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POINT-OF-VIEW

Climate impacts and oceanic top predators: moving from impacts to adaptation in oceanic systems

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Abstract Climate impacts are now widely reported from coastal marine systems, but less is known for the open ocean. Here we review progress in understanding impacts on large pelagic species presented at an international workshop for the Climate Impacts on Oceanic Top Predators programme, and discuss the future with regard to the next phase of adaptation-focused research. Recent highlights include a plan to map the distribution of key species in the foodweb using both acoustics and biochemical techniques, and development of a new data sharing and access tool for fisheries and associated data, including socio-economic information. A common research focus in pelagic ecosystems is on understanding climate variability and climate change impacts on marine species, but a greater emphasis on developing future scenarios and adaptation options is needed. Workshop participants also concluded that engagement with and provision of science support to regional fisheries management organisations are critical elements for ensuring successful uptake of research. This uptake will be required for future management of fisheries as global warming continues such that some open ocean top predators can be sustainably harvested, impacts on conservation-dependent species can be avoided, and ecosystem function is not compromised.

Keywords Climate variability · Climate change · Fisheries · Pelagic ecosystems

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Background

Almost half of the surface of the earth is ocean that is beyond national management and exclusive economic zones (EEZ), and is considered by some to be wild and untouched regions of the planet. Despite this remoteness, a range of impacts on these oceans and their ecosystems have been documented (Halpern et al. 2008; Game et al. 2009), with impacts of fishing considered to be the most important with regard to changes in population size of exploited (e.g. tuna), and bycatch (e.g. sharks seabirds, turtles) species (Stevens et al. 2000; Sibert et al. 2006; Lewison and Crowder 2007; Juan-Jorde et al. 2011; Croxall et al. 2012). Climate variability is a dominant driver of patterns of distribution and abundance in these open ocean species (Hollowed et al. 2001; Ekau et al. 2010), and thus complicates population assessments for many exploited species (Hobday and Evans 2013). Anthropogenic climate change is now an additional challenge for understanding and managing species on the high seas (Rijnsdorp et al. 2009; Hazen et al. 2013).

To address the combined impacts of climate variability and change on open ocean top predators, the Climate Impacts on Oceanic Top Predators (CLIOTOP) programme was initiated in 2004 as a GLOBEC Regional Programme. The general objective of CLIOTOP is to organise a large-scale worldwide comparative effort aimed at elucidating the key processes involved in 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. The focal taxa include tuna, billfish, sharks, and large iconic species such as marine mammals, seabirds, turtles and whales. The ultimate objective of CLIOTOP is to develop a reliable predictive capability for the dynamics of top predator populations and oceanic ecosystems that combines both fishing and climate (i.e. environmental) effects (Lehodey and Maury 2010).

The first phase of CLIOTOP under GLOBEC ran to 2009 and focused on the identification and modelling of the major processes driving oceanic ecosystems and their top predators (Lehodey and Maury 2010). The second phase (2010–2014) under the IMBER Programme continues that work, as well developing scenarios for oceanic ecosystems under anthropogenic and natural forcing in support of international governance. This work requires integrated research between scientists involved in climate and ocean physics, biogeochemistry, ecosystems, predators, fisheries, markets, as well as the managers and policy makers charged with operational open ocean governance (Fig. 1). The research is organised under six open-access working groups; (1) early life history, (2) distribution, movement and physiology, (3) trophic pathways, (4) socio-economic and governance, and (5) synthesis and modelling. A sixth working group was added in 2010 to address a data gap identified in ecosystem models—the estimation of mid-trophic level biomass.

The CLIOTOP scientific steering committee met in Hobart, Australia in September 2012 to review recent progress and discuss future research direction for CLIOTOP beyond this second phase. Updates from working group chairpersons provided a number of recent highlights from all six working groups, including synthesis publications, database and analytical tool development, dedicated workshops, and conference sessions and presentations.

Climate change impacts on large pelagic species and ecosystems

Through the efforts of many scientists, the impacts of climate change (global warming and ocean acidification) on oceanic ecosystems and top predators are being investigated. Novel tools, methods and analyses have been critical in recent discoveries regarding the early life history, movements, and trophic pathways of open ocean predators, while new modelling approaches are synthesising these findings, as illustrated in the following examples discussed by workshop participants.

Example 1: Early life history and climate

Recent work on the early life history stages of top predators such as billfish and tuna has focused on clarifying environmental attributes associated with spawning locations (Richardson et al. 2009a, b; Muhling et al. 2010; Alemany et al. 2010; Koched et al. 2012; Reglero et al. 2012), resolution of the early feeding habits (Catalán et al. 2007, 2011; Tanaka et al. 2008; Llopiz and Cowen 2008; Llopiz et al. 2010; Reglero et al. 2011; Laiz-Carrión et al. 2013; Llopiz 2013), and drivers of early growth (Sponaugle et al.

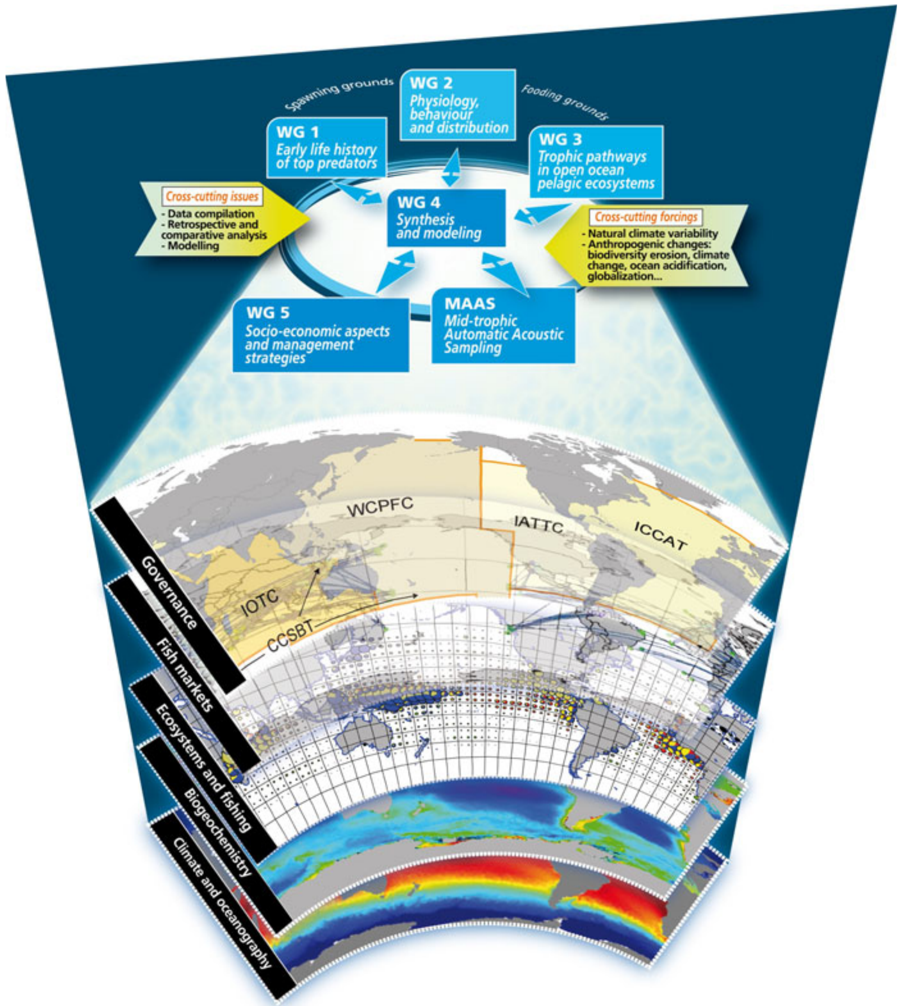

Fig. 1 The structure of the CLIOTOP programme (six working groups) and examples of the information that must be integrated to sustain fishing and conservation of top predators in the open sea under climate change. © IRD, P. Lopez 2010

2010). A combination of physical and biological oceanographic tools have been utilized to integrate individual observations with mesoscale circulation features, including tracking location of larval patches with Lagrangian- satellite tracked drifters to guide bio-physical sampling (Richardson et al. 2009b), and detailed (daily) age and growth estimates from otoliths extracted from individual larvae (Sponaugle et al. 2010). As a step towards improving resolution and in situ sampling of the early life history stages of top predators in combination with their prey (plankton) field, a new imaging system (In situ ichthyoplankton imaging system, ISIIS) has been developed for real-time, very high resolution imaging of larval stages of fishes and associated plankton (Cowen and Guigand 2008). This instrument can be used in rapid survey work to identify newly spawned patches of larval fish for more intensive bio-physical sampling. ISIIS is also capable of evaluating plankton patchiness and size structure, both of which are key elements in food web models. Combining information on the spatio-temporal distribution of the early life history stages with individual physiological responses is helping to define key environmental requirements for spawning, growth and early survival of top predators in light of environmental responses to climate change (e.g. Muhling et al. 2011).

Example 2: Climate and animal movements

Advances in telemetry techniques allowing the recording of marine animal movements, behaviour and physiology and the immediate environment encountered by individuals as well as analyses methods and tools are furthering our knowledge of these species and the roles they play in open ocean ecosystems (Costa et al. 2010; Estes et al. 2011). Fine-scale information on the movements of individuals in three dimensions are now possible (Yoda et al. 1999; Mitani et al. 2010), data are able to be gathered on earlier life stages than ever before (Shillinger et al. 2012), greater numbers of individuals are able to be studied allowing for investigation of population level parameters (Block et al. 2011; Robinson et al. 2012; Hazen et al. 2013) and oceanographic quality environmental data allowing assessment of environmental features dictating species distributions (Biuw et al. 2007; Costa et al. 2010) are also providing in situ information on ocean physical environments unable to be collected using traditional ocean sampling tools (Charrassin et al. 2008; Padman et al. 2010). Recent advances in telemetry formats and sensors included are supporting novel methods in determining position from archival tags. Dead-reckoning allows for the collection of temporally finely-resolved regular, sequential position data which is continuous and therefore is not subject to the same problems as point estimates of position collected via alternative techniques (e.g. geolocation, satellite resolved positions) (Wilson et al. 2007). The habitat requirements and movements of top predator species must also be known in order to understand their present interactions with the environment, and their likely responses to climate change. For example, studies of migration and behaviour in widely distributed shark species have revealed their associations with different oceanic provinces as well as proximate cues that appear to influence their movements; while also highlighting the fact that migratory periods may be characterized by immunity to proximate stimuli (Weng et al. 2008, 2012). Understanding of the energetics of open ocean species has also been advanced with accelerometry studies elucidating behavioural options and revealing costs of migration, foraging and other activities (Gleiss et al. 2011; Wilson et al. 2011; Wilson et al. 2012; Halsey et al. 2011).

Example 3: Trophic pathways

Work on trophic pathways of top predators in and between oceans, has used a range of traditional and biochemical approaches such as stomach contents (Young et al. 2010a), stable isotopes (Olson et al. 2010; Newsome et al. 2010) and signature fatty acids (Young et al. 2010b; Iverson et al. 2007). These studies have shown the potential of using latitude as a proxy for temperature in understanding the effects of climate change on top predator food webs. A major task has been to combine data from different oceans into one database so that comparative analyses can be made (e.g. Dambacher et al. 2010). Development of novel statistical analyses, such as classification trees (Kuhnert et al. 2012) now enable the identification of important physical and biological variables associated with shifts in diet from one region to another. The development of these new tools and databases will enable a more unified approach to understanding how pelagic ecosystems respond to the changes associated with climate induced changes in the worlds' oceans.

Example 4: Model syntheses

Climate and associated changes such as ocean acidification and de-oxygenation are modifying oceanic ecosystems at an alarming speed, leading to large scale changes in their structure and function and potentially pushing them towards radically different states with no analogues in the past. In this context, modelling is of prime importance to infer future changes and identify potential tipping points. For that purpose, the CLIOTOP Synthesis & Modelling Working Group (WG4) is developing integrated socio-ecological models spanning climate, biogeochemistry, ecosystems, top predators populations, fisheries and global markets. These models allow study of feedbacks which are responsible for nonlinearities that can lead to bifurcations in system trajectories. A large part of this work is undertaken in the framework of the French-funded MACROES project. Specifically, the IPSL-CM5 Earth System Model which includes the OGCM NEMO and the ocean biogeochemistry model PISCES, is being used to provide environmental (temperature, currents, light, oxygen) and trophic (two sizes of phytoplankton, two sizes of zooplankton, two sizes of particulate organic matter) forcing to the upper trophic level model APECOSM, both for historical reanalysis of historical conditions and for climate change projections. APECOSM (Maury et al. 2007a, b; Maury 2010) represents the 3D dynamics of size-structured generic pelagic communities (epipelagic, mesopelagic and migratory) in the global ocean. It represents size-structured trophic interaction, physiology and behaviour (3D movements, schooling) and includes the effects of life-history diversity in communities. Focal species (at present tropical tunas) are represented in more detail, including detailed individual bioenergetics based on dynamic energy budget theory (Kooijman, 2000), mechanistic description of movements (Faugeras and Maury 2007) and patterns of fishing effort. A simplified version of the focal species component is used for parameter estimation purposes using tuna fisheries data under a likelihood framework (Faugeras and Maury 2005; Dueri et al. 2012a, b).

It is clear from these examples that climate impacts will need to be considered when managing the sustainability and conservation of both exploited and unexploited open ocean species. However, global processes driving ecosystems and fisheries are currently not considered by Regional Fisheries Management Organisations (RFMOs) which provide governance for fisheries targeting these migratory and multi-jurisdictional species (Maury et al. in review). There is an urgent need to integrate a wider science perspective in support of regional and global governance, yet considerable barriers exist (Miller et al. 2010). With regard to non-exploited species, fisheries and non-fisheries interactions are also largely managed in an ad-hoc manner (Ban et al. 2013). In addressing these challenges, the CLIOTOP socio-economic working group is active in developing integrated ocean management solutions that build on existing institutions (Maury et al. in review)—it is apparent that a greater consideration of socio-economic factors and governance arrangements in management of open ocean predators is needed.

Advances in understanding depend on comprehensive data access

Collection of oceanic top predator data is difficult and expensive. One of the important elements of the CLIOTOP programme has been collection of new data and collation and provision of existing data to underpin future research efforts, and to make that data freely available. For example, working group 6 (MAAS) has developed a road map for predicting ecosystem dynamics in the open ocean based on acoustic methods (Handegard et al. 2012). Fundamental to this objective is the collection, processing and distribution of acoustic data. An example of this data handling is the development of the Australian Integrated Marine Observing System (IMOS) bio-acoustic programme based on ships of opportunity (www.imos.org, Kloser et al. 2009). This is complemented with the development of international metadata and calibration protocols through the ICES Fisheries Acoustic, Science and Technology working group (WGFAST). Currently the IMOS bioacoustics team monitors six fishing and three research vessels from the Indian, Southern and Pacific Oceans. Data are collected, calibrated, processed with data freely accessible from www.imos.org. Developments of data interpretation and uptake into ecosystem models will be facilitated with open access to these data.

The synthesis and modelling working group also reported significant progress on one of the CLIOTOP synthesis phase activities: development of a Model and Data Sharing Tool (MDST) aimed at gathering datasets of different variables and model outputs at the global scale. Developed as part of the French IRD MACROES project, this web-hosted database is being populated with a range of fishery, diet and isotope and coupled model data. It will allow connectivity with existing national databases, provided international standards are respected. This online database has already been used in CLIOTOP publications (e.g. Reygondeau et al. 2012) and will soon become publicly available. This resource will be of significant value to the oceanic science community, as it will facilitate integrative analyses and support development of ecosystem models capable of investigating the influences of climate variability across multiple spatial and temporal scales.

Gaps in the research agenda for open ocean systems

The efforts to date from the oceanic research community, including CLIOTOP-affiliated projects, have shown that climate variability is a strong driver of pattern in a range of pelagic predators, and evidence for the impacts of climate change is gathering for a range of species in open ocean foodwebs, as described earlier. While there is much still to be done in these areas, meeting participants agreed that two key elements; adaptation, and engagement with end-users of the science, were currently under-represented in research being carried out under CLIOTOP and require additional focus.

Moving from impacts to adaptation

In some countries the climate change research emphasis is shifting from a focus on the understanding of the impacts of climate change, to developing adaptation options (Bell et al. 2011; Frusher et al. in review). Adaptation will be necessary given the climate changes projected and the likely shortfall in global mitigation efforts to reduce global warming. Thus, there is an imperative for adaptation-focused research in a range of environmentally-exposed industries, including fisheries and agriculture. Both incremental and transformative adaptation will have a role to play (Stokes and Howden 2010; Bell et al. 2011) and participatory approaches will see stakeholder information and needs recognized in adaptation planning. The meeting participants agreed that developing adaptation options for open ocean management bodies should be a major focus of CLIOTOP beyond the current phase of research ending in 2014. Initial efforts to document both impacts and adaptation options for oceanic resources in the Pacific Ocean are already underway (Bell et al. 2011), and offer a model for other regions. These adaptation options can reduce vulnerability in both biological systems (e.g. improving breeding success in fishery-threatened seabirds via predator control at breeding colonies—Wilcox and Donlan 2007), and the human system (e.g. improving the range of alternative livelihoods for resource-dependent communities—Marshall 2010; Bell et al. 2011).

Adaptation options for resource-based industries include a wide range of approaches for the biological and human components of the socio-ecological system, including genetic engineering for warm-climate crops (Stokes and Howden 2010), and habitat enhancement for coastal species (Koehn et al. 2011). In the open sea, species may adapt autonomously, but directed biological adaptation strategies may be more difficult given the highly migratory nature of many species. Novel approaches will need to be considered and while some may initially be considered outlandish (e.g. Bowman 2012), thinking outside the box may be required to generate future options. Scenarios of climate change impacts on bycatch species such as seabirds, turtles and marine mammals should also be taken into consideration when considering conservation strategies and bycatch rules. Adaptation for the human part of the system is also likely, and may include modified fishing strategies and gears, spatial management strategies, and resource sharing between countries differentially impacted by the changing distribution of marine species (Bell et al. 2011). In developing adaptation options, information about thresholds and timeframes for action will be crucial for decision makers, while efforts to identify and avoid mal-adaptation and "short term win-long term loss" options should be paramount (Grafton 2010; Bell et al. 2011).

Development of tools such as end-to-end or whole of ecosystem models (Lehodey et al. 2003; Fulton 2010; Maury 2010) will continue to be an important element to identify current effects of climate variability and future impacts of climate change. Equipping these models with a wider range of physical, social and economic sub-models will provide more comprehensive investigations of scenarios impacting oceanic systems and allow great confidence in the outcomes (Fulton 2010; Miller et al. 2010). Generation and evaluation of scenarios with such models will also allow for the testing and evaluation of management options thereby providing guidance for future adaptation options. Limitations in observations available on suitable temporal and spatial time scales able to be included in, fit to, or used to force models however, will remain for some time, and so alternatives, such as qualitative models (e.g. Plagányi et al. 2011), must also be considered when evaluating adaption options.

Engagement with decision-makers

In planning for improved connection to a range of end-users of the science conducted under the CLIOTOP programme, the group focused on development of a range of communication elements that can be used to summarize scientific output. Examples discussed included the usual synthesis publications, information sheets, and web-pages. However, these one-way approaches assume that people will come looking for information which may not be the case with some time-poor stakeholders. Successful update of science is maximised with two-way engagement, and the group emphasized the importance of presenting CLIOTOP science at end user meetings, such as RFMO fora. Connection between other programmes that also work on climate and top ocean predators (e.g.

IMBER-ESSAS, PICES) should also be improved, and the opportunity to establish such links will be pursued at a workshop planned for late-2013. Without better engagement with end-users and decision makers, action around climate change will continue to lag.

This engagement and collaboration is difficult for researchers focusing on waters beyond EEZs. In considering the CLIOTOP goals, and the success of the collaborative approach, the group recognized that while the open sea might be considered a global commons, national programmes are still the dominant form of funding opportunity, which has limited several of the global comparative approaches proposed under CLIOTOP. Similarly, most scientists are primarily employed and funded to work at the national or sub-national scale, rather than internationally. Understanding these conditions is relevant with respect to realistic goal-setting by groups such as CLIOTOP in seeking to advance understanding of areas beyond the EEZs. For example, workshops continue to be the main fora through which CLIOTOP's international community progresses working group objectives, although considerable follow-up is typically required before analysis is completed, and funding for this follow-up often means progress is slow. Despite the challenges, in the last year for example, three different dedicated or conference-attached workshops at the Far Seas Fisheries Labs (Shimizu Japan, Sept 2011), Ocean Sciences Meeting (Utah, February 2012), and the Planet Under Pressure Conference (London, March 2012), have brought together scientists addressing a range of the CLIOTOP goals. Given the challenges in funding open ocean research, it will be important to continue to find opportunities to bring scientists together to discuss multi-disciplinary approaches to regional and global problems and to forge improved links with other related programmes, both under the IMBER framework and elsewhere. Given the challenges in funding open ocean research, it is important to forge improved links with other related programmes, both in the IMBER framework and elsewhere, in order to best engage and inform decision-makers.

Collaboration to support impacts and adaptation research

An increasingly sophisticated science is documenting the impacts of climate change on the physical structure of the worlds' oceans. This advance has been facilitated by satellite-based observations of surface ocean features and increasingly by in situ technologies such as ARGO floats capable of collecting spatially comprehensive data that provide for the documentation of changes in the vertical structure of oceans around the world (e.g. Durack et al. 2012). Further, the ability of animals to record oceanographic data is not only providing physical oceanographic data, but data on the characteristics of the animals habitat requirements that can be used to predict climate impacts (Biuw et al. 2007; Charrassin et al. 2008; Costa et al. 2010). However, comparable data collection programmes capable of examining changes in the biology of these oceans are lagging, particularly in relation to top predator species (Nicol et al. 2013), although the recently concluded Census of Marine Life TOPP programme was a standout in this regard (e.g. Block et al. 2011). Regional data exist for many of these open ocean species but few examples exist that attempt to bring these disparate studies together. By developing the tools and global databases discussed earlier, progress in both understanding of climate impacts and development and testing of adaptation options can be made more rapidly than through individual local studies.

The impacts of climate change on open ocean systems will extend beyond biology and could lead to considerable social and economic disruption for small island nations and large industrial fleets. There may be unforseen impacts on threatened and endangered species which may impact on non-extractive ocean uses, such as tourism. As yet, much work remains to determine likely future scenarios and adaptation options for both biology and human elements of the open ocean system. Multi-disciplinary approaches comparing different ocean regions are likely to lead to faster progress, and the meeting strongly endorsed the view that the study of pelagic species, ecosystems, and human uses must be a part of planned international initiatives, such as Future Earth (http://www.icsu.org/future-earth). Minimising future climate impacts and developing adaptation options for 50 % of the surface of the planet is critical if future generations are to enjoy all the benefits provided by the open sea. Action is needed now because the management measures needed to confer increased resilience to oceanic systems can take many years to be fully effective.

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