

SECOND INTERNATIONAL INDIAN OCEAN EXPEDITION (IIOE-2)

A Basin-Wide Research Program



Science Plan Addendum



EDITED BY

R. R. Hood, F. Al-Yamani, L. E. Beckley, G. L. Cowie, N. D'Adamo, J. Hermes,
H. T. Kobryn, N. Kiran Kumar, Aneesh A. Lotliker, R. M. Koll, A. Modi, E.
Pattabhi Rama Rao, M-A. Sicre, V. Sudheesh, and P. N. Vinayachandran

SECOND INTERNATIONAL INDIAN OCEAN EXPEDITION (IIOE-2)

A Basin-Wide Research Program

Science Plan Addendum (2026 – 2030)



Hood, R. R., F. Al-Yamani, L. E. Beckley, G. L. Cowie,
N. D'Adamo, J. Hermes, H. T. Kobryn, N. Kiran Kumar, Aneesh A.
Lotliker, R. M. Koll, A. Modi, E. Pattabhi Rama Rao, M-A. Sicre, V.
Sudheesh, and P. N. Vinayachandran (Eds.)

November 2025



Preface

This Addendum to the Second International Indian Ocean Expedition (IIOE-2) Science Plan is motivated by several factors. These include the impacts of the COVID-19 pandemic that resulted in a 3-year hiatus in in-person meetings and research cruises, and the loss of key IIOE-2 personnel. Moreover, although IIOE-2 has been highly successful, it has not yet achieved all of its stated objectives. In particular, there is still work that needs to be done to fully examine the biogeochemical and ecological impacts of anthropogenic influences on the ocean and how these will, in turn, impact coastal marine environments and human populations. There is also a need to focus more on coastal monitoring and management, data sharing, scientific engagement of Indian Ocean rim countries, and capacity development.

IIOE-2 was developed with joint sponsorship from the Scientific Committee on Oceanic Research (SCOR), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, and the Indian Ocean Global Ocean Observing System (IOGOOS) program, with support from the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program and its Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program, providing strong relevancies to IOC's High Level Objectives, which span the generic themes of marine hazards, climate change, ecosystem protection and associated marine natural resource management. IIOE-2 also has strong links with the Indian Ocean Regional Panel (IORP), sponsored by the Global Ocean Observing System (GOOS) and the Climate Variability and Predictability (CLIVAR) programs, and the Indian Ocean Observing System (IndOOS) Resources Forum (IRF), both under the auspices of IOGOOS.

This Addendum to the IIOE-2 Science Plan builds upon concepts and strategies formulated and discussed at three SCOR and IOC-sponsored meetings (convened in Perth, Western Australia, February 6-7, 2023; in Hyderabad, India, November 28-30, 2023; and in Lombok, Indonesia, March 4-5, 2024). These meetings included scientists from Indian Ocean rim nations, eastern Asia, Europe and North America. The meeting in Hyderabad was dedicated to the development of this Addendum, providing several key presentations, discussion notes and an outline for this document.

The IIOE-2 Science Plan Addendum provides the motivation and scientific justification for extending the Second International Indian Ocean Expedition for an additional five years (2026-2030). Scientists from all relevant fields are encouraged to collaborate and implement the IIOE-2 Science Plan Addendum to ensure that major outstanding questions about the Indian Ocean and Earth System are addressed in a fully integrated manner.

SCOR IIOE-2 Science Plan Addendum Development Committee, 2025:

<i>Raleigh R. Hood</i>	<i>Faizah Al-Yamani</i>	<i>Lynnath E. Beckley</i>	<i>Greg L. Cowie</i>
<i>Nick D'Adamo</i>	<i>Juliet Hermes</i>	<i>Halina T. Kobryn</i>	<i>N. Kiran Kumar</i>
<i>Aneesh A. Lotliker</i>	<i>R. M. Koll</i>	<i>Aditi Modi</i>	<i>E. Pattabhi Rama Rao</i>
<i>Marie-Alexandrine Sicre</i>	<i>V. Sudheesh</i>	<i>P. N. Vinayachandran</i>	

SCOR IIOE-2 Science Plan Addendum Reviewers, 2025:

<i>Wee Cheah</i>	<i>Eun Young Kwon</i>	<i>Mario Lebrato</i>	<i>Shailesh Nayak</i>
<i>Alice Newton</i>	<i>Shubha Sathyendranath</i>	<i>Penjai Somponchaiyakul</i>	

Table of Contents

Executive Summary	4
Background and Motivation	6
Background on IIOE-2	6
Development of the IIOE-2 Science Plan	7
Development of the IIOE-2 Implementation Strategy	10
Major IIOE-2 Milestones and Challenges	12
IIOE-2 50 th Anniversary Symposium and First Official Cruise	12
Joint India-Australia International Project Office Established	13
Establishment of the Early Career Scientists Network	14
IOC, IOGOOS and SCOR Approve 5 Year Extension	14
Impacts of the COVID-19 Pandemic	15
Progress and Current Status	15
Official Projects and International Participation	16
Working Groups and Research Themes	16
Synthesis Papers, Books and Special Issues	17
Scientific Highlights	18
IIOE-2 Science 2026-2030	24
Scientific Theme 1: Human Impacts	25
Knowledge Gaps and Challenges Related to Societal Benefits and Human Impacts	28
New Initiatives	34
In Situ Observations, Remote Sensing, Modeling and Assimilation	42
Revised Implementation Strategy	49
Integration	51
UN Decade of Ocean Science for Sustainable Development	51
New IOC Sub-Commission: IOCINDIO	52
WCRP: My Climate Risk Program	53
CoastPredict	54
Communication	54
Data and Information Management	56
Training and Education	57
Conclusions and Legacy	58
Appendices	60
Appendix I. Acronyms	60
Appendix II. IIOE-2-related Publications, Websites and Products	61
Appendix III. Detailed targets and key performance indicators	63
References	64

Please cite as follows: Hood, R. R., F. Al-Yamani, L. E. Beckley, G. L. Cowie, N. D'Adamo, J. Hermes, H. T. Kobryn, N. Kiran Kumar, A. A. Lotliker, R. M. Koll, A. Modi, E. Pattabhi Rama Rao, M-A. Sicre, V. Sudheesh, and P. N. Vinayachandran (2025) Second International Indian Ocean Expedition (IIOE-2): A Basin-Wide Research Program, Science Plan Addendum (2026 – 2030). Scientific Committee on Oceanic Research, Newark Delaware, USA.

Cover Figure: Indian Ocean exclusive economic zones (EEZs). Figure downloaded and modified from: https://deepseamining.ac/static_blog_img/large-eez.webp#gsc.tab=0.

EXECUTIVE SUMMARY

SCOR, IOC, and the Indian Ocean GOOS program (IOGOOS) are coordinating a new phase of international research focused on the Indian Ocean, which began in late 2015 and will continue through 2025. The goal is to assist ongoing research and stimulate new initiatives in this time frame as part of the Second International Indian Ocean Expedition - IIOE-2. This initiative has been highly successful, but has not yet achieved all of its stated objectives. In particular, there is still work that needs to be done to fully examine the biogeochemical and ecological impacts of anthropogenic influences on the ocean and how these will, in turn, impact coastal marine environments and human populations. There is also a need to focus more on coastal monitoring and management, data sharing, scientific engagement of Indian Ocean rim countries, and capacity development. The COVID-19 pandemic led to the cancellation and postponement of numerous planned meetings and research cruises during 2020–2022. However, there has been a rapid resumption of cruise activity since the COVID-19 lockdown and several new project endorsements. Given the current momentum of IIOE-2 and the clear need to address the remaining challenges, the IIOE-2 community is seeking to extend IIOE-2 for an additional 5 years to 2030.

The IIOE-2 has structured its research around six scientific themes. Core questions from Theme 1 (Human Impacts) are reiterated in this Addendum because they articulate many of the challenges and research questions that will be prioritized in the final phase of IIOE-2 (2026 – 2030). Key overarching questions under Theme 1 include: How are human-induced ocean stressors impacting the biogeochemistry and ecology of the Indian Ocean? How, in turn, are these impacts affecting human populations? ***But it is also important to emphasize that this document does not supersede the IIOE-2 Science Plan. The science priorities identified in the Science Plan will continue to be priorities in the final phase of IIOE-2. Rather, this document highlights areas of the Science Plan that will be prioritized in the final phase of IIOE-2, and describes some new initiatives and opportunities that have emerged under IIOE-2 that did not exist when the Science Plan was written.***

Since the first IIOE-2 cruise from India to Mauritius in December 2015, the IIOE-2 has grown to involve over 50 multi-disciplinary and multi-national projects endorsed by the IIOE-2 with some 20 participating countries. These often involve multiple voyages “of discovery” cruises that have now covered much of the Indian Ocean, engaging many of the world’s major international ocean scientific institutions through a wide global constituency of leading ocean and climate scientists. The emphasis on engaging small island and developing states is paramount, as is the focus on providing material opportunities for capacity development for early career scientists, ocean managers and policy makers from countries having relatively low levels of development in ocean sciences.

The IIOE-2 has motivated numerous synthesis papers and a book on the Indian Ocean, and it is continuing to compile and publish a Deep-Sea Research II Special Issue Series

that is well underway to publish an eighth volume. More than 100 papers have been published thus far via these venues, and yet they represent only a fraction of the total, considering the publications generated by the many programs and research expeditions that have been motivated under IIOE-2. Several examples of specific programs, research expeditions and achievements motivated under IIOE-2 are highlighted in this Addendum.

The IIOE-2 Science Plan places considerable emphasis on the biogeochemical and ecological impacts of anthropogenic influences on the ocean and how these will, in turn, impact coastal marine environments and human populations. The plan also emphasizes the need for coastal monitoring, data sharing, scientific engagement of Indian Ocean rim countries, and capacity development. Despite this emphasis, most of the research that has been carried out to date in IIOE-2 has been focused on the open ocean, and additional effort needs to be focused on engagement of Indian Ocean rim countries and capacity development. ***Knowledge gaps and challenges articulated here include: the need for more coastal monitoring and metadata sharing in exclusive economic zones (EEZs) of Indian Ocean rim nations; the need to engage with and promote marine spatial planning (MSP) efforts in the Indian Ocean; the need to increase scientific understanding and engagement of western Indian Ocean, the eastern Bay of Bengal and marginal seas research communities; and the need to increase capacity development efforts and promote early career scientists.***

This Addendum also highlights four new initiatives that will greatly facilitate addressing these needs: the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program, which is an established IMBeR/IOGOOS regional program focusing on biogeochemistry and ecosystem research, that the IIOE-2 community proposes to include in IIOE-2; ***the Korea-US Indian Ocean Scientific Imperatives (KUDOS) program***, which is an ongoing program that will continue to be a major focus of IIOE-2 in its final phase, focusing on the Seychelles-Chagos Thermocline Ridge (SCTR); ***the emerging Coastal Observations in a Box (COLaB) project***, which is a major opportunity for building a regional network for cross-validated coastal oceanographic data collection, and also for building capacity and training multi-skilled coastal oceanographers; ***and a new Marginal Seas Research Initiative is proposed*** here that will not only advance scientific understanding in several understudied regions of the Indian Ocean (Andaman Sea, Arabian Sea/Persian Gulf, Gulf of Aden, Red Sea, Sea of Oman), but will also provide new opportunities for scientific engagement of Indian Ocean rim countries which are not currently actively participating in IIOE-2.

New *in situ* observation, remote sensing, modeling and assimilation efforts that need to be embraced in the final phase of IIOE-2 are also articulated in this Addendum. The revised IIOE-2 Implementation Strategy and the new Data and Information Management policy are summarized. The need for integration with the new IOC Sub-Commission for the Central Indian Ocean (IOCINDIO), the UN Decade of Ocean Science for Sustainable Development, the WCRP My Climate Risk Program, and the Global Ocean Observing System's (GOOS) CoastPredict program is emphasized. This Addendum also articulates the need to improve communication efforts, especially those aimed at a wider audience, including policy makers, managers and the public. This Addendum emphasizes that the

IIOE-2 will continue to promote engagement across Indian Ocean scientists and associated institutions from developed and developing countries that are planning to undertake science activities in the region, which includes capacity-building components that will accomplish collaborative use of expertise and physical resources from within and outside the Indian Ocean region to accomplish training, joint research and analysis, and other activities.

Population increase in Indian Ocean rim countries has contributed to multiple stressors on both coastal and open ocean environments, including eutrophication, depletion of fresh groundwater, deoxygenation, atmospheric and plastic pollution, wastewater discharge, hydrocarbon contamination and overfishing. These regional stressors, combined with warming and acidification due to global climate change, are resulting in the loss of biodiversity in the Indian Ocean, as well as changes in the phenology and biogeography of many species. The main focus of the research that will be carried out in the final phase of IIOE-2 will be aimed at better understanding the impacts of multiple stressors on coastal environments and efforts will be motivated to communicate these findings to decision makers. ***Research carried out in the final phase of IIOE-2 will improve our ability to predict extreme events and monsoon variability and facilitate the development of national strategies to mitigate their impacts on human populations. In its final phase, the IIOE-2 will focus on motivating studies that are aimed at improving our understanding of higher trophic level species and the impacts of fishing pressure and habitat destruction on these species. The IIOE-2 will also motivate studies of direct anthropogenic impacts on coastal environments, including coastal erosion, loss of mangroves, and degradation of coral reefs and how these, in turn, might impact food security and fisheries. The IIOE-2 will work to raise awareness of the pressing need for ecosystem conservation in the Indian Ocean in order to safeguard both tourism and fisheries.***

The success of IIOE-2 will be gauged not just by how much it advances our understanding of the complex and dynamic Indian Ocean system, but also by how it contributes to the sustainable development of marine resources, environmental stewardship, ocean and climate forecasting, and training of the next generation of ocean scientists from the region. This vision of success can be fully realized in the final phase of IIOE-2.

BACKGROUND AND MOTIVATION

BACKGROUND ON IIOE-2

Although there have been significant advances in our ability to describe and model the Earth System, our understanding of geologic, oceanic and atmospheric processes in the Indian Ocean is still rudimentary in many respects. This is largely because the Indian Ocean remains under-sampled in both space and time, especially compared to the Atlantic and Pacific oceans. The situation is compounded by the Indian Ocean being a

dynamically complex and highly variable system under monsoonal influence. Many uncertainties remain in terms of how geologic, oceanic and atmospheric processes affect climate, extreme events, marine biogeochemical cycles, ecosystems and human populations in and around the Indian Ocean. There are also growing concerns about food security in the context of climate change and anthropogenic impacts on coastal environments and fisheries sustainability. These impacts include sea level rise, which leads to coastal erosion, loss of mangroves, and loss of biodiversity. There is a pressing need for ecosystem conservation in the Indian Ocean for both tourism and fisheries. To address these concerns, SCOR, IOC, and the Indian Ocean GOOS program (IOGOOS) are coordinating a new phase of international research focused on the Indian Ocean, which began in late 2015 and will continue through 2025. The goal is to assist ongoing research and stimulate new initiatives in this time frame as part of the Second International Indian Ocean Expedition - IIOE-2.

Since the first IIOE-2 cruise from India to Mauritius in December 2015, the IIOE-2 has grown to involve over 50 multi-disciplinary and multi-national projects endorsed by the IIOE-2 with some 20 participating countries. These have involved numerous cruises that have covered much of the Indian Ocean, and IIOE-2 has engaged many of the world's major international oceanographic institutions through a wide global constituency of leading ocean and climate scientists. The IIOE-2 has also emphasized engagement of small island and developing states, and it has focused on capacity development for early career scientists, ocean managers and policy makers from countries having relatively low levels of development in ocean sciences.

This IIOE-2 has been highly successful, but has not yet achieved all of its stated objectives. In particular, there is still work that needs to be done to fully examine the biogeochemical and ecological impacts of anthropogenic influences on the ocean and how these will, in turn, impact coastal marine environments and human populations. There is also a need to focus more on coastal monitoring and management, data sharing, scientific engagement of Indian Ocean rim countries, and capacity development.

The COVID-19 pandemic led to the cancellation or postponement of numerous planned meetings and research cruises during 2020–2022. Tragically, it also resulted in the passing of Dr. Satya Prakash, coordinator of the IIOE-2 Joint Project Office in India. Since 2023, IIOE-2 activities have experienced a strong revival, driven, among other things, by the fact that most of the research cruises and activities that were postponed due to the COVID-19 pandemic are now happening or are planned over the next few years. Given the current momentum of IIOE-2 and the clear need to address the remaining challenges, the IIOE-2 community is seeking to extend IIOE-2 for an additional 5 years to 2030.

DEVELOPMENT OF THE IIOE-2 SCIENCE PLAN

The IIOE 50-year anniversary symposium in 2015 and IIOE-2 discussions were initiated in April 2011 at an IMBER SSC meeting in Marseille (discussions with Ed Urban/SCOR). A seminal meeting followed in Cape Town, South Africa, in October 2012, leading to the IOC “Reference Group” meetings (led by Nick D’Adamo), which were convened in 2013

and 2014 in several Indian Ocean rim countries, including India, China and Mauritius. (see Hood and D'Adamo 2012, 2013 & 2014; D'Adamo 2014). These meetings provided the background information and core science questions that laid the foundation for developing the IIOE-2 Science Plan (Hood et al., 2015). SCOR, IOC and IOGOOS informally assumed leadership of the IIOE-2 planning process in 2014. The IIOE-2 Science Plan was commissioned by SCOR, and it was finalized for the Goa Symposium in November 2015 (Figure 1). Note that many of the authors of the IIOE-2 Science Plan are still involved in IIOE-2.

The overarching goal of IIOE-2 is to: Advance our understanding of interactions between geologic, oceanic and atmospheric processes that give rise to the complex physical dynamics of the Indian Ocean region, and determine how those dynamics affect climate, extreme events, marine biogeochemical cycles, ecosystems and human populations. This understanding is required to predict the impacts of climate change, pollution, and increased resource harvesting on the Indian Ocean and its surrounding nations, as well as the influence of the Indian Ocean on other components of the Earth System. New understanding is also fundamental to policy makers for the development of sustainable coastal zone ecosystem, and fisheries management strategies for the Indian Ocean. Other goals of IIOE-2 include helping to build research capacity and improving availability and accessibility of oceanographic data from the region.

The IIOE-2 Science Plan is structured around six scientific themes. Each of these includes a set of questions that need to be addressed in order to improve our understanding of the physical forcing that drives variability in marine biogeochemical cycles, ecosystems and fisheries in the Indian Ocean and develop the capacity to predict how this variability will impact human populations in the future. It is also important to emphasize that most of these questions are relevant to open ocean, coastal and marginal sea environments.

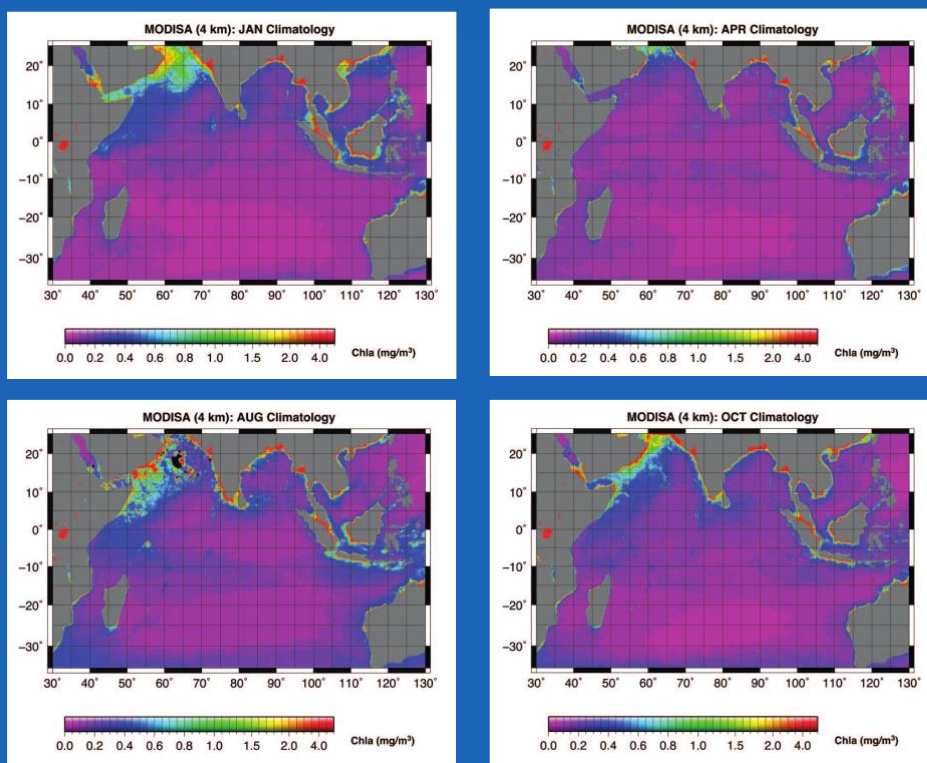
- **Theme 1: Human Impacts** (*How are human-induced ocean stressors impacting the biogeochemistry and ecology of the Indian Ocean? How, in turn, are these impacts affecting human populations?*)
- **Theme 2: Boundary current dynamics, upwelling variability and ecosystem impacts** (*How are marine biogeochemical cycles, ecosystem processes and fisheries in the Indian Ocean influenced by boundary currents, eddies and upwelling? How does the interaction between local and remote forcing influence these currents and upwelling variability in the Indian Ocean? How have these processes and their influence on local weather and climate changed in the past, and how will they change in the future?*)

SECOND INTERNATIONAL INDIAN OCEAN EXPEDITION (IIOE-2)

A Basin-Wide Research Program



Science Plan



EDITED BY

**R. R. Hood, H. W. Bange, L. Beal, L. E. Beckley, P. Burkill,
G. L. Cowie, N. D'Adamo, G. Ganssen, H. Hendon, J. Hermes,
M. Honda, M. McPhaden, M. Roberts, S. Singh, E. Urban, W. Yu**

Figure 1: Cover of the IIOE-2 Science Plan, published in November 2015 and edited by R. R. Hood, H. W. Bange, L. E. Beckley, P. Burkill, G. L. Cowie, N. D'Adamo, G. Ganssen, H. Hendon, J. Hermes, M. Honda, M. McPhaden, M. Roberts, S. Singh, E. Urban and W. Yu.

- **Theme 3: Monsoon Variability and Ecosystem Response** (*What factors control present, past and future monsoon variability? How does this variability impact ocean physics, chemistry and biogeochemistry in the Indian Ocean? What are the effects on ecosystems, fisheries and human populations?*)
- **Theme 4: Circulation, climate variability and change** (*How has the atmospheric and oceanic circulation of the Indian Ocean changed in the past, and how will it change in the future? How do these changes relate to topography and connectivity with the Pacific, Atlantic and Southern oceans? What impact does this have on biological productivity and fisheries?*)
- **Theme 5: Extreme events and their impacts on ecosystems and human populations** (*How do extreme events in the Indian Ocean impact coastal and open ocean ecosystems? How will climate change impact the frequency and/or severity of extreme weather and oceanic events, such as tropical cyclones and tsunamis in the Indian Ocean? What are the threats of extreme weather events, volcanic eruptions, tsunamis, combined with sea level rise, to human populations in low-lying coastal zones and small island nations of the Indian Ocean region?*)
- **Theme 6: Unique geological, physical, biogeochemical, and ecological features of the Indian Ocean** (*What processes control the present, past, and future carbon and oxygen dynamics of the Indian Ocean and how do they impact biogeochemical cycles and ecosystem dynamics? How do the physical characteristics of the southern Indian Ocean gyre system influence the biogeochemistry and ecology of the Indian Ocean? How do the complex tectonic and geologic processes and topography of the Indian Ocean influence circulation, mixing and chemistry and, therefore, also biogeochemical and ecological processes?*)

A key underpinning philosophy of IIOE-2 is that many of the world's critical ocean issues, especially those at ocean-wide scales that cut across the domains of many countries and the High Seas, cannot be tackled by individual countries on their own, both for their respective limitations in resources and mandate. It is only by joining forces and sharing resources and expertise in a complementary collegiate manner under a unifying mission (such as of the IIOE-2) that progress can be made to maximal effect in ocean science.

DEVELOPMENT OF THE IIOE-2 IMPLEMENTATION STRATEGY

In June/July 2014, the IOC established (through Resolution EC-XLVII.1) the IOC IIOE-2 Interim Planning Committee (IPC). The IPC was tasked to propose to the IIOE-2 sponsoring organizations (IOC, SCOR and IGOOS) the establishment of committees to oversee the planning and implementation of IIOE-2. The IOC Executive Secretary coordinated the establishment of the IPC (through a call via IOC Circular Letter No. 2541, in September 2014). The IPC met four times by teleconference and twice in person in 2015 to undertake these assigned tasks. The IIOE-2 Implementation strategy was

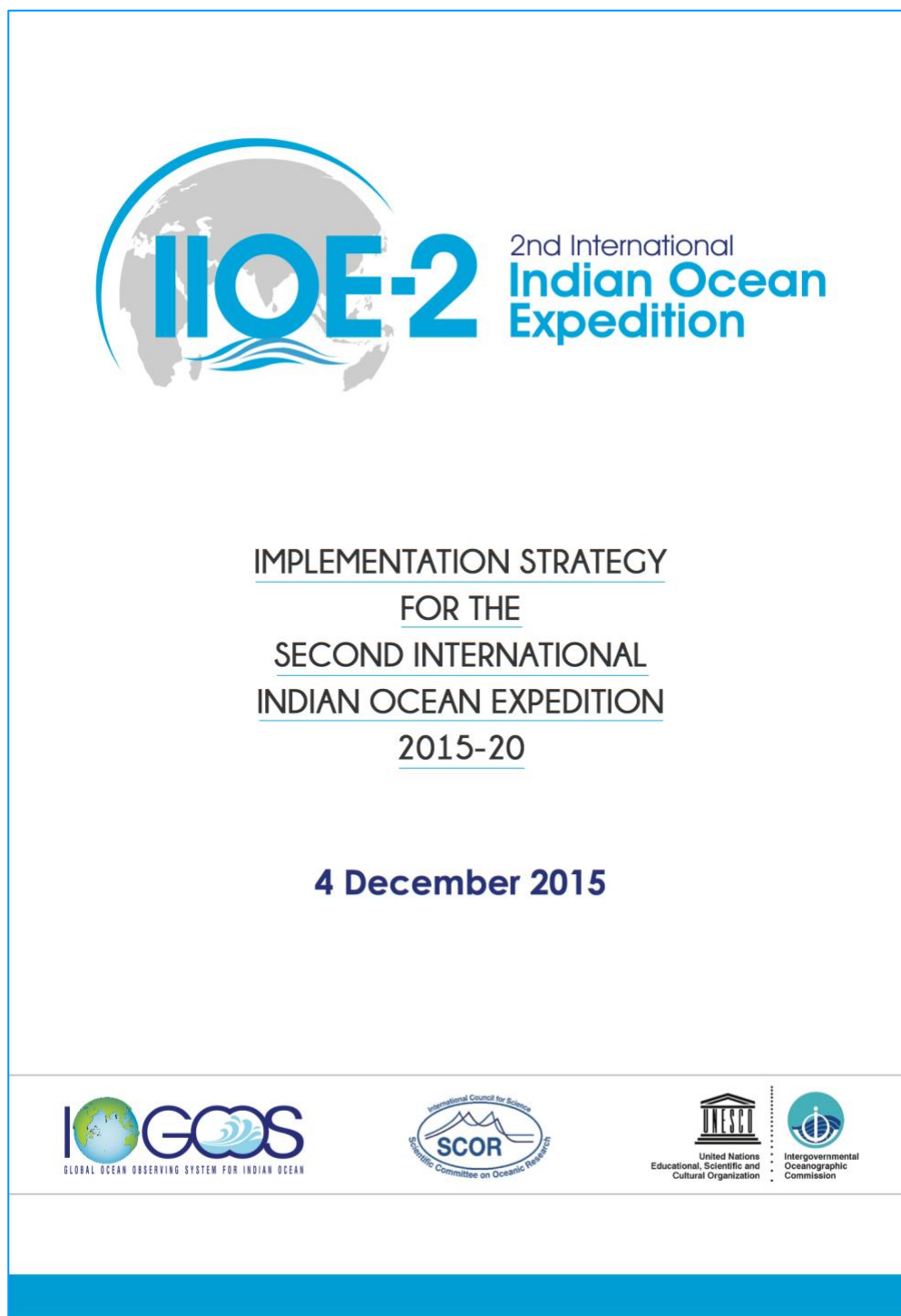


Figure 2: Cover page of the IIOE-2 Implementation Strategy, published in December 2015 and edited by P. Burkill, R. Fine, B. Gaye, K. Heywood, R. Hood, A. Johnson, S. Khokiattiwong, K. Lee, C. Jamori, Y. Masumoto, S. W. A. Naqvi, A. Schiller, J. Vialard, N. Zaker and H. Zhang.

finalized for Goa Symposium in November, 2015 (Figure 2; IPC, 2015). It had eight major sections that provide detailed plans for: 1) an IIOE-2 governance structure; 2) achieving IIOE-2 science and research objectives; 3) managing IIOE-2 data and information; 4) developing IIOE-2 research capacity; 5) IIOE-2 operational coordination; 6) IIOE-2 outreach and communication; 7) translating IIOE-2 research for society; and 8) developing IIOE-2 sponsorship and resources. The IIOE-2 Implementation Strategy also provided plans for establishing a Joint Project Office.

As specified by the Implementation Strategy, the IIOE-2 is co-ordinated by a committee, chaired by the IIOE-2's three founding principal sponsors (IOC, SCOR and IOGOOS). The IIOE-2 secretariat is currently run by the Indian National Centre for Ocean Information Services (INCOIS, under the Ministry of Earth Sciences, Indian Government), though from 2015-2021, it was jointly run with the former UNESCO IOC Perth Programme Office. The IIOE-2 website is at <https://iioe-2.incois.gov.in/>.

MAJOR IIOE-2 MILESTONES AND CHALLENGES

IIOE 50TH ANNIVERSARY SYMPOSIUM AND FIRST OFFICIAL CRUISE

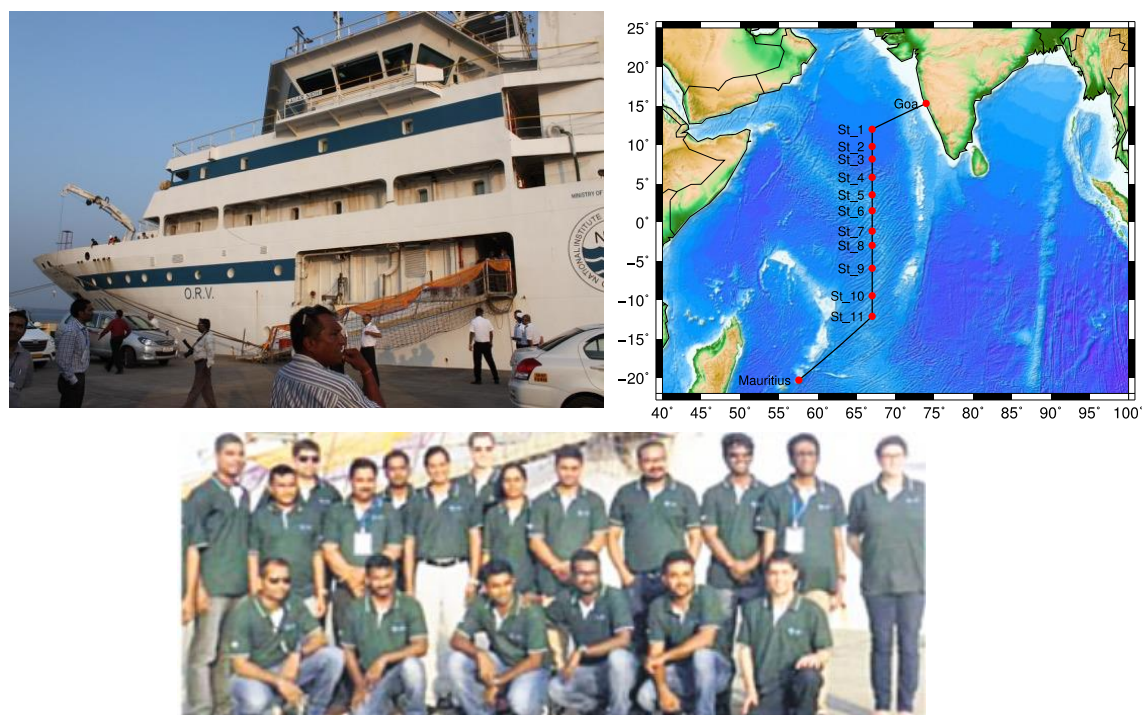


Figure 3: The first official cruise of IIOE-2 on the NIO vessel *RV Sagar Nidhi* (top left) departed from Goa immediately after the 50th Anniversary Symposium on December 5, 2015. The station line extended from Goa to Mauritius (top right), and there was strong international participation (bottom).

The IIOE 50th Anniversary Symposium was convened at the National Institute of Oceanography (NIO) in Goa, Nov. 30 – Dec. 4, 2015, “Dynamics of the Indian Ocean: Perspective and Retrospective”. There were more than 400 participants. The symposium’s special sessions were based on the six research themes of the IIOE-2 Science Plan.

The first Official Cruise of IIOE-2 on the NIO vessel *RV Sagar Nidhi* departed from Goa immediately after the Symposium on December 5, 2015 (Figure 3). The station line extended from Goa to Mauritius, and there was strong international participation. This was the first of several India-sponsored IIOE-2 cruises, along with many cruises funded by other countries.

JOINT INDIA-AUSTRALIA INTERNATIONAL PROJECT OFFICE ESTABLISHED

The IIOE-2 Joint Project Office (JPO) was established in 2015, with the India node hosted by ESSO-INCOIS in Hyderabad, India, led by Dr. Satya Prakash⁺, and the Australia node hosted by the UNESCO IOC Perth Program Office in Perth, Western Australia, led by Dr. Nick D’Adamo (Figure 4). The general roles and functions of the JPO were set up as specified in the Implementation Strategy and as such would be typical and expected for such major collaborative ocean science undertakings, with two JPO offices sharing, to varying degrees, all aspects of all JPO functions.



Figure 4: Screen shots of the web pages of the India (top left) and Australia (bottom left) nodes of the IIOE-2 Joint Project Office with pictures of the office leaders: Dr. Satya Prakash (+deceased, top right) and Dr. Nick D'Adamo (bottom right).

ESTABLISHMENT OF THE EARLY CAREER SCIENTIST NETWORK

The IIOE-2 Early Career Scientist Network (ECSN) originated as the result of a special session entitled “Recent Results from Early-Career Scientists in Indian Ocean Research” that was convened at the IIOE 50th Anniversary Symposium (Figure 5). The stated objectives of the ECSN are to facilitate ocean research and related fields for early career scientists; enhance scientific collaboration among early career researchers; organize meetings, workshops, training courses and other related events at regional and international levels; connect and collaborate with groups having complementary objectives; and connect the ECSN group with senior scientists under the IIOE-2 framework. The IIOE-2 ECSN currently includes >100 active registered members from 17 countries (<https://iioe-2.incois.gov.in/ecsn/index.html>).



Figure 5: First ECSN meeting on 2 December, 2015 at NIO, Goa. Photo courtesy of Ben Kurten.

IOC, IOGOOS AND SCOR APPROVE 5-YEAR EXTENSION

With momentum still building after 4 years of effort, IIOE-2 leadership requested an extension of IIOE-2 to 2025. All three co-sponsors (SCOR, IOC and IOGOOS)

enthusiastically approved this extension. A new and substantially simplified governance structure was also adopted (see Revised Implementation Strategy below).

IMPACTS OF THE COVID-19 PANDEMIC

The COVID-19 Pandemic had substantial negative impacts on IIOE-2 from 2020 to 2022 due to the cancellation of planned meetings and cruises. The 2020 International Indian Ocean Science Conference was cancelled just weeks before it was to be convened in person at NIO in Goa. This meeting was rescheduled and convened as a virtual meeting in 2022, which was a success, and it also included an ECSN workshop, but it did not have the galvanizing and motivating impact that was anticipated of the cancelled in-person meeting.

IIOE-2 cruises and research activity largely came to a halt in early 2020. This cessation of research activity had severe negative impacts on IIOE-2. For example, all RAMA (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction) moorings went offline except one as of February 2023 due to the cancellation of mooring deployment and servicing cruises (Sprintall et al., 2024). RAMA, which was designed to study the Indian Ocean's role in the monsoons, provides continuous core atmospheric and oceanographic measurements that are utilized by many IIOE-2 research projects. This situation raised awareness on the vulnerability of the ocean observing system and the need to quantify effectiveness and optimization while recovering, as well as considering future uncertainties such as budget cuts, reduced ship time and minimizing carbon footprint, which motivated the submission of a Working Group proposal to SCOR in 2025.

The pandemic also resulted in the tragic passing of Dr. Satya Prakash, who was the coordinator of the IIOE-2 Joint Project Office in India. Dr. Prakash played a key role in planning various activities leading to the formal launching of the IIOE-2 from Goa. He also participated in the first research cruise under IIOE-2 (Goa-Mauritius). He had been actively involved in numerous activities related to the IIOE-2, including being a part of the Editorial Team of the IIOE-2 newsletter and the Indian Ocean Bubble, as well as facilitating the hosting of the fourth meeting of the Steering Committee of the IIOE-2 in virtual space in April, 2021.

PROGRESS AND CURRENT STATUS

There has been a rapid resumption of cruise activity since the COVID-19 lockdown. Most of the research cruises and activities that were cancelled due to the COVID-19 pandemic are now happening or are planned over the next few years, and deployment and servicing of RAMA moorings has accelerated rapidly over the last year with more than half of the array (14 moorings) now functioning. In addition, new leadership has been established at the IPO at INCOIS in Hyderabad (Dr. Aneesh Lotiker / Kiran Kumar), which has taken

over the responsibilities of the Australia IPO. These are just a few of several developments that have motivated this request to extend IIOE-2 for an additional 5 years.

OFFICIAL PROJECTS AND INTERNATIONAL PARTICIPATION

Since the first IIOE-2 cruise from India to Mauritius in December 2015, the IIOE-2 has grown to involve over 50 multi-disciplinary and multi-national projects endorsed by the IIOE-2 with some 20 participating countries. These often involve multiple “voyage of discovery” cruises that have now covered much of the Indian Ocean, engaging many of the world’s major international ocean scientific institutions through a wide global constituency of leading ocean and climate scientists. Engaging small island and developing states has been paramount, along with a focus on capacity development for early career scientists, ocean managers and policy makers from countries having relatively low levels of development in ocean sciences.

WORKING GROUPS AND RESEARCH THEMES

The three IIOE-2 working groups/leaders are all active:

- Working Group 1: Science and Research (co-Chairs: Raleigh Hood and Hermann Bange)
- Working Group 2: Data and Information Management (co-Chairs: Pattabbhi Rama Rao and Harrison Ong’Anda)
- Working Group 3: Operational Coordination (IIOE2 IPO: Aneesh Lotiker and Kiran Kumar)

All of the six IIOE-2 research themes/leaders are active:

- Theme 1: Human Impacts (co-Chair: Halina Kobryn and Jérôme Harlay)
- Theme 2: Boundary current dynamics, upwelling variability and ecosystem impacts (co-Chairs: P. N. Vinayachandran and Yukio Masumoto)
- Theme 3: Monsoon variability and ecosystem response (co-Chairs: Birgit Gaye and Timothy Rixen)
- Theme 4: Circulation, climate variability and change (co-Chairs: Amit Tandon and Helen Phillips)
- Theme 5: Extreme events and their impacts on ecosystems and human populations (co-Chairs: Roxy Mathew Koll and Chari Pattiaratchi)
- Theme 6: Unique geological, physical, biogeochemical and ecological features of the Indian Ocean (co-Chairs: Lynnath Beckley and Marie-Alexandrine Sicre)

There has been some turnover / renewal of Working Group and Science Theme leaders in the second phase of IIOE-2 (2020 – 2025) and it is expected that this renewal will continue, with emphasis on engaging ECSN members. ***Efforts to make sure that all of the working group and research theme leaders are fully engaged and active will be redoubled in the final phase of IIOE-2.***

SYNTHESIS PAPERS, BOOKS AND SPECIAL ISSUES

Löscher, C. R., 2021, Reviews and syntheses: Trends in primary production in the Bay of Bengal—is it at a tipping point?: *Biogeosciences*, v. 18, no. 17, p. 4953-4963.

Nimit, K., 2021, Ideas and perspectives: Ushering the Indian Ocean into the UN Decade of Ocean Science for Sustainable Development (UNDOSSD) through marine ecosystem research and operational services—an early career's take: *Biogeosciences*, v. 18, no. 12, p. 3631-3635.

Pattiaratchi, C., van der Mheen, M., Schlundt, C., Narayanaswamy, B. E., Sura, A., Hajbane, S., White, R., Kumar, N., Fernandes, M., and Wijeratne, S., 2022, Plastics in the Indian Ocean—sources, transport, distribution, and impacts: *Ocean science*, v. 18, no. 1, p. 1-28.

Phillips, H. E., Tandon, A., Furue, R., Hood, R., Ummenhofer, C. C., Benthuyssen, J. A., Menezes, V., Hu, S., Webber, B., and Sanchez-Franks, A., 2021, Progress in understanding of Indian Ocean circulation, variability, air–sea exchange, and impacts on biogeochemistry: *Ocean Science*, v. 17, no. 6, p. 1677-1751.

Tegtmeier, S., Marandino, C., Jia, Y., Quack, B., and Mahajan, A. S., 2022, Atmospheric gas-phase composition over the Indian Ocean: *Atmospheric Chemistry and Physics*, v. 22, no. 10, p. 6625-6676.

Vinayachandran, P. N. M., Masumoto, Y., Roberts, M. J., Huggett, J. A., Halo, I., Chatterjee, A., Prakash, A., Gupta, G. V. M., Singh, A., and Mukherjee, A., Prakash, S., Beckley, L. E., Raes, E. J. and Hood, R., 2021, Reviews and syntheses: Physical and biogeochemical processes associated with upwelling in the Indian Ocean: *Biogeosciences*, 18: 1-63.



Figure 6: Titles and authors of six synthesis papers on the Indian Ocean that were motivated by IIOE-2 and published in 2021 and 2022 as a special issue of EGU journals.

1. Raleigh Hood et al., "Introduction to the Indian Ocean"
2. Timothy Walker, "A brief historical overview of the Indian Ocean"
3. Caroline Ummenhofer et al., "Past, present and future of the South Asian monsoon"
4. Charlotte Demott et al., "Intraseasonal variability in the Indian Ocean region"
5. Toshi Yamagata et al., "Climate phenomena of the Indian"
6. Ming Feng et al., "Extreme events in the Indian Ocean: Marine heatwaves, cyclones, and tsunamis"
7. Caroline Ummenhofer et al., "Indian Ocean impact on regional and global climate"
8. Helen Phillips et al., "Indian Ocean circulation"
9. Janet Sprintall et al., "Oceanic basin connections"
10. Tomoki Tozuka et al., "Decadal variability of the Indian Ocean and its predictability"
11. Francis Marsac et al., "Indian Ocean primary productivity & fisheries variability"
12. Raleigh Hood et al., "Oxygen, Carbon and pH variability in the Indian Ocean"
13. Raleigh Hood et al., "Nutrient, phytoplankton and zooplankton variability in the Indian Ocean"
14. Hermann Bange et al., "Air-sea exchange and its impacts on biogeochemistry in the Indian Ocean"
15. Carolin Loscher et al., "Microbiology of the Indian Ocean"
16. Faiza Al-Yamani et al., "Physical and biogeochemical characteristics of Indian Ocean marginal seas"
17. Michael McPhaden et al., "The Indian Ocean observing system (IndOOS)"
18. Toshi Shinoda et al., "Modeling the Indian Ocean"
19. Mahyar Mohtadi et al., "Paleoclimate evidence of Indian Ocean variability across a range of timescales"
20. MK Roxy et al., "Future projections for the tropical Indian Ocean"

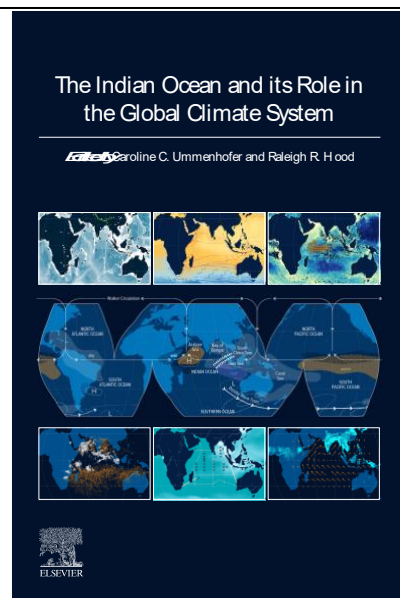


Figure 7: Lead author and titles (left panel) and cover (right panel) from the Elsevier book "The Indian Ocean and its Role in the Global Climate System", published in April, 2024 (Ummenhofer and Hood, 2024).

The IIOE-2 motivated six synthesis papers on the Indian Ocean that were published in 2021 and 2022 as a special issue of EGU Journals. These synthesis papers were inspired

by IIOE-2 Science Plan Research Themes (Figure 6). The IIOE-2 also motivated the development of 20 synthesis chapters on the Indian Ocean that were published as an Elsevier book in April, 2024: *“The Indian Ocean and its Role in the Global Climate System”* (Figure 7; Ummenhofer and Hood, 2024).

The IIOE-2 is continuing to compile and publish a Deep-Sea Research II Special Issue Series on the Indian Ocean: *“The 2nd International Indian Ocean Expedition (IIOE-2): Motivating New Exploration in a Poorly Understood Basin”*. More than 80 papers have been published thus far in seven special issues with an eighth special issue currently under development (Figure 8; Hood et al., 2019a; 2019b; 2020; 2022; Beckley et al., 2022; Hood et al., 2024).

Combined, more than 100 synthesis and research papers have been published thus far, and yet they represent only a fraction of the total considering the additional publications generated by many other programs and research expeditions (e.g., SOLSTICE-WIO, see next section) that have been motivated under IIOE-2.

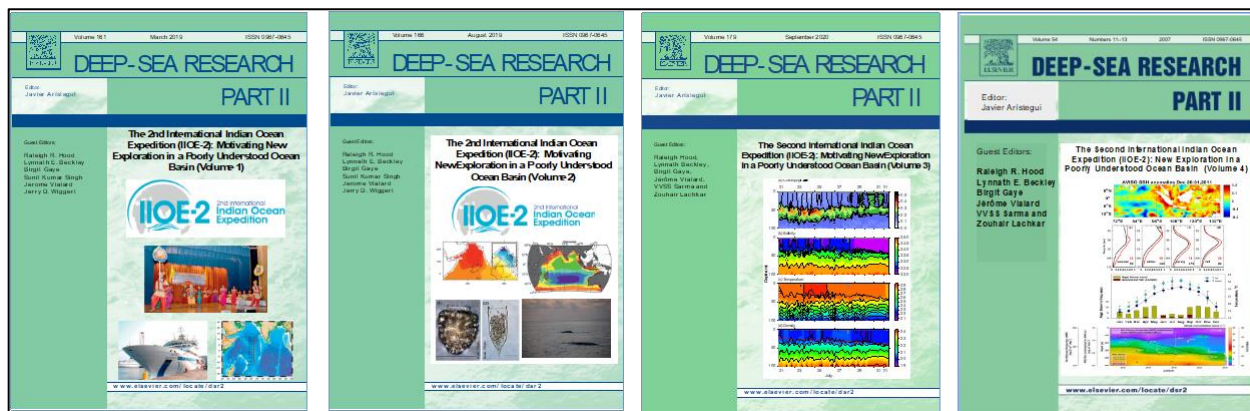


Figure 8: Editor teams and covers for volumes 1-4 of the IIOE-2 motivated Deep-Sea Research II, Special Issue Series on IIOE-2. More than 80 research papers have been published in this series thus far.

SCIENTIFIC HIGHLIGHTS

Some of the many aspects of ocean science receiving attention in the IIOE-2 include: meteorological-ocean phenomena such as monsoonal forcings and resultant seasonal ocean currents; vertical mixing in the ocean; ocean-wide movement of large masses of water (such as cross-basin equatorial currents); links between the ocean and weather (e.g., storms, waves, cyclones, Madden Julian Oscillations, Indian Ocean Dipole, Indian Ocean links to La Niña and El Niño); coastal boundary currents adjacent to Indian Ocean rim countries and the Indian Ocean's role in the global conveyor belt of heat and other ocean properties. The bio-physical ecology underpinning fisheries production; seabed/seamount and habitat mapping; the influence of vertical oxygen dynamics in fish ecology; biodiversity assessment; impacts of marine heat waves; and many other aspects

including acidification, temperature stress to corals, and links between transport and settlement of larvae are some of the more ecological aspects being investigated.

Complemented by a high-level examination of the requirements of an Indian Ocean Observing System out to 2030 (Beal et al., 2020), the IIOE-2 is achieving major advances in understanding societally important phenomena relating to major bio-physical characteristics and coupled ocean-meteorological processes in the Indian Ocean. The following provides several examples of specific programs, research expeditions and achievements motivated under IIOE-2.

A COUPLED BIO-PHYSICAL, ECOSYSTEM-SCALE, EXAMINATION OF AUSTRALIA'S INTERNATIONAL INDIAN OCEAN EXPEDITION 110°E LINE (IIOE2-EP06)

The fifth Special Issue of the DSR II Series on IIOE-2 was focused on a single research voyage undertaken in May-June 2019 with the Australian RV *Investigator* (Figure 9; Beckley et al., 2022). The voyage revisited an oceanic transect line along the 110°E meridian in the south-east Indian Ocean which was first studied from 1962 to 1963 during the First International Indian Ocean Expedition (e.g., Rochford, 1969; Tranter and Kerr, 1977).

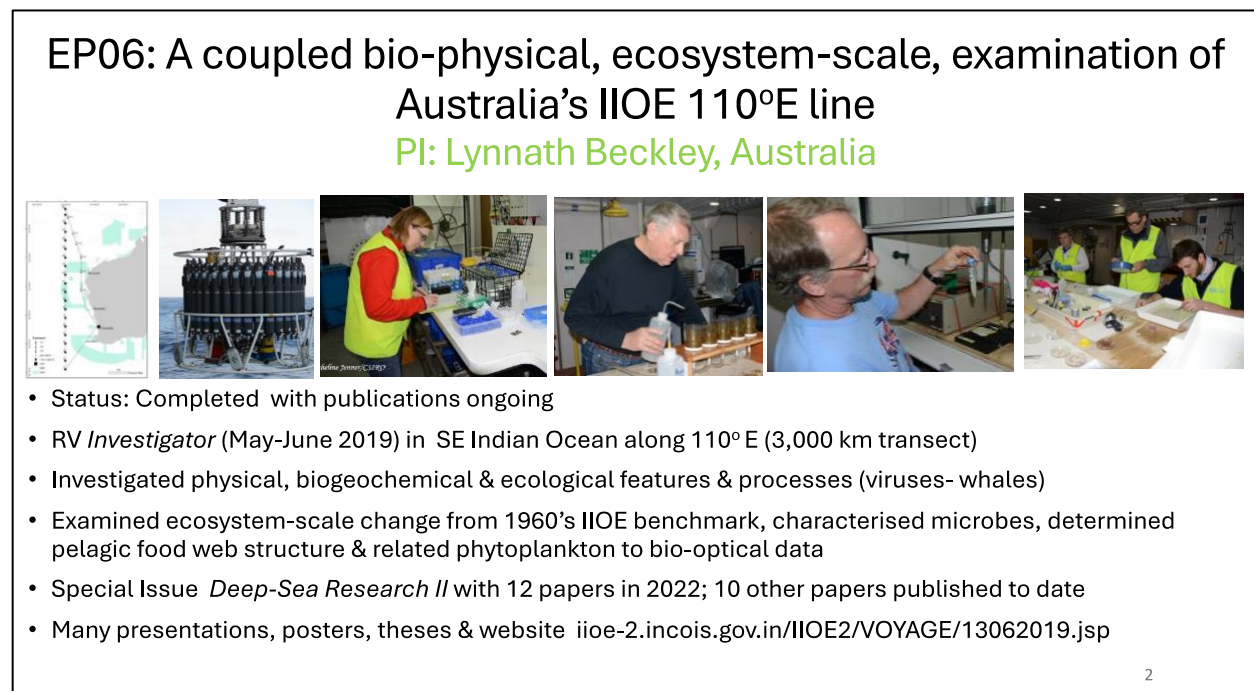


Figure 9: Summary of status, objectives, publications and presentations from "A coupled bio-physical, ecosystem-scale, examination of Australia's IIOE 110° E line" (IIOE2-EP06).

With the huge progress in technology and techniques in recent years and contemporary 21st century understanding, investigating the 110°E line again after nearly six decades enabled updated bio-physical information to be obtained and more ecological processes

to be explored along a latitudinal gradient in the south-east Indian Ocean. The fifth Special Issue includes 11 papers covering the results of some of the wide-ranging investigations conducted during the 2019 voyage. In addition to the physical oceanography, it highlights genomic and trophic process studies as well as traditional biological oceanographic studies ranging from plankton through to whales. This Special Issue contributed significantly to the research themes and goals of the IIOE-2 (Hood et al., 2015). The compiled papers highlight the complex oceanography, biological diversity and trophic processes in the region. They demonstrate a low nutrient ecosystem, dominated by recycling processes supporting picophytoplankton, small mixotrophic zooplankton, predatory copepods and mesopelagic fishes. Overall, the papers reflect a stepwise improvement in the understanding of the pelagic ecosystem in the oligotrophic south-east Indian Ocean.

SUSTAINABLE OCEANS, LIVELIHOODS AND FOOD SECURITY THROUGH INCREASED CAPACITY IN ECOSYSTEM RESEARCH IN THE WESTERN INDIAN OCEAN (SOLSTICE-WIO) (IIOE2-EP42) <https://solstice-wio.org/>

SOLSTICE-WIO was a six-year collaborative project funded by the UK Global Challenges Research Fund (GCRF). This project brought together recent advances in marine technologies, local knowledge and research expertise to address some of the challenges facing the Western Indian Ocean region in a cost-effective way via technology transfer, collaborative environmental and socio-economic research and hands-on training. SOLSTICE-WIO demonstrated its approach through three case studies, identified by the local project partners as important for food security and economic development in three WIO countries: 1) Kenya: Emerging fishery of the North Kenyan Bank: the next frontier for food security of the coastal population (led by Kenya Marine and Fisheries Research Institute); 2) Tanzania: Pemba Channel small pelagics: threats and opportunities of climate change (led by the Institute of Marine Sciences in Zanzibar); and 3) South Africa: Ecosystem shifts and fishery collapse: South African Chokka squid fishery (led by Nelson Mandela University).

To date, SOLSTICE-WIO has generated numerous publications (Figure 10 with example publications), including a Special Issue in the journal *Ocean & Coastal Management* entitled "East African Coastal Current: At the Frontier of Climate Change and Food Security". And a Special Issue in the journal *Deep-Sea Research Part II: Topical Studies in Oceanography* entitled "Dynamics of the Agulhas Bank, South Africa - ecosystem shifts and future trends in the squid fishery". Papers from this project have also been published in several other journals, including *Frontiers in Marine Science*, *Scientific Reports*, *Marine Policy*, and *Food Security*. SOLSTICE-WIO has also produced several policy briefs, practice notes and a wealth of outreach materials, including a Solstice MOOC (Massive Open Online Course) and a webinar series.



Figure 10: Example publications from SOLSTICE-WIO (IIOE2-EP42).

NEKTON INDIAN OCEAN MISSION (IIOE2-EP22) <https://nektonmission.org/missions/indian-ocean>

The Nekton Indian Ocean Mission was a major global scientific collaboration that aimed to create a step change in our knowledge of the Indian Ocean and catalyze its sustainable governance. The Mission consisted of six research cruises in six distinct regions of the Indian Ocean from West (Mozambique Channel and Seychelles), to Central (Chagos and Maldives) and East (Andaman and Sumatra). The Mission combined four major activities: scientific research, capacity development, advancement of policy and public engagement. A primary emphasis of the Mission was on understanding the distribution of species and biodiversity from the surface to 3000m depth and its environmental drivers.

The Nekton Indian Ocean Mission worked with Indian Ocean rim nations to survey their deep reefs and collect data on physical, chemical and biological parameters (community data, species lists, field ID guides, function and resilience across location and depth). These data have provided better understanding of the diversity of life at depth and its importance to humans in the face of a changing world, and they have facilitated modeling to support the conservation and sustainable management of sites. To date this project has generated many papers (Figure 11 with citations) and presentations.



Figure 11: Summary of major accomplishments and publications from Nekton Indian Ocean Mission (IIOE2-EP22).

DINITROGEN FIXATION IN THE INDIAN OCEAN: AN INTERBASIN AND SEASONAL COMPARISON (DINDE) (IIOE2-EP41)

The goal of DINDE was to decipher the role of N_2 fixation in the two sub-basins of the Indian Ocean, focusing on the two most unknown seasons: winter monsoon and inter-monsoon. DINDE examined the magnitude of N_2 fixation rates according to environmental variability, untangling the diversity of local diazotroph assemblages and their metabolic controls. Moreover, DINDE isolated strains with the aim of discovering diazotroph species unique to the Indian Ocean. Constraining N_2 fixation in the Indian Ocean is vital to improve the predictability of net primary productivity and future role of ocean as a climate change mitigator.

The *in situ* work was performed during four oceanographic cruises (two per basin in each target season, two in German vessels and two in Indian vessels). The project was carried out by the French and Indian collaborating scientists, with sample analyses shared among the two labs according to their expertise and equipment. Results show that diazotrophy is highly heterogeneous among sub-basins & seasons in the Indian Ocean, impacted by unique circulation and biogeochemical settings of each region. Several papers from this project have been published, and others have been submitted or are in preparation (Figure 12 with citations).

EP41: Dinitrogen fixation in the Indian Ocean: an inter-basin & seasonal comparison (DINDE)

PI: Mar Benavides, France

- Status: Completed
- Earth system models show uncertainty in net PP predictions due to poor understanding & response to changes in parameterisation of N_2 fixation in models
- Cruises in Arabian Sea, Bay of Bengal & Indian sector of Southern Ocean. Undertook N_2 fixation measurements & detailed biogeography of diazotrophic species
- Results show that diazotrophy is highly heterogeneous among sub-basins & seasons in Indian Ocean
 - Chowdhury, S. et al. 2024. Fronts divide diazotroph communities in the southern Indian Ocean. *FEMS Microbiology Ecology* 100 (8): fiae095.
 - Chowdhury, S. et al. 2023. Diazotrophy in the Indian Ocean: Current understanding and future perspectives. *Limnology and Oceanography Letters*. doi: 10.1002/lol2.10343.
 - Saxena, H. et al. 2023. The Bay of Bengal: An enigmatic diazotrophic niche. *J. Geophys. Res. Biogeosci.* 128. doi: 10.1029/2023jg007687

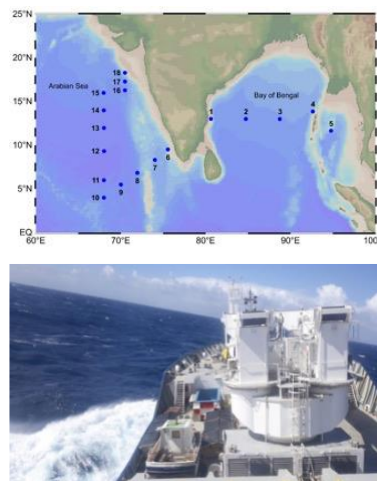


Figure 12: Summary of status, objectives, results and publications from "Dinitrogen fixation in the Indian Ocean: and inter-basin & seasonal comparison (DINDE)" (IIOE2-EP06).

BoBBLE: BAY OF BENGAL BOUNDARY LAYER EXPERIMENT

BoBBLE was a joint India -UK field experiment conducted in the southern Bay of Bengal during the summer monsoon of 2016. Although not an officially endorsed project under IIOE-2, BoBBLE was motivated by Indian Scientists who are core members of the IIOE-2 community and was considered to be an early core IIOE-2 project. The primary goal of this experiment was to produce new, high-quality, comprehensive observational data sets of ocean state and atmospheric fluxes through a dedicated field campaign in a key under-observed region, the southern Bay of Bengal. The cruise was conducted on board ORV *Sindhu Sadhana* (CSIR-NIO, Goa) from 23rd June – 24th July 2016. Both oceanic and atmospheric parameters were measured during the cruise. In the ocean, 148 CTD profiles, 930 underway-CTD (uCTD) profiles, 64 turbulence profiles, 37 radiometer profiles, 161 Argo profiles and 915 glider profiles were measured. In addition, continuous monitoring was carried out using Autosal and ADCP. Biological and chemical properties were measured using water samples. Atmospheric measurements were made using an automated weather station and an eddy covariance system. Radiosonde profiling was carried out twice every day. Among the instruments used, VMP and uCTD deployments combined with ship-aircraft observations of both atmosphere and ocean were carried out at one location: 10°N, 85°E (AR location in Figure 13).

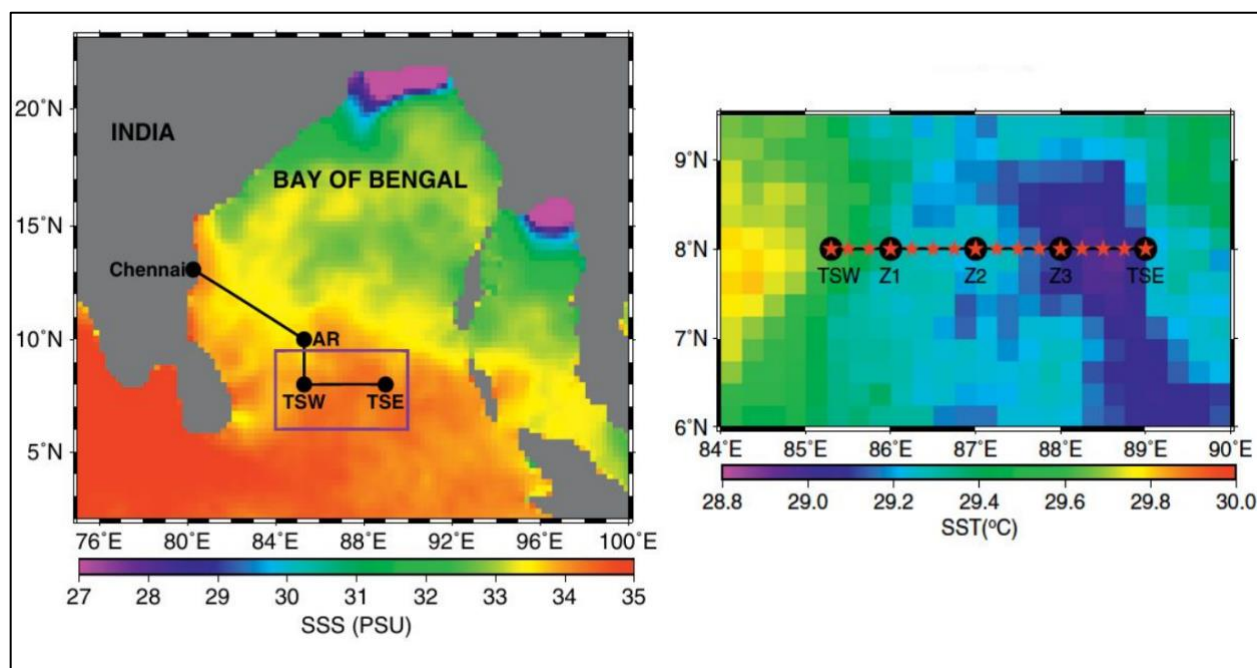


Figure 13: A map of the Bay of Bengal and the cruise track of the BoBBLE field program (left panel) sea surface salinity (SSS shading) is from SMAP. The section along which observations were made during BoBBLE (right panel). The positions (black circles of TSW, Z1, Z2, Z3, and TSE) represent glider deployment locations. Argo float deployments, IOP, radiometer, and VMP profiling as well as water sampling were also carried out at these locations. Stars indicate locations where additional CTD profiles were measured during the return leg of the cruise. At TSE, CTD profiles were measured from 4 to 15 July, 2016. Shading indicates SST from the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) (Vinayachandran et al., 2018). Figures courtesy of P. N. Vinayachandran.

The data collected during this experiment exposed several unknown features of this region and unraveled their underlying mechanisms. These include the high salinity core and its impact of physics, optics, and biogeochemistry. The presence of double diffusive mixing in this region, dynamics of the summer monsoon current, processes controlling the sub surface chlorophyll maximum, and oxygenation of Bay of Bengal by the high salinity core and Persian Gulf water are some of the key findings. The results from BoBBLE have been published in 28 journal papers, a special session at the IUGG 2017 in South Africa, an invited keynote presentation at IUGG 2023 in Berlin, and several other conferences worldwide.

IIOE-2 SCIENCE 2026-2030

The IIOE-2 has structured its research around six scientific themes that are summarized above and articulated in detail in the IIOE-2 Science Plan (Hood et al., 2015). Here, the core questions from theme 1 (Human Impacts) are reiterated because they articulate many of the challenges and research questions that will be prioritized in the final phase

of IIOE-2 (2026 – 2030). ***The IIOE-2 community believes that more action is needed to address the core questions of Theme 1. But it is also important to emphasize that this document does not supersede the IIOE-2 Science Plan. The science priorities identified in the Science Plan will continue to be priorities in the final phase of IIOE-2. Rather, this document highlights areas of the Science Plan that will be prioritized in the final phase of IIOE-2, and describes some new initiatives and opportunities that have emerged under IIOE-2 that did not exist when the Science Plan was written.***

SCIENTIFIC THEME 1: HUMAN IMPACTS

CORE QUESTIONS

1. How are human-induced ocean stressors (for example, warming, sea-level rise, saltwater intrusion, deoxygenation, acidification, eutrophication, atmospheric and plastic pollution, coastal erosion and overfishing) impacting the biogeochemistry and ecology of the Indian Ocean?
2. How, in turn, are these impacts affecting human populations?

Coastal megacities located around the Indian Ocean (such as Mumbai, Kolkata, Dhaka and Karachi) affect the adjacent ocean zones via high atmospheric pollution/aerosol load and the subsequent deposition of nutrients and contaminants as well as sewage outflow and eutrophication. Thus, emissions and discharges from megacities have a high potential to influence biogeochemical cycles, ecosystems and fisheries in the adjacent coastal zones. Moreover, human pressure on coastal ecosystems and the competition for land for aquaculture, agriculture, infrastructure and tourism are often high and are the major causes of (i) the loss of mangroves and other ecosystems and (ii) coastal pollution. Urban and industrial pollution includes plastics (including microplastics), metal contaminants, hydrocarbons, as well as nutrients. Microplastics have been found in shallow as well as deeper waters of the Indian Ocean (Pinheiro et al. 2023). ***How does coastal urbanization affect biogeochemical cycles, ecosystems and fisheries in the adjacent coastal zones (such as shelf regions, estuaries/deltas, mangroves, coral reefs, lagoons, beaches, etc.) of the Indian Ocean?***

The on-going rise of CO₂ in the atmosphere causes both warming and acidification of the ocean. Warming-induced stratification may reduce the upwelling of nutrients from deeper in the ocean to surface layers, resulting in decreased biological production and a reduction in nutrient supply. Any changes in biological productivity will, in turn, affect food webs and fisheries. Warming-induced sea level rise is increasing the environmental stress on beaches, coral reefs and mangroves. Moreover, coral reefs are especially vulnerable to the ongoing warming. Increasing CO₂ (= decreasing pH) in the upper ocean is leading to changes in primary productivity, altering the biogeochemistry of particulate organic matter respiration (including denitrification) and impacting calcifying organisms (coral reefs, coccolithophorids). Commercially fished species (e.g., molluscs) are vulnerable to ocean acidification. The Southern Ocean sector of the Indian Ocean could

experience major disruptions in upper levels of food webs because of effects on pteropods, which are the prey of many organisms. ***What is the effect of rising atmospheric CO₂ on biological productivity and fisheries as well as especially vulnerable coastal ecosystems (such as coral reefs, mangroves, etc.) in the Indian Ocean?***

Eutrophication of coastal zones and the open ocean via rivers, submarine groundwater discharge and atmospheric deposition is causing an increasing number of harmful algal blooms and it is enhancing deoxygenation (i.e., loss of O₂). Deoxygenation, in turn, may lead to an expansion of intermediate water layers with conditions favoring increased loss of bioavailable nitrogen under suboxic/anoxic conditions via denitrification and/or anammox reactions with unknown consequences for the overall productivity of the Indian Ocean system. Moreover, deoxygenation may lead to enhanced production and release of climate-relevant trace gases such as N₂O, CH₄ and DMS. Mesopelagic fish populations may be threatened by a reduction in suitable habitat as respiratory stress increases due to deoxygenation. ***How do eutrophication, atmospheric pollution and the loss of O₂ affect biogeochemical cycles, ecosystems and fisheries in coastal zones and the open Indian Ocean?***

The ongoing reduction of biodiversity and its associated changes in food webs will cause changes in the distribution of fish stocks which, in turn, will have direct impacts on coastal fisheries and hence human livelihoods and nutrition. ***What are the socio-economic consequences of altered biodiversity and changing food webs (including fisheries) in the Indian Ocean?***

Coastal waters receive large inputs of chemical and biological waste originating from land-based industrial, domestic and agricultural sources. Pollutants (such as hydrocarbons) are also introduced by shipping activities, offshore oil and gas exploration and atmospheric deposition of particles from industrial origin. Plastic pollution is a major issue in the Indian Ocean, particularly in Indonesia and in the southern subtropical gyre where, in the latter, there is a greater plastic particle abundance and weight count than the South Atlantic and South Pacific Oceans combined (Eriksen et al., 2014). Emerging pollutants such as polyfluoroalkyl substances (PFAS) and endocrine disrupting compounds (EDCs) can also interfere with marine organisms, disrupting their health and in turn affecting fisheries and biogeochemical cycles. Sewage pollution of coastal waters by pathogens and toxic waste can cause illness and death, and noise pollution is especially bad in coastal waters affecting marine mammals, fish, benthos and even plankton. Aquaculture activities can lead to eutrophication (and deoxygenation) of coastal waters. In turn, eutrophication enhances the risk of harmful algal blooms (HAB) and the release of HAB toxins. ***What are the consequences for human health caused by pollution, altered ecosystems and increasing aquaculture activities in the Indian Ocean?*** More generally, expected human-induced changes in ocean temperature and chemistry will alter microbial community structures in the Indian Ocean. ***How will these changes impact biogeochemical cycling and ecosystem dynamics in both open ocean and coastal environments of the Indian Ocean?***

The future sea-level rise and intensification of cyclones will cause substantial damage of coastal infrastructure and alter coastal ecosystems such as mangroves, beaches and coral reefs. Sea-level rise will impact on coastal fisheries owing to the destruction of habitats and nursery grounds (e.g., mangroves and coral reefs), leading to decreased nutritional and occupational opportunities in coastal communities. Damage of coastal infrastructure and ecosystems (e.g., bleached coral reefs due to warming and acidification) will impact tourism. ***What are the socio-economic consequences of increasing damage to coastal zones in the Indian Ocean caused by the loss of mangroves and coral reefs, intensification of cyclones, sea level rise, etc.?***

In general, a comprehensive IIOE-2 should reflect the link between terrestrial, coastal and marine research. Application of satellite data, remote sensing information, coastal land use data, tracer distribution patterns in coastal ground and seawater, and information about the distribution and abundance of pollutants and marine organisms will allow the localization and quantitative investigation and monitoring of terrestrial and marine system interaction and related processes. The scientific approach of the IIOE-2 must involve both the marine and the terrestrial perspectives by investigating not only purely marine and coastal environments, but also the freshwater-coastal-marine water continuum (rivers, swamps, wetlands, groundwaters, etc.).

There are already multiple endorsed projects that address the Human Impacts IIOE-2 theme and the socio-economic consequences of ecosystem change. For example, human impacts on the Indian Ocean are addressed in a newly endorsed IIOE-2 project that will investigate Kenyan coastal waters and sediments for Polyaromatic Hydrocarbons (PAHs) and microplastics (VOKCE, EP55), while the NEKTON mission is examining deeper reefs (up to 500 m depth) for water quality parameters and assessment of plastic debris. The air/sea exchange fluxes of gases are being examined by the project BIOCOT (EP07), specifically in the Bay of Bengal. This project is focusing on the key threats: air pollution, ocean warming and excess nutrient inputs. Many of the IIOE-2 endorsed projects also have strong community engagement components that address the socio-economic consequences of ecosystem change, e.g., NEKTON (EP22), Monaco Explorations (EP49), EP26 (Regional Research Cruises in the Western Indian Ocean) and SOLSTICE (EP42). The latter includes three case studies dealing with fisheries and socio-economics. ***In its final phase, IIOE-2 will focus on promoting and endorsing studies that fall under the Human Impacts theme. This focus aligns with and complements the following subsections of this Addendum that identify knowledge gaps and challenges related to societal benefits and human impacts, and these subsections provide additional strategies for how these issues will be addressed. In addition, a synthesis of results and key learnings from the Theme 1 endorsed projects will be prepared in the final phase of IIOE-2. This synthesis will be structured around the core questions (above) and will assess the extent to which the outcomes of the endorsed projects have addressed them. Efforts will also be undertaken to motivate a DSR2 IIOE-2 Special Issue on Human Impacts.***

KNOWLEDGE GAPS AND CHALLENGES RELATED TO SOCIETAL BENEFITS AND HUMAN IMPACTS

BACKGROUND

As reviewed in the previous sections, the IIOE-2 Science Plan places considerable emphasis on the biogeochemical and ecological impacts of anthropogenic influences on the ocean and how these will, in turn, impact coastal marine environments and human populations. The plan also emphasizes the need for coastal monitoring, and data sharing, scientific engagement of Indian Ocean rim countries, and capacity development. Despite this emphasis, much of the research that has been carried out to date in IIOE-2 has been focused on the open ocean, and additional effort needs to be focused on the engagement of Indian Ocean rim countries and capacity development. This section is included here to emphasize the need to focus on these aspects of the IIOE-2 Science Plan in the final 5 years (2026 – 2030) of IIOE-2.

COASTAL MONITORING AND META-DATA SHARING FROM EXCLUSIVE ECONOMIC ZONES (EEZS)

Thus far IIOE-2 efforts to embrace and promote coastal monitoring and data sharing from EEZs (Figure 14) have been limited to two examples: Australia's Integrated Marine Observing System (IMOS), and India's Marine Observation System Along the Indian Coast (MOSAIC) programs (see detailed descriptions below), with only the former allowing full access to their data. Getting countries to share data collected in their EEZs remains a challenge (except for countries like Australia, that have policies that require that data collected with support from national funding agencies be made publicly available in a timely manner, typically within a 2-year time frame). ***The strategy that will be pursued in the final phase of IIOE-2 will be to promote meta-data sharing with the IIOE-2 IPO, if full data access is not feasible. At the very least, IIOE-2 Working Group 2 (Data and Information Management) will determine where the data from its sponsored projects has been stored and make this information available via the IIOE-2 website. Working Group 1 will be engaged to assist in these efforts, as well as the Science Theme chairs who are in regular contact with endorsed project leaders, and they will specifically follow up projects for which no metadata exists in the IIOE-2 system (see the Data and Information Management section below). In its final phase, the IIOE-2 will also promote development of new, low-cost coastal monitoring efforts, especially in developing countries (see the new research initiative COLaB below). With this strategy, it will be possible to discover the data that is being collected in the EEZs of all Indian Ocean rim nations that are involved in IIOE-2 - even those that have national policies that prohibit sharing of data from their EEZs - and potentially access it by contacting the principal investigators or government agencies that are collecting data.***

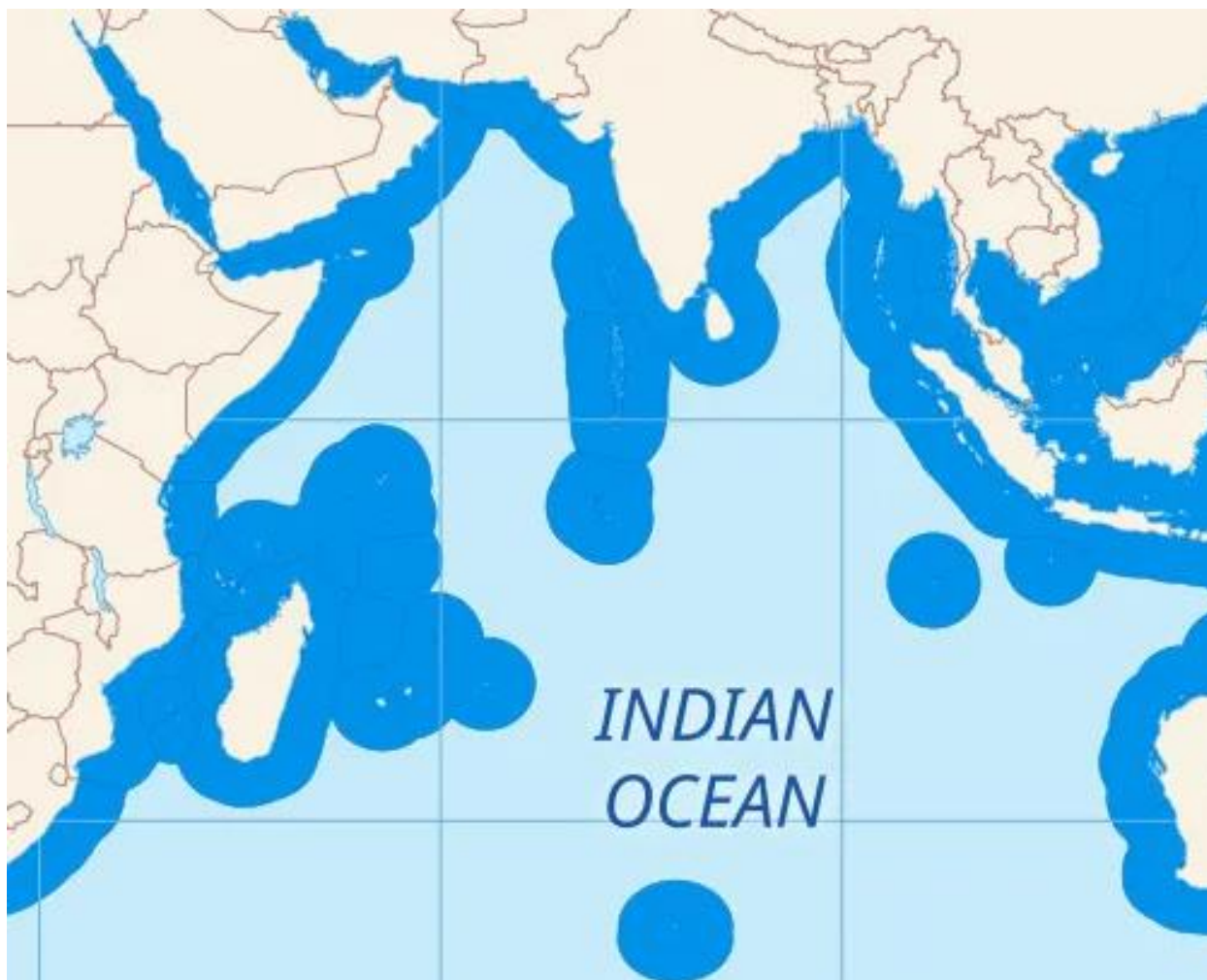


Figure 14: Indian Ocean exclusive economic zones (EEZs). Figure downloaded and modified from: https://deepseamining.ac/static_blog_img/large-eez.webp#gsc.tab=0.

MARINE SPATIAL PLANNING

Marine spatial planning (MSP) is an ecosystem-based process for balancing multiple human demands and activities with the ecological requirements for a healthy ocean that delivers multiple ecosystem services (Ehler, 2018; Ehler and Douvere, 2009). MSP is one component of integrated ocean management strategies that focuses on spatial aspects of management and is intended to support local, regional and global ocean sustainability goals, e.g., the United Nations (UN) Sustainable Development Goal 14. However, to deliver these outcomes in a changing ocean, MSP must be ‘climate-smart’, that is integrate climate-related knowledge, be flexible and adapt to changing conditions, and support climate adaptation and mitigation actions (Frazao Santos et al., 2020; 2024). Aligned with the Paris Agreement and the European Green Deal goals of reducing greenhouse gas emissions and adapting to climate impacts, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the European Commission recently launched a joint MSP roadmap that identifies the development of

climate-smart MSP as one of the six key priority areas for 2022–2027 (Commission, 2022).

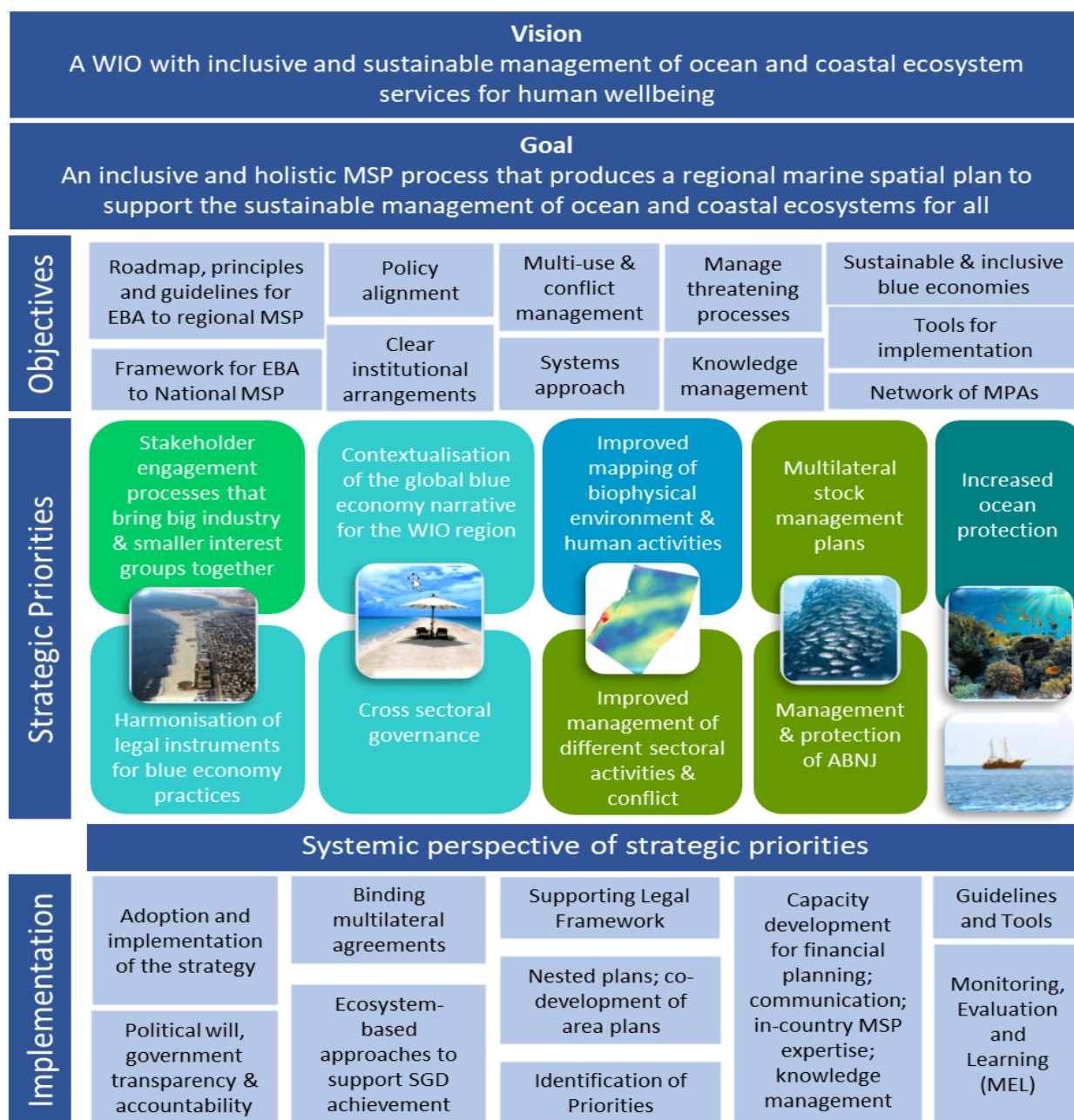


Figure 15: A structural view of the regional Marine Spatial Planning strategy for the Western Indian Ocean, based on questionnaire responses from members of the Technical Working Group from member states of the Nairobi Convention and civil society stakeholders (Lombard et al., 2022).

Marine Spatial Planning has spread widely over the past two decades to support sustainable ocean management and governance in several parts of the globe. Many African countries are now planning to use MSP as they embrace the “Blue Economy”.

However, at a practical level, marine managers, planners and governments in the Indian Ocean essentially require science to policy guidance on how to put MSP into action (Lombard et al. 2022). IIOE-2 will leverage a new IIOE-2 endorsed project that is being undertaken to create an MSP framework for the Western Indian Ocean for nine of the ten participating countries of the Nairobi Convention (Figure 15; Convention, 2025). This project provides a specific vision and roadmap to support implementation of MSP in the Northern Mozambique Channel. The IIOE-2 will also facilitate MSP via the new COLaB initiative (see below). ***The final phase of IIOE-2 will build on this framework and promote MSP efforts in other parts of the Indian Ocean, providing the support and guidance needed to ensure their success.***

SCIENTIFIC UNDERSTANDING AND ENGAGEMENT OF THE WESTERN INDIAN OCEAN, THE EASTERN BAY OF BENGAL AND MARGINAL SEAS RESEARCH COMMUNITIES

International participation in IIOE-2 has been strong with 20 countries involved / seeking project endorsement. However, the IIOE-2 has not successfully engaged some Indian Ocean rim countries and island nations, notably, from the northwestern Indian Ocean, and the central and eastern Bay of Bengal (Figure 16). As discussed below, many of these countries are being targeted in the COLaB initiative, which will provide entry points for engagement. Efforts will also be undertaken to engage and participate in WIOMSA (the Western Indian Ocean Marine Science Association) which will help raise awareness of IIOE-2 in the western Indian Ocean. Another important objective for IIOE-2 in its final phase will be to fully integrate the new IOC Sub-Commission for the Central Indian Ocean (IOCINDIO) into the IIOE-2 community (which includes many of the aforementioned Indian Ocean rim countries and island nations, see below). The IIOE-2 will also seek to convene its annual joint meetings in these countries to help promote engagement (see the Community Engagement subsection below). In addition, the IIOE-2 will undertake efforts to better engage the marginal seas research communities (Persian Gulf, Sea of Oman, the Red Sea, the Gulf of Aden and the Andaman Sea) through establishment of a new Marginal Seas Research Initiative (see below).

Many of these countries are under-resourced and lack the funding and infrastructure to carry out marine research. As a result, their EEZs are understudied, and baseline data and basic scientific understanding are often lacking. In contrast, affluent countries like Saudi Arabia have the resources to support research, but lack the ships and other marine research infrastructure to carry out research beyond their immediate coastal environments. Though a new Saudi research ship, the *RV Thuwal II*, is coming on line in 2026. This will be the first regional class research vessel for Saudi Arabia and enable complete access to the Red Sea, including coastal waters and the deep sea. See: <https://www.kaust.edu.sa/en/news/kaust-announces-building-of-the-first-regional-class-research-vessel-in-saudi-arabia>. Additionally, Kuwait has recently launched the *RV AlMostakshif*, a large multipurpose research vessel designed for high-quality surveys and sampling across a broad geographical range. The vessel is capable of operating in all marine areas of the Arabian/Persian Gulf, the Sea of Oman, and the Arabian Sea (<https://www.kisr.edu.kw/en/qi/7/details/>). ***By expanding participation from these***

countries, the IIOE-2 aims to promote and support collaborative research in the coastal regions, marginal seas, and open ocean environments of the Indian Ocean. This effort will lead to new discoveries, enhance our understanding, and improve our ability to monitor and predict the impacts of anthropogenic influences on valuable marine resources.

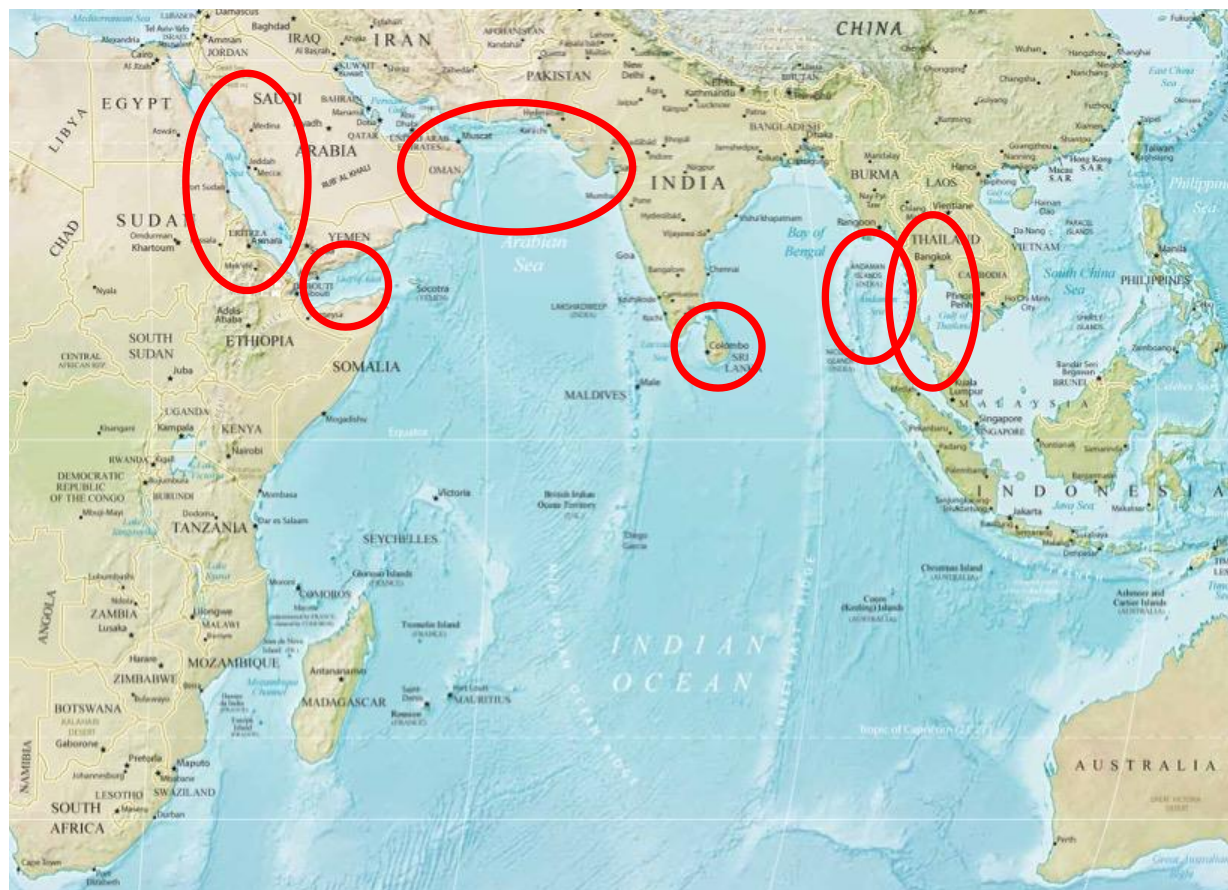


Figure 16: Regions of the Indian Ocean that the IIOE-2 has not yet successfully engaged, notably, from the northwestern Indian Ocean (e.g., Saudi Arabia, Oman), and the central and eastern Bay of Bengal (e.g., Sri Lanka, Thailand, Malaysia). Map downloaded and modified from: <https://www.geographicguide.com/africa-maps/indianocean.htm>.

COMMUNITY INVOLVEMENT

In its final phase, IIOE-2 will also emphasize community involvement in an effort to promote the inclusion of local communities (scientific, coastal, fishing, management, etc.) in research and decision-making. This will be achieved by rotating the annual IIOSC meetings to different Indian Ocean rim and island nations and inviting the participation of local stakeholders to present their views at these meetings. Stronger links will also be developed with WIOMSA that has 35-years of experience in co-designing and coordinating research programs with stakeholders and local communities and in organizing capacity and professional development, linking science to management, environmental advocacy, networking and dissemination of technical information.

WIOMSA has extensive knowledge and understanding of regional issues, priorities and processes, and a good working relationship with key individuals and regional institutions. WIOMSA now includes social scientists and practitioners complementing its earlier membership of natural scientists. IIOE-2 IPO will also target these stakeholder communities in its communication efforts (IO Bubble, Newsletters, etc.). As articulated in the section on Communication below, the IIOE-2 IPO will be tasked to ensure that information related to the main results and activities of IIOE-2 are made accessible to a wider audience, including policy makers, managers and the public via, for example, engaging with knowledge brokers, social media platforms and through the development of short videos and other products that can be distributed to a wide audience via YouTube and related platforms. Knowledge brokering is a major undertaking and has to be properly targeted to have any hope of getting science to policy uptake. An experienced knowledge broker will be engaged to look at the IIOE-2 portfolio of projects to see what can be done. Scientists from these Indian Ocean rim and island nations will also be encouraged to seek formal endorsement of their research projects which will increase the visibility of their work in IIOE-2.

Ensuring that local and indigenous knowledge systems are integrated into the IIOE-2 research framework will help bridge the gap between global scientific efforts and the lived experiences of coastal populations. This helps foster a sense of ownership and ensures the research has real-world applicability. In its final phase, IIOE-2 will also foster collaboration across borders, to bridge the gap between global researchers and local stakeholders, promoting co-design and co-leadership. IIOE-2 will explicitly promote regional collaboration, where different countries, especially smaller nations or island states, have equal opportunities to contribute to the research agenda. The new COLaB initiative will also facilitate regional collaboration (see below). Open ocean research and EEZ-focused studies can coexist, with the IIOE-2 providing an equitable framework for knowledge exchange, access to international expertise, and resources.

ECSN PROMOTION

The Early Career Scientist Network (ECSN) of IIOE-2 has been active since it was formed on December 2nd, 2015 at the aforementioned IIOE 50th Anniversary Symposium at NIO in Goa, India (Figure 5). Since then, ECSN has played a pivotal role in supporting early career researchers through scientific engagement, training, and regional collaboration across the Indian Ocean.

Building on the early successes of ECSN, IIOE-2 will vigorously pursue efforts to further promote and strengthen the ECSN during IIOE-2's final phase (2026–2030). This includes integrating ECSN members into IIOE-2 working groups, science themes and research activities, enhancing ECSN's global visibility through active involvement with the UN Ocean Decade's Early Career Ocean Professionals (ECOP) Programme—including representation under its Indian Ocean node—and maintaining and regularly updating the ECSN's official website (<https://iioe-2.incois.gov.in/ecsn/index.html>) to ensure accessibility, relevance, and engagement. Notably, the IIOE-2 ECSN leads the UN Ocean

Decade-endorsed project “Devising Early-Career Capacity Development in the Indian Ocean region (DECCaD-IO)”, which aims to advance the skills, visibility, and impact of early career researchers in the Indian Ocean rim countries.

To address key gaps, IIOE-2 will support ECSN in developing a more diverse and regionally representative core committee by initiating an open call for nominations and ensuring balanced representation from across the Indian Ocean rim and island nations. Efforts will also focus on strengthening digital outreach and implementing a concrete plan that includes regular capacity-building workshops, mentorship programmes, scientific communication initiatives, and collaborative research opportunities that align with the goals of IIOE-2 and the Ocean Decade. ***The IIOE-2 Early Career Scientist Network represents the future of Indian Ocean research. In its final phase, IIOE-2 is committed to ensuring that this next generation of scientists is diverse, visible, well-connected, and empowered to carry forward and expand the research momentum generated by IIOE-2.***

NEW INITIATIVES

SUSTAINED INDIAN OCEAN BIOGEOCHEMISTRY AND ECOSYSTEM RESEARCH (SIBER)

The Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program is an ongoing IMBeR (Integrated Marine Biosphere Research) regional program that is co-sponsored by IOGOOS (Figure 17; Hood et al., 2011). Given the central role that SIBER has played in IIOE-2, and the uncertainty surrounding the future of IMBeR, the IIOE-2 community proposes to include SIBER in IIOE-2 as a “new” research initiative.

The long-term goal of SIBER is to understand the role of the Indian Ocean in global biogeochemical cycles and the interaction between these cycles and marine ecosystem dynamics. To address this goal SIBER has structured its research plan around six scientific themes. Each of these include a set of scientific questions that need to be addressed in order to improve understanding of the biogeochemical and ecological dynamics of the Indian Ocean and develop a capability to predict future changes. These themes can be broadly separated into three that are regionally focused and three that address broad scientific questions. The regional scientific themes include: 1) boundary current dynamics, interactions and impacts; 2) variability of the equatorial zone, southern tropics and Indonesian throughflow and their impacts on ecological processes and biogeochemical cycling; and 3) Physical, biogeochemical and ecological contrasts between the Arabian Sea and the Bay of Bengal. And the general scientific themes include: 4) controls and fates of phytoplankton and benthic production in the Indian Ocean; 5) climate and anthropogenic impacts on the Indian Ocean and its marginal seas; and 6) the role of higher trophic levels in ecological processes and biogeochemical cycles.

To address these themes, SIBER has emphasized the analysis required to predict and evaluate the impacts of physical and anthropogenic forcing on biogeochemical cycles and

ecosystem dynamics in the Indian Ocean. SIBER has also focused on leveraging the sampling and monitoring activities of IndOOS, IMOS and several other coastal and open-ocean observing systems that are being deployed in the Indian Ocean, and it continues to provide basin-wide scientific coordination and communication.

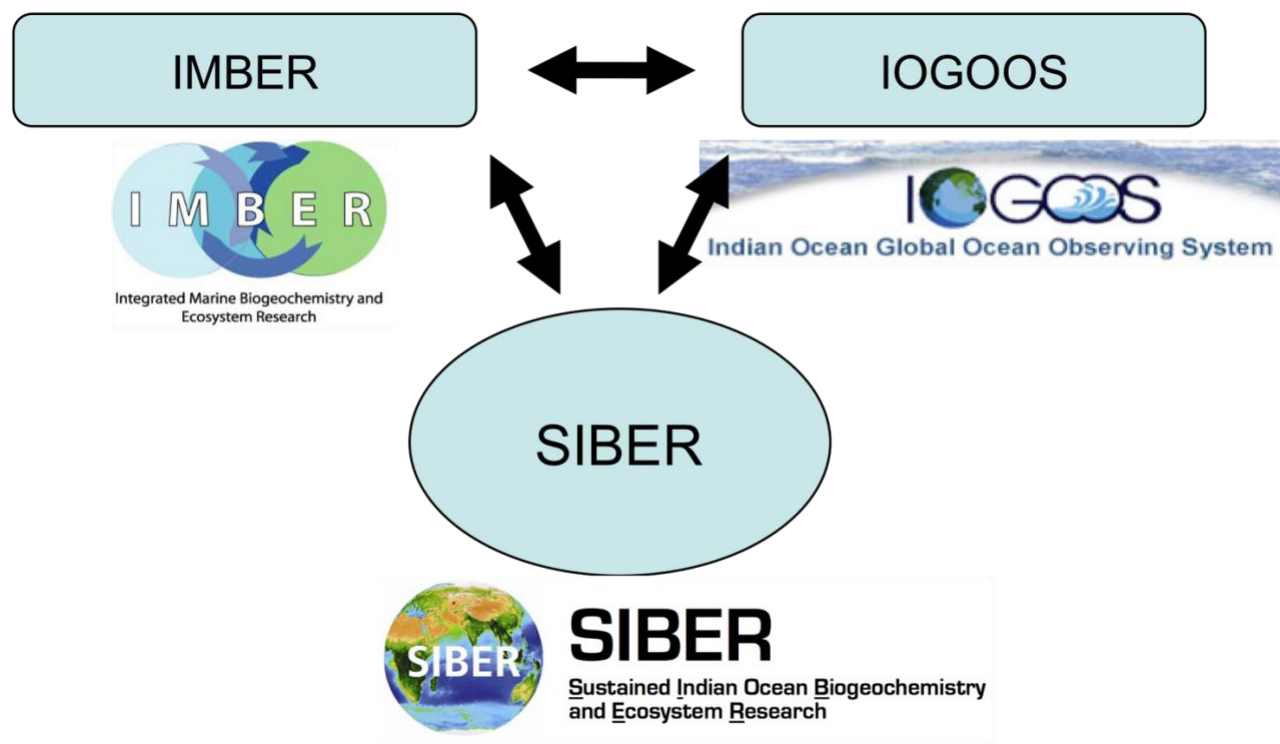


Figure 17: Schematic diagram showing the relationship between SIBER and the two international programs that have provided oversight and guidance since 2010. Figure reproduced from Hood et al. (2011).

The SIBER program is ambitious and very broad. It encompasses biogeochemical research from the continental margins to the deep sea and trophic levels ranging from phytoplankton to top predators including fish and humans. ***SIBER has been highly successful and is considered to be one of the most productive IMBeR regional programs. The IIOE-2 community believes that it is crucial to maintain SIBER, not only because it has played a major role in IIOE-2, but also because SIBER provides IIOE-2 with a strong biogeochemistry and ecosystem research dimension that is highly relevant to the human impacts focus of the final phase of IIOE-2. SIBER research is also complimentary to the atmospheric and physical oceanographic focus of IndOOS, IOGOOS and IORP. The SIBER Steering Committee will continue its role providing oversight of SIBER with support from IOGOOS.***

KOREA-US INDIAN OCEAN SCIENTIFIC IMPERATIVES (KUDOS)

The Korean-US Indian Ocean Scientific (KUDOS) research program is an outgrowth of a workshop held at Seoul National University over 29 November – 1 December 2017 attended by 30 Korean and U.S. scientists with shared interests in Indian Ocean research (<https://kiost-noaa-lab.wixsite.com/kudos>). The workshop was motivated by the successful maiden voyage to the Indian Ocean in July 2017 of the new Korean global class research vessel *Isabu*, operated by the Korean Institute of Ocean Science and Technology (KIOST), on which U.S. participants from the National Oceanic and Atmospheric Administration (NOAA) successfully recovered and deployed three moored buoys of the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA). KUDOS has emerged as an important new research initiative under IIOE-2 with strong participation by Korean scientists from KIOST. Although the *R. V. Isabu* cruises were cancelled in 2020 and 2021 due to the COVID pandemic, they have since resumed post-COVID pandemic. KIOST has institutionalized KUDOS cruises for the next 5 years, which will support RAMA and other international collaborative efforts.

The scientific focus of KUDOS is on the Seychelles-Chagos Thermocline Ridge (SCTR) (Figure 18; See McPhaden et al., 2018 and references cited therein). The SCTR is a feature that is unique to the Indian Ocean – it is a consequence of the meridional asymmetry in the Indian Ocean circulation that arises as a result of the geometry of the Indian Ocean and its strong monsoon forcing. The SCTR strongly influences atmospheric convection in both the Indian and Pacific Oceans via initiation of the Madden-Julian Oscillation (MJO) and it is also an important foraging ground for tuna. Yet, in large part because of its remote location, the current understanding of the physical dynamics of the SCTR remains rudimentary at best, while knowledge of the biogeochemical and ecological dynamics is even less developed. Moreover, sea level has been falling and the thermocline shoaling in the SCTR region in association with a trend towards rising SSTs in the Indian Ocean since the 1960s. These trends are likely due to changes in atmospheric circulation in response to anthropogenic greenhouse gas forcing. How future global warming may affect the SCTR and its impacts on patterns of weather variability in the Indian Ocean region and over East Asia, North America, and other parts of the globe, is poorly known if at all. Likewise, how marine biogeochemistry, carbon cycling, ocean acidification, ecosystems and fisheries will change in the SCTR under continued anthropogenic greenhouse gas forcing is highly uncertain.

The KUDOS science plan and implementation strategy for studying the SCTR (McPhaden et al., 2018) is structured around five themes: 1) ocean-atmosphere interactions; 2) ocean circulation; 3) biogeochemical and carbon cycles; 4) climate variability, change and extreme events; and 5) ecosystems and fisheries. Each of these themes presents significant opportunities for profound advances in the ability to understand and predict dynamical variability in the region, its far-field impacts, and its effects on biogeochemical processes and ecosystem function in the Indian Ocean.

The KUDOS research initiative is ongoing and will continue to be a major focus of IIOE-2 in its final phase.

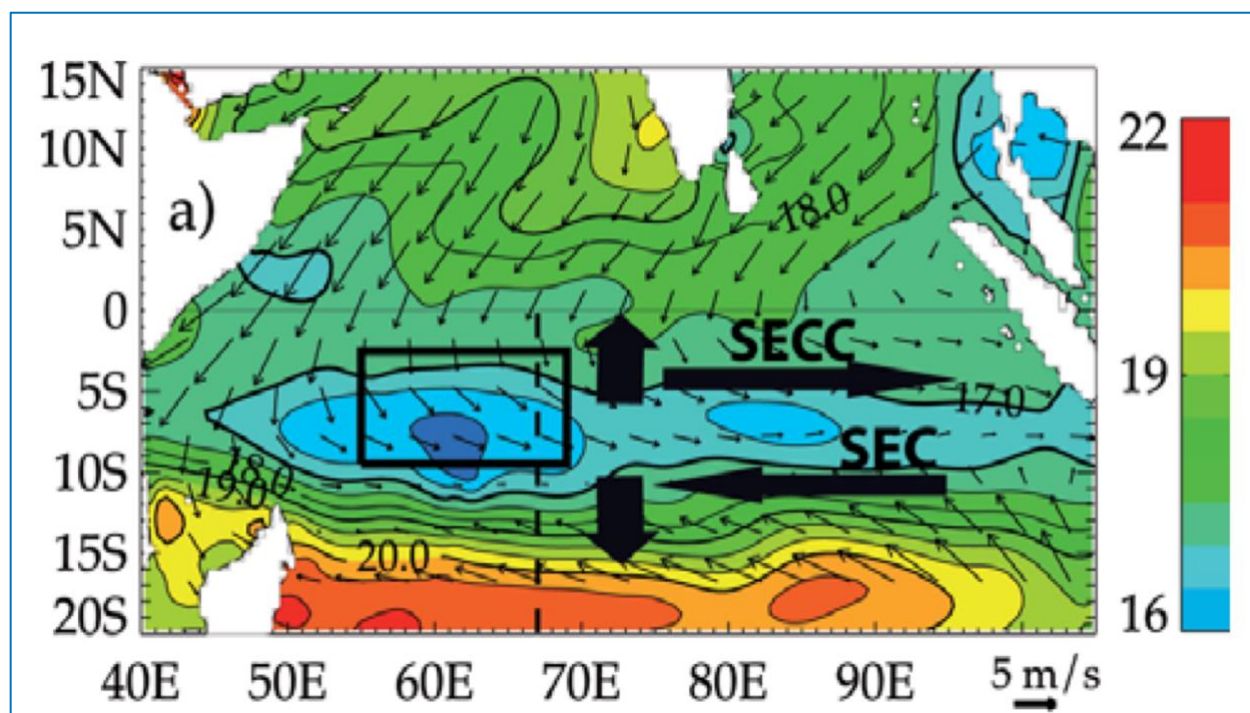


Figure 18: Regions and dynamics of interest in the Korea-US Indian Ocean Scientific Imperatives (KUDOS) program. The core of the Seychelles-Chagos Thermocline Ridge (SCTR) is denoted by the box. The SEC is the South Equatorial Current and the SECC is the South Equatorial Counter Current. Figure from Vialard et al. (2009)

COASTAL OBSERVATIONS IN UNDER-RESOURCED COUNTRIES (COLaB)

A critical lack of coastal observations across most of the Indian Ocean is due in large part to a lack of marine science research capacity in under-resourced rim and island nations, but also due to a misperception that reliable observations require expensive instruments, research vessels and laboratories. In an effort towards resolving this problem, a new marine science capacity-building project, [Coastal Observation Lab in a Box \(COLaB\)](#), has emerged. It is a collaboration between the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER; IMBeR) program and the Indian Ocean Regional Panel (IORP, CLIVAR), and is now endorsed by the United Nations Decade of Ocean Science and Sustainable Development, through the [CoastPredict](#) Program. It is also associated with the [Ocean Best Practices System \(OBPS\) Task Team on Coastal Observations in Under-resourced Countries](#). Built on assessments of regional end-user needs, through multiple in-person and virtual workshops, the project is committed to providing tools and training as a key foundation towards developing a cost-effective, innovative, standardised, and integrated impact observation and forecasting system to enhance the sustainable collection of essential ocean observations (EOVs) in coastal waters.

To achieve its objective, COLaB has adopted a holistic, responsive and integrated approach, including training activities, cost-effective instrument packages, calibration

activities, standardized practices and methods as well as data management and modelling tools (Table 1). Specifically, COLaB features development and deployment of low-cost, open-source instruments wherever possible with co-designed instrument packages (open-source and commercial) for diverse physical, biological and biogeochemical applications and determination of multiple Essential Ocean Variables (EOVs). COLaB revolves around portable instrument packages (“Lab in a Box”), with application from coastal wetlands to the shelf edge, that do not require a formal research vessel or laboratory. COLaB also promotes in-person training at regional training camps, combined with online support and regional instrument calibration hubs. This, combined with a user-friendly data management package (ERDAPP) and web-interfaced modelling tools, allow deployment not just by researchers but also by fisheries managers, NGOs, port authorities, the mariculture industry, etc. In particular, the COLaB initiative seeks to engage early career scientists to facilitate the training and development of multi-skilled oceanographers who can become trainers in their own right (which is key to IIOE-2 legacy).

A 10-day “proof of concept” study was undertaken in Ghana in July 2024 that also involved personnel from South Africa. A subset of COLaB tools was deployed in the Pra estuary as part of a study of sediment and mercury contamination from upstream illegal gold mining. A second pilot study was undertaken in September where COLaB principles were demonstrated as part of a summer school field camp in Watamu on the Kenyan coast, in the framework of VOKCE (EP55). Following that, and directly relevant to the Indian Ocean and IIOE-2, efforts are being undertaken to secure funds for a regional training camp in Mozambique, that will serve to train people from around south and east Africa, and possibly western Indian Ocean island nations. A future regional training camp for the Indian Ocean and IIOE-2 has also been confirmed at BRIN/Lombok (for the eastern Indian Ocean region). With these locations, and hopefully others, this effort will seek to span the entire Indian Ocean with COLaB deployments and training. Efforts have been undertaken to reach out to the IIOE-2 ECSN network, as well as ECOP-Africa, IMECAN (IMBeR) etc, to initiate active involvement of early career scientists in COLaB. In addition to involvement of early career scientists in organizing and delivering regional training camps, a training program is envisioned that would train Early Career Scientists as trainers in their own right, which would be an important legacy of COLaB involvement in IIOE-2.

It is anticipated that COLaB will provide tools to significantly expand coastal observing in the Indian Ocean with low-cost, region-specific, long-term observations. The tools and training provided by COLaB will facilitate a wide range of multi-faceted (physical, biological and biogeochemical) studies in locations ranging from wetlands, mangroves and reef systems out to the continental shelf. Such capability is a high priority for potential end-users in under-resourced countries.

When coupled with remote sensing and continued national coastal monitoring programs (e.g., IMOS, OCIMS and MOSAIC, see below), expanded to other countries, systematic use of COLaB methods (e.g., through cross-shelf transects carried out with regular servicing moored observing platforms) will also facilitate valuable cross-region

comparative datasets. These will enable wide-ranging insights into coastal ocean conditions, processes, ecosystem health, and climate change impacts and they will facilitate IIOE-2 Marine Spatial Planning and Community Engagement efforts. ***In its final phase IIOE-2 will focus on expanding coastal monitoring efforts in Indian Ocean rim countries and making the data from these efforts accessible to the scientific and stakeholder communities. The IIOE-2 community believes that there is a major opportunity to deploy COLaB, alongside the UN Decade and CoastPredict programs (see below), as leverage for building a sustainable regional network for cross-validated coastal oceanographic data collection and also for building capacity and for training multi-skilled coastal oceanographers.***

Table 1. Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) addressed by the COLaB Box

Instrument	EOVs/EBVs
Physical/Hydrography	
Conductivity, temperature, and depth sensor (CTD)	Subsurface Temperature; Subsurface Salinity
Temperature probes (thermistor string mooring)	Subsurface Temperature
Drifter current meter	Surface Currents; Seasurface Temperature; Seasurface Salinity; Sea State (Wave Height)
Fixed-point acoustic current meters	Surface Currents; Subsurface Currents
Acoustic Doppler Current Profiler (ADCP)	Subsurface Currents
Tilt current meter	Subsurface Currents
Secchi Disc	Turbidity
Biogeochemistry	
Spectrophotometer*	Nutrients
Fluorimeter*	Phytoplankton biomass and diversity (chlorophyll a, b, HPLC pigments); Phycoerythrin and phycocyanin (cyanobacteria/HAB indicators), coloured dissolved organic matter (CDOM), Turbidity (nephelometry)
Multiparameter sondes	Seasurface Temperature; Subsurface Temperature; Seasurface Salinity; Subsurface Salinity; Oxygen (Dissolved Oxygen), Inorganic Carbon (pH)
pH meter	Inorganic Carbon (pH)
Conductivity meter/salinometer	Seasurface Salinity; Subsurface Salinity
Titration equipment	Inorganic Carbon (Alkalinity), Oxygen (Dissolved Oxygen)
Biology	
Plankton nets	Phytoplankton biomass and diversity; Zooplankton biomass and diversity
Imaging equipment/ Baited underwater remote videos	Phytoplankton biomass and diversity; Zooplankton biomass and diversity, Fish species identification and size
Benthic survey tools (e.g., sieves)	
Zooplankton Metabarcoding	Zooplankton biomass and diversity
Filtration set-up	Phytoplankton biomass and diversity; Zooplankton biomass and diversity

MARGINAL SEAS RESEARCH INITIATIVE

The Indian Ocean, the third-largest oceanic division, is fringed by diverse ecosystems and rich cultural histories. Notable among its features are several marginal seas, which are partially enclosed bodies of water adjacent to the main ocean basin. The major marginal seas of the Indian Ocean (Figure 19; Al-Yamani et al., 2024) include the Andaman Sea, the Arabian/Persian Gulf, the Gulf of Aden, the Red Sea, and the Sea of Oman. These seas are critical to regional climates, marine biodiversity, and human livelihoods. However, they remain underexplored compared to other parts of the Indian Ocean. This research initiative aims to address this gap by conducting a comprehensive study of the marginal seas of the Indian Ocean to enhance understanding of these unique, complex, and dynamic systems. Addressing key areas such as physical, chemical, ecological, and geological oceanography, and assessing the impacts of climate change and human activities, will help in developing effective strategies for conservation, sustainable management, and resilience building in these vital regions.



Figure 19: Map of the marginal seas of the Indian Ocean (the Andaman Sea, the Sea of Oman, the Arabian Gulf, the Gulf of Aden, and the Red Sea). Source: Al-Yamani et al. (2024).

Significant oceanographic and marine science research accomplishments have been achieved by universities and research institutions across the Arabian/Persian Gulf, Gulf (Sea) of Oman, northwestern Arabian Sea, Gulf of Aden, and the Red Sea (Table 2). However, despite these efforts, there remains an urgent need for further research in several critical areas. These include air–sea interactions, long-term environmental monitoring, biodiversity mapping and genomics, bioprospecting, biogeochemical processes, ocean circulation, oxygen minimum zones, monsoon-driven upwelling and its

impact on fisheries, coastal fisheries sustainability, harmful algal bloom dynamics, and the development of integrated marine spatial planning tools.

Addressing data scarcity and establishing sustained ocean observation systems remain high priorities. Additionally, enhancing ocean literacy and fostering stronger policy engagement among national institutions are essential for the effective management and conservation of marine resources in the marginal seas of the Indian Ocean.

There is a major opportunity to promote much-needed research in the marginal seas of the Indian Ocean in the final stage of IIOE-2 (2026-2030). This complements the aforementioned need to increase scientific understanding and engagement of the western Indian Ocean, the eastern Bay of Bengal and marginal seas research communities. ***Motivating a Marginal Seas Research Initiative will not only advance scientific understanding in these understudied regions of the Indian Ocean, but will also provide new opportunities for scientific engagement of Indian Ocean rim countries that are not currently actively participating in IIOE-2. Achieving these goals will be key to establishing the legacy of IIOE-2. Efforts are already underway to motivate this initiative, starting with a planned workshop on Indian Ocean marginal seas at the 2025 International Indian Ocean Science Conference (IIOSC 2025) that will be convened December 1-5 in Hyderabad, India. This workshop will bring together scientists from the Indian Ocean's marginal seas research communities to discuss scientific progress and challenges. This workshop will also serve as a starting point for organizing a series of workshops on the Indian Ocean's marginal seas that will be one of the main activities of this initiative. Scientists from these communities will also be encouraged to attend and present their findings at the annual IIOSC meetings. Engagement with IOCINDIO (see below) will also facilitate making connections with scientists from the Indian Ocean's marginal seas research communities.***

Table 2. Key institutions conducting oceanographic and marine science research in countries bordering the northwestern Indian Ocean marginal seas and their primary research focus areas.

Country	Institution/Center	Location	Focus Areas
Kuwait	Kuwait Institute for Scientific Research (KISR)	Kuwait City	Oceanography, marine ecosystems, biodiversity, HABs, fisheries, pollution
	Kuwait University, Faculty of Marine Science	Shdadiyah	Marine biology, plankton ecology, coastal monitoring
Saudi Arabia	King Abdullah University of Science and Technology (KAUST)	Thuwal	Red Sea research, coral reefs, genomics, physical oceanography
	Saudi Aramco Environmental Protection Department	Dhahran	Marine monitoring, environmental impact
	King Fahad University of Petroleum and Minerals	Dhahran	Pollution, oil spill response and modeling, marine ecosystems, remote sensing, marine biotechnology and bioremediation
Qatar	Environmental Science Center, Qatar University	Doha	Coral reefs, fish ecology, oceanography, climate impacts
	Ministry of Environment and Climate Change (MoECC)	Doha	Marine biodiversity, conservation policy
Bahrain	Public Commission for the Protection of Marine Resources, Environment and Wildlife	Manama	Fisheries, coastal management, marine pollution
United Arab Emirates	Environment Agency – Abu Dhabi (EAD)	Abu Dhabi	Marine protected areas, sea turtles, dugongs, water quality
	New York University Abu Dhabi (NYUAD)	Abu Dhabi	Marine genomics, ecological research
	United Arab Emirates University – Biology Dept.	Al Ain	Marine biology and biodiversity
	Ministry of Climate Change and Environment (MOCCA)	Dubai	Policy-making, biodiversity conservation
Oman	Sultan Qaboos University – College of Agricultural and Marine Sciences	Muscat	Marine biodiversity, fisheries, biotechnology
	Marine Science and Fisheries Centre (MSFC), Ministry of Agriculture and Fisheries	Muscat	Aquatic resources, environmental studies
Iran	Iranian National Institute for Oceanography and Atmospheric Science (INIOAS)	Tehran	Physical oceanography, marine geology, pollution, modeling
	Persian Gulf and Oman Sea Ecological Research Institute (PGOSERI)	Bandar Abbas	Marine biodiversity, pollution, fisheries
	University of Tehran – Institute of Marine Science and Technology	Tehran	Coastal processes, marine biology
Yemen	Marine Science and Resources Research Center (MSRRC)	Aden	Coastal resources, marine ecosystems, fisheries
	University of Aden – Faculty of Marine Sciences	Aden	Marine biology, aquaculture, pollution

IN SITU OBSERVATIONS, REMOTE SENSING, MODELING AND ASSIMILATION

Long-term in situ observing and monitoring efforts are ongoing in several coastal and open ocean locations in the Indian Ocean. IIOE-2 will continue to target and build upon this existing research infrastructure in 2026 - 2030.

COASTAL MONITORING AND OBSERVATIONS

Australia's Integrated Marine Observing System (IMOS) is an example of a national observing system that deploys high-technology sampling devices for making routine

observations in its Indian Ocean EEZ (Figure 20; see: <https://imos.org.au>). Among other things, the Australian IMOS program is deploying long-term combined biological/physical moorings in shallow (< 200 m) waters off the west and northwest coasts of Western Australia. Investigations utilizing the data from this fixed infrastructure benefit greatly from an international effort that is collecting complementary ship-based observations in the region. ***In its final phase, IIOE-2 will continue to engage with and utilize the coastal observations that are being generated by Australia's IMOS program.***

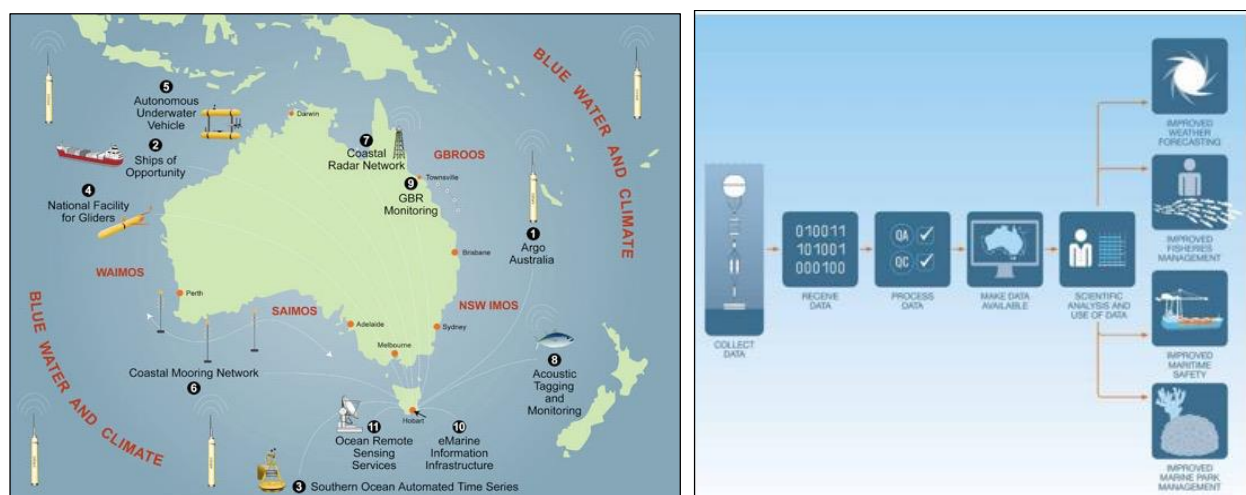


Figure 20: Observational assets of Australia's Integrated Marine Observing System (left panel), and flow diagram depicting how these data are processed and used improve weather forecasting, fisheries management, maritime safety and marine park management. Figures courtesy of IMOS.

South Africa's Oceans and Coastal Information Management System (OCIMS) was launched by the South African Government in 2015 to support the development and governance of the South African ocean economy (Figure 21; see: <https://ocims.environment.gov.za>). The OCIMS has established knowledge tools for marine spatial planning, maritime domain awareness, search and rescue, water quality and harmful algal bloom monitoring. Those tools are used daily by stakeholders across government departments, industry, and civil society. Unlike some other operational oceanographic and coastal systems around the world, the OCIMS was designed from its inception using inputs from stakeholders. Continuous engagements between developers and stakeholders have ensured that the system remains fit for purpose. Developments have been undertaken to ensure inter-operability with other systems in the world and promote the exchange and discovery of data. The OCIMS project has been able to leverage co-funding and the sharing of data and expertise through partnerships across the public and private sectors. These partnerships have been essential to the success of OCIMS and would not have been possible without continued engagements and the sustained funding provided by the South African national government. In addition, the South African government has invested in the South African Polar Research Initiative (www.sapri.ac.za) with the objective of enabling balanced research growth across the marine and polar disciplines, and maintaining and further expanding the world-class long-term observational datasets already established. SAPRI will provide infrastructure for use in the Indian Ocean including gliders and argo floats. ***In its final phase, the IIOE-2 will***

seek to engage with South Africa's OCIMS and SAPRI initiatives and motivate complementary ship-based observation in the region.

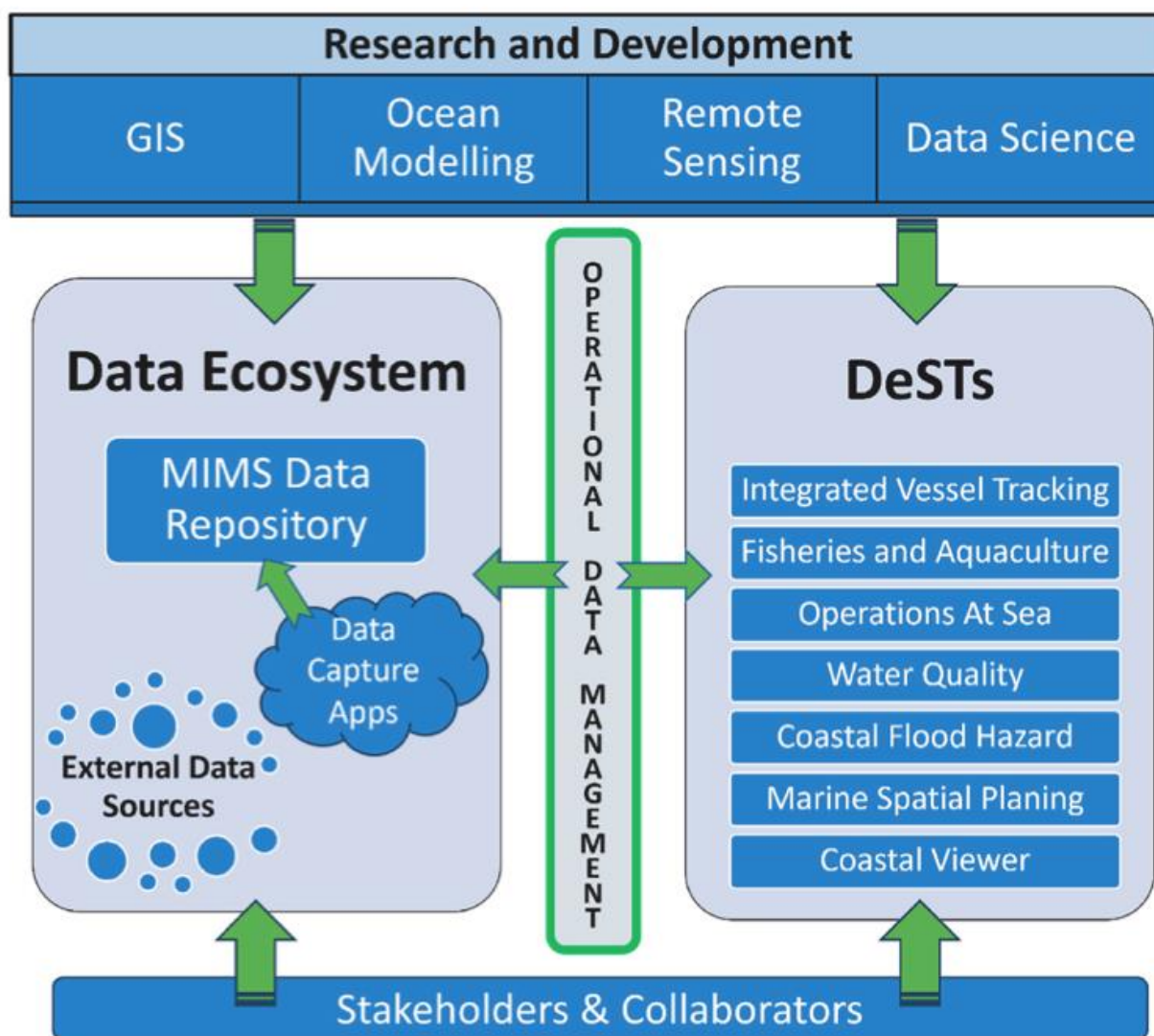


Figure 21: Schematic of OCIMS architecture. Figure from Krug et al. (2024).

India's Marine Observation System Along the Indian Coast (MOSAIC) program is another example of a national observing system that is deploying high-technology sampling devices for making routine observations in its Indian Ocean coastal zone (Figure 22; see: https://incois.gov.in/portal/rti_budget_2017-20.jsp). This program, which is funded by India's Ministry of Earth Sciences and managed by the Indian National Center for Ocean Information Services (INCOIS), has established sustained time-series observations using automated moored buoys at six different locations along the Indian coast to monitor and now-cast water quality of the Indian coastal waters (Figure 22). The MOSAIC program has several specific objectives which include deploying a moored automated buoy-based coastal observatory, establishing monthly time series stations at and in-between the buoy locations, and conducting geomorphological mapping of two selected estuaries. MOSAIC

will also conduct intensive sampling in selected river estuaries to monitor their health, generate in situ data for understanding the effect of physical forcing on biogeochemical processes along the east and west coast of India, and provide water quality forecasting for the selected coastal stations using high-resolution modelling and assimilation of real-time data. ***In its final phase, IIOE-2 will continue to engage with India's MOSAIC program and promote the sharing of data collected in India's EEZ. IIOE-2 will also facilitate networking with other countries to promote common best practices as well as standardized methods for monitoring of core parameters.***

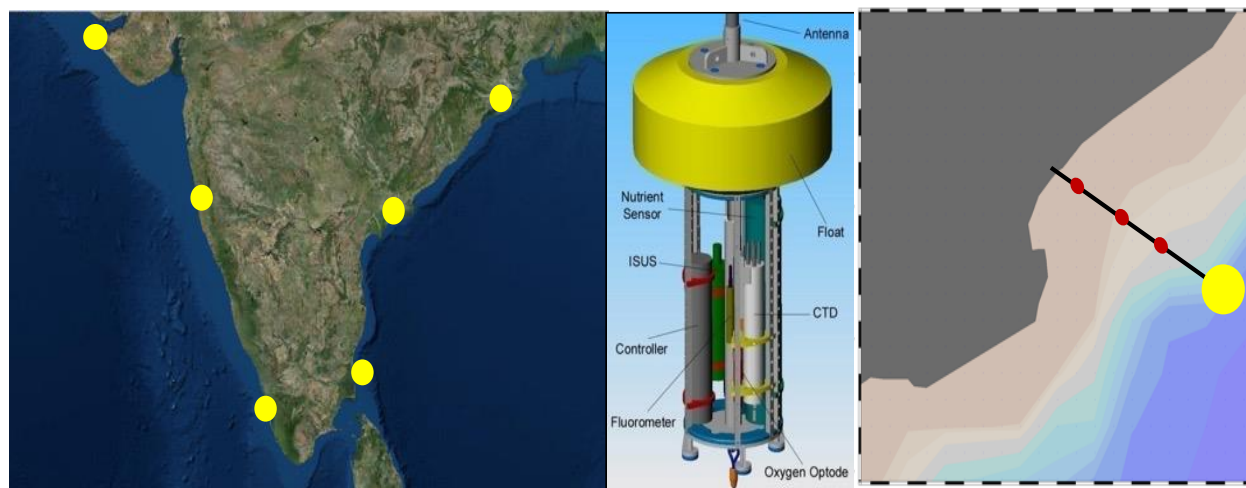


Figure 22: Coastal stations (left panel), mooring with sensors (middle panel) and coastal sampling transect for India's Marine Observation System Along the Indian Coast (MOSAIC) program. Figures courtesy of INCOIS.

OPEN OCEAN MONITORING AND OBSERVATIONS

Human impacts on the Indian Ocean go beyond the coasts, and therefore, where the capacity exists, IIOE-2 will continue to motivate investigations that extend into the open ocean. These investigations will take full advantage of open access data measured by ships, Argo, buoys, drifters, and satellites that are relevant to the Indian Ocean region.

In particular, CLIVAR/IORP and IOGOOS have developed a basin-scale observing system in the Indian Ocean (IndOOS) that is centered around the deployment of a mooring array (the Research moored Array for African-Asian-Australian Monsoon Analysis and Prediction or RAMA, sponsored by the U.S. National Oceanic and Atmospheric Administration) along with repeated XBT lines, surface and subsurface drifters and ship-based hydrography through GO-SHIP (Beal et al., 2020) and GEOTRACES (see: <https://www.geotraces.org>). The moorings are capable of measuring key variables needed to describe, understand and predict large-scale ocean dynamics, ocean-atmosphere interactions and the Indian Ocean's role in global and regional climate. Efforts have also been undertaken to deploy biogeochemical sensors on the RAMA moorings (e.g., Strutton et al., 2015). These mooring-based measurements can provide an excellent atmospheric and physical oceanographic observational foundation

for carrying out a wide variety of biogeochemical and ecological studies. ***In its final phase, IIOE-2 will continue its efforts to take advantage of IndOOS, GEOTRACES and GO-SHIP measurements to provide context for biogeochemical and ecosystem research with an emphasis on understanding human impacts on the Indian Ocean.***

An important new program that has emerged since the launch of IIOE-2 in 2015 is the Global Ocean Biogeochemistry (GO-BGC) Array. This project, which is funded by the US National Science Foundation, is building a global network of 500 robotic ocean-monitoring floats with chemical and biological sensors to monitor ocean health. This network of floats is collecting these data on the chemistry and the biology of the ocean from the surface to a depth of 2,000 m, augmenting the existing Argo array that monitors ocean temperature and salinity. The 500 floats in GO-BGC will represent half the desired global number of 1,000 floats proposed in the Biogeochemical Argo Science and Implementation Plan ([BAPG, 2016](#)) for a global BGC observing system. It is anticipated that an additional 500 floats will be deployed by international partners in the coming years, and many efforts are already underway (see: <https://biogeochemical-argo.org>).

Data streaming from the float array is freely available (see: <https://biogeochemical-argo.org>) within a day of being collected via the Argo data system, and is being used by researchers around the world. These data are allowing scientists studying the Indian Ocean to pursue fundamental questions concerning ocean ecosystems, observe ocean health and productivity, and monitor the elemental cycles of carbon, oxygen, and nitrogen in the ocean through all seasons of the year. Such essential data are needed to improve computer models of ocean fisheries and climate, and to monitor and forecast the effects of ocean warming and ocean acidification on sea life in the Indian Ocean. ***In its final phase, IIOE-2 will continue its efforts to facilitate GO-BGC float deployment in the Indian Ocean and the use of these data in scientific research with an emphasis on understanding human impacts on the Indian Ocean.***

REMOTE SENSING

IIOE-2 studies in the Indian Ocean will continue to take full advantage of remote sensing to characterize physical and biological variability in the ocean, in coastal waters and on adjacent land masses. Relevant measurements, with corresponding representative mission(s) with NASA as a principal contributor, include satellite ocean color (retrospective SeaWiFS and MODIS-Aqua and the new PACE mission), sea surface temperature (SST; NOAA/AVHRR), sea surface height (SSH; T/P and Jason), surface vector winds (ISS-RapidScat) and precipitation (Global Precipitation Mission, GPM). In addition, IIOE-2 studies in the Indian Ocean will take full advantage of the European Union's Copernicus mission.

PACE is of particular relevance to the final phase of IIOE-2. PACE is NASA's Plankton, Aerosol, Cloud, ocean Ecosystem mission. It was launched on February 8, 2024, extending and improving NASA's > 20-year record of satellite observations of global ocean biology, aerosols, and clouds. PACE has two fundamental science goals: to extend key systematic ocean color, aerosol, and cloud data records for

Earth system and climate studies, and to address new and emerging science questions using its advanced instruments, surpassing the capabilities of previous and current missions. The Ocean Color Instrument (OCI) on PACE is a hyperspectral radiometer. PACE's OCI represents a leap forward because it can view a very broad spectrum from 350 to 885 nanometer (nm) wavelengths at 5 nm intervals – making it hyperspectral. The range that PACE's instruments will observe includes the UV (350-400 nm), visible (400-700 nm), and near-infrared (700-885 nm), as well as several shortwave infrared bands. Thus, the OCI will provide an unprecedented view of the Indian Ocean without the "blind spots" of previous sensors.

The European Union's Copernicus mission is served by a set of dedicated satellites (the Sentinel families, see: <https://www.copernicus.eu/en/about-copernicus/infrastructure-overview/discover-our-satellites>) and contributing missions (existing commercial and public satellites). The Sentinel satellites are specifically designed to meet the needs of the Copernicus services and their users. Since the launch of Sentinel-1A in 2014, the European Union set in motion a process to place a constellation of almost 20 more satellites in orbit before 2030. Copernicus also collects information from in situ systems (see: <https://www.copernicus.eu/en/about-copernicus/infrastructure-overview/situ-component>) such as ground stations, which deliver data acquired by a multitude of sensors on the ground, at sea or in the air. The Copernicus services transform this wealth of satellite and in situ data into value-added information by processing and analyzing the data. Datasets stretching back for years and decades are made comparable and searchable, thus ensuring the monitoring of changes; patterns are examined and used to create better forecasts, for example, of the ocean and the atmosphere. Maps are created from imagery, features and anomalies are identified and statistical information is extracted. The information provided by the Copernicus services can be used by end users for a wide range of applications in a variety of areas. Those most relevant to IIOE-2 include: the Copernicus Atmosphere Monitoring Service (CAMS), which provides continuous data and information on atmospheric composition; the Copernicus Marine Service (or Copernicus Marine Environment Monitoring Service), which provides free, regular and systematic authoritative information on the state of the Blue (physical), White (sea ice) and Green (biogeochemical) ocean, on a global and regional scale; and the Copernicus Climate Change Service (C3S), which supports society by providing authoritative information about the past, present and future climate in Europe and the rest of the World.

In addition to these US and EU missions, regional satellites, such as India's Oceansat-1, -2 and -3 satellites will be utilized as well. India's ocean color satellites, developed by the Indian Space Research Organization (ISRO), primarily focus on monitoring ocean ecosystems and providing data for various applications like fisheries management and climate studies. These satellites carry instruments like the Ocean Colour Monitor (OCM) to gather data on ocean color, which is then used to derive information about phytoplankton, chlorophyll, and other ocean constituents.

The need for, and access to, long time-series of satellite measurements will also be emphasized in the final phase of IIOE-2. For example, ocean-color missions have

accumulated continuous chlorophyll data for over two decades since the launch of SeaWiFS (Sea-viewing Wide Field-of-view Sensor) in 1997. However, the on-orbit life of a single mission is about five to ten years. To build a dataset with a time span long enough to use in climate change related studies, it is necessary to merge the data from multiple sensors. The European Space Agency has developed two sets of merged chlorophyll products, namely GlobColour and OC-CCI (Ocean Colour Climate Change Initiative), which have been widely used. Nonetheless, issues remain in the long-term trend analysis of these two datasets because the inter-mission differences in estimating chlorophyll concentration have not been completely corrected. To obtain more accurate long-term chlorophyll trends in the global oceans, some new products have been recently generated. For example, Yu et al. (2023) have merged chlorophyll records from the SeaWiFS, MODIS (Medium-spectral Resolution Imaging Spectrometer), MERIS (Moderate Resolution Imaging Spectroradiometer), VIIRS (Visible Infrared Imaging Radiometer Suite), and OLCI (Ocean and Land Colour Instrument) with inter-mission differences more fully corrected. These kinds of merged products are extremely valuable for studying, among other things, climate change-induced long-term trends in chlorophyll, temperature, etc. in the Indian Ocean.

It is anticipated that IIOE-2 will make extensive use of PACE and Copernicus data, as well as regional satellites flown by India, and also merged long-term time-series for both physical and biogeochemical studies focused on the Indian Ocean, and will also provide in-situ measurements for calibration and validation.

MODELING AND ASSIMILATION

Remote sensing studies of the ocean can and should be combined with modeling studies, although there are still substantial challenges associated with modeling the intense variability observed in many regions of the Indian Ocean. Eddy-resolving models are required in order to capture the physical and biological variability in Indian Ocean boundary current and upwelling systems. The eddy fields that are associated with these currents have been successfully modeled using, for example, the 1/16th degree resolution Navy Layered Ocean Model (NLOM) that assimilates SSH data (Smedstad et al., 2003). Through the employment of such data assimilation methods in high-resolution models, realism of the simulated mesoscale eddy field is significantly enhanced.

The Ocean Forecasting Australia Model (OFAM) is another relevant eddy-resolving model applied in the Indian Ocean under the auspices of BLUELink (see <http://www.cmar.csiro.au/bluelink/>). The current 1/10th degree implementation of OFAM in the coastal waters of Australia, successfully resolves the Leeuwin Current and its eddies. OFAM's 1/10th degree implementation has been expanded to include the entire Indian Ocean. OFAM is currently generating “nowcasts” and short-term forecasts in support of field studies, as well as retrospective studies. An important question in the context of boundary current and upwelling studies is how well these models represent cross-shelf exchange, which is unknown.

As detailed in the IIOE-2 Science Plan (Hood et al., 2015), combined remote sensing and modeling studies will be used for modeling circulation, variability and change; biogeochemical processes and change; impacts of riverine and atmospheric inputs; and higher trophic level modeling. Regarding the latter, applying coupled models to study ecosystem dynamics and higher trophic levels is still a significant research challenge. At present these models are primarily being used to simulate and understand biogeochemical variability and lower trophic level dynamics (e.g., NPZD-type dynamics and interactions). New modeling approaches for simulating higher trophic levels that have emerged from IMBER regional programs (e.g., CLIOTOP) and SCOR Working Groups (e.g., 137) and other programs can, and should, be leveraged in the final phase of IIOE-2.

In its final phase, IIOE-2 will continue its efforts to embrace and promote modeling and data assimilation research to advance understanding of ocean physical, biogeochemical and higher trophic level variability and change. These approaches also provide a means to synthesize remote sensing and observational data that are being collected in the Indian Ocean.

NEW TECHNOLOGIES

There are several new technologies (e.g., observations, monitoring, advanced modeling and forecasts) and opportunities that IIOE-2 will take advantage of in its final phase, for example, the aforementioned the Global Ocean Biogeochemistry (GO-BGC) Array, new low-cost coastal observing technologies like those that are being deployed in the COLaB initiative, and new hyperspectral remote sensing missions like PACE. Applications of Machine Learning (ML) and Artificial Intelligence (AI) in data analysis and synthesis are important new research technologies that will also be embraced. ***In its final phase, IIOE-2 will seek to take full advantage of these advanced methods that are providing exciting new ways to deal with the ever-expanding data volumes that are emerging from technological advances in ocean observation.***

REVISED IMPLEMENTATION STRATEGY

The Revised Implementation Strategy for IIOE-2 2015-30 (D'Adamo et al., 2025) plays a key role in supporting the IIOE-2's mission: *to advance our understanding of interactions between geologic, oceanic and atmospheric processes that give rise to the complex physical dynamics of the Indian Ocean region, and determine how those dynamics affect climate, extreme events, marine biogeochemical cycles, ecosystems and human populations.*

This not only builds on the four formative years of consultations, planning and institutional advocacy that were undertaken during 2012-2015 for the IIOE-2 involving the Indian Ocean's regional constituency as well as complementary regional stakeholders (e.g.

NGOs such as the Western Indian Ocean Marine science Association (WIOMSA), or IGOs, as for instance the Indian Ocean Commission) but also takes account of the developments in the scientific outputs, revised scientific foci (e.g., this document), and operational running of the IIOE-2 since its launch on 4 December 2015. It was produced to align with the IIOE-2 International Steering Committee's decision at its 7th major meeting during the 4-5 March 2024 (IIOE-2 SC7) to extend the IIOE-2's tenure out to 2030. It complements, as a guiding document designed to help run the IIOE-2, the IIOE-2 Science Plan Addendum (Hood et al., 2025). It is noteworthy to recall that the original Implementation Strategy of 4 December 2015 was underpinned by material that was derived from a series of planning workshops, meetings and institutional deliberations by the co-sponsors IOC, IOGOOS and SCOR during 2012-15 and available through the IIOE-2 Project Office at ESSO-INCOIS, Hyderabad, India or through the IIOE-2 website (<https://iioe-2.incois.gov.in/>, and see also Hood and D'Adamo 2012, 2013 & 2014; D'Adamo 2014). As with the original Implementation Strategy, the Revised Implementation Strategy (D'Adamo et al., 2025) was designed to provide a guiding *strategy* rather than a detailed operational procedure for the Expedition. Operational details will continue to be developed and arranged through the IIOE-2 Steering Committee in conjunction with the IIOE-2 Project Office, and through its associated elements including the science theme leaders and the three Working Groups. The Revised Implementation Strategy therefore continues the original focus of providing motivations and related objectives with associated recommended actions (in some cases committed actions) in response to the major elements of the IIOE-2 portfolio. It suggests and recommends how the aspirational frameworks of the Steering Committee and its Working Groups can be best achieved but acknowledging that, as for all major initiatives of this nature, resource limitations and operational constraints can limit the attainment of the ideal operational framework in terms of executing the IIOE-2.

The major sections cover the structure of the IIOE-2 Steering Committee, its associated Governance, its elemental membership, and the functions of the six science themes, the three Working Groups and the IIOE-2 Early Career Scientists Network. The Steering Committee's framework remains practically very close to what it was, albeit with some minor structural changes in representation. For example, originally IIOE-2 had seven Working Groups, whereas those seven now consolidate into three, WG1, WG2 and WG3 (below). In addition, attention is also given to improving the engagement and integration of the ECSN into the Science Theme and Working Group networks.

- **WG1 Science and Research** (*as it was and remains*).
- **WG2 Data and Information Management** (*as it was and remains*).
- **WG3 Operational Coordination** (*being a consolidation of the former WGs 3-7: i.e. former WG3 Capacity Development + former WG4 Operational Coordination + former WG5 Outreach and Communication + former WG6 Translating Science for Society + former WG7 Sponsorship and Resources*).

The Project Office, which since October 2021 has existed as a sole node in India, is addressed in terms of its structure and functions.

Again, a strong emphasis is placed on ensuring that the IIOE-2 is efficiently and professionally run, administered, and resourced. Another key emphasis is to guide the underpinning operational support needed for the IIOE-2 to achieve science of contemporary relevance, of a high standard and integrated within the thematic elements of the Science Plan. Working Group 1 focuses on this aspect of IIOE-2. Priority is also given to ensuring that the data and information management thereof supports the optimal utilisation of the science effort that will continue to be assigned to IIOE-2, as reflected through the aims of Working Group 2.

Another key aspiration is that the Revised Implementation Strategy again supports an aim of IIOE-2 to leave a legacy throughout the Indian Ocean region, as did the original IIOE of 1959-65, by establishing the basis for improved scientific knowledge transfer to wider segments of society and regional governments. The importance of these objectives is reflected in the maintenance of the foci of Capacity Development and Translating Science for Society within Working Group 3. Furthermore, it aims to support the educational and capacity development opportunities of IIOE-2 in support of regional and early career scientists, as reflected in the enhanced explicit engagement of ECSN members within the ST and WG networks.

This Revised Implementation Strategy is designed so that it may be reviewed and updated if and as required on an annual basis, with the review process to be informed by input through the IIOE-2 Steering Committee.

INTEGRATION

UN DECADE OF OCEAN SCIENCE FOR SUSTAINABLE DEVELOPMENT

Another important objective for IIOE-2 in 2026 – 2030 will be to participate in the UN Decade of Ocean Science for Sustainable Development (Ocean Decade). Launched in January 2021, the Ocean Decade provides a convening framework for a wide range of stakeholders across the world to engage and collaborate outside their traditional communities to trigger nothing less than a revolution in ocean science. Throughout the Ocean Decade, partners will generate the data, information and knowledge needed for more robust science-informed policies and stronger science-policy interfaces at global, regional, national and even local levels. By collectively aligning research, investments and initiatives around a set of common challenges, the Ocean Decade community will contribute to a well-functioning, productive, resilient, sustainable and inspiring ocean. The Ocean Decade Vision is: *‘The science we need for the ocean we want’* and the Ocean Decade Mission is: *‘Transformative ocean science solutions for sustainable development, connecting people and our ocean.’*

Building on existing achievements in ocean science, the Ocean Decade seeks to stimulate action at all levels while catalyzing transformation to deliver change across all

geographies, genders, sectors, disciplines and generations. The Ocean Decade Actions are the tangible initiatives carried out across the globe over the course of the Decade to achieve “the science we need for the ocean we want”. Hundreds of Actions are being implemented globally, with many more expected over the next five years, by research institutes, governments, UN entities, intergovernmental organizations, business and industry, philanthropic and corporate foundations, NGOs, ocean sports, educators, community groups, and more.

Actions contribute to fulfilling the 10 Ocean Decade Challenges, which articulate the most immediate priorities for the Ocean Decade:

1. Understand and beat marine pollution
2. Protect and restore ecosystems and biodiversity
3. Sustainably feed the global population
4. Develop a sustainable and equitable ocean economy
5. Unlock ocean-based solutions to climate change
6. Increase community resilience to ocean hazards
7. Expand the global ocean observing system
8. Create a digital representation of the ocean
9. Skills, knowledge and technology for all
10. Change humanity’s relationship with the ocean

IIOE-2 will embrace all of these challenges in 2026 – 2030, which coincides with the final five years of the Ocean Decade.

NEW IOC SUB-COMMISSION: IOCINDIO

The IOC Sub-Commission for the Central Indian Ocean (IOCINDIO) Regional Committee was established in 1982 by a resolution of the IOC Assembly. This resolution established it as a regional subsidiary body within the framework of the IOC of UNESCO. Its primary purpose was to facilitate collaboration among member states bordering the Central Indian Ocean on matters related to marine science and services. But the first official intergovernmental session for IOCINDIO was not held until 1988, six years after its establishment. Over the next two decades, IOCINDIO sessions were held sporadically, with a significant gap between 2005 and 2016. This indicates challenges with maintaining consistent engagement among member states. Since 2016, IOCINDIO appears to have seen a renewed focus on regional cooperation. Sessions have been held more regularly, suggesting increased engagement from member states.

In a significant development, the IOC Assembly voted in June 2023 to elevate IOCINDIO's status from an IOC Regional Committee into an IOC full-fledged Sub-Commission, a regional intergovernmental subsidiary body of the IOC. This signifies a recognition of the importance of regional cooperation in the Indian Ocean and empowers IOCINDIO with a broader mandate. The IOCINDIO Sub-Commission's primary mission is to promote regional and international cooperation in the Indian Ocean basin. This includes: facilitating the development and coordination of IOC programs related to marine science and

services; supporting ocean observation systems, data and information management, capacity development, and related activities specific to the Indian Ocean region; and taking into account the specific interests and priorities of member states bordering the Indian Ocean (e.g., sea level rise and ocean prediction).

The new Subcommission is expected to enhance the delivery and benefits of IOC programs for member states in the Indian Ocean and offer member states a broader scope for participation in international and regional activities related to ocean science and governance. It is expected that it will also strengthen regional collaboration on critical ocean issues like sea level rise, climate change adaptation, pollution management, and sustainable fisheries. All of these issues are central to IIOE-2.

The future of IOCINDIO as a Sub-Commission holds promise for enhanced regional collaboration and improved delivery of IOC programs related to ocean science in the Central Indian Ocean region, like IIOE-2. ***An important objective for IIOE-2 in 2026 – 2030 will be to fully integrate IOCINDIO into the IIOE-2 community. This represents a major opportunity to more fully engage IOCINDIO Member States which include: Australia, Bangladesh, France, India, Indonesia, Iraq, Iran, Kuwait, Malaysia, Maldives, Myanmar, Oman, Pakistan, Qatar, Saudi Arabia, Sri Lanka, Thailand, United Arab Emirates, United Kingdom.***

WCRP: MY CLIMATE RISK PROGRAM

In its final phase IIOE-2 will participate in the World Climate Research Program's (WCRP) "My Climate Risk Lighthouse Activity" which aims to develop and mainstream a 'bottom-up' approach to regional climate risk assessment, which starts with the requirements of decision-makers. In this effort, risk is defined as the combination of hazard, vulnerability, and exposure that is particular to a given regional context. By developing a new framework for assessing and explaining regional climate risk using all the available sources of climate information (observations, re-analyses, model simulations, better understanding, etc.), climate information will be made meaningful at the local scale. Whilst any application of the framework will inevitably be specific and tailored to local concerns, the framework itself will be generic, hence flexible and applicable across a number of region types (large scale, urban, typical SREX region, etc.) and intended to become much-needed support for the development of climate services. At the same time, the activity can identify needs to be addressed by the WCRP Core Projects and other Lighthouse Activities (e.g., implications of model biases). A canonical activity would be to discuss current risk in a given situation, with proximate explanations, and then develop storylines of future climate-related risk based on those explanations. In this way, the past can be related to the future within a risk framing.

My Climate Risk will primarily use a case-study approach, in the form of labs (communities of practice) that provide dynamic, exploratory, transdisciplinary environments. These communities of practice could take a variety of forms in the Indian Ocean under IIOE-2, depending on local needs and interests. The COLaB

research initiative, described above, provides an obvious avenue for engagement with and development of My Climate Risk Lighthouse Activities.

COASTPREDICT

As discussed above, through COLaB, IIOE-2 will engage with the Global Ocean Observing System's (GOOS) CoastPredict program. CoastPredict is a UN Decade endorsed program that aims to develop an integrated coastal and open ocean observing and modelling system and improved, multidisciplinary, and extended range predictive capability for the coastal zone. The specific objectives of CoastPredict are to establish:

1. A predicted Global Coastal Ocean.
2. A fit-for-purpose oceanographic information infrastructure benefiting stakeholders such as specialized users who interpret, share and sometimes sell information to end users such as businesses, government and individuals.
3. An integrated coastal ocean observing and forecasting system adhering to best practices and standards, designed as a global framework and implemented locally.
4. Open and free access to coastal information and the growth of ocean literacy.
5. Innovative and sustainable applications for coastal solutions/services.

The concept at the center of CoastPredict is consideration of all coastal ocean regions as an interface area. Atmosphere, land, ice, hydrology, coastal ecosystems, open ocean and humans interact on a multiplicity of space and time scales that need to be resolved with proper scientific methods and consideration of uncertainties. The answer is to have a unique framework that integrates observations and predictions from the short to the climate time scales. A coastal focus will engage island nations and indigenous or local people and inspire early career ocean professionals.

Through engagement with CoastPredict, IIOE-2 can make a real difference to the outcomes for vulnerable, currently underserved coastal communities in the Indian Ocean, and support sustainable marine activities and adaptation around climate change as well as early warnings and preparedness for extreme coastal events.

COMMUNICATION

Given the international nature of IIOE-2, communication is fundamental to its success, and this will continue to be an important component of the IPO's efforts in the final phase of IIOE-2. IIOE-2 communication has taken many forms, including the following:

- IIOE-2 Website (<https://iioe-2.incois.gov.in/>): The IIOE-2 IPO coordinates and publicizes the activities of the expedition and associated national and international programs through the IIOE-2 website, providing the latest news and information

on projects and progress, and a forum for communicating IIOE-2 science to the widest possible audience.

- Articles in international scientific magazines, newspapers and newsletters: these have included the *CLIVAR Bulletin* and American Geophysical Union's *Eos*. Regular updates and features on the IIOE-2 have also been published in the quarterly *Indian Ocean Bubble-2* and the monthly in the IIOE-2 newsletters, both of which are focused exclusively on the IIOE-2 and Indian Ocean research. Highlights of the COLaB & VOKCE field camp were also recently published in a WIOMSA Newsbrief. Publication of findings via these outlets will continue in the final phase of IIOE-2.
- IIOE-2 science meetings and special sessions: Numerous meetings and special sessions have been motivated by IIOE-2 investigators in association with, for example, IUGG, IAPSO, AGU, EGU, OCB and IMBER conferences and meetings, as well as separate/dedicated IIOE-2 annual joint meetings, and major IIOE-2 symposia every 5 years. These efforts will continue in the final phase of IIOE-2.
- Communication aimed beyond the scientific community: The results from IIOE-2 will continue to be published in scientific journals and reports. However, it is envisaged that, in its final phase (2026 – 2030) the IPO should endeavor to ensure that information related to the main results and activities of IIOE-2 are made accessible to a wider audience, including policy makers, managers and the public via, for example, engaging with knowledge brokers, social media platforms and through the development of short videos and other products that can be distributed to a wide audience via YouTube and related platforms that will include involving the IIOE-2 ECSN. Knowledge brokering is a major undertaking and has to be properly targeted to have any hope of getting science to policy uptake. An experienced knowledge broker will be engaged to look at the IIOE-2 portfolio of projects to see what can be done. Scientists from these Indian Ocean rim and island nations will also be encouraged to seek formal endorsement of their research projects which will increase the visibility of their work in IIOE-2.

The scientific outcomes of IIOE-2 have been successfully communicated at national and international meetings and published extensively in scientific journals, but their translation to public policy or societal relevance requires more attention. Efforts to improve this translation will be one of the major foci of the IPO in the final phase of IIOE-2. Along these lines, IOCINDIO can/should be utilized to communicate at the policy interface. Communicating the background and results of the many IIOE-2 studies also needs to be conducted using local languages through websites, articles, or newsletters, especially when communicating with audiences outside the scientific community, where language can be a barrier to understanding. The Marginal Sea Research Initiative will also engage new countries/member states that are active in IOCINDIO but not yet connected to IIOE-2 (Kuwait, Saudi Arabia, Qatar, Bangladesh, United Arab Emirates, Iran, Oman, etc.).

DATA AND INFORMATION MANAGEMENT

Basic scientific research requires sound data management practices and one of the overarching objectives of IIOE-2 is to support the collection and curation of all data to encourage data sharing using internationally agreed rules of data exchange, and to facilitate data discovery and use in the long term. Timely and unrestricted sharing of data and other research outcomes is critical for the success of ocean research programs that aspire to inform the decision-making process. Therefore, explicit and dedicated emphasis has been assigned to data and information management in IIOE-2 (see above WG-2) from the outset of the program.

Scientists participating in research activities, projects and programs endorsed by IIOE-2 (<https://iioe-2.incois.gov.in/IIOE-2/EndorsementForm.jsp>) are expected to comply with the IIOE-2 data policy. The IIOE-2 Data Policy is consistent with the IOC Oceanographic Data Exchange Policy (<https://www.iode.org/index.php?Itemid=100040>) and informed by data sharing policies of similar, contemporary global research programs. However, exceptions are allowed in cases where this policy is in conflict with a Member State's national data access policies. It is acknowledged that Member State policies take precedence over the IIOE-2 data policy. ***The reality is that many Indian Ocean rim nations have national policies that prohibit sharing of data from their Exclusive Economic Zones (EEZs). In such cases, the IIOE-2 will focus on promoting the sharing of metadata with the IIOE-2 International Project Office. At the very least, in its final phase IIOE-2 Working Group 2 will determine where the data from its sponsored projects has been stored and make this information available via the IIOE-2 website. Working Group 1 will be engaged to assist in these efforts, as well as the Science Theme chairs who are in regular contact with endorsed project leaders, and they will specifically follow up projects for which no metadata exists in the IIOE-2 system. This approach will enable the discovery of data being collected within the EEZs of these nations and facilitate access by directing interested parties to the principal investigators and/or government agencies responsible for the data collection and long-term storage.***

The intent of the IIOE-2 data policy is to promote practices that support the FAIR data principles (<https://www.force11.org/group/fairgroup/fairprinciples> and <https://www.gofair.org/>) that research data be Findable, Accessible, Interoperable and Reproducible (FAIR). That objective is compatible with common practices of collaborative, scientific research programs wherein researchers require access to a broad range of transdisciplinary research outcomes to achieve the scientific outcomes of the research plan. ***IIOE-2 strives to be inclusive of all national programs and therefore the data policy is intended to encourage open data sharing in an effort to facilitate the scientific goals of IIOE-2, while respecting national data and information exchange policies. The IIOE-2 Data Policy is written to support scholarly exchange, but not be a deterrent to participation.***

TRAINING AND EDUCATION

IIOE-2 continues to promote engagement across Indian Ocean scientists and associated institutions from developed and developing countries that are planning to undertake science activities in the region. This includes capacity-building components that will accomplish the collaborative use of expertise and physical resources from within and outside the Indian Ocean region, such as training, joint research and analysis, and other activities. This motivation has been embraced by scientists both within the region and internationally. In the final phase of IIOE-2, the project will continue to implement its approach, which includes logistical operations, data acquisition, management and processing, and applying scientific results for societal benefit. Training and education efforts in IIOE-2 are also designed to leverage existing international programs:

IOC OCEANTEACHER AND INCOIS ITCOOcean

The IOC's International Oceanographic Data and Information Exchange (IODE) provides one convenient and logical institutional and programmatic framework to organize and implement IOC's capacity building activities under IIOE-2. IODE has significant experience in training, in-country, at IODE headquarters, and through distance learning techniques such as OceanTeacher (see <http://classroom.oceanteacher.org/>) and infoHUB (<https://fust.iode.org/en/oih>). Efforts to leverage IOC training and education programs will be an important focus of IIOE-2 in its final phase.

For example, ESSO-INCOIS (Earth System Science Organization-Indian National Centre for Ocean Information Services), Ministry of Earth Sciences, signed a Memorandum of Agreement with IOC in Paris on 4th July, 2013 to conduct training programs at the International Centre for Operational Oceanography (ITCOOcean) established at ESSO-INCOIS, Hyderabad, India. ITCOOcean is aimed at promoting the development and optimization of a scientific base, technology and information system for operational oceanography at national, regional and global scales. ***The trained manpower that is being generated through ITCOOcean will continue to help translate the results and findings from IIOE-2 to real-time use by end users such as fishermen, shipping industries, ports and harbors, oil and natural gas industries, disaster management agencies etc.***

SCIENTIFIC COMMITTEE ON OCEANIC RESEARCH (SCOR)

SCOR has included a capacity building mission since its inception in 1957, including as part of the original IIOE. SCOR's current activities in capacity building focus on travel support to scientific meetings, training in oceanographic observations (with the Partnership for Observation of the Global Oceans, POGO, see next section), and SCOR Visiting Scholars. SCOR-sponsored research projects—the Integrated Marine Biosphere Research (IMBeR) project, the Surface Ocean – Lower Atmosphere Study (SOLAS), and GEOTRACES—each has its own capacity building experience and approaches that can be leveraged by IIOE-2. ***In particular, SOLAS and IMBeR have significant experience in conducting summer schools, which are an important approach for capacity***

building related to IIOE-2. SCOR has sent several Visiting Scholars to the Indian Ocean region including Bangladesh, India, and South Africa. IIOE-2 will continue to support and engage with these SCOR-motivated capacity building efforts in its final phase.

PARTNERSHIP FOR OBSERVATION OF THE GLOBAL OCEANS (POGO)

POGO is a non-governmental consortium of oceanographic institutes. POGO uses several different capacity building approaches, including fellowships for ocean observations (with SCOR), Visiting Professorships, and a Centre of Excellence in Operational Oceanography. ***In its final phase, IIOE-2 will endeavor to facilitate and participate in POGO capacity building efforts in the Indian Ocean.***

The IPO will be tasked to carry out an assessment of IIOE-2 training and education efforts as soon as possible so that a plan to build capacity in the Indian Ocean region is realized in its final phase (see also Appendix III on Detailed Targets and Key Performance Indicators). Toward this end, a specific workshop on training will be organized where the national delegates will be asked to itemize the capacity building efforts in each country bordering the Indian Ocean.

Finally, the study of ocean acidification in the region still requires the development of accurate and comparable pH measurement techniques. Capacity-building and training in this area will be prioritized through enhanced interactions with GOA-ON (see: <https://portal.goa-on.org>). Iran's Category 2 Training Center, will also be leveraged via IOCINDO and the Marginal Seas Research Initiative to enhance capacity-building and training (along with ITCOcean in Hyderabad). In addition to enhancing the capacity and capabilities of scientists and laboratories, intercalibration between laboratories will be encouraged. Training for trainers is another activity that will be prioritized. ***These will all be explicit priorities in the final phase of IIOE-2 and will be achieved by leveraging the existing international training and education programs reviewed above, and also via the new COLaB initiative. Additionally, IIOE-2 will promote partnerships between local universities in Indian Ocean coastal rim nations and universities in developed countries to organize educational programs aimed at producing graduates in ocean science. These efforts will be undertaken in addition to those articulated in the section above on Community Engagement.***

CONCLUSIONS AND LEGACY

Population increase in Indian Ocean rim countries has contributed to multiple stressors on both coastal and open ocean environments, including eutrophication, depletion of fresh groundwater, deoxygenation, atmospheric and plastic pollution, and overfishing. These regional stressors, combined with warming and acidification due to global climate change, are resulting in loss of biodiversity in the Indian Ocean, as well as changes in the phenology and biogeography of many species. ***The main focus of the research that***

will be carried in the final phase of IIOE-2 will be aimed at better understanding the impacts of multiple stressors on coastal environments and efforts will be motivated to communicate these findings to decision makers.

In addition, the impacts of climate change on ocean circulation, sea level rise, extreme events, and monsoon variability are a growing concern. The high exposure and vulnerability of many developing nations to these threats suggest that negative human consequences from extreme events and changes in monsoon forcing will dramatically increase for nations in and around the Indian Ocean in the coming decades. ***Research carried out in the final phase of IIOE-2 will improve our ability to predict extreme events and monsoon variability and it will also facilitate the development of national strategies to mitigate their impacts on human populations.***

There are also concerns about food security and fisheries and direct anthropogenic impacts on the coastal environments of the Indian Ocean. The declining state of both artisanal and industrial fisheries is of particular concern for Indian Ocean rim nations. ***In its final phase, the IIOE-2 will focus on motivating studies that are aimed at improving our understanding of higher trophic level species and the impacts of fishing pressure and habitat destruction on these species. The IIOE-2 will also motivate studies of direct anthropogenic impacts on coastal environments, including coastal erosion, loss of mangroves, and degradation of coral reefs and how these, in turn, might impact food security and fisheries. The IIOE-2 will work to raise awareness of the pressing need for ecosystem preservation in the Indian Ocean in order to safeguard both tourism and fisheries.***

The success of IIOE-2 will be gauged not just by how much it advances our understanding of the complex and dynamic Indian Ocean system, but also by how it contributes to the sustainable development of marine resources, environmental stewardship, ocean and climate forecasting, and training of the next generation of ocean scientists from the region. This vision of success can be fully realized in the final phase of IIOE-2.

APPENDICES

APPENDIX I. ACRONYMS

SCIENTIFIC ACRONYMS

AVHRR	Advanced Very High Resolution Radiometer
CTD	Conductivity/Temperature/Depth
EEZ	Exclusive Economic Zone
MERIS	Medium Resolution Imaging Spectrometer
MJO	Madden-Julian Oscillation
MODIS-Terra MODIS-Aqua	Moderate Resolution Imaging Spectroradiometer (Terra – AM Equatorial Crossing; Aqua – PM Equatorial Crossing)
SCTR	Seychelles-Chagos Thermocline Ridge
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SSH	Sea Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
uCTD	Underway CTD

PROJECT, PROGRAM AND ORGANIZATIONAL ACRONYMS

BLUELink	Australian oceanic forecasting model
CLIVAR	Climate Variability and Predictability (WCRP)
CSIR	Council for Scientific and Industrial Research (India)
CSIRO	Commonwealth Scientific and Research Organization (Australia)
GEOTRACES	A collaborative multi-national program to investigate the global marine biogeochemical cycles of trace elements and their isotopes (SCOR)
IMBeR	Integrated Marine Biosphere Research (SCOR, Future Earth)
IMOS	Integrated Marine Observing System (Australia)
IndOOS	Indian Ocean Observing System
IOCINDIO	The Sub-Commission of the IOC for the Indian Ocean
IODE	The IOC's International Oceanographic Data and Information Exchange
IOGOOS	Indian Ocean Global Ocean Observing System
NASA	National Aeronautics and Space Administration (USA)
NIO	National Institute of Oceanography (India)
NOAA	National Oceanic and Atmospheric Administration (USA)
RAMA	Research moored Array for African-Asian-Australian Monsoon Analysis and Prediction
SCOR	Scientific Committee on Oceanic Research
SIBER	Sustained Indian Ocean Biogeochemical and Ecosystem Research (IMBER)
SOLAS	Surface Ocean-Lower Atmosphere Study (SCOR, IGBP, WCRP, iCACGP)

WCRP	World Climate Research Programme
WIOMSA	Western Indian Ocean Marine Science Association

APPENDIX II. IIOE-2-RELATED PUBLICATIONS AND WEBSITES

PUBLICATIONS AND ARTICLES (ORDERED BY DATE OF PUBLICATION)

- Hood, R. R., M. J. McPhaden and E. Urban (2014) New Indian Ocean program builds on a scientific legacy. *Eos*, 95(39): 349-360.
- Hood, R. R., M. J. McPhaden, N. D'Adamo and E. Urban (2015) SCOR and IOC motivate a second International Indian Ocean Expedition. *Indian Ocean Bubble-2*, Issue no. 2, January 2015. Available at:
<http://www.incois.gov.in/portal/iioe/bubble.jsp>
- Meyers, G. (2015) The Indian Ocean Observing System and Ocean-reanalysis in IIOE2. *Indian Ocean Bubble-2*, Issue no. 2, January 2015. Available at:
<http://www.incois.gov.in/portal/iioe/bubble.jsp>
- Hood, R. R., H. W. Bange, L. Beal, L. E. Beckley, P. Burkill, G. L. Cowie, N. D'Adamo, G. Ganssen, H. Hendon, J. Hermes, M. Honda, M. McPhaden, M. Roberts, S. Singh, E. Urban and W. Yu (2015) The Second International Indian Ocean Expedition (IIOE-2): A Basin-Wide Research Plan. Scientific Committee on Oceanic Research, Newark, Delaware, USA.
- Hood, R. R., E. R. Urban, M. J. McPhaden, D. Su, and E. Raes (2016) The 2nd International Indian Ocean Expedition (IIOE-2): Motivating new exploration in a poorly understood basin. *ASLO Bulletin*, 25(4): 117-124.
- Hood, R. R., L. Beal, H. Benway, C. Chandler, V. Coles, G. Cutter, H. Dick, A. Gangopadhyay, J. Goes, S. Humphris, M. Landry, K. Lloyd, M. McPhaden, R. Murtugudde, B. Subrahmanyam, D. Susanto, L. Talley, E. Urban, J. D. Wiggert, C. Zhang (2018) United States Contributions to the Second International Indian Ocean Expedition (US IIOE-2), 2018-08-02, DOI:10.1575/1912/10510, <https://hdl.handle.net/1912/10510>, 65 pp.
- Hood, R. R. (2018) *R. V. Ron Brown* Completes GO-SHIP IO7N repeat line in the Indian Ocean. *IIOE-2 Newsletter*, Vol. 2, Issue 6.
- Hood, R. R., H. Bange, N. D'Adamo, and E. Urban (2018) IIOE-2 Working Group-1 Science and Research Meeting, Kiel, 28-30 November, 2018. *IIOE-2 Newsletter*, Vol. 2, Issue 12.

- Hood, R. R. (2018) A new partnership between Korea and the United States under IIOE-2. *IIOE-2 Newsletter*, Vol. 2, Issue 10.
- Burkill, P., S. Shenoi, V. Ryabinin, H. W. Bange, R. Hood, S. Nayak, N. D'Adamo, S. Prakash, and E. Urban (2019) Proposed new structure for delivering IIOE-2. *IIOE-2 Newsletter*, Vol. 3, Issue 2.
- Hood, R. R., H. Bange, N. D'Adamo, and E. Urban (2019) IIOE-2 Working Group-1 Science and Research Meeting, Kiel, 28-30 November, 2018. *The Indian Ocean Bubble-2*, Issue 10.
- Hood, R. R., L. E. Beckley, S. K. Singh, J. Vialard, and J. D. Wiggert (2019) The 2nd International Indian Ocean Expedition (IIOE-2): Motivating New Exploration in a Poorly Understood Ocean Basin (Volume 1). *Deep-Sea Research II*, 161: 1 – 105.
- Hood, R. R., L. E. Beckley, S. K. Singh, J. Vialard, and J. D. Wiggert (2019) The 2nd International Indian Ocean Expedition (IIOE-2): Motivating New Exploration in a Poorly Understood Ocean Basin (Volume 2). *Deep-Sea Research II*, 166: 1 – 171.
- Beal, L. M., J. Vialard, M. K. Roxy, J. Li, M. Andres, H. Annamalai, M. Feng, W. Han, R. Hood, et al. (2020) A roadmap to IndOOS-2: Better observations of the rapidly-warming Indian Ocean. *Bulletin of the American Meteorological Society*, 101(11), DOI: 10.1175/BAMS-D-19-0209.1.
- Hood, R. R., Beckley, L. E., Vialard, J., and Gaye, B., 2020, The 2nd International Indian Ocean Expedition (IIOE-2): Motivating New Exploration in a Poorly Understood Ocean Basin (Volume 3): Deep-Sea Research, part II, v. 179: DOI: 10.1016/j.dsr2.2020.104876.
- Hood, R. R., Beckley, L. E., Vialard, J., and Gaye, B., 2022, The 2nd International Indian Ocean Expedition (IIOE-2): New Exploration in a Poorly Understood Ocean Basin (Volume 4): Deep-Sea Research, part II, v. 197: DOI: 10.1016/j.dsr2.2022.105047.
- Hood, R. R., Beckley, L. E., Sarma, V. V. S. S., and Vinayachandran, P. N., 2024, The 2nd International Indian Ocean Expedition (IIOE-2): New Exploration in a Poorly Understood Ocean Basin (Volume 6): Deep-Sea Research, part II, Virtual Special Issue Editorial, v. 218: DOI: 10.1016/j.dsr2.2024.105427.
- Beckley, L. E., Hood, R. R., and Thompson, P., 2022, Revisiting 110°E in the Second International Indian Ocean Expedition (volume 5): Deep-Sea Research, part II, v. 206: 105205.

INCOIS (2024a) The Indian Ocean Bubble 2. Issue Nos. 1 – 18, Available at: <https://iioe-2.incois.gov.in/IIOE-2/Bubble.jsp>

INCOIS (2024b) IIOE-2 Newsletter. Volumes 1 – 8, Available at: https://iioe-2.incois.gov.in/IIOE-2/Publications.jsp?mode_pub_id=NL

WEBSITES

SCOR IIOE-1

http://www.scor-int.org/IIOE/IIOE_History.htm

SECOND INTERNATIONAL INDIAN OCEAN EXPEDITION (IIOE-2)

<https://iioe-2.incois.gov.in/IIOE-2/index.jsp>

INDIAN NATIONAL CENTER FOR INFORMATION SERVICES

<https://incois.gov.in>

US IIOE-2

<https://web.who.edu/iioe2/>

APPENDIX III. DETAILED TARGETS AND KEY PERFORMANCE INDICATORS

The IIOE-2 Working Group 1 will be tasked to formulate a set of quantifiable measures that demonstrate how effectively IIOE-2 is achieving its strategic goals and objectives. Toward this end, WG1 should lead a workshop that includes all six Science Theme leaders and also endorsed project leaders to determine IIOE-2 objectives and strategic goals and define Key Performance Indicators (KPIs). These KPIs will be used to help track progress in the final phase of IIOE-2 and also make data-driven decisions. All of these directives, including the one articulated above related to doing an assessment of IIOE-2 training and education, will be discussed with at the 2026 IIOSC joint meeting to initiate these KPI efforts. WG1 will be asked to adhere to the following key aspects of KPIs:

- They should be measurable, allowing for objective assessment of IIOE-2 performance;
- They should be tied to the specific objectives detailed in the IIOE-2 Science Plan (Hood et al., 2015) and this Addendum (Hood et al., 2025), and help determine if those objectives are being met;
- They should provide insights that can be used to improve performance and make better decisions;
- They should be aligned with the overall strategic goals of IIOE-2 as describe in the IIOE-2 Science Plan;
- They should be applied to different levels of the organization following the organizational structure of IIOE-2 as detailed in the revised IIOE-2 Implementation Strategy (D'Adamo et al., 2025).

REFERENCES

- Ahusan, M., Rico-Seijo, N., Amjad, F., and Stefanoudis, P., 2023, The Nekton Maldives taxonomic workshop: Exploring the biodiversity of shallow, mesophotic and deep-sea communities in Maldives: Research Ideas and Outcomes, v. 9.
- Al-Yamani, F. Y., Burt, J. A., Goes, J. I., Jones, B., Nagappa, R., Murty, V., Polikarpov, I., Saburova, M., Alsaafani, M., and Kalampokis, A., 2024, Physical and biogeochemical characteristics of the Indian Ocean marginal seas, *The Indian Ocean and its Role in the Global Climate System*, Elsevier, p. 365-391.
- Beal, L., Vialard, J., Roxy, M. K., Li, J., Andres, M., Annamalai, H., Feng, M., Han, W., Hood, R., and Lee, T., 2020, A road map to IndOOS-2: Better observations of the rapidly warming Indian Ocean: *Bulletin of the American Meteorological Society*, v. 101, no. 11, p. E1891-E1913.
- Beckley, L. E., Hood, R. R., and Thompson, P., 2022, Revisiting 110°E in the Second International Indian Ocean Expedition (volume 5): *Deep-Sea Research*, part II, v. 206: 105205.
- Chowdhury, S., Raes, E., Hörstmann, C., Ahmed, A., Ridame, C., Metzl, N., Bhavya, P., Sato, T., Shiozaki, T., and Bonnet, S., 2023, Diazotrophy in the Indian Ocean: Current understanding and future perspectives: *Limnology and Oceanography Letters*, v. 8, no. 5, p. 707-722.
- Commission, I.-U. E., 2022, Updated Joint Roadmap to Accelerate Marine/Maritime Spatial Planning Processes Worldwide–MSProadmap (2022–2027), Paris, UNESCO.(IOC Technical Series, 182) [https://unesdoc.unesco.org/ark](https://unesdoc.unesco.org/ark....)
- Convention, U.-N., 2025, Towards integrated ocean governance in the Western Indian Ocean: A shared vision and roadmap for the implementation of marine spatial

- planning in the Northern Mozambique Channel region.: WWF and Nelson Mandela University.
- D'Adamo, N., 2014, International Indian Ocean Expedition 50th Anniversary Initiative (IIOE-2): Report of the Western Indian Ocean Regional Focus Group Meeting to Help Plan the International Indian Ocean Expedition 50th Anniversary Initiative (IIOE-2), Quatre Bornes, Mauritius, 6 and 7 March, 2014.
- D'Adamo, N., Lotlicker, A., Kumar, K., and Kumar, N., 2025, Revised Implementation Strategy for the Second International Indian Ocean Expedition 2015-30: IIOE-2 Project Office, Indian National Centre for Ocean Information Services (INCOIS), Ministry of Earth Sciences, Hyderabad, India. <https://iioe-2.incois.gov.in/>.
- Ehler, C., and Douvère, F., 2009, Marine Spatial Planning: a step-by-step approach toward ecosystem-based management. Intergovernmental Oceanographic Commission and Man and the Biosphere Programme.
- Ehler, C. N., 2018, Marine spatial planning: an idea whose time has come, *Offshore energy and marine spatial planning*, Routledge, p. 6-17.
- Eriksen, M., Lebreton, L. C., Carson, H. S., Thiel, M., Moore, C. J., Borerro, J. C., Galgani, F., Ryan, P. G., and Reisser, J., 2014, Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea: *PloS one*, v. 9, no. 12, p. e111913.
- Fassbender, N., Stefanoudis, P. V., Filander, Z. N., Gendron, G., Mah, C. L., Mattio, L., Mortimer, J. A., Moura, C. J., Samaai, T., and Samimi-Namin, K., 2021, Reef benthos of Seychelles-A field guide: *Biodiversity Data Journal*, v. 9.
- Frazão Santos, C., Agardy, T., Andrade, F., Calado, H., Crowder, L. B., Ehler, C. N., García-Morales, S., Gissi, E., Halpern, B. S., and Orbach, M. K., 2020, Integrating climate change in ocean planning: *Nature Sustainability*, v. 3, no. 7, p. 505-516.
- Frazão Santos, C., Agardy, T., Crowder, L. B., Day, J. C., Pinsky, M. L., Himes-Cornell, A., Reimer, J. M., García-Morales, S., Bennett, N. J., and Lombard, A. T., 2024, Key components of sustainable climate-smart ocean planning: *npj Ocean Sustainability*, v. 3, no. 1, p. 10.
- Gates, A., Durden, J., Richmond, M., Muhando, C., Khamis, Z., and Jones, D., 2021, Ecological considerations for marine spatial management in deep-water Tanzania: *Ocean & Coastal Management*, v. 210, p. 105703.
- Hood, R. R., Al-Yamani, F., Beckley, L. E., Cowie, G. L., D'Adamo, N., Hermes, J., Kobryn, H. T., Kumar, K., Lotiker, A., Roxy, M. K., Modi, A., Rama Rao, P., Sicre, M.-A., and Vinayachandran, P. N., 2025, Science Plan Addendum of the Second International Indian Ocean Expedition (IIOE-2): A Basin-Wide Research Program: Scientific Committee on Oceanic Research.
- Hood, R. R., Bange, H. W., Beal, L., Beckley, L. E., Burkill, P., Cowie, G. L., D'Adamo, N., Ganssen, G., Hendon, H., Hermes, J., Honda, M., McPhaden, M., Roberts, M., Singh, S., Urban, E., and Yu, W., 2015, Science Plan of the Second International Indian Ocean Expedition (IIOE-2): A Basin-Wide Research Program: Scientific Committee on Oceanic Research.
- Hood, R. R., Beckley, L. E., Sarma, V. V. S. S., and Vinayachandran, P. N., 2024, The 2nd International Indian Ocean Expedition (IIOE-2): New Exploration in a Poorly

- Understood Ocean Basin (Volume 6): Deep-Sea Research, part II, Virtual Special Issue Editorial, v. 218: DOI: 10.1016/j.dsr2.2024.105427.
- Hood, R. R., Beckley, L. E., Singh, S. K., Vialard, J., and Wiggert, J., 2019a, The 2nd International Indian Ocean Expedition (IIOE-2): Motivating New Exploration in a Poorly Understood Ocean Basin (Volume 1): Deep-Sea Research II, v. 161, p. 1 - 105.
- Hood, R. R., Beckley, L. E., and Vialard, J., 2019b, The second International Indian Ocean Expedition (IIOE-2): Motivating new exploration in a poorly understood ocean basin (volume 2): Deep Sea Research Part II: Topical Studies in Oceanography, v. 166, p. 3-5.
- Hood, R. R., Beckley, L. E., Vialard, J., and Gaye, B., 2020, The 2nd International Indian Ocean Expedition (IIOE-2): Motivating New Exploration in a Poorly Understood Ocean Basin (Volume 3): Deep-Sea Research, part II, v. 179: DOI: 10.1016/j.dsr2.2020.104876.
- Hood, R. R., Beckley, L. E., Vialard, J., and Gaye, B., 2022, The 2nd International Indian Ocean Expedition (IIOE-2): New Exploration in a Poorly Understood Ocean Basin (Volume 4): Deep-Sea Research, part II, v. 197: DOI: 10.1016/j.dsr2.2022.105047.
- Hood, R. R., and D'Adamo, N., 2012, The 50th Anniversary of the International Indian Ocean Expedition: A Prospectus and Charge for an Organizing Committee.
- Hood, R. R., and D'Adamo, N., 2013, International Indian Ocean Expedition 50th Anniversary Initiative (IIOE-2): Report from the IIOE-2 Reference Group Meeting No. 1, Hyderabad, India, 14 - 14 May, 2013.
- Hood, R. R., and D'Adamo, N., 2014, International Indian Ocean Expedition 50th Anniversary Initiative (IIOE-2): Meeting Notes from the IIOE-2 Reference Group Meeting NO. 2, Qingdao, China, 20 - 21 November, 2013.
- Hood, R. R., Naqvi, S. W. A., Wiggert, J. D., Landry, M. R., Rixen, T., Beckley, L. E., Goyet, C., Cowie, G. L., and Maddison, L. M., 2011, SIBER Science Plan and Implementation Strategy, 111 p.:
- IPC, 2015, Implementation Strategy for the Second International Indian Ocean Expedition.
- Jebri, F., Raitsos, D. E., Gittings, J. A., Jacobs, Z. L., Srokosz, M., Gornall, J., Sauer, W. H., Roberts, M. J., and Popova, E., 2022, Unravelling links between squid catch variations and biophysical mechanisms in South African waters: Deep Sea Research Part II: Topical Studies in Oceanography, v. 196, p. 105028.
- Krug, M., Naidoo, A., and Williams, L., 2024, South Africa's oceans and coastal and information management system towards improved ocean access, protection, and governance: Journal of Environmental Management, v. 354, p. 120255.
- Lombard, A., Clifford-Holmes, J., Snow, B., Goodall, V., Smit, K. P., Strand, M., Truter, H., and Horigue, V., 2022, A regional marine spatial planning strategy for the Western Indian Ocean: WIO Science to Policy Series, v. 1, no. 1, p. 139-144.
- Löscher, C. R., 2021, Reviews and syntheses: Trends in primary production in the Bay of Bengal—is it at a tipping point?: Biogeosciences, v. 18, no. 17, p. 4953-4963.
- McPhaden, M. J., Kang, H. W., Anderson, R., Hood, R., Choi, S. H., Jang, C. J., Kang, D. J., Lee, Y. H., Nam, S., Rho, T., Send, U., Wiggert, J., and Yi, U., 2018, A Korea-US inDian Ocean Scientific (KUDOS) Research Program on the Physical,

- Biogeochemical and Ecological Dynamics of the Seychelles-Chagos Thermocline Ridge: Report from a workshop held at Seoul National University over 29 November to 1 December 2017, 26 pp., p. Available at: <https://kiost-noaa-lab.wixsite.com/kudos2018/logistic-information>.
- Mutia, D., Carpenter, S., Jacobs, Z., Jebri, F., Kamau, J., Kelly, S. J., Kimeli, A., Langat, P. K., Makori, A., and Nencioli, F., 2021, Productivity driven by Tana river discharge is spatially limited in Kenyan coastal waters: *Ocean & Coastal Management*, v. 211, p. 105713.
- Nimit, K., 2021, Ideas and perspectives: Ushering the Indian Ocean into the UN Decade of Ocean Science for Sustainable Development (UNDOSD) through marine ecosystem research and operational services—an early career's take: *Biogeosciences*, v. 18, no. 12, p. 3631-3635.
- Pattiaratchi, C., van der Mheen, M., Schlundt, C., Narayanaswamy, B. E., Sura, A., Hajbane, S., White, R., Kumar, N., Fernandes, M., and Wijeratne, S., 2022, Plastics in the Indian Ocean—sources, transport, distribution, and impacts: *Ocean science*, v. 18, no. 1, p. 1-28.
- Phillips, H. E., Tandon, A., Furue, R., Hood, R., Ummenhofer, C. C., Benthuyssen, J. A., Menezes, V., Hu, S., Webber, B., and Sanchez-Franks, A., 2021, Progress in understanding of Indian Ocean circulation, variability, air–sea exchange, and impacts on biogeochemistry: *Ocean Science*, v. 17, no. 6, p. 1677-1751.
- Pinheiro, H. T., MacDonald, C., Santos, R. G., Ali, R., Bobat, A., Cresswell, B. J., Francini-Filho, R., Freitas, R., Galbraith, G. F., and Musembi, P., 2023a, Plastic pollution on the world's coral reefs: *Nature*, v. 619, no. 7969, p. 311-316.
- Pinheiro, M., Martins, I., Raimundo, J., Caetano, M., Neuparth, T., and Santos, M. M., 2023b, Stressors of emerging concern in deep-sea environments: microplastics, pharmaceuticals, personal care products and deep-sea mining: *Science of The Total Environment*, v. 876, p. 162557.
- Rochford, D., 1969, Seasonal variations in the Indian Ocean along 110°E: Hydrological structure of the upper 500 m: *Marine and Freshwater Research*, v. 20, no. 1, p. 1-50.
- Saxena, H., Sahoo, D., Nazirahmed, S., Chaudhari, D., Rahi, P., Kumar, S., Benavides, M., Krishna, A. V., Sudheer, A., and Singh, A., 2023, The Bay of Bengal: An enigmatic diazotrophic niche: *Journal of Geophysical Research: Biogeosciences*, v. 128, no. 9, p. e2023JG007687.
- Sekadende, B., Scott, L., Anderson, J., Aswani, S., Francis, J., Jacobs, Z., Jebri, F., Jiddawi, N., Kamukuru, A. T., and Kelly, S., 2020, The small pelagic fishery of the Pemba Channel, Tanzania: What we know and what we need to know for management under climate change: *Ocean & Coastal Management*, v. 197, p. 105322.
- Smedstad, O. M., Hurlburt, H. E., Metzger, E. J., Rhodes, R. C., Shriver, J. F., Wallcraft, A. J., and Kara, A. B., 2003, An operational eddy resolving 1/16° global ocean nowcast/forecast system: *Journal of Marine Systems*, v. 40-41, p. 341-361.
- Sprintall, J., Nagura, M., Hermes, J., Roxy, M., McPhaden, M. J., Rama Rao, E. P., Tummala, S. K., Thurston, S., Li, J., and Belbeoch, M., 2024, COVID Impacts Cause Critical Gaps in the Indian Ocean Observing System: *Bulletin of the American Meteorological Society*, v. 105, no. 3, p. E725-E741.

- Stefanoudis, P. V., Fassbender, N., Samimi-Namin, K., Adam, P.-A., Ebrahim, A., Harlay, J., Koester, A., Samoilys, M., Sims, H., and Swanborn, D., 2023a, Trait-based approaches reveal that deep reef ecosystems in the Western Indian Ocean are functionally distinct: *Science of the Total Environment*, v. 872, p. 162111.
- Stefanoudis, P. V., Talma, S., Fassbender, N., Swanborn, D., Ochieng, C. N., Mearns, K., Komakoma, J. D., Otwoma, L. M., Mbije, N. E., and Osuka, K. E., 2023b, Stakeholder-derived recommendations and actions to support deep-reef conservation in the Western Indian Ocean: *Conservation Letters*, v. 16, no. 1, p. e12924.
- Stefanoudis, P. V., Talma, S., Samimi-Namin, K., and Woodall, L. C., 2020, Deep reef ecosystems of the Western Indian Ocean: addressing the great unknown: *Research Ideas and Outcomes*, v. 6.
- Strutton, P. G., Coles, V. J., Hood, R. R., Matear, R. J., McPhaden, M. J., and Phillips, H. E., 2015, Biogeochemical variability in the central equatorial Indian Ocean during the monsoon transition: *Biogeosciences*, v. 12, no. 8, p. 2367-2382.
- Swanborn, D., Fassbender, N., Huvenne, V., Pittman, S., Stefanoudis, P., and Woodall, L., 2022a, Geomorphological drivers of deeper reef habitats around Seychelles: *Coral Reefs*, v. 41, no. 4, p. 1001-1016.
- Swanborn, D., Huvenne, V., Malpas, T., Pittman, S., Rogers, A., Taylor, M., and Woodall, L., 2023a, Seamount seascape composition and configuration shape Southwest Indian Ridge fish assemblages: *Deep Sea Research Part I: Oceanographic Research Papers*, v. 191, p. 103921.
- Swanborn, D. J., Huvenne, V. A., Pittman, S. J., Rogers, A. D., Taylor, M. L., and Woodall, L. C., 2023b, Mapping, quantifying and comparing seascape heterogeneity of Southwest Indian Ridge seamounts: *Landscape Ecology*, v. 38, no. 1, p. 185-203.
- Swanborn, D. J., Stefanoudis, P. V., Huvenne, V. A., Pittman, S. J., and Woodall, L. C., 2022b, Structure-from-motion photogrammetry demonstrates that fine-scale seascape heterogeneity is essential in shaping mesophotic fish assemblages: *Remote Sensing in Ecology and Conservation*, v. 8, no. 6, p. 904-920.
- Talma, S., and Woodall, L. C., 2022, Co-producing deep sea science for a more equitable and inclusive future: *Panorama - Solutions for a healthy planet: IUCN*.
- Tegtmeier, S., Marandino, C., Jia, Y., Quack, B., and Mahajan, A. S., 2022, Atmospheric gas-phase composition over the Indian Ocean: *Atmospheric Chemistry and Physics*, v. 22, no. 10, p. 6625-6676.
- Tranter, D. J., and Kerr, J. D., 1977, Further studies of plankton ecosystems in the eastern Indian Ocean. III. Numerical abundance and biomass: *Australian Journal of Marine and Freshwater Research*, v. 28, p. 557-583.
- Turner, J. A., Andradi-Brown, D. A., Gori, A., Bongaerts, P., Burdett, H. L., Ferrier-Pagès, C., Voolstra, C. R., Weinstein, D. K., Bridge, T. C., and Costantini, F., 2019, Key questions for research and conservation of mesophotic coral ecosystems and temperate mesophotic ecosystems: *Mesophotic coral ecosystems*, p. 989-1003.
- Ummenhofer, C. C., and Hood, R. R., 2024, *The Indian Ocean and Its Role in the Global Climate System*, Elsevier.
- Vialard, J., Duvel, J. P., McPhaden, M., Bouruet-Aubertot, P., Ward, B., Key, E., Bourras, D., Weller, R., Minnett, P., Weill, A., Cassou, C., Eymard, L., Fristedt, T.,

- Basdevant, C., Dandoneau, Y., Duteil, O., Izumo, T., Montégut, C. d. B., Masson, S., Marsac, F., Menkes, C., and Kennan, S., 2009, Cirene: Air-sea interactions in the Seychelles-Chagos thermocline ridge region: *Bulletin of the American Meteorological Society*, v. 90, no. 1, p. 45-61.
- Vinayachandran, P., Matthews, A. J., Kumar, K. V., Sanchez-Franks, A., Thushara, V., George, J., and Vijith, V., 2018, BoBBLE (Bay of Bengal Boundary Layer Experiment): Ocean–atmosphere.
- Vinayachandran, P. N. M., Masumoto, Y., Roberts, M. J., Huggett, J. A., Halo, I., Chatterjee, A., Amol, P., Gupta, G. V., Singh, A., and Mukherjee, A., 2021, Reviews and syntheses: Physical and biogeochemical processes associated with upwelling in the Indian Ocean: *Biogeosciences*, v. 18, no. 22, p. 5967-6029.
- Wilson, R. J., Sailley, S. F., Jacobs, Z. L., Kamau, J., Mgeleka, S., Okemwa, G. M., Omukoto, J. O., Osuka, K. E., Samoilys, M., and Sauer, W., 2021, Large projected reductions in marine fish biomass for Kenya and Tanzania in the absence of climate mitigation: *Ocean & coastal management*, v. 215, p. 105921.
- Woodall, L. C., and Talma, S., 2022, Working towards a better understanding of Western Indian Ocean deep sea ecosystems: UNEP / Nairobi Convention.
- Yu, S., Bai, Y., He, X., Gong, F., and Li, T., 2023, A new merged dataset of global ocean chlorophyll-a concentration for better trend detection: *Frontiers in Marine Science*, v. 10, p. 1051619.

