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Towards Operational Management Of Pelagic Ecosystems

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Abstract

Satellite data and operational ocean models provide the necessary inputs for ecosystem models of the lower to mid- and upper trophic levels. One key explanatory variable that is usually missing to understand the dynamics of key exploited or protected marine species is the dynamic of the micronekton that is at the Mid-Trophic Level (MTL) in the ecosystem, and thus being both prey of large predators and predator of eggs and larvae of fishes. We present the development of an operational model of mid-trophic functional groups driven by physical and biogeochemical variables. Once a reasonable prediction of MTL organisms is achieved, the number of applications for near real-time management and monitoring of marine ecosystems and resources should increase rapidly, as illustrated by the examples provided here, and including the prediction and forecast of feeding and spawning habitat of many exploited or protected species, their movements and spatial distributions, and finally their population dynamics under the combined effects of natural (climate variability) and anthropogenic forcings (fishing, climate warming).

Key-words: climate, ecosystem, fisheries, habitat, management, micronekton, operational model, ocean forecast, population dynamics.

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Introduction

The management of marine pelagic ecosystems is facing serious issues, including overfishing, the protection of biodiversity and the threats on several endangered species, that are gaining more and more space in the medias and the public awareness. Accordingly, the demand increases for new innovative tools and products for a more efficient management. Several tendencies are emerging that should determine the development of these tools in the coming decade: the need to strictly control the fishing and maritime activities, the development of spatial and temporal management measures, the responsiveness to accidental pollution, the expansion of observing networks, the assimilation of these observations in models, and the possibility to conduct quickly “on demand” new stock assessment studies with updated fishing mortality (and eventually accidental mortality), as well as forecast with various scenarios of management. In short, today’s management, typically established on an annual basis should evolve towards operational management, i.e., interacting with real time monitoring, offering much more precise, diverse and rapid options for conservation and management measures.

Several of the necessary components are already available to develop the operational management of marine ecosystems. There are several operational systems providing real time and forecast of the ocean physical state at global or regional levels with sufficient spatial resolution (e.g., 1/4 to 1/32th deg) and achieving realistic prediction of mesoscale activity thanks to the assimilation of data both from satellites (altimetry and SST in particular) and *in situ* networks (e.g., Argo floats). Similarly, appropriate assimilation of ocean color satellite data in biogeochemical models should help to obtain sufficiently realistic outputs of the primary production at the basis of the marine foodweb. As an immediate alternative, primary production can also be deduced from satellite-derived data, for example using the VGPM model of Behrenfeld and Falkowsky (1997) or similar approaches based on optical properties (Morel 1988, Morel and Berthon 1989).

This oceanic environment offers a global continuous time series since the first reception of images of the satellite SeaWiFS in September 1997. Associated to coastal networks of observation, it should be sufficient for developing many new applications for monitoring small exploited pelagic species, closely linked to the primary level of the trophic food web. To connect higher biological levels to this oceanic environment however, one key explanatory variable is missing since the dynamics of large predators is strongly linked to those of their prey organisms that are at the mid-trophic level (MTL), i.e., macrozooplankton and micronekton, inhabiting all the vertical layers of the ocean between surface and bathypelagic depths. By definition, micronekton are small organisms that can swim, but due to their small sizes they are however strongly impacted by oceanic circulation from large to mesoscale. Predicting their dynamics and distribution would open the way to a new approach to monitor the fisheries of oceanic large predators that are either targeted by fisheries (e.g., tuna, swordfish), strictly controlled in the by-catch (bluefin, sharks), or fully protected (turtles, seabirds, marine mammals). A modelling approach based on a definition of functional groups of these species has been proposed recently (Lehodey et al., 2010a). This approach allowed to link the spatial population dynamics of tuna species to the ocean physics and this simplified representation of the ocean food web. However the focus was on the large-scale dynamics of tuna species over the historical fishing period (the last 50 years) under the influence of both the fishing activity and the environmental variability (Lehodey et al. 2008; Senina et al. 2008) or the climate change (Lehodey et al., 2010b), and the simulations used low resolution basin-scale reanalyses produced from coupled physical-biogeochemical models.

We have conducted simulations with the MTL model using inputs from an ocean circulation operational model and the satellite-derived primary production. We present preliminary results on potential operational applications.

The Mid-Trophic Level model

Despite their central position in the marine ecosystem, pelagic mid-trophic species are virtually unknown because they are not exploited, i.e. no catch data are available, and cannot be observed through a continuous synoptic approach, i.e., with satellites, and no fisheries independent survey exists. Developing modeling approaches that capture the essential features of these organisms is thus a critical and challenging step for a better understanding of the ocean ecosystem. An approach has been proposed (Lehodey et al 2010a), that is a component of the Spatial Ecosystem And POPulation DYNamics Model (SEAPODYM) modeling the spatial age-structured population dynamics model of large oceanic predator (Lehodey et al. 2008).

The SEAPODYM-MTL model (Lehodey et al., 2010a) has six functional groups following a temperature-linked time development relationship (Fig. 1). The functional groups are based on the vertical behaviour of organisms. There are three vertical layers and pelagic micronekton is therefore divided into epipelagic, mesopelagic and bathypelagic groups, the last two groups being subdivided into vertically migrant and non-migrant species. Since light intensity is likely a major factor that controls diel vertical migrations of meso- and bathypelagic organisms, the euphotic depth appears as a logical and convenient way to define the vertical boundaries of the three layers. Thus epipelagic layer corresponds to euphotic depth, and the boundary between the two other layers is defined by three times the euphotic depth.

Recruitment, ageing, mortality and passive transport with horizontal currents are modeled by a system of Advection-Diffusion-Reaction (ADR) equations, taking into account the vertical behavior of organisms. Since the dynamics is represented by a relationship of temperature-linked time development, there are only six parameters in the model that have to be estimated. The first one (E) defines the total energy transfer between primary production and all the MTL groups. The others are the relative coefficients (E'_n) redistributing this energy through the different components (the sum of which being 1). A first parameterization has been achieved according to (limited) information from the literature.

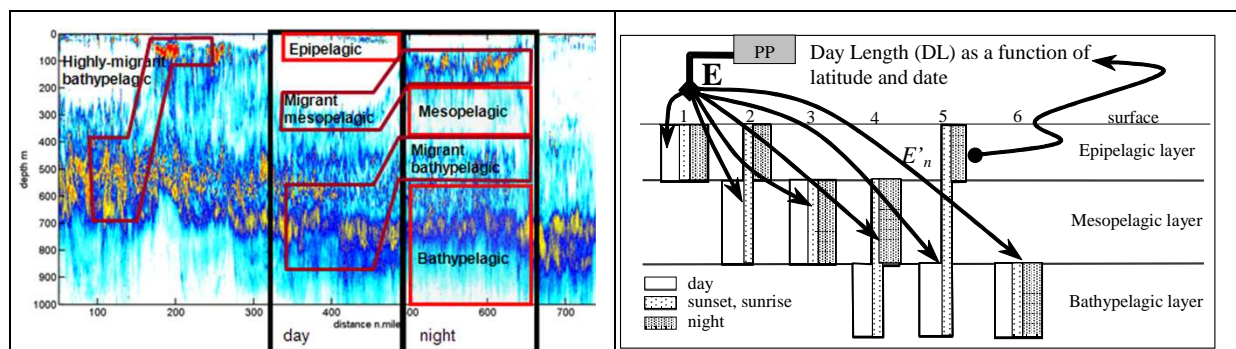


Figure 1: Identification of MTL functional groups on acoustic echogram (kindly from R. Kloser, CSIRO) and conceptual model (redrawn from Lehodey et al. 2010a).

Input forcing

Physical fields

With the project GLORYS (GLObal Ocean ReanalYsis and Simulations) that is supported by the French Groupe Mission Mercator Coriolis, a first eddy permitting global ocean reanalysis

(GLORYS1V1) has been produced with the ocean general circulation model configuration ORCA025 NEMO (Barnier et al., 2006). The assimilation method is based on a reduced order Kalman filter (SEEK formulation, Pham et al. 1998) adapted to eddy permitting global ocean model configuration (Tranchant et al., 2008). We used this reanalysis at a resolution of $\frac{1}{4}$ deg x 6 days with satellite derived primary production at the same resolution (Fig. 2) to run a simulation with the SEAPODYM-MTL model, for the period 2002-2009.

GLORYS1V1 overall performance is of high-quality. The data assimilation system is stable and produced for all the observations satisfying “hindcast” skills consistent with the observation error specified. It allowed a correction of the global surface heat flux, realistic location and intensity of surface currents, with eddy field variability in good agreement with altimetric data. Surface eddy kinetic energy compares very well with observations. However, there is an underestimation of the intensity of the currents in the Antarctic Counter Current (ACC) and the tropics. Climate signals are close to available observation of temperature and salinity fields in the first 300 meters. Analysis of tropical SST and SLA shows very realistic equatorial wave propagations at all wavelength (intensity, phase and phase velocity). Subsurface thermohaline structure also exhibits a mean state and annual to interannual variability in good agreement with observations. The meridional heat transport is realistic in intensity at all latitude. Finally, ENSO variability is well captured by the model both in surface and subsurface.

Primary production

Depth-integrated primary production estimates are obtained from satellite ocean color-based VGPM model provided by the ocean productivity team (www.science.oregonstate.edu/ocean.productivity/). These data have been interpolated on the grid of the model. Thanks to the data assimilation in the MERCATOR model, a very good match is observed between physics and primary production at the mesoscale level (Fig. 2).

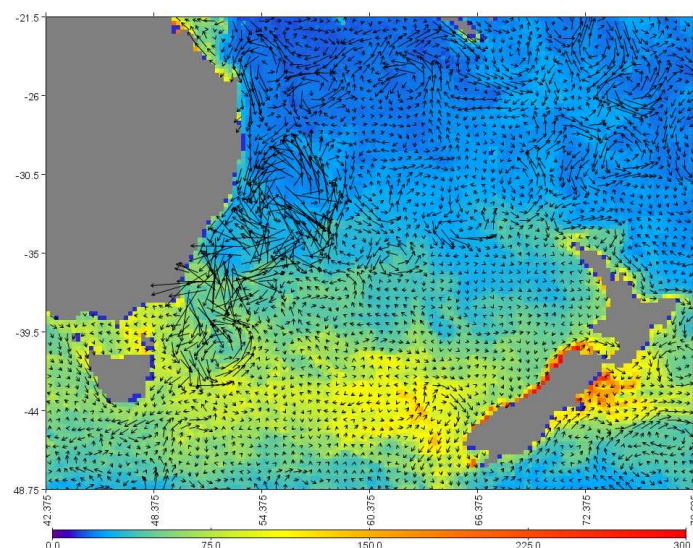


Figure 2. Snapshots showing the SeaWiFS-derived primary production computed following the model of Behrenfeld and Falkowsky (1997) (www.science.oregonstate.edu/ocean.productivity/) with superimposed surface currents (average in the euphotic layer) predicted in MERCATOR GLORYS reanalysis (glorysproducts@mercator-ocean.fr).

MTL prediction and calibration

The domain of the model is global between latitude 66.5°N and 60°S. Production and biomass for the 6 components are recorded. To obtain the biomass during the day and night in each layer, it is needed to sum the components according to their day and night position. For example, the surface layer is inhabited only by the epipelagic group during the day but the sum of epipelagic, migrant mesopelagic and highly migrant bathypelagic groups during the night (Fig. 3).

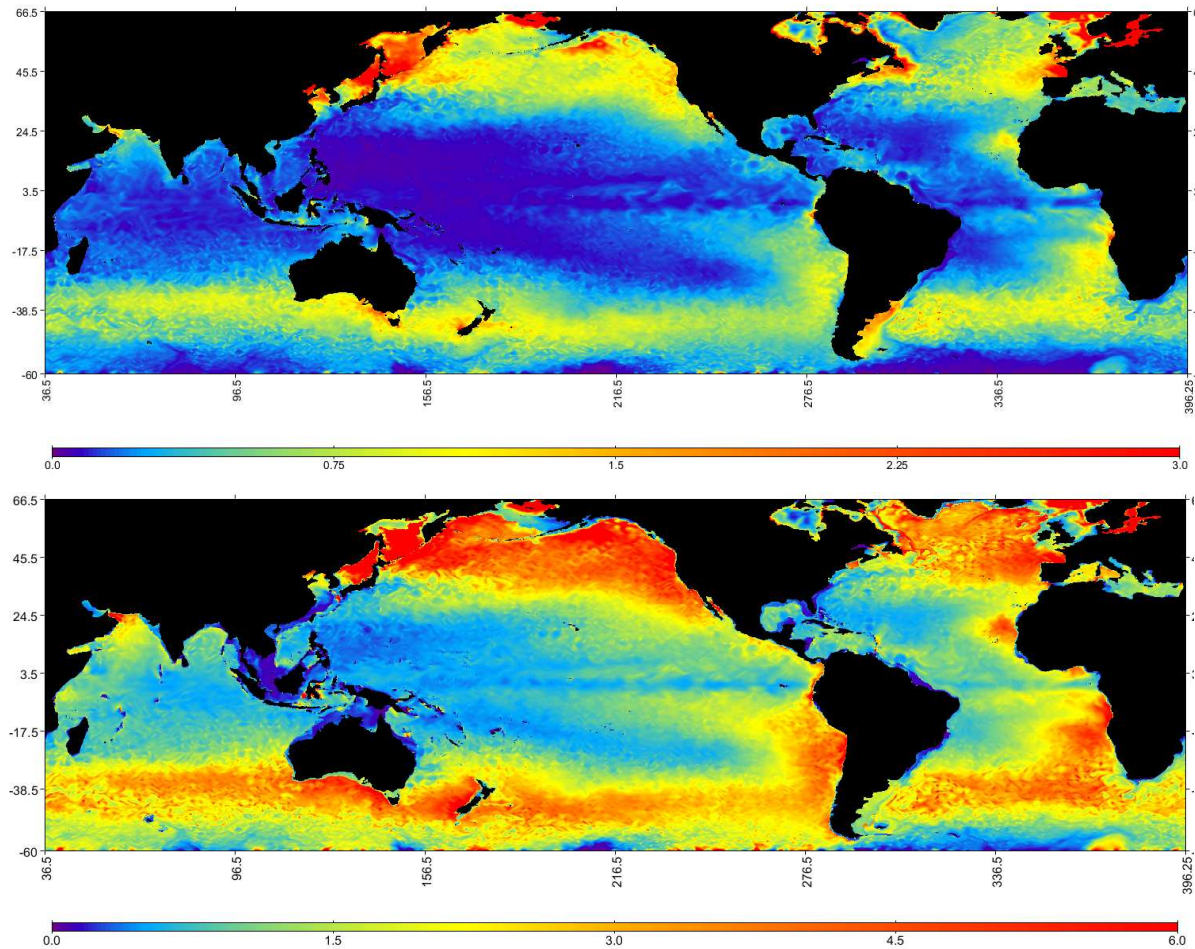


Figure 3. Biomass of MTL groups in the epipelagic layer (i.e., euphotic depth) during day (top) and night (bottom) predicted with GLORYS1V1 physical fields and VGPM satellite derived primary production for the 6-day period centred on 1st Dec 2009.

We are starting to evaluate the model outputs against various acoustical data. The simple modelling approach used to describe the MTL components with a limited number of parameters is helpful to implement a method of parameter estimation using data assimilation. The parameterization of E , i.e., the total energy transfer, requires absolute biomass estimates of MTL. They will be estimated using calibrated biomass estimates combining acoustic and micronekton net sampling used to carefully convert backscatter values in micronekton biomass. However, the matrix of E'_n coefficients can be estimated simply using relative day and night values of acoustic backscatter integrated in each of the three vertical layers of the

model (Fig. 4). The use of relative integrated backscatter values should facilitate the combination of different un-standardized acoustic profiles. In our preliminary experiments for the Pacific Ocean we are using acoustic profiles collected by CSIRO, Australia, between Tasmania and New Zealand (Kloser et al., 2009) and by the Pacific Islands Fisheries Science Center, NOAA-NMFS, USA in the Central Pacific around American Samoa, Hawaii and Guam (R. Domokos). There are many other sources of existing acoustical data that could be used in the global ocean, and an international initiative (Handegard et al. 2010) proposes to develop a network of mid-trophic automatic acoustic sampling (MAAS), which could be for ecosystem models the equivalent of the so successful ARGO program for ocean circulation models.

One example of integration of acoustical signal along a transect collected between Tasmania and New Zealand is shown on figure 5. For each of the three layers, the acoustic signal is vertically integrated according to the depth boundaries definition and averaged over the spatial resolution of the model ($1/4^\circ$). According to the local time of the day, these values can be compared to the relative distribution of predicted biomass in the same layers, accounting for the different combination of MTL components due to vertical migration. Sunset and sunrise time periods are excluded. The optimization approach we are developing will search for the optimal parameterization that provides the best fit with all similar available data.

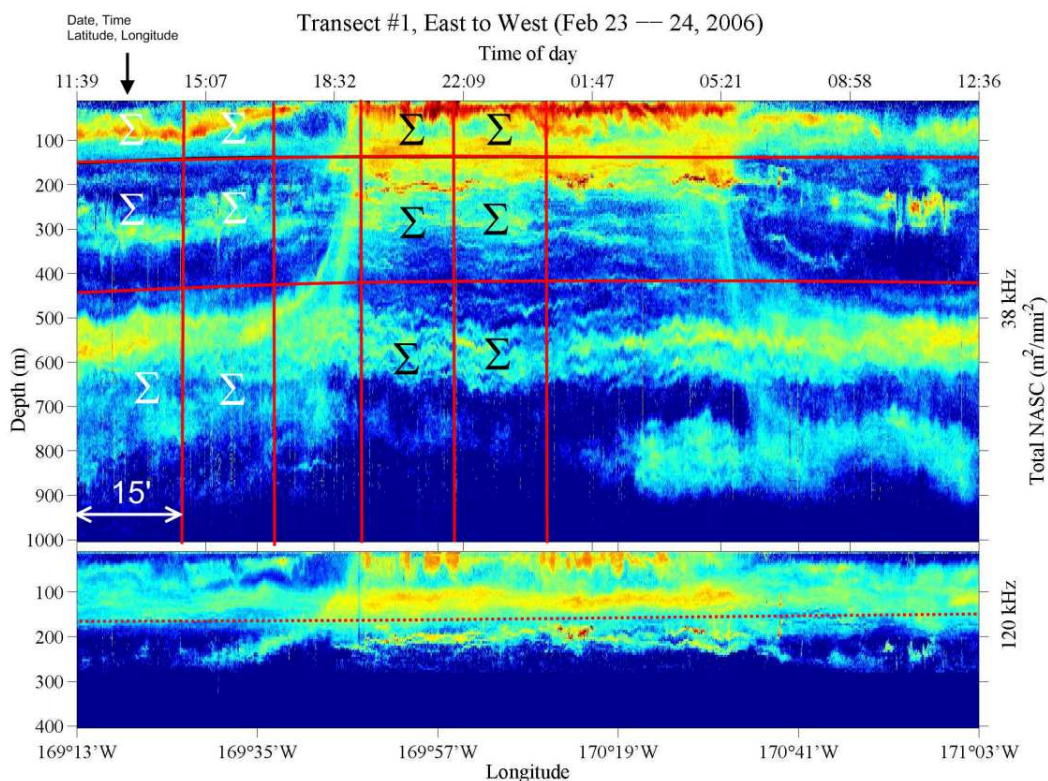


Figure 4. Integration of the acoustic signal to be used for assimilation (Acoustic profile provided by R. Domokos). After the vertical layers have been defined the signal strength is vertically integrated and then averaged at the spatial resolution of the grid of the model ($1/4$ deg) after excluding the sunset and sunrise time periods.

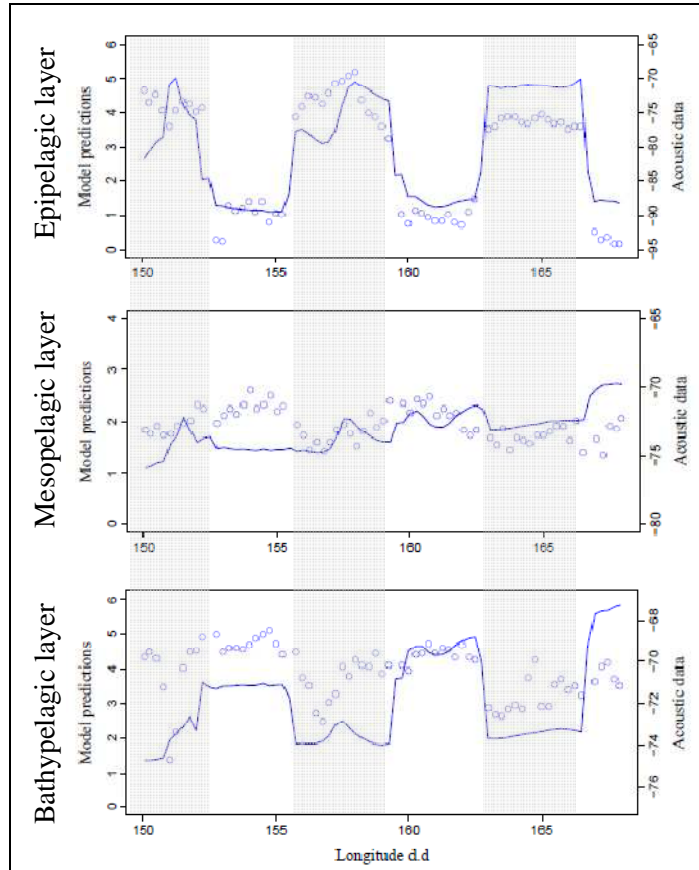


Figure 5. Predicted biomass (g/m^2) of micronekton (line) and observed acoustic signal (circles) in the three vertical layers for a transect starting on 14 June 2005 between Tasmania and New Zealand (data provided by R. Kloser). Night-time is represented by shaded areas.

Applications

The interest of modelling micronekton is obvious for investigating the feeding habitat of large predator species. Once the feeding habitat can be predicted, it becomes possible to explore and simulate the mechanisms controlling the movement and feeding behavior of predators. In addition, the predicted micronekton provides a new interesting input to explore the mechanisms that control the larvae mortality and to model spawning habitats and larvae concentration indices.

Feeding habitats and movements

Predicting in real time the feeding habitat and thus the probability of presence of some marine species that are either over-exploited (e.g., bluefin tuna) or protected species (e.g., sea turtles, albatrosses, marine mammals) would represent a key step for operational management. Based on the MTL components we defined a feeding habitat based on the accessibility Θ_z of predator species to different layers z and hence to the micronekton (mid-trophic) functional groups F inhabiting these layers (Lehodey et al., 2008):

$$H = \sum_{z=1}^{nz} \Theta_z \left(\tau \sum_{k=1}^{nz} F_{zk} + (1-\tau) \sum_{k=1}^{nz} F_{kz} \right),$$

where the first index denotes MTL daily layer and the second refers to the layer where this micronekton group migrates at night (see Fig. 1). The τ denotes the ratio between day and night length. The accessibility to the layer depends of tuna temperature preferences and oxygen demands, which are formulated as Gaussian and sigmoid functions correspondingly. Hence, the parameterization of the habitat relies on four parameters only: optimal temperature, oxygen critical value and two slope parameters defining thermal and oxygen tolerance. This habitat definition is used in the model SEAPODYM to constrain the movement of fish cohorts (see Lehodey et al 2008, 2010b; Senina et al. 2008).

A project funded by the Large Pelagic Research Center (LPRC, USA) allowed to develop an approach to estimate the best habitat and movement parameter values of bluefin tuna in the north west Atlantic by directly assimilating movement data from electronic tags in the model of habitat as defined in SEAPODYM (Senina et al, *in prep.*). The seasonal variability and mesoscale activity of predicted bluefin feeding habitat matched fairly well the movements of individual bluefin deduced from satellite tags (Fig. 6).

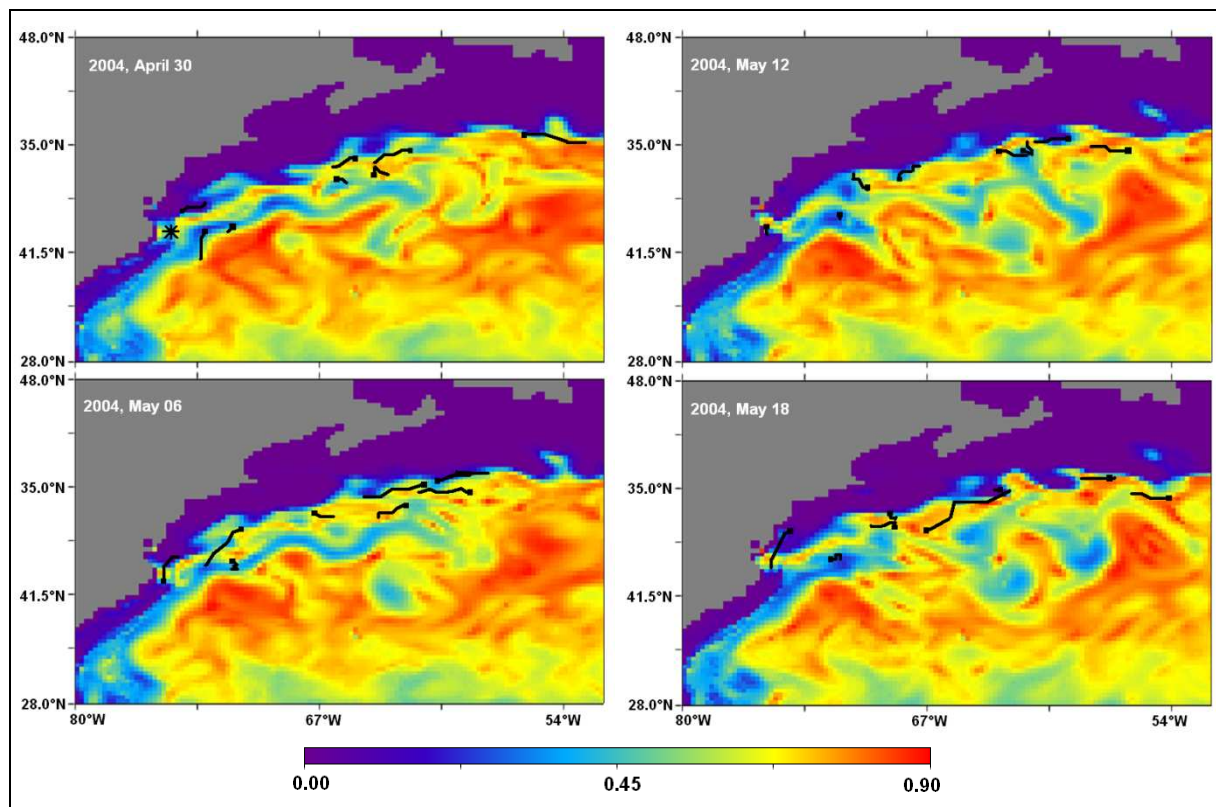


Figure 6. Continuous 6-day time step series of predicted bluefin tuna feeding habitat with superimposed movements of individuals (black thick lines) observed from bluefin tracking using satellite pop-up tags (Lutcavage et al 2000). The star indicates where the fish were tagged and released in July 2003.

The habitat definition can be modified easily to account for specificity of animals. For example, dissolved oxygen has no impact on air-breathing animals (turtles, sea birds, marine mammals) but these species have different aptitudes to dive and to reach the deepest layers. Turtles are endangered species requiring the highest measures of protection to reduce longline fisheries by-catch of sea turtles. An obvious strategy to reduce sea turtle by-catch is to avoid by-catch hotspots through fleet communication programmes and area and seasonal closures. This requires modeling the turtle habitats and then to predict and forecast these habitats and to

communicate with fishermen in real time to help them to avoid turtle by-catch. Such an approach is developed in the North Pacific, by the Pacific Islands Fisheries Science Center (NOAA, Hawaii, USA), focusing on the pelagic habitat and movements of loggerhead turtles.

As in the bluefin tuna case above, individual tracks of turtles suggest that these animals are strongly influenced by the dynamics of mesoscale eddies (Gaspar et al., 2006), and that they are not simply drifting with currents. This is clearly confirmed by habitat simulation experiments using the GLORYS and MTL outputs (Fig. 7). Here the habitat is defined using temperature and MTL biomass available in the surface layer only (Abecassis et al., *in prep.*) since the loggerhead turtle is known to rarely dive below the first 30-50 m. A large dataset of electronic tagging data for this species (Polovina et al., 2004; Kobayashi et al., 2008) is used to parameterize the habitat model.

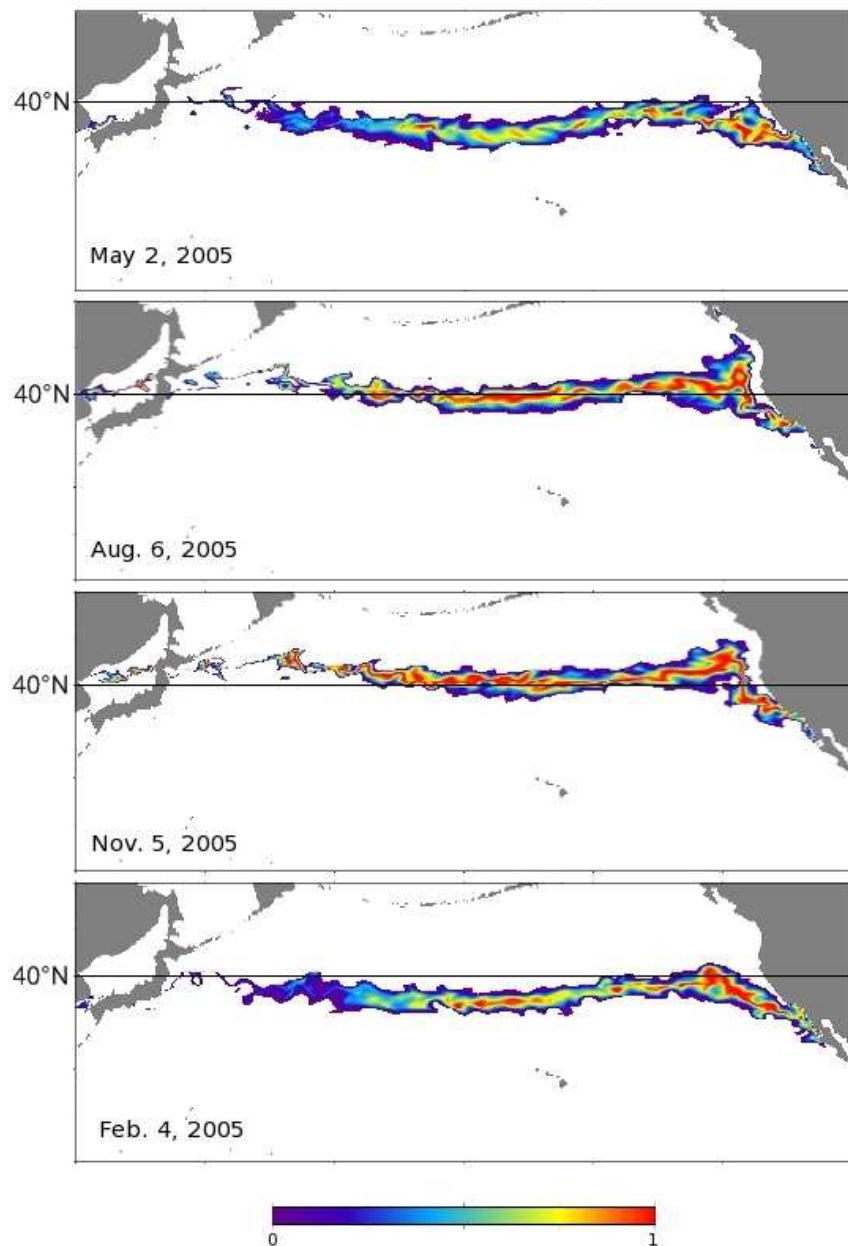


Figure 7. Preliminary loggerhead turtle feeding habitat in the North Pacific Ocean inferred from satellite tagging data (From Abécassis et al., *in prep.*) showing a seasonal latitudinal displacement between 35°N and 45°N over the year.

Spawning habitat and larvae dynamics

The search for mechanisms that explain the variability in larvae survival rate and then the strength of the oldest cohorts recruited in the adult population is one of the major quests in fisheries science. We have combined four of these mechanisms in the modeling of spawning habitat and larvae dynamics taking advantage of the MTL modeling that provides a new key variable to include the impact of predation, since macrozooplankton and micronekton organisms are the main predators of eggs and larvae of all pelagic fishes. These mechanisms are:

- the definition of a spawning temperature window for an optimal growth;
- the coincidence of spawning with presence or absence of food for larvae, i.e. the match/mismatch mechanism proposed by Cushing (1975);
- the coincidence of spawning with presence or absence of predators of larvae;
- the redistribution of larvae by the oceanic circulation with natural mortality related to new habitat

The first mechanism is described using a Gaussian distribution $\Phi_o(T_o) = N(T_o^*, \sigma_o)$ with standard deviation σ_o and optimal mean temperature T_o^* . The second and third mechanisms are combined in a larvae prey-predator tradeoff using the ratio between primary production (a proxy for the abundance of food for larvae) and the biomass of micronekton in the surface layer during the day and at sunset and sunrise, when predation pressure is the highest. A third parameter, α , is used to control the amplitude of the prey-predator trade-off effect, so that if $\alpha = 0$, only temperature has an effect on the spawning, while the trade-off effect between presence of food and predators increases relatively to the temperature effect with increasing α (see Lehodey et al., 2008 for more details). The fourth mechanism, i.e., redistribution by currents leading to higher or lower mortality according to the retention in favorable habitat or the drift in unfavorable habitat is included in the treatment of the spatial dynamics using a system of Advection-Diffusion-Reaction equations (for details see Lehodey et al. 2008 and Senina et al. 2008).

In basin-scale low resolution simulations of tuna dynamics, this approach was sufficiently flexible to have successful prediction of spawning grounds and larvae dynamics (e.g., Lehodey et al. 2008). We are now testing the modeling of the spawning habitat of Atlantic-Mediterranean Bluefin tuna with the high resolution model outputs. Results from a sensitivity study (Dessert, 2010) with different values of optimal temperature and α were compared with observations from the literature (Fig. 8), i.e., the regions and the dates where bluefin larvae have been collected and spawning aggregation observed (Mather et al. 1995; Garcia et al. 2002, 2005; Karakulak et al. 2004; Oray et al. 2005). The timing and the peaks of spawning seasons are particularly useful to calibrate the parameter values since there is a clear propagation of the favorable spawning index starting in the eastern Mediterranean Sea in May and moving west with a peak in the Balearic region in June-July (Fig. 8). The interannual variability also is helpful. For example, in 2003 a heat wave over Europe produced positive temperature anomaly in the Mediterranean Sea. Using 24°C and 1°C for respectively optimal temperature and standard deviation, the spawning season during this particular year is predicted ending too earlier compared to observation in the Balearic region (Alemany et al. 2010). Thus parameterization will have to be revised to agree with these observations. Further developments especially including larvae data and aerial survey of adult spawning aggregations will help to achieve optimal parameterization and thus to provide a useful indicator for management when produced in real-time.

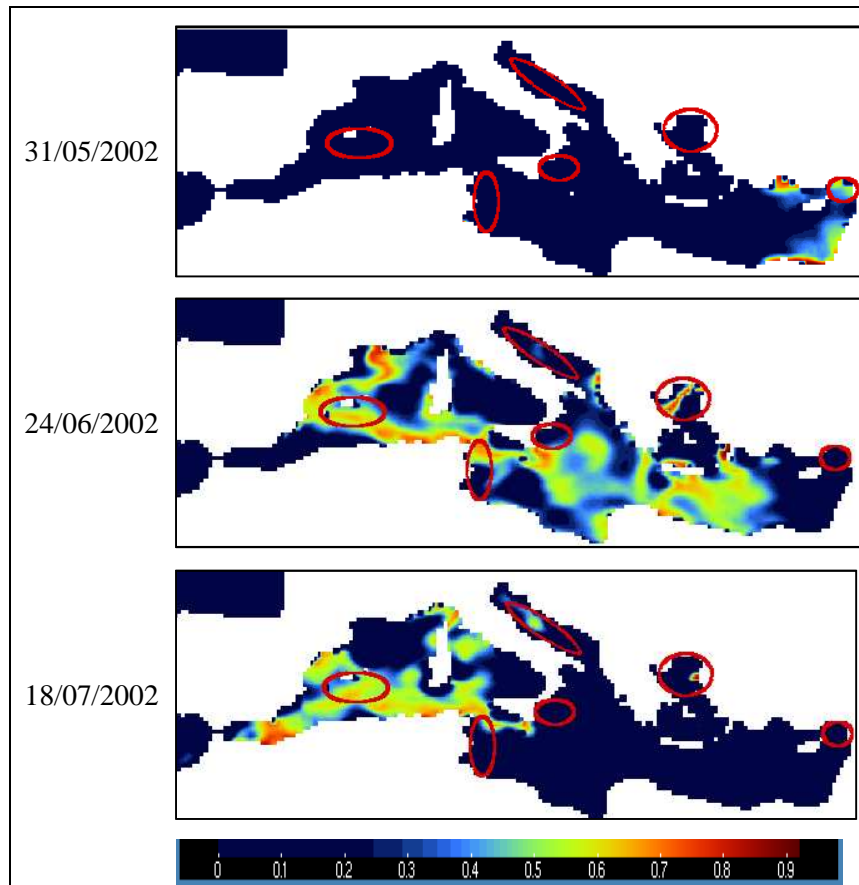


Figure 8. Preliminary simulation of spawning habitat of bluefin tuna in the Mediterranean Sea with optimal spawning temperature of 24°C (std. dev. = 1°C) and $\alpha = 0.3$. Red circles highlight the regions where bluefin larvae have been observed. Note the east-west propagation with time.

Conclusion

Australia has already implemented a system of regulation for its longline fisheries using bluefin tuna habitat maps predicted every two weeks (Hobday and Hartmann 2006). These habitat maps, simply based on a temperature preference relationship of the species, inform the fishermen that are not allowed to catch bluefin tuna in the areas they should avoid. With a comparable approach, the Pacific Islands Fisheries Science Center (NOAA, USA) in Hawaii defined a thermal habitat of loggerhead turtles to routinely update experimental maps of this habitat (Howell et al., 2008). These maps are posted on a web site (TurtleWatch: <http://www.nmfs.hawaii.edu/eod/turtlewatch.php>) to help longline fishermen to avoid interactions with loggerhead turtles. There is no doubt that more similar applications will be developed in the coming years. Hopefully, the development and improvement of micronekton models and observations (Handegard et al., 2010) should bring important new explanative variables to assist in the modeling of these habitats.

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