Executive Summary

IndOOS-2
A roadmap to sustained observations of the Indian Ocean for 2020-2030

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Sponsored by

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Executive Summary

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Key functions of the Indian Ocean Observing System (IndOOS)

IndOOS is the sustained observing system for the Indian Ocean, a network operated and supported by various national agencies and coordinated internationally under the Global Ocean Observing System (www.goosocean.org) framework by the CLIVAR/IOC-GOOS Indian Ocean Region Panel (see Appendix A for a list of acronyms). The IORP is made up of an international group of scientists and science leaders from countries and institutions within and outside the Indian Ocean region who have a commitment to sustained observations of the Indian Ocean.

About one third of the global population live around the Indian Ocean, many in small islands, developing states and least developed countries that are especially vulnerable to climate impacts. There is growing societal demand for monitoring, understanding, and predicting the state of the Indian Ocean and its climatic influences in a time of accelerating changes and rapid growth in the blue economy. Despite its relatively small size, the Indian Ocean has accounted for 30% of the global oceanic heat content increase over the last two decades, while it is home to 30% of the world's coral reefs and 13% of global wild-catch fisheries. Cyclones, floods, droughts, and heatwaves are becoming more extreme around the Indian Ocean, with anthropogenic climate change increasingly impacting weather patterns and threatening marine and terrestrial resources. Moreover, natural climate phenomena with global impacts, such as the Madden-Julian Oscillation (MJO) and the Indian Ocean Dipole (IOD), originate in the Indian Ocean. The goal of IndOOS is to provide sustained high-quality oceanographic and marine meteorological measurements that can support knowledge-based decision-making and policy development through improved scientific understanding, and ultimately, improved regional weather, ocean, and climate forecasts.

Why IndOOS-2?

The existing IndOOS design was established on the basis of an Implementation Plan drafted by the CLIVAR IORP in 2006. Since then, societal and scientific priorities and measurement technologies have evolved, many practicalities of implementation have been learned, and the pace of climatic and oceanic change has accelerated. The main objective of this document is to review the successes and failures of the IndOOS and to incorporate these practicalities, together with new priorities, into actionable recommendations for future observing system components that will make up IndOOS-2. In essence, the review findings provide a roadmap to address *the clear and urgent need for expansion of a global ocean observing system designed to meet the requirements of a broad suite of users*, as recognized in the GOOS 2030 Strategy.

This review and the resulting roadmap was sponsored by the OOPC, an expert panel of GOOS, as a *system-based evaluation to renovate or fill gaps in the IndOOS and increase its readiness level*. It was conducted and written by a group of sixty international scientists, under the guidance of the IORP in partnership with SIBER and under the scrutiny of an independent review board appointed through various partners of GOOS (see Appendix B for the full list of contributors).

Document overview

A description of the review process that led to IndOOS-2 is given in the Introduction, which also includes background on the societal motivations for observing the Indian Ocean, the broad scientific and operational drivers of the IndOOS, and its observing system components. In the 25 chapters that follow we: (1) Review the current status of the IndOOS, component by component, including past successes and failures (Chapters 1-8); (2) Assess the demands that operational products and forecasts place on the IndOOS (Chapters 9-11); and (3) Articulate the oceanic and climatic phenomena that the observing system must capture (Chapters 12-25). Each chapter identifies a set of essential ocean variables (EOVs) with their required geographical coverage and spatio-temporal resolution as well as a list of Actionable Recommendations for upgrades and enhancements to the observing system that address the most important gaps and needs. Finally, in the Synthesis the major outcomes of these chapters are summarized, the process of consolidating and prioritizing the Actionable Recommendations is described, and the Recommendations are listed in the context of observing system components.

This Executive Summary stands alone and presents a comprehensive summary of the outcomes of the review, providing a roadmap to the proposed evolution of the IndOOS during 2020-2030 in terms of the core findings and a prioritized list of Actionable Recommendations.

Core findings

The first decade or so of IndOOS has provided unprecedented measurements of weather, ocean, and climate phenomena. These observations have, for instance: Supported the study and forecast of tropical cyclones and marine heatwaves (Chapter 12); Improved our understanding of the MJO and MISO (Monsoon Intra-Seasonal Oscillation) and their influence on sub-seasonal variations of the global hydro-climate (Chapters 13-15); Mapped the equatorial and monsoon circulations and captured variability of the Indonesian throughflow (Chapters 14, 17); And elucidated year-to-year climate variations in the tropical Indian Ocean (Indian Ocean Dipole, IOD) and their relationship to tropical Pacific climate variations (El Niño-Southern Oscillation, ENSO) (Chapter 19).

There remain, however, significant limitations and gaps in the existing IndOOS such that, so far, it falls short of meeting many of society's demands for climate forecasting and prediction. These limitations are starkly illustrated by the low prediction skill of sub-seasonal to seasonal forecasts, which lack sufficient information of initial upper-oceanic conditions (Chapter 9), and by large discrepancies in climatologies of heat exchange at the air-sea interface. These discrepancies exceed 30 Wm^{-2} over boundary current and upwelling regions, such as the Agulhas and Somali Current systems and the Java-Sumatra upwelling cells (Chapter 10). IndOOS must also support ocean state estimations that are used to initialize climate predictions and drive biogeochemistry models. Large uncertainties remain in these critical products and, while technical limitations of data assimilation systems are partially to blame, lack of sustained observations, particularly in high flux boundary regions and in the deep ocean, leave these products poorly constrained (Chapter 11).

Several key gaps in the observing system have been identified through the work of this review. The Arabian Sea and western equatorial Indian Ocean have suffered from an extreme lack of observations, largely as a result of piracy and vandalism. Here, the uniquely seasonal Somali Current and western boundary upwelling system are associated with strong oceanic productivity and an expansion of regional sub-surface anoxia (Chapters 18, 20), while semi-annual variability in mixed layer depth and air-sea fluxes influence monsoon variability and predictability (Chapters 13, 14). With piracy now dormant, long-planned RAMA sites were finally occupied in the Arabian Sea in June 2018, while a further three remain unoccupied (Chapter 1). **We recommend that IndOOS coverage of the Arabian Sea and western equatorial Indian Ocean, including biogeochemical measurements, be rapidly intensified.**

Better measurements of the mixed layer, the upper oceanic layer that interacts with the atmosphere, and of barrier layers, a salinity-stratified layer below the mixed layer, are needed to improve sub-seasonal to seasonal forecasting. Diurnal cycles in near-surface-ocean stratification impact regional Sea Surface Temperature(SST) patterns, winds, and the development and propagation of the MJO and MISO, that in turn influence monsoon rainfall and global hydroclimate (Chapters 13, 14). Hot spots of this fine-scale vertical variability occur in regions of upwelling at the eastern equatorial boundary near Sumatra, in the southeastern Arabian Sea, and in the Seychelles-Chagos Thermocline Ridge, as well as in the salinity-stratified Bay of Bengal. These are also regions of high variability in air-sea fluxes of CO_2 and in primary productivity. **We recommend enhanced vertical and temporal resolution of upper-ocean measurements in these regions and the addition of near-surface biogeochemical observations.**

Recent studies suggest that the Indian Ocean has stored an astounding 30% of the global oceanic heat uptake from the atmosphere over the last two decades. This heat uptake has strongly contributed to the temporary slowdown in global surface atmosphere temperature warming often referred to as the climate change “hiatus”. The heat is thought to have largely entered the basin from the Pacific via the Indonesian Throughflow, yet its relationship to warming in the southern subtropics and to regional sea level rise is unclear. And its ultimate fate, regarding a possible return to the atmosphere to contribute to a future acceleration in global warming, is unknown. This motivates the need for observations that can monitor the dominant oceanic fluxes of mass and heat (Chapter 23) and ultimately constrain basin-scale budgets associated with decadal variability and change. **We recommend the establishment of boundary flux arrays in the Agulhas and Leeuwin Currents, an enhancement of Indonesian Throughflow monitoring, and an increase in observations of the deep ocean below 2000 m.**

There is an overarching need for sustained biogeochemical measurements as an integral part of the IndOOS. De-oxygenation and acidification trends, the marine carbon cycle, primary productivity variability, and ecosystem changes are largely unconstrained throughout the Indian Ocean. Management of the Indian Ocean’s natural resources, including coral reefs and wild-catch fisheries, under a changing climate will require a step-change in the amount of biogeochemical data collected. **We recommend an increase in biogeochemical measurements throughout the basin, initially targeted to regions of high variability and change, such as the Arabian Sea, Bay of Bengal, and eastern equatorial Indian Ocean.**

In addition to *in situ* observing system needs, there are three additional ingredients necessary for the future advancement and success of the IndOOS. First, **satellite measurements are central to the IndOOS**, providing the only basin-wide view of the ocean and of air-sea fluxes. Continuous, overlapping satellite missions are vital, as are the *in situ* observations that calibrate and validate these missions. Second, **there is urgent need for advancements in data assemblage and coupled data assimilation techniques**. Quality control, archiving, inter-calibration, and mapping of oceanographic datasets can be fragmented and uneven and need to be improved if these data are to connect with end-users and decision-makers. There is a need for an efficient data management system for all observing platforms that follows international best practices (metadata reporting, community accepted standards for quality assurance and control (QA/QC)), and data publication that enables interoperable discovery and free, open access. Advancements in assimilation techniques are needed to better leverage the potential of the IndOOS observations in products, state estimations, and predictions. Finally, **there is a necessity for increased engagement and partnerships among Indian Ocean rim countries**. Much of the expansion of the IndOOS into coastal and upwelling regions will be reliant on increased involvement and cooperation of regional countries and agencies, along with their commitment to observing best-practices, and to data sharing and dissemination. Collaboration, resource sharing, and capacity building between nations are essential in this. These challenges are not new to ocean observing and the Framework for Ocean Observing, GOOS, GOOS partners, and the GOOS regional alliances provide the tools and models for success (www.goosocean.org). For the Indian Ocean, a pro-active and inclusive IORP, IO-GOOS, and Indian Ocean Resources Forum (IRF) are essential to entrain, guide, facilitate, support, collaborate with, and provide resources for new IndOOS partners and components. These bodies will require ongoing and recommitted support via the WCRP from the World Meteorological Organization, the International Council for Science, and the Intergovernmental Oceanographic Commission of UNESCO. These recommendations are summarized in Figure ES.1, which shows all the observing system components for the next phase of IndOOS.

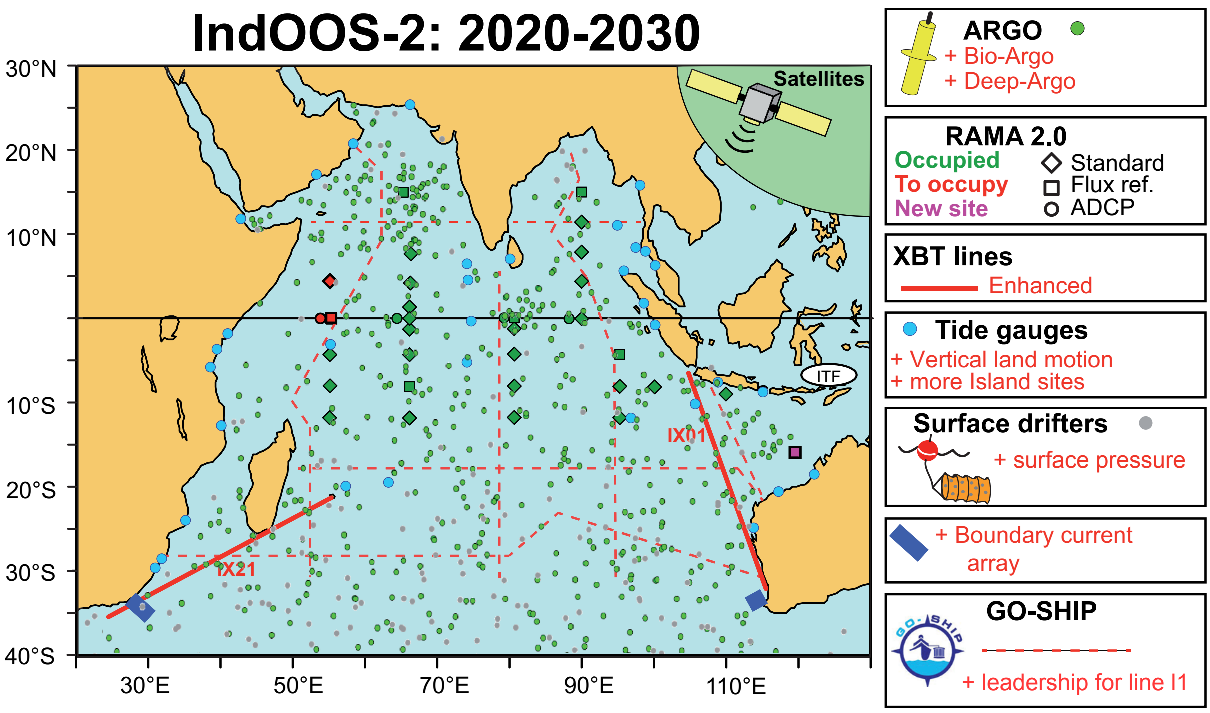

Figure ES.1 IndOOS-2: 2020-2030. **Argo**: Maintain the core 3° x 3° array; add 200 Biogeochemical (BGC)-Argo floats; develop a Deep-Argo program. **RAMA**: Consolidate to RAMA-2.0, occupying 3 remaining sites in Arabian Sea; increase resolution of upper-ocean measurements and add biogeochemical measurements at flux reference sites; add new site off Northwestern Australia. **XBT**: Maintain IX01 and IX21 lines; install auto-launchers and increase near-coastal resolution on IX01. **Tide gauges**: Add colocated measurements of land motion; add sites in Southwest Indian Ocean and on islands. **Surface drifters**: Maintain core 5° x 5° array, evaluate addition of barometric pressure measurements. **Boundary current arrays**: Add measurements of mass, heat, and freshwater fluxes of the Agulhas and Leeuwin Currents, including hydrographic end-point moorings to capture basin-scale overturning. **GO-SHIP**: Find national commitment for section I01; add measurements of phytoplankton community structure. **Satellites**: Maintain overlapping, inter-calibrated missions; enhance spatial resolution of Sea Surface Height (SSH) or currents directly.

Following is a list of actionable recommendations, prioritized based on their number of applications and/or unique importance. For instance, the Argo program is of highest priority, being cited in 13 of the 17 chapters herein on science drivers, while development of SOOP-CO_2 measurements are a high priority because there are no long-term records of surface carbon flux in the Indian Ocean, an important climate parameter. A full justification of these recommendations and their ranking is provided in the Synthesis at the end of this review.

Actionable Recommendations

Tier I: Maintain and consolidate essential capacities, while better considering practicalities.

The most essential observing networks of the IndOOS are: Argo, RAMA, satellite missions, tide gauges, XBT lines, and surface drifters and GO-SHIP. These networks have supported, and should continue to support, understanding and prediction of many important phenomena, including the monsoons (Chapter 14), tropical cyclones and rainfall variability (Chapters 12, 13, 15), heat and freshwater cycles (Chapters 15, 17, 23, 25), regional sea level change (Chapter 21), and tropical modes of sub-seasonal to decadal climate variability (Chapters 13, 19, 22) in the Indian Ocean. The continuation of these networks is essential for the future detection and attribution of anthropogenic changes in the Indian Ocean (Chapter 25).

A. The Argo program is extraordinarily successful (Chapter 1) and should be maintained at highest priority. We recommend enhancement with biogeochemical- and Deep-Argo programs, as itemized in Tier II below.

B. We recommend RAMA be consolidated to a new design — **RAMA-2.0 — reducing the original plan from 46 sites to 33** in consideration of issues such as vandalism and available ship time (Chapter 2). **Three western equatorial sites (55°E) need to be occupied at highest priority to complete RAMA-2.0.** Scientific capacity will be largely maintained with fewer moorings while also providing more opportunity and flexibility to add new sites, upgrade technology, and add new sensors. **Coordination between RAMA and the Indian array OMNI is a priority** and will improve operational efficiency as well as data accessibility and standards.

C. The tide gauge network will continue to grow in importance as more regional climate predictions are demanded. The network should be consolidated with **more colocated GNSS (land motion) stations**, prioritizing sites where records are longest (Chapter 5), and with **more island stations** (in particular in the southwestern tropical Indian Ocean), which are highly effective for comparisons with satellite data and for combined reconstructions of long-term regional sea level changes.

D. Satellite missions provide the only spatially coherent view of the ocean, albeit only at the surface. Continuous, inter-calibrated surface winds at diurnal timescale, all-weather sea surface temperature, as well as sea surface height, sea surface salinity, and ocean color are of highest priority (Chapter 6). **Space-based capabilities for measuring meso- and sub-mesoscale variability should be enhanced.**

E. Much of the XBT network has been superseded by Argo (Chapter 3). However, Argo does not capture regions of high variability, intense narrow flows, or shallow water. **The outstanding priority is to maintain IX01**, which captures the interannual variability of geostrophic Indonesian Throughflow (ITF) transport over the upper 700 m. To consolidate IX01 **we recommend installation of automated launchers** to increase data resolution and return, denser profiling over the shelf/slope regions, plus a **regional enhancement**

of Argo to provide more measures of salinity. **IX21 should be enhanced with collection of pCO_2** (Chapter 24) and its potential for capturing changes in the Agulhas Current investigated. **Data from IX14 across the Bay of Bengal should be shared and made accessible.**

F. The surface drifter program should be maintained at current design density **and enhanced with more barometric pressure observations, with the optimal density of pressure observations to be evaluated at highest priority (Tier I)** (Chapters 4, 12, 15).

G. The GO-SHIP provides the only means to collect a comprehensive suite of colocated hydrographic, biogeochemical, and tracer measurements, through shipboard water sample collection and laboratory analysis (Chapter 7). These occupations should continue at decadal interval and it is **a priority to identify national or multi-national support for the occupation of I01E and I01W sections across the Bay of Bengal and Arabian Sea.**

Tier II: Extend IndOOS capacities to better address scientific and operational drivers.

Enhancements of the IndOOS are necessary to meet growing societal needs for data, forecasting, and prediction at a time when extreme events, such as cyclones and heatwaves, are intensifying, when floods and droughts are growing in number, and when marine ecosystem changes and their impacts on fisheries are becoming evident. Climate and climate variability are changing fast and a global climate observing system, with a fit-for-purpose IndOOS component, will provide our only means of mapping those changes and predicting what may happen next.

A. Foremost, we recommend **development of sustained measurements towards understanding the carbon cycle and ecosystem variability and change** in the Indian Ocean. Until now, these measurements are extremely sparse. For example, not one of the 1698 stations of primary productivity used to develop the satellite ocean color algorithm for estimating ocean primary productivity globally, comes from the Indian Ocean. Of particular importance are observations in the Arabian Sea, where profound biogeochemical and ecosystem changes may have already occurred (Chapters 16, 20, 24). These observations must be made alongside physical measurements.

   (A1) **A suite of 200 biogeochemical-Argo floats** (measuring nutrients, bio-optics, and oxygen in addition to temperature and salinity) in the Indian Ocean, as part of the global biogeochemical-Argo implementation plan (Chapters 1, 16, 18, 20, 24, 25). Floats should be targeted to regions with strongest de-oxygenation trends, upwelling zones, high primary productivity variability, and regions important for the marine nitrogen cycle. These include the Arabian Sea and Bay of Bengal oxygen minimum zones, the Seychelles-Chagos Thermocline Ridge (SCTR), and the eastern equatorial region. (A2) **$MAPCO_2$ systems and biogeochemical measurements at RAMA Flux Reference sites**, targeting regions with high variability in CO_2 fluxes and/or primary productivity, and/or rapidly decreasing pH, with the Arabian Sea and SCTR highest priority (Chapters 24,25). (A3) **Establish SOOP-CO_2 measurements in the southern Indian Ocean (IX21)**, and in the northern Arabian Sea and Bay of Bengal. (A4) **Add observations of chlorophyll concentration and phytoplankton community structure on key GO-SHIP lines and RAMA maintenance voyages** to validate ocean color satellite data and track changes in productivity and the biological carbon pump. (A5) **Establish a Continuous (video) Plankton Recorder survey** for the Indian Ocean to measure zooplankton community composition variability and change (Chapter 16).

B. **Key processes of the near-surface ocean, including diurnal mixed layer and barrier layer variability, need to be better measured** to meet the need for improved subseasonal to seasonal forecasting and surface flux products (Chapters 9, 10). In particular, these measurements will refine our understanding of the MJO and MISO and their influence on monsoon rainfall and hydro-climate (Chapters 13, 14, 15), while direct measures of surface fluxes are needed to validate bulk algorithmic estimates (Chapter 2, 10, 14).

    (B1) **A new RAMA flux reference site between Australia and Indonesia** in the outflow of the ITF (14°S, 115°E), where tropical SST and rainfall intraseasonal variability are highest. (B2) **Direct flux measurements and increased vertical resolution of temperature and salinity (T/S) sensors** (0.5 m, 1 m, 2 m, 3 m, 5 m, 7 m, 10 m, and every 5 m down to 50 m) at RAMA flux reference sites on the equator and in the Arabian Sea, Bay of Bengal, and SCTR.

C. **The IndOOS must be expanded into shelf/slope regions, with an emphasis on the subtropics**, where swift boundary currents and their fluxes dominate basin-wide heat, freshwater, and nutrient budgets (Chapters 11, 21, 23, 25) and where coastal upwelling systems influence primary productivity, air-sea fluxes, and climate variability (Chapters 9, 18, 19, 20). In particular, key climate modes in the subtropics, such as Subtropical Dipole and Ningaloo Niño (Chapters 12, 19), as well as the gyre and overturning cell which carry and store anthropogenic heat and other properties (Chapters 23, 25), need to be constrained with boundary flux measurements.

    (C1) **Re-establish an Agulhas Current volume, heat, and freshwater transport array** at the western boundary near 34°S, colocated with altimeter ground track and including an "end-point" mooring to measure basin-wide geostrophic overturning down to 2000 m. Measure full-depth T/S, oxygen, and core nutrients during maintenance cruises and, ideally, combine with periodic glider surveys to capture small scale flows over the shelf and slope. (C2) **Enhance the Leeuwin Current array** to measure full-depth volume, heat, and freshwater fluxes through combined mooring and glider observations at the eastern boundary, including an"end-point" mooring down to 2000 m to measure basin-wide geostrophic overturning when paired with the Agulhas Current "end-point" mooring. (C3) Monitor T/S fluxes, dissolved oxygen, and core nutrients with **gliders or autonomous underwater vehicles in the Sumatra-Java upwelling region and South Java Current**, the eastern pole of the IOD. (C4) Monitor T/S fluxes, dissolved oxygen, and core nutrients with **gliders or AUVs along the west coast of India** where monsoon currents, upwelling, and the Arabian Sea oxygen minimum zone intersect and societal implications are greatest.

D. We recommend that the IndOOS be expanded into the deep ocean below 2000 m. Here circulation and thermohaline changes affect sea level change and decadal-to-multidecadal variability. Coupled climate models and their projections rely on ocean data assimilation products that remain almost entirely unconstrained in the deep ocean (Chapters 11, 21, 25).

    (D1) A suite of **Deep-Argo floats**, with priority in the southern subtropical Indian Ocean where deep heat content change is largest.

Tier III: Pilot projects to investigate efficacy, sustainability, and potential for integration into the IndOOS.

In some cases, where observing technology needs further advancement, where scientific understanding is too limited to yet design effective monitoring programs, or where the efficacy or feasibility of additional measurements is uncertain, initial pilot studies are needed.

A. A pilot study within the **Somali Current and upwelling system** in the western Arabian Sea. Potentially a surface flux buoy (with turbulence measurements) and/or wave glider, biogeochemical-Argo deployments with specialized missions, such as shallower profiling and higher temporal sampling, and/or glider sections. This study should include a capacity development component (Chapters 17, 18).

B. A pilot project to **double the number of Argo profiles in the tropics** in order to capture upper-ocean, intra-seasonal variability of MJO and MISO. The number of Argo floats could be enhanced or floats programmed for shallower, higher frequency profiling while within 10° of the equator (Chapter 1).

C. A pilot study of **air-sea interaction and carbon uptake in the southeast subtropical Indian Ocean** subduction zone, potentially utilizing new sensor technologies.

D. **Continued exploration of the Indian Ocean with new autonomous and expendable platforms and new sensor technologies** that may improve or revolutionize the IndOOS in the future, including directional wave spectra drifters (with SST and GPS sensors), χ-SOLO floats (turbulence), X-Spar floats, Saildrones, Wave Gliders, and Minimets (Chapter 8).

Applications: Validation and Improvement of Data Products, Models, and Predictions

In addition to actionable recommendations for the observing system, this review has highlighted a number of other priorities for the Indian Ocean community that involve **data-mining, analyses, and collaborations towards the validation and improvement of the products, models, and predictions** that derive from the IndOOS. These include:

A. Find and digitize historic sea level data.

B. Analyze existing observations to determine the locations of largest productivity variability and prioritize these locations for biogeochemical observations.

C. Compare *in situ* chlorophyll and productivity observations to collocated satellite ocean color to quantify the accuracy of satellite algorithms and develop regionally tuned algorithms, if necessary.

D. Engage with the atmospheric reanalysis community to help evaluate and guide future improvement of tropical convective parameterizations.

E. Speed development of coupled ocean-atmosphere data assimilation techniques.

F. Improve capabilities for reanalysis, prediction, and observing system evaluation through stronger collaborations among data assimilators, modelers, and observationalists.

G. Develop collaborations with the paleo-proxy community to provide long records of surface temperature variability in the IOD eastern pole and of sea level variability near the west coast of Australia, in the Chagos archipelago, and Mascarene Islands.

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Dr Gary Meyers, CSIRO Hobart. Photo by Bruce Miller. Copyright CSIRO Australia

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