GLOBEC Report No.18

CLimate Impacts on Oceanic TOp Predators

Science Plan and Implementation Strategy

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GLOBAL OCEAN ECOSYSTEM DYNAMICS

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LIST OF ACRONYMS

ADRM	Advection-Diffusion-Reaction Model
APECOSM	Apex Predators ECOSystem Model
AUV	Autonomous Underwater Vehicle
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CCSBT	Commission for the Conservation of Southern Bluefin Tuna
CICMAR	Centro Interdisciplinario de Ciencias Marinas
CLIOTOP	Climate Impacts on Oceanic TOp Predators
CLIVAR	Climate Variability and Predictability
CMarZ	Census of Marine Zooplankton
CoML	Census of Marine Life
CPUE	Catch Per Unit Effort
ELH	Early Life History
ENSO	El Niño-Southern Oscillation
FAD	Fish Aggregating Device
FAO	United Nations Food and Agricultural Organization
FMAP	Future of Marine Animal Populations
GAIM	Global Analysis, Integration and Modelling
GLOBEC	Global Ocean Ecosystem Dynamics
IATTC	Inter-American Tropical Tuna Commission
IBM	Individual-Based Model
ICCAT	International Commission for the Conservation of Atlantic Tunas
IDGEC	Institutional Dimension of Global Environmental Change
IGBP	International Geosphere-Biosphere Program
IHDP	International Human Dimensions Programme
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IO-GOOS	Indian Ocean – Global Ocean Observing System
IOTC	Indian Ocean Tuna Commission
IRI	Index of Relative Importance
MAR-ECO	Patterns and Process of the Eco-systems of the Northern mid-Atlantic
NPZD	Nutrients, Phytoplankton, Zooplankton, Detritus models
OGCM	Ocean General Circulation Model
PEEZ	Performance of Exclusive Economic Zones
PFRP	Pelagic Fisheries Research Program
PICES	North Pacific Marine Science Organization
PIRATA	Pilot Research Moored Array in the Tropical Atlantic
POM	Particulate Organic Matter
RFB	Regional Fishery Body
RFMO	Regional Fishery Management Organization
RSMAS	Rosenstiel School of Marine and Atmospheric Science, University Of Miami
SCOR	Scientific Committee on Ocean Research
SEAMAP	Spatial Ecological Analysis of Megavertebrate Species
SEAPODYM	Spatial Ecosystem And Populations Dynamics Model
SIA	Stable Isotope Analysis
SOLAS	Surface Ocean - Lower Atmosphere Study
SPACC	Small Pelagics And Climate Change
SSC	Scientific Steering Committee
TAO	Tropical Atmosphere and Ocean
TOPP	Tagging of Pelagic Predators
TRITON	Triangle Trans-Ocean Buoy Network
WCRP	World Climate Research Programme

1. EXECUTIVE SUMMARY

CLIOTOP (CLimate Impacts on Oceanic TOp Predators) is a regional[1] project implemented under the international research program GLOBEC (http://www.globec.org), a component of the International Geosphere-Biosphere Programme (IGBP). CLIOTOP is devoted to the study of oceanic top predators[2] within their ecosystems and is based on a worldwide comparative approach, i.e. among regions, oceans and species. It requires a substantive international collaborative effort. The project aims at identifying, characterizing and modeling the key processes involved in the dynamics of oceanic pelagic ecosystems in a context of both climate variability and change and intensive fishing of top predators. The goal is to improve knowledge and to develop a reliable predictive capacity for single species and ecosystem dynamics at short, medium and long term scales.

CLIOTOP is based on the idea that the variety of climatic and oceanographic conditions in the three oceans (Atlantic, Indian and Pacific) provides a unique opportunity for large-scale comparative analysis of open ocean ecosystem functioning.

Objectives of the CLIOTOP Science Plan are ambitious and are defined on a long term (10 year) perspective. Activities proposed for its implementation are defined for the first 5 year period and will be revised and updated after the synthesis of this first phase.

1.1. Project Description and Objectives

The general objective of CLIOTOP is to organize a large-scale **worldwide comparative effort** aimed at identifying the impact of both climate variability (at various scales) and fishing on the structure and function of open ocean pelagic ecosystems and their top predator species by elucidating the key processes involved in open ocean ecosystem functioning.

The ultimate objective is the **development of a reliable predictive capability** for the dynamics of top predator populations and oceanic ecosystems that combines **both fishing and climate (i.e. environmental) effects**.

To be able to conduct standardized worldwide comparative analysis, **homogeneous comprehensive records of climate variability, ocean and atmospheric circulation changes and related regional and local environmental changes** will be used as well as synthesized **long-term fisheries data over the last 50 years** (i.e. the industrial fishing era) , providing an unprecedented framework for comparative studies.

CLIOTOP is aimed at improving understanding of oceanic top predators in their ecosystem. However, its successful implementation should have a significant impact on the management of the very important fisheries that exploit tunas and tuna-like species. These fisheries are managed by international organizations, which rely on international scientific consensus in understanding the dynamics of the populations they exploit. A comparative project such as CLIOTOP, by improving understanding will provide the basis for better fisheries management.

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[1] "Regional" in the GLOBEC terminology refers to the largest category of projects. This project is indeed covering all the pelagic regions of the world ocean.

[2] Top predators encompass potentially all the large marine animals which exploit the top of the trophic chains: large pelagic fishes such as tunas, billfishes or sharks, marine mammals, turtles and seabirds.

CLIOTOP should develop strong interactions with the already existing multi-national GLOBEC project OFCCP (Oceanic Fisheries and Climate Change Project) that shares common general objectives, but is limited to the Pacific Ocean. It is believed that the CLIOTOP comparative approach between the three Oceans (Atlantic, Indian and Pacific) will bring a major additional value to the research developed in each Ocean separately. In addition, given the complex nature of its foci, the CLIOTOP program strongly encourages **co-operation and exchange** with other IGBP programs such as SOLAS, GAIM and IMBER as well as WCRP programs such as CLIVAR, the SCOR affiliated CoML projects (CMarZ, TOPP, SEAMAP, MAR-ECO and FMAP), and the International Human Dimensions Programme (IHDP) on Global Environmental Change. Being able to make use of the tools and expertise provided by those international programs will be crucial for an effective “open sea” project.

1.2. Key Questions Hypotheses

CLIOTOP is designed to investigate the **processes** linking top predators with their environment, their **responses** to environmental and anthropogenic forcings and the **management** consequences of the above.

To address this, two main integrated components are envisaged:

1. to evaluate the impact of fishing and climate variability on marine ecosystems inhabited by oceanic top predators by analyzing and comparing long-term data sets, ocean/atmosphere and biogeochemical reanalyses, field observations, *in situ* and laboratory experiments and measurements;
2. to use modeling and extensive simulations in a comparative framework to deduce and understand the dynamics of the ecosystem(s) and dependent resource populations, leading towards the development of next-generation models which embody a high degree of realism and predictive skill. Models will help in identifying the main processes of the system (those indispensable for realistic predictions) and how they interact together.

1.3. Organization of the Project and Working Groups

CLIOTOP is organized around five flexible working groups focused on key processes and scales to be studied:

- **WG1:** Early life history
- **WG2:** Physiology, behavior and distribution
- **WG3:** Trophic pathways in open ocean ecosystems
- **WG4:** Synthesis and modeling
- **WG5:** Socio-economic aspects and management strategies

Working groups are related by cross-cutting issues and forcings.

Each working group is organized around a set of key questions relevant to CLIOTOP's objectives, and a set of strategic approaches to address those questions:

WG1 Early life history

1. What environmental characteristics define spawning areas and the timing and intensity of reproduction?
2. What environmental and biological characteristics most influence larval survival?

WG2 Physiology, behavior and distribution

1. To what extent do spatial dynamics result from proximate cues?
2. How do school size, fidelity and species migration paths vary in relation to climate variability and change?
3. What determines the time and place of reproductive and feeding-related behavior?
4. How do anthropogenic forces such as fishing interact with environmental impacts on distribution and population structure?

WG3 Trophic pathways in open ocean ecosystems

1. What are the main trophic pathways of oceanic top predators and how do they differ among and within oceans?
2. Is there evidence of change in trophic pathways over time and space consistent with climate scale variability – can seasonal and spatial variability be used to explore the impacts of climate variability?
3. What is the relative importance of mesopelagic versus epipelagic prey resources to oceanic top predators, and how does this vary within and among oceans. How does climate variability affect the distribution and availability of mesopelagic and epipelagic prey?
4. Is it possible to identify indicators, such as prey species or size spectra, that would highlight significant changes in trophic pathways?

WG4 Synthesis and modeling

1. What is the relative importance of fisheries exploitation and the dynamic environment in structuring pelagic ecosystems?
2. Does any one mechanism (e.g. match/mismatch) explain observed variation across species, trophic pathways, regions, etc.? Do alternative mechanisms have equally good explanatory power? Which mechanism(s) provide the greatest predictive capabilities?
3. What alternative states occur in historical pelagic ecosystem records, how might they be characterized (e.g. can they be described by indicators), how might they be caused, what are their consequences, and are they reversible, given that the climate changes continuously?
4. Does knowledge about environmental forcing and the nature of fisheries (e.g. the species composition of the catch, growth variability, egg production rates by size/age) suggest an optimum allocation of fishing activities?

WG5 Socio-economic aspects and management strategies

1. What are the socio-economic pressures on, and context of, top predators' fisheries?
2. How have fisheries organizations (whether local, national, regional, or international) addressed climate change issues?
3. What are the flows in capital and knowledge among the world's large fisheries and how do they respond to variability?
4. Can we evaluate how useful are the fisheries management decision support tools developed by WG4?

2. INTRODUCTION

Following the "Climate and Fisheries" meeting held in Hawaii in November 2001[1], it has been decided to develop a new international research project devoted to the worldwide comparative analysis of open ocean ecosystems and associated top predators' populations. The GLOBEC SSC endorsed the development of a Science Plan for this activity in Qingdao, China (October 2002) and allocated IPO resources to assist in the process. Amongst other preparatory meetings, an organizational meeting was held in Sète, France in November 2003 (see Annex, page 41). The present working group structure of CLIOTOP and the basis for a Science Plan were elaborated during the Sète meeting. A draft Science Plan was presented to the GLOBEC SSC in Swakopmund, Namibia (April 2004). It was peer-reviewed and modified accordingly and finally approved by the GLOBEC Executive Committee as a GLOBEC Regional Program in October 2004.

Objectives of the CLIOTOP Science Plan are defined on a long term (10 year) perspective. Activities proposed for its implementation are defined for the first 5-year period and will be revised and updated after the synthesis of this first phase.

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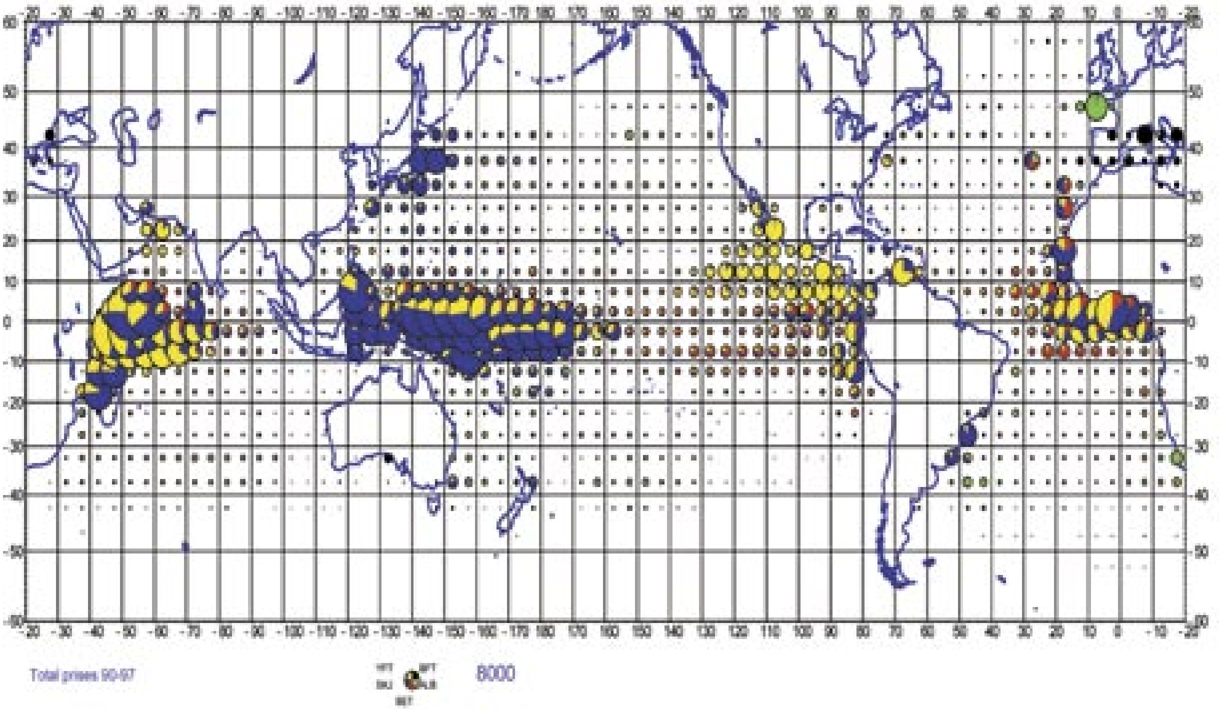
[3] http://iri.columbia.edu/outreach/publication/irireport/FisheriesWS2001.pdf

3. BACKGROUND AND RATIONALE

Open ocean ecosystems[4] occupy the largest area of the world oceans. Amongst the top predator species in the vast pelagic ecosystem, tunas and tuna-like fishes, billfishes and sharks[5] have the greatest commercial importance either in term of catch (e.g. skipjack tuna is the 4th most productive and fished marine species in the World, after Peruvian anchoveta, Alaska Pollock and Atlantic Herring) or economic value (for instance, the bluefin tuna price frequently reaches more than 100 US$ per kg on the sashimi market). Tunas, billfishes and tuna-like species are migratory species that are fished worldwide, from the Equator to temperate regions, by multiple national fleets using many different fishing gears. Some species have been exploited since antiquity, e.g. bluefin tuna in the Mediterranean Sea. The first industrial tuna fishery can be associated with the development of the madrague system in Sicilia in the 12th Century. However, it is during more recent decades that tuna fisheries have expanded their range worldwide with a continuous increase of fishing effort and fishing capacity leading to a dramatic increase in catches (Fig. 1).

Figure 1. Worldwide distribution of tuna catches cumulated over 1990-1997 (tonnes). In yellow the yellowfin tuna, in blue the skipjack, in red the bigeye tuna, in green the albacore tuna and in black the bluefin tuna. Data source: FAO, figure courtesy of A. Fonteneau.



Today, industrial fisheries (mostly purse seine, longline and pole and line fishing) have reached unprecedented levels of fishing effort with a worldwide geographical coverage. Non-targeted bycatch species are also removed from the oceans in unknown quantities. The bycatch of oceanic top predators include charismatic species such as sharks, marine mammals, turtles or birds. Furthermore, some shark species experience very high mortality levels due to the rapid worldwide development of shark fishing for the shark fin market.

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[4] Ecosystems include both the physical environment and the set of all living organisms and their interactions in space and time, with each other and with the physical environment.

[5] The tunas include skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), bigeye (*T. obesus*), albacore (*T. alalunga*), Atlantic northern bluefin (*T. thynnus*), Pacific northern bluefin (*T. orientalis*), and southern bluefin (*T. maccoyii*), and the billfishes include swordfish (*Xiphias gladius*), Atlantic blue marlin (*Makaira nigricans*), Indo-Pacific blue marlin (*M. mazara*), black marlin (*M. indica*), white marlin (*Tetrapturus albidus*), striped marlin (*T. audax*), Atlantic sailfish (*Istiophorus albicans*), and Indo-Pacific sailfish (*I. platypterus*). There are many other species of tuna, and several other species of billfish, of lower abundance and lesser economic importance. The most common shark species in longline bycatch is the blue shark (*Prionace glauca*). Other predominant sharks are the oceanic whitetip shark (*Carcharhinus longimanus*) and silky shark (*Carcharhinus falciformis*). Less frequent species are thresher sharks (Alopiidae), hammerhead sharks (Sphyrnidae) and mako sharks (Lamnidae).

At present, open ocean ecosystems support approximately 6 to 7 x 10^6 tonnes per year of catches of large pelagics (mostly tunas, billfishes and sharks). Because they mostly comprise the highest trophic levels, **there is an increasing concern about the potential top-down cascading effects that fishing may have on the overall ecosystem**. For example, the question of the impact of the removal of two to three hundred thousand tonnes of yellowfin tuna each year in the Eastern Tropical Pacific Ocean has been posed for a long time, given that yellowfin in the region consume a very large proportion of *Auxis thazard*, one of the most voracious and metabolically active of all thunnids.

At the same time, environmental variability determines phytoplankton abundance and distribution at various scales and leads to **important bottom-up effects on forage species and then on top predator abundance and distribution**. Studying simultaneously those bottom-up and top-down effects in open ocean pelagic ecosystems requires the development of new approaches and appropriate models.

Regional tuna fisheries monitoring and management bodies[6] have been created to compile fisheries data, to develop research and to provide scientific advice for management of the open ocean pelagic resources. They have been very successful in fulfilling their mission and they remain pivotal institutions for developing regional research programs on tuna and tuna-like species, improving the monitoring of their fisheries and the management of their stocks. However, as stated during a consultation organized by the FAO[7] and gathering experts from all these Regional Fisheries Bodies, "*Because of the similar nature of tuna stocks and tuna fisheries in the different oceans, there is the need for closer collaboration among RFBs and scientists involved with tuna stocks of different oceans*".

In particular, extensive collaboration is essential for considering complex issues such as **the impacts of climate variability on the dynamics of oceanic ecosystems and top predator populations**. Climate variability may be influential on seasonal, interannual, or decadal time scales, and may affect various biological and ecological processes. In the longer term, global change will modulate this variability and may have unexpected effects on ecosystem dynamics. There is ever-increasing evidence of the impact of climate variability on tuna stocks and ecosystems. In this context, the GLOBEC-CLIOTOP project is seen as a timely initiative to develop an international framework of collaboration and exchange with a multi-disciplinary comparative approach for considering these issues, and in particular, the following questions:

> **Processes:** How are the adaptive strategies of the different species structured at the different time-space scales of environmental variability? How do adaptive processes interact? How can they be differentiated? Can we predict adaptation in relation to climate forcing?
>
> **Responses:** What are the respective impacts of fisheries and climate variability on the structure and functioning of oceanic ecosystems? Are ecosystem dynamics well defined, e.g. abilities of ecosystems to respond to continuously changing forcing, from climate and fisheries, particularly regime shifts and global synchronies? What is predictable, what is not? What should be measured and monitored to maintain "status information" on individual species and the larger ecosystem(s). What information is needed to develop predictive models and how do we evaluate predictions?
>
> **Management:** How are/can ecosystem dynamics be accounted for in present management? What is needed from the scientists, e.g. which indicators? What is needed politically, i.e. what institutions and processes? How might both socio-economic strategies/behaviors and ecosystem dynamics be addressed by management within the context of climate variability?

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[6] ICCAT in the Atlantic Ocean; IOTC in the Indian Ocean; IATTC in the eastern Pacific Ocean and CCSBT specifically for the southern bluefin tuna stock. Western and central Pacific Ocean are the last areas not covered by an official international tuna commission with a management mandate, but it is the subject of a series of Multilateral High Level Conferences to establish a regional fisheries body in this region. The convention is already signed and the Preparatory Conference (PrepCon) is taking charge of both scientific and management issues until the Convention comes into effect.

[7] FAO expert consultation on implications of the precautionary approach for tuna biological and technological research, Thailand, 7-15 March 2000.

To address these questions, two main integrated initiatives are envisaged:

1. Evaluation of the impact of both fishing and climate variations on marine ecosystems inhabited by oceanic top predators, by analyzing and comparing long-term datasets, ocean/atmosphere and biogeochemical reanalyses, field observations, *in situ* and laboratory experiments and measurements;
2. Modeling and simulation in a comparative framework to identify key processes, deduce and understand the dynamics of the ecosystem and its dependent resource populations, leading toward development of next-generation models which embody a high degree of realism and predictive skill.

The comparative approach constitutes the backbone of CLIOTOP. Comparing various species, regions and ecosystems by searching for regularities and differences is indeed of fundamental importance because universal patterns would reveal common principles underlying the organization of open ocean ecosystems and their response to climate forcing. Unique patterns will provide insights into species-specific adaptations to local and regional dynamics.

4. OBJECTIVES

The general objective of CLIOTOP is to organize a large-scale **worldwide comparative effort** aimed at identifying the impact of both climate variability (at various scales) and fishing on the dynamics of top-predator species[8] in relation with the structure and changes of open ocean pelagic ecosystems. The ultimate objective is the **development of a reliable predictive capability** of the dynamics of top predator populations and oceanic ecosystems that combines **both fishing and climate (i.e. environmental) effects**.

These objectives require an approach involving research teams currently working in process-oriented projects which address the mechanisms linking physical forcing, zooplankton production, prey abundance and distribution and apex predator behaviors, with modelers involved in climate, physical and biogeochemical oceanography, and individual, population or ecosystem dynamics.

To be able to conduct standardized worldwide comparative analysis, **homogeneous comprehensive records of climate variability, ocean and atmospheric circulation changes and related regional and local environmental changes** will be used. Such records are already available in several research centers and are being used by various scientists. CLIOTOP should serve to improve the availability of these data sets to the ocean and fishery science communities, and to encourage incorporation of historical archived data. This should provide a unique opportunity to synthesize long-term fisheries data over the last 50 years (i.e. the industrial fishing era) and yield a more inclusive, explanatory framework for CLIOTOP comparative studies.

Integrative process-oriented studies (including retrospective analysis, field experiments, surveys and monitoring) in a comparative framework are a key objective. In this respect, **a strong modeling component** is also fundamental for CLIOTOP. This will include a range of models of different complexity from simple box models through more detailed energy budget and behavioral models to spatially explicit ecosystem models driven by OGCMs. The validation of ongoing ocean modeling and the development of more realistic models is a prime objective.

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[8] Top predators encompass potentially all the large marine animals which exploit the top of the trophic chains: large pelagic fishes such as tunas, billfishes or sharks, marine mammals, turtles and seabirds.

5. GENERAL ORGANIZATION OF CLIOTOP

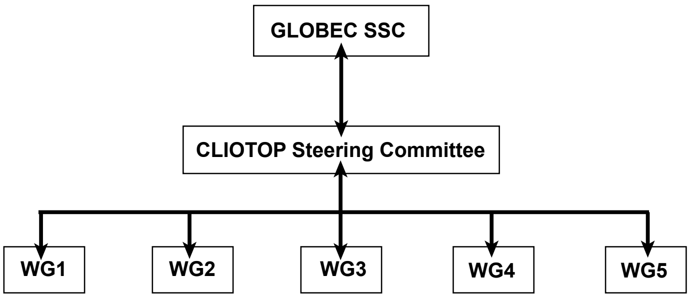
The organization of CLIOTOP serves two major objectives. These are:

1. **Coordinate collaboration among** international scientific projects and research groups already working in the field;
2. Conduct a global **comparative study among oceans, regions, species and models** for pattern recognition concerning the key processes linking the dynamics of oceanic top predators to climate forcing at various scales ranging from subcellular processes at millisecond time scales to basin-scale processes at multi-decadal time scales.

5.1. Coordination

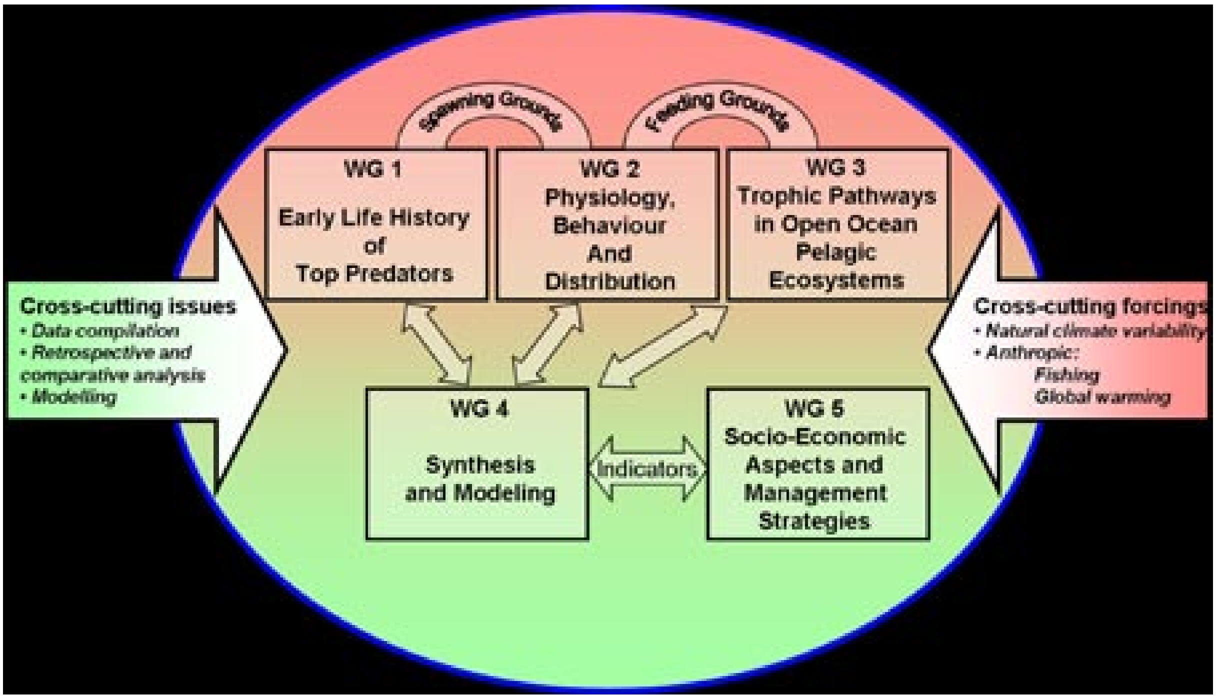
CLIOTOP is composed of interacting working groups. Two chairpersons[9] and a steering committee manage the project (Fig. 2). Based on the information provided by the working groups, the CLIOTOP Steering Committee prepares and presents the activity reports for reporting to the GLOBEC SSC. The working groups are inter-connected and all working groups have links with the modeling working group.

Figure 2. CLIOTOP general structure



In the mid-term an international office responsible for the management and administration of the program should be developed. In the interim, the co-Chairs and the steering committee are responsible for the management and administration of the program, assisted by the GLOBEC IPO.

Figure 3. Organization of CLIOTOP working groups, cross-cutting issues and forcings



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[9] Present chairpersons of CLIOTOP and the Working Groups are listed on page 40

5.2. Working Groups

CLIOTOP is organized around flexible **working groups, workshops and meetings** focused on key processes and scales to be studied. Five working groups[9] were defined during the organizational meeting in Sète, France, 4-7 November 2003 (Fig. 3):

- **WG1:** Early life history
- **WG2:** Physiology, behavior and distribution
- **WG3:** Trophic pathways in open ocean ecosystems
- **WG4:** Synthesis and modeling
- **WG5:** Socio-economic aspects and management strategies

The working groups' main foci correspond to the key processes and scales to be studied, related by cross-cutting issues and forcings.

CLIOTOP should develop strong interactions with the already existing multi-national GLOBEC project OFCCP (Oceanic Fisheries and Climate Change Project) that shares common general objectives, but is limited to the Pacific Ocean. It is believed that the CLIOTOP comparative approach between the three Oceans (Atlantic, Indian and Pacific) will bring a major additional value to the research developed in each Ocean separately. In addition, given the complex nature of its focus, the CLIOTOP program strongly encourages **co-operation and exchange** with intergovernmental scientific organizations such as PICES, other IGBP programs such as SOLAS, GAIM and IMBER as well as WCRP programs such as CLIVAR, the SCOR affiliated CoML projects (CMarZ, TOPP, SEAMAP, MAR-ECO and FMAP), and The International Human Dimensions Programme on Global Environmental Change (IHDP). Being able to make use of the tools and expertise provided by those international programs will be crucial for an effective "open sea" project.

Typically, each working group is expected to have at least one workshop for implementation and one for the synthesis work. Intermediate workshops will be organized as necessary and according to opportunities and funding availability. Working groups are expected to organize their work in order to maximize their efficiency in securing the necessary financial resources, international expertise and time to achieve their objectives.

5.3. Timetable

CLIOTOP recognizes the need for international communication and participation by partners across the globe to achieve its scientific goals. Consequently, CLIOTOP intends to convene meetings of the Working Groups every 12 to 18 months, rotating around the oceans of interest. A tentative schedule is given below:

- January 2003: Beginning of the project, first meeting of the Steering Group
- 4-7 November 2003: Project planning meeting (Sète, France). WG creation
- 2004-2008: several meetings for each working group
  - May-June 2004: 1st WG3 meeting – CICMAR, La Paz, Mexico
  - December 2004: 1st WG2 meeting – PFRP, Honolulu, Hawaii, USA
  - December 2004: 1st WG4 meeting – PFRP, Honolulu, Hawaii, USA
  - December 2004: 1st WG5 meeting – PFRP, Honolulu, Hawaii, USA
- 2006: 1st CLIOTOP symposium and working group meetings
- 2008: CLIOTOP mid-term review meeting
- 2010: CLIOTOP synthesis symposium

6. IMPLEMENTATION OF THE WORKING GROUPS

6.1. Working Group 1 – Early Life History

6.1.1. Rationale

As with most marine fishes, the early life history dynamics of oceanic top predators are likely driven by a combination of density-dependent and -independent processes, each of which affect survival, and ultimately year-class strength.

These early life history dynamics are tightly linked to environmental processes, many of which are demonstrably influenced by climate variability. For example, changes in climate can impact ocean temperature distribution, timing and depth of stratification, the formation of mesoscale structures such as fronts and gyres, upwelling and consequently production. Changes in production can directly influence rates of growth and mortality of larval stages of top predators, either impacting their survival, or, via migratory movements of the adults, the temporal and spatial distribution of spawning. How movements of large pelagic predators modify spawning and early life history dynamics is unclear, particularly as large scale movements might mediate local or regional changes in environmental conditions.

Therefore, knowledge of the factors that define spawning locations and survival of the resulting early life history stages of top predators is critical for an informed understanding of the role that both seasonal dynamics and climate change may play on these organisms, as well as, the feedbacks that might ensue.

Figure 4. Bluefin tuna larva - Mediterranean Sea (Balearic Sea) (A. Garcia)

Figure 5. Sailfish larva – Straits of Florida (R.K. Cowen)

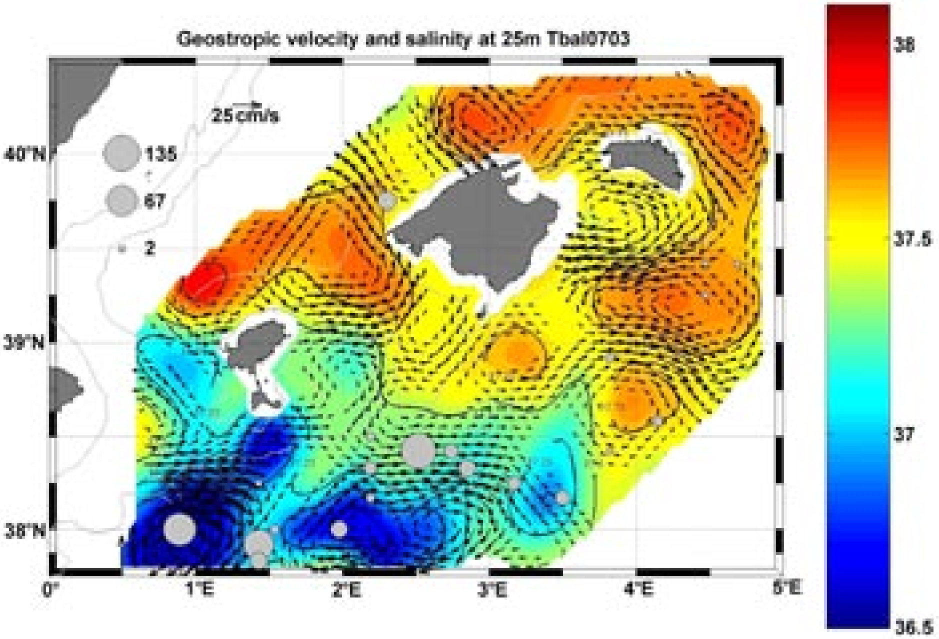


Figure 6: Bluefin larval catch (grey dots), geostrophic velocity (arrows) and salinity (colors) at 20m depth off the Balearic archipelago (Source: A. Garcia).

6.1.2. Key questions

Two questions are the key to assessing the impact that environmental variability may impart on top predator populations in the context of their early life history (ELH). Taken together, answers to these two questions will address the factors that determine when and where spawning occurs, how the relative success of each spawning event is driven by the local environmental conditions, and ultimately, how large scale (multi-decadal) atmospheric or oceanic forcing impacts larval survival and recruitment.

Question 1: What environmental characteristics define the timing and intensity of reproduction and spawning areas?

Question 2: What environmental and biological characteristics most influence larval survival?

A comparative approach will be useful to understand the impacts of climate variability on open ocean ecosystem dynamics. This approach can provide information on habitat quality and distribution for ELH stages throughout the spectrum of different open sea systems as well as about the processes involved in larval survival. In order to cover a complete range of habitat conditions, it is important to examine both central and marginal habitats for the same or similar species. The identification of key species, highly sensitive to changes in the conditions of spawning habitats, is also highly recommended.

Specific Objectives:

1. Identify the spatial and temporal distribution of spawning within and among years.
2. Identify which environmental variables (physical and biological) best define spawning habitat.
3. Determine the relative contribution among specific spawning sites and times to year class strength and how they may vary over time.
4. Identify and quantify the density-dependent and -independent processes and related environmental factors that define larval and juvenile survival.
5. Determine how critical biological rates (e.g. metabolism, growth, mortality) of different ELH stages are affected by environmental change.
6. Identify the bioenergetic requirements of ELH stages.
7. Identify the distribution of key organisms at other trophic levels influencing ELH stages (i.e. their predators and prey) at the small-, meso-, and large-scale relative to hydrological conditions.
8. Examine the food web dynamics of ELH stages. Similarly, identify the role ELH stages play in food web dynamics.
9. Identify and quantify the human impact on ecosystem functioning and how these affect ELH dynamics.
10. Identify multi-decadal processes for key areas.

Many of these and related issues are not unique to oceanic top predators. However, it is unclear whether the ELH stages of oceanic top predators are more responsive to particular processes, or whether they have stronger direct impact on the food web they are a part of, when compared to other fish species. Light, temperature, stratification, turbulence, water clarity are all physical properties that may vary over many temporal and spatial scales. To what extent are oceanic top predators responsive to these properties in terms of choosing spawning sites, and moreover, in terms of the growth and survival of their young under various conditions? If year class variation is more stable than for other species, is this because the larval stages are more tolerant of varying conditions, e.g. perhaps they are capable of utilizing a broad spectrum of prey sizes and types that minimizes or filters variability in prey abundance? Alternatively, spawning success may be linked to a combination of several favorable factors that would increase survival rates, either in narrow patches of high larvae concentration or conversely, in lots of relatively smaller more diffusely distributed isolates.

The chance to encounter such sparse and dynamic favorable spawning zones would be facilitated by mobility and dispersion of the adults, their extremely high fecundity, reproductive opportunism, and known potential for serial spawning behavior.

6.1.3. Implementation

Implementation will begin with the identification and review of previous studies and survey data. This will enable gaps in the present knowledge to be identified and highlight new methods of sampling and improvements in analytical techniques. It will also help in coordinating research efforts among different areas. Standardizing existing data and selecting standard methods for future studies will be the first important objective to achieve.

Analyses of long time series data such as from CalCOFI are useful for identifying inter-annual and decadal variation in spawning habitat distribution and linkages of year class success to environmental variability. Additional data sets will need to be identified for comparative studies of the scales of population responses to environmental variability.

Resolution of the above objectives requires collaborative efforts among laboratory, field-oriented and modeling studies. There is a need to develop techniques, and even perhaps facilities, to maintain early life history stages for laboratory measurements and experiments. Similarly, the large spatial scales over which some species may spawn may require development of novel sampling techniques and/or coordinated efforts for adequate resolution of spawning distributions and their associated environmental conditions.

Laboratory studies are required to address growth and bioenergetic rates under controlled food, ration and physical conditions. Obtaining sufficient numbers of larvae requires either the development of techniques for reproduction in captivity, or some means of collecting large number of young larvae alive from the field. Alternative methods might include utilization of mesocosm enclosures within the field once larval patches are identified.

Field studies should include detailed egg and stage-specific larval distribution studies coupled with the measurement of available prey fields and other environmental characteristics. Development or utilization of novel technologies may be required to adequately survey large areas of the ocean where spawning may be occurring. Once larval patches are identified, drifters with real-time reporting may be needed for repeat sampling which is required for growth and mortality rate estimates. Growth rates determined from otoliths, coupled with measures of condition will enable the determination of sources of growth variability in the natural environment, which will then be compared to laboratory measured rates.

Microchemistry of otoliths may be useful in determining contribution to year class population structure from specific spawning sites. It will be useful to develop standard protocols to coordinate the use of larval collections for multiple studies including growth, stomach contents, condition, etc.

One life history stage that is particularly under-studied is the juvenile phase, those individuals that have survived beyond the larval stage, but have not yet entered into the fishery. The key to success in this area will be the development of appropriate sampling techniques. Juveniles may vary in their spatial distribution from that of the larvae and adults, thus coordinated efforts may be required to adequately sample these stages.

Modeling efforts will require integration of ocean circulation with NPZD type models, to provide spatially explicit environmental conditions. From there, spatial modeling within both Eulerian and Lagrangian frameworks will be required to capture the fundamental biological responses to environmental conditions while accounting for the dispersal of young.

6.1.4. Outputs

- Standardized public data sets of key variables (observations and predictions)
- Development of new standard sampling strategies and tools
- Improved understanding of spatial distribution of spawning and nursery areas
- Improved understanding of processes governing egg, larval and juvenile survival and hence of stock fluctuations in relation to environmental variation
- Improved understanding of the impacts of climate changes on recruitment
- Improved understanding of yearly and decadal scale variability in migratory patterns in relation to environmental cues, and consequent changes in the spatial and temporal distribution of spawning (links with WG2)
- Improvement of existing, and development of new conceptual and quantitative models, leading to a better understanding of the functioning of open ocean ecosystems. Provision of a scientific basis for the development of ecosystem-based management strategies, aimed at the conservation and sustainable exploitation of marine habitats and resources.

6.2. Working Group 2 – Physiology, Behaviour and Distribution

6.2.1. Rationale

Oceanic top predators (e.g. tunas, billfishes, sharks, birds, mammals, turtles) are highly adapted to exploit the pelagic environment. They therefore must deal with the natural variability inherent in this environment occurring over a broad range of scales in time and space. The overarching theme for this Working Group is the challenge of integrating knowledge across scales from processes occurring within organisms and their constituent organs and cells, through individual to population scale spatial dynamics, with time scales ranging from millisecond to multi-decadal.

Physiology and sensory biology

“Physiology” is generally defined as the processes by which organisms maintain a relatively dependable, if not always constant internal milieu, thereby supporting normal cellular function. Physiology is, therefore, the collection of internal cellular and organ-scale processes permitting (amongst other things) the conversion of ingested food to expendable energy for maintenance, growth, locomotion and reproduction, and the detection and capture of prey. For our purposes, however, physiology can best be thought as the **transfer function** that relates the physical environment to the behavior and distribution of oceanic top predators throughout their life cycle. As such, it is essential to develop a thorough understanding of the physiological abilities and tolerances of oceanic top predators in order to understand, and eventually predict, behavior and distribution in time and space.

A thorough understanding of the sensory biology of oceanic top predators is likewise important, as animal behavior is clearly dependent on sensory biology. Sensory mechanisms (vision, olfaction, hearing, electro- and mechano-detection) allow animals to sample their environment in the search for food and mates, and to stay within physiologically tolerable ambient temperature and oxygen conditions. Yet we know relatively little of these mechanisms or the sensory biology of oceanic top predators in general. Clearly, we need to develop a better understanding of sensory systems themselves (i.e. detection thresholds and sensitivities) as well as the properties of any given stimulus being detected (i.e. emission magnitudes/rates). This in turn will permit effective modeling of physical processes taking place that influence the distribution and movement of oceanic top predators at different spatio-temporal scales (i.e. dispersion of smells, propagation of sound, deterioration of visual images, sensing of geomagnetic fields, etc.).

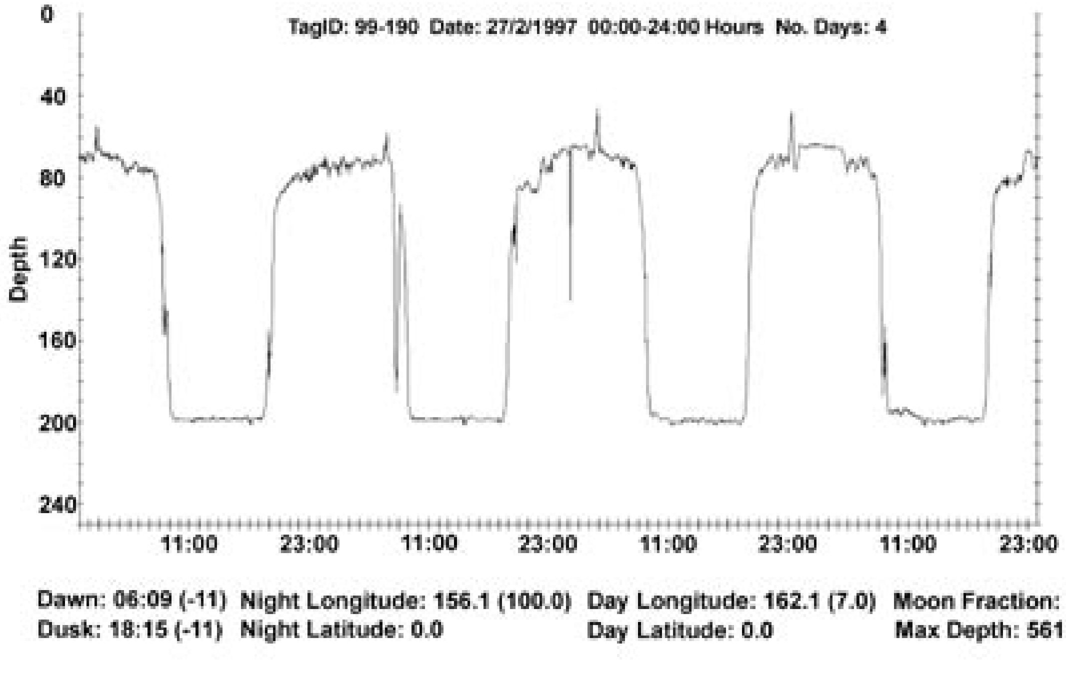
Vertical movements

Oceanic top predators can be broadly classified by a key behavioral trait: the extent of their daily vertical migrations. Some pelagic predators (and their prey) are confined to the surface mixed layer, which is relatively warm, well lit and rich in oxygen, whereas others are able to dive much deeper, across the thermocline, into waters that are dark, cold and contain little oxygen. Species such as bigeye tuna, swordfish, bigeye thresher sharks and leatherback turtles conduct regular migrations to depths in excess of 500 m. Other species, such as yellowfin tuna, are apparently only able to forage within the thermocline and to make occasional but brief excursions to deeper waters. Foraging by birds is confined to surface waters and there are other organisms, such as skipjack tuna and dolphin fish (mahimahi), which are confined to the surface mixed layer and only very exceptionally descend below it, possibly as an escape response to predation rather than for foraging.

As animals undertake these vertical excursions, they are also usually subjected to rapid changes in temperature, pressure, and oxygen conditions. The physiological mechanisms that allow such behavior are, however, complex and are not yet fully understood. For example, blood-oxygen binding characteristics apparently unique to bigeye tuna allow this species to extract oxygen from the low ambient oxygen environments occurring at depth, yet simultaneously deliver and offload oxygen to the tissues quickly enough to support elevated metabolic rates. On the other hand, the more sensitive albacore tunas are apparently far less able to rapidly compensate for depth changes, although quite capable of inhabiting deep ocean environments as they grow to maturity. What specific and unique physiological/biochemical adaptations permit the other parts of the bigeye, albacore, and bluefin tunas cardio-respiratory system (e.g. cardiac muscle) to function under the demanding conditions of cold temperatures and low ambient oxygen occurring at depth remain unknown.

A general pattern observed for vertical migrators is descent at dawn and ascent at dusk (Fig. 7). This behavior allows the various predators to better exploit the movements of the “deep scattering layer” of zooplankton and micronekton, which also migrates towards the surface at night and to deeper waters during the day. If feeding is the motivation for vertical migration of predators then we must assume that this behavior enhances prey capture rates despite the minimal visibility. Hence, prey concentrations must be considerably higher at depth than in surface waters. Furthermore, the vertically migrating predators must have specific adaptations to localize prey organisms at depths only lighted by residual luminosity and the bioluminescence of meso- and bathy-pelagic organisms.

Figure 7. Depth vs. time plot for Bigeye tuna in the southwest Pacific. The data is from an archival tag and shows a clear pattern of depth preference over a 4-day period.



Horizontal movements

Two types of horizontal movements have to be distinguished: exploratory foraging movements that presumably are highly dependent on local environmental features and migratory movements that may be independent of local environmental characteristics (Fig. 8).

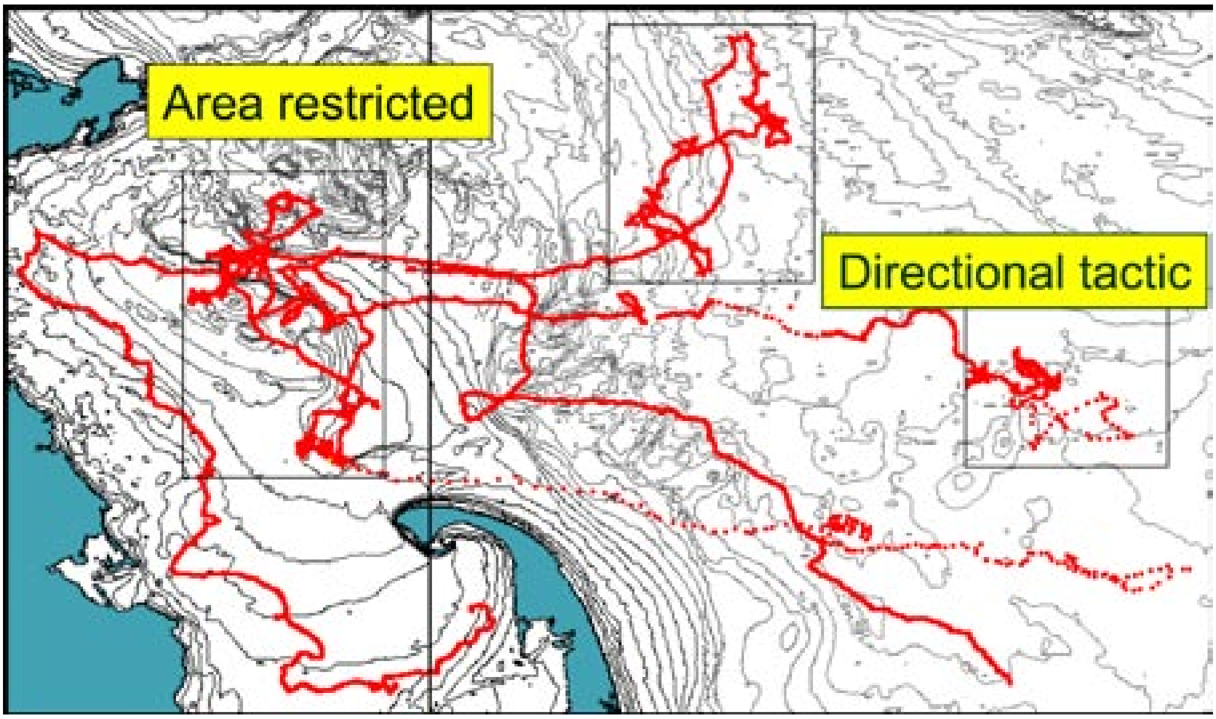
Temperature is a fundamental characteristic of oceanic water masses, driving thermohaline circulation and the redistribution of heat. Horizontal temperature gradients are relevant to oceanic predators, although they are generally two to three orders of magnitude less steep (i.e. Δ°C/unit distance) than vertical temperature gradients, except at fronts that mark the boundary between different water masses.

Chlorophyll (i.e. phytoplankton) concentrations suggest increased productivity at the higher trophic levels which provide prey for the top predators but result in decreased water clarity and therefore visibility. Phytoplankton and zooplankton can also severely reduce oxygen availability. Chlorophyll concentrations in the ocean range across several orders of magnitude, being extremely low in the centre of ocean gyres due to nutrient limitation and much enhanced in upwelling zones and regions of freshwater influence. Water clarity is negatively correlated with chlorophyll concentration, and visual range is exponentially related to water clarity. This means that minor changes in chlorophyll concentration will have major impacts on prey detection rates. Observations that Atlantic bluefin tuna prefer waters in the mid-range of chlorophyll concentrations may reflect this trade off between prey abundance and detectability.

Spatial distribution

Habitat choice in the horizontal dimension is reflected in the different spatial distributions exhibited by oceanic top predators in relation to the dynamics of water masses, features and processes. The spatial distribution of the population at any snapshot in time is the net result of all individual and collective movements. It can be discerned from well monitored fisheries catch and effort data at sufficiently high spatial resolution and then in more temporal detail from conventional tagging (i.e. mark-recapture) studies. The latter are also central to the derivation of population parameters such as natural and fishing mortality based on time at liberty.

Figure 8. Tracks from sonic tagging experiments on North Atlantic bluefin. Two movement modes are apparent: directional movement (i.e. feeding migration) and area-restricted search (i.e. foraging). In feeding areas (boxed) density estimates are 6x higher than outside (Image courtesy of N. Newlands).



The spatial distribution of top predators is often seasonal, with migrations taking place for feeding and/or spawning (Fig. 9). The availability of suitable habitat, including large quantities of prey organisms, can be a major constraint on the spatial distribution of oceanic top predators, particularly for early life history stages. As their spatial distribution becomes more restricted they may become more vulnerable to both environmental and anthropogenic influences on that essential habitat.

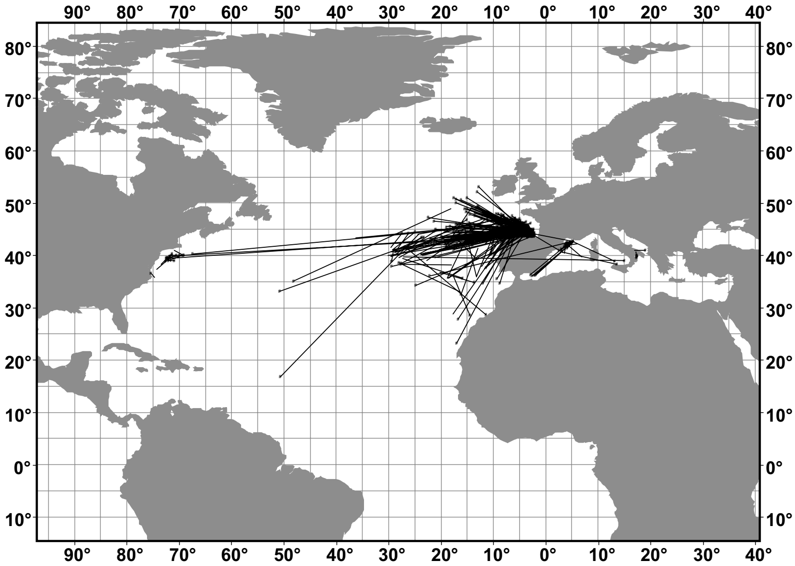


Figure 9. Spatial distribution of albacore in the North Atlantic Ocean based on conventional tagging studies. Adults (>90 cm FL) migrate annually to the Sargasso Sea (western tropical Atlantic) and reproduce in warm waters (>24°C) from April to late September. When the fish become juveniles they migrate towards the central Atlantic and at 6 months they are found wintering close to the Azores Islands. When spring arrives those juveniles move towards feeding grounds in the north east Atlantic (south-west of Ireland, the UK and the Bay of Biscay), following the seasonal warming of sea surface temperature. This allows the development of summer surface fisheries. At the end of summer and beginning of autumn these fish return to the wintering area near the Azores. Albacore in the Mediterranean form a different stock from the Atlantic (Image courtesy of Haritz Arrizabalaga)

6.2.2. Key questions

Question 1: To what extent do spatial dynamics result from proximate cues and to what extent is spatial dynamics independent of local environmental cues?

Oceanic top predators sense various environmental properties at finer scales than we are usually able to observe ourselves. Whether environmental information is relevant to behavior and spatial dynamics depends on the context and scale of observation. For example, average and/or large-scale distributions of top predators might be clearly related to environmental variables (e.g. sea-surface temperature or mixed layer depth) but finer scale observations might be more influenced by processes that are often averaged out or not observed (e.g. food availability, predator avoidance). We also seek to distinguish exploratory foraging behavior, which presumably is highly dependent on local environmental cues, from migratory movements where the local environmental characteristics must be endured whether or not it is especially favorable.

Question 2: How does school size and fidelity vary in relation to environmental variability and climate change?

Associative behavior, whether to conspecifics (schooling) or to some other external factor (aggregation to fronts or FADs), is often observed to varying extents in oceanic top predators. There is often an ontogenetic shift in associative behavior, with juveniles being more social or otherwise aggregated than adults (e.g. North Pacific albacore, southern bluefin tuna), but some species are generally gregarious throughout their lives (e.g. skipjack tuna, Atlantic bluefin tuna). The degree of social interaction and aggregation often determines where, when and how top predators are targeted by fisheries and so any changes in aggregative behavior will have broader implications. For example, both yellowfin and skipjack tuna schools appear to aggregate as a function of the gradient in thermocline depth, highlighting the importance of ocean observations in order to interpret CPUE.

Question 3: What determines the time and place of reproductive and feeding-related behavior?

Feeding and reproduction are the most important behavioral processes required to sustain and perpetuate populations of top predators. Instantaneous habitat choice in pursuit of successful feeding can be considered as a process optimizing energy balance and thereby allowing growth and sexual maturation. Some species of top predators are plastic in their choice of spawning grounds (e.g. skipjack, yellowfin), while others (e.g. bluefin tuna, turtles, albatrosses) are restricted in their time and areas of spawning. Therefore there is a need to identify areas and times favorable to larval survival and growth (i.e. high food, low predation), to identify what mechanisms determine the shift between both reproductive and feeding-related behavior, and whether there are differential impacts of long term climate change on species with different reproductive strategies.

Question 4: How do anthropogenic forces such as fishing interact with environmental impacts on distribution and population structure?

The different external factors imposing variability in the population dynamics and distribution of top predators include both environmental and anthropogenic forcing. The most obvious example of the latter is the direct removal of individuals from populations by fishing, through deliberate capture of targeted species or incidental capture of non-targeted species. Fishing also has indirect effects on predator populations. The widespread use of fish aggregating devices (FADs) may adversely impact both small-scale foraging behavior and large-scale migrations to the extent that associative behavior of tunas becomes maladaptive. Populations of top predators may also be impacted by other human activities such as predation and/or destruction of beach nesting sites in the case of marine turtles, and the effects of pollutants. It is an analytical challenge to isolate the effects of different causes of population variability but such analysis will be of most use for resource management.

6.2.3. Implementation

Investigation of the research themes identified by this working group will be carried out through collation and comparison of results from controlled laboratory experiments, conventional and electronic tagging experiments and a suite of modeling studies. Existing data will be re-analyzed and new studies proposed. Standardizing data, methods and scales are high priority to achieve CLIOTOP WG2 objectives. We will also promote the development of new technologies to support our research.

Comparative studies

Comparative analysis is a key aspect of CLIOTOP. This working group will investigate spatial and temporal coherence among physical and biological variables at a range of scales within each ocean, and compare the behavior and distribution of any one species in relation to the physical characteristics of the ocean basins in which it resides. Comparisons between species will investigate different physiological and behavioral traits in relation to possible impacts of climate variability and change. Case studies for this work will focus initially on the following, for which there are existing datasets:

- Albacore tuna in the north Atlantic and north Pacific
- Bigeye tuna in the Indian Ocean, the Pacific and the east Atlantic
- Bluefin tuna in the north Pacific and north Atlantic, and also southern bluefin tuna
- Skipjack tuna in the Atlantic, Indian and Pacific Oceans
- Yellowfin tuna at the basin scale, little tagging to date
- Leatherback and loggerhead turtles in the Atlantic and Pacific
- Laysan and black-footed albatross populations in the Pacific

Table 1. Data available for comparative studies. Before comparative studies can proceed, these data need to be made available to CLIOTOP researchers in an easily accessible, consistent format and with metadata documenting inherent constraints to the application of the data to specific analysis. Additional field work is required to address some of the more significant data gaps.

Data type	Fisheries			Conventional			Archival			Satellite			Acoustic		
Species or group	Atlantic	Indian	Pacific	Atlantic	Indian	Pacific	Atlantic	Indian	Pacific	Atlantic	Indian	Pacific	Atlantic	Indian	Pacific
Albacore	✓	✓	✓	✓	×	✓	✓		✓		×	✓		×	✓
Bigeye	✓	✓	✓	✓	✓	✓	✓	✓	✓		×	✓		×	✓
Bluefin	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Skipjack	✓	✓	✓	✓	✓	✓	×	×	✓	×	×	×		✓	✓
Yellowfin	✓	✓	✓	✓	✓	✓	×	✓	✓		×	✓		✓	✓
Billfish	✓	✓		✓	×	✓		×	✓	✓	×	✓	✓	×	✓
Sharks	✓	✓	✓	✓	×	✓		×	✓	✓	×	✓		×	✓
Turtles	✓		✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	×	✓
Mammals				✓	✓	✓	✓	✓	✓	✓	×	×	✓	×	✓
Birds		✓		✓	✓	✓	✓	✓	✓	×	×	×	×	×	×

✓: data exist ×: data do not exist blank: data not known to exist

Technological frontiers

Field studies on the physiology, behavior and distribution of pelagic predators are highly dependent on the availability of appropriate technology. From physiological microsensors through multi-sensor drifting buoys to autonomous tracking vehicles and space-based satellite remote sensing, there are a range of technologies which need to be encouraged in order to address the aims of the project and of this working group in particular. Some examples are listed below:

- Listening stations around FADs and moorings
- Drifting buoys that sample water column properties (e.g. temperature, oxygen, chlorophyll)
- Autonomous Underwater Vehicles (AUVs) that can be used for tracking predators
- Automatic acoustic surveys of forage distribution using hydrophone arrays or AUVs
- Tags that record the presence of other fish
- Tags that record internal condition (hunger state, feeding events, energy reserves)
- Tags that record swimming speed (burst, cruise), tail-beat frequency
- Tags that deliver higher geolocation resolution

Modeling studies

A key component of the CLIOTOP project is the development of models to integrate and quantitatively represent available knowledge and to explore scenarios for relating the impacts of credible climate changes on oceanic top predators. In this working group there will be an emphasis on spatially explicit models representing individual/population response to environmental variability at various scales. These will include the following approaches, all of which incorporate observed and/or modeled oceanographic data:

- Individual Based Models (IBMs): Mechanistic models of physiology-environment-behavior
- Rule-based models based on data from tagging/laboratory studies
- Large-scale deterministic models of population dynamics (e.g. Advection Diffusion Reaction Models or ADRMs)
- Statistical movement models (e.g. Markov Chain Monte Carlo models)
- Scale-spanning models that are compatible with both IBMs and ADRMs

Parameters essential to the models will be derived from direct measurement or estimated within the model, either through simulated evolution in the case of life-history models, or by optimization comparing model output with observations.

Links to other Working Groups

- Characterization of spawning grounds in relation to oceanography (WG1)
- Characterization of feeding grounds, acoustic studies of forage distribution (WG3)
- Quantitative integration of knowledge through development of models at various scales (WG4) including ecological (WG3) and socio-economic (WG5) interactions

6.2.4. Outputs

- Standardized public data sets of key variables (observations and predictions)
- Development of new standard sampling strategies and tools
- Improved understanding of spatial distribution and migration routes of the main top predator species
- Improved understanding of processes governing the vertical and horizontal behavior of top predator species
- Improved understanding of yearly and decadal scale variability in migratory patterns in relation to environmental cues, and consequent changes in the spatial and temporal distribution of forage distribution (links with WG1)
- Improvement of existing and development of new conceptual and quantitative models
- Collaborative papers in peer-reviewed journals detailing results of comparative and retrospective analysis and the development and application of models.

6.3. Working Group 3 - Trophic Pathways in Open Ocean Ecosystems

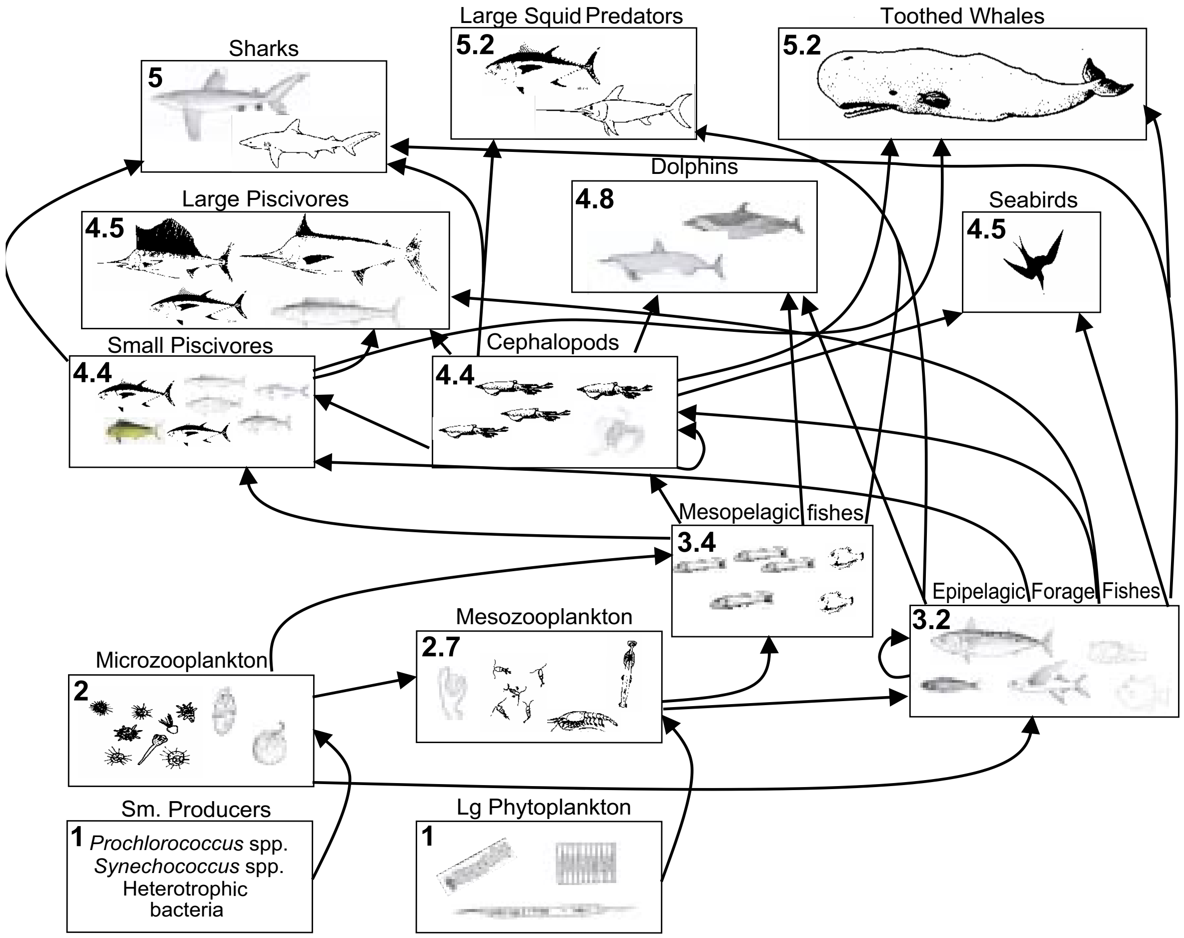
6.3.1. Rationale

There is growing evidence that climate variability affects primary producers in marine systems, imparting bottom-up forces on food webs via trophic pathways. Simultaneously, fisheries removals of upper-level predators can have cascading effects on the underlying trophic levels. The objective of CLIOTOP Working Group 3 (WG3) is to obtain an improved understanding of the trophic pathways that underlie the production of tunas and other oceanic top predators, and the natural variability forced by the environment.

Classical diet studies have provided most of the historical information on trophic pathways in pelagic ecosystems. The subjects of these studies have most often been the animals occupying the upper trophic levels (Fig. 10), because they are the objects of fisheries or because of their sensitive status. These include several species of tuna and tuna-like fishes, dolphins, swordfish, and seabirds. Many of these are near, but not at the apex of the food web (Fig. 10). More recently, attention has focused more on the top predators taken incidentally by high-seas tuna fisheries, and research efforts to discern their trophic ecology have increased. These top predators include marlins and sailfishes, sharks, and toothed whales.

The largest gap in our knowledge of trophic pathways in pelagic ecosystems remains the intermediate trophic levels. The small fishes, cephalopods, and crustaceans that occupy intermediate trophic levels (Fig. 10) comprise the forage base of the predators that are the targets or bycatches of pelagic fisheries. There is clearly a need to delineate the key trophic pathways linking primary production to the upper trophic levels through the forage groups, and to understand how the sources of primary production and trophic pathways change among productivity regimes and ecosystems. Research coordinated by WG3 will be carried out in a multiplicity of regions and oceans. In the first instance, however, the main focus will be on the eastern and western tropical Pacific Ocean, the western temperate Pacific Ocean, the eastern Atlantic Ocean, and the western Indian Ocean.

Figure 10. Major components of pelagic ecosystems, indicating approximate trophic level (in each box) and the principal trophic pathways between components. Baleen whales (trophic level 3.8), and their principal pathways to mesozooplankton and epipelagic forage fishes, are not shown. After Olson and Watters (2003). Some graphics provided by A. Fonteneau.



6.3.2. *Key questions*

Question 1: What are the main trophic pathways and how do they differ within and among oceans?

Modeling is an important tool for exploring the ecological consequences of fishing and improving our knowledge of how climate variability influences the structure and function of ecosystems. However, models of open ocean ecosystems are few, and often rudimentary. Key inputs for these models derive from the qualitative and quantitative representations of trophic pathways of key taxa and functional groups. Identifying the dietary components of key predator taxa using stomach contents analysis remains the foremost tool of the trophic ecologist to identify the pathways linking key components and functional groups. However, stable carbon and nitrogen isotope analysis (SIA) is a powerful new technique for delineating and quantifying trophic pathways in food webs, and discerning the relative trophic positions of the component species. SIA has been applied to many problems in ecology, but only recently is being used in open ocean ecosystems. New techniques and better mass spectrometers have resulted in the potential for analyzing greater sample sizes at lower cost and greater reliability.

Question 2: Is there evidence of change in trophic pathways over time and space consistent with climate variability. Can seasonal and spatial variability be used to explore the impacts of climate variability?

Variability in food web structure forced by the environment should be explored at contrasting temporal and spatial scales. Further insight in understanding the effects of long-term climate change might be forthcoming if an assumption can be justified that variability observed at seasonal or inter-annual scales provides a corollary to ecosystem changes due to long-term climate change. For example, ocean general circulation models have generated hypotheses describing the future response of the El Niño-Southern Oscillation (ENSO) in the equatorial Pacific Ocean to greenhouse warming during the 21st century. Some models have predicted a gradual shift of average oceanic conditions toward present-day El Niño conditions, but with increased amplitude and frequency of ENSO events. Thus, emphasis on understanding ecosystem responses to present-day inter-annual and decadal environmental events should be encouraged. In addition, insight will derive from comparisons of spatially-adjacent food webs in regions of diverse oceanography, such as the studies described for Question 1.

Question 3: What is the relative importance of mesopelagic versus epipelagic prey resources to oceanic top predators, and how does this vary within and among oceans. How does climate variability affect the distribution and availability of mesopelagic and epipelagic prey?

Tunas and other oceanic top predators utilize mesopelagic and epipelagic prey communities in different degrees in different regions and oceans. Some tuna species, for example, feed deeper than others, and evidence indicates that the same species often relies on different proportions of mesopelagic and epipelagic forage organisms in different regions. Once the main trophic pathways of different species are better known (Question 1), it is important to understand the dynamics that influence mesopelagic/epipelagic tradeoffs in trophic pathways among productivity regimes and ecosystems.

The mesopelagic community constitutes an important prey component of many large pelagics. Whereas the large scale horizontal distribution of those organisms largely constrains the movements of large predators, the spatio-temporal distribution and dynamics of those communities are poorly known. Furthermore, their vertical distribution, diel vertical migrations, and small scale schooling structure determine their accessibility to predators.

Question 4: Is it possible to identify indicators, such as prey species or size spectra, that would highlight significant changes in trophic pathways?

As fisheries scientists and managers expand their attention from single species to ecosystems, community metrics based on the composition of species assemblages are increasingly sought. Indicators for assemblages and communities should be responsive to changes in trophic pathways forced from both the bottom up by climate variability and the top-down by fisheries. These may include prey species, functional groups, and size spectra in the stomachs of key predators and in the environment, detected by acoustic methods.

Changes in trophic pathways that may occur during climate regime shifts can involve major portions of entire ecosystems, but may become detectable only after several years of observation of a variety of species at a variety of scales. By closely associating observation (Question 1), modeling (Question 1), and retrospective analyses (Questions 2 and 4), patterns of responses that could serve as indicators of change may be derived. Accumulating empirical data is essential for developing a basic understanding of size-spectral and other characteristics of food webs.

6.3.3. Implementation

Diet analysis

One of the tasks of WG3 will be to standardize methods of diet analysis. Some studies, particularly the earlier ones, did not identify prey to the lowest taxon possible, and this limits the utility of these data for making comparisons. Whenever possible, three indices of dietary importance, weight (W) or volume, number of individuals (N), and occurrence (O), should be measured in concert, and interpretation should never be based entirely on the Index of Relative Importance (IRI). Rates of food consumption are important inputs for ecosystem models, and methods of approximating daily rations when insufficient information exists for direct estimates should be encouraged.

Stable isotope analysis

Research efforts incorporating SIA are recently underway or being planned in the Pacific, Atlantic, and Indian Oceans. In the Pacific, food-web patterns are being studied on large-, medium-, and small-scale. A three-year study of the pelagic food webs in the eastern, central, and western equatorial Pacific is completing its first year. A medium-scale project will start in 2004 in the eastern Australian ecosystem to study food-web patterns of tunas and other pelagic predators in relation to the regional oceanography. Near the Hawaiian Islands, SIA is being used to study the trophic patterns of tunas that associate with natural and man-made aggregating structures. In the eastern Atlantic and western Indian Oceans, studies of trophic pathway are conducted in selected pelagic areas that exhibit features common to both oceans (convergence zones where tunas are caught in association with drifting FADs, spawning zones of yellowfin tuna (*Thunnus albacares*), and areas where tunas and marine mammals are associated). This research program began in 2001 and will continue through 2004. Another quadrennial program focusing on the Indian Ocean is planned to begin subsequent to the current program. In the north-western Atlantic, diet and stable isotope techniques were used recently to examine the trophic status of bluefin tuna (*Thunnus thynnus*) in New England waters.

CLIOTOP will provide the forum to standardize research approaches and analytical methods of SIA in open-ocean ecosystems. For example, comparisons will be useful for establishing the role of Particulate Organic Matter (POM) in defining the stable isotopic signature at the base of the food web. Filter-feeding organisms encrusted on oceanographic buoy arrays (TAO/TRITON in the Pacific Ocean, PIRATA in the Atlantic Ocean, IO-GOOS in the Indian Ocean) are easy to collect, and are expected to integrate the isotopic signal of POM over time. Their utility for establishing the long-term baseline of the food web should be explored.

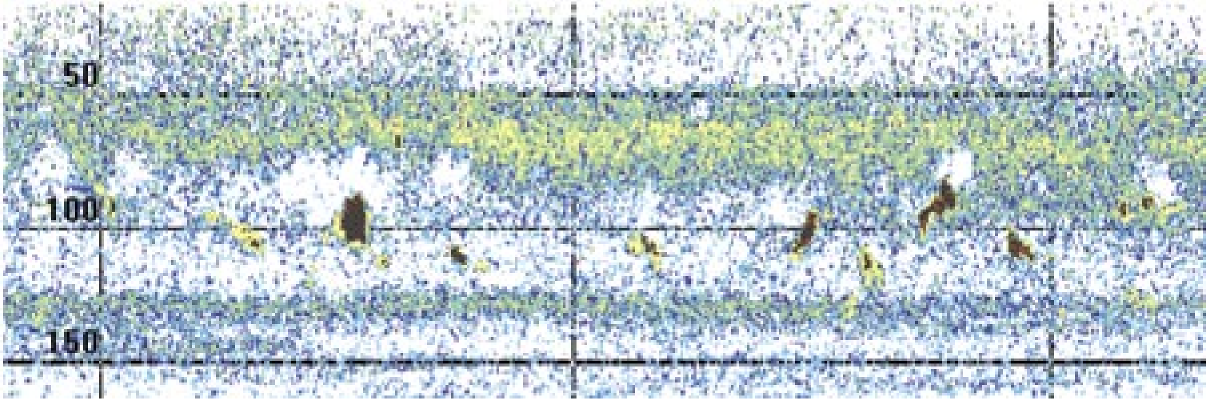
Methods also need to be developed to analyze frozen zooplankton for stable isotope composition, either in bulk or by taxonomic or size strata. Forage (prey) animals can be obtained for SIA from the stomach contents of their predators, by dipnetting from drifting vessels at night, and from trawls. Considerable interest exists in determining to what degree mixing rates and diet switching can be inferred by analyzing the stable isotopes in tissues that turnover at markedly different rates (e.g. muscle and liver). Efforts to experimentally measure differential tissue turnover rates in captive tunas should be promoted.

Hydroacoustics

Acoustic methods have the potential to provide simultaneous two- or three-dimensional observations of various communities of the ecosystem, from plankton to large predators, at a variety of scales. Hydroacoustic studies enable the direct observation of ecological relationships (Fig. 11) and can provide quantitative estimates of forage biomass. Given the spatial extent of open-ocean pelagic ecosystems, technological innovations are required. For example, automated acoustical monitoring stations might be incorporated on existing oceanographic buoys or onboard commercial vessels. These monitoring stations could incorporate autonomous calibrated scientific echo sounders with automatic data analysis and processing.

Prey size spectra and functional groups (e.g. epipelagic micronekton, mesopelagic micronekton, and epipelagic-mesopelagic vertical migrants) which could be used for building ecosystem indicators could be monitored using acoustic methods.

Figure 11. Acoustic observation of horse mackerel (dense patches) foraging in a scattering layer of mesopelagic fish during the night and depleting it locally (courtesy of A. Bertrand).



Comparative and retrospective analyses

Tunas and other pelagic predators are better samplers of micronekton forage taxa than scientists are. Existing diet data, if analyzed in a comparative approach, may provide previously undetected evidence of change in trophic pathways within ecosystems. Numerous diet studies of tunas have been conducted in many regions and over different time periods. Recovery, compilation and retrospective analysis of these data should be encouraged. Inherent difficulties in conducting such an analysis owe primarily to the relatively short temporal and spatial scales of some of the studies and to the unequal taxonomic resolution in the identification of prey items. These problems notwithstanding, large-scale patterns in the occurrence of common prey taxa compared with environmental patterns may yield insights. Of special interest are spatially-adjacent food webs in regions of diverse oceanography.

Retrospective analyses of the data from historical micronekton and ichthyoplankton surveys may hold promise for identifying indicators of change in trophic pathways. Acoustic studies, conducted in several areas and oceans, could also yield clues when compiled and subjected to retrospective analysis.

Modeling

Accurate representations of food-web dynamics in ecosystem models are essential for evaluating the top-down implications of fisheries management measures on ecosystems via trophic interactions, undetectable in single-species stock assessment models. Existing models of open-ocean pelagic ecosystems describe the western and central Pacific Ocean, the eastern tropical Pacific Ocean, the eastern Atlantic equatorial area, and the south-eastern Australia. The latter study will soon be extended to cover the area fished by the Australian longline fishery off eastern Australia. In collaboration with WG4, methods to evaluate these models should be sought, especially through comparisons among them and with other modeling approaches. Efforts to validate the models should be increased, using all available observations, such as fisheries data and stable isotope data.

6.3.4. Outputs

- Standardized public data sets of key variables (observations and predictions)
- Development of new standard sampling strategies and tools
- Improved understanding of trophic structures in the pelagic ecosystem leading to the main top predator species
- Improvement of existing and development of new conceptual and quantitative models (link to WG4)
- Collaborative papers in peer-reviewed journals detailing results of comparative and retrospective analysis and the development and application of models.

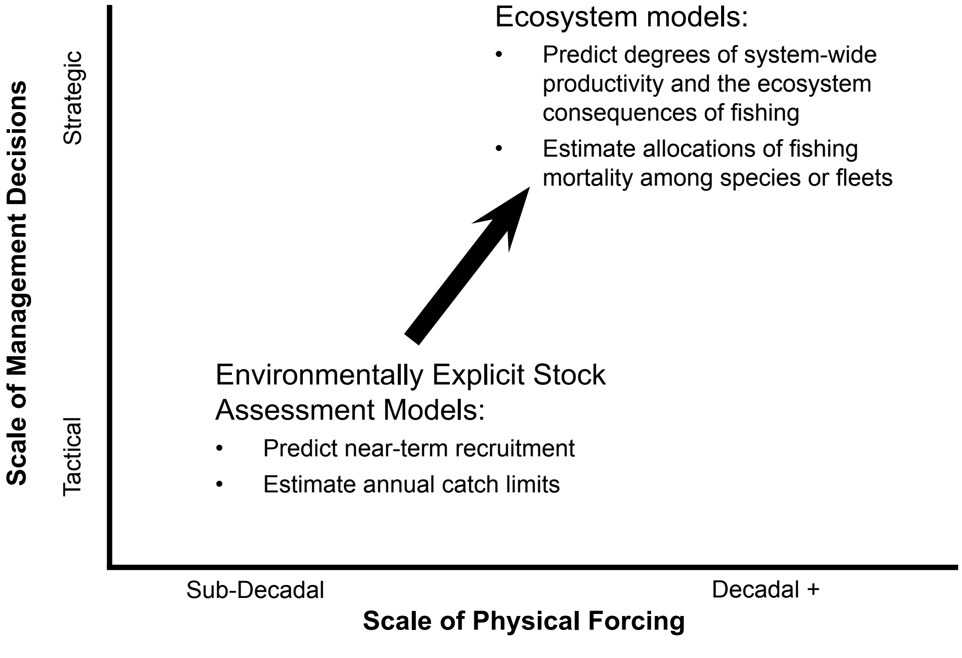
6.4. Working Group 4 - Synthesis and Modeling

6.4.1. Rationale

The modeling approaches that are adopted and developed by the Synthesis and Modeling Group will provide an array of predictive capabilities. Since no single modeling approach is likely to have predictive power at all spatial and temporal scales of interest and management decisions must be made on both strategic and tactical scales, embracing a variety of approaches is essential. In general, models with a larger ecological scale (e.g. trophically or spatially explicit ecosystem models) are expected to describe decadal scale forcing related to changes in whole-system productivity, predict the ecosystem consequences of changes in system productivity and fishing mortality, and provide strategic management advice (e.g. advice on allocating fishing mortality under alternative productivity regimes) (Fig. 12). In contrast, models with smaller ecological scales (e.g. single-species assessment models that include environmental forcing) will typically describe sub-decadal scale forcing on population-dynamics processes like recruitment, predict the consequences of environmentally-forced variability in these processes under alternative patterns of fishing mortality, and provide tactical management advice (e.g. annual harvest quotas). Maintaining an appropriate perspective on the predictive capacities of models developed by the Synthesis and Modeling Group is important because, despite the CLIOTOP's important work to understand the effects of climate forcing and fishing on high-seas pelagic ecosystems, it seems likely that uncertainty about the structure and function of these ecosystems will remain substantial.

Quantitative indicators that characterize ecosystem status and the ongoing performance of fishery management systems can forge links between resource managers, stakeholders, and scientists. Such indicators provide a mechanism for discussing the conservation and exploitation of living marine resources in an ecosystem context, and the Synthesis and Modeling Group will endeavor to identify a set of indicators that can be easily communicated among these constituent groups. The Synthesis and Modeling Group will use models both to develop potentially useful indicators and to evaluate them. Environmental (e.g. sea-surface temperatures and winds in an area critical for recruitment) and ecological (e.g. the species composition of bycatches) indicators can be used to characterize the probability of recent and impending changes in ecosystem structure and function.

Figure 12. Schematic description of the likely predictive capacities and management utilities of current modeling tools that will be developed by the Synthesis and Modeling Group.



Economic indicators are widely used as the basis for tactical and strategic decision making both by individual stakeholders (e.g. personal investors) and by business managers (e.g. in determining interest rates and commerce strategies). Appropriate environmental and ecological indicators have similar potential to be used by stakeholders and resource managers who make decisions related to the conservation and exploitation of living marine resources. Economic indicators are also used to measure performance (e.g. gross domestic product), and analogous indicators can be used for measuring success in meeting conservation and exploitation objectives for high-seas pelagic ecosystems. Developing such "reference points" for marine ecosystems is a challenge that is currently being addressed in many fisheries forums. The Synthesis and Modeling Group will be uniquely placed to respond to this challenge, and will capitalize on its development of multiple modeling approaches to identify a suite of potential ecosystem reference points that are pertinent to the management of oceanic fisheries.

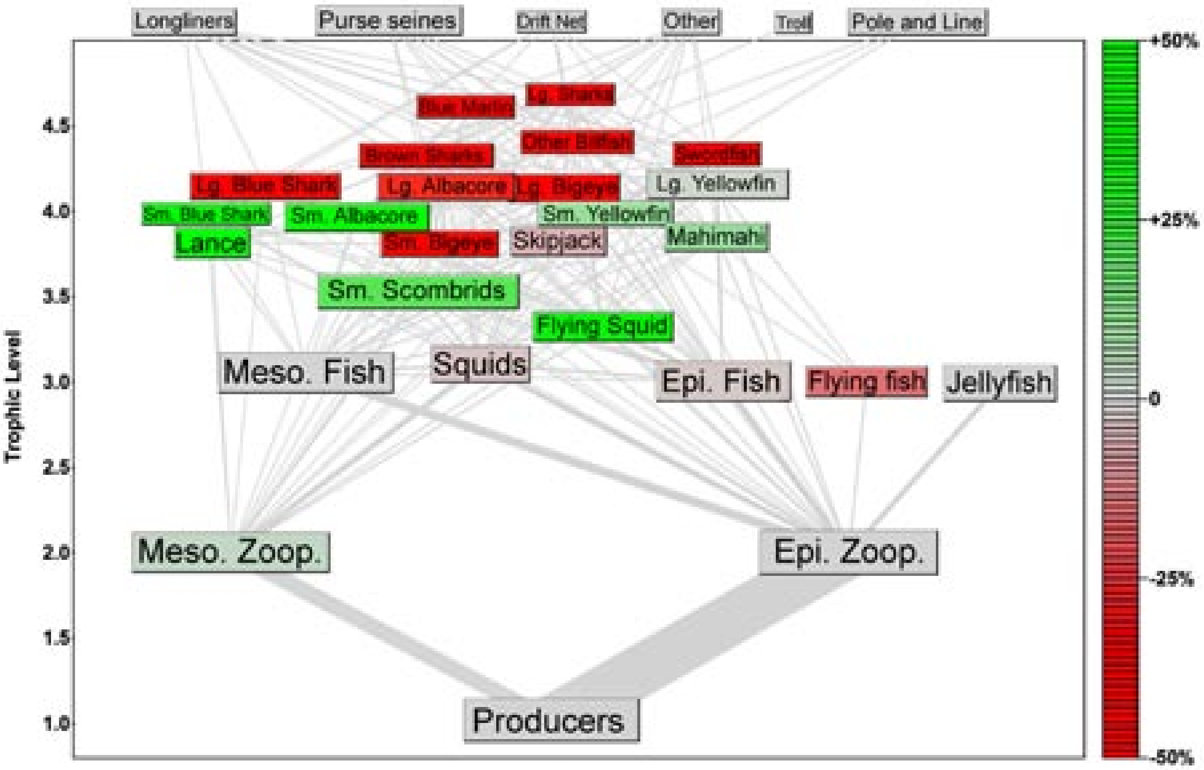
6.4.2. Key questions

Question 1: What is the relative importance of fisheries exploitation and the dynamic environment in structuring pelagic ecosystems?

The first question is motivated from recent suggestions that changes in primary production rarely cascade upward to affect biomass of marine pelagic consumers and the recognition that fisheries have reduced the abundance and biomass of predators at high trophic levels throughout the world's high-seas pelagic ecosystems. Results from different modeling approaches differ in the explanation of the mechanisms that control interannual variation of tuna populations in the high-seas pelagic ecosystems. Cox *et al*. (2002) using a trophically explicit but spatially aggregated model suggest that the increase in biomass of yellowfin tuna in the recent decades is due to a decline in predation mortality of young fish associated to the removal of their main predators (sharks, blue marlin) by the fisheries. Watters *et al*. (2003) used a trophically explicit but spatially aggregated model and found that a parameterization with only bottom-up forcing could not produce a realistic amount of variation in the recruitment of yellowfin tuna. Conversely, Lehodey *et al*. (2003) using a spatially explicit but trophically aggregated ecosystem model found that skipjack tuna recruitment fluctuations are controlled through physical (temperature and advection), bottom-up (primary production being food of larvae) and "middle-down" (larvae predation by epipelagic micronekton) rather than top-down mechanisms, the intermediate "middle" component including the juvenile tuna.

Regardless of these results, it is clear that bottom-up processes form a template on which top-down forces act, and low-frequency (e.g. decadal) variation in system-wide productivity must be controlled from the bottom of high-seas pelagic food webs. Furthermore, spatial heterogeneity of fisheries and regionalization of ecosystems play a crucial role which has not yet been analyzed. Ocean basins are indeed highly heterogeneous and regional ecosystems may be structured in completely opposite ways. Neglecting this heterogeneity may be misleading. Hence, whether fishery removals have caused cascading effects throughout open ocean ecosystems remains unclear. Several authors using the same trophically explicit but spatially aggregated modeling approach (ECOPATH) came indeed to different conclusions on this topic. Except for yellowfin tuna (cf. above), Cox *et al*. (2002) had difficulty detecting substantial cascading effects from fishery removals of high-level predators in the central north Pacific, and commented that this difficulty most likely resulted from an inherent limitation in the modeling approach. In contrast, Hinke *et al*. (2004) suggested that declines in high-level predator biomass have cascaded through high-seas pelagic ecosystems in the Pacific, causing increases in the biomass of some animals at middle trophic levels (Fig. 13).

Figure 13. Predicted consequences of fishing in the central north Pacific. Historical (1951-1999) patterns of fishing effort were used to predict how removals of top predators might have had cascading effects throughout the food web. Each box in the food web diagram is colored according to an estimate of relative biomass in 1999, where the reference conditions are from a simulation with no fishing mortality. Animals at middle trophic levels (e.g. small scombrids and flying squid) are predicted to have benefited from the removal of predators. Source: Hinke *et al* (2004).



Other workers have suggested additional complications. For example, fishing might exacerbate environmental effects by trapping fish in less productive areas (Menard *et al*., 2000) , or environmental effects might buffer the effects of fishing. Despite a suite of recent papers, there is substantial uncertainty about the degree to which fishery removals of high-level predators cascade through such ecosystems. The topic cannot be adequately addressed without simultaneous consideration of fishing and climate forcing, and, therefore, the models developed by the Synthesis and Modeling Group will include both effects.

Question 2: Does one mechanism (e.g. match/mismatch) explain observed variation across species, trophic pathways, regions, etc.? Do alternative mechanisms have equally good explanatory power? Which mechanism(s) provide the greatest predictive power?

Question 2 is motivated by the recent work of Patrick Lehodey and colleagues. Estimates of recruitment for three tuna species from the Pacific are correlated with climate indices that reflect differences in the intensity and frequency of El Niño and La Niña events (Fig. 14). Two tropical species, skipjack and yellowfin tunas, appear to have increased recruitment during periods dominated by El Niño, while the recruitment of a subtropical species, albacore, is apparently increased during periods dominated by La Niña. Lehodey *et al*. (2003) suggest that this pattern of opposite effects is produced from the match/mismatch mechanism of favorable conditions controlled by advection, temperature and the ratio between food and predators of larvae. In the western and central Pacific, primary production in the main spawning grounds of yellowfin and skipjack tunas is determined by environmental conditions that vary out of phase with those in the spawning grounds of albacore. Thus, conditions that set up a match between primary production and spawning activity for yellowfin and skipjack may, simultaneously, set up a mismatch for albacore. This mechanism is appealing because the ecosystem model used by Lehodey *et al.* (2003) can reasonably describe both time series variation in skipjack biomass and spatial variation in skipjack catches. A similar model has also been developed for yellowfin tuna in the Atlantic (Maury *et al*., 2001) . Although Lehodey *et al*. argue that "recruitment is the fundamental process that drives population biomass variability of tropical tunas," the match/mismatch hypothesis does not need to be invoked to explain recruitment variation. Various other mechanisms might influence recruitment by acting on mature fish rather than larvae. While developing an individual-based model to describe foraging behavior, Kirby *et al*. (2000) illustrated how the general reproductive ability of an individual tuna (including, but not limited to, skipjack) might vary substantially as a function of its energy reserve and thermal stress. Thus, multiple hypotheses can be forwarded to explain variation in the dynamics of pelagic fishes like tunas, but a concerted effort to evaluate a suite of hypotheses within a comparative modeling framework has yet to be undertaken. The Synthesis and Modeling Group will, therefore, make important and useful contributions by addressing this question.

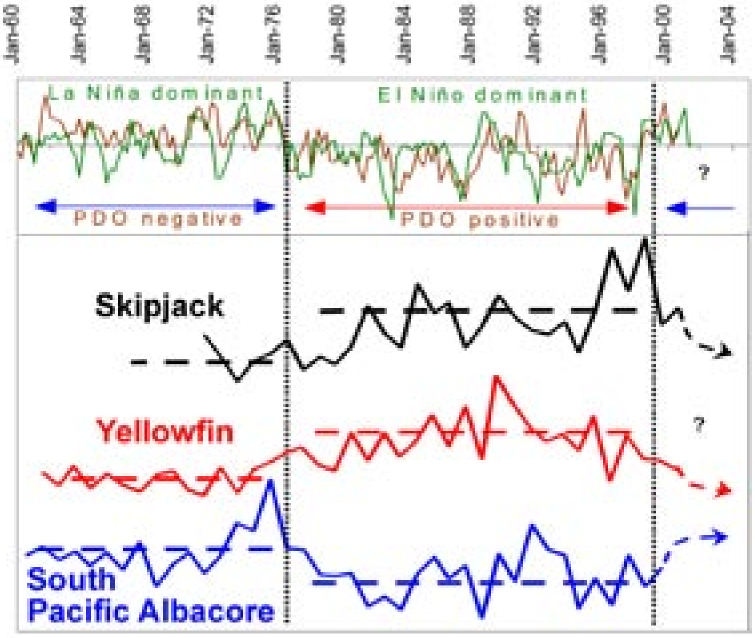
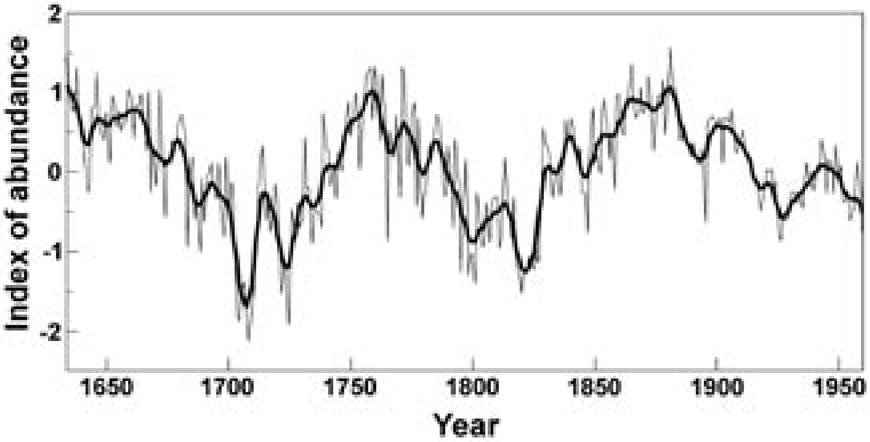


Figure 14. Variations in the Southern Oscillation Index (green line), the Pacific Decadal Oscillation (brown line), and recruitment of three tunas from the Pacific Ocean. Source: Lehodey *et al*. (2003).

Question 3: What alternative states might occur in pelagic ecosystems, how might they be characterized (e.g. can they be described by indicators), how might they be caused, what are their consequences, and are they reversible, given that the climate changes continuously?

Question 3 is motivated by the comparison of open ocean ecosystems to other marine ecosystems. Many workers have identified dramatic state shifts in benthic and coastal pelagic ecosystems (Jackson *et al*., 2001) . For example, there have been shifts between shrimp-dominated ecosystems and gadid-dominated systems in both the north Pacific and the north Atlantic (Botsford *et al*., 1997; Worm and Myers, 2003), and shifts between sardine-dominated and anchovy-dominated ecosystems off the coasts of California and Peru (Chavez *et al*., 2003). These shifts occur on time scales that are at least decadal and have been attributed both to climate forcing and to top-down forcing. Such dramatic shifts have scarcely been identified in high-seas pelagic ecosystems, where variability is most recognizable at sub-decadal time scales. Hints of decadal scale shifts in ecosystem structure are, however, indicated by periods of increased or decreased productivity for a few predator species (Figs. 14 and 15), but there is little or no indication that these changes are linked to simultaneous effects on animals at other places in the food webs supporting these predators.

Figure 15. Relative abundance of bluefin tuna from the eastern Atlantic and Mediterranean. The bold line is considered to be an index of abundance that is representative of long-term trends in abundance. The index illustrates periods of increased and decreased abundance with long-term cycles that have a period of approximately 100 years and medium-term cycles of about 20 years. The index was developed from historical records of catches in bluefin traps. Source: Ravier and Fromentin (2001) .



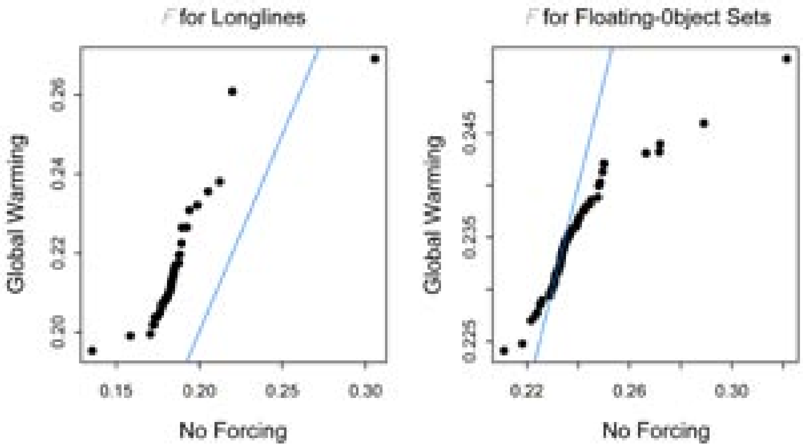
Question 4: Does knowledge about environmental forcing and the nature of fisheries (e.g. the species composition of the catch, growth variability, egg production rates by size/age) suggest an optimum allocation of fishing activities?

Many workers have noted that predictions about the effects of climate change must be considered in the context of possible, concomitant, changes in fishing mortality (Jurado-Molina and Livingston, 2002) , but it is unclear whether such predictions suggest an optimal allocation of fishing mortality. The final question that will be addressed by the Synthesis and Modeling Group is motivated by recent, unpublished work that was developed from work conducted by Watters *et al*., (2003). Since different fleets (or fishing methods) catch a different mix of species (both as targets and as bycatches), impacts of these fishing fleets are supported by different regions of the trophic web. Hinke *et al*. (2004) illustrated that, in the Pacific, the food webs supporting longline fisheries have been generally more complex than those supporting purse-seine fisheries. These differences suggest that how an ecosystem responds to top-down influences from fishing may depend on the allocation of fishing mortality among long-lining and purse seining.

Similarly, since the species and size compositions of the phytoplankton can change in response to climate forcing, the pathways transporting energy from the bottom of the food web may also be influenced by climate. Together, these observations suggest that an "optimal" allocation of fishing mortality among gear types might be determined if: 1) a management objective is quantitatively specified, perhaps in relation to an ecological indicator or reference point, and 2) an hypothesis about the nature of climate forcing is considered.

Watters and Olson (unpublished data) illustrated this concept using the ecosystem model developed by Olson and Watters (2003). Watters and Olson specified an arbitrary management objective and solved for two "optimal" sets of fishing mortality rates: one solution for a case in which no climate forcing was assumed to exist, and one for a case in which global warming was assumed to change the species and size compositions of the phytoplankton in the eastern tropical Pacific (Fig. 16). Model predictions suggested that the optimal allocation of fishing mortality might depend on climate forcing, but the results of such an exercise are sensitive to the management objective that is specified. Therefore, identifying appropriate and useful indicators and reference points for high-seas pelagic ecosystems will be paramount when the Synthesis and Modeling Group addresses its fourth working question.

Figure 16. Quantile-quantile plots of solutions to an optimization problem in which fishing mortality rates (Fs) for longliners and purse seiners setting on floating objects in the eastern tropical Pacific were found to satisfy an arbitrary management objective. The management objective can be satisfied by a distribution of Fs for each gear type (i.e. there are multiple solutions to each optimization problem). The plots contrast these distributions in a case with no climate forcing and a case in which global warming affects the size and species compositions of the phytoplankton. Black points represent the quantiles of the distributions of F, and the grey line is a 1:1 line. Since the black dots do not follow the grey lines, global warming can be interpreted to have influenced the optimal allocation of F among the longline and purse-seine fleets. In the case of longliners, global warming shifted the distribution of optimal Fs, and Fs under conditions of global warming would, optimally, be slightly higher than those computed under conditions of no (or average) climate forcing. In the case of purse-seine sets on floating objects, global warming caused the distribution of optimal Fs to have lighter tails (i.e. the variance of optimal Fs was reduced). Note that the shapes of such plots are sensitive to the management objective that is specified, and, therefore, this figure is presented only to motivate the Synthesis and Modeling Group's fourth working question. The sensitivity of such results to specification of a management objective illustrates the importance of finding appropriate and useful indicators and reference points for high-seas pelagic ecosystems. Source: Watters and Olson (unpublished data).



6.4.3. *Implementation*

The Synthesis and Modeling Group will work to achieve two proximate and two ultimate objectives. The proximate objectives of this Working Group will be to collaborate with the four other CLIOTOP Working Groups in the development of models that describe, with both explanatory and predictive power, how climate and fisheries affect (1) the dynamics of oceanic top predators, and (2) the structure and function of open ocean ecosystems. Explanatory power will be developed by constructing models based on sound processes in a retrospective framework; predictive power will be developed by fitting models to and/or assimilating existing data. As the name of the Working Group indicates, this assimilation will provide a mechanism for integrating and synthesizing results produced by the other CLIOTOP Working Groups. Communication with other CLIOTOP Working Groups will inform the development of appropriate models and models will be used to identify important knowledge gaps and specify hypotheses that require further, detailed, investigation. The ultimate objectives of the Synthesis and Modeling Group are: (1) to predict the possible outcomes of climate change and how these outcomes interact with the effects of fishing, and (2) to develop quantitative indicators that characterize ecosystem status and the ongoing performance of fishery management systems. The Working Group will endeavor both to make predictions that are useful for tactical and strategic decision-making and to develop indicators that facilitate communication among scientists, stakeholders, and resource managers.

The Synthesis and Modeling Group will address its objectives by adopting an array of complementary modeling approaches. These modeling approaches may include, but will not be limited to, individual-based models (Olson and Watters, 2003), environmentally explicit stock assessment models (Maunder and Watters, 2003) , spatially explicit but trophically aggregated models coupled with OGCMs and NPZD types models (e.g. SEAPODYM - Lehodey *et al.*, 2003 and APECOSM - Maury *et al.*, 2001), spatially aggregated but trophically explicit models (e.g. ECOPATH and ECOSIM studies), and meta analyses (Micheli, 1999) . Both the continued development of existing models and the construction of new models will be encouraged.

Comparisons will be made by using these alternative modeling approaches to address each of four working questions. By making such comparisons, the Group expects to learn from differences in model structure rather than focus on the shortcomings of any particular modeling approach. Conclusions that are robust to differences in model structure are more likely to lead to reliable predictions than those that are sensitive to model structure.

It is unclear whether dramatic shifts in ecosystem state have not been identified from open ocean ecosystems because appropriate time-series data were not collected (or have not been analyzed) or because the systems themselves have dynamic properties that preclude such effects. The Synthesis and Modeling Group will address this uncertainty in at least two ways: by identifying unanalyzed or underutilized time-series data on animals at middle trophic levels and retrospectively considering them, and by using a variety of modeling approaches to hindcast previous ecosystem states.

6.4.4. Outputs and Time-line

The four questions that will be posed to the models developed by the Synthesis and Modeling Group are motivated from recent work. The Group will make progress on addressing these questions by convening a series of meetings. An initial meeting will be held to develop an overall work plan, and subsequent meetings will be held to compare and synthesize results from intersessional work. It is envisaged that the Group will develop scientific manuscripts (both for the peer-reviewed literature and for other reporting vehicles) from the comparisons and syntheses developed at its meetings. A special effort will be made to deliver standardized public products derived from modeling simulations to facilitate evaluation of the models through collaborative studies with colleagues of the other working groups and other projects. A global public database of oceanic fishing data at the best spatio-temporal scale in agreement with the various policies of data confidentiality in the different tuna commissions will be developed.

6.5. Working Group 5: Socio-Economic Aspects and Management Strategies

6.5.1. Rationale

This working group will seek to better understand:

- the factors that drive human impacts on top predator species (both directly through harvesting and indirectly through climate change);
- the efforts to manage those human impacts through local, national, regional, and international scientific and regulatory efforts; and
- the impacts and implications of these scientific and regulatory efforts, together with changes in stocks and catch of top predator species on those communities dependent on them.

A wide range of local, national, regional, and international institutions conduct scientific research on oceanic top predators in an effort both to understand the ecology and population dynamics of those species and to manage human predation upon them. Yet, careful comparative analyses of those institutions and their effects have remained relatively rare. There have been few studies that have brought together natural and social scientists to evaluate how changes in human harvests of top predator species reflect the effects of natural variation, previous human predation (top-down pressures), and anthropogenic climatic and biogeochemical impacts (bottom-up pressures). And few studies have produced integrated models of the socio-economic drivers (from macro-scale factors such as globalization to micro-level factors such as interactions among local stakeholders) of these top-down or bottom-up pressures on the one hand, nor the impacts of changes in top predator species stock levels on human welfare. In addition, there is a critical need to better understand the roles of uncertainty and information in the management of oceanic top predators and other highly migratory species, particularly in the context of highly competitive multinational fisheries.

Comprehending how humans understand and interact with oceanic top predators requires examining the interaction among scientists, fishery regulators and managers, fishing firms, fishermen, and other stakeholders. The large variety of social institutions that attempt to manage human interactions with oceanic top predators provide a valuable set of cases that can be compared and analyzed to identify lessons to help humans manage those interactions more successfully. The wide array of Regional Fishery Management Organizations (RFMOs) at the international level, of different national management strategies and approaches, and of different local and community level relationships to fisheries provide a rich set of cases in which the sources of variation in the effects and effectiveness of different social institutions can be identified through careful case comparisons and integrated modeling. In line with some of the vulnerability themes being advanced by IHDP, fish stocks made vulnerable by human predation and poor management can, in turn, produce vulnerabilities among various actors, especially among tightly-coupled human-environment systems such as coastal fisheries in which multiple stresses (climate change and globalization, for instance) can make fishers and local populations, more generally, very vulnerable to relatively small changes in fish stocks. This working group seeks to engage these and related questions by bringing together interdisciplinary teams of natural scientists (e.g. population biologists, oceanographers, biogeochemists), social scientists (e.g. political scientists, economists, sociologists), and system modelers (of both natural and human-environment coupled models) to address specific questions delineated in the research project statements below.

The operational objective of WG5 is to identify effective, efficient and equitable methods of managing the exploitation of top predator species in a context in which the abundance and physical distribution of the fish stocks are affected by climate variability and/or climate change, and different social groups vary in their vulnerability to these impacts. Achieving that goal requires analyses that take into account both measures of ecosystems dynamics, which will result from the work of WGs 1 through 4, and socioeconomic constraints, behavior, institutions, and strategies. The scientific objective is to address this through a multidisciplinary approach.

6.5.2. Key questions

Question 1: What are the socio-economic pressures on, and context of, tuna fisheries?

Pressures on tuna stocks reflect a complex combination of sources. The dynamics of most tuna fisheries involve complex interplays among a variety of actors facing different types of pressures and constraints. Fisheries involve local, national, and foreign actors; harvesters employ a range of artisanal and industrial techniques; and pressures may be driven by markets or by production exigencies. Behavioral constraints reflect national regulation and deregulation, international rules, and local norms and customs, competing constraints imposed by international trade law and international environmental and fisheries law, and the different political pressures of highly industrialized and still developing economies. A complete and accurate understanding of such fisheries and the communities that depend on them requires an ability to recognize the local effects of globalization and technological change and the global effects that are the aggregation of divergent and unsystematic but no less important behavior across many countries and cultures.

Addressing these issues requires examining pressures from such sources as multinational processing and marketing companies, boat-owning conglomerates, consumption patterns in both local and export markets and their national/regional fisheries subsidies. Equally important, we need to understand the geopolitical dimensions of management.

Question 2: How have fisheries organizations (whether local, national, regional, or international) addressed the impacts of climate variability and climate change?

Scientists and scientific committees have been central elements of most efforts at fisheries management from national to regional to international levels. Scientific assessments have usually focused largely on creating models to produce population estimates to help establish management levels for the fishery. The experience of numerous such management efforts provides a rich, but largely untapped, resource for understanding how science is integrated into fisheries management. In the CLIOTOP context, it is of particular interest to examine how known changes in “bottom up” variables, such as temperature and primary production, have been incorporated into population models and the extent to which such changes have affected the influence of those models with stakeholders and fisheries managers. In short, it would be helpful to know how fisheries organizations (whether local, national, regional, or international) have addressed climate change issues, if at all.

For those fisheries organizations that have incorporated climate variables or other large scale environmental changes in their models, understanding successful strategies and potential pitfalls would help clarify how such organizations disaggregate direct fishing pressure (top down effects) from both natural variability and non-fishing anthropogenic pressures (bottom up effects such as pollution). How do such organizations factor environmental uncertainties and variation (that influence recruitment and mortality rates), as well as lack of scientific consensus into stock assessment models? How is uncertainty communicated to policymakers, the fishing industry, and the general public? How do assessments of stock size and location avoid relying exclusively on historical trends that do not reflect best-guess future environmental trajectories (e.g., increasing ocean temperatures) and how do scientists asked to recommend management strategies balance between environmentally sustainable options that are political “non-starters” against politically acceptable but environmentally disastrous ones? This research will examine the conditions and ability of various institutions to adopt different approaches to decision-making under uncertainty.

This part of the project may also examine how scientific advice influences management strategies. Under what conditions are scientific recommendations accepted or dismissed? How does significant uncertainty and lack of scientific consensus cause, or provide a rationale for, political conflict? Why do some scientific committees gain policy influence over time while others lose it? Particularly, in communities that significantly depend on tuna fisheries, how, if at all, are the vulnerabilities and concerns of stakeholders taken into account in scientific modeling and management decisions made at higher levels of governance? How can science be developed so that it provides answers that are relevant to stakeholder decision-making and have enough credibility and legitimacy to be adopted? How do the various actors involved and the interplay between science and policy influence the ability of decision makers and affected individuals to understand and respond to the scientific complexities and uncertainties that are characteristic of the impact of climate change on top predator species?

Finally, how well do governance institutions, like those that are the focus of recent IDGEC efforts, do at “managing” stock levels, in terms of both the health of the stock and the sustainability of local fishers dependent on those stocks and their vulnerability to perturbations? Building on literature on “regime effectiveness” and critical global political economy, close collaborations between natural and social scientists could identify cases in which the influence of institutions could be better understood and analyzed. Work of many social scientists has begun to compare the effectiveness of various international fishery management organizations at governing tuna and other fisheries, which work could be coupled with different domestic approaches to fisheries policies.

Question 3: What are the flows in capital and knowledge among the world's large fisheries and how do they respond to variability?

Fisheries boom and bust for many reasons, including overexploitation, implementation of regulations intended to restrict catch, and natural variability. What happens to the communities dependent on these fisheries as well as the associated equipment (vessels, plants, etc.) and knowledge (captains, managers, etc.)? Such dramatic shifts in economic resources certainly have important implications only for the community previously dependent on them. But in some cases, the overcapitalization and overexploitation that causes collapse in one region simply "moves on" to repeat the process in other previously unexploited, fisheries, with no global reduction in fishing pressure. The small Eastern Pacific pelagic fishery as well as the industrial tuna fisheries in the Western Indian Ocean and in the Western Pacific tuna appear to involve just such dynamics.

Another scenario of capital flow is evident in the overexploitation of bluefin tuna, in which decreased landings appear to have induced rapid growth in bluefin tuna aquaculture, a transformation of existing capital into new forms of investment. Yet another potential dynamic involves capital accumulation and its shifting between fisheries with different economic characteristics. Capital in the form of ships and gear that is excess to an old and small fishery may be attracted to a larger fishery with the additional capital influx causing rapid, and unexpected, overexploitation. And at least in the international whaling case, regulations themselves exacerbated these economic pressures causing even greater overcapitalization of the fleet. The interaction between globalized economic markets for fish and segmented international regulation of fisheries creates a complex institutional interplay in which regimes targeting particular species and stocks have significant but unintended effects on a wide range of other species. Successful efforts by certain countries to regulate certain species in certain ocean areas may lead to increased exploitation of those same species in those same areas by other countries taking advantage of the restraint of others, and may also lead those countries being regulated looking for other sources for the fish foregone, either switching to other species or other areas. There is considerable room for greater analytic attention to how economic factors behave in a global context best characterized as a patchwork of international regulations consisting of both regulatory overlaps and regulatory gaps.

One important theme of interest in the work identified here will be the domestic-international interface. In developed countries, public opinion, business lobbies, and various domestic political forces play central roles in outcomes whereas, in developing countries, the relationship between those countries and multinational corporations from developed countries appear to wield considerably more influence. Developing country governments' short-term concerns with indebtedness, elections, service provision, "modernization" and development trajectories often take precedence over longer-term resource sustainability issues. The response of developing countries to international regulations may depend on the distinction between vulnerable communities in large countries (e.g. in the Philippines, Thailand, Kenya) and countries dependent on industrial fisheries (e.g. Fiji, the Seychelles). An in-depth study of the political economy of these countries and their relationship to the fishing industry would clarify the conditions and processes that determine whether fisheries regimes have significant or limited power, especially in the face of major pressures from developed country industrial fisheries.

Question 4: Can we evaluate how useful are the fisheries management decision support tools developed by WG5?

A central element of the WG5 effort will be to undertake the foregoing projects, and other projects coordinated through CLIOTOP, in ways that promote effective use of the scientific findings, both of WG5 and the other WGs. Given the more complete understanding of a variety of management regimes, including constraints and incentives for adoption of scientific information, we will be better able to judge the potential utility of scientific advances made by the other CLIOTOP working groups, especially WG5. Thus, this "capstone" question will integrate efforts from across the spectrum of activities associated with CLIOTOP. This part of the project seeks to evaluate the feasibility and efficiency of management tools identified by WG5 in ways that can help inform efforts from local to global levels in stemming the overexploitation of tuna and other top predator species.

6.5.3. Implementation

Carefully selected **case studies** and their **comparisons** will be used to highlight and illustrate particular aspects of the interplays in management of large oceanic fisheries, by holding other elements of these interactions relatively constant. For example, comparing the pressures, responses, and effects of industrial and artisanal fisheries to changes within a specific national or international setting can clarify how different types of fisheries respond to the same institutional change. By careful selection and analyses of cases, the studies would clarify major factors contributing to socio-economic pressures on top predator species (Question 1) while avoiding the pitfall of concluding merely that: "the interplay among these various factors is complex." Similarly, comparative analyses will be undertaken into the influence of governance institutions on stock levels (Question 2).

Efforts to understand the micro-level processes of larger macro-level socio-economic pressures would be developed through **surveys** and **interviews** of stakeholders from international fisheries managers to fisheries scientists to industry executives to fishermen and women in local fishing communities. By examining data on both the social, economic, political, and institutional context within which these actors operate, WG5 will seek to develop a fuller picture of the constraints, opportunities, incentives, values, resources and information that inform the choices that different actors make that influence fish stocks.

We will extend the analysis to comparing management regimes. The development of globalized markets in both the supply of and the demand for fish has placed intensive and extensive pressure on fish stocks over the past 50 years. Yet, over this same period, literally dozens of fisheries regimes have been in place to regulate overexploitation of these species. How have these regimes influenced, if at all, the speed and character of fish stock overexploitation? Using existing data on fish harvest and on the regulation of specific species and stocks, WG5 will examine the influence of these fisheries regimes.

Appropriate **modeling** techniques using aggregate data can be combined with narratives that provide a sense of how variables shown to be related to overexploitation actually play out in practice. Agent-based modeling can show how fishermen and fishing firms respond to price signals, capital constraints, market opportunities, regulations, and fish stock availability in pursuit of market profits. Involving stakeholders in analytic efforts to look at various scenarios for stabilizing incomes over the medium to long term while fostering nature conservation might provide useful ways of improving the "uptake" of insights from the study (Question 1) among stakeholders.

The goal of WG5 will be to determine what drives changes in stocks, harvests, and socioeconomic benefits of the fisheries and to assess the extent to which institutional variables contribute to our understanding of those changes. This goal will be addressed using both qualitative studies of particular cases in which changes in specific rules or exogenous forces within a specific fishery management system allow causal forces to be identified, and studies using quantitative methods that look across a larger range of cases. Thus, in a quantitative approach, the goal would be to try to explain stock levels, catch, CPUE, estimated profits or other relevant proxies for "stock health" and fishery sustainability in terms of such factors as the number of boats in relevant fleets, the price of the species and relevant substitutes, weather patterns and climate shifts such as the Pacific Decadal Oscillation, and the institutions engaged in regulating the fishery. Case studies could provide richer insight into how these institutions and processes influence both the fisheries and the communities dependent on them.

Finally, significant efforts will be made to conduct the research in ways that promote uptake of the findings. Thus, efforts will be made to involve industry representatives, local fishermen, and national and international fishery managers in the various projects. This is to ensure that the questions being asked are those that such stakeholders need answered and that the often complex and uncertain results of scientific research can be better understood, thereby helping to influence the thinking and behaviors of those most directly influenced by the fate of the world's oceanic top predators.

6.5.4. Outputs

Much of the foregoing description assumes that there is considerable variability across fisheries management efforts at local, national, regional, and international scales. WG5 also starts from the assumption that few fisheries management efforts are "getting it all right" but that many such efforts have lessons (both negative and positive) to teach other management efforts. Equally important, we believe that all fisheries management efforts face a daunting task in adapting and improving their performance in making the tough decisions they will face as the impacts of climate variability on oceanic top predators become ever more visible. WG5 seeks to contribute to such improvements by shedding light on the sources of success and failure in past efforts at understanding the complex relationship and vulnerability of humans to changes in the fates of oceanic top predators and in past efforts to manage that relationship. WG5 seeks to integrate the efforts of the other working groups while also ensuring connections with the broad array of policymakers, stakeholders, and scientists currently involved in various fisheries to answer the questions relevant to their decision-making. Thus, WG5 plans to work with various existing research efforts as well as foster new initiatives, with the expectation of producing published research results. In addition, WG5 will foster research that involves scientists, stakeholders, and policymakers and will also ensure that the results of the research that is undertaken under the CLIOTOP rubric is explicitly and self-consciously made available to those actors in order to foster better understanding and management of oceanic top predators in the future.

Interactions with other Programs:

The WG will develop collaborations with other natural and social science programs that are investigating various aspects of fisheries and responses to global change. These will include:

- connections with GLOBEC's Focus 4 Working Group on "Feedbacks from marine ecosystem changes", which has a component examining the resilience/vulnerability of natural marine ecosystems and human coastal communities to local/global changes;
- the Canadian "Coasts under Stress" program, which is examining the impact of social and environmental restructuring on environmental and human health issues in coastal communities in Canada (http://www.coastsunderstress.ca/home.php);
- the flagship team on the Performance of Exclusive Economic Zones (PEEZ), sponsored by the IHDP core program on the Institutional Dimensions of Global Environmental Change (http://fiesta.bren.ucsb.edu/~idgec/science/flagship.html);
- the IHDP Core program on Global Environmental Change and Human Security (http://www.ihdp.org/);
- and the joint IHDP-IGBP program on Land-Use and Land-Cover Change (http://www.ihdp.org/). Although the focus for this program is to improve understanding of the dynamics of land-use and land-cover change and their relationship with global environmental change, the nature of problems are similar to those of CLIOTOP's WG5, and therefore conceptual advances in one program will be of interest to the other program.

7. CONCLUSION

CLIOTOP will address:

- The need for a global comparative approach to processes linking climate to oceanic top predators and their ecosystems.
- The need for an international effort to urgently elucidate those processes in a global change context, which is a constant and rapid process with no equivalent in any ocean systems to date.
- The need to both improve our basic knowledge and to develop more reliable predictive capability.
- This project will coordinate collaboration among international scientific projects and research groups already involved in these topics.

CLIOTOP is aimed at improving understanding of oceanic top predators in their ecosystem, in a context of strong fishing pressure and environmental variability and change. However, its successful implementation might have a significant impact on the management of the very important fisheries that exploit tunas and tuna-like species. These fisheries are managed by international organizations, which rely on international scientific consensus in understanding the dynamics of the populations they exploit. A comparative project such as CLIOTOP, by improving understanding will provide the basis for a better open ocean resource management.

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