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Preface

CLimate Impacts on Oceanic TOp Predators (CLIOTOP): Introduction to the Special Issue of the CLIOTOP International Symposium, La Paz, Mexico, 3–7 December 2007

1. Introduction

In November 2001, an international workshop on research issues related to interactions between climate variations and fisheries was co-organized by the IRI and the IPRC in Honolulu, Hawaii (Bakun and Broad, 2001). From the animated discussions that took place during the meeting, a general consensus emerged based on the notion that "although the effects of environmental variability on fish stocks and fisheries can no longer be ignored, we remain stuck in a paradigm that has existed for half a century and that is not solving the problem in any general way". It was recognised that more effort was needed toward a general synthesis that can generate testable hypotheses in search for the mechanisms and processes that underlie observed correlations. The multi-national Oceanic Fisheries and Climate Change Project (OFCCP) developed in GLOBEC for the Pacific region (Lehodey, 2002) was presented. The idea of developing a similar framework for a worldwide comparative research project was proposed and received a strong support. Given its international context, the concept of such a global "umbrella" project (code-named "CLIOTOP" for CLimate Impacts on Oceanic TOp Predators) was later submitted for consideration by GLOBEC. One year later, after intense email consultations and discussions, the CLIOTOP project was presented to the GLOBEC SSC at its meeting in Qingdao, China, and formally encouraged to be developed.

The first CLIOTOP meeting was held in IRD, Sète, France, 4–7 November 2003, to discuss and revise the draft Science Plan (SP) of the project that had been prepared and circulated during the previous months and establish its Implementation Strategy (IS). An enthusiastic group of 40 scientists from France, Spain, USA, England, Japan and Australia attended this organizational meeting, demonstrating the worldwide international interest of CLIOTOP. This meeting led to the definition of the present structure (Fig. 1) of the Program. The revised CLIOTOP SP/IS was peer-reviewed and modified accordingly and was finally approved by the GLOBEC Executive Committee as a GLOBEC Regional Program in October 2004 (Maury and Lehodey, 2005). The program aims at stimulating international scientific collaborations to improve our knowledge of the processes and dynamics of oceanic pelagic ecosystems, in a context of both climate variability and change and intensive fishing of top predators. Such collaborative works are indeed the backbone of CLIOTOP with the idea that the variety of climatic and oceanographic conditions in different oceans provides a unique opportunity for large-scale comparative analysis of open-ocean ecosystem functioning. The ultimate goal is to develop a reliable predictive capacity for single species and ecosystem dynamics at short, medium and long-term scales.

While CLIOTOP's long-term (10 years) objectives are defined in its Science Plan, their implementation was only established for the first 5 years of the project and included the organization of an international symposium which was held in the beautiful environment of La Paz, Mexico, from 3 to 7 December 2007. Nearly 200 participants, including many students and young scientists, from 25 different countries attended the symposium. By bringing together scientists working on the biology and ecology of pelagic top predators, the functioning and modeling of their ecosystem, and their management and conservation in a climate change perspective, this first international symposium was a key step in the implementation of CLIOTOP towards the achievement of its objectives. The 28 articles that compose this first CLIOTOP Special Issue largely reflect the diversity of oral communications and posters that were presented during the La Paz Symposium. They provide the marine science community with an up-to-date view on research and knowledge on top predators and their ecosystems, in a global change context. They also bring to the fore the challenges that will have to be addressed in the future to be in a position to sustainably manage these species and ecosystems, in a changing world.

2. Early life history

Considering the relative scarcity of research on the early life history of top predators, this topic was very well represented at the symposium and in this Special Issue. Many presentations focused on the early life history of billfishes and tunas, with a diversity of approaches investigating the assemblage of their larvae and the characteristics of their environment. Based on remarkable sampling efforts, the studies by Richardson et al. (this issue) in the Straits of Florida and Alemany et al. (this issue) around the Balearic archipelago show that while larvae of many oceanic predators are often observed in the same areas and season, each species seems to have developed specific environmental preferences to surface temperature, salinity, oxygen, and bathymetry, therefore leading to different responses to important climate events such as during the 2003 summer heat wave in the Mediterranean Sea. However in all cases, the mesoscale activity and in particular the presence of front and eddies, is highlighted as a major factor that controls the spawning activity, the species diversity and the survival of larvae. The Kuroshio Current is another good example of how mesoscale activity can determine the fate of bluefin larvae. The study by Kimura et al. (this issue) combining rearing experiments of larvae and modeling suggests that under a climate change scenario, the warming of waters where Pacific bluefin spawning currently takes place could exceed the optimal thermal window of the species.

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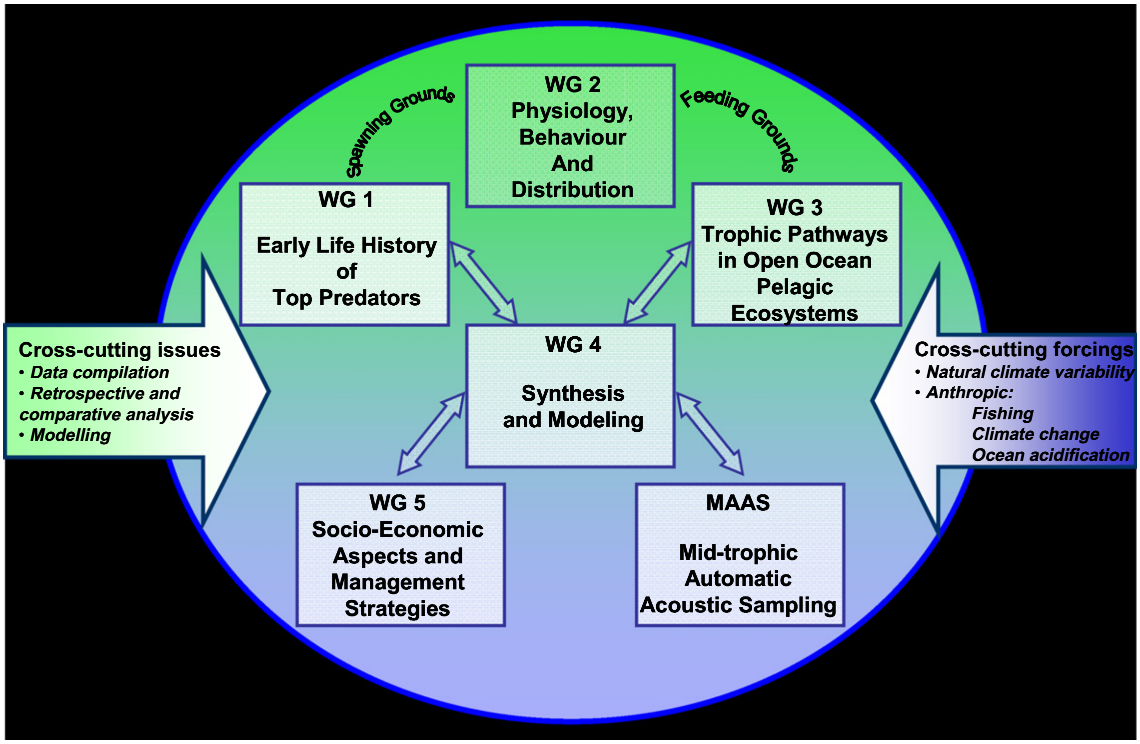

Fig. 1. CLIOTOP working groups.

Thus the recruitment of juvenile bluefin in the nursery grounds in Japanese coastal waters could decrease drastically, unless new favorable spawning areas emerge from the combination of future oceanic conditions and the ability of the species to adapt its life history and population dynamics to these new conditions. Another modeling study of the Lagrangian drift of bluefin larvae in the Mediterranean Sea by Mariani et al. (this issue) in the area sampled by Alemany et al., illustrates the interest of CLIOTOP to provide international research teams with a modeling framework to compare their results and approaches. By combining highly detailed observations of larval patches and powerful modeling tools like the hydrographic backtracking approach, we can expect to identify the exact condition of spawning for a given species and thus develop our understanding of these so critical early life stages. Therefore, laboratory experiments, more realistic modeling tools, innovative sampling equipments and techniques (e.g., the measurement of RNA/DNA ratios as a condition index of larvae or the molecular identification of larvae) are all promising new developments that need to be combined to understand the mechanisms explaining the spatial and temporal distribution of top predator larvae as a function of their physical, chemical and biological environment.

3. Physiology, behavior and distribution

For over a decade, field studies of the physiology, behavior and distribution of large marine predators have increasingly used electronic devices to record both horizontal and vertical movements of individual animals and the related physical, and in some case physiological, conditions. After an extensive deployment on large fishes (e.g., tuna, billfish) and air-breathing animals (e.g., turtles, sea birds, seals …), marine biologists are now starting to extend the use of these technologies to smaller and/or less familiar and less known species. A good example is provided in this issue with two articles devoted to the jumbo squid (*Dosidicus gigas*), for which the interest has been growing recently due to its dramatic range expansion in the eastern Pacific Ocean, and speculations whether climate variability and/or fishing on squid predators or competitors could have caused this increase. The report of a CLIOTOP workshop organized to discuss these issues provides a good overview on the current research on the ecological role of squid in oceanic ecosystems worldwide (Olson and Young, 2007).

In spite of their importance in pelagic ecosystems, both as prey and predators, squids and their ecology are not well understood. This is largely because of their ability to avoid being captured by conventional marine sampling techniques. Following a first successful attempt in the Gulf of California (Gilly et al., 2006), the records of four satellite tags deployed on jumbo squid off this same Gulf are presented by Bazzino et al. (this issue), and confirm that this is a promising approach to resolve some of the questions surrounding squid. As for other diel migratory species, light sensors used to detect sunset and sunrise time are imprecise, and the standard light-based geolocation methods are difficult to apply to get a detailed analysis of horizontal movements. However, progress is being made with existing and new methods that should help in the coming years to exploit the massive amount of information that has been collected using archival tags (Royer and Lutcavage, 2009). Nevertheless, a striking feature emerging from these first jumbo squid tagging experiments is the close association of this species with the oxygen minimum layer (OML) which is well developed in this region, both inside and outside the Gulf of California. Furthermore, a high level of activity seems to persist in this hypoxic zone despite the high metabolic rate associated with the inefficient jet propulsion system of this species (O'Dor and Webber, 1986). The physiological mechanisms that can explain these paradoxical performances are investigated by Rosa and Seibel (this issue) through controlled experiments. They showed that part of the explanation at least is a pronounced slowdown of metabolism at low oxygen and temperature levels which are characteristic of the oxygen minimum layer. With pressing questions about the impact of changes in temperature, ocean acidification, and expanding OML in tropical oceans (Stramma et al., 2008), such complementary studies are fundamental to investigate the effects of global warming on the pelagic ecosystem.

Although satellite and archival tags provide key detailed information on individual behavior and physiological abilities and tolerances, it is nevertheless necessary to increase the number of tags deployed as well as their time of recording to reach a representative level sufficient to understand species behavior and distribution in time and space. Due to urgent management issues, tuna species are often placed first on the list. Therefore, the studies by Howell et al. (this issue) on Pacific bigeye tuna, and by Boustany et al. (this issue) on Pacific bluefin tuna are representative of the research efforts developed for these valuable species. The bluefin study relies on an exceptional data set of 253 bluefin tagged off the coast of California. With such a level of tagging effort, it becomes possible to describe the habitat and seasonal movements, though the interpretation still has to be carefully restricted to the size range of the sampled population, i.e., in this case, mainly immature fish. Like squids, bigeye tuna have evolved complex and very efficient physiological mechanisms allowing deep dives in cold and low oxygen waters. These mechanisms include thermo-regulation and blood–oxygen binding characteristics allowing them to extract oxygen from low ambient oxygen environments, yet simultaneously deliver and offload oxygen to the tissues quickly enough to support elevated metabolic rates (Lowe et al., 2000). In association with the advancement of knowledge about physiology, the approach to classify diving behavior according to oceanographic conditions proposed by Howell et al. will help to understand and model the behavior and distribution of oceanic top predators in relation to their environment during the different stages of their life. This classification is also useful for the standardization of Catch Per Unit of Effort (CPUEs) used to monitor the fisheries. Given the number of similar past and ongoing tuna tagging projects carried out by the tuna commissions (WCPFC, IATTC, ICCAT, IOTC) and various institutes and fishing agencies around the world (CSIRO, SPC, Japan Fisheries Agency, IRD, etc.), a collaborative standardized analysis of all tagging data would dramatically add to the value of this information collected at a very high cost. CLIOTOP provides an ideal framework to gather all those data and to conduct such a comparative study and is strongly supportive of such an initiative.

4. Trophic pathways in oceanic ecosystems

Prey-predator relationships and trophic pathways are central to understand the dynamics of large marine predator populations and the whole pelagic ecosystem. From individuals to populations, most of the vertical and horizontal movements such as those described in the preceding section are motivated by foraging behavior. At the ecosystem level, bottom-up controls linked to the variability of primary production propagate through food webs, and top-down effects due to changes of the predation pressure exerted by top predators, potentially linked to fisheries removals, can cascade down to lower trophic levels.

Most of the historical information on trophic pathways in pelagic ecosystems comes from classical diet studies, i.e., based on stomach-content analyses. This type of "who eats who" analysis remains a fundamental tool to identify the trophic pathways linking key species and functional groups. However, combining such studies with other complementary approaches has been shown to be strongly beneficial. Four articles in this issue illustrate the diversity and novelty of techniques developed in recent years to investigate the trophic pathways of the pelagic systems. In the Bay of Biscay, which is an important feeding zone for juvenile Atlantic albacore and bluefin tuna, Lezama et al. (this issue) use acoustic surveys to study spatial relationships between albacore tuna, as inferred from CPUE, and their prey aggregations, particularly anchovy. This approach, well adapted to large spatio-temporal analyses, allows the authors to detect a clear change during the extreme warm event in 2003. During the same period, Goñi and Arrizabalaga (this issue) measured the fat content of several juvenile albacore and bluefin tunas in the same area, highlighting different seasonal trends likely reflecting individual differences in feeding movements and different use of this summer feeding habitat. In the Pacific Ocean, Olson et al. (this issue) examine the trophic status of yellowfin tuna in the food web using simultaneously stable isotope analyses (SIA) and stomach-content analyses. By investigating the broad-scale spatial relationship of stable nitrogen isotope values of omnivorous copepods and yellowfin tuna, they show the importance of determining the nitrogen signal at the base of the food web when interpreting results from different water masses. Once this bias is accounted for in the analysis, the authors find an east–west gradient of the isotopic content of yellowfin tuna and explore the different mechanisms that might explain this pattern: spatial differences in yellowfin tuna sizes in their samples, seasonal isotopic variability at the base of the food web, yellowfin tuna movement patterns, and spatial differences in diet composition. The still more recent development of techniques based on the analysis of fatty acid is used by Young et al. (this issue) to characterize the diet of swordfish in waters off eastern Australia. The results, supported by traditional stomach-content analyses, suggest that this new approach can be added to the previous ones to facilitate large spatial sampling and monitoring coverage.

While available information on marine food webs and the various trophic pathways connecting key species and functional groups accumulate, it becomes critical to propose standardized methods and to encourage comparative studies between different regions with different environmental conditions that can serve as alternatives to investigate the effects of climate change when experiments are impossible and long-term datasets are lacking. It is a major objective of CLIOTOP and several workshops have been organized recently by the CLIOTOP WG3 to initiate this work. Modeling tools are needed to describe the food webs and to test hypotheses about changes of trophic fluxes. ECOPATH has been very popular among marine biologists during the last 15 years, but it may lack flexibility in its structure (Metcalf et al., 2008) to adequately allow accurate descriptions of oceanic food webs that are highly variable in time and space. Other complementary approaches exist, in some cases coming from disciplines other than ecology, e.g., qualitative network analyses used in social sciences. In this issue, Dambacher et al. (this issue) propose an analysis of the pelagic food web based on a graph-theory approach and the concept of network described by more or less influential nodes and links. Using diet studies of top pelagic predators from three different regions of the Pacific, they identify ten key players of trophic networks, but none is common to all three regions. Interestingly, they come to the same conclusion as Kitchell et al. (2002), that sharks do not appear to play a key role in the Central Pacific.

One important gap that has been highlighted in the CLIOTOP Science Plan and during the symposium remains the intermediate trophic levels. The small fishes, cephalopods, and crustaceans that occupy the intermediate or mid-trophic level from surface to more than 1000 m in depth constitute the forage base of the large marine predators. Therefore in addition to web analyses, there is a fundamental need for describing, quantifying, modeling and monitoring these mid-trophic level organisms. This major component of pelagic ecosystems is indeed crucial for understanding the propagation of climatic and lower trophic level variability and changes to the upper trophic levels. It is also important for the top-down control of planktonic systems involved in biogeochemical cycles, such as CO_2 fixation and export. In recent years, acoustic technologies have dramatically matured, and the community using those techniques is still growing. These acoustic sampling technologies, owing to the long-range propagation of sounds into the water, are the only means to efficiently observe the large biomass of mid-trophic levels at ecologically relevant temporal and spatial scales (Kloser et al., 2009). CLIOTOP has appointed a new working group to initiate a collaborative effort to utilize these new techniques and develop a global ocean ecosystem Mid-trophic Automatic Acoustic Sampler (MAAS) (Maury, 2007; Handegard et al., 2010). The objective is to provide near-real-time global-scale monitoring of mid-trophic-level organisms using a variety of platforms with automated acoustic recorders. If CLIOTOP is successful in implementing this project, it will be a significant achievement for the whole marine science community.

5. Socio-economic aspects and management strategies

Though the Ecosystem-Based Fisheries Management (EBFM) has become the new paradigm of fishery science during the last decade, all exploited large pelagic predators are still managed on the basis of monospecific analyses, and most of the time without any consideration of the variability of the climate-driven oceanic environment. Why is there such a huge discrepancy between the political message which has been delivered in international instances since at least the Earth Summit in Rio in 1992 and the reality of science and management in the local, national, regional, and international institutions in charge of the management of oceanic top predators? The answer is neither simple nor unique. Comprehending how humans understand and interact with oceanic top predators requires examining the interactions among scientists, fishery regulators and managers, fishing firms, fishermen, and other stakeholders and the ecosystems. A challenge for CLIOTOP is to bring together interdisciplinary teams of natural scientists (e.g., biologists, population ecologists, oceanographers, biogeochemists), social scientists (e.g., political scientists, economists, sociologists), and system modelers (integrating physical, biogeochemical, ecological and human systems into coupled models) to evaluate how changes in human harvests of top predator species reflect the effects of natural and anthropogenic forcings, and to provide new modern tools for effective, efficient and equitable methods of managing the exploitation of top predator species and governing fisheries. Achieving these goals requires analyses considering ecosystems dynamics, socioeconomic constraints, behavior, institutions, and strategies (see the CLIOTOP Science Plan for more details).

Tuna economy is characterized by both highly industrial and competitive fisheries and artisanal fisheries interacting in a globalized market. Tropical tuna and skipjack in particular show high levels of market integration with the six major markets (Japan, Thailand, American Samoa, Americas, Ivory Coast and Spain) forming a single integrated market with prices moving jointly in the long run (Jeon et al., 2007). Results are less clear for yellowfin however, and Jiménez-Toribio et al. (this issue) extend this analysis to the European markets major consumers of canned yellowfin. By identifying the main economic factors driving the interactions between different production areas and between different target species, this type of analysis should have significant consequences for the management of tuna fisheries and for modeling scenarios of projected fishing effort. But while thinking globally, can we act locally when managing large highly migratory species? The answer to this question is yes according to the study by Jensen et al. (this issue) on the effects of longline closures for striped marlin fisheries near Baja California. They show that temporary closures of the Mexico Exclusive Economical Zone (EEZ) to longlining had a rapid effect on the local abundance of this species.

After a quick and useful review of the first principles of fishery economy, McIlgorm (this issue) examines long-term economic implications of climate change on the tuna purse seine fishery in the tropical western Pacific. The author argues that due to existing economical constraints, e.g., the necessary long-term investment of capital in fishing vessels and fish processing plants, and recurrent problems of subsidies leading to overcapitalization and subsequently to overfishing, the future changes in distribution and abundance of stocks associated to climate change and the consequences of the expected increase of fuel prices should be quickly investigated to provide adaptation and policy mitigation alternatives to government and industry. Together with tuna, oceanic sharks have taken a heavy toll from the exploitation of oceanic resources since the beginning of industrial fisheries. However, the concern for the management of these species has remained very limited until only recently. The reasons for this lack of interest are explored by Jacques (this issue), through a quantitative content analysis of government reports and academic fishery-related journal articles, a standard approach in social science. From his analysis, the author argues that the social values of both sharks and the broader ecological changes are secondary compared to the "economistic" paradigm enforced by country-actors, industry, and international law.

6. Mesoscale: the new frontier

A special session during the symposium was devoted to the mesoscale that appears as the new frontier to be explored for oceanographers, marine biologists and modelers. Several presentations highlighted the structuring role of eddies and fronts which aggregate pelagic communities and drive their movements, leading in some cases to semi-permanent structures acting like "hot spots" and high-use areas. A large number of taxa have been covered and represented in this issue. In addition to tuna species for which the importance of mesoscale features for spawing has been highlighted above, great frigatebirds in the Indian Ocean (Weimerskirch et al., this issue; Tew-Kai and Marsac, this issue), loggerhead turtles in the Atlantic (McCarthy et al., this issue), the king penguins in the southern Polar Front Zone (Scheffer et al., this issue), and two species of albatrosses around Hawaiian Islands (Kappes et al., this issue) are represented in this section. Fascinating foraging strategies are revealed and there is a great opportunity within CLIOTOP for a large comparative study of the strategies of these animals sharing the same forage species but with different physical and physiological skills to detect and to reach their prey.

It is useful to analyze the reasons of these successful studies as they have common characteristics. All animals are air-breathing species tracked by the ARGOS positioning and data collection satellite system. In this case, animal positions are quite accurate and the state of the ocean at the position of the animal can be precisely determined using high-resolution satellite observations (SST, sea color, sea winds and altimetry). And finally, the forage species of these predators are essentially in the surface layer, with only king penguins being able to dive to 200–250 m to search for deeper forage organisms. This surface forage seems to be aggregated along the edge of mesoscale eddies, that are detectable from the satellite data. Thus, in this ideal situation, all conditions are met to allow detailed studies of the correlations between animal behavior and their mesoscale environment.

The situation is quite different for fish and other animals that can only be tracked using archival techniques. First, the light-based geolocation techniques currently do not provide sufficient accuracy. Progress can be expected in the near future with new technical developments (e.g., geomagnetic sensors, higher memory capacity and power of battery, and increased data transmission) and better statistical treatment of the recorded data, including the use of auxiliary information such as temperature data over the recorded vertical profiles. The latter approach is linked intimately to the availability of realistic predictions from ocean general circulation models. Important progress has been made in this domain during the last few years using assimilation of *in situ* (e.g., Argo buoys) and satellite data (altimetry and SST in particular). A second notable difference between these animals and the air-breathing species mentioned above is the frequent use of deep mesopelagic forage, not visible from the surface and not necessarily associated to surface physical features. Here, the only possibility to obtain realistic mesoscale predictions of forage groups seems to combine innovative modeling approaches of these communities (e.g., Lehodey et al., 2009, 2010; Maury et al., 2007; Maury, 2010) coupled to ocean circulation models and assimilating acoustic data collected in an extensive and low cost network as proposed in the MAAS project mentioned above.

7. Climate variability and climate change

One major legacy of the GLOBEC program is the recognition of the influence of climate variability on marine species and community dynamics at various temporal and spatial scales (e.g., Stenseth et al., 2005; Lehodey et al., 2006; Alheit et al., 2010). Recent observations and modeling efforts have shown that the ecology and dynamics of the populations of large pelagic species are, like other marine species, closely linked to the ocean condition driven by the climate variability at different time scales, including the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the North Atlantic Oscillation (NAO) or the Pacific Decadal Oscillation (PDO). The last series of articles in this Special Issue add more evidence supporting this tight relationship.

In the polar regions of the Atlantic Ocean, sea ice dynamics vary across the eastern and western Atlantic. Analyzing satellite images, Friedlaender et al. (this issue) confirm a correlation between the North Atlantic Oscillation (NAO) index and the amount of sea ice cover off Canada in western North Atlantic that is a breeding area of harp seals. They also find an opposite correlation in the easternmost breeding areas of this species, thus leading to an out-of-phase signal between the western and eastern (particularly the White Sea) North Atlantic. The harp seals that need sea ice for breeding have apparently adapted their life-history strategies to cope with this year-to-year variability.

For pelagic fishes, it is often necessary to rely on indirect approaches to explore the relationships between climate fluctuations and population dynamics, using for example long time series of catch data. Rouyer et al. (this issue) use powerful signal analysis techniques to investigate whether fluctuations of tunas and billfishes CPUE time series during the last 50 years in the Atlantic Ocean are affected by environmental noise and whether life-history traits of species modulate this response. With similar techniques, Corbineau et al. (this issue) compare the patterns of variation of these large pelagic fishes in both the Atlantic and Indian Ocean, and show that the spatial criteria – here they use Longhurst's biogeographical provinces – is the most important factor structuring the patterns of variability. Surprisingly, the analysis at this very large spatial scale suggests that CPUE might reflect poorly the underlying population dynamics of tuna and billfish. Knowing the importance of the analysis of CPUE trends in the monitoring and stock assessments of these fisheries, this result should be debated in future management meetings. Analyzing fishing data, Dufour et al. (this issue) provide the first evidence of a change in the phenology of migration and the spatial distribution of tuna in the Bay of Biscay. As observed for an increasing number of terrestrial species, the timing of migration has changed over the last decades, with albacore tuna arriving about 8 days earlier than 40 years ago and bluefin tuna arriving 14 days earlier than 25 years ago to this summer feeding ground. A trend in the spatial distribution of albacore is also detected with a shift toward higher latitudes over time.

These results are typically the sort of impacts that can be expected from the adaptation of species to the changing climate, especially the warming water, due to anthropogenic release of greenhouse gases. Indeed, the development of industrial oceanic fisheries since the 1950s occurred in a warming ocean (IPCC, 2007). With the projections of Earth Climate Models becoming available to marine biologists and modelers, it becomes possible to investigate the potential impact of future climate change on ocean ecosystems and large pelagic species. Hobday (this issue) uses output from multiple climate models to construct an ensemble analysis and to examine the potential changes in the distribution of 14 large pelagic species captured by longline fisheries off the coasts of Australia. The approach relies on simple but robust relationships between temperature and catch distribution. As expected, the result is a general southward (poleward) shift of the core habitats, but the analysis also predicts a contraction of these habitats and rates of change are an order of magnitude higher than those observed for terrestrial systems.

Though temperature is a major factor that determines the spatial distribution of species-specific habitats, other critical environmental changes will occur in the ocean due to the release of greenhouse gases and global warming. Therefore, more complex approaches are also needed to investigate in details the effects of the combination of these multiple factors. One example is given in the last article of this issue (Lehodey et al., this issue), with an approach combining a climate model and a biogeochemical model, and the latest version of the Spatial Ecosystem and Population Dynamics Model (SEAPODYM). This model predicts size- and age-structured tuna populations in space and time and uses fisheries data with data assimilation techniques for calibration. This optimization method and the hindcast validation against historical fishing data give confidence in the skills of the model to capture the main characteristics in the tuna population dynamics under the influence of both fishing and environmental variability. Future applications to several large pelagic species, using multiple environmental forcings in the framework of comparative studies between oceans and between models should help CLIOTOP to achieve its ultimate goal of developing a reliable predictive capacity for large pelagic species and ecosystem dynamics at short-, medium- and long-term scales.

8. Conclusion

The suite of articles presented in this Special Issue covers an incredibly rich variety of species and taxa, regions, scales, disciplines, new techniques and models developed in a unique broad international and multi-disciplinary framework. The symposium was still more diverse and stimulated many new collaborations. Thus, the very first objective of CLIOTOP, that was to build an international network in the marine science community working on top predators, their ecosystems and their potential exploitation in a global change context seems to be on a good track. As expected, gaps have been identified. Addressing them will need to strengthen our collective endeavour involving everyone and a variety of different approaches. Observational efforts will have to continue, and while technological barriers are pushed forward, long-term data time-series need to be pursued. New links with Regional Fisheries Management Organizations need to be developed and existing ones need to be reinforced.

The comparative approach will remain the foundation of CLIOTOP, searching for common principles underlying the dynamics of populations, the organization of ecosystems and their responses to climate forcing and fishing pressure. The challenge is immense, first to understand and model the impacts of both fishing and climate variations on marine ecosystems inhabited by open ocean top predators, and then to be in a position to attempt to forecast future changes under different scenarios of climate warming, ocean acidification, fishing effort evolution and market reorganization according to alternative governance strategies. It is also urgent, because the exercise is not purely academic but necessary to provide understanding and tools for mitigation and adaptation to global changes impacting both a major socio-economic sector and the largest ecosystem of the Earth. The next decade will be decisive, not only for CLIOTOP.

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Patrick Lehodey
MEMMS (Marine Ecosystems Modelling and Monitoring by Satellites), CLS Space Oceanography Division, Ramonville, France
Tel.: +33 561 393 770.
E-mail address: PLehodey@cls.fr

Olivier Maury
IRD (Institut de Recherche Pour le Développement) – UMR 212 EME, Department of Oceanography, University of Cape Town, Private Bag X3, Rondebosch, Cape Town 7701, South Africa

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