# REPORTING FORM 2025

***IMBeR Regional Program CLIOTOP – Climate Impacts On Top Order Predators***

*Operating Period as an IMBeR Member:*

*Start Year: 2004*
*End Year: 2025*

*List of Authors:*

*SSC: Heidi Pethybridge, Anne Lorrain, Kylie Scales, Barabara Mueling, Yunkai Li, Guillermo Ortuno.*

*Task Team Chairs: Stephanie Brodie, Lauren Meyer, Lian Peng, Anela Choy, Anais Médieu*

*IPO support: Fang Zue, Gi Hoon Hong*

## 1. Ongoing activities, in line with the IMBeR Grand and Innovation Challenges

*(Among other uses, information will be used to update the IMBeR Annual Report to SCOR)*

CLIOTOP has seen a dynamic period marked by impactful communications, events, and activities supporting its four active Task Teams.

**Task Team 2023-24/1: Global Trophic Linkages in the Mesopelagic Zone** is co-led by Anais Médieu (IRD, France) and Anela Choy (Scripps, USA), and includes over 40 members from 17 research institutions across 7 countries. The team's core objective is to *advance understanding of spatial patterns and environmental drivers influencing trophic connections and mercury concentrations in abundant mesopelagic and mid-trophic organisms.*

Since May 2024, co-leads and key members have been in regular communication to:

1. Advance the global dataset compilation, which now includes over 8,900 stable isotope and 1,700 total mercury concentration records—an approximate 30% increase since the last reporting period (Figure 1 below). This compilation includes biological and sampling details, and cover more than 125 families of fishes, molluscs, crustaceans, and gelatinous taxa. It specifies 2 diel vertical migration (DVM) patterns and four vertical foraging layers.
2. Progress two scientific manuscripts:
    - *Environmental Drivers of Micronekton Trophodynamics from Stable Isotopes Across Global Mesopelagic Provinces*
    - *Patterns and Drivers of Mercury Bioaccumulation and Cycling Across Global Mesopelagic Provinces*

To fulfil these objectives the Task Team have:

- Organised a hybrid workshop held at SPC in Noumea in Nov 2023 with all the members of the task team
- Completed a comprehensive literature review
- Cleaned up datasets so they are ready for analysis and publication
- Undertaken preliminary analyses of the compiled datasets

Task Team co-leads and key members, including three early career scientists and two senior researchers, will meet in September 2025 to finalise the team's work and prepare draft manuscripts for co-author review and feedback.

*Global databases and two manuscripts are on track for completion by the end of 2025.*

**Task team 2023/2: Climate Impacts of Marine Heatwaves on Top Predators**

Co-led by Peng Lian (ECR, CAS, China) and Barbara Muhling (NOAA, USA), this Task Team set out to *develop advanced AI methodologies to investigate the ecological impacts of marine heatwaves (MHWs) on tropical tunas in the eastern Pacific*.

- Regular online communications (via email and video) between co-leads have supported ongoing collaboration, with preliminary research results generated and discussed.
- Two presentations were delivered at academic conferences in May 2024:
    - *the Third AI Oceanography Forum (China), and*
    - *the 9th Youth Geoscience Forum, "Excellent Poster Award"* *https://imber.ecnu.edu.cn/32/d8/c35742a602840/page.htm*
- Research is ongoing into the effects of subsurface thermal signals, with a focus on how the intensity and cumulative duration of MHWs influence tuna ecology.
- An in-person Task Team meeting was held alongside the PICES Annual Meeting in Honolulu, Hawaii, October 2024. A TEDx activity was also scheduled following the event.
- An illustration of Task Teams workflow for data preparation, progress and analysis including the framework of the XAI analysis (see Appendix Figure 2 below).

*A draft manuscript is being prepared and is on track for submission by the end of 2025*

**Task team 2023-24/3: Global analysis of white shark trophic role** is co-led by Lauren Meyer and Charlie Huveneers (Flinders University, Australia) and includes >30 members from 10 countries.

Following the successful White Shark Global workshop in November 2023, the task team is continuing to advance two scientific manuscripts:

- *Global trends and recommendations for white shark research methodologies*
- *Global analysis of ontogenetic and spatial (coastal vs. pelagic) diet shifts*

Since May 2024, key activities to progress this objective have included:

- Analysing survey responses from over 40 participants, including early and late-career researchers, government officials, tourism operators, and NGO representatives.
- Identifying global and regional research priorities, such as coastal vs. pelagic feeding, ontogenetic dietary changes, regional diet variation, non-pinniped prey contributions, feeding specialisation, isotope use for movement and habitat analysis, and diet shifts linked to human impacts.
- Developing a list of global research priorities for white shark trophic ecology and outlining a proposed path forward.
- Beginning the compilation of regional diet datasets for a global meta-analysis.
- Conducting a qualitative assessment of human-driven influences on white shark diet.

*The two scientific manuscripts are on track for submission before the end 2025.*

**Task Team 2023-24/4: Exploring New Horizons, Barriers, and Bottlenecks in Marine Ecological Forecasting for Oceanic Top Predators**

Led by Kylie Scales (University of the Sunshine Coast, Australia) and Stephanie Brodie (CSIRO, Australia), this Task Team includes 11 additional international members. Their primary goal is to *develop a scientific paper providing a roadmap for ecological forecasting to support the management of living marine resources.*

Since the last report, the team has made strong progress through a series of hybrid (in-person and online) meetings, including:

- Completing a comprehensive literature review to assess the current state of marine ecological forecasting for oceanic top predators.
- Establishing a real-world case study in collaboration with the Inter-American Tropical Tuna Commission (IATTC), focused on non-target bycatch species in Eastern Tropical Pacific purse-seine fisheries and how marine heatwaves affect these interactions.
- Finalising a structural framework for the paper, which will:
  (i) evaluate current practices in ecological forecasting within applied marine management contexts, and
  (ii) deliver concrete, science-based, and actionable recommendations to guide researchers and decision-makers in mitigating climate impacts on oceanic top predators and ecosystems.
- Developing a conceptualised figure to illustrate their Ecological forecasting roadmap (see Figure 3 below).

*All activities and milestones are progressing, with the research paper on track for completion by the end of 2025.*

## 1.a. Grand Challenge I

*Understanding and quantifying the state and variability of marine ecosystems* - with focus on Research Objectives 1 to 3:

***Research Objective 1**. Evaluate and predict the cumulative effect of multiple stressors*
***Research Objective 2**. Integration of climate change and climate variability*
***Research Objective 3**. Impacts on society – preparation for a changed future*

Task Team 2023/2 is actively addressing the grand challenge of understanding climate impacts on marine ecosystems by focusing on the effects of marine heatwaves (MHWs) on top predators in tropical oceans. The team's primary contribution lies in developing advanced deep learning models to improve predictions of bigeye tuna (*Thunnus obesus*) distribution in the eastern Pacific, particularly under El Niño and high-frequency MHW conditions. By integrating MHW metrics into AI-based habitat models, the team is uncovering how surface and subsurface thermal anomalies influence tuna movements and ecological interactions. This work is critical for understanding how climate-driven ocean changes affect commercially important species such as yellowfin (*Thunnus albacares*), bigeye, and skipjack tuna (*Katsuwonus pelamis*), which are essential to global food security and the sustainability of tropical tuna fisheries. Through a real-world application of these models, the Task Team aims to anticipate how changing ocean conditions may reshape tuna communities, informing adaptive fisheries management strategies.

Ultimately, CLIOTOP's Task Team research supports global efforts to enhance climate resilience in marine systems and contributes directly to the United Nations Sustainable Development Goals, particularly SDG 13 (Climate Action) and SDG 14 (Life Below Water), by improving our ability to forecast and mitigate climate impacts on key oceanic species.

### 1.b. Grand Challenge II

*Improving scenarios, predictions and projections of future ocean-human systems at multiple scales* - with focus on Research Objectives 4 to 6:

***Research Objective 4**. Development of integrated data systems and approaches for predictions and projections*
***Research Objective 5**. Development of predictive models and projections for use at regional scales*
***Research Objective 6**. Development of alternative scenarios to bridge the gap between physical climate sciences and humanities*

Task Team 2023-24/4 is supporting CLIOTOP's Grand Challenge by bringing together experts to identify limitations and pathways for enhancing marine ecological forecasting applications and capacity worldwide. Ecological forecasting predicts biological and ecosystem responses to environmental variability on management-relevant timescales. Recent advances now enable skilful ocean condition forecasts up to nine years ahead, opening new opportunities while highlighting challenges such as regional oceanographic predictability, which remains underexplored globally. Recognising that accurate forecasting is critical for sustaining marine biodiversity and fisheries amid increasing climate variability, the Task Team's roadmap paper will guide researchers, managers, and policymakers toward more resilient, climate-informed marine resource management. While marine ecological forecasting has primarily focused on target species distributions, this Task Team also addresses the need to mitigate fisheries interactions with non-target and threatened species. Leveraging ongoing collaborations and emerging data streams, the team is reviewing regional constraints on forecast skill and exploring integrated forecasting approaches within national Exclusive Economic Zones. Their goals include sharing best practices, defining future research directions, and producing outputs that advance the global ecological forecasting community toward sustainable fisheries and ocean stewardship.

Further to this, activities proposed by task team 2023/1 will assist CLIOTOP in meeting Grand Challenge II by developing and using predictive models to provide an assessment of how different food webs around the world may change under various future climate and environmental scenarios.

### 1.c. Grand Challenge III

*Improving and achieving sustainable ocean governance* - with focus on Research Objectives 7 to 9:

***Research Objective 7**. Develop knowledge on best practices for multilevel governance approaches to ocean climate adaptation and mitigation*
***Research Objective 8**. Develop understanding on key ingredients for transformation towards more sustainable, equitable and inclusive governance approaches to fisheries and aquaculture*
***Research Objective 9**. Support implementation of post-2020 biodiversity targets for marine spatial planning and marine protected areas*

Task teams 2023-24/1 and 2023/3 have undertaken work that will directly assist CLIOTOP in addressing the overarching scientific questions in relation to advanced understanding of marine ecology, food web dynamics, movements of top predators in a changing climate, and ocean biogeochemistry. Marine organisms are fundamentally linked and explicitly interact through marine trophodynamics (predator – prey relationships). Delineating and quantifying these linkages is however, challenging on both regional and global scales. Stable isotope analysis has proven to be a powerful tool to establish, represent and quantify linkages, interactions and ecological feedbacks between individual species and marine ecosystems. Most importantly, many global research groups have undertaken stable isotope analyses in top marine predators so there is a large and already collected dataset from which to draw from. The work undertaken by these task teams have facilitated future comparative analysis and research into food web structure and functioning, including carbon fluxes. By grouping and quantitatively analysing the stable isotope dataset generated in this project from the global ocean, the respective scientific papers will allow for a broader understanding of the food webs underlying fisheries production and a more complete understanding of the trophic ecology of commercially important tunas. Furthermore, an understanding of top predator movements in the open ocean is crucial to both stock assessments of commercially important species, and to determine shifts in patterns in a changing climate. The work is focused on elucidating key interactions and linkages between biogeochemical cycles, food webs, potential fishing impacts, and climate variability.

The Micronekton Trophodynamics Task Team's global dataset on mercury concentrations in tuna and a historical reconstruction spanning five decades, has demonstrated that mercury levels in tuna flesh have remained largely unchanged, despite a substantial decrease in atmospheric mercury following reduction in anthropogenic emissions. This highlights the ocean's inertia and suggests that stronger emission reductions are required under the Minamata Convention to achieve a measurable impact on marine biota. This research has received wide media coverage, including *The New York Times* and *BBC News*, and the dataset has been selected as a case study by the expert panel to support the first effectiveness evaluation of the Minamata Convention. It is also expected to be formally recognized as a temporal reference series for mercury in marine organisms. This underscores the significant contribution of the CLIOTOP work to global policy frameworks and its integration into major international environmental assessment efforts.

## 1.d. Innovation Challenge 3

*To advance understanding of ecological feedbacks in the Earth System*

Task teams 2023-24/1 and 2023/3 are advancing our understanding of ecological interactions (predator-prey dynamics, competition, etc.), by providing compiling datasets and developing models that provide insights into how ecological feedback mechanisms operate in response to environmental changes. Task teams 2023-24/1 are compiling and assessing global mercury and carbon isotope datasets that feed into global Earth System and Climate Models. Through sustained monitoring efforts, CLIOTOP tracks changes over time, which is crucial for understanding long-term ecological feedbacks and trends.

## 1.e. Innovation Challenge 4

*To advance and improve the use of social science data for ocean management, decision making and policy development*

Collaborative efforts led by all CLIOTOP task teams are improving stakeholder engagement and data sharing. All task teams are attempting to translate their research findings into actionable strategies for managing and mitigating the impacts of climate change on marine ecosystems.

### 1.f. Innovation Challenge 5

*Interventions to change the course of climate impacts*

CLIOTOP has not recently sponsored activities directly related to this Innovation Challenge

### 1.g. Innovation Challenge 6

*Sustainable management of Blue Carbon ecosystems*

Research conducted under CLIOTOP helps elucidate how climate variability and change affect Blue Carbon ecosystems. Understanding these impacts is vital for developing strategies to protect and restore these habitats. By promoting the sharing of data and research findings, CLIOTOP supports a comprehensive understanding of Blue Carbon ecosystems across different regions, leading to more effective global management strategies.

CLIOTOP promotes the development of integrated management plans that consider the interconnectedness of marine ecosystems and the importance of preserving Blue Carbon habitats for their ecological and climate benefits.

## 2. Selected highlights

### 2.a. Selected scientific highlights since last report (1-5)

*Last report was submitted to SCOR, August 2024*

- Global mercury datasets developed by Task Team 2023/01 are directly informing the Minamata Convention's first effectiveness evaluation and shaping global policy assessments.
- International representation and presentation by CLIOTOP SSC members.
- Strong engagement and proactive participation of international members in CLIOTOP's four Task Teams. This includes numerous online meetings, in-person workshops, and conference presentations.
- Expansion of compilation of global ecological (stable isotope and mercury) databases, including 8,900 records for 240 marine taxa.
- Five scientific manuscripts are currently in the early stages of results formulation or drafting, expected to be completed in late 2025.
- Peng Lian, Task Team co-lead and IMBeR Junior Fellow, was appointed to PICES Advisory Panel on Early Carer Ocean Professionals
- Peng Lian was appointed Youth editorial board member of Marine Environmental Engineering (2025-2026)
- Peng Lian was awarded Excellent Poster Award at the Third-AI Oceanographic Forum

### 2.b. Publications since last report

*Please add all publications since last report to the table below (see notes for details on "Class" and "Activity" fields).*

| ***Publication*** *with DOI* | ***Class*** | ***Activity**** |
|---|---|---|
| ***Médieu, A., Point****, D., Sonke, J.E., Angot,* ***H., Allain, V., Bodin****, N., Adams, D.H., Bignert, A., Streets, D.G., Buchanan, P.B., Heimbürger-* | *1* | *Task Team Micronekton stable* |

| | | |
|---|---|---|
| *Boavida, L.-E**., Pethybridge, H**., Gillikin, D.P., **Ménard, F., Choy, C.A.,** Itai, T., Bustamante, P., Dhurmeea, Z., Ferriss, B.E., Bourlès, B., Habasque, J., Verheyden, A., Munaron, J.-M., Laffont, L., Gauthier, O., **Lorrain, A., 2024.** Stable Tuna Mercury Concentrations since 1971 Illustrate Marine Inertia and the Need for Strong Emission Reductions under the Minamata Convention. Environ. Sci. Technol. Lett. 11, 250–258. https://doi.org/10.1021/acs.estlett.3c00949* | | *isotopes and Hg* |
| *Zhang, B**., Pethybridge, H.** and **Li, Y**., 2025. Mercury bioaccumulation and biomagnification in mesopelagic biota. Marine Pollution Bulletin, 218, p.118209. https://doi.org/10.1016/j.marpolbul.2025.118209* | *2* | *Task Team Micronekton stable isotopes and Hg* |
| ***Lian P.,** Gao L**. 2024.** Contrasting physical mechanisms of yellowfin tuna fluctuations between the western and eastern Indian Ocean, Journal of Oceanology and Limnology. https://doi.org/10.1007/s00343-023-2330-3* | *2* | *Task Team Marine Heat waves and AI applications* |
| ***Lian P.,** Gao L. **2024.** Impacts of central-Pacific El Niño and physical drivers on eastern Pacific bigeye tuna. Journal of Oceanology and Limnology. https://doi.org/10.1007/s00343-023-3051-3* | *2* | *Task Team Marine Heat waves and AI applications* |
| *Yuewen Zhang, **Lian P**., Xiong Zhang 2024. Seasonal distribution patterns and conservation gaps of blue sharks in the Indo-Western Pacific Ocean. Diversity and Distributions. https://doi.org/10.1111/ddi.13828* | *2* | *Task Team Marine Heat waves and AI applications* |
| ***Médieu, A., Point, D., Allain, V., Bodin**, N., Lemire, M., Ayotte, P., Dhurmeea, Z., Waeles, M., Laffont, L., Gohalen, A.L., Roupsard, F., **Lorrain, A**., **2025.** Species-specific mercury speciation in billfishes and its implications for food safety monitoring and dietary advice. Environment International 195, 109252. https://doi.org/10.1016/j.envint.2025.109252* | *2* | *Task Team Micronekton stable isotopes and Hg* |
| | | |
| *[Add more rows if needed]* | | |

**If appropriate, please list the IMBeR activity through / by / from / during which the publication arose*

*******Notes on publications********

Publications are logged in the IMBeR Zotero library which is publicly accessible online –

Publications since 2016 | Publications prior to 2016

Publications are categorised by "Class" and linked to "Activities":

***Class 1 publications*** are specifically generated through/by/from/during ***IMBeR activities*** - for example, arising from IMBIZOs and IMBeR conferences such as the IMBeR open science meeting and the IMBeR West Pacific symposia and from the activities of the working groups, regional programmes and the SPIS scoping teams.

***Class 2 publications*** are on topics relevant to the IMBeR Science Plan that benefitted from some interaction with IMBeR or ***IMBeR activities***, for example by IMBeR symposium attendees, past and present SSC members, working group, regional programme and endorsed project members, or national contacts.

***Class 3 publications*** are on topics relevant to the IMBeR Science Plan but for which there is no direct link to or benefit from an IMBeR activity. These might include publications by SSC members, working group, regional programme or endorsed project members or members of the IMBeR international community that were written as part of the normal scientific activity of the authors and would have occurred irrespective of IMBeR's existence. You can report Class 3 publications, but they will no longer be logged in the IMBeR database.

[See "What is an IMBeR publication?" for further information]

***Why list 'Class' and 'Activity'?*** This helps us to declare authentically which publications IMBeR has helped to generate, and it makes it easier for us to demonstrate the value of the Regional Programmes, the Working Groups, and IMBeR in general, and it helps us to justify support for IMBeR activities when we can list tangible outputs.

### 2.c. Events, Meetings, and Workshops

*List all international and national events, meetings and workshops. Describe the level of participation: e.g. chairing session/workshop, organising meeting. Include Endorsed Projects committee meetings and workshops.*

*Format: Title of event. Date. Location. Description of participation. Any other pertinent details.*

1. Third-AI Oceanographic Forum, May 2024, Lian Peng, Climate Impacts of Marine Heatwaves on Tropical Tunas.
2. Deep Sea Biology Symposium, Hong Kong, December 2024, Anela Choy,
3. PICES-ICES Small Pelagic Fish Working Group SSC meeting, February 2025, Anela Choy and Heidi Pethybridge.
4. IMBeR Future Oceans 3 Meeting, May 2025, Heidi Pethybridge, CLIOTOP Synthesis Presentation
5. Several CLIOTOP SSC and task team members are engaged in international research to be shared at the United Nations Ocean Conference (UNOC2025) in France, June 2025.
6. PICES annual meeting, Oct. 2024, Lian Peng, Deep learning techniques for evaluating the ecological impacts on the spatio-temporal variations of tuna in the eastern Pacific Ocean.

## 3. International collaboration and links

CLIOTOP has an extensive network of participants, which was updated late last year and includes 620 members from >30 countries. Our level of diversity and spread across genders, career levels, and geographical regions is impressive and growing. Co-leads and members of our task teams include early to senior, male and female proponents from all habitable continents (Asia, South and North America, Australasia, Europe and Africa).

The IMBeR Regional Program *Ecosystem Studies of Subarctic and Arctic Seas* (ESSAS) approached the CLIOTOP SSC with a proposal to hold a joint conference alongside their Open Science Meeting in Japan, scheduled for June 2025. This potential collaboration was shared with prospective members engaged in Antarctic top predator research; however, it was ultimately not pursued.

CLIOTOP has engaged with the FISHMIP Coordination Team (https://fishmip.org/), a diverse network of regional and global ecosystem modellers, to explore potential collaborations—particularly around the use of trophic and other biological datasets generated through CLIOTOP Task Team activities.

## 4. Input to management, policy and SOCIETY* over the last year

*Add anything that is not covered under "1.c. Grand Challenge III"*

**As previous reporting forms requested 'input to management and policy' only, please add any 'input to society' not captured in previous reports*

There is nothing additional to report here over the last 12 months

## 5. Education, outreach and Capacity Development

Outputs from CLIOTOP are made available through the publication of special issues of journals in association with each symposia held. They are also made available via the CLIOTOP website. Webpage content has been updated over the last few months, with assistance from IMBeR-IPO, to enhance our outreach.

## 6. Planned activities

### 6.a. Activities and Outreach and how they link to the Challenges (including, but not limited to convening sessions, meetings, summer schools, workshops, etc)

As described above several highly successful and well attended international task team workshops and meetings have been undertaken over the last 12 months. In addition, task team and CLIOTOP SSC members have communicated their and CLIOTOP's research at several international symposia.

- Future Oceans 3, Shanghai, China, May 2025
- International Congress for Conservation Biology, Brisbane, Australia, June 2025

### 6.b. Upcoming papers (Community-Position-Review-etc)

Seven manuscripts, directly resulting from the activities of the CLIOTOP four Task Teams are expected to be drafted and submitted to high-impact journals before the end of 2025. Tentative titles are included in the first section of this report.

3. *Medieu, Choy, et al. Environmental Drivers of Micronekton Trophodynamics from Stable Isotopes Across Global Mesopelagic Provinces*
4. *Medieu, Choy, et al. Patterns and Drivers of Mercury Bioaccumulation and Cycling Across Global Mesopelagic Provinces*
5. *Meyers, Huveneers, et al. Global trends and recommendations for white shark research methodologies*
6. *Meyers, Huveneers, et al. Global analysis of ontogenetic and spatial (coastal vs. pelagic) diet shifts*
7. *Scales, Brodie, et. al. A roadmap for ecological forecasting to support the management of living marine resources*
8. *Pethybridge et al. International collaboration on marine top predator research - benefits, challenges and future priorities.*

## 8. Changes to Organisational Structure

For CLIOTOP to continue a restructure to the current SSC is planned as several members have been and continue to be inactive for at least one year with limited interaction or response to chair communications. An invitation seeking new members will be sent to our broad network of members, with particular interest to see greater engagement with Task Team co-chairs.

The terms of conditions were updated in late 2023 to provide the chairs with more power in making changes to the SSC.

## 9. Images / Figures

*****It is always good to have some recent photos / figures / infographics to create more exposure for the Regional Programmes, Working Groups, etc. These can range from those suitable for a very scientific audience, to those that would engage the general public. IMBeR would use these, on the website (e.g. http://www.imber.info/ and http://www.imber.info/en/news), in tweets (@imber_ipo), in presentations, etc. In addition, Future Earth (one of our sponsors) regularly asks us to provide high quality images for their glossy reports. These can highlight the activities of IMBeR and their other Global Research Projects (see pdfs of past Future Earth reports here https://futureearth.org/publications/annual-reports/)*

*So, please provide any images that you might think are useful. These can be pasted in this document or emailed as an attachment to imber@ecnu.edu.cn.*****

Please see three corresponding figures in the Appendices and four Tables in sections 11 and 12 below.

## 10. Notable achievements over the IMBeR decade (2016-2025)

1. Since its inception, CLIOTOP has brought together over 600 members from across the globe and has benefited from an outstanding and diverse leadership team, representing many different countries and scientific disciplines.

2. CLIOTOP has been a leader in science that matters and delivered on its original vision of *understanding key patterns and processes driving the interaction between climate variability and human use on the structure and functioning of oceanic ecosystems and their top predators.* At the heart of this vision is collaboration which includes bringing together international and multidisciplinary networks to undertake broad-scale comparative research. CLIOTOP has consistently aimed to build predictive capacity and advance methods that support the management of these complex socio-ecological systems, while also assessing adaptation options for future sustainability. The network actively collaborates closely with other research initiatives and stakeholders to share data, promote interdisciplinary science, and support outreach.

3. Recognition of impact through symposia. The CLIOTOP community has held four well-attended Symposia in 2007, 2013, 2015 and 2018 across four continents. Each symposium has served as an important forum for assessing progress in our understanding of oceanic predators and the impacts of climate change on ocean ecosystems over the lifetime of the CLIOTOP program. These gatherings have also been key opportunities for the community to come together, exchange ideas, build collaborations, and develop new approaches to the challenges facing oceanic top predators and the ecosystems they depend on.

4. Recognition of impact through publication. CLIOTOP have published four Special Issues, first in Progress in Oceanography and later in Deep-Sea Research II, which followed on from each Symposia. Together, and through other related outputs, the CLIOTOP community has produced >150 peer-reviewed scientific publications. These works span a range of topics from climate impacts on predator distributions and ecosystem structure, to bioenergetics, migration, fisheries interactions, and modelling approaches. This body of research has not only advanced scientific understanding but has also informed management decisions and influenced international marine policy. The diversity of authors, disciplines, and regions represented in these publications reflects the truly global and collaborative nature of CLIOTOP.

5. The CLIOTOP community has directly support IMBeR's contribution to the United Nation's Sustainable Development Goals (SDGs), particularly those associated with Responsible Consumption and Production (SDG 12), Climate Action (SDG 13) and Life Below Water (SDG 14). CLIOTOP have done this through three main mechanisms: (1) building new regional and global datasets; (2) developing digital tools and models, including novel statistical and process-based approaches, and (3) generating new knowledge on topics that align with IMBeR's Grand and Innovation Challenges.

6. CLIOTOP's work has been grounded in addressing core scientific questions such as: *How do individuals and populations of marine species respond to climate variability, climate change, and other drivers like fishing*? and *How do human systems interact with oceanic predators, and what does that mean for ecosystem functioning?* Through this work, CLIOTOP has helped bridge science with policy, providing tools and insights that support sustainable ocean management.

## 11. A list of Synthesis Products

A network of >600 researchers

>150 peer reviewed publications, including five special issues:

1. Progress in Oceanography, July 2010, CLIOTOP, Volume 86, 30 papers: https://www.sciencedirect.com/journal/progress-in-oceanography/vol/86/issue/1
2. Deep-sea Research II, Squid Focus, October 2013, Volume 95: https://www.sciencedirect.com/journal/deep-sea-research-part-ii-topical-studies-in-oceanography/vol/95/suppl/C
3. Deep-sea Research II, CLIOTOP, March 2015, Volume 113, 26 papers: https://www.sciencedirect.com/journal/deep-sea-research-part-ii-topical-studies-in-oceanography/vol/113/suppl/C

4. Deep-sea Research II, CLIOTOP, June 2017, Volume 140: https://www.sciencedirect.com/journal/deep-sea-research-part-ii-topical-studies-in-oceanography/vol/140/suppl/C
5. Deep-sea Research II, CLIOTOP, May 2020, Volume 175, 29 papers: https://www.sciencedirect.com/journal/deep-sea-research-part-ii-topical-studies-in-oceanography/vol/175/suppl/C

Key, high-impact and/or highly cited, papers are listed on our webpage and also include:


- Young, J.W., Hunt, B.P., Cook, T.R., Llopiz, J.K., Hazen, E.L., Pethybridge, H.R., Ceccarelli, D., Lorrain, A., Olson, R.J., Allain, V. and Menkes, C., 2015. The trophodynamics of marine top predators: current knowledge, recent advances and challenges. *Deep Sea Research Part II: Topical Studies in Oceanography*, *113*, pp.170-187.
- Hobday, A.J., Young, J.W., Abe, O., Costa, D.P., Cowen, R.K., Evans, K., Gasalla, M.A., Kloser, R., Maury, O. and Weng, K.C., 2013. Climate impacts and oceanic top predators: moving from impacts to adaptation in oceanic systems. *Reviews in fish biology and fisheries*, *23*, pp.537-546.
- Evans, K., Arrizabalaga, H., Brodie, S., Chang, C.T., Llopiz, J., Phillips, J.S. and Weng, K., 2020. Hobday, A.J., Arrizabalaga, H., Evans, K., Scales, K.L., Senin, I., Weng, K.C. (2017). International collaboration and comparative research on ocean top predators under CLIOTOP. Deep Sea Research Part II: Topical Studies in Oceanography, 140: 1-8. doi:10.1016/j.dsr2.2017.03.008
- Médieu, A., Point, D., Sonke, J.E., Angot, H., Allain, V., Bodin, N., Adams, D.H., Bignert, A., Streets, D.G., Buchanan, P.B., Heimbürger-Boavida, L.-E., Pethybridge, H., Gillikin, D.P., Ménard, F., Choy, C.A., Itai, T., Bustamante, P., Dhurmeea, Z., Ferriss, B.E., Bourlès, B., Habasque, J., Verheyden, A., Munaron, J.-M., Laffont, L., Gauthier, O., Lorrain, A., 2024. Stable Tuna Mercury Concentrations since 1971 Illustrate Marine Inertia and the Need for Strong Emission Reductions under the Minamata Convention. Environ. Sci. Technol. Lett. 11, 250–258. https://doi.org/10.1021/acs.estlett.3c00949
- Llopiz, J.K., R.K. Cowen, M.J. Hauff, R. Ji, P.L. Munday, B.A. Muhling, M.A. Peck, D.E. Richardson, S. Sogard, S. Sponaugle. (2014). Early life history and fisheries oceanography: New questions in a changing world. Oceanography 27(4): 26-41.
- Arrizabalaga, H., Dufour, F., Kell, L., Merino, G., Ibaibarriaga, L., Chust, G., Irigoien, X., Santiago, J., Murua, H., Fraile, I. and Chifflet, M., 2015. Global habitat preferences of commercially valuable tuna. *Deep Sea Research Part II: Topical Studies in Oceanography*, *113*, pp.102-112.
- Erauskin-Extramiana, M., Arrizabalaga, H., Hobday, A.J., Cabré, A., Ibaibarriaga, L., Arregui, I., Murua, H. and Chust, G., 2019. Large-scale distribution of tuna species in a warming ocean. *Global change biology*, *25*(6), pp.2043-2060.
- Hazen, E.L., Abrahms, B., Brodie, S., Carroll, G., Jacox, M.G., Savoca, M.S., Scales, K.L., Sydeman, W.J. and Bograd, S.J., 2019. Marine top predators as climate and ecosystem sentinels. *Frontiers in Ecology and the Environment*, *17*(10), pp.565-574.
- Olson, R.J., Duffy, L.M., Kuhnert, P.M., Galvan-Magana, F., Bocanegra-Castillo, N. and Alatorre-Ramirez, V., 2014. Decadal diet shift in yellowfin tuna *Thunnus albacares* suggests broad-scale food web changes in the eastern tropical Pacific Ocean. *Marine Ecology Progress Series*, *497*, pp.157-178.
- Hobday, A.J., Arrizabalaga, H., Evans, K., Nicol, S., Young, J.W. and Weng, K.C., 2015. Impacts of climate change on marine top predators: Advances and future challenges. *Deep Sea Research Part II: Topical Studies in Oceanography*, *113*, pp.1-8.
- Muhling, B.A., Brodie, S., Smith, J.A., Tommasi, D., Gaitan, C.F., Hazen, E.L., Jacox, M.G., Auth, T.D. and Brodeur, R.D., 2020. Predictability of species distributions deteriorates under novel environmental conditions in the California Current System. *Frontiers in Marine Science*, *7*, p.589.
- Young, J.W., Olson, R.J. and Rodhouse, P.G., 2013. The role of squids in pelagic ecosystems: an overview. *Deep Sea Research Part II: Topical Studies in Oceanography*, *95*, pp.3-6.
- Llopiz, J.K. and Hobday, A.J., 2015. A global comparative analysis of the feeding dynamics and environmental conditions of larval tunas, mackerels, and billfishes. *Deep Sea Research Part II: Topical Studies in Oceanography*, *113*, pp.113-124.
- Dueri, S. and Maury, O., 2013. Modelling the effect of marine protected areas on the population of skipjack tuna in the Indian Ocean. *Aquatic Living Resources*, *26*(2), pp.171-178.


Four well attended symposia, with key outputs summed up on our webpage and published:

1. La Paz, Mexico, December 2007: *Interactions between climate variations and fisheries*. Included 200+ participants from 20 Countries
   Lehodey, P. and Maury, O., 2010. CLimate Impacts on Oceanic TOp Predators (CLIOTOP): introduction to the special issue of the CLIOTOP international symposium, La Paz, Mexico, 3–7 December 2007. *Progress in Oceanography*, *86*(1-2), pp.1-7.

2. Noumea, New Caledonia, Feb 2013. *Certainty of change in pelagic systems*. included 70+ participants from 18 Countries
   Hobday, A., K. Weng. (2013). The 2nd CLIOTOP Symposium. IMBER Newsletter 23: 2.1.

3. San Sebastián, Spain, Sep 2015: *Future of oceanic animals in a changing ocean*. Included 200+ participants from 24 Countries. https://imber.info/the-3rd-cliotop-symposium/

4. Keelung, Taiwan, November 2018: *Oceanic biodiversity under climate change*. Included 66 participants from 8 Countries. https://imber.info/4th-cliotop-symposium/

Workshop & proceedings with summaries and outcomes published, including:

- Young, J.W., Olson, R.J., Ménard, F., Kuhnert, P.M., Duffy, L.M., Allain, V., Logan, J.M., Lorrain, A., Somes, C.J., Graham, B. and Goñi, N., 2015. Setting the stage for a global-scale trophic analysis of marine top predators: a multi-workshop review. *Reviews in Fish Biology and Fisheries*, *25*, pp.261-272.
- Young, J. and Olson, R., 2007. Workshop report: the ecological role of squid in pelagic ecosystems. University of Hawaii, Honolulu, 16–17 November 2006. *GLOBEC Int. Newsl.*, *13*, pp.43-44.

Annual reports reflecting scientific impact, progress and contributions to IMBeR's Science Goals

Compilation of large global datasets available online:

- A global biochemical database: Bodin, N., Pethybridge, H., Lorrain, A., Allain, V., Ménard, F. and Graham, B., 2021. Global data set for nitrogen and carbon stable isotopes of tunas. *Ecology*, *102*(3).

- Global prey composition datasets: Duffy, L.M., Kuhnert, P.M., Pethybridge, H.R., Young, J.W., Olson, R.J., Logan, J.M., Goñi, N., Romanov, E., Allain, V., Staudinger, M.D. and Abecassis, M., 2017. Global trophic ecology of yellowfin, bigeye, and albacore tunas: understanding predation on micronekton communities at ocean-basin scales. *Deep Sea Research Part II: Topical Studies in Oceanography*, *140*, pp.55-73.

Development of new code, statistical approaches and ecosystem models:

- Kuhnert, P.M., Duffy, L.M., Young, J.W. and Olson, R.J., 2012. Predicting fish diet composition using a bagged classification tree approach: a case study using yellowfin tuna (Thunnus albacares). *Marine Biology*, *159*, pp.87-100.
- Maury, O., 2010. An overview of APECOSM, a spatialized mass balanced "Apex Predators ECOSystem Model" to study physiologically structured tuna population dynamics in their ecosystem. *Progress in Oceanography*, *84*(1-2), pp.113-117.
- Lehodey, P., Senina, I. and Murtugudde, R., 2008. A spatial ecosystem and populations dynamics model (SEAPODYM)–Modeling of tuna and tuna-like populations. *Progress in Oceanography*, *78*(4), pp.304-318.

Time-series analyses or global meta-analyses of large international datasets, for example:

- Lorrain, A., Pethybridge, H., Cassar, N., Receveur, A., Allain, V., Bodin, N., Bopp, L., Choy, C.A., Duffy, L., Fry, B. and Goñi, N., 2020. Trends in tuna carbon isotopes suggest global changes in pelagic phytoplankton communities. *Global Change Biology*, *26*(2), pp.458-470.

- Wu, Y.L., Lan, K.W. and Tian, Y., 2020. Determining the effect of multiscale climate indices on the global yellowfin tuna (*Thunnus albacares*) population using a time series analysis. Deep Sea Research Part II: Topical Studies in Oceanography, 175, p.104808.
- Médieu, A., Point, D., Sonke, J.E., Angot, H., Allain, V., Bodin, N., Adams, D.H., Bignert, A., Streets, D.G., Buchanan, P.B. and Heimbürger-Boavida, L.E., 2024. Stable tuna mercury concentrations since 1971 illustrate marine inertia and the need for strong emission reductions under the Minamata Convention. *Environmental Science & Technology Letters*, *11*(3), pp.250-258.
- Pethybridge, H., Choy, C.A., Logan, J.M., Allain, V., Lorrain, A., Bodin, N., Somes, C.J., Young, J., Ménard, F., Langlais, C. and Duffy, L., 2018. A global meta-analysis of marine predator nitrogen stable isotopes: Relationships between trophic structure and environmental conditions. *Global Ecology and Biogeography*, *27*(9), pp.1043-1055.
- Olson, R.J., Duffy, L.M., Kuhnert, P.M., Galvan-Magana, F., Bocanegra-Castillo, N. and Alatorre-Ramirez, V., 2014. Decadal diet shift in yellowfin tuna *Thunnus albacares* suggests broad-scale food web changes in the eastern tropical Pacific Ocean. *Marine Ecology Progress Series*, *497*, pp.157-178.
- Logan, J.M., Pethybridge, H., Lorrain, A., Somes, C.J., Allain, V., Bodin, N., Choy, C.A., Duffy, L., Goni, N., Graham, B. and Langlais, C., 2020. Global patterns and inferences of tuna movements and trophodynamics from stable isotope analysis. *Deep Sea Research Part II: Topical Studies in Oceanography*, *175*, p.104775.


Interviews of CLIOTOP research and collaboration:

- Karen Evans, UN Ocean Decade: https://www.youtube.com/watch?v=srJZPNTS9K0

Visual products and infographics to help with outreach and communication to the broader scientific community has occurred throughout CLIOTOP's history with examples including:

- https://www.franciscoblaha.info/blog/2020/1/29/analysis-of-stable-isotopes-in-tuna-meat-as-to-identify-decadal-changes-in-the-ocean-carbon-cycle

## 12. Reflections

There are several reflections to make in terms of CLIOTOP's legacy and evolution.

Over its 20 years of operation, CLIOTOP has successfully brought together international researchers to advance our understanding of oceanic top predators and their responses and vulnerabilities to climate change. Collaborative research generated and supported by CLIOTOP has produced new methods, datasets, and knowledge that have advanced key management objectives including ecosystem-based management (EBM), integrated ocean management (IOM), fisheries management, and marine spatial planning (MSP), with a focus on adaptive management and conservation.

CLIOTOP's continued success is rooted in its people. We have seen that there is immense value in drawing on diverse perspectives and datasets across regions and disciplines to better understand complex ocean–climate–predator interactions. This diversity has strengthened the quality of our scientific outputs. Furthermore, CLIOTOP has actively engaged with many early career researchers (ECRs), providing a forum for ECRs to become involved and be integrated with the community. Such engagement has helped to grow the CLIOTOP community, and IMBERs impact more broadly, and facilitated the career development of ECRs from participating countries around the world.

Combining regional studies into meaningful global analyses is inherently challenging and requires a coordinated international effort. Global datasets and meta-analyses play a vital role in expanding knowledge and supporting both regional and global fisheries and ecosystem-based management objectives.

Operating under IMBeR has provided additional opportunities for the CLIOTOP community to participate and support IMBeR activities. For example, CLIOTOP community members have been involved in ClimEco summer schools, Future Oceans conferences, IMBIZO workshops, and IMECaN, as well as involvement in the IMBeR Scientific Steering Committee. Integration with IMBeR activities has further enhanced CLIOTOPs research impact through learnings from other disciplines, and increased collaborative networks around the world.

Stemming from a CLIOTOP workshop held at SPC in Noumea, November 2023, participants came together to identify key elements for enabling impactful international collaboration (Table 1). The group noted that such collaboration enhances the impact of regional research and strengthens connections across the field. It provides early-career researchers with valuable opportunities for high-impact science, career development, and broader networking. Scientifically and organizationally, it supports knowledge exchange, standardization of methods, tool development, and improved access to funding and training.

**Table 1. Key benefits or opportunities of international collaboration.** Taken from: Pethybridge et al. In Prep. International collaboration on marine top predator research - benefits, challenges and future priorities.

| Benefit Category | Additional details |
|---|---|
| Professional advancement and fulfilment | Provides a greater sense of purpose to extend the utility of regional work and connecting with others in the field |
| | Enhanced opportunities for ECR's - high impact science and exposure to an extended network of researchers |
| | Enhanced opportunities for career growth through being a regional leader and point of contact |
| | Professional visibility through networking opportunities (workshops, meetings) |
| Networking | Knowledge exchange |
| | Supportive community |
| | better communication and understanding |
| | Broad scale understanding |
| | Validation and peer review: a platform to present work and receive feedback |
| | standardisation of methodologies |
| | Development of new tools |
| Scientific advancement | Promotes a more holistic approach to problem-solving and comprehensive understanding of scientific issues and solutions |
| Funding and organisational advantages | Platform to acquire funding |
| | Providing extended educational opportunities |
| | Capability developments |

A list of 28 imminent challenges associated with achieving successful international collaboration were also noted in the workshop (Table 2). This included financial limitations, temporal constraints, leadership and administrative hurdles, capacity and motivational barriers, cultural and objective variances, challenges related to data-sharing, team building issues, and the inherent scientific complexity of the endeavour.

**Table 2. key challenges or limitations of international collaboration.** Taken from: Pethybridge et al. In Prep. International collaboration on marine top predator research - benefits, challenges and future priorities.

| Constraint | Additional details |
|---|---|

| | | |
|---|---|---|
| 1 | Financial | Limited funding for staff time and research in international programs |
| 2 | Temporal | Extended timelines exceeding 10 years for most international studies<br>Cumbersome proposal requirements leading to time-intensive processes |
| 3 | Leadership and | Requirement for determined and energetic leaders for large projects |
| 4 | Administrative Hurdles | Insufficient administrative support causing organizational complexities |
| 5 | Capacity and Motivational | High dependence on individuals with constrained availability and motivation, especially in resource-stretched developing nations.<br>Communication is difficult if too many people participant |
| 6 | Cultural and Objective Variances | Diverse backgrounds and ways of working affect communication and collaboration<br>Need to deal with varied objectives among scientists and stakeholders<br>Threats to collaboration when scientists lack freedom to discuss their work with the government |
| 7 | Data-sharing | Difficulties in achieving FAIR (Findable, Accessible, Interoperable, and Reusable) data standards<br>Confidentiality of fishery-dependent data |
| 8 | Team building issues | Communication barriers and time zone differences |
| 9 | Scientific complexity | Dealing with complex species and ecosystem dynamics<br>Involvement of social scientists with communication and project component overlap issues<br>Challenges in conducting transdisciplinary science, especially with large-scale projects |
| 10 | Training and innovation focus | Limited funds for continuing old techniques and approaches,<br>Emphasis on training in new technologies, guiding ECR's towards innovative methods |

## 12. Recommendation for future work

While CLIOTOP's research outputs are widely cited within the scientific community, there remains a need for stronger integration of its science into major global environmental reporting processes such as the IPCC reports, the UN World Ocean Assessment, and the Global Biodiversity Outlook. It is encouraging to see progress in this area, with the long-running Trophodynamics (now Micronekton) Task Team contributing their global mercury dataset in tunas to the integrated analysis for the first effectiveness evaluation of the Minamata Convention.

In support of CLIOTOP's continuation, the community has undertaken a thoughtful examination of future research needs and priorities to continue progressing oceanic top predator and climate change research. It recognised 18 key research gaps or remaining need (Table 3).

**Table 3. Unexplored frontiers and outstanding questions in top-order predator research.** Taken from: Pethybridge et al. In Prep. International collaboration on marine top predator research - benefits, challenges and future priorities.

| Research gap or need | Focus |
|---|---|
| Mechanistic Understanding | Explore environmental and biological drivers for a deeper understanding. |
| Climate Change Impacts on Fisheries | Investigate effects on fisheries stocks, addressing abundance, size, and spatial-temporal changes. Assess winners and losers in the |

| | |
|---|---|
| | context of climate change. |
| Drivers of Movement/Migration | Examine factors influencing the movement and migration of species. |
| Contaminants and Climate Change | Evaluate the impact of climate change and human-induced changes on contaminants, fatty acids, and related factors. |
| Ecosystem Maintenance | Explore strategies for maintaining functional ecosystems. |
| Deep Sea Ecosystems | Assess the impacts of deep-sea mining on ecosystems. |
| Offshore Wind Farms | Study the effects of offshore wind farms on top predators. |
| Oceanographic Stressors | Identify the impact of oceanographic stressors on top predators. |
| Informed Science Programs | Enhance science programs and survey designs through informed scientific approaches. |
| Consumption Patterns | Investigate missing information on national populations' consumption, especially among islanders, to address food security. |
| Protected Areas | Explore the role of protected areas and ecosystem restoration efforts. |
| Ocean-Basin Scale Surveys | Conduct surveys and observations at ocean-basin scale, including high seas and areas beyond national jurisdiction. |
| GOOS EOVs and Top Predators | Explore the integration of top predators into Global Ocean Observing System Essential Ocean Variables (GOOS EOVs). |
| Carbon Cycling and Global Modeling | Study global-scale carbon cycling and modeling. |
| Species Evolution in Response to Climate Change | Investigate the potential for species to evolve faster than the progression of climate change. |
| Fisheries Development Impacts on Mesopelagic Fishes | Identify impacts of fisheries development on mesopelagic fishes. |
| Seabird Contributions to Coastal Biogeochemical Cycles | Assess the contributions of seabirds to coastal biogeochemical cycles. |
| Science Pollution | Question the value and potential impacts of scientific activities on the environment. |

The CLIOTOP community have identified and prioritized 13 essential technologies and approaches crucial for advancing top predator research (Table 4). Participants identified a range of emerging technologies as essential for advancing top predator research, including genomics, eDNA, acoustic systems, drones, and autonomous platforms like gliders and BGC-Argo. The use of big data, AI, and machine learning was highlighted as key for efficient data analysis. Integrating human dimensions and social science was seen as critical for a multidisciplinary approach. Together, these tools provide a roadmap for tackling complex ocean challenges and deepening our understanding of marine ecosystems.

**Table 4. List of technologies or approaches for advancing the understanding of climate impacts on oceanic top predators and their ecosystems.** Taken from: Pethybridge et al. In Prep. International collaboration on marine top predator research - benefits, challenges and future priorities.

| |
|---|
| 1. Science Communication |
| 2. Utilizing Existing Tools (Ecosystem Models) and Large Datasets |
| 3. Genomics |
| 4. Environmental DNA (eDNA) |
| 5. Big Data - Machine Learning/Artificial Intelligence Methods (ML/AI) |
| 6. Acoustics (Research Vessels or Autonomous/Uncrewed Vehicles) |

| |
|---|
| 7. Taxonomy<br><br>8. Moving Beyond Simple Spatial Distribution<br><br>9. Autonomous profiling for acoustics (e.g. Saildrones or Argofloats)<br><br>10. Drones (Air and Ocean)<br><br>11. Gliders, BGC-Argo, Autonomous Samplers<br><br>12. Compound-Specific Isotope Analysis (CSIA) on amino acid, fatty acid, methylmercury<br><br>13. Integration of Human Dimensions/Social Science |

## 13. Anything not covered above

## 14. Appendices

*Add appropriate meeting / workshop reports and include URLs (this helps to track where online content is missing)*

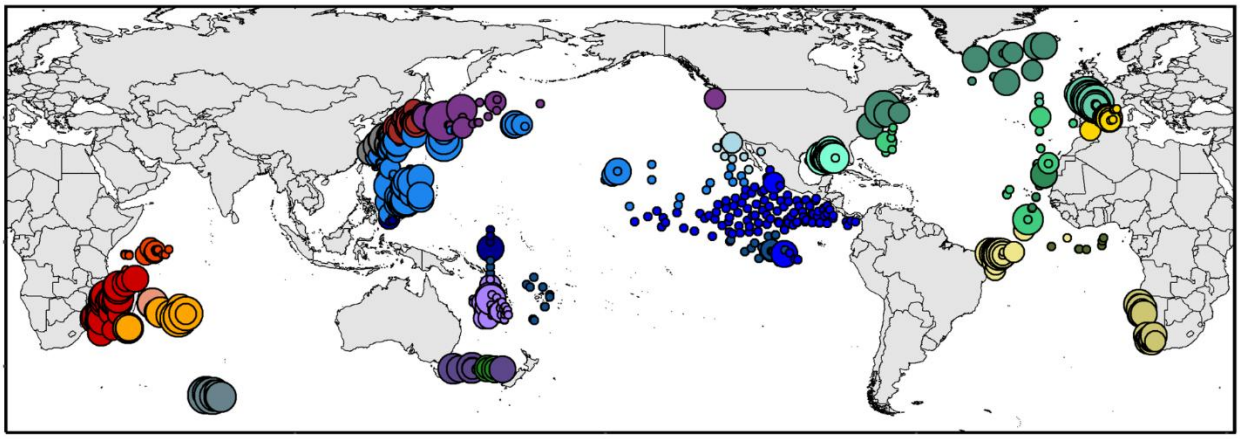
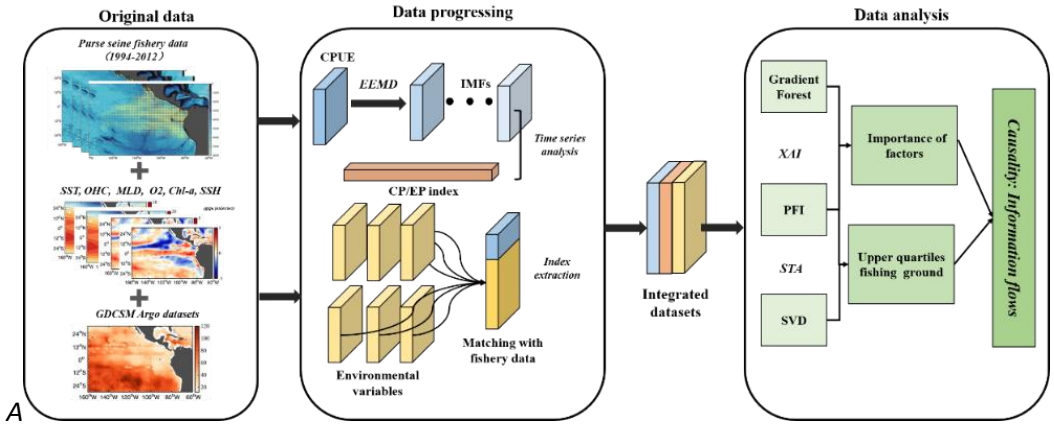
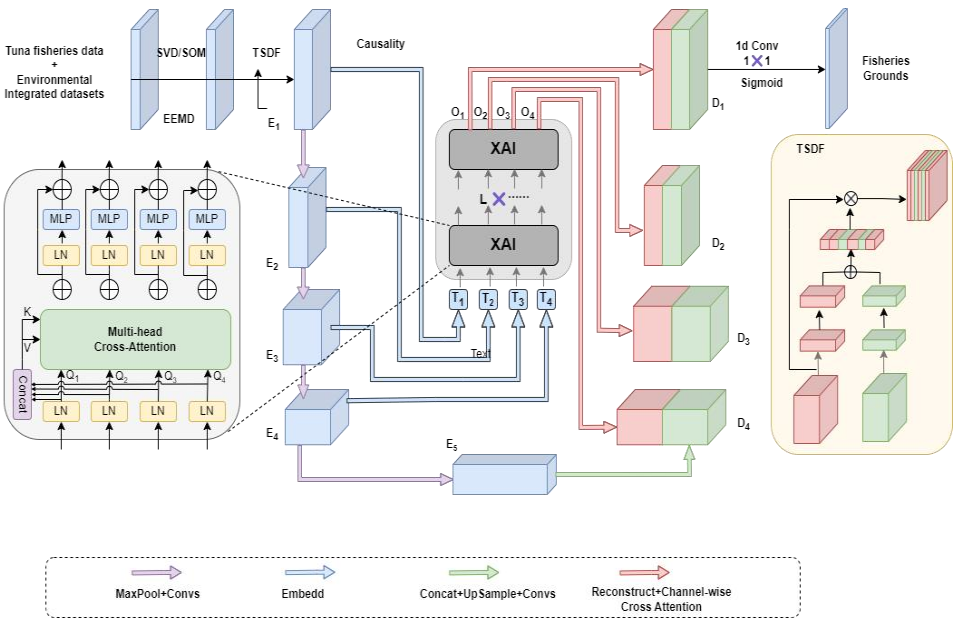


***Figure 1**. Sample locations of stable isotope and mercury concentration data compiled by Task Team 2023/01 to undertake global analyses to better understand the spatial patterns and environmental drivers of trophic diversity and mercury cycling in abundant mesopelagic organisms. The color code corresponds to the biogeographic classification of the mesopelagic zone, as defined in Sutton et al.* (2017)






B

***Figure 2**: Progress and science advancements undertaken by Task Team 2023/02 as shown through a (A) flow chart of the tuna data preparation, progress and analysis, and (B) framework of XAI analysis to reconstruct global tropical tuna habitats.*

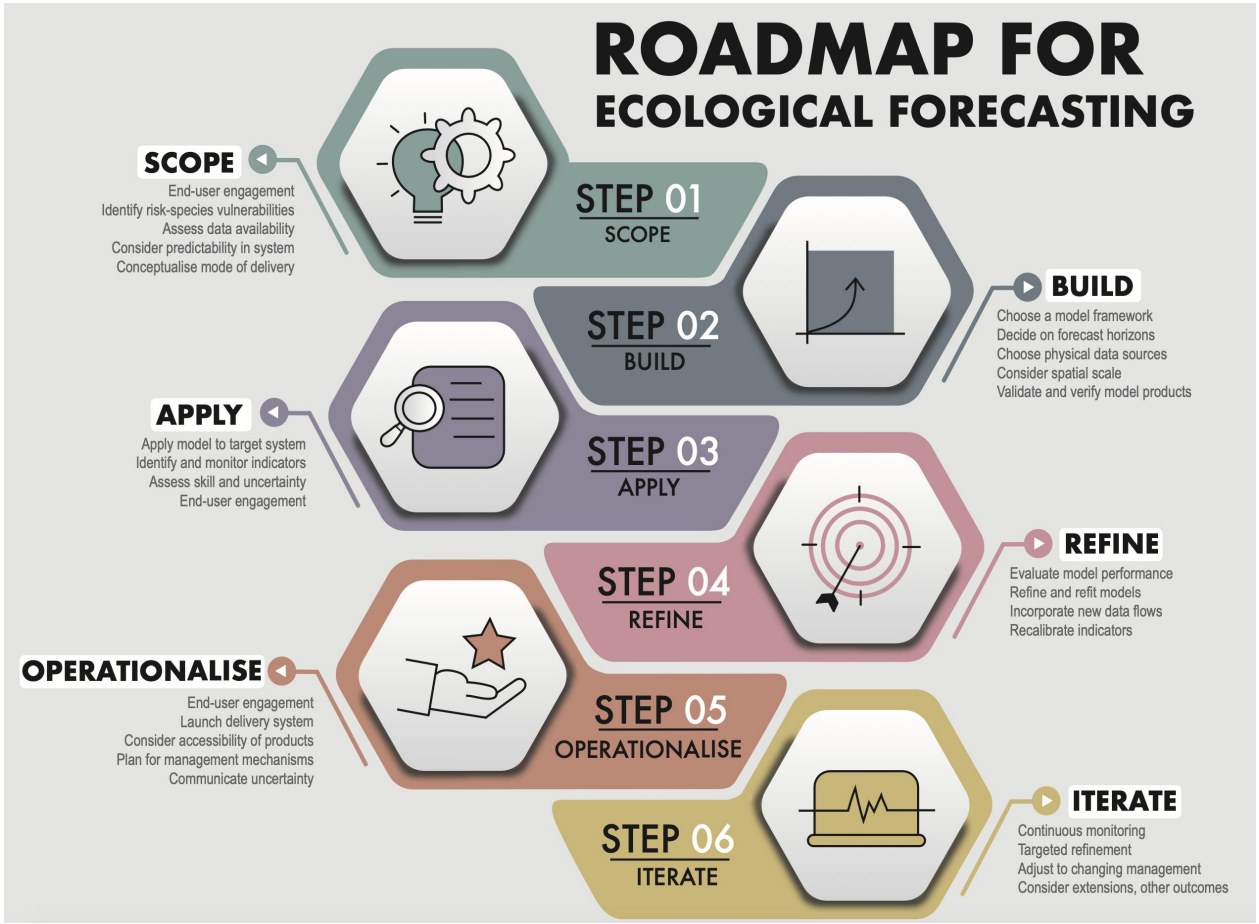


***Figure 3:*** *Roadmap for ecological forecasting developed by Task Team 2023/03 outlining six iterative steps—Scope, Build, Apply, Refine, Operationalise, and Iterate—designed to guide the development, implementation, and continuous improvement of ecological models for decision support.*