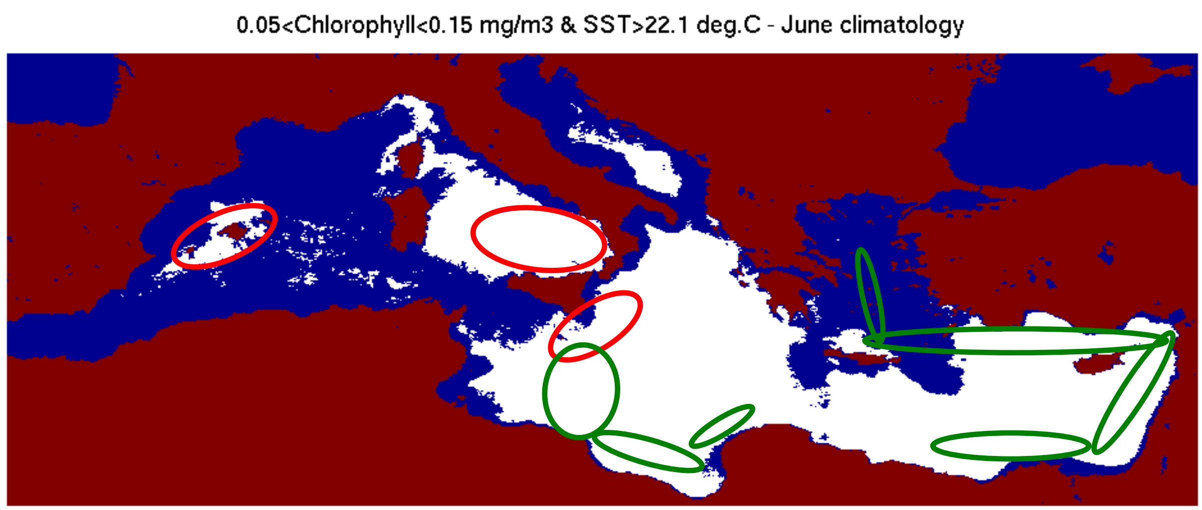

Figure 3: BFT spawning criterion (white, see title) derived from figures 1 and 2. Red circles show the major BFT spawning areas (Ravier and Fromentin 2004 from Mather 1995) and green circles are more recently discovered spawning areas (EU Commission Scientific, Technical and Economic Committee for Fisheries, STECF 2006, and Fishing Industry).

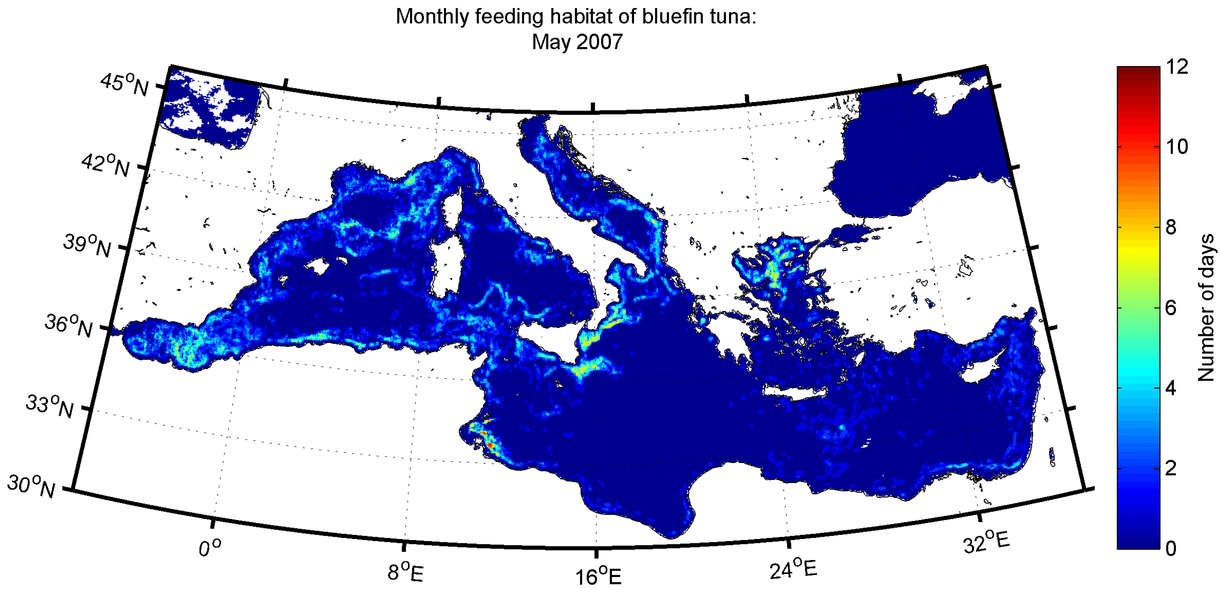

Figure 4: BFT **feeding** habitat mapping for **May 2007** (in number of days) derived from daily environmental data (SST and Chlorophyll-a, preliminary result).

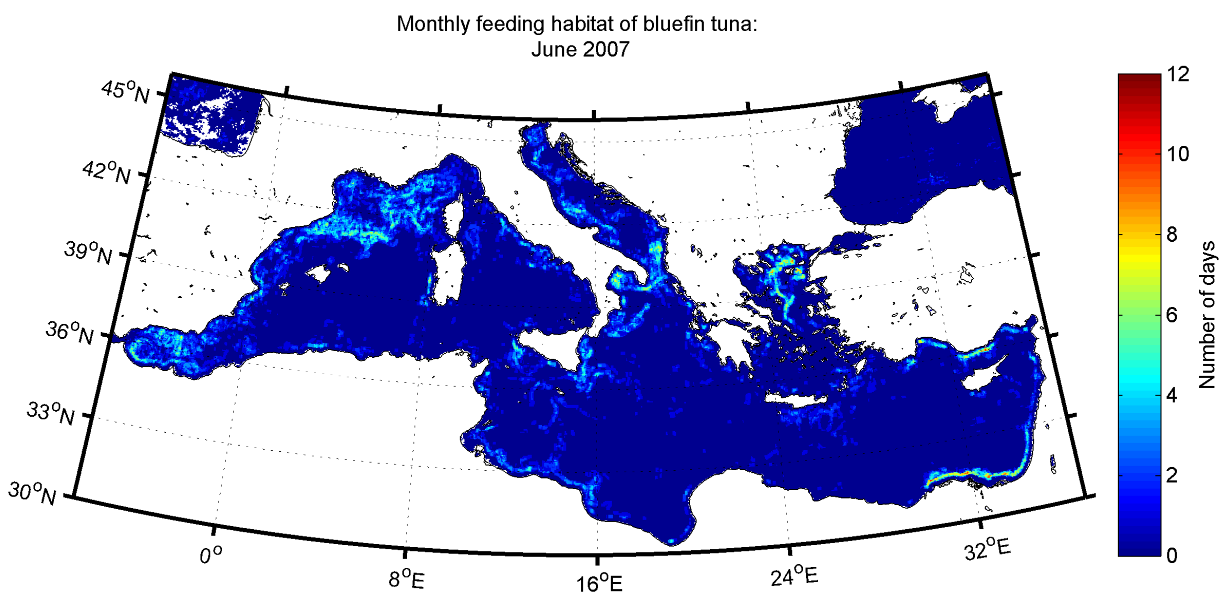

Figure 5: BFT **feeding** habitat mapping for **June 2007** (in number of days) derived from daily environmental data (SST and Chlorophyll-a, preliminary result).

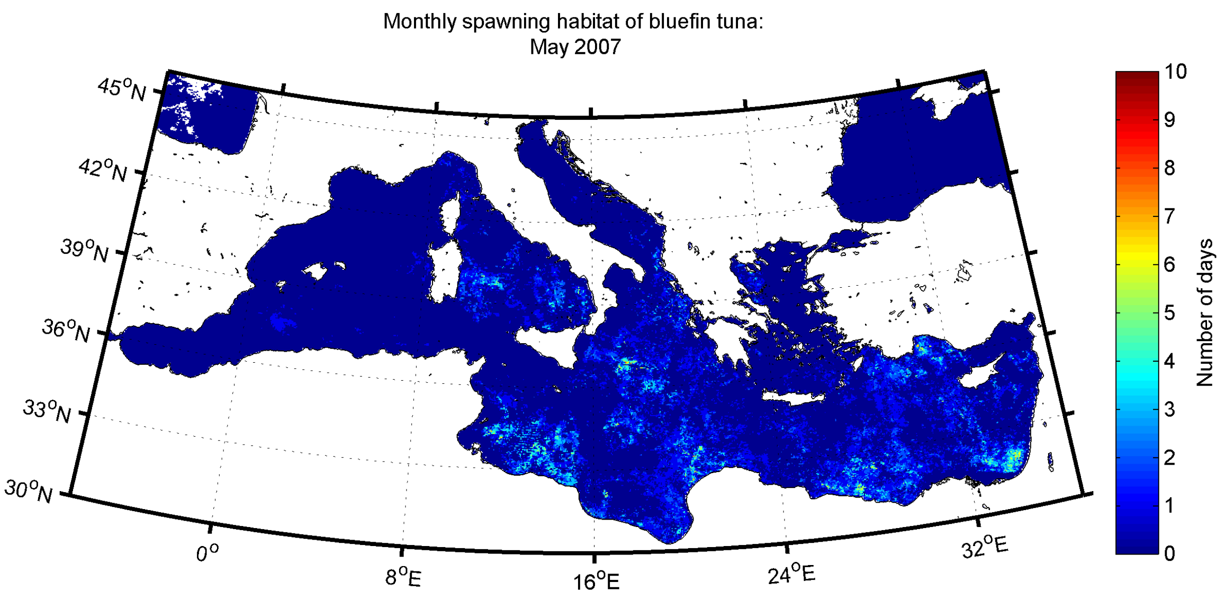

Figure 6: BFT **spawning** habitat mapping for **May 2007** (in number of days) derived from daily environmental data (SST and Chlorophyll-a, preliminary result).

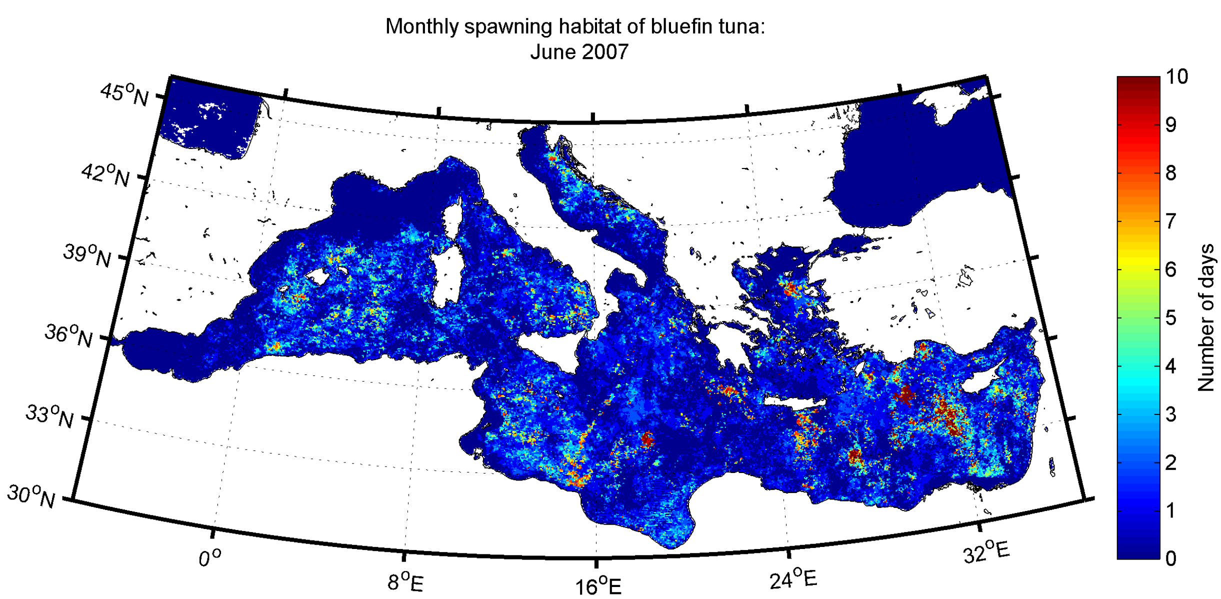

Figure 7: BFT **spawning** habitat mapping for **June 2007** (in number of days) derived from daily environmental data (SST and Chlorophyll-a, preliminary result).

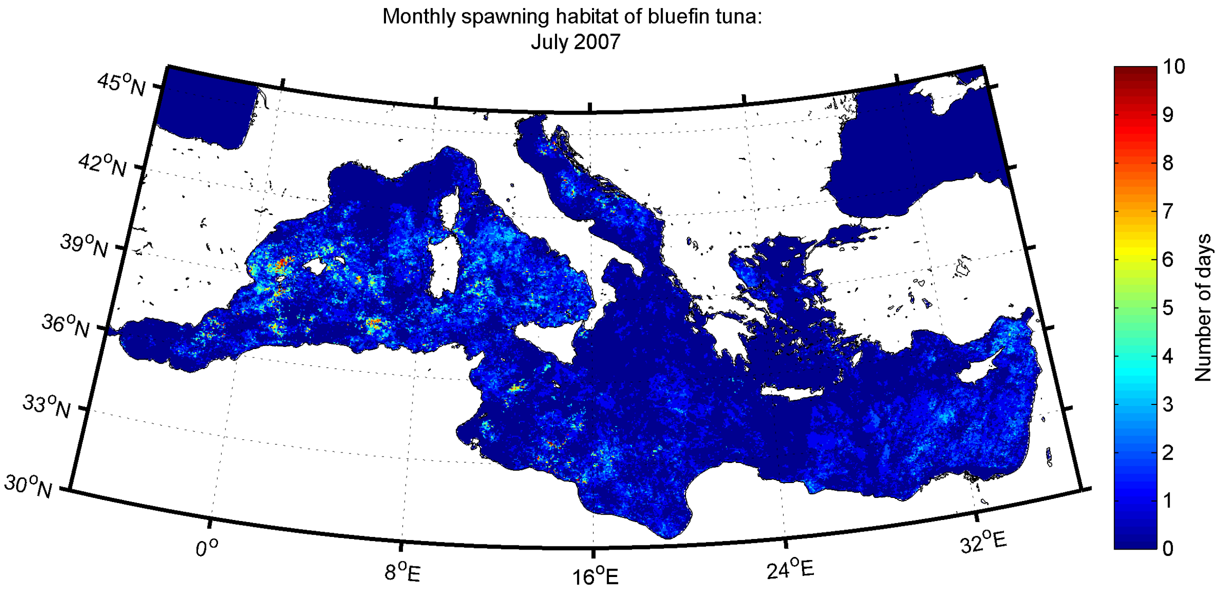

Figure 8: BFT **spawning** habitat mapping for **July 2007** (in number of days) derived from daily environmental data (SST and Chlorophyll-a, preliminary result).

The Mediterranean Sea seems to be a favourable region to seek spawning ground using sea surface parameters because this confined basin is more subject to atmospheric forcing (Royer and Fromentin 2007). The other major known spawning ground, i.e. the Gulf of Mexico, is also heated by the Caribbean current which may reduce the efficiency of surface parameters to track low turbulence levels.

The parameters of importance for identifying the feeding and spawning behaviours are primarily the SST and surface chlorophyll-a concentration. Among other sensors, MODIS-AQUA and MODIS-TERRA from NASA are of particular interest because they measure simultaneously, or with a 12 hours shift for the night SST, both parameters since July 2002 and February 2000 respectively. The full resolution of MODIS is high (~1 km), however only the 4.6 km daily data is mapped and available with a global coverage. MODIS-TERRA is not used yet since the data quality is significantly lower than MODIS-AQUA and requires further processing.

Wind data and sea surface height (SSH) from radar satellite remote sensing could also be of importance in case of persistent cloud cover when using the NRT mapping. The mean wind condition over a two to three weeks floating window may be efficient to trace SST maximum. In addition, SSH traces efficiently meso-scale features such as eddies where, at the edge, phytoplankton, grazers and forage fish may develop if persistent.

Validation data of the habitat mapping: requirements and limitations

The calibration and validation of the BFT preferred habitat mapping requires the observation of BFT schools precisely located in the Mediterranean Sea provided mostly by scientific campaigns (airborne, e.g. Figure 9, or satellite-tagging system) or by the fishermen or through the mandatory landing and positioning (VMS) data if a fishing action can be identified. It must be emphasized that the BFT preferred habitat does not include transition locations where schools are between two feeding spots or are evolving towards a more favourable spawning area. For this reason, a *statistically significant number* of observations for validation (which is difficult to estimate) is required. It is thus foreseen that a fraction of the observations is not likely to be within the preferred habitat location. To counteract this problem, data from electronic tagging[2] could be used to analyse the tuna positioning as regards to its preferred habitat. Although this tagging method suffers from approximate positioning, it could be fruitfully used in complement of traditional visual methods.

Figure 9: Bluefin tuna school observed by airplane (left) and underwater (right).

It is also likely that a strong correlation will be found between the preferred habitat mapping and the VMS data archive of vessels which were acknowledged fishing BFT. However, since the habitat mapping aims to better control the fishing activity independently of VMS data, in case e.g. the VMS is not active, the VMS data set cannot be part of the validation strategy.

Implementation strategy and perspectives

A first set of preferred habitat mapping will be created based on historical data, processing daily data for July 2002 – now (MODIS-Aqua sensor), in order to provide a reliable habitat mapping on a fortnight basis to support the programming of control campaigns.

[2] A single fish is equipped with an electronic tag that automatically pops-up after few months using satellite communication for collecting the data, or stays permanently on the fish until it is caught again by fishermen.

A second step will be to process NRT satellite environmental data to provide three-day and seven-day habitat maps which could help control means to explain vessel movements, improve catch estimates from VMS data and contribute to guide the control by VDS.

Further satellite data (SeaWiFS and AVHRR-Pathfinder) will be collected to gather five more years of chlorophyll content and SST (Sep. 1997 – now) for studying further the inter-annual variability of BFT habitat and increase the spatial coverage for the recent years.

The approach once validated on BFT could be transposed to other pelagic species of economic importance (e.g. cod, hake, mackerel) to identified the spatial and temporal distribution of their habitat for improving catch estimates (including in near real time for control purposes) and stock assessment.

The use of the habitat mapping to identify favourable or unfavourable fishing ground, targeting either feeding or spawning depending on stock level, would efficiently preserve pelagic stocks by optimizing recruitment, ensure a better distribution of the benefits of the industry by fishing on the same grounds and reducing days at sea, while it would enforce the control by concentrating the fleet.
Furthermore, the habitat-guided management would contribute to better comply with UNCLOS regulations on ecosystem and habitat protection[3] evolving towards an ecosystem-based management. It would also contribute to fulfil the UN Millennium Development Goal on fisheries by improving management to reduce depletion of fish stocks.

[3] Article 94 (5) of the United Nations Convention on the Law of the Sea obliges States to take measures necessary to protect and preserve rare or fragile ecosystems as well as the habitat of depleted, threatened or endangered species and other forms of marine life.

West Atlantic and Gulf of Mexico – *Mediterranean Sea* – *Eastern Pacific Ocean*										
Life Stage			**Species Distributions**		**Habitat Characteristics**		**Trophic Relationships**			**Rates and Associations**
Stage	**Size**	**Age**	**Location**	**Season**	**Temp (C)**	**Other**	**Food**	**Predators**	**Preference**	**Growth**
Eggs	1.0 mm	24 hrs	No eggs identified from the western Atlantic	Unknown	Unknown		N/A	Coryphaena	N/A	Unknown
Larvae	2.5-15 mm	15 days	Gulf of Mexico, Florida Straits. A few off of the Carolinas *Highest concentrations around southern Italy*	In GoMex mid-April - May; In Carolinas mid-June	22 °C - 28.1 °C		Piscivorous	Coryphaena, gelatinous zooplankters	In GoMex and in stable stratified areas of Gulf Stream	87% of larvae in G of M at 24 °C - 26.1 °C higher or lower is outside of optimal growth.
Early Juveniles	15-100 mm	weeks	<25 mm Gulf of Mexico, 25-115 mm June to July off Dry Tortugas	Unknown	Unknown		Euphausids, decapods, amphipods, larval and small fishes (e.g. clupeids, cephalopods, stomatopods, heteropods, tunicates)	Coryphaena	Unknown	Unknown
Later Juveniles	100-250 mm	weeks - months	In coastal waters from Cape Hatteras North to 41°N. Aug-Oct in N GoMex+near Cape Cod	Mid July on.	Unknown		Fishes, cephalopods, crustaceans.	Fishes predominantly other tunas. Terns.	Unknown	Unknown
Adults	196 cm; 145 kg	8 yrs *4.5 yrs*	From Cape Hatteras to Newfoundland. S into Gulf of Mexico and Caribbean. Spring migration early May to Mid-June off Cat Cay and Bimini to Cape Cod and Nova Scotia in Summer and Fall - feeding grounds. As far N as 53-55°N in W Atl.	July-Oct. Spread over a larger area in Winter	Spend 90% of time >12 °C, <12 °C for short periods e.g. feeding dives. Mean 15.5 °C Range 14 - 21 °C in GoMa + fronts (dist.20-40km), 24-25 and 26-27°C in the GoMex *Med (Sep)20-22°C+ fronts (dist.=10-15 km) Fishermen target fronts* *EPO: 17-23°C*	GoMex (~May) *Med (Sep)* **Chl mg/m3:** 0.10-0.16 *0.2-0.3+ fronts (dist.=10-12km)* **Wind m/s:** 6-7, 9-9.5 **TKE cm2/s2:** 251-355 **Outside edge of warm eddies** (counter-clockwise)	Feed mainly at dusk and dawn. Anchovies, mackerel, herring, sand lance, sardine, sprat, bluefish, but also squid, sauries, hakes, crabs, octopus, menhaden, dogfish, salps, jellyfish, porcupine fish, occasional plant material.	Orcinus, pilot whales, blackfish, Xiphias, sharks	Unknown	Unknown
Citations:		Fromentin and Fonteneau 2001			Teo et al. 2007, Schick et al. 2004, *Royer et al. 2004*, *Bayliff 1994*	Teo et al. 2007, *Royer et al. 2004*				
Spawning Adults	196 cm; 145 kg	8 yrs *4.5 yrs (>27.5 kg)*	Primarily GoMex, FL Straits from Cuba to Little Bahama Bank esp. Bimini and Cat Cay April-May to mid-June *Med and Adriatic from late May to early August*	April-May	22-27 °C, 25-29°C, *19-21.6°C (Roule 1924), Fishermen target high SST*	Never observed in western Atlantic	Probably not feeding or eating very little.	Unknown	Unknown	Unknown

Annex 1: Regional comparison of environmental preferences

Annex 2: Description of the feeding habitat processing

A Canny filter is applied to chlorophyll-a and SST daily data to detect fronts. This filter first smooth the image with a Gaussian filter (with a width of 6 cells), then the norm of the horizontal gradient is computed (figure A2.1 b). The third step consists in applying a threshold to remove secondary features (figure A2.1 c) and the last step interpolates to find the pixels where the norms of gradient are local maximum.

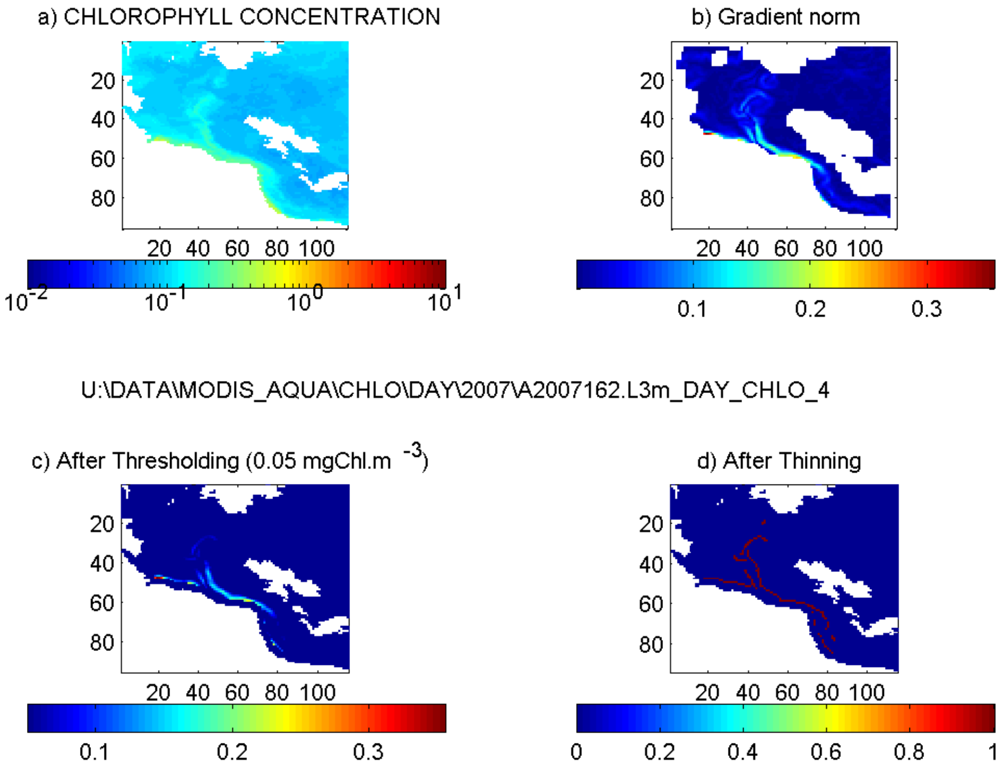

Figure A2.1: Sea surface chlorophyll-a (a, mg m^{-3}), norm of horizontal chlorophyll-a gradient using the Canny filter before (b, mg m^{-3} $pixel^{-1}$) and after thresholding (c, mg m^{-3} $pixel^{-1}$), and chlorophyll-a front detection after thinning (d, no unit) for waters off Libya on June 11th 2007.

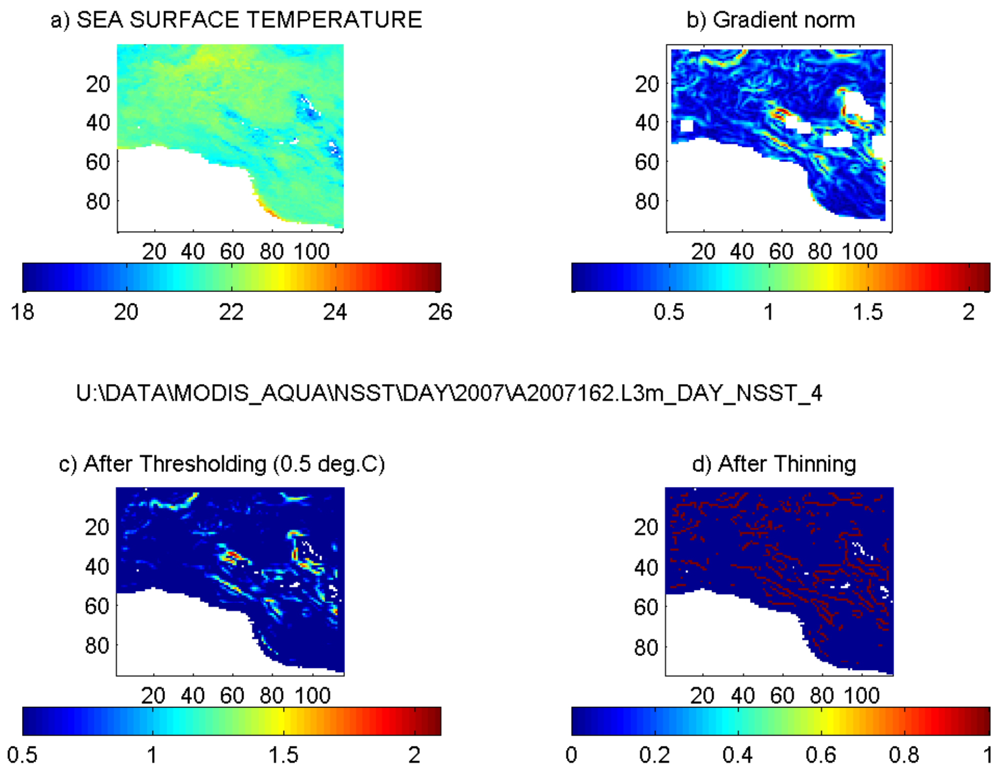

Figure A2.2: Sea surface temperature (a, deg.C), norm of horizontal SST gradient using the Canny filter before (b, deg.C $pixel^{-1}$) and after thresholding (c, deg.C $pixel^{-1}$), and SST front detection after thinning (d, no unit) for waters off Libya on June 11th 2007.

The same processing is applied to both observation of chlorophyll-a and SST (figures A2.1 and A2.2). The threshold values are chosen to emphasize the most stable fronts which could allow the development of a phytoplankton-zooplankton-forage fish food web (**the current threshold values used for the feeding habitat estimate are 0.75°C $pixel^{-1}$ and 0.05 mg m^{-3} $pixel^{-1}$**).
In order to check the stability of fronts and to test if the front's displacement corresponds to known current velocities in the area, the displacement of a chlorophyll-a front during 24 hours is shown in figure A2.3. Most fronts on *day1* (June10th) are visible on *day2* (June11th) and the front's displacement (in the range 0-2 pixels which leads to a velocity of 0-9.2 $km.d^{-1}$, i.e. 0-10.6 $cm.s^{-1}$) agrees with common velocities measured in the Mediterranean Sea.

The SST and chlorophyll-a fronts are then enlarged according to the respective distance from fronts for which BFT was acknowledge to evolve and which is described by the feeding habitat criterion (figure A2.4). The overlap between both SST and chlorophyll-a enlarged frontal areas is detected (dark red in figure A2.4) and restricts, together with the chlorophyll-a range of 0.1-0.5 mg m^{-3}, the preferred habitat of feeding BFT.

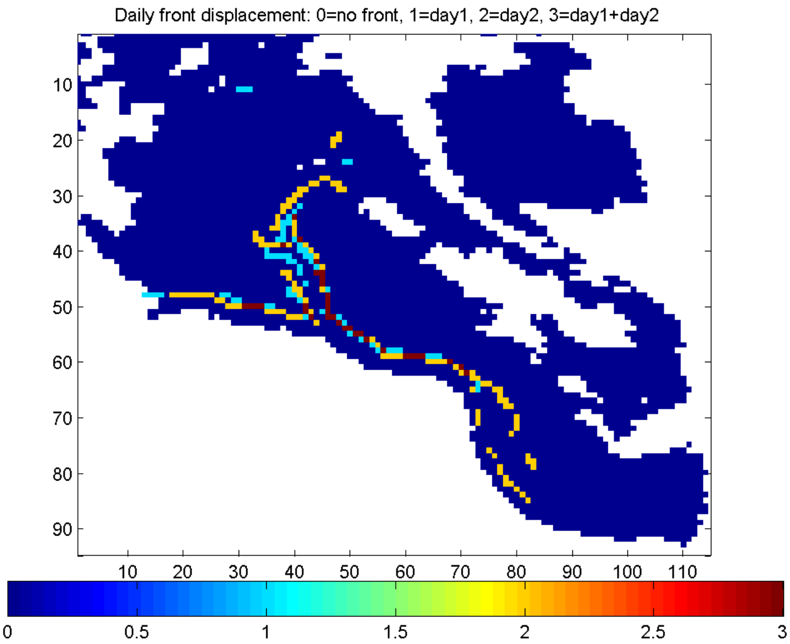

Figure A2.3: Chlorophyll-a front displacement for waters off Libya between June 10th (*day1*) and June 11th (*day2*) 2007 using the same threshold than in figure A2.1.

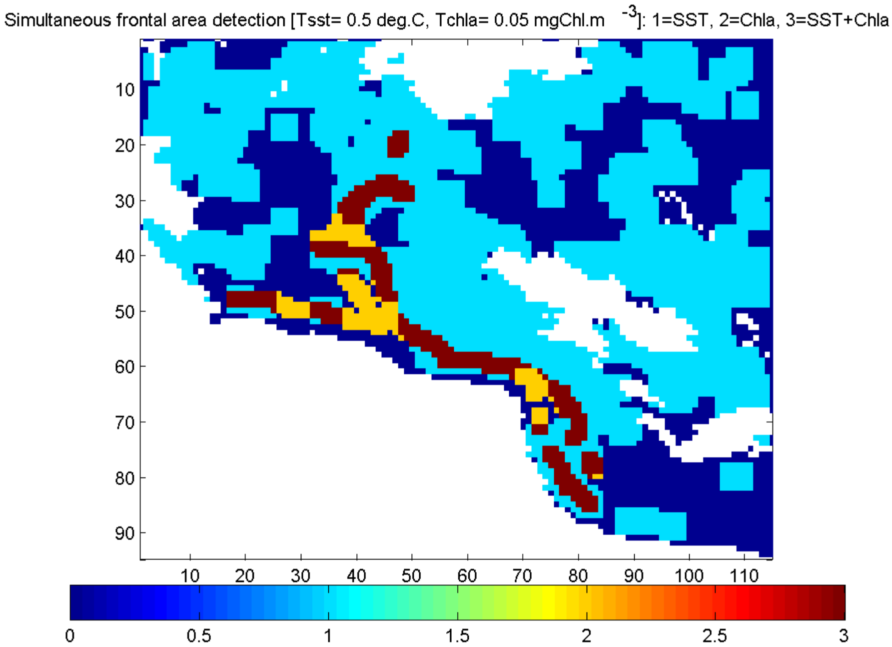

Figure A2.4: Simultaneous front detection after enlargement according to the feeding habitat criterion (~15 km for SST and ~10 km for chlorophyll-a) for waters off Libya on June 11th 2007.

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Abstract
This report details the preliminary study performed for the development of the feeding and breeding habitat of bluefin tuna (BFT) in the Mediterranean Sea derived from satellite remote sensing data. The related bibliography on BFT is synthesized in order to elaborate criterion for each habitat and a first guess for the parameterization. Potential use of the habitat mapping for the BFT fisheries management and control are also described.

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