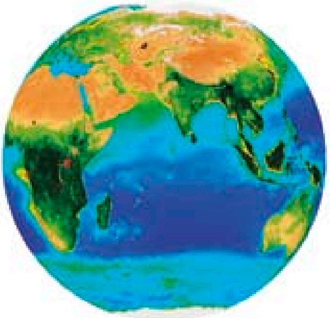

SIBER

Sustained Indian Ocean Biogeochemistry and Ecosystem Research

Science Plan and Implementation Strategy

IMBER Report No.4 - IOGOOS: pr: 07: SIBER/01 - SIBER Report No.1

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Integrated Marine Biogeochemistry and Ecosystem Research
IMBER Report No.4

Indian Ocean Global Ocean Observing System
IOGOOS: pr: 07: SIBER/01

Sustained Indian Ocean Biogeochemistry and Ecosystem Research
SIBER Report No.1

SUSTAINED INDIAN OCEAN BIOGEOCHEMISTRY AND ECOSYSTEM RESEARCH

(**SIBER**)

A BASINWIDE ECOSYSTEM PROGRAM

SCIENCE PLAN AND IMPLEMENTATION STRATEGY

R.R. Hood, S.W.A. Naqvi, J.D. Wiggert, M.R. Landry, T. Rixen, L.E. Beckley, C. Goyet, G.L. Cowie and L.M. Maddison (Eds.)

Preface

The Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) Science Plan and Implementation Strategy described in this document are motivated by the need to understand the role of the Indian Ocean in global biogeochemical cycles and the interaction between these cycles and marine ecosystem dynamics. This understanding is required to predict the impacts of climate change, eutrophication and harvesting on the global oceans and the Earth System and is fundamental to policy makers for the development of management strategies for the globally important Indian Ocean. The improved understanding that SIBER will bring to the characterization and prediction of fundamental biogeochemical and ecological processes also has strong relevance to the ecology and people of the islands and continental rim communities of the region.

The SIBER program reflects the importance placed on these issues by the International Geosphere-Biosphere Program (IGBP), the Scientific Committee on Oceanic Research (SCOR) and the Global Earth Observing System of Systems (GEOSS). SIBER has been developed with the approval of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project and the Indian Ocean Global Ocean Observing System (IOGOOS), providing strong relevancies to the High Level Objectives of UNESCO's Intergovernmental Oceanographic Commission, which span across the generic themes of marine hazards, climate change, ecosystem health and environmental management. SIBER also has strong links with the Indian Ocean Panel (IOP) 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.

The Science Plan and Implementation Strategy builds upon concepts and strategies formulated and discussed at the first SIBER Conference convened in Goa, India in October 2006 (Hood et al., 2008; Hood et al., 2007) involving more than 200 participants, and the second SIBER Workshop also convened in Goa, India in November 2007 (Hood et al., 2008) with 30 participants. Both meetings included scientists from Indian Ocean rim nations, Europe and North America. The information and ideas from these meetings have been condensed into six major themes, each of which identifies key issues and priority questions that need to be addressed in the Indian Ocean. This document will be supplemented by more detailed plans for specific aspects of the program as it progresses. Two SIBER web sites have been established to provide program updates on a regular basis (http://www.imber.info/SIBER.html and http://www.incois.gov.in/Incois/siber/siber.jsp).

The SIBER Science Plan 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. It should be emphasized that this plan is intended to provide scientific themes for different countries to consider as potential research foci in the Indian Ocean. This approach is necessary in order to accommodate the broad (and often regional) interests of many countries that seek to pursue research in the Indian Ocean.

We encourage scientists from all relevant fields to collaborate and implement the SIBER Science Plan to ensure that major questions about the Indian Ocean and Earth System are addressed in a fully integrated manner.

SIBER Steering Committee, January 2011

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Greg Cowie	Catherine Goyet	Raleigh Hood	Somkiat Khokiattiwong
Hiroshi Kitazato	Michael Landry	Wajih Naqvi	M. Ravichandran
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CONTENTS

EXECUTIVE SUMMARY

Although there have been significant advances in our ability to describe and model the oceanic environment, understanding of the physical, biogeochemical and ecological dynamics of the Indian Ocean is still rudimentary in many respects. This is partly due to the fact that the Indian Ocean remains substantially 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. The biogeochemical and ecological impacts of this complex physical forcing are not yet fully understood.

The Indian Ocean is warming rapidly, but the impacts of this warming on the biota, carbon uptake, and nitrogen cycling are unquantified. The increasing population density and rapid economic growth of many of the countries surrounding the Indian Ocean make the coastal environments particularly vulnerable to anthropogenic influences. Warming and anthropogenic effects are also impacting valuable fish species. These influences and their socio-economic impacts need to be quantified. Understanding the processes that drive biogeochemical and ecological responses to anthropogenic effects is necessary to provide a sound basis for the sustainable management of this globally important ocean. An understanding of these processes is also necessary to predict the impacts and feedbacks of the Indian Ocean as part of the Earth System.

Deployment of coastal and open ocean observing systems in the Indian Ocean have created new opportunities for carrying out biogeochemical and ecological research there. International research efforts need to be motivated to exploit these opportunities to advance our understanding. Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) is a decade-long, multidisciplinary international program, whose science plan and implementation strategy is designed to leverage observing systems and other international programs in order to advance understanding of biogeochemical cycles and ecosystem dynamics of the Indian Ocean in the context of climate and human-driven changes.

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.

This understanding is required to predict the impacts of climate change, eutrophication and harvesting on the global oceans and the Earth System and is fundamental to policy makers for the development of management strategies for the Indian Ocean. To address this goal, emphasis will be given to the analysis required to predict and evaluate the impacts of physical and anthropogenic forcing on biogeochemical cycles and ecosystem dynamics of the Indian Ocean. SIBER will leverage the sampling and monitoring activities of several coastal and open ocean observing systems that are being planned and deployed in the Indian Ocean and it will provide the basinwide scientific coordination and communication required to predict Indian Ocean biogeochemical cycles and ecosystem dynamics in the context of climate change and other anthropogenic influences.

To address this long-term goal SIBER has structured its research around six scientific themes.

Each of these include a set of scientific questions that need to be addressed in order to improve our 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.

Regional scientific themes

- **Theme 1: Boundary current dynamics, interactions and impacts.**
  How are marine biogeochemical cycles and ecosystem processes in the Indian Ocean influenced by boundary current dynamics?

- **Theme 2: Variability of the equatorial zone, southern tropics and Indonesian Throughflow and their impacts on ecological processes and biogeochemical cycling**.
  How do the unique physical dynamics of the equatorial zone of the Indian Ocean impact ecological processes and biogeochemical cycling?

- **Theme 3: Physical, biogeochemical and ecological contrasts between the Arabian Sea and the Bay of Bengal.**
  How do differences in natural and anthropogenic forcings impact the biogeochemical cycles and ecosystem dynamics of the Arabian Sea and Bay of Bengal?

General scientific themes

- **Theme 4: Control and fate of phytoplankton and benthic production in the Indian Ocean.**
  What are the relative roles of light, nutrient and grazing limitation in controlling phytoplankton production in the Indian Ocean and how do these vary in space and time? What is the fate of this production after it sinks out of the euphotic zone?

- **Theme 5: Climate and anthropogenic impacts on the Indian Ocean and its marginal seas.**
  How will human-induced changes in climate and nutrient loading impact the marine ecosystem and biogeochemical cycles?

- **Theme 6: The role of higher trophic levels in ecological processes and biogeochemical cycles.**
  To what extent do higher trophic level species influence lower trophic levels and biogeochemical cycles in the Indian Ocean and how might this be influenced by human impacts, e.g. commercial fishing?

The SIBER Science Plan 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. It should be emphasized that this plan is intended to provide a set of scientific themes for different countries to consider as potential research foci in the Indian Ocean. This approach is necessary to accommodate the broad (and often regional) interests of many countries that are interested in pursuing research in the Indian Ocean.

Implementation strategy

The implementation plan for SIBER is divided into three major science activities: 1) remote sensing, 2) modeling, and 3) *in situ* observations which all have the potential for leveraging existing infrastructure. The following provides a brief summary of these approaches as they apply to SIBER and Indian Ocean research.

Remote sensing

The starting point for addressing the long-term goal of SIBER is through the use of remote sensing to better characterize the intense variability that is observed in the Indian Ocean. There is still a need for carrying out first-order descriptive science based on remote sensing. Interdisciplinary retrospective and process-oriented remote sensing studies should seek to improve quantification of both the physical (sea surface temperature and sea surface height) and biological (ocean color) variability, understand the impact of physical forcing on biological processes, and also characterize longer-term change.

Modeling

Remote sensing and *in situ* data should be combined with modeling studies. However, there are still substantial challenges associated with modeling the highly dynamic regions in the Indian Ocean. Eddy-resolving models (e.g. 1/10th of a degree or less) are required in order to resolve the physical and biological variability in many Indian Ocean current systems and data-assimilation techniques will need to be employed to optimize both physical and biological models. SIBER will encourage the use of existing eddy-resolving models in the Indian Ocean and also the development of new data-assimilating models. Applying coupled physical-biological models to study ecosystem dynamics and higher trophic levels is still a significant research challenge. In the context of IMBER, the interaction between biogeochemical cycles and ecosystems must be addressed. SIBER will encourage the development and use of end-to-end food web modeling approaches, and especially new model structures that are adaptive and/or generate emergent behavior.

In situ observations and potential for leveraging existing infrastructure

Initial emphasis in SIBER will also be on data mining, i.e. identifying and compiling existing sources of information into accessible electronic databases. Intensive *in situ* biological studies in the Indian Ocean have mostly been focused in the Arabian Sea. First-order, descriptive *in situ* observational studies need to be undertaken elsewhere in the Indian Ocean to characterize the assemblages and seasonality of phytoplankton, zooplankton and nekton. Existing long-term monitoring stations also need to be maintained. SIBER will promote the use of innovative approaches for conducting marine research. These efforts should include installation of biogeochemically relevant sensors on observational platforms and vehicles (e.g. Argo floats, moorings and gliders); ships of opportunity outfitted with “ferry packs” or a continuous plankton recorder (CPR); and deployment of tagging and tracking devices (e.g. backpacks with acoustic sensors) to study higher trophic levels. However, these high-technology approaches cannot completely replace traditional net and trawl-based zooplankton and fisheries surveys. Targeted process studies should be motivated at specific sites and times that focus on addressing the core questions identified in this document. A program of systematic benthic process studies is needed, and benthic sampling and experiments should be integrated with pelagic process studies where possible to elucidate relationships and mechanisms in benthic-pelagic coupling. Studies motivated as a part of SIBER must target and build upon existing monitoring and research infrastructure, e.g. Australia’s IMOS program, the Dutch mooring array in the Mozambique Channel, India’s recently established time series station in the Arabian Sea and the basinwide CLIVAR/GOOS Indian Ocean Observing System (IndOOS).

Integration and synthesis will be an ongoing process linking the three main science activity areas (remote sensing studies, modeling studies and *in situ* observations). To manage the three core activity areas and their relationship with the SIBER objectives, a Scientific Steering Committee (SSC) has been formed of scientists with expertise in relevant disciplines and a broad international representation. The SSC will form working groups based on the six major research themes that will be charged with identifying, motivating and coordinating relevant research under each theme. These will be flexible, cross-cutting teams that are focused on accomplishing SIBER objectives.

Programmatic Linkages

SIBER has been developed under the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, and the Indian Ocean GOOS (IOGOOS) program with support from the Intergovernmental Oceanographic Commission (IOC). SIBER will coordinate with international research efforts such as the IMBER regional programs: Climate Impacts on Oceanic Top Predators (CLIOTOP), Ecosystem Studies of Sub-Arctic Seas (ESSAS) and Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED), and the International Study of Marine Biogeochemical Cycles of Trace Elements and their Isotopes (GEOTRACES). SIBER will also leverage several coastal and open ocean monitoring programs in the Indian Ocean. These include the CLIVAR- and GOOS-sponsored Indian Ocean Observing System (IndOOS), Australia's Integrated Marine Observing System (IMOS) and several regional GOOS programs. To develop a broader understanding of the Indian Ocean ecosystem, SIBER will coordinate its efforts with the Western Indian Ocean Marine Science Association (WIOMSA), the South African Network for Coastal and Oceanic Research (SANCOR), the Agulhas and Somali Current Large Marine Ecosystems project (ASCLME) and the Bay of Bengal Large Marine Ecosystem project (BOBLME). As SIBER develops it is envisaged that the number of participants, institutes and programs involved will increase. SIBER will provide the innovation, direction and coordination required to build a critical mass of multidisciplinary science and scientists to deliver this ambitious but achievable and globally important program.

Legacy

The coordination and integration of Indian Ocean biogeochemical and ecosystem research through SIBER will advance our knowledge of this under-sampled basin and provide a major contribution to the understanding of how regional and global change may impact biogeochemical cycles and ecosystem function, not only in the Indian Ocean, but in the Earth System, creating a lasting legacy on which future research can build. The scientific findings will inform scientists in the international community and provide a focus for future research on important regional, basinwide and global issues. These findings will also provide policy makers with a sound scientific basis upon which to make decisions on how to manage Indian Ocean ecosystems. SIBER will leverage and strengthen IOGOOS and IMBER by promoting coordinated, international, multidisciplinary research in developed countries, as well as building human capacity and infrastructure in many developing Indian Ocean rim countries.

INTRODUCTION

GENERAL BACKGROUND

The Indian Ocean (IO) is a remarkable place. Even a cursory glance at a global map reveals some striking aspects that clearly distinguish it from other major ocean basins (**FIG. 1**). Unlike the Pacific and Atlantic, it has a low latitude land boundary to the north and the Indian subcontinent partitions the northern basin. Much of the Eurasian landmass to the north is extremely arid (i.e. the Thar Desert of NW India, northern Africa and the Arabian Peninsula) and/or dominated by high mountainous terrain (e.g. the ranges of Afghanistan, Pakistan, India, Nepal and southwestern China). The northern IO extends only a few degrees beyond the Tropic of Cancer and thus has no subtropical or temperate zones. As a result, high-latitude densification of surface waters and subsequent ventilation of intermediate and deepwater masses does not occur. A second striking feature of the IO is the low latitude exchange between the Indian and the Pacific Oceans, known as the Indonesian Throughflow (ITF). Thus, in comparison to the Atlantic and Pacific, the IO is highly asymmetric, both zonally (with deep water, high latitude exchange happening only to the south) and meridionally (with shallow water exchange along the eastern rim).

As a result of the proximity of the Eurasian landmass and the heating and cooling of air masses over it, the IO is subjected to strong monsoonal wind forcing that reverses seasonally, i.e. the South West Monsoon (SWM) blows from the SW towards the NE in the boreal summer (June-September) and the North East Monsoon (NEM) blows in the opposite direction in the boreal winter (December-March) (for a review see Schott and McCreary, 2001). These winds profoundly impact both the Arabian Sea (AS) and the Bay of Bengal (BoB), and their effects are clearly apparent down to ~10ºS. The IO is also biogeochemically unique, having one of three major open ocean oxygen minimum zones (OMZs) in the north (the others are in the eastern tropical Pacific, one on either side of the equator). Oxygen concentrations in the intermediate water (~100-800m) decline to nearly zero (e.g. Morrison et al., 1999), which has profound biogeochemical impacts.

Another important aspect of the IO is the large dust and aerosol inputs that occur year round. The various dust source regions around the northern IO include the Arabian Peninsula, the African continent (Somalia) and Asia (Pakistan/India) (Leon and Legrand, 2003; Pease et al., 1998). The southern IO also has significant dust regions that source from southern Africa in the west and from Australia's Great Western Desert in the east (McGowan et al., 2000; Piketh et al., 2000). Anthropogenically-derived inputs are also prevalent, particularly the brown haze from industrial pollution and biomass burning on surrounding continents that lingers over the AS, the BoB and the southern tropical IO (Lelieveld et al., 2001; Ramanathan et al., 2007). Finally, the IO is ecologically unique in a variety of ways. One striking ecological feature is the presence of the largest mesopelagic fish (myctophids) stocks in the world in the AS (Gjøsaeter, 1984). These fish are specially adapted to the intense OMZ where they reside during the day to escape predation.

Perhaps the most important consideration is that more than 16% of the world's population lives in the coastal and interior regions of the northern IO and they are directly impacted by the vagaries of the monsoons and associated rains. Many other IO processes, such as seasonal variations in oceanic circulation and the biogeochemical and ecological responses associated with them, also directly and indirectly impact these populations. It is therefore important to obtain a better understanding of the dynamics of the IO, to be able to predict how it will respond to global climate change.

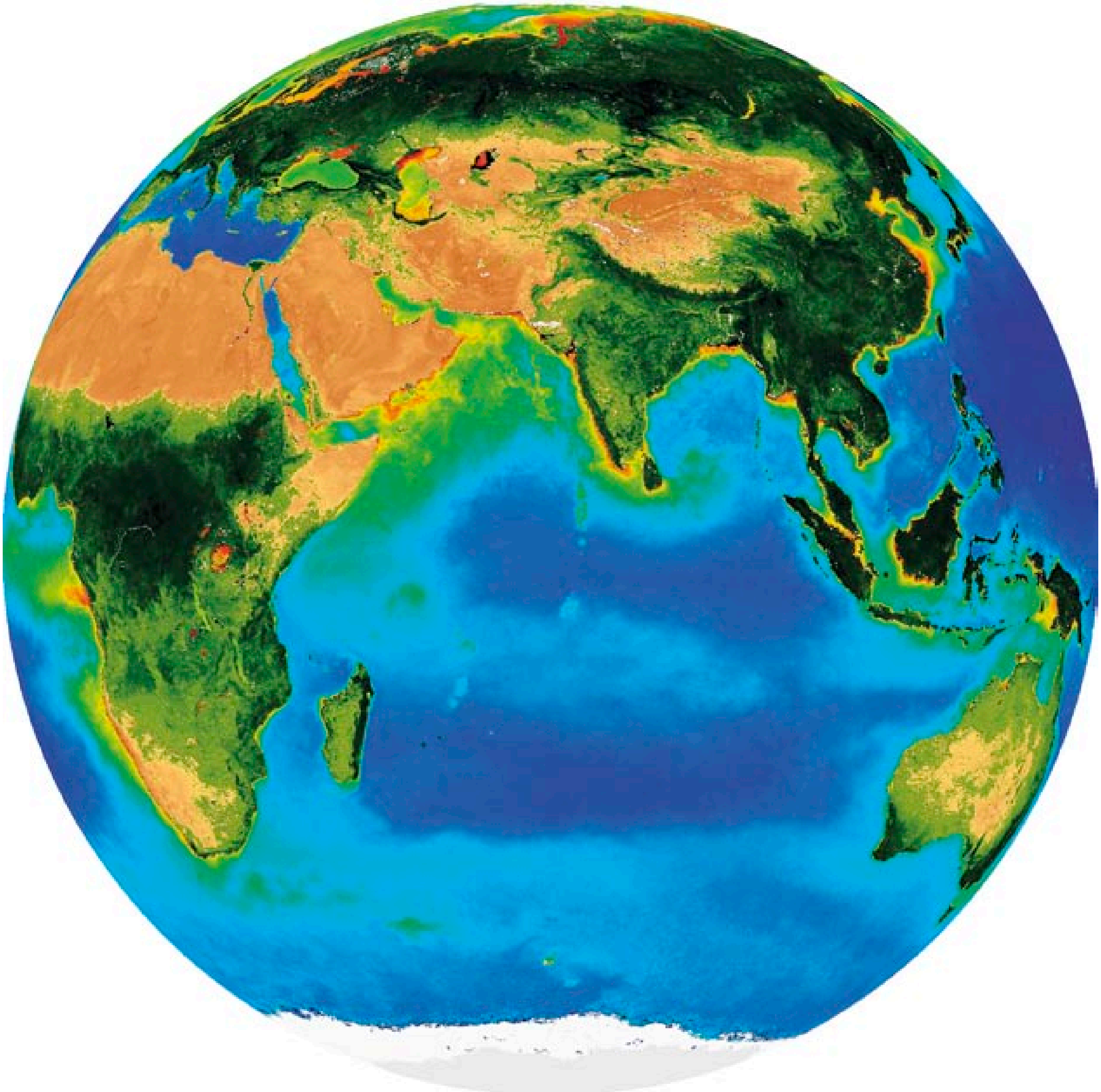

FIGURE 1: SeaWiFS biosphere image of the Indian Ocean region showing land vegetation and marine surface phytoplankton concentrations for boreal summer/austral winter.

Image from http://oceancolor.gsfc.nasa.gov/SeaWiFS

Historical background

In comparison to the Atlantic and the North Pacific the IO has received relatively little research attention. It was essentially neglected in the early days of oceanography; the Challenger expedition (1872-1876) made a single leg from Cape Town to Melbourne (see review by Benson and Rehbock, 2002). The first major expedition to the IO (principally the AS) – the John Murray Expedition - was undertaken on an Egyptian vessel, the *Mabahiss*, in 1933-1934 (Sewell, 1934), during which the intense mesopelagic oxygen deficiency was first recorded. During preparation and execution of the International Geophysical Year (1957-1958), oceanographic exploration of the southern IO was carried out by Australian, French, Japanese, New Zealand and Soviet researchers. Nevertheless, the IO was one of the least known seas when the Scientific Committee on Oceanic Research (SCOR) planned the International Indian Ocean Expedition (IIOE, 1960–1965). This basinwide survey resulted in a comprehensive hydrographic atlas (Wyrtki, 1971) and a number of regional studies (e.g. Swallow and Bruce, 1966). Subsequent research built on the work of that expedition (for further summary of early AS efforts, see Wiggert et al., 2005). The IIOE also led to capacity building in the region, particularly in India where the National Institute of Oceanography (NIO) was established in 1966. Over subsequent years, research at NIO has greatly improved our understanding of oceanographic processes in the AS and BoB.

The next intensive study involving researchers from outside the region was the Indian Ocean Experiment (INDEX, 1976-1979), which investigated the physical response of the Somali Current to the SWM (Swallow et al., 1983) and provided a first look at the associated biological and chemical distributions (Smith and Codispoti, 1980). The two institutes in Sevastopol, Ukraine (Marine Hydrophysical Institute and Institute of Biology of the Southern Seas) undertook ten expeditions mostly in the 1980s (Goldman and Livingston, 1994). However, in comparison to the Atlantic and the North Pacific, there have been very few studies and major expeditions in the IO.

The next cycle of investigations began with the Netherlands Indian Ocean Program (NIOP, 1992-1993; see review by Smith, 2005), part of the international Joint Global Ocean Flux Study (JGOFS), which focused on the western AS. Due to the uniqueness of the region, JGOFS selected the AS as one of four areas for detailed process studies during the 1990s. These investigations focused on the biogeochemical dynamics of the central and western AS and were largely limited the upper 500 to 1000m of the water column. The World Ocean Circulation Experiment (WOCE), implemented at about the same time, had a much wider geographical coverage in the IO. Although there have been expeditions mounted by individual countries (India, France, Germany, Japan, UK, and the USA), focused primarily on studies of physical processes, there have been no coordinated international expeditions since JGOFS, focusing on the biogeochemistry and/or ecology of either the pelagic realm or the benthos in the IO. One notable nationally coordinated effort, which may be viewed as a follow-up to the JGOFS AS efforts, is the Bay of Bengal Process Studies (BOBPS) program organized by the Indian oceanographic community (Madhupratap et al., 2003). Nevertheless, more than a decade has passed since the last major international research program in the IO ended. Efforts to mount a new program need to be initiated to consider the important questions that emerged from JGOFS that have not yet been addressed, as well as some exciting new questions that have arisen in recent years (see below).

Scientific background

Some fundamental scientific issues of relevance to SIBER are outlined in this section to set the scene for the program.

Ocean currents and biogeochemical variability

The physical dynamics of the IO arise largely as a result of the seasonal cooling and warming of the Eurasian land mass to the north, which, among other things, gives rise to the strong semi-annually reversing monsoon winds (**Fig. 2**, upper panels). These drive intense upwelling and downwelling circulations and seasonally reversing surface currents (see review by Schott and McCreary, 2001) that cause substantial variations in marine biogeochemical and ecosystem response (Lévy et al., 2007; Naqvi et al., 2006b). In the case of the Somali Current in the western AS, the reversal is equivalent to a seasonally reversing Gulf Stream in the Atlantic. Unusual current patterns, such as the poleward flowing eastern boundary current of western Australia (Leeuwin Current), also generate atypical biological signatures such as warm core rings with enhanced productivity (Waite et al., 2007). How do coastal and pelagic species respond across the IO basin to such dramatic changes in the physical regime? Does the semi-annual timescale associated with its current reversals promote greater distinctiveness between the biomes of the northern IO and the southern IO relative to other basins? Do these current reversals contribute to the differences between the BoB and AS?

In general, we need to better characterize and understand the ecological and biogeochemical responses to the complex IO physical forcing (**Fig. 2**) and how these in turn will be impacted by climate change. Many questions remain about primary production variability and dynamics in the IO (Resplandy et al., 2009; Wiggert et al., 2009). Some of these questions relate to the equatorial waters where the zonal thermocline and nutricline shoal toward the west rather than the east as in the Pacific and Atlantic Oceans. The equatorial IO is also strongly influenced by oscillations and perturbations that do not occur in other oceans, such as the Wyrtki Jets, the Madden-Julian Oscillation, and the Indian Ocean Dipole (McPhaden et al., 2009; Schott and McCreary, 2001). The state of understanding in the IO is in marked contrast to the Atlantic and Pacific, where the biogeochemical and ecological dynamics of the boundary currents and equatorial circulations have been intensively investigated and described, along with the impacts of inter-annual influences such as the North Atlantic Oscillation (NAO) and the El Niño-Southern Oscillation (ENSO). Although the Indian Ocean Dipole (IOD) is similar to La Niña in the Pacific, we still have a poor understanding of how climate oscillations impact the biogeochemistry and ecology of the upper ocean in the IO. Are IO ecosystems uniquely suited to this particularly dynamic and fluctuating environment? Furthermore, unlike the Atlantic and Pacific, large volumes of water (some 10 million m^3/s) flow into the IO at low latitudes from the Pacific through the ITF (McCreary et al., 2007). This inflow must impact nutrient concentrations in the IO and it must transport tropical plankton and even juvenile fish, but the magnitude and extent of this connectivity and its impacts are unknown.

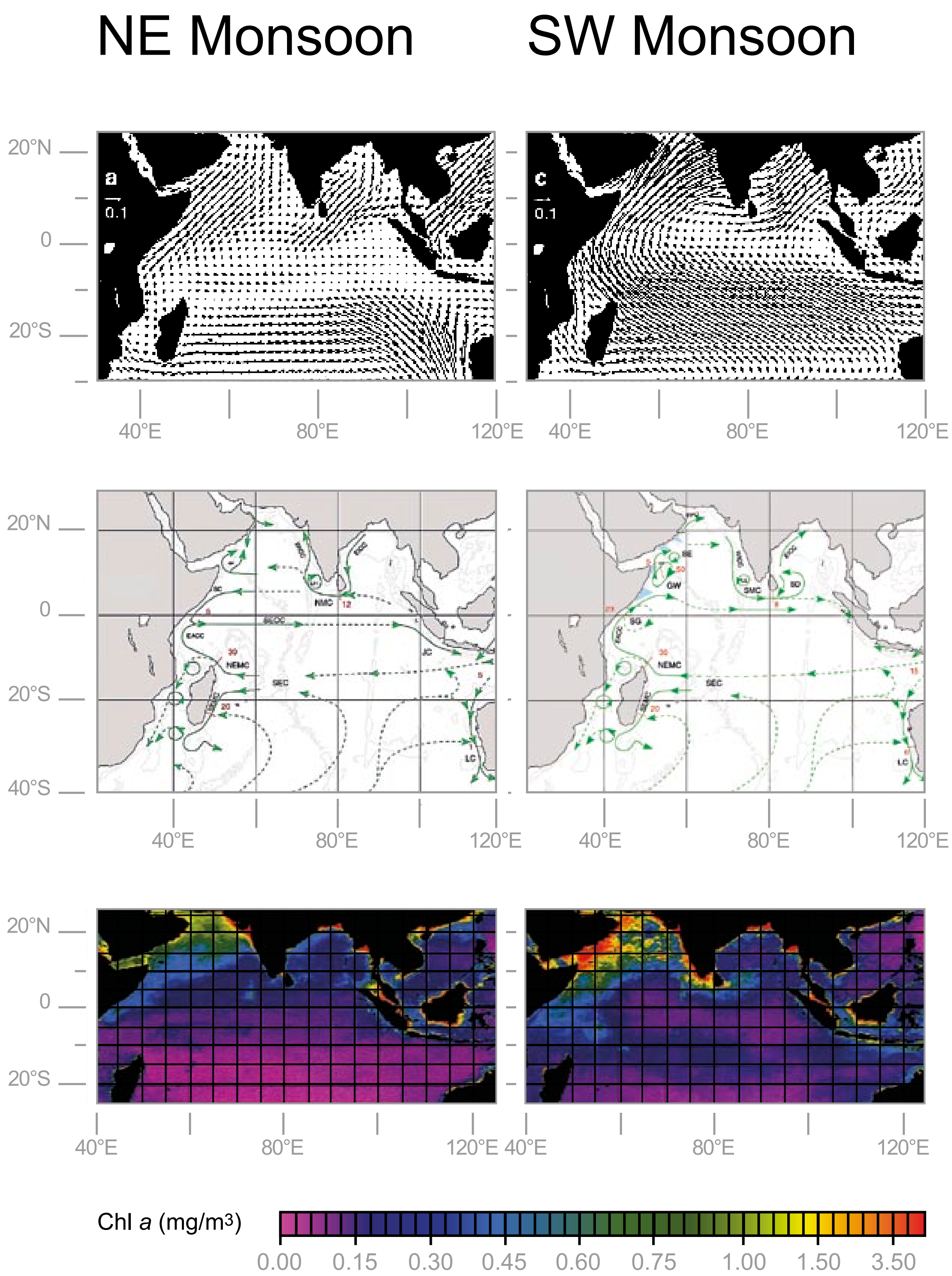

Figure 2 Comparison of winds (top), surface ocean circulation (center), and satellite-derived chlorophyll concentration (bottom) between the January-February (left column) and July-August (right column) periods in the IO.

The wind and circulation fields reproduced with permission from Schott and McCreary (2001), and the satellite chlorophyll concentrations with permission from Wiggert et al. (2006).

Control and fate of primary production

There are major questions and hypotheses that emerged from previous IO studies that still need to be addressed, such as the roles of zooplankton grazing and iron (Fe) availability in limiting phytoplankton production. For example, it has been hypothesized that some crustacean zooplankton species migrate from depth to the surface during the SWM in the AS and, through grazing, prevent accumulation of phytoplankton biomass (Smith, 2001). However, a new hypothesis has emerged that, due to upwelling of low Fe:N waters, Fe can limit phytoplankton production, despite elevated dust fluxes from bordering landmasses (Moffett et al., 2008; Naqvi et al., 2010; Wiggert and Murtugudde, 2007). The relative influence of grazing and Fe limitation needs to be explored in this region because the implications for biogeochemical cycling in the face of a changing climate differ under the two scenarios.

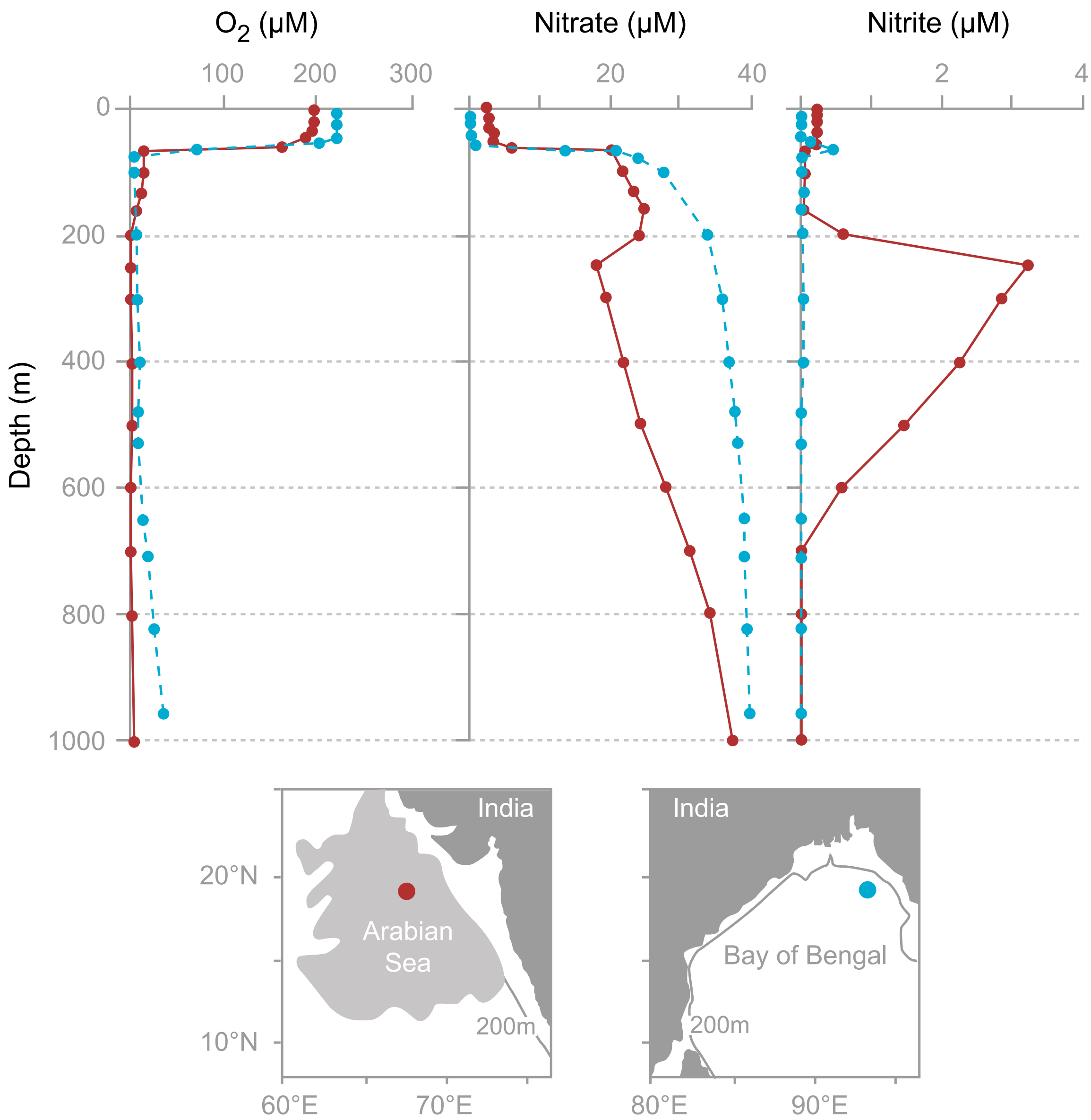

Figure 3 Comparison of vertical profiles of (a) oxygen, (b) nitrate and (c) nitrite in the AS (red circles) and BoB (blue circles). Maps (bottom) show station locations, and the AS depiction also shows the limit of the denitrification zone to the eastern-central basin.

Reproduced with permission from Naqvi et al. (2006b).

Moreover, the degree to which Fe limitation is active over the entire basin, and any linkages of its spatio-temporal variability to monsoonal forcing, are open questions (Behrenfeld et al., 2009; Mackie et al., 2008; Wiggert et al., 2006; Piketh et al., 2000; Mc Gowan et al., 2000).

There are profound physical and biogeochemical differences between the AS and the BoB. The AS is a globally important zone of open ocean denitrification (Naqvi et al., 2005), where NO_3 and NO_2 are converted to N_2O and N_2 gas, which are then released to the atmosphere (**Fig. 3**). Thus, denitrification removes N from the ocean and generates N_2O, which is a prominent greenhouse gas (Ramaswamy et al., 2001). This process occurs in oxygen-depleted subsurface waters (200–800m) in the eastern-central AS and contributes ~20% to global open ocean denitrification (Codispoti et al., 2001). In contrast, mesopelagic dissolved oxygen concentrations in the BoB are slightly higher so it remains poised just above the denitrification threshold. What are the relative roles of biological oxygen demand from surface organic matter export versus circulation and ventilation in maintaining subtle differences in the deep oxygen field along with the profound differences in biogeochemical cycling in these two regions? How have these differences been maintained over the last few decades and how are they likely to change in response to global climate change? Recent modeling studies suggest that OMZs will expand in response to global warming (Doney, 2010; Stramma et al., 2008), but uncertainties in model predictions are large, especially in the IO where global simulation models fail to reproduce the observed oxygen distributions. It should also be noted that the northern IO contains about two thirds of the global continental margin area in contact with oxygen deficient (O_2 < 0.3 ml l^{-1}) water (Codispoti et al., 2001), which is expected to expand and significantly impact benthic biogeochemical and ecological processes. Yet currently, rather little is known about these low oxygen impacts (Cowie, 2005).

The IO may also be a globally important zone of nitrogen fixation, where N_2 is split by diazotrophic cyanobacteria and converted to ammonium that can be readily utilized by phytoplankton. It has been estimated that 30-40% of euphotic zone nitrate in the AS is derived from N_2 fixation (Brandes et al., 1998) and this region's annual input of new N via this process has been estimated to be 3.3 Tg N yr^{-1} (Bange et al., 2005). However, there are very few direct N_2 fixation rate measurements from the IO. Thus, while it is agreed that the IO plays important roles in the global N cycle and budget, there is still not enough information to quantify the net atmosphere - ocean N flux in this basin.

Global change and anthropogenic impacts

The AS and BoB differ markedly in terms of freshwater flux and terrestrial nutrient loading (Seitzinger et al., 2005). The AS experiences net evaporation, whereas the BoB has large freshwater inputs from direct rainfall and surrounding major river systems such as the Ganges-Brahmaputra complex (**Fig. 4**). Coastal environments in the BoB are particularly vulnerable due to high river nutrient loadings in surrounding countries that are experiencing rapid increases in population density and economic growth (Millennium Ecosystem Assessment, 2005). Cholera in Bangladesh has already been linked to changes in sea surface temperature and height (Lobitz et al., 2000). To what extent are coastal environments in the BoB impacted by anthropogenic effects? How will they be impacted in the future? What are the potential human consequences?

Overall the AS is a source of CO_2 to the atmosphere because of elevated pCO_2 within the SWM-driven upwelling (**Fig. 5**). Whether the BoB is a CO_2 source or sink remains ill-defined due to sparse sampling in both space and time (Bates et al., 2006a). The southern IO appears to be a strong net CO_2 sink, but the factors that maintain this sink are unclear; cold temperatures certainly increase CO_2 solubility in the austral winter, but there is also evidence

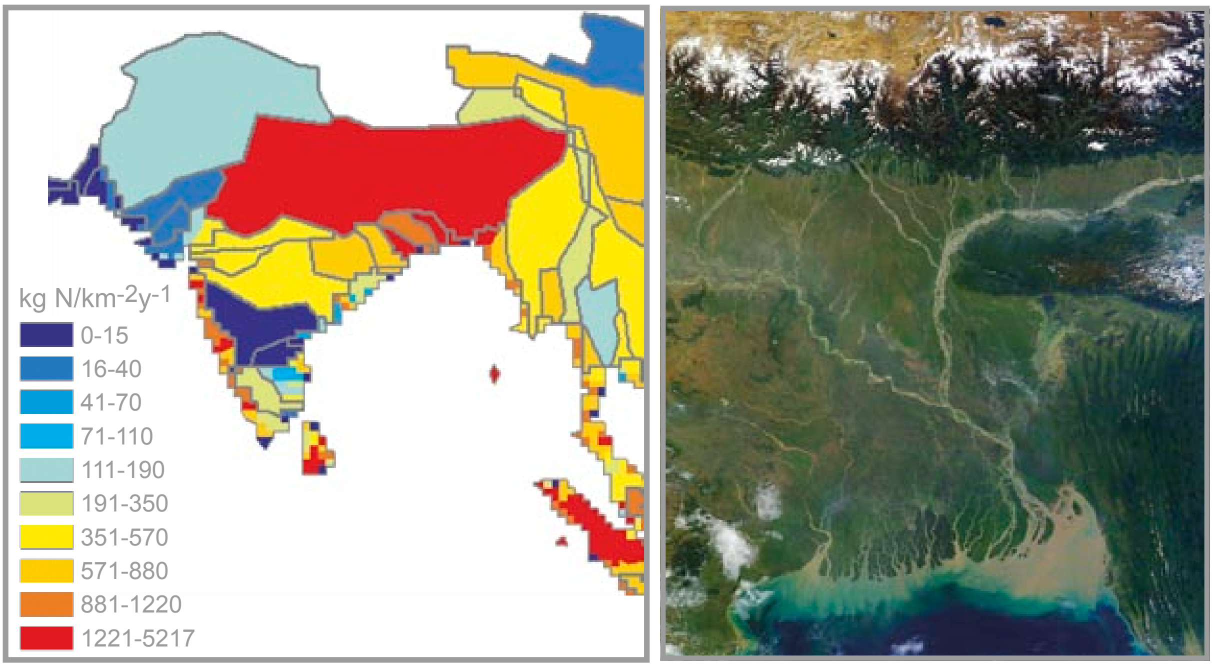

FIGURE 4 Predicted dissolved inorganic nitrogen (DIN) export (kg N/km^2/yr) for the IO region as estimated by the Global News model (left panel) and satellite visual imagery of the Ganges Brahmaputra River complex and sediment loading into the northern BoB (right panel).

The Global News model results were modified from Dumont et al. (2005).
The satellite visual imagery is reproduced from the Earth Snapshot (Eosnap web site).

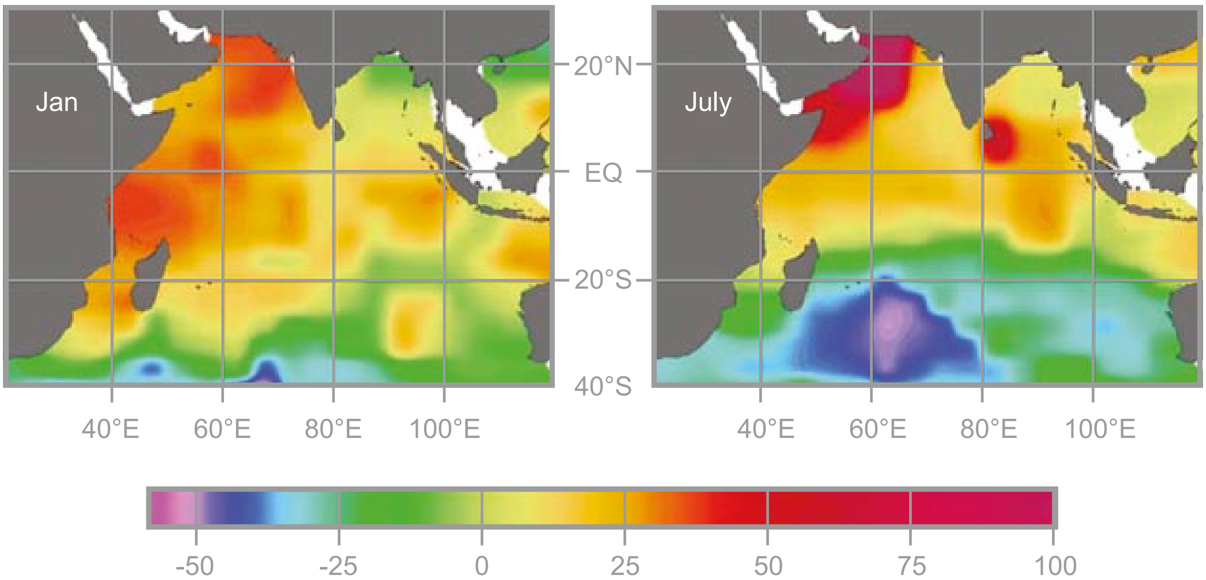

FIGURE 5 Air-sea pCO_2 difference (matm) between atmosphere and ocean for January and July from the climatology of Takahashi et al. (2002). Data are averaged over 4° x 5° areas and corrected to 1995. Regions with negative and positive values are ocean sinks or sources for atmospheric CO_2, respectively.

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that chemical and biological factors are important (Piketh et al., 2000; Wiggert et al., 2006). What combinations of factors control these sources and sinks of CO_2 in the IO, and how will they respond to increasing nutrient inputs and global warming? Regardless, the global trend of increasing atmospheric and oceanic CO_2 concentrations will lead to lower pH and acidification of the IO over the coming decades, with potential negative impacts on coral reefs and other calcifying organisms (Doney, 2010). How will this alter biogeochemical cycles, ecosystems and higher trophic levels in the IO? What will the human impacts be?

Because of its rapid warming (Alory and Meyers, 2009; Alory et al., 2007; International CLIVAR Project Office, 2006) the IO may provide a preview of how climate change will affect the biogeochemistry and ecology of other ocean basins and also human health. The SWM appears to be intensifying as a result of warming and it has been suggested that this is driving increased upwelling, primary production and ecosystem change in the AS (Goes et al., 2005; Gomes et al., 2009). Changes in the strength and duration of the monsoons will impact vertical mixing and freshwater and nutrient inputs in both the AS and the BoB and these in turn will impact human populations, especially in coastal areas. Increasing temperatures will also have direct impacts on marine ecosystems in the IO, likely altering food web dynamics, species distributions and the incidence of disease (Hoegh-Guldberg and Bruno, 2010). Increased frequency of coral bleaching events is also expected, which will lead to significant negative socioeconomic impacts (Wilkinson et al., 1999).

Role of higher trophic levels in ecological processes and biogeochemical cycles

Finally, it is important to consider the role of higher trophic levels in ecological processes, biogeochemical cycles and human health. The mesopelagic myctophid fish stocks in the AS (**Fig. 6**) are of global significance, both economically and ecologically (Gjøsaeter, 1984). This stock has been estimated at 100 million tons with a potential yield (harvest) of ~200,000 tons per year. These biomass and yield estimates need to be better constrained, and their time-space variability quantified. What role do these fish play in the ecological and biogeochemical

Figure 6 Myctophid fish caught by the fishing and oceanographic research vessel *Sagar Sampada* in the Arabian Sea.

Photographs courtesy of P. K. Karuppasamy.

dynamics of the AS? How do they interact with and tolerate the OMZ? Is commercial harvesting impacting stocks? How might climate change, including ocean acidification, affect the population? Migration of tuna in equatorial waters is strongly influenced by the anomalous forage distributions that result in response to climate phenomena like the IOD (Marsac et al., 2006). What are the dynamics of this impact? How are commercial pelagic species (like tuna) impacted by fishing? How will these stocks be impacted by global warming and what will the human consequences be?

Summary

The IO is an open frontier for oceanographic research. It is one of the most undersampled and least understood of the world's ocean basins. It also appears to be particularly vulnerable to climate change and anthropogenic impacts and could therefore provide crucial insights into how such alterations will affect the world's oceans. Yet it has been more than a decade since the last coordinated international study of biogeochemical and ecological processes was undertaken. To obtain a better understanding of the atmospheric and oceanic variability in the IO, CLIVAR (the Climate Variability and Predictability program) and GOOS (the Global Ocean Observing System) are deploying a basinwide observing system in the IO (the Indian Ocean Observing System, IndOOS) (International CLIVAR Project Office 2006). Although there are significant challenges, deployment of an array of more than 30 buoys, spanning the entire basin, is planned between 20°N and 20°S (the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction, RAMA). These deployments, are already well underway (McPhaden et al., 2009) and are accompanied by continuing deployment of Argo floats and a variety of physical oceanographic survey and mooring support cruises. In addition, several nations in the IO (most notably India, Oman and Australia) are deploying coastal observing systems. All these programs provide a unique opportunity for staging international, interdisciplinary research in the IO, to address research questions highlighted in this plan.

Science plan and implementation strategy

This section provides additional background information, identifies the major science questions that need to be addressed in the IO, and provides the basis for the planning and development of SIBER. This will be supplemented by more detailed information for specific aspects of the program as it progresses.

Introduction to SIBER

SIBER (Sustained Indian Ocean Biogeochemistry and Ecosystem Research) is an international program that aims to advance understanding of biogeochemical cycles and ecosystem dynamics of the IO. **The overarching goal of the program is to "understand the role of the IO in global biogeochemical cycles and the interaction between these cycles and marine ecosystem dynamics".** This understanding is required in order to predict the impacts of climate change, ocean acidification, eutrophication and harvesting on the global oceans and the Earth System. Such predictions are fundamental for policy makers to develop management strategies for the globally important IO. SIBER is therefore, highly relevant to the UNESCO Intergovernmental Oceanographic Commission (IOC) mission, by providing the underpinning science for the IOC's four High Level Objectives, which span across the generic themes of marine hazards, climate change, ecosystem health and environmental management.

To address this overarching goal, emphasis will be given to the analysis required to predict and evaluate impacts of natural and anthropogenic forcing on biogeochemical cycles and ecosystem dynamics in the IO. SIBER will leverage the sampling and observation activities of several coastal and open ocean observing systems (briefly discussed above and elaborated in the implementation plan below) that are being planned and deployed in the IO, and it will provide the basinwide scientific coordination required to predict IO biogeochemical cycles and ecosystem dynamics in the context of climate change and other anthropogenic influences.

SIBER has been developed to conform to the goals and scientific themes of the IMBER (Integrated Marine Biogeochemistry and Ecosystem Research) and IOGOOS (Indian Ocean Global Ocean Observing System) projects (**Fig. 7**). IMBER, with its focus on ocean biogeochemical cycles and ecosystems and their interactions, is building on the successes realized by the JGOFS and GLOBEC (Global Ocean Ecosystem Dynamics) projects. The IMBER vision is to "provide a comprehensive understanding of, and accurate predictive capacity for, ocean response to accelerating global change and the consequent effects on the Earth System and human society". By contrast, IOGOOS is a regional association of marine operational and research agencies that aims to promote GOOS in the IO region. IOGOOS is designed to: 1) monitor, understand and predict weather and climate; 2) describe and forecast the state of the ocean, including living resources; 3) mitigate damage from natural hazards and pollution; 4) protect life and property on coasts and at sea; and 5) enable scientific research. SIBER is a regional program of IMBER, with strong links to and joint oversight by IOGOOS. One potential benefit of this dual programmatic structure will be to promote links and coordination between IMBER and IOGOOS.

SIBER is a fusion of IMBER and IOGOOS with specific focus on major IO research questions. It is important to emphasize that SIBER embraces the complementary IOGOOS and IMBER goals of developing a monitoring and predictive capacity for detecting and predicting ocean responses to accelerating global change and consequent effects on the Earth System and human society. It is also important to emphasize that informed decisions require an understanding of which parts of the Earth System are most sensitive to change, and the nature and extent of anticipated impacts. This requirement is a major motivation for SIBER, i.e. there is evidence to suggest that the IO is particularly sensitive to global change, yet it is one of the most poorly understood basins in terms of its physical, biogeochemical and ecological dynamics.

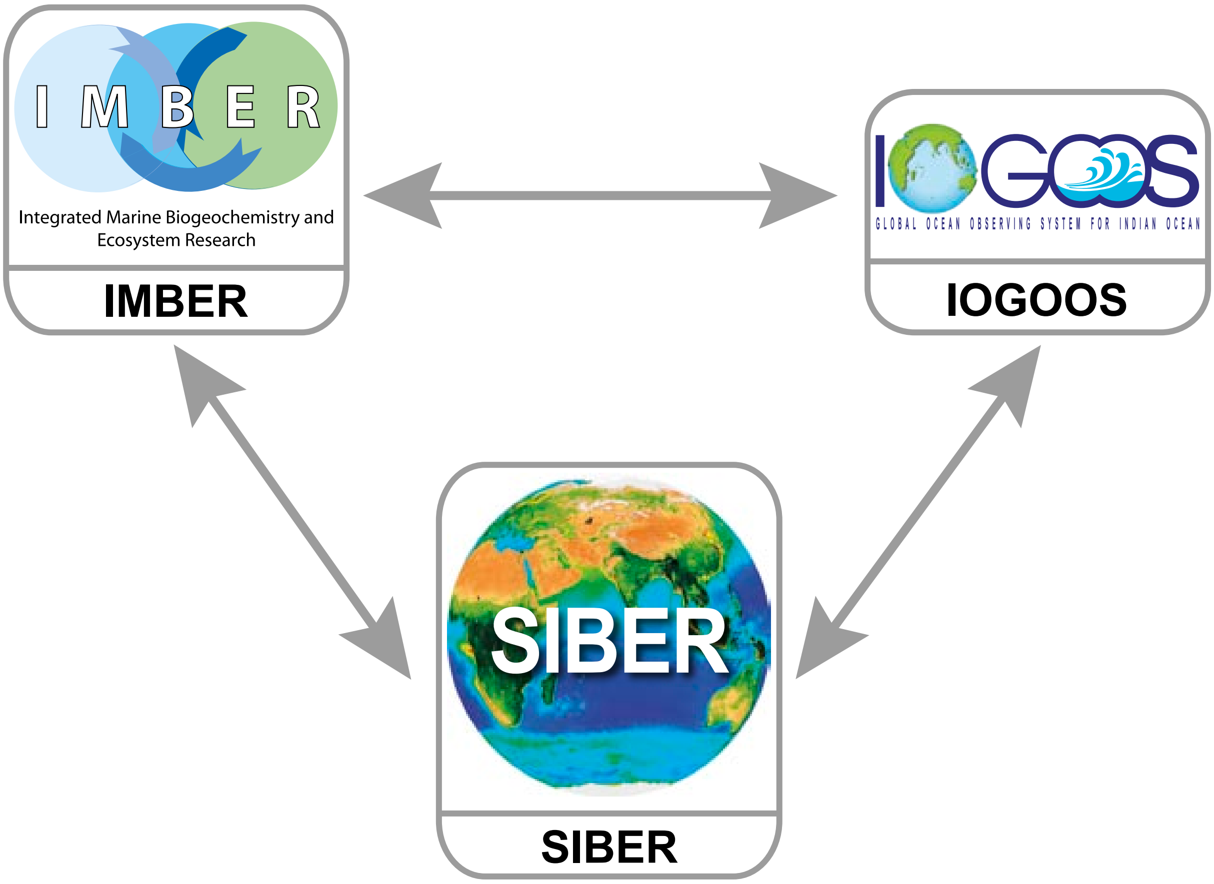

Figure 7 Schematic diagram showing the relationship between SIBER and the two international projects that will provide oversight and guidance.

Scientific themes

SIBER is structuring its research around six scientific themes, each focusing on a specific set of issues that need to be addressed in order to improve understanding of the biogeochemical and ecological dynamics of the IO and develop a predictive capability. These themes can be broadly separated into three that are regionally focused (Themes 1-3) and three that address wider scientific questions (Themes 4-6).

Regional scientific themes

Theme 1: Boundary current dynamics, interactions and impacts

How are marine biogeochemical cycles and ecosystem processes in the IO influenced by boundary current dynamics?

Background

Boundary currents mediate the transfer of global and regional forcings to local coastal scales. In this process, they fundamentally alter biogeochemical fluxes and ecosystem processes. One major mechanism is the generation of mesoscale eddies by boundary currents, which in turn impinge on coastal regions with profound impacts. In the IO, several boundary current systems are seasonally reversing (e.g. the Somali Current (SC), West (WICC) and East (EICC) India Coastal Currents, and the Java Current (JC), **Fig. 2**). These reversing surface currents are unique to monsoon-driven systems. The southern currents (Agulhas and Leeuwin) both flow poleward throughout the year (**Figs. 2, 8 and 9**). The Leeuwin Current (LC) is particularly anomalous in that it is the world's only major eastern boundary current that flows poleward. The LC is driven by the ITF (**Figs. 2 and 8**), which is a complex set of pathways that connect the IO with the eastern Pacific (Domingues et al., 2007; McCreary et al., 2007). In general, the biogeochemistry and ecology of southern hemisphere currents have been less comprehensively studied than their northern counterparts and significant uncertainties still exist regarding their dynamics and interactions.

The primary mechanisms whereby boundary currents impact ecosystems include control of local water temperature, nutrient supply and mixed-layer depth. Impacts are influenced by the intermediate water masses that feed boundary currents and therefore, determine their physical and chemical properties. Boundary currents also mediate alongshore and cross-shelf transport of whole planktonic ecosystems, including early growth stages of commercially important finfish and shellfish species. Flow instabilities are commonly observed in boundary currents. They can be initiated through interaction with shelf topography or develop spontaneously in deeper waters. These instabilities give rise to mesoscale eddies, localized fronts or filaments, all of which can mediate cross-shelf transport of nutrients and plankton communities. These features can also form important aggregation points that promote larval recruitment and draw fish and megafauna to regions of enhanced nutrients, plankton and food supply.

Biological variability in boundary current systems is driven by remote (e.g. propagation of coastally trapped or open ocean Rossby waves) and local (e.g. coastal sea breezes by diurnal land warming) forcings. It is important to disentangle the relative impacts of these forcing mechanisms in future studies, particularly those aimed at assessing impacts of climate variability and climate change on IO biogeochemistry and ecology. Since boundary current systems are dynamic and complex, remote sensing and modeling are crucial investigative

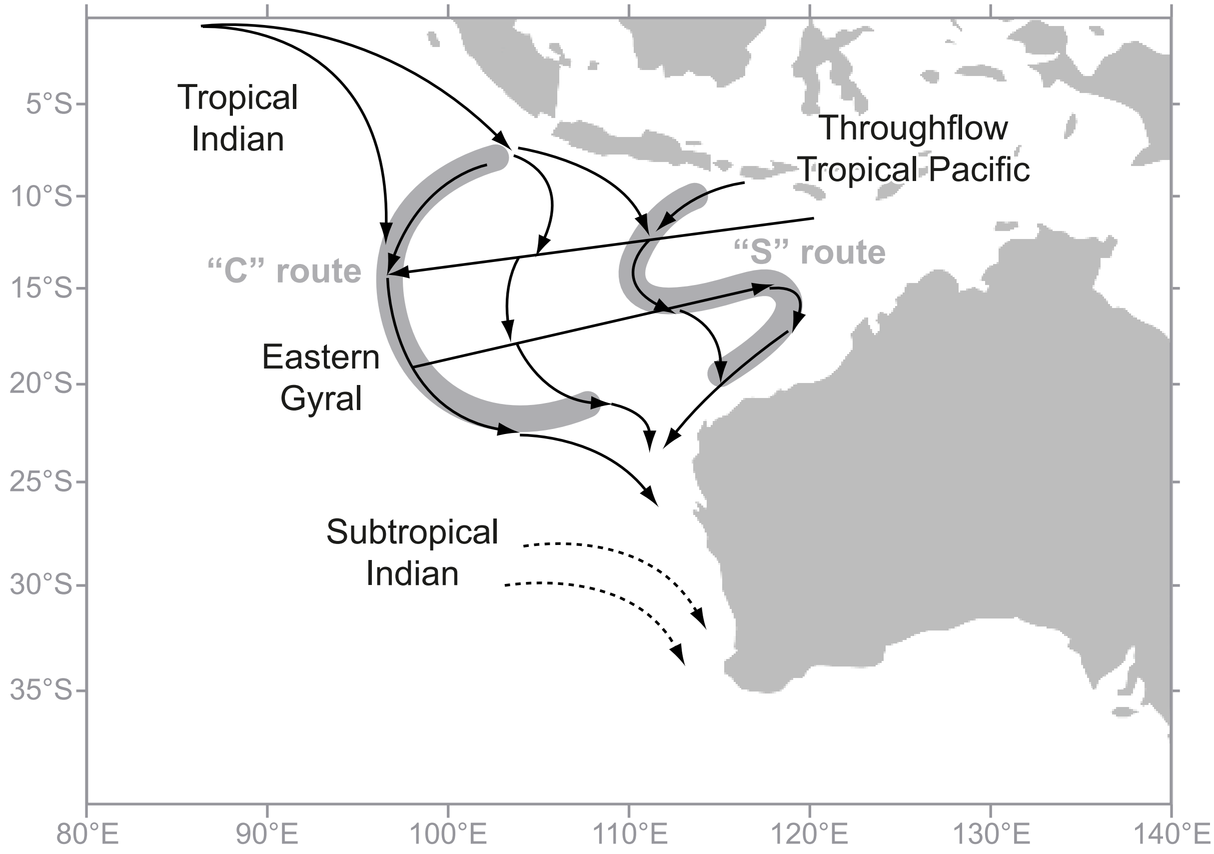

FIGURE 8 Sources of the Leeuwin Current.

Reproduced with permission from Domingues et al, 2007.

tools, along with new, rapid, *in situ* sampling technologies. Modeling boundary current systems is also challenging because it requires very high resolution models (see Implementation Strategy below). How accurate are the state-of–the-art models in representing key processes like nutrient and particle fluxes in the boundaries of the IO? What observations are needed to appropriately test the skill of these models?

Core questions

The questions below should be addressed with specific reference to the influence of local versus remote forcing, and interactions with intermediate and adjacent water masses. Remote sensing and modeling should play important roles, especially in initial and more exploratory studies of IO boundary current systems (see Implementation Strategy below).

1) What are the biogeochemical and ecological impacts of seasonally reversing currents in the northern IO?

The biogeochemical and ecological impacts of the seasonally reversing boundary current systems in the northern IO are poorly understood. Their temperature, sea surface height anomaly and chlorophyll signatures, and how physical processes dictate the seasonal phases, remain unclear. Impacts of current reversals on higher trophic levels (e.g. behavior of zooplankton and nekton and spawning patterns of fishes) are not understood. The implications of these current reversals for human populations and how these currents and their impacts might alter with climate change are further topics for investigation. Northern IO current systems that could be targeted for study include the Somali Current system (which includes the Southern Gyre and the East African Coastal Current), the Oman Coastal Current system (which includes the

Oman Coastal Current, the Great Whirl, and the Socotra Eddy), the WICC and EICC, and the JC (**Fig. 2**).

2) What are the biogeochemical and ecological impacts of the poleward flowing boundary currents of the southern Indian Ocean?

Although the physical dynamics of the Agulhas Current (AC) and its source waters are reasonably well understood (Lutjeharms, 2007), the biology is relatively understudied. The two major source regions for the AC are from the north through the Mozambique Channel and from the east via the East Madagascar Current (**Figs. 2 and 9**). On average, the AC retroflects south of the continent to return eastward and the deep mesoscale eddies (rings) generated here potentially have strong impacts on the ecology and biogeochemistry of the marine ecosystem. The key physical processes and trophic links that support the oceanic tuna fisheries of the western IO, including those within the Mozambique Channel (Poitier et al., 2007), require further elucidation. An understanding of the physical and/or biological processes (e.g. N_2-fixation) that drive the elevated chlorophyll and productivity signatures that have been observed in association with the East Madagascar Current is required (Uz, 2007). Similarly, the physical processes that drive elevated chlorophyll concentrations inshore of the AC, and the role played by the AC system in supporting higher trophic level production off the SE coast of Africa (Beckley, 1998; Beckley and van Ballegooyen, 1992; Olivar and Beckley, 1994) need further study. Recent evidence of a regional regime shift in productivity and ecosystem

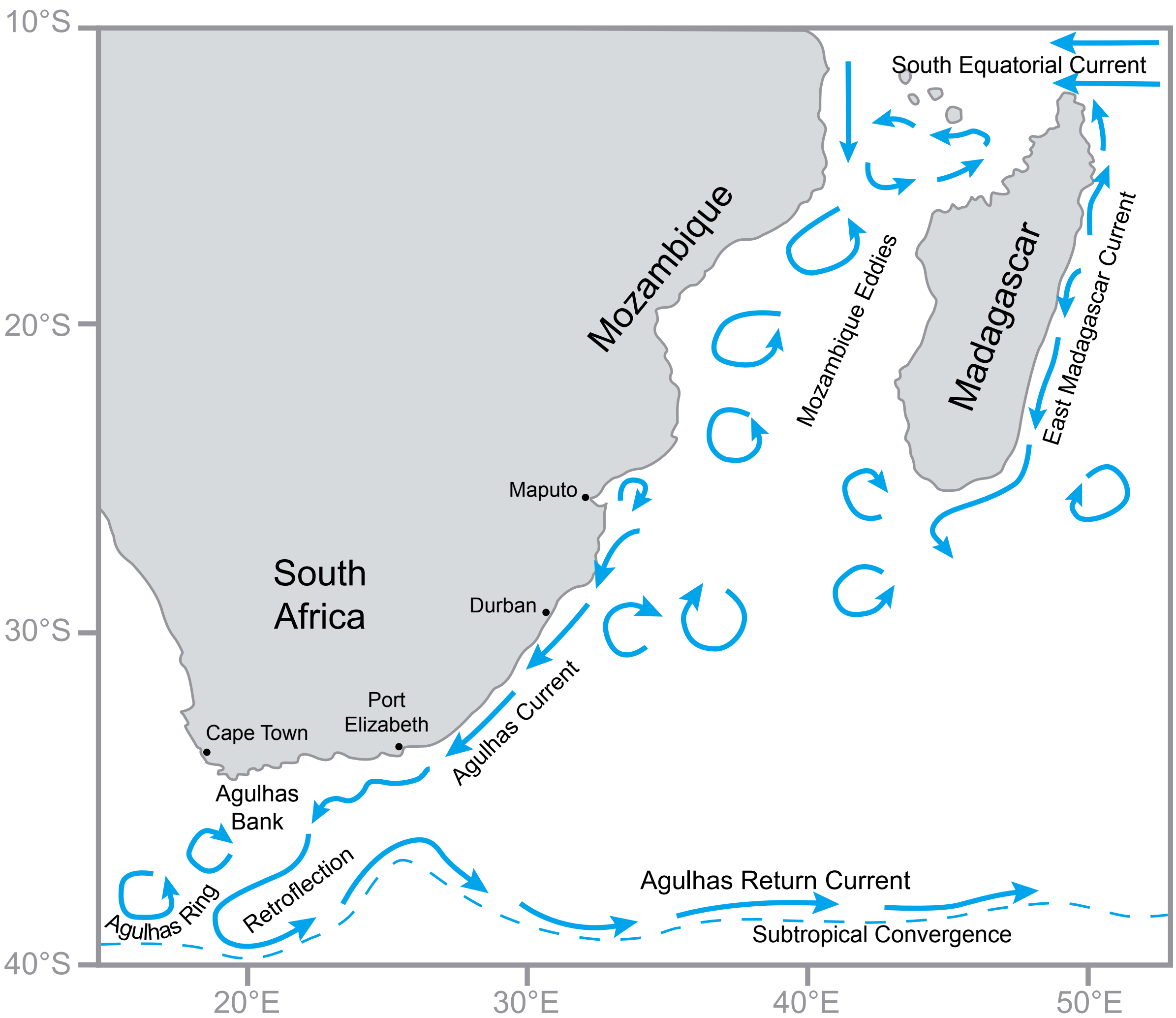

Figure 9 Flow in the Agulhas Current.

Reproduced with permission from Lutjeharms (2006).

structure from west to east around the South African coast (Coetzee et al., 2008) warrants further investigation. Does the warm water of the AC retroflection stabilize the cool temperate water of the subtropical front south of Africa and lead to increased phytoplankton biomass in the southern IO? Finally, an exploration of the potential impacts of climate change on the inter-basin transfer of heat and biogeochemical signatures of the AC rings that follow a NW trajectory into the Atlantic is needed.

The poleward flow of the Leeuwin Current (LC) is unique among eastern boundary currents of the southern hemisphere. It has many unusual attributes, including the generation of warm core eddies that have enhanced productivity (Hanson et al., 2007), induction of "cryptic upwelling" where the nutricline and thermocline are lifted towards the surface but do not outcrop (Gersbach et al., 1999; Twomey et al., 2007), and a planktonic ecosystem structure dominated by very small organisms. Further, strong empirical correlations have been found between rock lobster recruitment and LC transport (Caputi, 2008) (**Fig. 10)**, but the mechanisms underlying this relationship are not understood. Elucidation of net cross-shelf transport in the LC region and the mechanisms that drive this flux are required. The impact of "cryptic upwelling" on nutrient cycling, primary production, phytoplankton community structure and higher trophic levels in

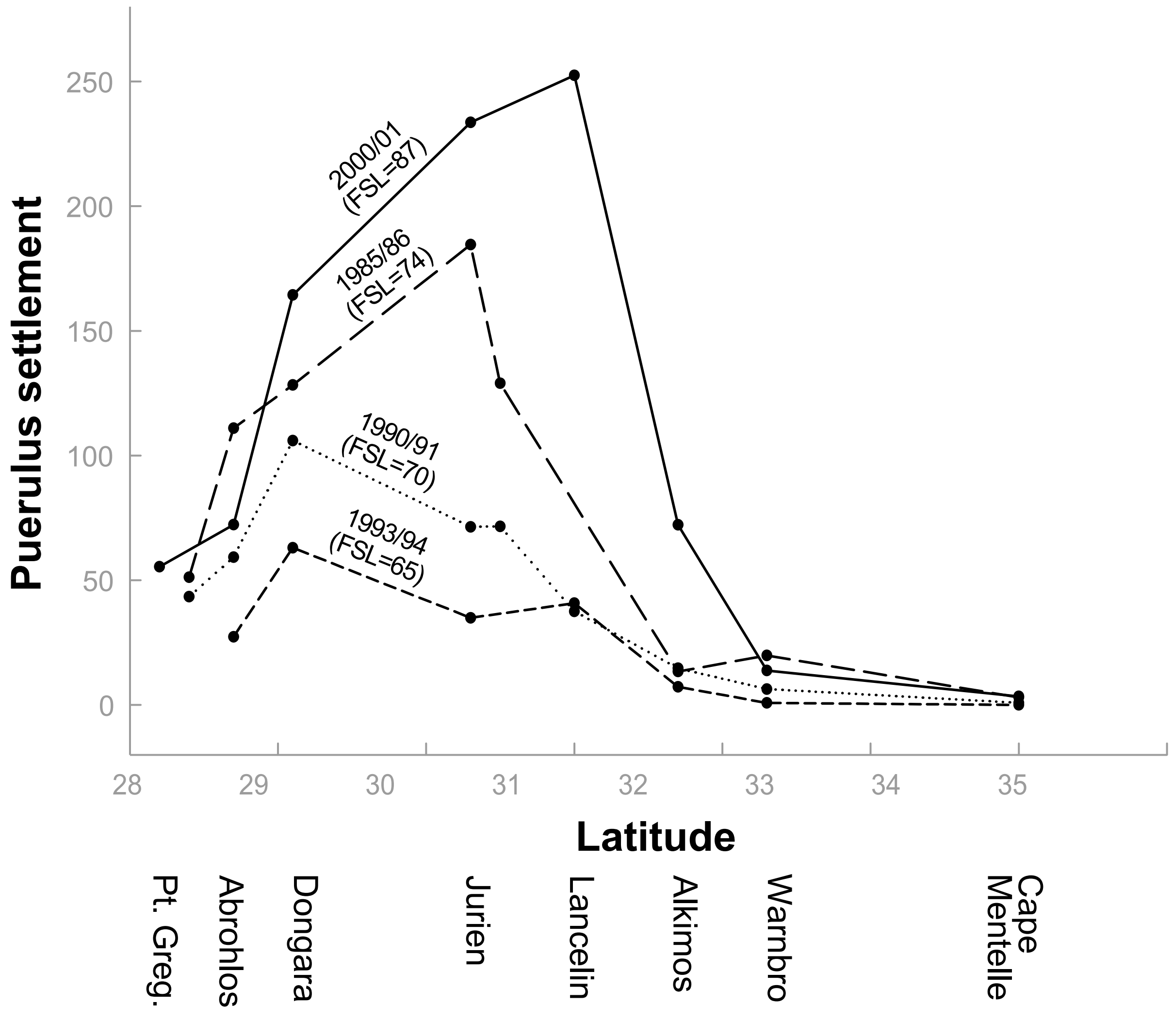

Figure 10 Spatial distribution of western rock lobster (*Panulirus cygnus*) puerulus (post-larval stage) settlement (number of puerulus per collector per year) for four years of contrasting Leeuwin Current strength shown by the index of annual Fremantle sea level height (FSL in cm).

Reproduced with permission from Caputi (2008).

this oligotrophic region needs further exploration. Similarly, the biogeochemical impact of the LC's anomalous (small) planktonic ecosystem structure remains elusive, as does the impact of variability in the LC system on the transport of larvae. Finally, a better understanding of the climate-induced fluctuations associated with the ENSO and Southern Oscillation Index modes on the transport of biogeochemical and ecological properties of the LC is needed.

3) How do the mechanisms that cause mesoscale eddies vary between the AS and BoB?

Due to the influence of the strong and seasonally reversing monsoon winds, the AS and BoB are highly energetic systems which generate numerous mesoscale eddies. The primary mechanisms that generate these eddies and how these differ between the AS and the BoB is not yet known. Further, the impact of these eddies on the biogeochemical properties of coastal waters, ventilation of subsurface waters and distribution of the oxygen minimum zones, warrants examination. Do these eddies impact regional biodiversity by influencing biogeochemical properties which in turn force shifts in planktonic species composition such as *Noctiluca* and/or *Trichodesmium* dominance in the northwestern AS (Parab et al., 2006), and thus also higher trophic levels? Are sub-mesoscale chlorophyll features and filaments ecologically important for higher trophic levels? Does eddy-induced production and/or vertical mixing play a role in determining the intensities and distribution of the oxygen minimum zones in the AS and the BoB?

Theme 2: Variability of the equatorial zone, southern tropics and Indonesian throughflow and their impacts on ecological processes and biogeochemical cycling

How do the unique physical dynamics of the equatorial zone of the IO impact ecological processes and biogeochemical cycling?

Background

There is a striking contrast between equatorial biological distributions in the IO and those in the Pacific and Atlantic Oceans. The IO typically exhibits elevated chlorophyll concentrations in the west and highly oligotrophic conditions in the east (**Fig. 2, bottom panels**) that result from the westward shoaling of the thermocline and nutracline. While the physical processes of the equatorial IO have been comprehensively investigated (see below), the associated biogeochemical and ecological spatio-temporal variability has not, and there are few examples of either observational or modeling efforts (Hanson et al., 2007; Resplandy et al., 2009; Waite et al., 2007; Wiggert et al., 2006). Given the equatorial IO's atypical, dynamic and fluctuating physical environment, does this lead to unique adaptations and/or species complements within the marine ecosystems? If so, do these in turn lead to subtle contrasts in attendant biogeochemical variability in comparison to the other oceans? The fundamental overarching question here is: what physical forcing mechanisms are responsible for the observed variability in biogeochemical processes and ecosystems in equatorial IO waters and the southern tropics?

Beyond seasonal monsoon dynamics that extends southward to ~10°S, the equatorial and southern regions of the IO are fundamentally affected by additional physical processes on intraseasonal to interannual time scales. Within the equatorial band, eastward propagating Wyrtki Jets occur semi-annually during intermonsoon periods, developing primarily as a result of equatorial westerlies (Han et al., 1999; Wyrtki, 1973). The main impact of these jets on biogeochemical distributions is to depress the thermocline/nutracline in the eastern side of the basin upon their arrival in May and November. The equatorial wind regime precludes development of tropical instability waves and the associated biological responses that are

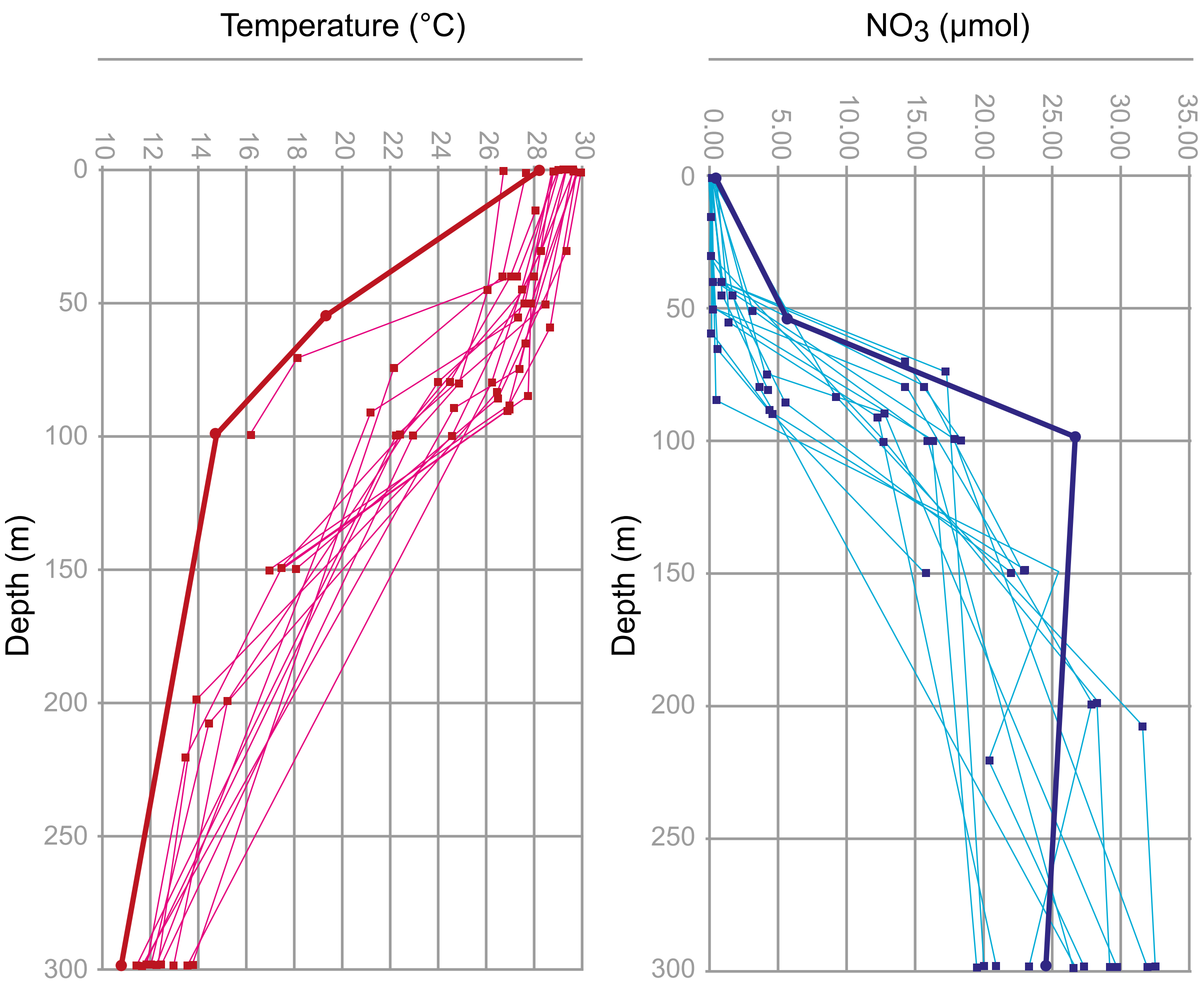

Figure 11 Observations by Subramaniam (unpublished) during the March 1999 INDOEX cruise, a period unaffected by the IOD, revealed the typical elevated thermocline (left panel) and nutracline (right panel) structure in the Seychelles-Chagos Thermocline Ridge.

common to the equatorial Atlantic and Pacific (Chelton et al., 2000; Strutton et al., 2001). In the southern tropical IO (STIO), seasonally varying advection associated with the ITF and its connection to the western Pacific plays a primary role in defining STIO dynamics (Gordon and Fine, 1996; Potemra, 1999). Moreover, the STIO is the site of Rossby waves that modulate thermocline/nutracline depth as they progress westward across the basin. The Madden-Julian Oscillation (MJO) is characterized by 40-60 day variability in the atmospheric convection associated with strong perturbation of the surface (heat, momentum, freshwater) fluxes and SST (Madden and Julian, 1994). Finally the basin's inherent climate mode, the IOD, is characterized by anomalous upwelling in the eastern IO, anomalous equatorial winds and increased oceanic heat content in the 5-10°S band (Saji et al., 1999; Vinayachandran et al., 2009). When it is active, the IOD modulates the flux of the ITF, the Wyrtki Jets and the MJO (Shinoda and Han, 2005); all of these contribute to prominent ecosystem anomalies that manifest throughout the basin (Resplandy et al., 2009; Wiggert et al., 2009).

A region that is especially affected by forcing over all of these time scales is the Seychelles-Chagos Thermocline Ridge (SCTR, Vialard et al., 2009), which is characterized by a shallow mixed layer (~30m) across the IO within the 5-15°S band of the STIO. Recent observations have shown that the SCTR is established by a combination of ITF input from the east and a permanent thermocline ridge set up by the typical wind curl distribution. Observations by Subramaniam (unpublished) during the March 1999 INDOEX cruise, a period unaffected by the IOD, reveal standard depths of the thermocline and nutracline (**Fig. 11)**. The SCTR is depressed at intraseasonal and interannual time scales in association with MJO and IOD activity. Recent studies suggest a clear impact of the MJO and IOD on the region's upper ocean chlorophyll concentration, with the IOD acting to significantly reduce biological response to MJO events due to an anomalously deepened thermocline and nutracline (Resplandy et al., 2009; Vialard et al., 2009).

Core questions

The Southern Tropical Indian Ocean (STIO):

1) How do local and remote forcing mechanisms and the Indonesian Throughflow combine to prescribe the physical environment that in turn drives variability in the biological distributions, primary productivity and export flux of the southern tropical IO?

The ITF connects the Pacific and Indian Ocean basins providing an estimated input to the IO of ~10Sv (Gordon and Fine, 1996; McCreary et al., 2007). This influences water mass properties of the IO through heat and freshwater exchange; indeed, it has been suggested that ITF waters propagate across the STIO and into the AS via the Somali Current during the SWM (Song et al., 2004). Exchange and transport of nutrients, plankton and even juvenile fish via the ITF could fundamentally influence biogeochemical and ecological variability, especially in the southeastern IO, but the extent of this impact is unknown. What is the total nutrient flux contributed by the ITF directly to the IO, how do ITF dynamics contribute to nutrient fluxes regionally, and how are these nutrients subsequently distributed? More specifically, do these inputs influence the biogeochemical properties of the South Equatorial Current (SEC) and the Leeuwin Current (LC **Fig. 2**) (Feng et al., 2009) and what are the dominant scales of temporal variability of this nutrient input? The LC and its attendant mesoscale features clearly contribute significantly to the spatio-temporal variability of chemical, biological and ecological distributions off NW Australia (Hanson et al., 2007; Muhling et al., 2007; Pearce et al., 2006), but further studies are needed. Regional hydrological processes result in differential phasing of phytoplankton seasonal cycles throughout the Indonesian archipelago (Kinkade et al., 1997) while the influence of Indo-Pacific exchanges that occur in the ITF is manifested in the distribution of plankton concentration, planktonic foraminifera and fish (Martinez et al., 1998; Ovenden et al., 2002). What are the underlying mechanisms? Is passive east to west transport primarily responsible? Are there meridional speciation gradients across the ITF passage? Do organisms take advantage of subtle circulations beyond the ITF's zonal transport in determining their distribution patterns? How are these patterns altered in response to perturbations associated with the IOD and MJO? How significantly do freshwater inputs from the Indonesian archipelago affect regional ecosystem and biogeochemical variability? How do the ITF and its fluctuations affect nutrient concentrations and ecosystem processes of the Kimberley and the NW shelf of Australia?

Local wind curl and the ITF fundamentally prescribe thermocline depth within the SCTR, with modulations imposed by westward propagating Rossby waves. However, more knowledge of the interaction of these mechanisms is needed, especially to reveal how they collectively generate associated biogeochemical variability. Finally, as vast areas of the STIO are remote from the terrigenous dust sources of the IO they are likely to be influenced by the availability of dissolved Fe. Indeed, independently derived results from a coupled physical-biogeochemical modeling study and remote-sensing based distributions of phytoplankton physiological state suggest that Fe limitation affects much of the STIO, particularly in the west (Behrenfeld et al., 2009; Wiggert et al., 2006). What is the magnitude of primary production in the SCTR and how significantly does it contribute to higher trophic levels? How prominent and widespread is Fe limitation and how does this affect the accumulation of phytoplankton biomass that supports these higher trophic levels? What contribution does the SCTR make toward supporting commercially significant fisheries? In general, what role does the SCTR play in the biogeochemical and ecological dynamics of the STIO? How are the biogeochemical and ecological signatures of the SCTR modulated by intraseasonal, seasonal and interannual perturbations associated with the IOD, MJO, etc.? Within the broader STIO, do Rossby wave-induced chlorophyll signatures have a significant impact on regional production and export flux? Do pelagic fish track these features and do commercial fisheries target them in turn?

Seasonal variability:

2) What biophysical mechanism(s) associated with semi-annual Wyrtki Jets drive seasonal biogeochemical and ecological variability within the equatorial waveguide?

The seasonally reversing monsoon winds give rise to strong seasonality in surface ocean circulation, especially in equatorial waters and in the northern IO. The Wyrtki Jets, described above, are pronounced equatorial manifestations of this forcing. These semi-annual jets have no equivalent in other ocean basins, and their impact on biogeochemical cycles and ecosystem dynamics has received little attention. Is this impact exerted via horizontal advection of nutrients or solely by their influence on nutracline depth as postulated by Wiggert et al. (2006). What role might these jets play in the life cycles of planktonic organisms? Do they provide a west to east transport vector for communities of phytoplankton, zooplankton and larval fish in equatorial waters of the IO? We can anticipate that the strong seasonal forcing in the IO also induces much stronger seasonality in the zonal thermocline/nutracline structures and upwelling patterns in the equatorial zone compared to the Atlantic and the Pacific. However, this seasonality in biogeochemical and ecological patterns has yet to be characterized. It is therefore, essential to initially consider how seasonality in equatorial waters impacts zonal equatorial primary production and how this propagates up to higher trophic levels.

Intraseasonal variability:

3) What is the impact on the stocks and fluxes of the pelagic ecosystem during intraseasonal or episodic events and how significantly do these contribute to regional or local biogeochemical budgets?

Intraseasonal phenomena are characterized by variability on subseasonal timescales. One prominent example in the IO is the MJO, noted above. Remote sensing data suggest that sea surface winds associated with MJO events typically induce phytoplankton blooms (Resplandy et al., 2009; Waliser et al., 2005), which presumably have associated impacts on apex predators (e.g. tuna). This can so far only be inferred. Is there a constant, systematic biogeochemical and ecological signature that manifests in response to MJO events? There is also bi-weekly atmospheric variability over the IO (Chatterjee and Goswami, 2004) that elicits a clear oceanic response along the equator (Sengupta et al., 2004). Do the strong vertical velocity signals associated with the bi-weekly variability in the equatorial region modulate the distribution of biogeochemical properties? The westward propagating Rossby waves, are another aspect of intraseasonal variability that are the combined result of atmospheric forcing and internal instabilities (Zhou et al., 2008). These Rossby waves have clear signatures in the ocean color data (Cipollini et al., 2001), and interpretations of biophysical modeling studies diverge on whether these biological signals are associated with nutracline or deep chlorophyll maximum (DCM) uplift (i.e. growth vs. vertical transport) (Kawamiya and Oschlies, 2001; Wiggert et al., 2006). The biogeochemical significance of these features remains to be established. Do intraseasonal variations associated with these various physical processes or episodic events, such as cyclones, contribute significantly to the biogeochemical budgets of the equatorial and southern tropical IO regions that are generally oligotrophic?

The Indian Ocean Dipole:

4) How does IOD affect regional biogeochemical fluxes, fisheries activities and the impact of higher frequency forcings, and to what degree are these responses a preview of climate change?

The dominant biological signature associated with the IOD is the anomalous elevated chlorophyll that appears along the southwest coast of Java/Sumatra and extends westward within the equatorial and southern tropical IO during fall (**Fig. 12**). This develops as a result of the combined weaker Wyrtki Jet and anomalous winds in the east that promote shoaling of the eastern thermocline/nutracline. Analysis of a remote-sensing based production algorithm indicates that carbon uptake can double (Murtugudde et al., 1999; Wiggert et al., 2009). How does the altered physical environment of the IOD act to redistribute primary production, export production and carbon flux throughout the IO and to what degree do IOD manifestations modulate the influence of the higher frequency-mechanisms described above (e.g. the MJO)? Do the anomalous atmospheric forcings that stimulate IOD appearance also result in pronounced change of atmospheric dust (and Fe) deposition patterns?

During the 1997/98 IOD, there were also significant responses in the central AS and southern BoB (Vinayachandran and Mathew, 2003; Wiggert et al., 2002) (**Figs. 12 and 13**). Moreover, during this IOD catch per unit effort (CPUE) for the equatorial IO tuna fishery shifted eastward (Marsac and Le Blanc, 1999; Menard et al., 2007) and there were catastrophic losses of coral communities in western subtropical waters (Spencer et al., 2000). Is this diverse assortment of ecosystem responses typical or is there significant variation in how IOD events alter biogeochemical processes within the equator and STIO, or the other IO regions? How do these perturbations combine and propagate through the food web and influence apex predators such as tuna? Finally, what are the socio-economic impacts of the IOD? Rainfall patterns around the IO are significantly altered (Ashok et al., 2004; Meyers et al., 2007; Saji and Yamagata, 2003), which must also modify patterns of runoff and nutrient loading in coastal waters of the IO rim nations. Do these influence coastal fisheries or human health directly? To what degree does the IOD impact the intensity of coastal and open ocean OMZs and the unique biogeochemical cycles and fluxes that are associated with them?

Theme 3: Physical, biogeochemical and ecological contrasts between the Arabian Sea and the Bay of Bengal

How do differences in natural and anthropogenic forcings impact the biogeochemical cycles and ecosystem dynamics of the AS and the BoB?

Background

Although both the AS and the BoB are strongly influenced by the monsoons and are similar in terms of size, latitude and proximity to the northern land boundary, they also have many important physical, biogeochemical and ecological differences. These differences are expressed, for example, in their response to global warming, which is much stronger in the AS than in the BoB (**Fig. 14**), as well as in CO_2 emission. While the AS is clearly a net emitter of CO_2 to the atmosphere (Goyet et al., 1998; Sarma et al., 1998), the BoB seems to be a sink in winter and a weak source in summer (**Fig. 5**).

The most striking difference between the two basins is the impact of the monsoons. The SWM winds are stronger over the AS, forming an intense atmospheric (Findlater) jet (**Fig. 2, upper right**) that drives vigorous upwelling along the coasts of Oman, Yemen and Somalia, as indicated by high chlorophyll concentrations (**Fig. 2, bottom right**). Surface circulation in both basins reverses seasonally (**Fig. 2, middle panels**) but chlorophyll-rich filaments, jets and eddies that extend offshore can be seen only in the western AS (**Fig. 2, bottom right**). Upwelling-favorable winds also blow northeast along the east coast of India during the SWM (**Fig. 2, upper right**), but they are much weaker and therefore do not generate such a strong surface upwelling signature. In general, the SWM winds produce much higher levels of surface kinetic energy in the AS compared to the BoB. Similarly, during the NEM the winds blow from the northeast over the AS and the BoB. However, the winds reaching the AS from the Tibetan Plateau are colder and dryer and impinge upon a less stratified and more saline surface water

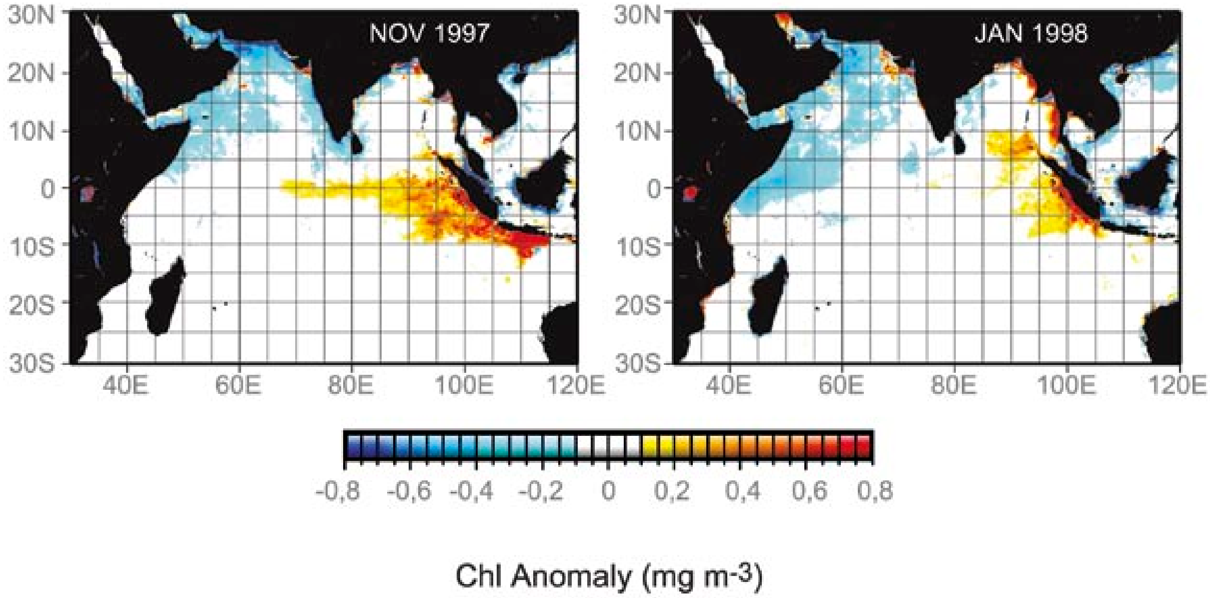

FIGURE 12 Distribution of chlorophyll anomaly observed by SeaWiFS during the 1997/98 IOD. Values in the range of ±0.1 mg m^{-3} have been masked in order to highlight the features of interest.

Reproduced with permission from Wiggert et al. (2009).

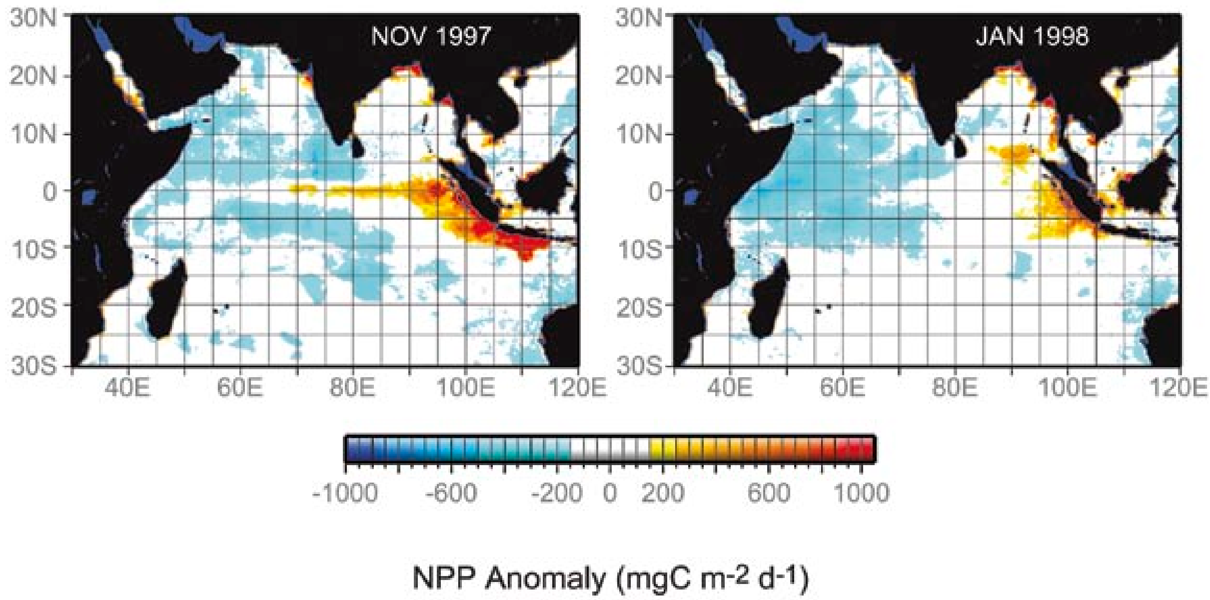

FIGURE 13 Distribution of net primary production anomaly (NPPa, mgC m^{-2} d^{-1}) during the 1997/98 IOD, where NPP is obtained with the production model of Behrenfeld et al. 2005. Values of NPPa in the range of ±175 mgC m^{-2} d^{-1} have been masked in order to highlight the features of interest.

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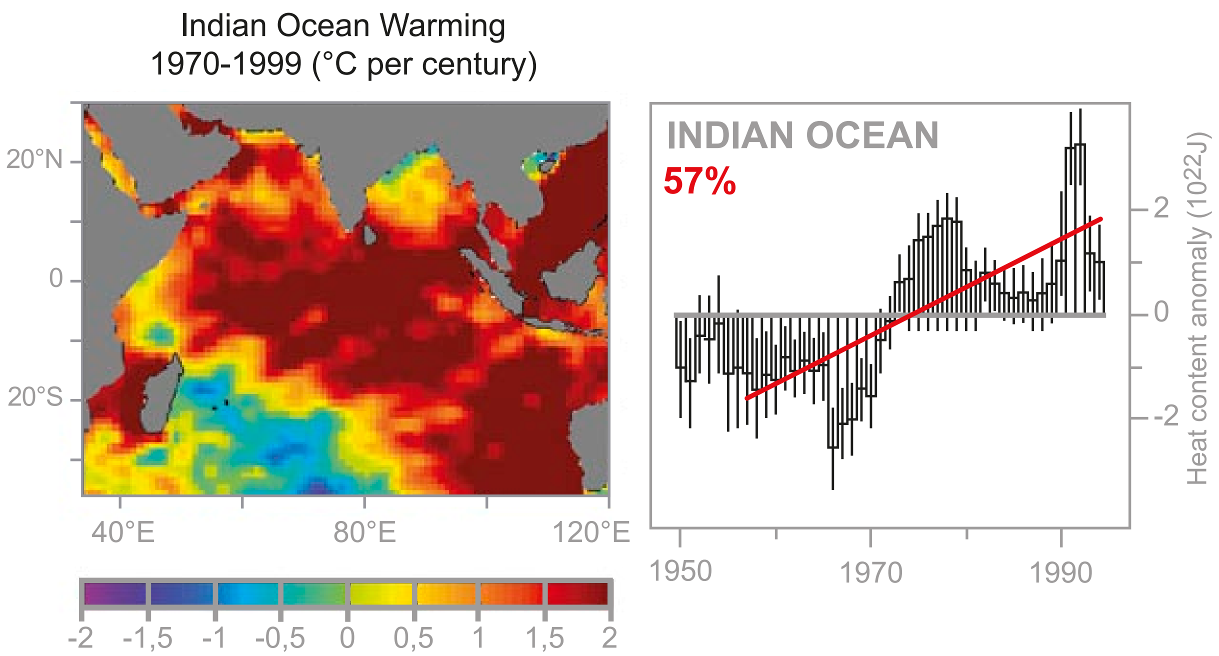

Figure 14 Indian Ocean warming as assessed from satellite sea surface temperature data (left panel). Indian Ocean total heat content anomaly trend (right panel).

Left panel reproduced with permission from International CLIVAR Project Office (2006). Right panel reproduced from Levitus et al. (2000).

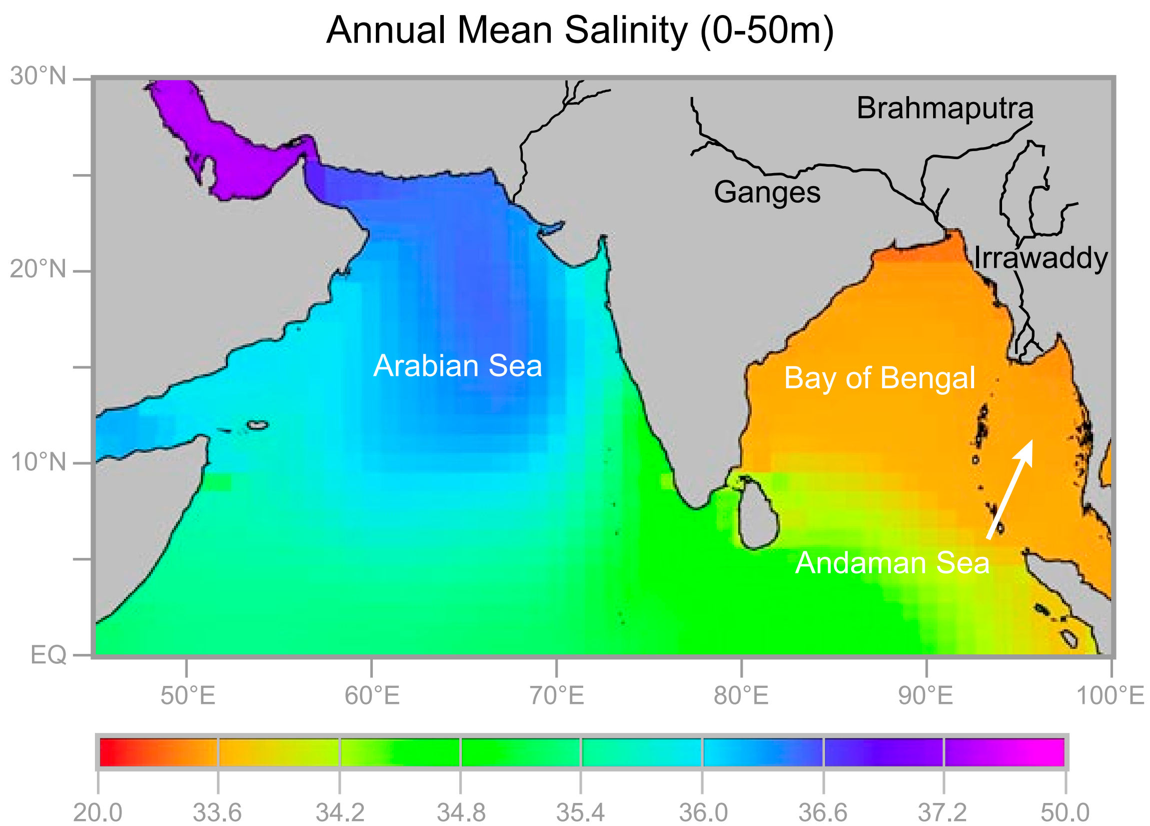

Figure 15 Annual mean salinity in the surface waters of the northern Indian Ocean.

Data were obtained from the World Ocean Atlas 2001 (Conkright et al., 2002).

mass, and thus drive convective mixing deeper than in the BoB. The net result is a generally stronger biological response in the AS than in the BoB.

The AS and BoB also differ markedly in terms of freshwater influx as shown by surface water salinities (**Fig. 15**). The AS experiences net evaporation, whereas the BoB receives net precipitation. In addition, the BoB, together with the Andaman Sea receives the bulk of the runoff from major rivers such as the Ganges/Brahmaputra and the Irrawaddy into the IO. Differences in freshwater forcing have an enormous impact on stratification – a buoyant low-salinity layer greatly inhibits vertical mixing thus limiting mid-water ventilation and caps off weak, wind-driven upwelling along the Indian east coast (Kumar et al., 1996). In the AS, surface cooling and the net excess of evaporation over precipitation and runoff lead to weaker stratification during both the SWM and NEM.

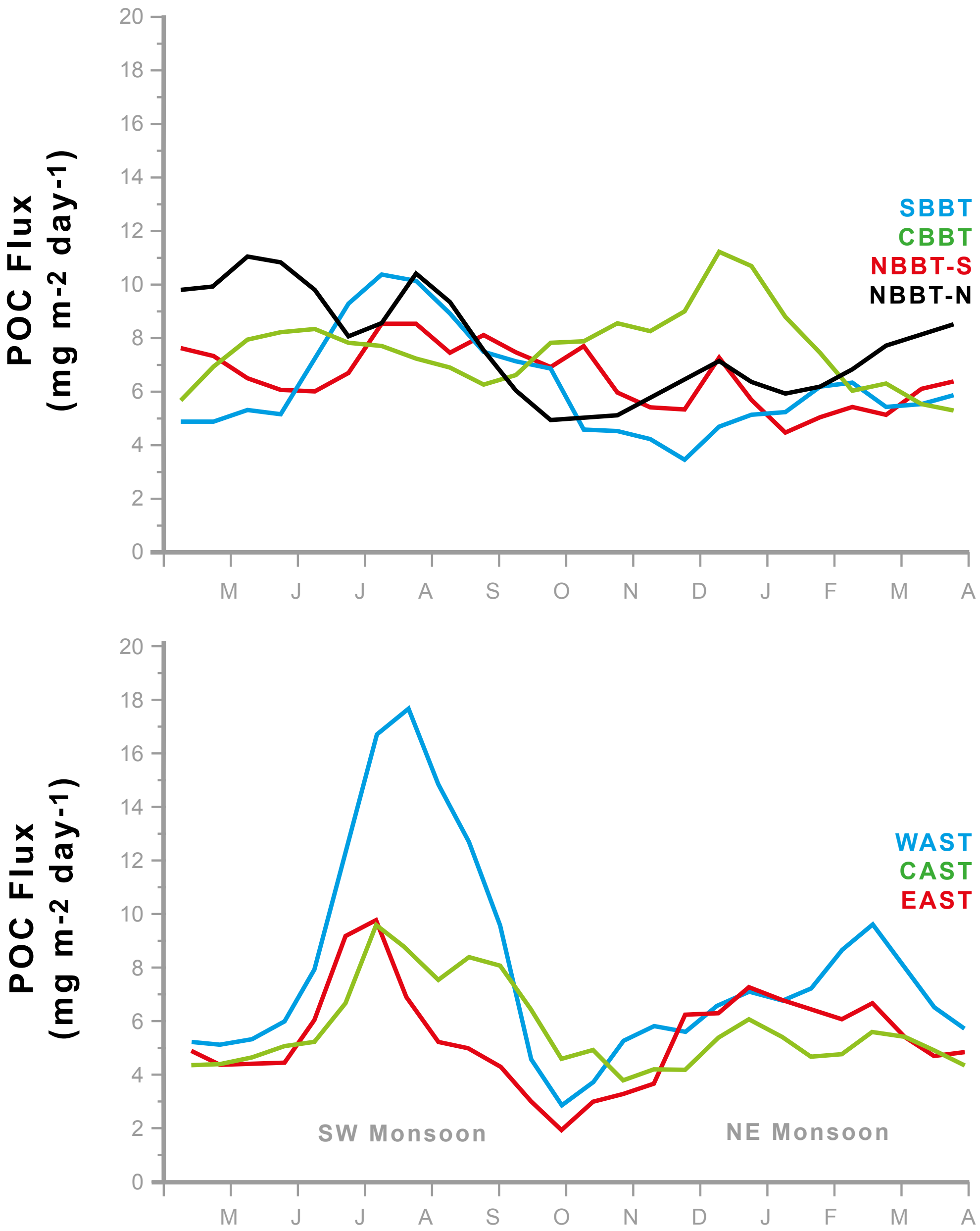

Figure 16 Monthly mean organic C fluxes (POC) measured at depths < 1000m in the northern (NBBT N/S), central (CBBT) and southern Bay of Bengal (SBBT), as well as in the western (WAST), central (CAST) and eastern Arabian Sea (EAST).

Reproduced with permission from Rixen et al. (2009) .

As a result of these differences in monsoonal forcing there are profound biogeochemical differences between the AS and BoB as indicated, for example, by export fluxes from the euphotic zone (Rixen et al., 2005; Rixen and Ittekkot, 2007). Contrary to the AS where upwelling during the SWM and convective mixing during the NEM produce a clear monsoon-synced signal in export flux, high freshwater inputs produce a rather diffused seasonal pattern for export flux in the BoB (**Fig. 16**).

Furthermore, there are small but critical differences in intermediate water oxygen concentrations (**Fig. 3**). In the AS, oxygen is almost completely depleted from a wide mesopelagic layer, and bacteria begin to utilize nitrate as the terminal electron acceptor for respiration, finally converting it to inert N_2 gas, which is then released to the atmosphere (Codispoti et al., 2001; Naqvi, 1987; Ward et al., 2009). This process, known as denitrification, occurs at ~150 - 600m in the eastern-central AS. The AS OMZ contributes ~20% to global water column denitrification (Bange et al., 2000; Codispoti et al., 2001), although there is some debate about the relative contributions of denitrification versus the chemosynthetic anammox reaction to N_2 gas production in the AS (Ward et al., 2009). Upwelling of oxygen-depleted waters over the shelf leads to formation of the world's largest natural low-oxygen zone, over the continental shelf off the Indian west coast. Evidence suggests that this oxygen deficiency has intensified in recent years due to human activities, such as enhanced fertilizer loading from land. Anoxia (sulphate reduction following complete denitrification) has been found to recur every year since 1998 during late summer/autumn in the inner-shelf region north of about 12°N (Naqvi et al., 2000). By contrast, because the mesopelagic dissolved oxygen concentrations in the BoB are slightly higher, it remains poised just above the denitrification threshold (**Fig. 3**), and studies of oxygen variability and depletion on the Indian east coast are generally lacking and/or unpublished.

Nitrogen fixation carried out by cyanobacteria (diazotrophs) is the process that splits N_2 and converts it to "fixed" forms of N that can then be readily utilized by other phytoplankton. Nitrogen fixation, favored by the mid-water nitrate losses and resulting nitrate deficits in the upwelled water (Rixen et al., 2009), could in principle balance mid-water nitrate losses due to denitrification. There is evidence from *in situ* measurements (Capone et al., 1998) as well as satellite ocean color observations (Westberry and Siegel, 2006; Westberry et al., 2005) of potentially high N_2 fixation rates in the AS, due to extensive blooms of the diazotrophic cyanobacterium *Trichodesmium* (**Fig. 17**). The annual input of new N via this process has been estimated to be 3.3 Tg N yr^{-1} (Bange et al., 2005; Bange et al., 2000). This could account for 20–40% of the entire export flux from the euphotic zone into the deep sea (Brandes et al., 1998; Rixen et al., 2002) but falls well below the estimated mid-water nitrate loss rates of ~ 33 Tg N yr^{-1} due to denitrification. By contrast, although there have been anecdotal sightings of *Trichodesmium* blooms in the coastal BoB (Gomes et al., 2000; Jyothibabu et al., 2003), nitrogen fixation may be less extensive there than in the AS because of the absence of water column denitrification and the resulting nitrate deficits that favor diazotroph growth.

Core questions

1) How do natural and anthropogenic forcings influence the OMZs and therefore ecosystem structure and biogeochemical processes in the AS and the BoB?

Very small differences in the mid-water oxygen concentrations between the AS and the BoB give rise to profound differences in biogeochemical cycling in these two basins, i.e. there is open ocean denitrification in the former but not the latter. This suggests that small changes in mid-water oxygen concentration of either basin could have global impacts. Further studies are needed of the physical and biogeochemical mechanisms that set up and maintain the OMZs, and, for example, control N cycling, in the AS and the BoB. How have these changed in the past and how might they change in the future in response to global warming?

2) How will export fluxes respond to environmental changes and how will resulting variations in the quantity and quality of export fluxes affect mid-water and benthic processes in the AS and BoB?

Export fluxes, which differ in terms of quantity, quality and seasonality in the AS and the BoB, strongly affect mid-water oxygen and nitrate concentrations through the decomposition of exported organic material. Benthic communities also respond to changing quantities and composition of sinking material. How do such changes influence the benthos in terms of productivity, species composition, biogeochemical cycling and ecological function? These processes could provide important feedbacks to the water column through microbial processes such as sedimentary denitrification and methanogenesis, and associated benthic fluxes. N_2 released from the sediments could, for example, contribute to observed N_2 excess in the offshore OMZ, and to dissolution of gas hydrates that destabilize continental slopes and affect water column oxygen concentrations through oxidation of methane. Differences in benthic-pelagic coupling and their causes need to be studied in the two basins in order to understand the ultimate fate of C, nutrients and especially P (phosphogenesis) introduced to the basins.

3) How will climate and land use changes affect internal (upwelling, vertical mixing) and external deliveries of nutrients and ballast material to surface waters and how will food web structures and export fluxes respond to these changes in the BoB and the AS?

One of the key processes controlling the export of organic matter is primary productivity. It is markedly different in the two basins, which might reflect differences in nutrient inputs into the

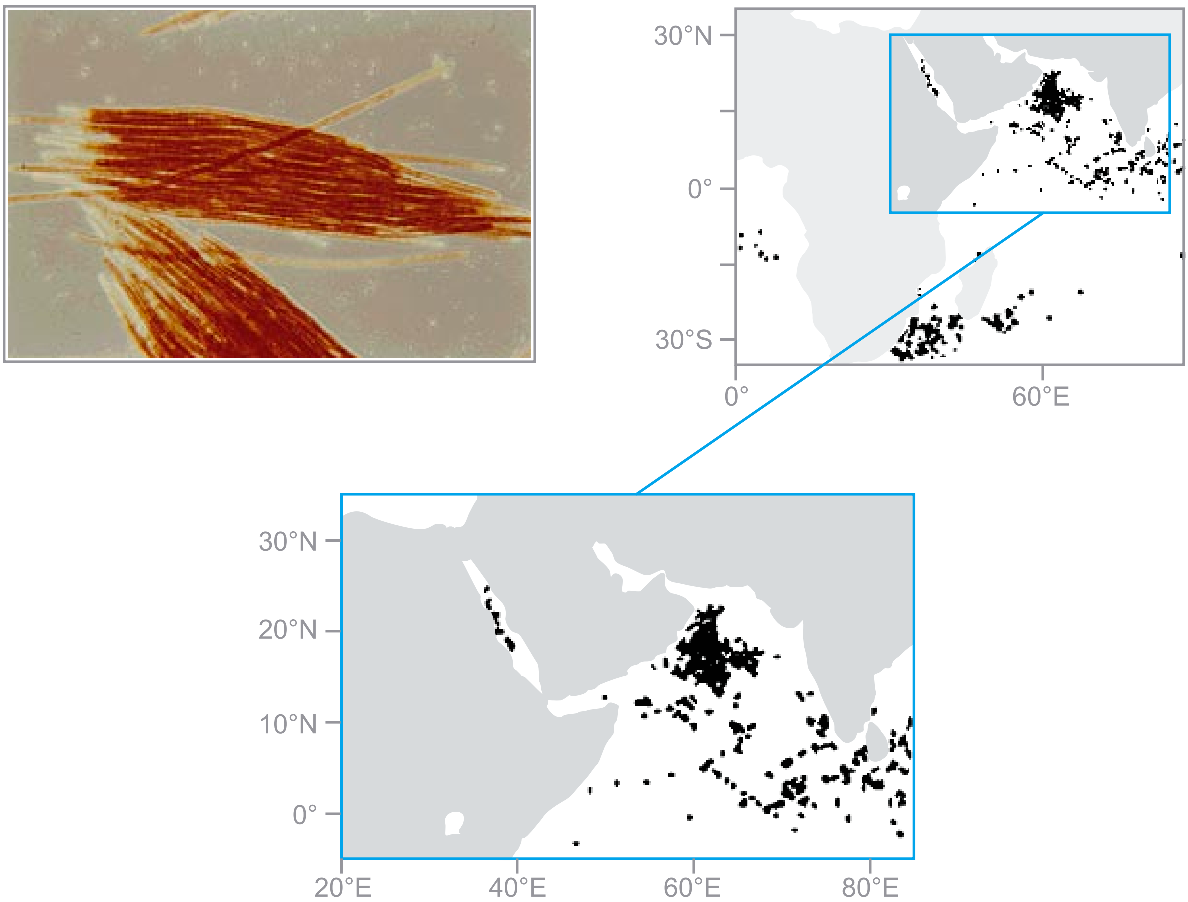

Figure 17 *Trichodesmium* colony (photograph from http://www.usc.edu/dept/LAS/biosci/tricho/) presence in the western Indian Ocean and the Arabian Sea (dark points in mapped areas) as assessed from ocean color measurements.

Maps modified and reproduced with permission from Westbury et al. (2005).

surface ocean or utilization within the food web. Basic questions regarding, for example, the role of N_2 fixation for productivity and export flux have received very little attention. There are very few direct measurements of N_2 fixation rates in the AS and no known measurements in the BoB. Accordingly, N_2 fixation rates must be determined, the dominant N_2-fixing organisms need to be identified and their response to changing environmental conditions studied.

Like N_2 fixation, river and aeolian inputs are considered as external nutrient sources, but also provide sediment and dust, which act as ballast for sinking particles. Ballast materials reduce the decomposition of organic material by reducing its residence time in the water column and could have an enormous impact on the biologically mediated uptake of CO_2 from the atmosphere (Ittekkot, 1993; Kwon et al., 2009).

In contrast to the AS, the BoB is surrounded by some of the world's most heavily populated land (**Fig. 4**) and will be a "hot spot" for multiple nutrient inputs in the future (Harrison et al., 2005; Seitzinger et al., 2005). Anoxic events are occurring in many parts of the world due to eutrophication of the coastal zones (Diaz and Rosenberg, 2008). As pointed out earlier, extensive hypoxia already develops seasonally over the shelf in the eastern AS, but whether the same occurs in the BoB, and if so, how it varies seasonally is unknown, as are the magnitudes of denitrification in shelf and slope waters in the BoB and the Andaman Sea. Given the large freshwater and nutrient inputs onto the broad shelf in the northern BoB, the questions are: What are the differences in drainage basin processes influencing the nature of sediment and nutrient delivery to the two seas and what is the role of the coastal ecosystems in controlling the fate of nutrients and their environmental impact on the coastal ocean and the central basins?

As opposed to river discharges which mainly affect the coastal ocean, atmospheric deposition, which is also predicted to increase in the next few decades, mainly affects more offshore sites (Duce et al., 2008). However, given the large loads of terrestrial particulate matter in both the AS (e.g. from dust) and the BoB (e.g. from rivers), several questions arise: How do these differences influence trace metal cycles and how do these cycles in turn impact on the food web structure and the resulting spatial variability of export fluxes? What roles do particle adsorption/desorption processes play in carbon/nutrient cycles? What role does terrestrial organic matter play, what is the effect of mineral ballast and how does it affect export fluxes and mid-water oxygen demands?

4) What role do the marginal seas play in determining productivity and how do their outflows affect mid-water oxygen concentrations in the AS and the BoB?

In addition to the oxygen consumption caused by remineralization of exported organic material, ventilation controls the mid-water oxygen concentrations in the OMZs of the AS and BoB, which is strongly influenced by vertical mixing of different water masses. Boundary current dynamics and the unique physical dynamics of the equatorial zone are addressed in Themes 1 and 2. The question is: How do marginal seas influence productivity, biogeochemistry and the OMZs in the two basins? In general marginal seas seem to be more important in the AS compared with the BoB. The Andaman Sea in the BoB is very different from the marginal seas of the AS in that it is only partially enclosed by the Andaman and Nicobar Island chains. The ridge topography associated with these islands restricts deep water exchange, i.e. because the sill depth is around 1.4 km, the deep water (depth > 4 km) in the Andaman Basin is warmer and less oxygenated than the water at same depth in the BoB. Nevertheless, it is important to know how these regions communicate with each other, which processes are responsible for renewal of the Andaman waters and the importance of internal waves in the Andaman Sea. In the AS, even though the outflows from the Red Sea and the Persian Gulf are < 0.4 Sv, they exert a notable influence on the intermediate water composition due to their high salinity (> 40 psu in Persian Gulf waters exiting the Straits of Hormuz). What influences do these outflows have on biogeochemical cycles and ecosystem dynamics in the AS? How do these markedly different marginal sea exchanges in the AS and the BoB contribute to the dramatic differences that are observed in physical, biogeochemical and ecological properties between these two basins?

General scientific themes

Theme 4: Control and fate of phytoplankton and benthic production in the Indian Ocean

What are the relative roles of light, nutrient and grazing limitation in controlling phytoplankton production in the IO and how do these vary in space and time? What is the fate of this production after it sinks out of the euphotic zone?

Background

Understanding regulatory processes and mechanisms that act on lower trophic levels is essential for predicting ecosystem responses to human-caused activities and climate change. Like elsewhere, primary production in the IO should be regulated principally by light, nutrients, trace elements (bottom-up control) and grazing (top-down control), where the latter can be influenced through connections to higher consumers via trophic cascades. However, the control mechanisms and fate of primary production in the IO are unique in many respects due to the large seasonal wind reversals, the presence of a permanent, spatially extensive OMZ, and the rapid rate of warming compared to other tropical/subtropical ocean basins. Moreover, there are large natural and anthropogenic dust sources and riverine/nutrient inputs. What is known has been derived largely from studies in the northern IO, and especially the Arabian Sea. Relatively little is known about the control and fate of primary production in the southern hemisphere of the IO beyond that which can be deduced from remote measurements and large scale physical and chemical surveys.

Phytoplankton production in the northern subtropical and tropical IO is strongly regulated by the physical forcing of monsoon winds. In the AS, for example, SWM winds drive upwelling along the coasts of Somalia, Oman and southwest India, with the associated delivery of new nutrients to surface waters accounting for a large proportion of the basin's annual production. Similarly these winds drive the equatorial circulation which gives rise to anomalous zonal productivity patterns and marked intraseasonal variability associated with the Wyrtki Jets and the MJO.

A major paradox of the AS is that it produces a very weak and delayed phytoplankton (diatom) response compared to other systems. During JGOFS, for example, detailed analyses of the phytoplankton community revealed a < 2-fold range of variability in mean (1.2-1.8 gC m^{-2}) and station maximum (1.8-2.9 gC m^{-2}) estimates of autotrophic biomass for cruises conducted over the range of seasonal conditions (Garrison et al., 2000). Diatoms were most prevalent during the late SWM (September); even so, their biomass at near-shore station S2, where the maximum was measured during this period, was within an order of magnitude of the values recorded during the most oligotrophic times of the year. In contrast to the muted diatom response in the AS, upwelling systems off Peru and north Africa produce very strong diatom blooms, which develop tightly coupled to the intensifying winds and extend over much of the inshore region (Huntsman and Barber, 1977; MacIsaac et al., 1985; Smith et al., 1981). A weak diatom response also has the important consequence of delaying carbon export in the AS and shifting it offshore of the coastal upwelling area toward the eastern basin, which overlies the OMZ (Buesseler et al., 1998). Elucidating mechanisms controlling diatom blooms in the AS is thus central to understanding the unique characteristics of this system's ecology and carbon fluxes.

The winds of the NEM also give rise to elevated primary production and export in the AS, but the mechanism is different, with cool dry winds inducing buoyancy mixing and entrainment of nutrient-rich water from depth. As a result, light limitation due to relatively deep convective mixing can be an important factor controlling primary production during the NEM. The influence of the monsoon winds on phytoplankton production extends also into the BoB where they induce pronounced seasonal reversals in the surface currents and "cryptic upwelling" in offshore waters (Vinayachandran et al., 2005).

With the exception of chemosynthetic systems (e.g. hydrothermal vents) deep sea benthic communities are supported by sunlight-driven surface primary production, i.e. export flux from surface waters. In general, the rate and magnitude of phytoplankton production strongly influences export fluxes and consequently benthic processes and the formation of coastal and open ocean OMZs. However, it is important to note that in the AS, the geographic distribution of the OMZ does not reflect that of surface production, the greater proportion of which occurs on the western side of the basin. As discussed in the previous section, the extensive region of hypoxic waters in the northern IO gives rise to globally significant biogeochemical processes such as denitrification (benthic as well as pelagic). In addition to seasonal variability, longer (millennial and higher) time scale changes in circulation, monsoons and hypoxia have been inferred from sediment records. Such changes have major significance for C, N, and P cycling, sequestration in the sediments, and ocean inventories and productivity. Yet the Indian margin of the AS and almost all of the BoB have had little or no study to date with regard to benthic processes and in particular how they relate to the fate of primary production in surface waters. Investigations of nutrient flows and food chain dynamics (including the microbial loop) are needed to understand mechanisms of transfer of primary production to higher trophic levels, to interpret trends in C cycling, and to predict fluxes to benthic systems.

The little that is known about the controls and fate of primary production in the southern hemisphere open ocean of the IO is derived from a small number of basinwide remote sensing and modeling studies (e.g. Behrenfeld et al., 2009; Lévy et al., 2007; Resplandy et al., 2009; Wiggert et al., 2006) which are informed by large-scale physical and chemical surveys (e.g. the World Ocean Circulation Experiment and the ongoing global CO_2 surveys) and a few process studies (e.g. Planquette et al., 2007; Pollard et al., 2007; Poulton et al., 2007; Poulton et al., 2009). Although, as in the Atlantic and Pacific Oceans, the southern IO subtropical gyre is oligotrophic, it is subjected to unique influences derived from the anomalous, warm poleward-flowing LC in the east (**Figs. 2 and 8**), and the southward-flowing Agulhas and East Madagascar Currents in the west (**Figs. 2 and 9**), and their associated eddies, as discussed in Theme 1 above. Studies of sea surface height variability have revealed intense, westward-propagating eddy variability between 20° and 30°S in the eastern tropical and southern subtropical IO basin (D.B. Chelton et al., unpublished data), but the biogeochemical and ecological impacts of these open ocean eddies have not been investigated. Large-scale open ocean phytoplankton blooms have been observed extending southeastward from the southern tip of Madagascar in the southern hemisphere summer in satellite chlorophyll data (Uz, 2007). It has been confirmed that these are associated with blooms of diazotrophic cyanobacteria and diatom-diazotroph associations (Poulton et al., 2009), but the relative contributions of nitrogen fixation versus other nutrient sources has not been quantified. Finally, questions about the potential role of Fe limitation in controlling phytoplankton production, and also carbon export to depth pertain to the entire IO basin (Hood et al., 2009).

Core questions

1) How do phytoplankton production and its controlling factors vary across the IO and with season?

First-order basinwide descriptive studies are needed to better characterize and understand the many unique aspects of the IO's circulation features and their productivity signals, ecological responses and biogeochemical relationships. Indeed, major questions that emerged from the JGOFS expeditions remain unanswered. For example, crustacean zooplankton (e.g. *Calanoides carinatus*) migrate from hundreds of meters depth to the surface during the SWM in the western central AS (Idrisi et al., 2004). It has been suggested that grazing by this species prevents accumulation of phytoplankton biomass in response to upwelling of nutrients (Smith, 2001). This hypothesis might also explain why the phytoplankton bloom occurs toward the end of the SWM in this region, after the grazers migrate back to deeper waters. It has also been suggested that grazing, here and elsewhere in the AS, prevents complete utilization of the nitrate supplied via upwelling. By contrast, a new hypothesis posits that Fe and Si limit phytoplankton production during the SWM in the AS, despite large mineral fluxes from the surrounding dust source regions (Moffett et al., 2008; Wiggert and Murtugudde, 2007). That is, low Si concentrations in the initially upwelled waters limit diatom growth and promote blooms of other species like *Phaeocystis*, and low Fe concentrations limit phytoplankton growth in general and thus prevent complete exhaustion of nitrate. This effect appears to be most strongly manifested toward the end of the SWM in offshore waters where local dust deposition is greatly reduced because the Findlater Jet acts as a barrier to offshore transport (Moffett et al., 2008). There are clearly open questions even in the best-understood region of the IO regarding the relative influence of grazing and nutrient limitation. What are the temporal and spatial patterns of primary production in the IO? What roles do micro- and mesozooplankton grazing versus nutrient limitation play in regulating primary production in different IO subregions, and how do these change seasonally?

Iron limitation is believed to occur throughout the Southern Ocean due to lack of input from continental sources (Boyd et al., 2007), presumably extending into the IO sector (30°–120°E). This supposition is supported by the results of a "natural" iron experiment (CROZEX, Pollard et al., 2007) in waters downstream of the Crozet Islands that demonstrate a sharp delineation in phytoplankton speciation associated with spatial variation in dissolved Fe availability (Planquette et al., 2007; Poulton et al., 2007). Despite this, the extent of Fe depletion and Fe limitation in the IO sector of the Southern Ocean and its northward extension into the southern IO basin remains unknown. Which nutrients limit phytoplankton production (N, P, Fe, Si) in different areas of the IO and at different times of the year?

It has been suggested that eastward aeolian Fe transport from South Africa alleviates Fe limitation in the subtropical South IO (Piketh et al., 2000). That in turn would stimulate carbon fixation and export in a broad swath across the southern IO. This appears to be borne out by the strong autotrophy and net CO_2 sink found in the 20-35°S zone (Bates et al., 2006a,b). By contrast, modeling suggests that vast areas of southern tropical waters (5°–20°S) are Fe limited, extending west and north along the western IO rim, particularly during the SWM (**Fig. 18**) (Wiggert et al., 2006). This lack of Fe may then play the opposite role in helping to form carbon source regions (ocean to atmosphere) in these tropical waters, along the western IO rim and further north in the AS. As discussed above, global distributions of fluorescence quantum yield obtained from a new ocean color algorithm indicate that phytoplankton in the SW IO are nutrient-stressed in precisely the region that model results suggest are Fe limited (Behrenfeld et al., 2009). Clearly, *in situ* Fe enrichment and Fe stress/physiological studies need to be carried out in the IO to determine conclusively the spatial and temporal extent of Fe limitation and its potential role in the carbon cycle. These studies should include measurements of dust deposition and Fe solubility in the dust, which will vary according to its source.

Barber et al. (2001) argued that phytoplankton production in the central AS is not generally light-limited. Modeling studies, however, suggest that during the NEM in particular, primary production can be sensitive to mixed layer depth (MLD) (McCreary et al., 2001; Wiggert et al., 2000). When and where the MLD becomes too deep, the average light may drop below the level needed by phytoplankton to cover metabolic and grazing losses. Is the magnitude of primary production per unit area in any part of the IO north of the southern subtropical convergence limited by light availability?

Finally, what role do the competing processes and denitrification and nitrogen fixation play in modulating nitrogen and phosphorus availability regionally and basinwide in the IO and how does this in turn influence phytoplankton productivity and species composition? As discussed above, there is evidence that N_2-fixation plays an important role in fueling phytoplankton blooms in the southern IO off Madagascar. Do N_2-fixation supported blooms happen elsewhere in the IO? What fraction of the N supply does N_2-fixation account for in these regional blooms and also over larger tropical and subtropical areas of the IO? How do nitrogen fixation and denitrification in the northern IO and especially the AS influence N:P ratios in surface waters and how does this in turn influence nutrient limitation and phytoplankton species composition.

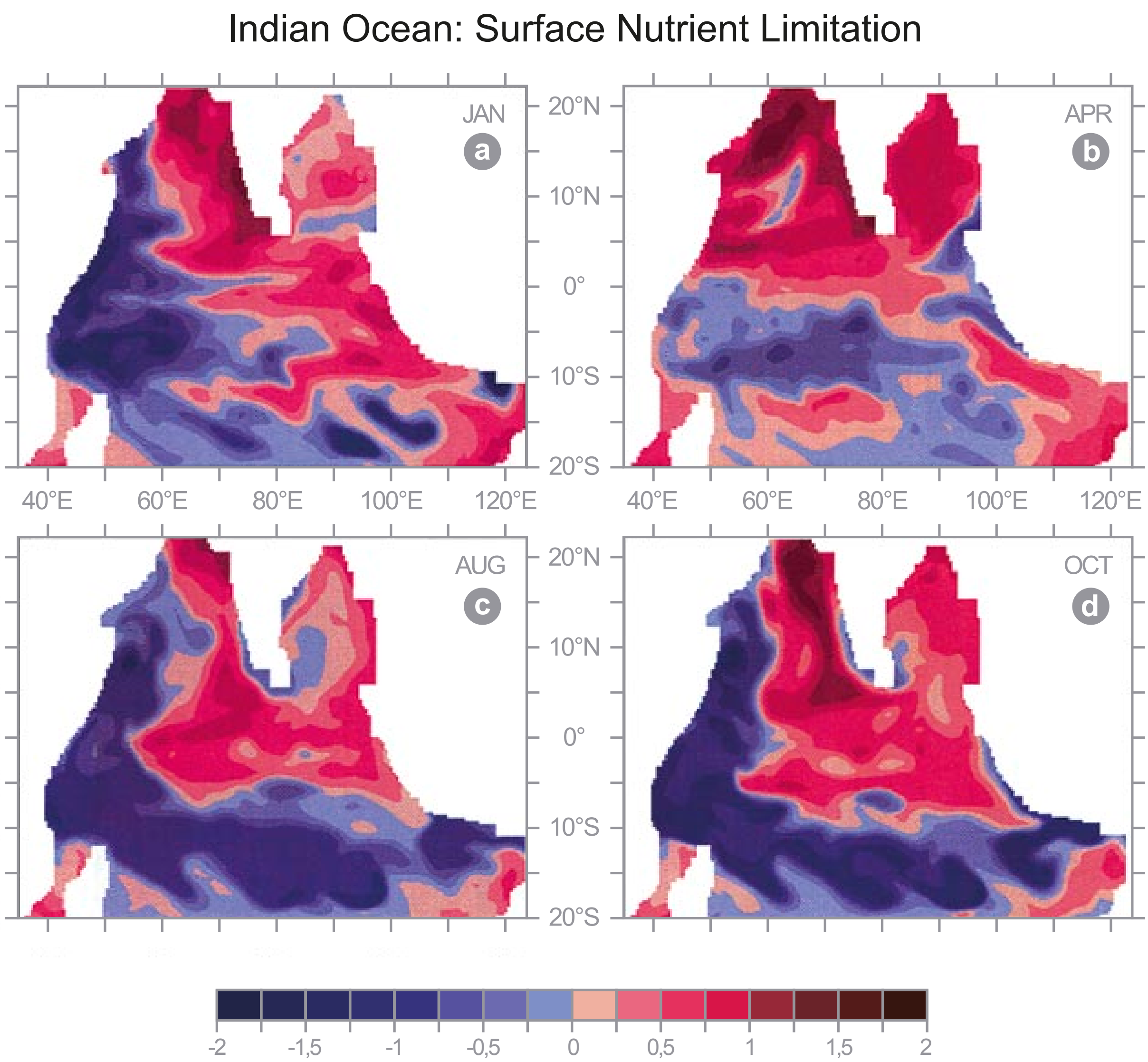

Figure 18 Seasonal evolution of most limiting surface nutrient for netplankton, with blue (red) indicating Fe (N) limitation.

Reproduced with permission from Wiggert et al. (2006).

2) What fraction of phytoplankton production is exported to the deep sea, and how are the benthic communities, and mid-water and benthic processes driven by this export? How do these phenomena vary, with season, from abyssal plain to continental shelf, and between IO basins?

Export production and its influence on water column processes and benthic production, community structure and processes in the IO are also understudied and there is a need to carry out first-order descriptive science. The potential significance of benthic processes and benthic-pelagic coupling to marine biogeochemical cycling is established, but they remain poorly studied or quantified, especially in the IO. The extreme seasonal and/or spatial variability across the IO, in terms of primary production and oxygen depletion, give it wide-ranging importance with respect to global biogeochemical cycles, but also as a natural laboratory for benthic process studies.

There is a primary need to quantify the fraction of primary production that is exported from the euphotic zone and in turn the portion of this export that is processed in the water column (and where). Quantification and characterization of the flux of organic matter that escapes pelagic recycling and is delivered to the sea floor are also required, as is assessment of the impacts on benthic communities in terms of biomass, diversity and activity patterns. Studies should address the degree to which regional variability in surface-ocean processes is mirrored in the deep sea, how particulate organic fluxes to continental margin and deep sea communities differ, and how the IO compares to other oceans in terms of variability in benthic communities and processes. What are the effects of pelagic food web processes and water column biogeochemistry (e.g. extent and intensity of oxygen depletion, denitrification and N_2-fixation rates) on organic matter delivered to the sea floor? The roles of benthic fauna and microbial processes (aerobic through methanogenesis) in the cycling and burial of carbon and other bioelements, and how these vary from the abyssal plain to the continental shelves, need to be clarified. It is also important to improve understanding of the nature and extent of benthic-pelagic coupling; how the benthos responds to pelagic forcing and, especially in shallow marginal environments, how benthic processes and associated sediment-water fluxes of dissolved gases, nutrients, organic matter and trace metals impact on the pelagic environment. How, on balance, do benthic solute fluxes serve in terms of sources or sinks in ocean inventories, and what influences do benthic fluxes and benthic-pelagic coupling have on productivity? Ultimately, future studies should establish the wider biogeochemical significance of the processes and fluxes associated with export production and recycling (pelagic and benthic), and how these vary with season and across IO basins and marginal seas, with contrasting depth and hydrography, seasonal monsoon influence, riverine impacts and oxygen depletion.

As discussed in Theme 3, the seasonal hypoxic zone over the western Indian shelf is the largest in the world, occupying an area of 0.2×10^6 km^2. It is an order of magnitude greater than the better-known “dead zone” off the Mississippi mouth in the Gulf of Mexico (Naqvi et al., 2000). The presence of large and expanding coastal hypoxic zones has major implications for the large human populations living around the northern IO (e.g. with respect to water quality, fisheries resources, etc.). The presence of low-O_2 water also has profound impacts on benthic biogeochemical cycles and fluxes because it dramatically alters faunal composition and gives rise to chemical reactions like denitrification and anaerobic ammonium oxidation (anammox). Furthermore, the relative importance of pelagic versus sedimentary denitrification/anammox in the northern IO and the influence of varying O_2 concentrations on N cycling and redox-sensitive N fluxes (N_2, NO_3, NO_2, NH_4) in the benthic boundary layer, need to be clarified. Also, studies are needed to assess the directions and magnitudes of benthic solute fluxes (gases, nutrients, DOM, DIC and metals) across IO margins, and how these relate to bottom water oxygen.

Theme 5: Climate and anthropogenic impacts on the Indian Ocean and its marginal seas

How will human-induced changes in climate and nutrient loading impact the marine ecosystem and biogeochemical cycles?

Background

The latest IPCC AR4 report concluded that climate change is occurring and the most recent atmospheric CO_2 data show that atmospheric levels are increasing faster than even the most pessimistic projections used in the AR4 climate simulations (Raupach et al., 2007). It appears that both the rate of global warming and ocean acidification are accelerating. Further, many countries bordering the IO are experiencing rapid economic development (e.g. India and Australia), which will place greater strains on the terrestrial, coastal and marine environments. Given the expected future climate change and human development there is a pressing need to understand climate and anthropogenic impacts on the marine ecosystems of the IO and its marginal seas. Addressing this important issue will require improved understanding of marine ecosystems, targeted long-term observations to monitor and detect change, and mechanistic model simulations to investigate different impact scenarios.

Recent research has documented a number of climate and anthropogenic impacts on IO ecosystems. Because of its rapid warming (International CLIVAR Project Office, 2006, **Fig.14**), the IO may provide a preview of how climate change will affect the biogeochemistry and ecology of other ocean basins and also human health. The observed warming trend in the Eurasian region over the past decade appears to have induced an increase in AS productivity (Goes et al., 2005). A new study suggests this warming trend will be amplified by the solar absorption caused by biomass burning and fossil fuel consumption (Ramanathan et al., 2007).

The large-scale coral bleaching events of 1998 and 2005 highlight the susceptibility of the IO to warming and changes in ocean circulation (McClanahan et al., 2007). For instance, the 1998 bleaching event influenced higher trophic levels by altering the age distribution of commercially harvested fish (Graham et al., 2007). Coral reef ecosystems may be at greater risk than previously thought because of the combined effects of acidification, human development and global warming (Hoegh-Guldberg et al., 2007). These studies have started to explore climate and anthropogenic impacts on the IO, but much more research is needed to help mitigate the impacts and to assist adaptation to the changing environment.

At the recent Asian Fisheries Forum (Kochi, 2007) there was widespread concern about the decrease in the mackerel population over the western continental shelf of India. It is assumed that the fish have moved to cooler, deeper waters beyond the shelf. This will cause far-reaching socioeconomic problems in the coastal states. There has also been a drastic decrease in the mackerel fishery in the last decade (CMFRI, Special Publication No. 98).

With regard to river basins that drain into the IO there are several simultaneous developments that may have profound impacts on primary production, biodiversity and the carbon cycle, both in the coastal margins and the open ocean. First, the population of most countries proximal to IO river basins is increasing rapidly. Between 1970 and 2000 India's population increased by more than 75% (UN, 2004). Together with economic growth this leads to a rapid increase in food production and a shift towards more protein-rich food such as meat and milk. The input of N and P fertilizers increased 7-8 fold between 1970 and 2000 (FAO, 2008) and has probably led to increased inputs to surface waters. FAO projections indicate that in the next three decades there will be a further 50% (N) to 80% (P) increase in fertilizer use in India (Bruinsma, 2003). Second, urbanization and the associated construction of sewage systems are promoting river nutrient export. This leads to rapidly increasing nutrient flows into surface water and eventually coastal seas. In many river basins draining into the IO, the investment in wastewater treatment systems lags behind that of sewage systems (Bouwman et al., 2005). Third, anthropogenic alteration of hydrological systems is increasing the mean passage time of water through river systems, increasing the standing stock of river water over pre-impounded conditions, and dramatically altering river flow in a number of large rivers through water extraction (Vörösmarty et al., 1997). In particular, the construction of dams in rivers for hydropower and reservoirs for irrigation water may lead to retention of Si.

The effect of increasing river N export to estuarine, coastal, and marine ecosystems depends on the availability of P and Si. N and P limit the growth of phytoplankton, macroalgae, and vascular plants, while Si limits the growth of diatoms. Increased P fluxes have occurred during previous decades (Smith et al., 2003), while Si loads have remained constant or even decreased in many rivers primarily as a result of dam construction (Conley, 2002). Taken together, these river-borne nutrient loadings have often altered the stoichiometric balance of N, P, and Si, which affects not only the total production in freshwater and coastal marine systems, but also its quality. When diatom growth is compromised by Si limitation, non-diatoms may be competitively enabled, leading to dominance of flagellated algae including noxious bloom-forming species (Turner et al., 2003). Thus, food web dynamics may be altered by the relative availability of N, P and Si, which in turn will affect fisheries harvests and human health.

These anthropogenic influences will likely impact the carbon cycle in the IO as well. For example, a three-fold increase in inorganic N export to African and South American coastal systems is predicted by 2050 (relative to 1990) (Seitzinger et al., 2002), with almost half of the total global increase in N export predicted for those regions alone. The input of an additional 8 Tg N yr^{-1}, assuming it is all fixed and exported to the deep ocean, would decrease the CO_2 efflux in the IO by ~40-50 Tg C yr^{-1}. This represents about 10% of current estimates of CO_2 net efflux from the IO (Bates et al., 2006a; Sabine et al., 2000). Thus, anticipated future increases in N loading are very likely to have a profound impact on the IO carbon cycle and the role of the IO in the global carbon cycle.

The impacts from increased N loading will be particularly acute on the shelves in the BoB and the AS where the extent of anthropogenically-induced hypoxia will expand (Naqvi et al., 2000). Similar impacts and concerns exist for the relatively pristine western coastal environments of Australia and also African coastal waters. These will not only effect biogeochemical cycles, but also coastal marine food webs, which will in turn, directly impact human activities including commercial fishing. Large coastal infrastructure projects, increased urban development, and tremendous population growth along the shores pose a great danger to the marine environment of the Persian Gulf countries in particular.

For the past 30 years French scientists have maintained long-term time series programs, mostly in the area between the French islands of La Réunion, Crozet, Kerguelen and Amsterdam (**Fig. 19**). Results from the MINERVE (1991-1995) and OISO (1998-2007) studies indicate that the trend of pCO_2 increase in the atmosphere is 1.722 (+/- 0.004) ppm per year from ship measurements and 1.701 (+/- 0.003) ppm per year from the station located on Amsterdam Island (37°S in the central IO). The increase trend in seawater is 2.6 (+/- 1.6) ppm per year (Metzl, 2009).

A study was undertaken in the IO sector of the Southern Ocean to quantify interannual and decadal variations of CO_2 flux across the air-sea interface between Hobart (Tasmania) and Dumont D'Urville (Antarctica). Observations obtained between 1996 and 2006 indicate a weakening of the CO_2 flux within the sub-Antarctic zone (**Fig. 20**). The findings also demonstrate a strengthening of the CO_2 flux within the Antarctic zone during summer, and a weakening of the flux over both zones during spring, with the Antarctic zone becoming a small source of CO_2 to the atmosphere (Laika et al., 2009).

Although sparse, these observations reveal that the southern IO is responding to increases in atmospheric CO_2 concentrations and probably also to changes in ocean temperature, circulation and production in complex ways that are altering CO_2 fluxes between the atmosphere and the ocean. These fluxes need to be quantified to determine the role of the southern IO in the global carbon cycle.

Core questions

Impacts of rising atmospheric CO_2 levels:

1) How are warming and acidification influencing biogeochemical cycles and ecosystem dynamics in the IO and how will their impacts propagate in the future?

The IO is warming rapidly (Alory and Meyers, 2009; Alory et al., 2007). Warming impacts oceanic stratification, directly and indirectly, through the varied influences of evaporation and precipitation. How will changes in precipitation rates and patterns impact river discharge rates and associated nutrient loadings to the coastal zones? How will changes in stratification in the IO alter nutrient supply to the upper ocean? How will changes in stratification and nutrient supply impact the balance between biological O_2 demand and ventilation in the OMZs? Will the OMZs expand, as suggested by Stramma et al. (2008)? What are the relative influences in the AS and the BoB? How will the large-scale circulation patterns respond to warming, and how will this affect the development and distribution of OMZs? How will changes in the OMZs impact biogeochemical cycles and ecosystem dynamics? In particular, how will warming-induced changes to the OMZs influence open ocean and shelf denitrification and therefore, the N budget in the IO and the global ocean?

Warming will influence the surface pelagic ecosystem directly via kinetic (physiological) effects and indirectly through changes in mixing/entrainment, upwelling, etc. Evidence is already accumulating that the latter is happening in the AS and that this is leading to phytoplankton speciation shifts (Goes et al., 2005; Gomes et al., 2009). How is warming affecting phytoplankton, harmful algal blooms (HABs) and higher trophic levels in the AS and elsewhere in the IO? Will changes in stratification alter production of N_2-fixing phytoplankton and how will this in turn impact the N budget in the IO? How is warming impacting the frequency of occurrence of coral bleaching? Impacts of warming in surface waters are already apparent. Are these impacts propagating down to the sediment-water interface on the continental shelf and slope and to even greater depths? Is warming influencing benthic-pelagic coupling? How will warming influence bottom-water temperatures and therefore stability of gas hydrates in continental slope sediments?

As discussed earlier, it has been estimated that the IO as a whole accounts for ~1/5 of the global oceanic uptake of atmospheric CO_2 (Takahashi et al., 2002). Where does anthropogenic carbon uptake occur? How does storage of anthropogenic carbon evolve with time (Coatanoan et al., 2001; Sabine et al., 1999)? Declines in pH (i.e. ocean acidification) will be detrimental not only to coral reefs and their associated ecosystems, but also to pelagic calcifying species like coccolithophorids and foraminifera. Will declines in these species influence export flux and biological O_2 demand in the OMZ and/or production in the benthos? Will changes in the IO alter the release of other greenhouse gases to the atmosphere (e.g. N_2O, CH_4)? If the extent and intensity of the OMZs change substantially (Stramma et al., 2008) then so will the efflux of N_2O into the atmosphere derived from denitrification and enhanced production through nitrification in suboxic waters. How will increased total dissolved carbon alter primary production and N_2-fixation? It has been shown that rates of N_2-fixation in *Trichodesmium* are sensitive to ambient CO_2 concentrations (Hutchins et al., 2007). Will increases in CO_2 therefore significantly increase the abundance of *Trichodesmium* and N_2-fixation in the IO?

In order to assess the impacts of temperature and CO_2 rise in the IO, we need to know the recent evolution of temperature and anthropogenic CO_2 penetration throughout the water

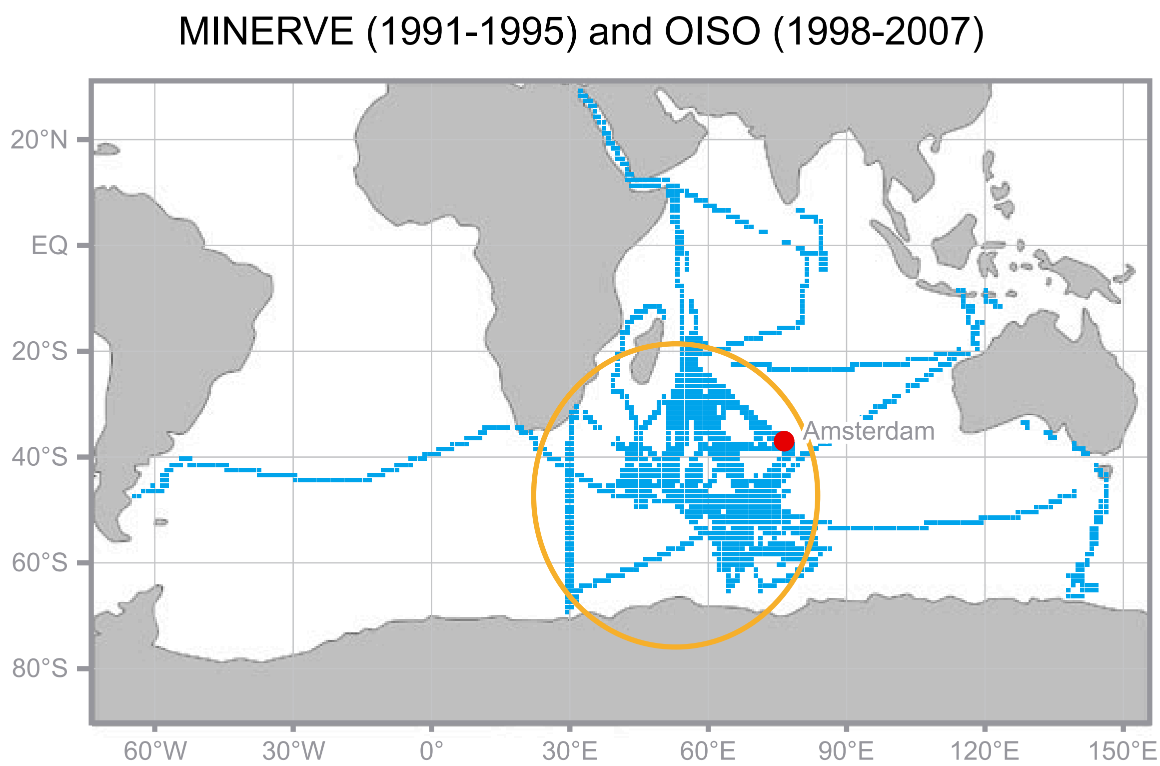

FIGURE 19 Cruise tracks for MINERVE and OISO programs conducted in the southwestern Indian Ocean during 1991–2007.

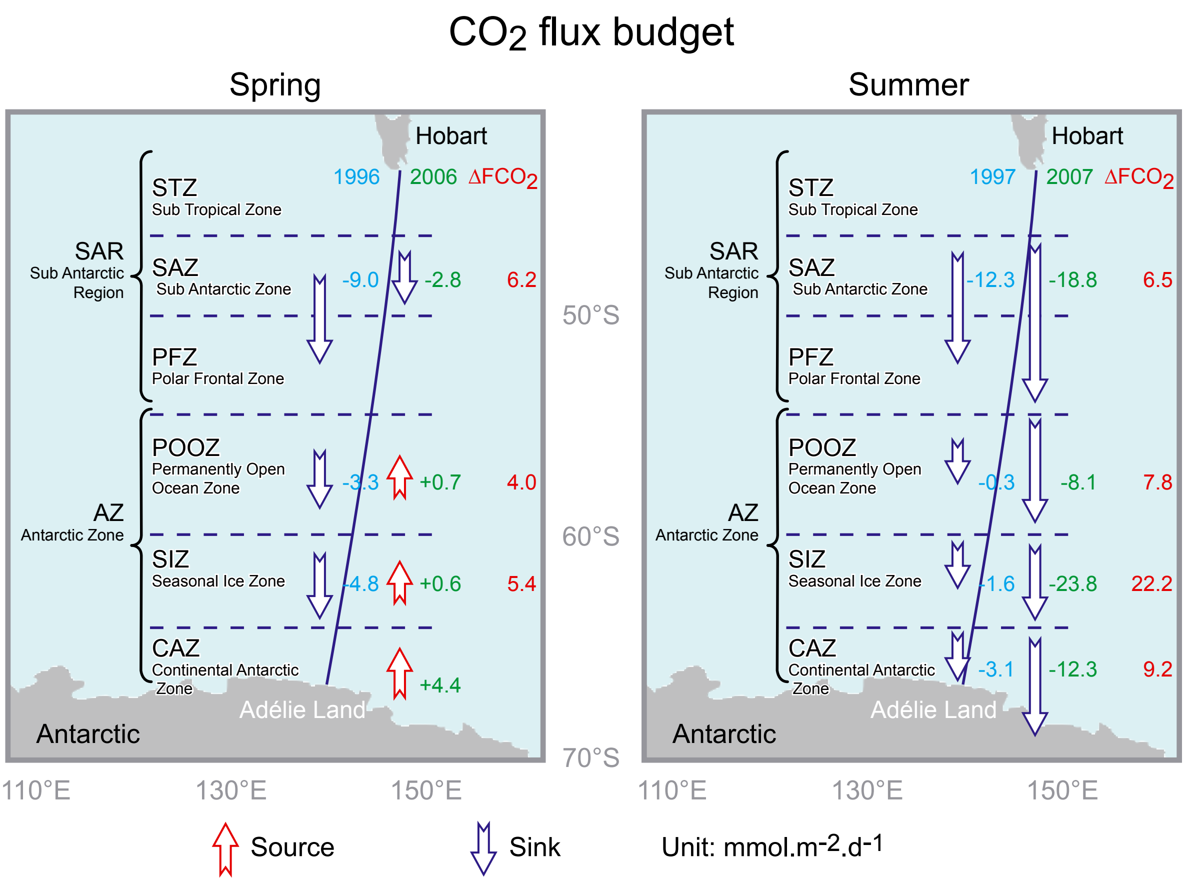

FIGURE 20 CO_2 fluxes in spring and summer of 1996 and 2006.

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column. In addition to large-scale spatial measurements (transects), time series measurements of nutrients, hydrographic, and CO_2 system properties provide important information needed for modeling future impacts. There is a particularly pressing need for additional measurements in the southern IO and the IO sector of the Southern Ocean. The 30-year observational record from the southwestern IO discussed above provides a cornerstone for quantifying temperature and CO_2 increases in the southern IO and it is expected that their continuation will provide crucial information on the carbon cycle and climate impacts in this under-sampled region.

Human Activities:
2) How are present day increases in human populations and coastal development influencing biogeochemical cycles and ecosystem dynamics in the coastal zone of the IO and how will these impacts be manifested in the future?
How, in general, is coastal development affecting marine ecosystems around the IO rim? How do these pressures and impacts differ in the coastal environments of different countries, for example in developing (e.g. Bangladesh in the northern IO) versus developed countries (e.g. western Australia in the southern IO). How in turn does sea level rise affect coastal development and human populations in these areas? In many areas, coastal development is synonymous with urbanization and industrial development. What will be the impacts of urbanization (e.g. increased sewage discharge and changes in water use) and industrial development (e.g. construction of dams, desalination plants, and power plants) on coastal marine ecosystems? How, specifically, will changes in material transport (riverine, groundwater, and aeolian) and deposition (e.g. volatile organic compounds, nutrients, sediments, and heavy metals) alter coastal marine environments? Coastal development usually involves changes in land use. What will be the impacts of land use changes (e.g. agriculture, deforestation, desertification) on coastal marine ecosystems in the IO?

Similarly, coastal development involves changes in water use, i.e. diversion and rerouting of water supplies for both urban and agricultural purposes. How will future increases in water use change the seasonal and spatial distribution of freshwater inputs and how will subsequent decreases in discharge affect circulation, productivity, food web structure and biogeochemical processes in coastal waters? These questions are particularly relevant to marginal seas where alterations in freshwater inputs can have major impacts (e.g. the damming of the Indus River and the salinization of the delta). More generally, how are the river loads and the stoichiometric ratios of C, N, P and Si changing in the IO? What is the role of river carbon and nutrient export, and what is the impact of changing river loads and modified stoichiometric ratios on open ocean biodiversity and primary production through changing food web structure in the coastal seas?

Human activities also influence atmospheric transport of particulate matter and deposition in coastal and open ocean waters. In general, how do natural changes (e.g. seasonal and interannual) affect marine IO environments through deposition of nutrients and minerals and scavenging of POC and DOC? Both natural and anthropogenic aerosols can have particularly high concentrations in the northern IO. How important is aeolian input to biogeochemical cycles (e.g. Fe, N, Si, P)? Is this input disproportionately important compared to other oceans? How does dust deposition transmit through the water column and the pelagic food web and ultimately impact benthic-pelagic coupling in coastal waters and shallow seas? How does potential increasing monsoon intensity (Goes et al., 2005) affect air mass trajectories, aerosol and mineral fluxes, and how will these processes affect the biological production and biogeochemical cycles in the northern IO? How are aerosols (both natural and anthropogenic) affecting the incident radiation into the IO and what are the biogeochemical and ecosystem consequences? How will all of these influences change in the future climate? For example, how will changes in the frequency of extreme weather patterns (drought/floods, fires) affect sources of mineral dust to marine environments in the IO?

Human activities on the ocean also have direct impacts on the marine environment. Aquaculture industries are growing in many countries around the IO rim. How does aquaculture influence coastal water quality? What will be the impact of the growing aquaculture industry (e.g. deforestation of coastal mangroves, eutrophication, etc.) on coastal marine communities and biogeochemical processes? Will the frequency and intensity of HAB events change due to increased anthropogenic nutrient inputs associated with aquaculture? Fish aquaculture typically involves substantial inputs of organic matter in the form of feed. How does aquaculture demand for feed affect wild-caught fisheries in the IO? How will these human activities influence rates of species evolution and extinction? For example, will introduction of genetically altered farm species impact the gene pools of wild populations?

Many human activities are likely to impact sensitive coral reef environments in the IO. What are the anthropogenic (climate change, land use) impacts (SST, pH, sediment and nutrient loading due to runoff, etc.) on coral reefs? What are the important contaminants (oil, pesticides, radionuclides, heavy metals, organics, etc.) and their sources and sinks in the IO, and how do the inputs of these contaminants change over time (seasonal, interannual)? How are these contaminants processed/recycled in the ecosystem, and what are their residence times?

Theme 6: The role of higher trophic levels in ecological processes and biogeochemical cycles

To what extent do higher trophic level species influence lower trophic levels and biogeochemical cycles in the IO, and how might this be influenced by human impacts (e.g. commercial fishing)?

Background

Assessing the role of pelagic consumers on ecosystem dynamics and biogeochemical cycles (and vice versa) and developing an end-to-end food web understanding are important considerations for IMBER. Trophic networks comprised of protists, metazooplankton, nekton and top predators (tuna, squid, sharks) are important in both the epipelagic and mesopelagic zones, with many of the larger animals bridging and influencing both habitats. In addition, turtles, seabirds and mammals, even fishermen may be important to consider in the context of some science issues. Questions of relevance relate to the physiologies and behaviors of the organisms themselves, but even more so to the impacts of top-down versus bottom-up controls and the interactions between ecosystem processes and biogeochemical cycles. For example, the well-known ecological relationship between environmental stress and reduced species diversity is relevant to potential future climate impacts on the OMZ as well as to coastal eutrophication issues facing both the AS and the BoB.

Despite their size range differences, micro- and mesozooplankton are both functionally diverse assemblages with multiple trophic levels, complex feeding relationships and broadly overlapping prey resources. For instance, appendicularians feed efficiently on prey as small as bacteria (Scheinberg et al., 2005), while some large dinoflagellates are notable selective consumers of large diatoms (Strom and Buskey, 1993). According to a synthesis of JGOFS results by Landry (2009), micro-herbivores consume 71% of daily primary production in the AS, with little evidence of substantial differences in seasonal averages. At finer spatial scale, the rates of microzooplankton grazing on phytoplankton tend to follow production, decreasing from the coast to offshore for most of the year, but with high rates extending well offshore during the deep convective mixing associated with the NEM. Microzooplankton grazing rates can be high in the upwelling region during the SWM, and they generally account for the utilization of ~50% of diatoms (Brown et al., 2002), a role often attributed entirely to larger mesozooplankton in ecosystem models. Carbon estimates of food web fluxes through microzooplankton suggest that 7-24% of daily primary production can be transferred to mesozooplankton through a protist grazing chain of one or two steps (Landry, 2009), which provides a steady and important supplement to direct phytoplankton consumption by larger consumers.

Grazing rate studies of the mesozooplankton were not conducted as intensively as those of the microzooplankton during JGOFS; hence, what is known from direct experimental studies is presently inadequate to fully support (or refute) the hypothesis that they play a major role in controlling phytoplankton standing stock and production, especially during SWM upwelling (e.g. Barber et al., 2001; Smith, 2001). The available rate data do, however, suggest that mesozooplankton consume about 25% of daily primary production on average from direct feeding on phytoplankton, while indirect estimates from empirical production models based on size-structured biomass and temperature put mean total consumption of mesozooplankton (including microzooplankton, detritus and carnivory) at ~40% of primary production, with relatively modest seasonal variability (Landry, 2009; Roman et al., 2000). Overall, mesozooplankton production (i.e. the flux of carbon that passes through zooplankton to support higher trophic levels) in the AS is ~12% of primary production (Roman et al., 2000), or about 0.15 tons C km^{-2} d^{-1}.

Water column studies of mesozooplankton in the AS during the 1990s produced several significant discoveries (Smith, 2005). The apparent paradox of high standing stocks of zooplankton coinciding with low standing stocks of phytoplankton during the NEM was resolved; the high biomass of mesozooplankton is sustained by primary productivity stimulated by convective mixing and by an active microbial food web. Another important observation is that the SWM (upwelling) season supports a burst of mesozooplankton growth. At the end of that season, diapause causes at least one very abundant copepod (*Calanoides carinatus*) to leave the epipelagic zone. The JGOFS observations also illuminated a potential linkage between mesozooplankton speciation associated with OMZ conditions. One copepod that withstands the conditions in the OMZ (*Pleuromamma indica*) appears to have increased in abundance over the past 30 years suggesting that the OMZ may have grown in size or intensity in that time. Finally, abundance of the cyclopoid copepod genus *Oithona* during fall intermonsoon and the NEM seasons were much higher in the 1990s than in collections made with comparable nets 60 years previously (John Murray Expedition), suggesting a possible long-term alteration of the base of the food web.

Long-term changes in copepod species abundance have also been observed elsewhere in the IO. Specifically, dominant coastal upwelling copepod abundances have declined off the SW coast of India (R. Stephens, personal communication). This may indicate long-term ecological change in coastal waters during the SWM, potentially attributable to climate effects on the physical system or to a more proximate cause, such as hypoxia.

Among the higher-level consumers that feed on mesozooplankton and above, mesopelagic myctophids have been characterized as “annual fish” because of their fast growth rates and short (i.e. 1-year) lifespan. Squid exhibit similar life strategies. Population biomass levels of these groups should therefore respond quickly to climate variations. While longer-lived top predators, such as sharks and tunas generally have slower population response to climate variability, changing conditions can cause them to significantly alter behavior. For example, migrations of tunas in equatorial waters are strongly influenced by climate phenomena like the IOD (Marsac et al., 2006). Behavioral changes may provide early indications of adjustments to degrading or evolving environmental circumstances, and are important to understand for both short- and long-lived key species.

As discussed in Themes 3 and 4, the NW IO contains one of the three major OMZs of the open ocean (Naqvi et al., 2006a). Strong OMZs have substantial impacts on the abundance and distribution of mesopelagic organisms. OMZ species are typically diurnal vertical migrators, which rise to more oxygenated waters during the night (Childress, 1968; Saltzman and Wishner, 1997; Vinogradov and Voronina, 1961). Mesopelagic organisms may employ biochemical and metabolic modifications that enhance their ability to live or take advantage of OMZ conditions. In general, however, very little is known. Vigorous data-mining efforts and new experimental work on growth efficiencies and life at low O_2 levels are needed.

Although the mesopelagic zone is poor in food availability, many different types of organisms are known to thrive there. These mainly consist of a large group of mesopelagic fishes, pelagic decapods and pelagic squids (Menon, 1990). During their diel migrations to surface waters, these micronekton are prey for tunas, sharks and barracuda. Among the mesopelagic fishes, the most common and abundant are the lanternfishes of the family Myctophidae. Some 30 Myctophidae species reside in the AS north of 9°N (Tsarin and Boltachev, 2006). Myctophids are often major contributors to the deep scattering layer and are key members of the food web (Barham, 1966). Among the migratory myctophids, some species feed primarily on one or two specific copepod species (Kinzer et al., 1993). They may thus exert a strong top-down impact on the pelagic food web through selective predation. Through their vertical migration they also facilitate the transfer of carbon to higher trophic levels in the deep sea and bring both nutrients and CO_2 to deeper layers in or near the OMZ (Balanov et al., 1994; Butler et al., 2001). Thus, a large stock of myctophids in the IO will have direct and substantial impacts on the biogeochemical cycles.

It has long been recognized that mesopelagic fish can be extremely abundant in the IO. From trawls and signal returns from ship echo sounders on five extensive cruises during 1975-1976, the stock biomass of mesopelagic fishes (dominated by myctophids) in the northern and western AS has been estimated to range from 56 to 148 x 10^6 tons of wet weight (Gjøsaeter, 1984). Later trawl and acoustical surveys of diel-migrating myctophids have arrived at biomass estimates about 52 x 10^6 tons for the AS during the NEM and half that for the SWM (Tsarin and Boltachev, 2006). Large stocks of myctophids reside all along the outer edges of the coastal zone of the Arabian Peninsula, off Pakistan and in the Gulf of Oman, with sizeable populations also off Somalia and northern India (Kinzer et al., 1993). Considering that the entire world's annual catch for commercial marine fisheries is between 40 and 100 million tons, if the above stock estimate for AS myctophids is accurate, then these fish must be an extremely important food source for predatory fish, squid and other top predators and they have the potential to be a very large fishery. In addition to the mesopelagic fishes, there are epipelagic stocks, as well as demersal species. The biomass of the latter made up about half of that of the pelagics along the coasts of Arabia and the northern AS during 1975-1976 (Venema, 1984; their Table 20).

A few species of myctophids, especially *Benthosema pterotum*, dominate in the NW AS and adjacent Gulf of Oman (Gjøsaeter, 1984; Gjøsaeter and Kawaguchi, 1980), where populations of other species are atypically small (i.e. low diversity). A good deal is known about the biology of *B. pterotum*. Gjøsaeter & Tilseth (1983) reported on stomach contents that showed a diet of copepods and mesozooplankton generally. The species has a life span that is no more than a year, which implies that the entire stock of up to 100 million tons (wet weight) turns over annually. This is a staggering sum, and begs comparison with the estimated production of mesozooplankton prey (0.15 tons C km^{-2} d^{-1}) from Roman et al. (2000). This translates to 0.6 million tons C daily, or about 15 million tons (wet weight) d^{-1}. With mesopelagics typically consuming a few percent of their body mass per day in zooplankton prey, which for an annual biomass turnover would imply a rate of at least 0.2% d^{-1}, there appears to be plenty of prey production to support high estimates of *B. pterotum* stocks and rates. Stemming from this estimate, it would be interesting to investigate the coupling between epipelagic production processes and mesopelagic bioenergetic requirements to assess more closely: 1) how they compare in areas of high mesopelagic biomass concentration; 2) the possible role of *B. pterotum* in top-down regulation of mesozooplankton and 3) the relative strengths of alternate pathways of carbon flux (passive settling of particles versus active migration) to the mesopelagic realm. This would establish potential roles and relationships that could change substantially with large fishery impacts on mesopelagic stocks.

Climate change impacts on myctophid habitat can translate to leading order modification of the distribution, survival and recruitment success of myctophid larvae. This, in combination with their extreme stock size, makes myctophid fish in the AS (particularly *B. pterotum*) an exciting target species for research that couples climate impacts on pelagic biology on multiple trophic levels.

Although zooplankton and myctophids in the AS are obvious targets for additional study, it is important to emphasize the pressing need for higher trophic level investigations elsewhere in the IO. As discussed under Theme 4, the role of zooplankton grazing versus nutrient and light limitation in controlling phytoplankton production also needs to be assessed in equatorial waters and in the southern subtropical gyre. As discussed under Theme 5, increasing anthropogenic impacts on higher trophic levels are of particular concern in the BoB, where there is a pressing need for the establishment of national and regional mechanisms for coordinating research, monitoring and management of marine resources and higher trophic level species. These efforts are being undertaken by the Bay of Bengal Large Marine Ecosystem (BOBLME) Project, which involves eight rim countries (Bangladesh, India, Indonesia, Malaysia, Maldives, Myanmar, Sri Lanka and Thailand). Similarly, in the western equatorial IO, the Agulhas and Somali Current Large Marine Ecosystems (ASCLME) Project, which involves nine countries in the region (Comoros, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, Somalia, South Africa and Tanzania), has been established to ensure the long-term sustainability of living resources through research, monitoring and ecosystem-based management. In the southwestern IO the South African Network for Coastal and Oceanic Research (SANCOR) facilitates and coordinates marine and coastal research off South Africa aimed at maintaining a healthy coastal marine environment and fisheries. In the southeastern IO the Western Australia Integrated Marine Observing System (WAIMOS) has been established to promote research aimed at understanding the influence of the Leeuwin Current system on both pelagic and benthic ecosystems and commercially important higher trophic level species like the rock lobster discussed in Theme 1. Although the management aspects of these projects are beyond the scope of SIBER, as discussed below, the establishment of strong linkages with the BOBLME, ASCLME, SANCOR and WAIMOS to promote higher trophic level research and monitoring is an important objective of SIBER.

Core questions

1) At lower levels of the food web, where small consumers interact with primary producers and biogeochemical cycling, what are their roles in regulating the composition and structure of planktonic communities and the magnitudes and directions of carbon and nutrient fluxes?

As noted in Theme 4, the little information we have about secondary production and lower-level food web cycling in the IO derives mostly from AS studies in the 1990s (e.g. Dennett et al., 1999; Hitchcock et al., 2002; Landry et al., 1998; Roman et al., 2000). Direct experimental assessment of mesozooplankton contribution to grazing were relatively sparse during JGOFS, yet zooplankton grazing emerged as the main hypothesis to explain depressed blooms of phytoplankton, and diatoms in particular, during the SWM (Smith, 2001). From previous studies therefore, a central question for lower trophic levels is clear: Do grazers actually control phytoplankton standing stock and primary production during the SWM, or are other factors (such as Fe, light, Si) involved or perhaps even more important? In the broader IO context, there is a critical need to further our understanding of how the seasonally and spatially varying balance among grazing, light and nutrient limitation control primary production, as discussed in Theme 4.

Direct and indirect effects of global warming and ocean acidification, such as enhanced stratification, climatic/regime shifts and reduced calcification of key plankton species, may have significant impacts on community structure and elemental cycling in the IO (Hood et al., 2006). If these shifts occur in the absence of established regional climatologies and baseline knowledge of the lower food web, it will be difficult to differentiate them from natural interannual variability. Moreover, if simultaneous changes occur in fishing effort, with possible cascading effects through the food web, identifying climate-induced change will be even more challenging. In areas like the AS that have some historical databases of integrated stock and process measurements, one might therefore ask whether underlying food web relationships have already changed significantly in response to climate forcing. Are there indicator processes, species or food web effects that are showing signs of long-term changes due to anthropogenic impacts? The answer appears to be yes, at least for some zooplankton species, as discussed above. In addition, in contrast to trophic studies in the euphotic zone, the IO provides a unique opportunity to investigate the regulation of food webs and biogeochemical cycles under varying conditions of oxygen content and organic fluxes in the OMZ.

2) At intermediate and higher trophic levels, what are the dynamics, impacts and vulnerabilities of dominant stocks/populations like myctophids, and how do their biomass variations affect lower trophic levels and vice versa?
Net sampling and acoustic data suggest that myctophids are extremely abundant in the IO. However, survey data on these and other mesopelagic species are very limited. First-order descriptive sampling and survey work is needed to determine the seasonal and interannual variability of biomass and composition of the mesopelagic stocks. In addition, elemental compositions should be measured so that the stocks can be related to biogeochemical budgets and cycles, as well as to the physiological requirements of the organisms and their potential contributions as food resources to higher trophic levels. Basic taxonomic work needs to be done so that the IO stocks can be referenced to the literature for other ocean basins. The apparent diminished role of euphausiid crustaceans (krill) is an interesting basic science problem for IO ecosystems. It is tempting, for example, to suggest that myctophids "replace" euphausiids in the AS, or that myctophids occupy the euphausiid niche. A careful study of euphausiid biology and ecology in conjunction with the myctophids is necessary. If myctophids are the shelf break/upper slope dominants, this may be very different to similar habitats elsewhere. In the upwelling system off NW Africa, for example, euphausiids at the shelf break support a large hake fishery.

For assessing ecological relationships and fluxes among mesopelagic system dominants, we need to know major trophic pathways and rates. Gut content analyses, for example, can tell us about dietary compositions, as well as where in the water column and approximately when they feed. Gut throughput, defecation and metabolic rates (via shipboard and lab studies) are also needed so that consumption rates and food requirements can be estimated. They would also allow the impact of diel vertical migrants on biogeochemical cycles to be assessed, i.e. how much C, N and P is transferred between the epipelagic and mesopelagic zones, and are these fluxes significant at basin scales? To what extent do mesopelagics respond to interannual fluctuations in surface production and export? Finally, studies of the C and N stable isotope compositions of key consumers, like myctophids, are needed in order to quantify their position in the pelagic food web.

For ecosystem dominants, emphasis needs to be focused on species-level investigations, which should in turn allow development of appropriate fisheries and biogeochemical models for synthesis and prediction. How do species' distributional patterns relate to variables like temperature, salinity, O_2 and food availability (for deeper layers, the supply of food from export fluxes)? Recruitment, growth and mortality rates (including predation) need to be determined for most mesopelagic stocks, particularly myctophids. The role of behavior also needs to be investigated, e.g. foraging mechanisms, extent of vertical migration, and species differences in depth of OMZ penetration. If diel migratory behavior is a strategy for predator avoidance, does it vary as a function of predator density or predation pressure? Global warming may impact mesopelagic species by influencing the extent and intensity of the OMZ (see Themes 3 and 5). If many pelagic stocks depend on the OMZ as a refuge and for food, will global warming lead to the expansion of this zone (Stramma et al., 2008), and what will be the likely consequences for food web relationships and biogeochemical cycling?

3) At the top of the trophic hierarchy, what are the climate and human (fisheries) influences on major predator stocks (such as tuna) that could exert top-down pressures on the functioning of food webs?
As discussed in Theme 2, natural climate variability associated with phenomena such as the MJO and the IOD in particular, have influences that manifest strongly not only at the equator but also into the AS and BoB basins, changing patterns of phytoplankton surface productivity (Wiggert et al., 2009) as well as distribution of commercially important top predators such as tuna (Marsac et al., 2006). One overarching question is how such changes propagate upwards and downwards through food webs? What are the likely consequences of such trophic cascades with future climate changes?

Human harvesting of fish and squid can be expected to have an overriding top-down effect in the open sea. A gross decline in the open IO of catch per unit effort has been observed, and the lessons from the warm parts of the north Atlantic cannot be ignored for long. Stock assessments of tunas and other large pelagics are beyond the scope of SIBER. However, many aspects of the biogeochemical and ecological impacts of these organisms need to be studied. For example, is fishing on tuna stocks in equatorial waters in the IO sustainable? Will commercial harvest of myctophids, as recently begun by Iran, be large enough to impact the stocks? If profitable uses are found for the fish oil and protein products, will this fishery expand to other countries and regions in the IO, possibly through fleets from outside the region? What are the potential biogeochemical and ecological impacts of such a fishery expansion?

Anthropogenic impacts are also apt to increase during the next decades due to increasing population density, especially around the AS and the BoB (see discussions above and in Theme 5). The influence of pollution due to eutrophication and aquaculture on higher trophic levels in coastal waters and marginal seas needs to be investigated with regard to causes and extent of anthropogenically-induced fish kills, and the potential impacts of overfishing need to be assessed. What are the human impacts of these losses and their potential feedbacks to pelagic and benthic food webs?

Implementation Strategy

In order to deliver its goals and objectives SIBER will focus on promoting three major areas of science activity: 1) remote sensing studies, 2) modeling studies and 3) *in situ* observation and potential for leveraging existing infrastructure. All of these will require close collaboration and multidisciplinary integration of knowledge obtained by teams of researchers operating throughout the IO. To link these three areas there will be a continual process of integration and synthesis, drawing together the outputs of the various activities (**Fig. 21**). This will be an ongoing process that will gather speed over the course of the program.

The three major areas of science activity are discussed below; the remote sensing studies are presented first as they lay the initial observational foundation for the SIBER science program and provide the 1st order descriptive data for the subsequent sections on modeling and field activities. There are currently varying levels of detail in the different sections; the balance will be appropriately redressed as SIBER becomes established and further develops the plans and strategies in each of the activity areas.

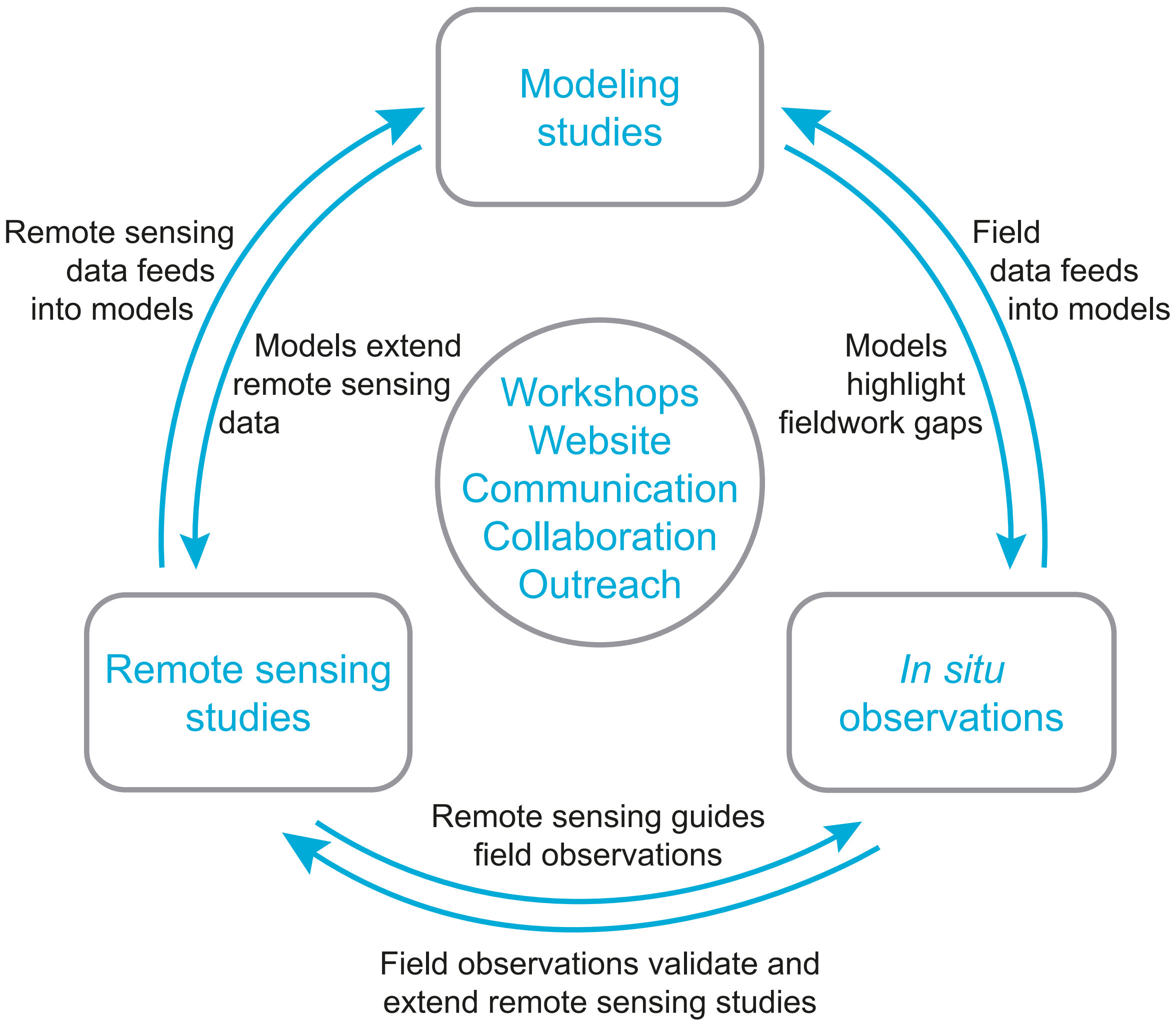

Figure 21: Simplified representation of SIBER activities illustrating links between the three main areas: modeling studies, remote sensing studies and *in situ* observations, all of which will be guided by close collaboration and multidisciplinary integration of knowledge from research groups operating throughout the IO. The three main activity areas and their outputs will be linked together through workshops and other communication strategies, resulting in a responsive and dynamic program.

Remote sensing studies

The obvious starting point for carrying out regional studies in the IO is through the application of remote sensing to characterize physical and biological variability of these systems. Relevant measurements, with corresponding representative mission(s) with NASA as a principal contributor, include satellite ocean color (SeaWiFS, MODIS-Aqua), sea surface temperature (SST) (NOAA/AVHRR, MODIS-Terra/Aqua), sea surface height (SSH) (T/P and Jason), surface vector winds (QuikSCAT) and precipitation (TRMM). Remote sensing should be applied specifically to study the seasonal variability and transitions in IO boundary current systems, to define and characterize the dominant scales of spatial variability and also to characterize interannual variability, especially as it relates to climate change. Interdisciplinary remote sensing studies must seek to elucidate both the physical (SST and SSH) and biological (chlorophyll and primary production) dynamics and understand the impact of physical oceanography on biological processes in the IO. In addition to studies based upon the US deployed satellites noted above, opportunities exist to utilize remote sensing data obtained via other national agencies or multi-national consortia. For example, India's Oceansat-1 and recently launched Oceansat-2 provide physical (SST and wind) and ocean color measurements starting from 1999; straightforward provision of these high-resolution data to non-Indian scientists needs to be ensured. The European Space Agency (ESA) has also launched a number of satellite missions (e.g. ERS-1,2 and Envisat) that provide ongoing measurements of ocean color (MERIS), SST (AATSR), SSH (RA-2) and winds (ASCAT). In addition, since November 2009, ESA's SMOS (Soil Moisture and Ocean Salinity) mission has been providing the first regular global mapping of sea surface salinity (SSS) (Berger et al., 2002). This remote sensing capability will soon be reinforced with the launch of NASA's Aquarius mission that will also provide SSS measurements (Lagerloef et al., 2008). The continuous observations of SSS provided by SMOS and Aquarius will address a manifest need that SIBER should capitalize on, given the influence that the hydrological cycle exerts on the dynamics of the northern and eastern IO.

As with boundary current studies, satellite observations can and should play a central role in studying seasonal, intraseasonal and interannual biogeochemical variability of equatorial waters of the IO. Many of the phenomena discussed above in Theme 2 are amenable to satellite studies, i.e. characterization of the typical annual cycle in surface temperature, sea surface height, chlorophyll and primary production and the physical and biogeochemical responses to perturbations associated with the IOD, the MJO, Wyrtki Jets and other high frequency forcing phenomena such as cyclones. Retrospective studies should be motivated. The satellite SST measurements based upon the AVHRR have been reprocessed and extend back in time to 1981, i.e. that is a 30-year record. This record has been used to demonstrate warming globally, including the prominent response observed in the IO (Arguez et al., 2007). In the often cloudy regions of the IO, the SST microwave data (TMI and AMSR-E) are very useful, thanks to their ability to "see through clouds" and monitor strong cooling under convective systems (e.g. Duvel et al., 2004; Harrison and Vecchi, 2001).

Ocean color data acquired by SeaWiFS, MODIS and other orbiting sensors extend from 1997 to the present. These datasets have already been utilized to reveal anomalous biological distributions during IOD manifestations (Murtugudde et al., 1999; Wiggert et al., 2002) and phytoplankton bloom characteristics along the equator and within the STIO (Lévy et al., 2007; Uz, 2007; Wiggert et al., 2009) and blooms associated with the MJO in the SCTR (McCreary et al., 2009; Resplandy et al., 2009). However, more comprehensive elaboration of IO bloom dynamics and biophysical processes, and how these are impacted by the IOD, are needed. There has also been considerable effort in recent years to extend the utility of ocean color measurements from SeaWiFS and MODIS to provide estimates of net primary production and phytoplankton physiological state (Behrenfeld et al., 2005; Behrenfeld et al., 2009) and a more concerted effort to specifically apply the insight these products can provide to the IO must be targeted. Basic characterization of the typical seasonal cycles of ecological and biogeochemical processes in equatorial waters is critical, particularly as a comparative baseline for determining how the annual variability is altered on intra- and interannual timescales (i.e. by MJO and IOD). These analyses can potentially be augmented by India's OCM (Ocean Color Monitor) sensors on Oceansat-1 and 2 and by ESA's MERIS sensor.

Ocean color measurements have also been used in studies of regional and basinwide biological response to climate change (Goes et al., 2005; Gregg et al., 2005). Additional studies along these lines should be motivated. Presumably, climate change is differentially impacting the sub-basins of the IO; e.g. what regions of the IO are warming fastest, and how are chlorophyll concentrations and productivity responding to these changes? At some level, retrospective remote sensing studies can also be focused on anthropogenic impacts in coastal waters, e.g. true color imagery can be used to characterize long-term trends in terrigenous inputs to coastal zones around the IO rim (e.g. **Fig. 4, right panel**). In addition to chlorophyll, standard ocean color products provided by the NASA-Goddard DAAC such as diffuse attenuation, CDOM, POC and FLH (fluorescence line height) can be employed to investigate interannual to interdecadal variation in these properties that can be of particular relevance for coastal regions impacted by riverine influence.

Satellite ocean color data (SeaWiFS, MODIS-Aqua and OCM) have already revealed striking contrasts in the chlorophyll distributions and seasonal cycles between the AS and the BoB (Lévy et al., 2007; Wiggert et al., 2006). However, specific comparative remote sensing studies that focus on the differences in the ocean color variability between the AS and the BoB have not been undertaken. Satellite SST, SSH and SSS measurements can/should be similarly analyzed focusing on differences in the physical variability (upwelling, filaments, eddy structures, etc.) between the two regions. Combining ocean color, SST and SSH remote sensing measurements provides potential means to study, for example, differences in upwelling signatures between the AS and the BoB, e.g. it may be possible to "see" and characterize cryptic upwelling variability in the BoB because upwelling and eddies that do not outcrop at the surface should have a strong signature in SSH but a weak signal in SST and ocean color. Remote SSS measurements can also be combined with ocean color, SST and SSH to study differences in the freshwater inputs and sea surface density variability between the AS and the BoB and how this impacts biological response. Satellite remote sensing can also be gainfully applied to study atmospheric transport, i.e. transport of dust during the SWM and anthropogenic pollutants particularly during the NEM.

Atmospheric correction problems are still a significant issue for ocean color measurements, especially in the northern AS where SWM-period aeolian dust loadings are a particular concern (Banzon et al., 2004). Efforts need to be made to develop better atmospheric correction algorithms that are specific to the IO.

Although it is not possible to directly detect and survey protozoan, metazoan and higher trophic level species using satellites, remote sensing can provide useful data. Satellite-derived SST data can be used to define thermal regimes for micro- and mesozooplankton species. Ocean color data are particularly useful because they provide the means to map phytoplankton distributions, i.e. the food source of zooplankton. In general, zooplankton biomass increases in proportion to phytoplankton biomass, and zooplankton composition may, with study, be found to vary with chlorophyll concentration in predictable ways. This linkage between phytoplankton and zooplankton (and often also larval fish) is particularly well defined in strongly advective regimes, e.g. in filaments where coastal water with high chlorophyll concentration is rapidly advected offshore and in eddies (e.g. Logerwell and Smith, 2001). Satellites should, in particular, be employed in combination with *in situ* process studies that seek to define relationships between food web parameters and large-scale physical and biological (chlorophyll) patterns.

For higher trophic levels, satellite-derived SST data has been routinely used by commercial fishermen for locating productive fishing grounds in, for example, the California Current off the west coast of the USA (**Fig. 22**). These satellite data can also provide SST input patterns for use in individual-based models (IBMs) that simulate fish migrations within a specified environmental setting. Such models exploit the fact that many higher trophic level species (like tuna) seek out concentrated patches of prey associated with physical fronts (i.e. convergence zones) in the open ocean. IBMs using simple random walk and forage behavioral models can provide important insights into how large predators migrate in the open ocean.

It has also been shown that ocean color patterns can be related to CPUE of the tuna fishery in IO equatorial waters. In particular, Marsac et al. (2006) identified a clear relation between SeaWiFS-observed chlorophyll and CPUE distributional shifts during IOD events. Thus, ocean color data could potentially be combined with SST data to provide not only behavioral clues, but also as guidance on the location of optimal foraging grounds as tuna populations move zonally in equatorial waters under changing climatic conditions.

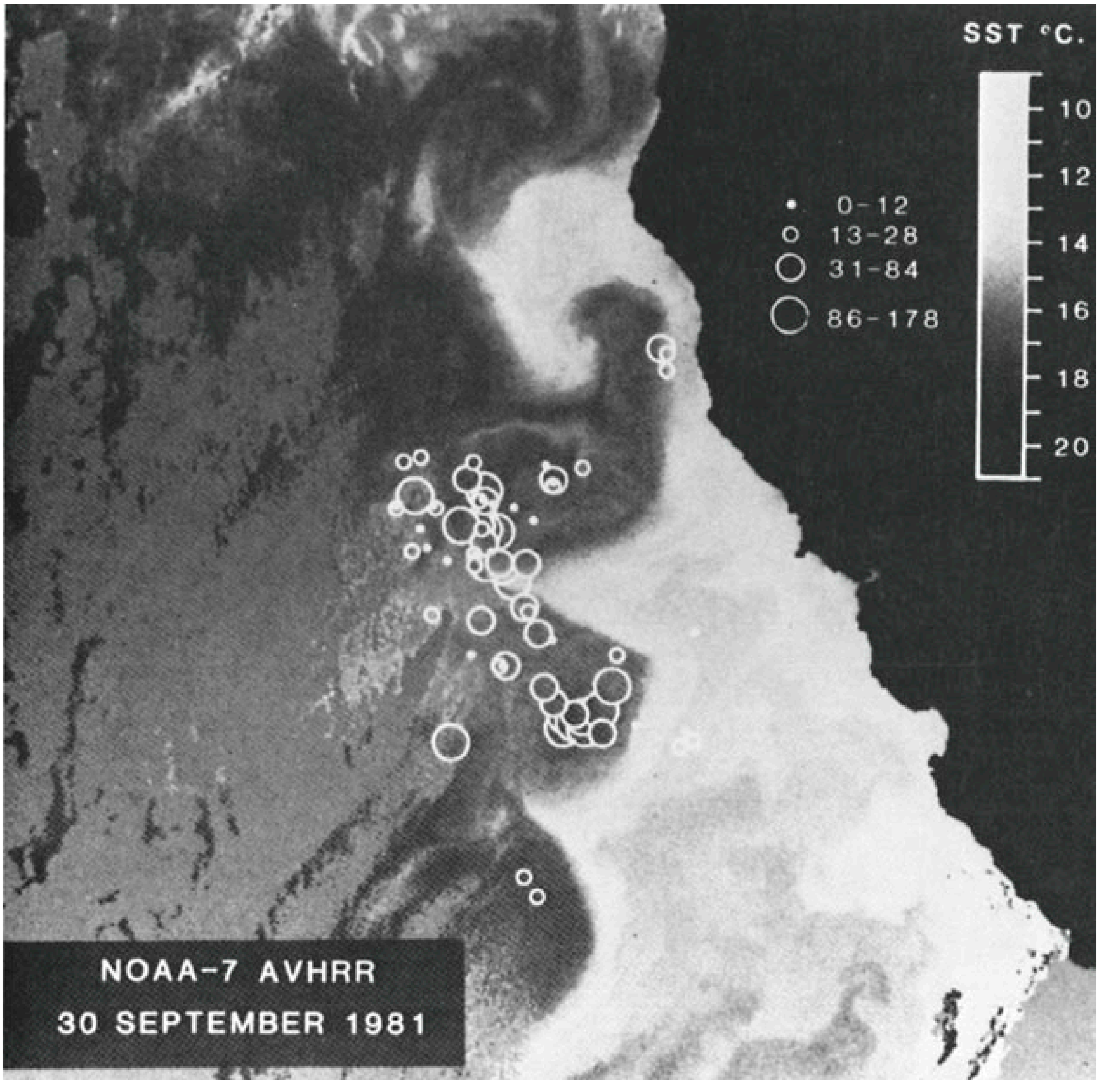

Figure 22 Central California (USA) daily albacore tuna catches, September 27 to October 2, 1981, and sea surface temperature from NOAA 7 AVHRR, channels 4 and 5, September 30, 1981.

Figure and caption reproduced with permission from Njoku et al. (1985).

Modeling studies

Remote sensing studies 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 IO. Eddy-resolving models are required in order to capture the physical and biological variability in IO boundary current 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) (**Fig. 23**). Through 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 IO 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 LC, a principal feature off the western coast. OFAM's 1/10th degree implementation will soon be expanded to include the entire IO (R. Matear, personal communication). OFAM is currently generating "nowcasts" and short-term forecasts in support of field studies (see below), as well as retrospective studies. An important question yet to be answered in the context of boundary current studies, is how well these models represent cross-shelf exchange. Efforts aimed at developing stronger interactions among different IO modeling groups would be well placed to promote leveraging and shared use of forcing and boundary condition fields, which could be applied for focused regional applications. These could in turn be used for applying complex biogeochemical sub-models that would provide insight into IO ecosystem processes.

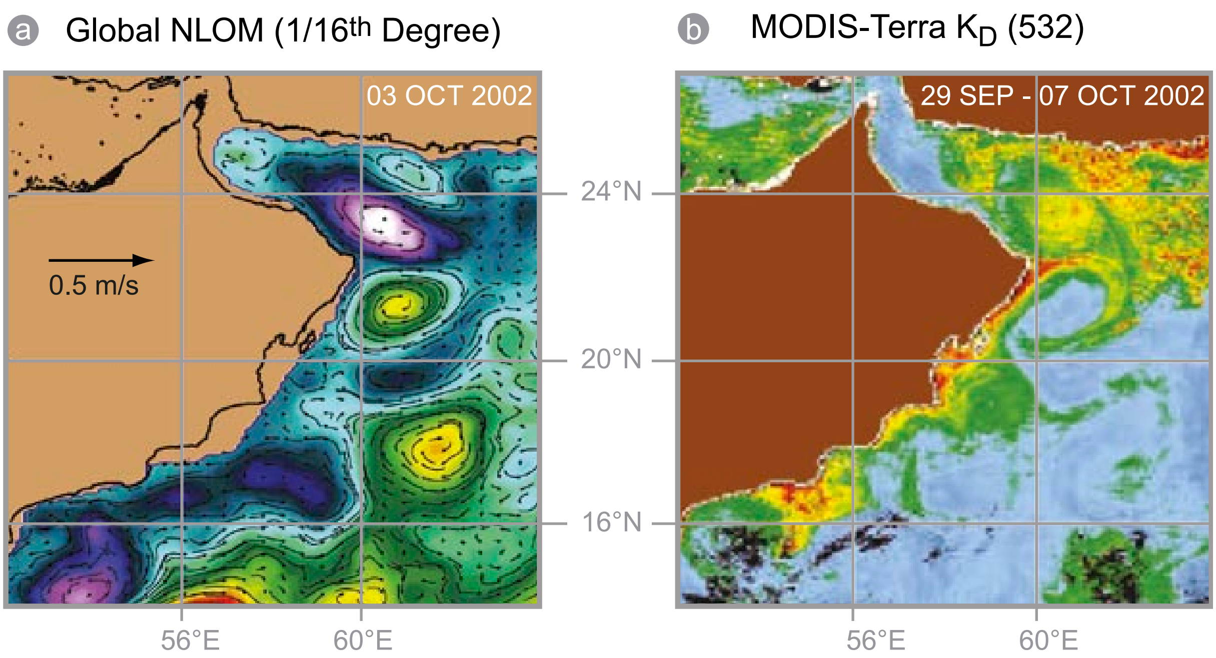

Figure 23 Comparison of 1/16th degree NLOM simulation snapshot of surface layer velocity and sea surface height with diffuse attenuation coefficient at 532nm observed by the MODIS-Terra color sensor.

Reproduced with permission from Wiggert et al. (2005).

Modeling biogeochemical processes, climate variability and long-term change

Much of the IO biogeochemical modeling effort so far has consisted of regional applications that have focused on the northern basin or its two sub-regions (Anderson et al., 2007; Hood et al., 2003; McCreary et al., 2001; McCreary et al., 1996; Sharada et al., 2008; e.g. Swathi et al., 2000; Vinayachandran et al., 2005). Only recently have region model applications outside of the northern IO been a focal point, primary example is the implementation of physical-biogeochemical modeling applied to investigate how the MJO and IOD influence biological processes in the SCTR (Resplandy et al., 2009). In areas such as the SCTR where biological dynamics are largely localized to the deep chlorophyll maximum, the utility of ocean color measurements is reduced and the dependence on coupled physical-biogeochemical model applications to provide relevant insight is amplified.

Obviously, satellites and coupled physical-biogeochemical models can both be applied to study planetary wave-induced chlorophyll and productivity responses in equatorial and subtropical waters, in a similar manner to analyses focusing on other ocean basins and the south eastern IO (e.g. Feng et al., 2009; Waite et al., 2007). Interestingly, a recent study of STIO physical-biological interaction has documented a counterintuitive link between westward propagating Rossby waves in the 15-35°S band that stimulate primary productivity (based on SeaWiFS-observed chlorophyll) and exhibit an inverse correlation with tuna longline catches (White et al., 2004).

Given the dramatic differences in the surface eddy kinetic energy between the AS and the BoB, modeling studies aimed at contrasting these two regions should provide good first-order information about dynamic differences. Coupled physical-biological models can also be applied to study biogeochemical and ecological responses to physical forcing. It has been shown that it is possible to capture first-order differences in the biogeochemical dynamics between the AS and the BoB with coupled models (Koné et al., 2009; Wiggert et al., 2006), although having sufficient resolution to resolve the observed variability, especially in the AS could be an issue. As discussed above, planned implementation of high-resolution (eddy-resolving) models in the IO (e.g. OFAM) will provide an excellent opportunity for performing comparative modeling studies of the AS and BoB using simple (NPZD-type) biogeochemical-ecological model formulations. These simple models are appropriate for assessing the leading-order biogeochemical differences between the two regions and can also be applied to study the biogeochemical and ecological impacts of semi-persistent or cyclical features, such as the Great Whirl, the Ras al Hadd Jet, the Laccadive High, the Sri Lanka Dome and the Wyrtki Jets.

In addition to studies focused on surface variability, models can and should be applied to investigate intermediate and deepwater processes, i.e. linkages between surface production, export and remineralization and how these fuel and impact the OMZs in the AS and the BoB. Coupled models can be used to characterize first-order differences in these processes between the two basins. Similarly, studies should be undertaken that focus on the formation of the OMZs, and that aim to simulate the differences in the intensity and distribution of the OMZs between the AS and the BoB. Successfully simulating the subtle differences between the oxygen fields in these two basins is a significant research challenge and success in this endeavor would be an important first step toward understanding the balance of forcings that give rise to the OMZs in the AS and the BoB. Similarly, coupled models can be used to study export flux patterns and variability and first-order differences between the AS and the BoB. The lesser known OMZ that is present in the eastern Equatorial IO (Stramma et al., 2008) is also a feature of interest due to linkage with the Pacific Ocean through the ITF passage and the potential impact of the IOD that can significantly alter the quantity of organic matter exported vertically from the euphotic zone.

There are very few biogeochemical modeling studies that have addressed basinwide variability (Kawamiya and Oschlies, 2001; Kawamiya and Oschlies, 2003; Wiggert and Murtugudde, 2007; Wiggert et al., 2006). To date, only Wiggert et al. (2006) and Koné et al., (2009) have attempted to provide holistic insight into all sub-regions and their interconnections. It is nevertheless clear from these initial efforts that regional interconnectivity plays a critical role in defining the basin's biological and biogeochemical variability. The impact of the IOD on surface chlorophyll concentrations and productivity (**Figs. 12 and 13**) during the prominent occurrences of the 1990s has been simulated successfully (J. Wiggert, personal communication), but applications of retrospective biogeochemical modeling to study weaker IOD events (Annamalai et al., 2005; Meyers et al., 2007) are generally lacking. Forcing data are available to extend modeling simulations back to the late 1940s (Kistler et al., 2001). Retrospective studies along these lines could be used to investigate how IOD events affected biogeochemical variability pre-SeaWiFS.

Similarly, long-term retrospective and climate forecast model simulations can be used to identify climate change impacts on both the physical and biogeochemical dynamics of the IO. Model projections focused specifically on the IO and its sub-regions should be run out to the year 2050 and beyond. Existing earth system models that include processes like river run-off (and associated nutrients supply), atmospheric deposition (Fe, Si, N, C), ocean biogeochemical processes and ecosystem dynamics can and should be used to develop these projections. Downscaling techniques should also be applied, i.e. using larger scale climate models to force higher resolution regional simulations that can capture local variability and change with greater realism. In this context it is important to emphasize the need to engage scientists from outside the earth system modeling community who have specific expertise in IO basin-scale and regional modeling. Emphasis should also be placed on combining retrospective modeling (coupled physical-biological models) with satellite observations (SST, SSH, SSS and ocean color etc.) to investigate climate change.

Modeling the impacts of riverine and atmospheric inputs

As with satellites, models can be applied to study the sources, fate and impacts of freshwater and nutrient inputs in the AS and the BoB. Model simulations can be run with nutrient and freshwater fluxes that can be turned on and off to quantify their impact on physical structure and biogeochemical cycles in both basins. These would help to answer fundamental questions such as the degree to which freshwater inputs are responsible for the observed physical and biogeochemical differences between the AS and the BoB. Similarly, model simulations can and should be applied to study the influences of marginal seas, e.g. the spreading and impact of Persian Gulf and Red Sea water in the AS and the exchange of deep water between the Andaman Sea and the BoB. With the advent of the SSS remote sensing missions (SMOS and Aquarius), a major additional component will be available for assessing the veracity of models that include both terrigenous and atmospheric freshwater sources and highly saline inputs from marginal seas. Modeling studies of atmospheric dust and pollution fluxes should also be undertaken because of the importance of dust to particle fluxes and sedimentation in the AS and other IO regions. Also, retrospective watershed modeling simulations should be motivated to simulate how riverine nutrient loads have changed in the past and that project how they are likely to change in the future with increasing population density and associated changes in land use. These simulations could then be used to force coastal circulation and biogeochemical models to project these changes in the watershed onto coastal biogeochemical cycles and ecosystem dynamics.

As for modeling the river inputs themselves, there are major gaps in existing knowledge for the river basins draining to the IO. The global dataset of Meybeck and Ragu (1995) of river discharge and carbon and nutrient loads does not include many river basins and available data are scarce. For understanding the impact of river carbon and nutrient discharge on coastal and open ocean biology, more long-term measurements are required of both river discharge and loadings of nutrient and organic matter. The Global NEWS modeling project (Seitzinger et al., 2005) made a major effort to collect these data on a global scale, including the IO. However, for the purpose of investigating changes in primary production, export and ecosystem impacts, more regionally-oriented efforts focused on processes specific to the IO should be motivated.

Higher trophic level modeling

Applying coupled models to study ecosystem dynamics and higher trophic levels is still a significant research challenge. At present these models are primarily used to simulate and understand lower trophic level dynamics (e.g. NPZD-type dynamics and interactions). New modeling approaches for simulating higher trophic levels that emerged from GLOBEC and other programs, can and should be leveraged. SIBER should encourage the development and use of new, alternative end-to-end modeling approaches; especially model structures that are adaptive and/or generate emergent behavior. Such models will be needed to investigate the sensitivity of marine biogeochemical cycles and ecosystems to long-term global change (i.e. decades and longer) as environmental changes on these timescales are likely to give rise to shifts in marine ecosystem structure that are due to evolution and therefore cannot be anticipated. There are several recently developed alternative modeling approaches that are based on more fundamental ecological principles (e.g. Follows et al., 2007; Laws et al., 2000; Maury et al., 2007) that can capture such adaptive and/or emergent behaviors. Modeling efforts of this type, with specific application to the IO, should be undertaken.

As discussed above, “offline” individual-based modeling (IBM) approaches can be applied to study higher trophic levels, for example, fish behavior and migration in simulated physical environments. Significant opportunities exist for applying such models to study behavioral responses of commercially important fish (e.g. tuna) to physical and biogeochemical variability in equatorial waters (as applied to the Pacific Ocean by Lehodey et al., 1998).

More traditional food web modeling approaches may also be productively applied to study the dominant pathways of trophic interactions in ecological processes in the IO, and their potential vulnerabilities to climate change. Such models include the Ecopath with Ecosim package (EwE, see http://www.ecopath.org), which can be used to provide a static, mass-balanced snapshot of the ecosystem, as well as temporally and spatially dynamic simulations. Although the data requirements of these models will likely exceed the available information, efforts towards constructing them would provide a good overarching goal for food web studies and help to define data needs.

Unlike tuna, SST and ocean color data cannot be used with IBM models to simulate the distribution of myctophid stocks in the IO because their behavior is not keyed to oceanic fronts observable by remote sensing platforms. However, idealized modeling studies should be undertaken to obtain insight into the behavior of this species. For example, simple 1-D and 2-D models can be constructed to investigate predator-prey interactions under idealized scenarios where food supplies are restricted to surface waters and refuge areas employed by myctophids (i.e. the OMZ) that occur only in deep waters. Diurnal variations in light and visual predator success can be imposed, along with differences in O_2 tolerance between predator and prey, in simulations that seek to reveal how OMZ regions may function as a refuge from predation. These kinds of modeling studies, which have not yet been undertaken, could provide important insight into why myctophid species migrate the way they do and their biogeochemical and ecosystem impacts. Such modeling investigations could also provide a means of synthesizing existing information on metabolic characteristics, low O_2 tolerance and other behaviors of these fish.

IN SITU OBSERVATIONS AND POTENTIAL FOR LEVERAGING EXISTING INFRASTRUCTURE

DATA MINING

In terms of *in situ* observations, the obvious starting point is to identify and compile existing sources of information. Some potential data sources for the IO include the INCOIS (Indian National Centre for Ocean Information Services, which currently provides open access to the IO Argo float database), the NIO (National Institute of Oceanography) cruise program, WAMSI (Western Australia Marine Science Institution), WAIMOS (Western Australia's Integrated Marine Observing System), ASCLME (Agulhas and Somali Currents Large Marine Ecosystem Project), ACEP (African Coelacanth Ecosystem Programme), BOBLME (Bay of Bengal Large Marine Ecosystem Project) and SANCOR (South African Network for Coastal and Oceanic Research). However, many of these data sources do not include higher trophic level observations (Kyewalyanga et al., 2007; Pearce et al., 2006). The WAIMOS data sets will soon be publicly available and will include drifter, glider and radar-based observations.

In addition, data mining efforts need to be undertaken to look at long-term trends in physical and biological fields in the past in much the same way that is advocated above for satellite measurements. Historical data from IO expeditions are available from the International Indian Ocean Expedition (1960-1965). Extensive data sets have also been collected by Russian expeditions. These data should be mined, compiled and combined into consistent, formatted electronic data sets. Data are also available from a series of international studies including the Netherlands Indian Ocean Program (NIOP, 1992-1993) and JGOFS in the mid-1990s. A compilation of IO data, including hydrographic and biological observations is available from the NIO data center.

Efforts should also be made to identify existing data sets and studies in the ITF region and in the vicinity of Christmas Island. For example, CSIRO carried out a number of research cruises to Christmas Island in the 1960s and 70s. What specific measurements were taken and what was the sampling regime? Have these data been archived and are they available to provide an historical baseline for new research efforts in this region? Researchers involved in ITF studies (e.g. S. Wijffels, G. Meyers, A. Gordon) should be contacted to determine the kinds of ongoing research in the ITF, their relevance and potential for being leveraged and augmented as part of SIBER-related efforts. Have any biogeochemical and/or ecological studies been carried out in association with these physical oceanographic studies? Similarly, Dutch research activities conducted in these waters in collaboration with Indonesia need to be identified.

COASTAL MONITORING AND OBSERVATIONS

All regional studies motivated as a part of SIBER should target and build upon existing research infrastructure. Australia's IMOS is an obvious example of a nationally-based observing system that is deploying high-technology sampling devices for making routine observations in its IO coastal zone. Amongst other things, the Australian IMOS program, particularly WAIMOS, is deploying long-term combined biological/physical moorings in shallow (< 200m) waters off the south, west and northwest coasts of western Australia. These will be serviced monthly via a combination of Australian, Commonwealth and state funding, including ship time contributions from direct stakeholders such as the Department of Fisheries, Western Australia and CSIRO, and could potentially be augmented with additional biogeochemical sensors. Investigations utilizing the data from this fixed infrastructure would benefit greatly from an international effort that focused on complementary ship-based observations in the region. Additional examples include the Dutch mooring array in the Mozambique Channel that has been deployed to measure transport along the shelf of southeastern Africa. Although these arrays do not extend up to the ocean surface, the infrastructure could potentially be augmented with additional near-surface biological moorings and sensors. Oman is deploying two cabled observatories on the shelf (off Oman) in the AS and is motivating observational studies in the northern AS as well. This infrastructure could potentially be leveraged as part of an AS boundary current study. India has established an open ocean time series station in the AS (discussed in detail below), which will involve regular cross-shelf sampling cruises in the eastern AS that could be leveraged as part of a boundary current study.

Human resource support for some form of boundary current study off central east Africa is potentially available through, for example, the Kenyan Marine and Fisheries Institute, but this organization has little to offer in the way of oceanographic infrastructure support. However, the ASCLME project may provide a good opportunity for research in this region, including ship time. Similarly, the BOBLME project in the BoB could be leveraged to help coordinate international research there. The potential for leveraging ongoing programs is particularly strong in the southern hemisphere, e.g. the LC and the Mozambique Channel, where there are few political impediments to carrying out research in the coastal waters. A regime shift appears to be happening along the south east African coast (Coetzee et al., 2008) that could provide motivation for a study focused on this region that could also leverage the ongoing Mozambique Channel transport studies. Interest and involvement by France, the Netherlands and Iceland could make an international study in this region feasible. The international relevance is particularly strong as the tuna fisheries off the east African coast are important to several European countries. Data from previous studies in this region may also be available. In addition, SANCOR (see http://sancor.nrf.ac.za/) is building a comprehensive observation program of the Agulhas Current system, complemented by seasonal to climate-scale simulation experiments, to better understand its role in IO climate. Like IMOS, this budding effort would benefit greatly from an international program (SIBER) that focused on complementary ship-based observations in the region.

The Java Current is another seasonally reversing current that could be targeted by SIBER for study. Christmas Island is a territory of Australia and could form a base for deployment of gliders and other types of *in situ* observations in the Java Current. The EEZ of Christmas Island abuts the EEZ of Indonesia and so provides direct access to the region. A Chinese mooring in the region could provide long-term oceanographic measurements as the foundation for an international study.

Political constraints will be an important issue in any effort to carry out boundary current studies in the IO and these are likely to be problematic in the northern IO. Developing political contacts and agreements that can provide a means to relieve these constraints are essential elements of any program development.

Open ocean monitoring and observations

CLIVAR and IOGOOS are developing a basin-scale observing system in the IO (IndOOS) centered around the deployment of a mooring array (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction or RAMA) along with repeated XBT lines, surface and subsurface drifters and ship-based hydrography (International CLIVAR Project Office, 2006; McPhaden et al., 2009) (**Fig. 24**). The moorings are capable of measuring key variables needed to describe, understand and predict large-scale ocean dynamics, ocean-atmosphere interactions and the IO's role in global and regional climate. Marine meteorological variables include those needed to characterize fluxes of momentum, heat and freshwater across the air–sea interface, namely, surface winds, SST, air temperature, relative humidity, downward short- and long-wave radiation, barometric pressure and precipitation. Physical oceanographic variables include upper-ocean temperature, salinity and horizontal currents. From these basic variables, derived quantities, such as latent and sensible heat, net surface radiation, penetrative shortwave radiation, mixed-layer depth, ocean density, and dynamic height (the baroclinic component of sea level) can be computed. Thus, the mooring-based measurements can provide an excellent atmospheric and physical oceanographic observational foundation for carrying out a wide variety of biogeochemical and ecological studies.

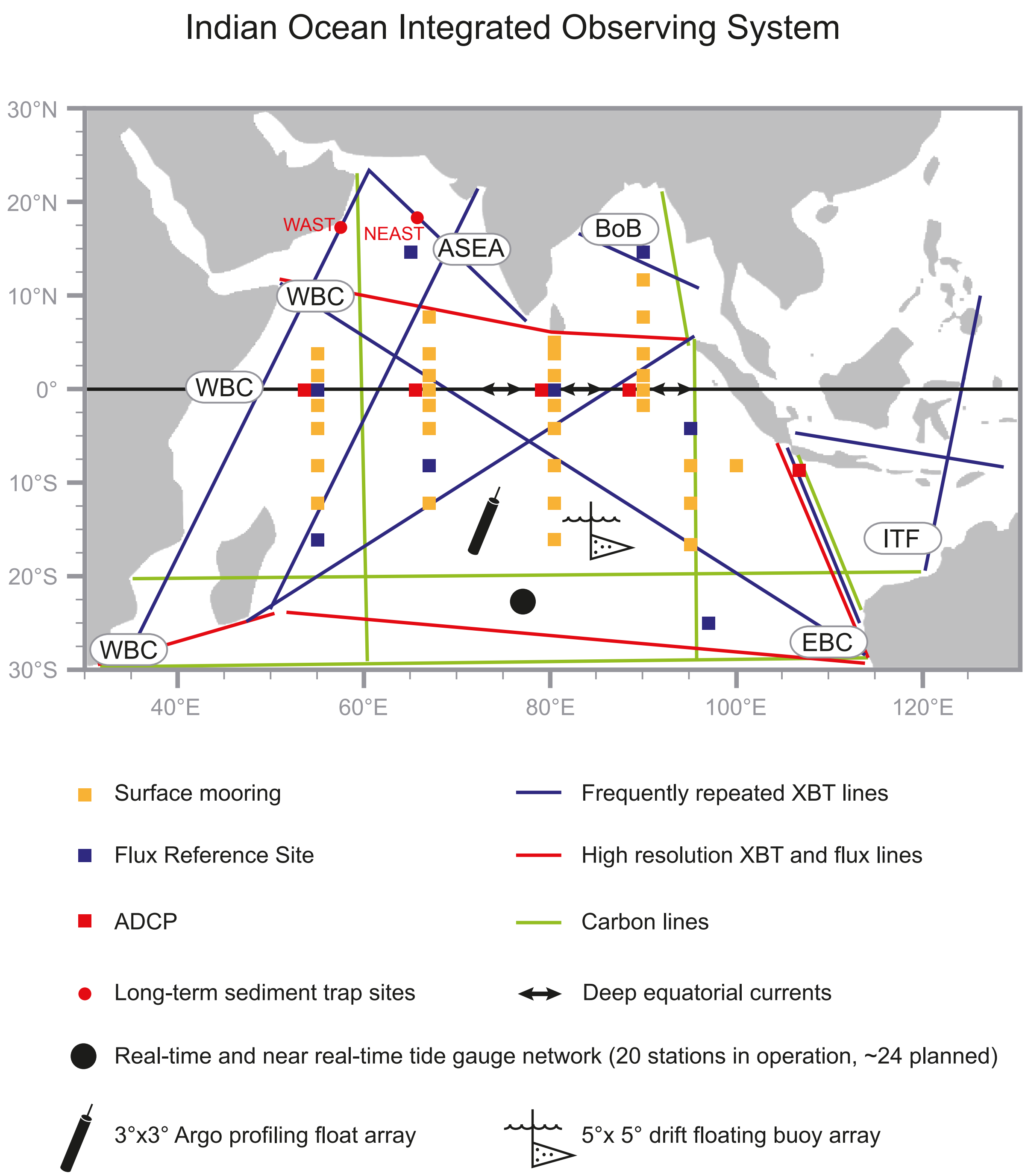

Figure 24 The integrated observing system with basin-scale observations by moorings, Argo floats, XBT lines, surface-drifters and tide gauges; as well as boundary arrays to observe boundary currents off Africa (WBC), in the Arabian Sea (ASEA) and Bay of Bengal (BoB), the Indonesian Throughflow (ITF), off Australia (EBC) and deep equatorial currents.

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The mooring array is intended to cover the major regions of ocean–atmosphere interaction in the tropical IO, namely: the AS, the BoB, the equatorial waveguide, where wind-forced intraseasonal and semi-annual current variations are prominent; the eastern and western index regions of the IO SST Dipole mode (10°N–10°S, 50–70°E; 0–10°S, 90–110°E); the thermocline ridge between 5°S and 12°S in the STIO, where wind-induced upwelling and Rossby waves in the thermocline affect SST; and the southwestern tropical IO, where ocean dynamics and air–sea interaction affect cyclone formation (Xie et al., 2002). The bulk of the array is concentrated in the area 15°N–16°S, 55–90°E (**Fig. 24**). Thus, the mooring array will be ideally situated to study the equatorial biogeochemical and ecological impacts of phenomena such as the IOD, MJO and Wyrtki Jets. The transmission of data to shore in real-time mode is required for monitoring evolving climatic conditions, oceanic and atmospheric model-data assimilation and analyses, weather, climate and ocean forecasting, and forecast verification. Real-time transmission also allows for accelerated scientific analysis of the observations and provides backup in case moorings are lost.

A variety of biological and chemical sensors can now be deployed for extended periods on moorings, and transmission of real-time observations is potentially feasible. These sensors/observations include *in situ* light transmission and spectral optical characteristics, chlorophyll fluorescence, oxygen, carbon, pH and nutrient concentrations, and acoustic measurements of zooplankton and potentially even fish. A major challenge here is integrating these biological and chemical sensors into existing moorings along with the physical sensors due to power constraints and other physical limitations. There are already precedents for simultaneous deployment of fluorescence and optical sensors on NOAA/ATLAS buoys (Chavez et al., 2000; Kuwahara et al., 2003; Subramaniam et al., 2003) in the Atlantic, Pacific and, most recently, Indian Oceans. In the system described by Subramaniam et al. (2003) that was deployed in the tropical Atlantic, the package also included an independent telemetry system that transmitted the data via the Argo network on a daily basis. Although biofouling eventually degrades data return, anti-fouling capabilities are continually evolving (Chavez et al., 2000), with extended deployments (6-12 months) featuring high-quality measurements becoming a more realistic expectation. Thus, while the servicing schedule may be longer than the length of the highest-quality data from these sensors, the measurements still have great value. Efforts are currently underway to deploy biogeochemical sensors on more RAMA moorings. Specific plans and priorities for these are described in detail in Appendix IV.

The ongoing Argo program in the IO is a continuation of the exploratory float measurements made during the WOCE (World Ocean Circulation Experiment). Argo is designed to obtain global 3° coverage of temperature and salinity profiles every 10 days. The data from the Argo program are highly complementary with satellite altimetry data (also sampled at 10-day intervals) for research applications and operational oceanography and the floats can be deployed with a limited suite of biological and/or chemical sensors. Specifically, Argo-compatible sensors for measuring chlorophyll and CDOM fluorescence, particle backscatter, downwelling irradiance, and oxygen concentration are available. An additional proven application of the Argo floats is to equip them with transmissometers. These so-called “Carbon Explorers” were used during the SOFEX cruises to measure the downward flux of carbon (Bishop et al., 2004). The IO to 40°S requires 450 floats to meet the Argo network design criterion of one float per 3°×3° latitude/longitude, with 125 deployments per year needed to maintain this coverage. Deployment of these floats is ongoing and a limited number have onboard oxygen sensors, but many more with this capability can and should be deployed. Such float deployments provide a tremendous leveraging opportunity for making combined physical, biological and chemical measurements over broad scales in the IO. The potential for obtaining information about oxygen distributions is particularly valuable. At present, open ocean oxygen concentration distributions are notably under sampled throughout the IO (cf. Stramma et al., 2008), particularly in equatorial and southern hemisphere waters.

XBT lines, in combination with Argo floats, are an effective means for developing heat, freshwater and momentum budgets of the upper ocean, providing a method for monitoring and understanding the role of ocean dynamics in climate variations. They are also effective for monitoring specific areas, such as the upwelling zones of Java/Sumatra and the SCTR that are regions of biogeochemical and ecological interest that exhibit clear sensitivity to climate variability. XBT survey lines also provide long-term monitoring of the ITF, which represents the principal exchange pathway between the IO and the tropical Pacific (**Fig. 24**). The XBT network is now largely operated by national agencies and is coordinated by the Ship of Opportunity Programme Implementation Panel (SOOPIP, http://www.ifremer.fr/ird/soopip/) under the Joint Committee for Oceanography and Marine Meteorology (JCOMM) (http://ioc.unesco.org/goos/jcomm.htm). A potential opportunity exists whereby the ships of opportunity used in the XBT deployments could be leveraged as platforms for carrying out parallel biological and chemical measurements, i.e. using surface flow-through chlorophyll-fluorescence and underway measurements (e.g. Lee et al., 2000) and by towing instruments such as a continuous plankton recorder (CPR).

Hydrographic survey and mooring support cruises also provide potential leveraging opportunities for carrying out biogeochemical and ecological studies in the equatorial and southern tropical waters of the IO. Mooring support operations, in particular, afford the possibility of coordinating activities such that focused process studies in the vicinity of the mooring location could be incorporated into the overall cruise plan. The CIRENE cruise represents a prime example of such a merger of coordinated mooring support and physical and biogeochemical sampling effort (Vialard et al., 2009). A follow up to the CIRENE effort is planned; this activity is also being designed as a means of combining RAMA mooring support with intensive *in situ* physical and biogeochemical sampling that would transect the STIO along 8°S (J. Vialard, personal communication). In general, such mergers of buoy maintenance and targeted *in situ* studies are a cost effective means of obtaining biological and chemical samples that help justify the maintenance costs of the RAMA array.

Christmas Island provides a good potential location for staging studies not only in the Java Current but also in the inflow region of the ITF. Similarly, manpower and resources on Cocos Island (Australian weather station) could be leveraged for SIBER-related research. Routine commercial freighter traffic through the ITF region transiting to China provides the potential for ships of opportunity sampling, i.e. routine biological and chemical monitoring of surface waters in the ITF region and specifically through the Lombok Strait.

More generally, SIBER planning must also include documentation of existing infrastructure around the IO basin and synthesis of information on current/planned observational resources. There are upcoming studies by Indian scientists in the Andaman Islands focusing on dynamics and physics. Of relevance here is the question of whether or not there are tide gauges along the Andaman Islands that could provide insights into coastal wave propagation. The SIBER program recommends that investigating and enabling this possibility should be a priority. Also of interest and potential relevance is a US military base on Diego Garcia, an atoll within the Chagos Island archipelago located about 1000 miles south of Sri Lanka. Would it be possible to make use of this facility as a staging area and for supporting SIBER (and IndOOS)-related research in equatorial waters? Similarly, Reunion Island (France), Seychelles and Mauritius could possibly act as staging areas for SIBER-related research activities in the western basin.

In addition to IndOOS, GOOS is promoting and coordinating several national efforts to establish coastal observing systems around the IO rim. These include SEAGOOS (southeast Asia), NEAR-GOOS and INAGOOS in the northeast Asia and Indonesian regions, and WAGOOS in the west Australian region. SIBER should endeavor to support and participate in all these regional efforts to help establish and coordinate coastal and open ocean biogeochemical and ecological time series measurements in the IO.

New *in situ* observations

Glider technologies are highly relevant and applicable, in particular to boundary current studies, as they cross all the time and space scales of interest and can be deployed and retrieved in coastal waters. Although there are still some technical issues, compact optical sensors are now available that can be deployed on gliders for measuring chlorophyll fluorescence, back scatter, CDOM and other chemical properties, thus providing the means to obtain co-located physical and biogeochemical measurements. In the future these types of sensors may also be linked to higher trophic level studies via dynamic coupling of tracking devices on animals to glider navigation (O. Schofield, personal communication).

Although high technology sampling devices, such as gliders, can be used to augment time series measurements (adding a spatial dimension), these technologies are not (at present) ideally suited for making long-term measurements and they are too expensive for many IO rim countries to maintain and operate. This is in contrast to the low technology approach of taking a suite of simple water quality measurements (temperature, chlorophyll, nutrients, light penetration and zooplankton biomass) periodically from ships or small vessels that can operate in coastal waters. The latter is in the realm of feasibility for many IO rim nations, including developing countries. Time series also need to be established to measure basic atmospheric parameters, including aeolian material inputs into the IO. However, obtaining atmospheric measurements adds another level of expense and effort to time series measurements and requires appropriate sampling platforms (i.e. ships with atmospheric sampling towers, etc.). These measurements are very likely only feasible for countries with established oceanographic research facilities and ships. Atmospheric measurements are being initiated by NIO to supplement the oceanographic data from its shallow water time series station in the AS.

Process studies

Successfully leveraging IndOOS would provide both an opportunity for obtaining long-term *in situ* biogeochemical and ecological observations and the possibility of acquiring time series measurements and real-time monitoring of biogeochemical and ecological properties in equatorial waters that could in turn provide a foundation for carrying out focused process studies. Utilizing long-term mooring-based physical and biogeochemical measurements as context for short-term, intensive physical and biogeochemical process studies is a powerful approach that can be applied to investigations of many of the equatorial forcing phenomena described above. For example, a broader understanding of IOD impact could be obtained through the combined use of satellite observations, objectively analyzed Argo float data, IndOOS/RAMA monitoring of physical properties over broad areas of the equatorial IO and strategically placed mooring-based biogeochemical measurements (see Appendix IV). Such continuous measurements could then be augmented with specific ship-based process studies aimed at more fully contrasting basinwide IOD biogeochemical and ecological impacts against typical annual evolution of these processes. The MJO, Wyrkti Jets, off-equatorial planetary waves and variability in the SCTR could all be studied using similar approaches.

Organized comparative process studies are also needed in the AS and the BoB. These should include observations at fixed stations along fixed transacts as well as large-scale regional surveys. A strategy for observations in the AS is proposed below involving repeat samplings at the Indian time series sites and along a transect extending offshore from the Omani coast. A similar long-term monitoring program should also be implemented in the BoB. NIO in Goa, India has already initiated time series data collection off Visakhapatnam (located on the east coast of India). However, time series measurements from waters beyond the shelf break are also critically needed. In the immediate future, planned cruises include observations in both the AS and BoB under the GEOTRACES program, however problems with piracy in the western AS and equatorial waters will very likely impact AS cruises (discussed further below).

Comparative AS and BoB process studies should also include assessments of the benthos, benthic biogeochemical processes and fluxes, and benthic-pelagic coupling, across margins, OMZs and seasons.

Existing mooring locations at key biogeochemical locations in the AS should be targeted as process study focal points. Two such sites are India's time series station in the AS (17ºN 68ºE) at the core of the OMZ (see detailed description below) and the long-term Indo-German time series station (16ºN 60ºE) located within the upwelling zone off Oman. Known as the WAST site in the literature (Rixen et al., 1996), sediment trap observations dating back to 1986 were suspended in 1999, but were resumed again in November 2007 (**Fig. 24**). These sites should be maintained much like BATS and HOT for long-term measurements. They would also be appropriate sites for deployment of benthic landers in order to investigate benthic processes. Furthermore, deployment of sediment traps, benthic landers and time series samplers (e.g. cameras) below and in shelf/slope areas impacted by low OMZ waters would also be very valuable. Similar moorings should also be deployed in the central BoB for making physical and biogeochemical measurements. Both the central AS and BoB regions are currently targeted for deployment of moored instrumentation by IndOOS/RAMA (**Fig. 24**) and Indian investigators. Process studies could leverage on-going time series efforts as well as planned IndOOS/RAMA mooring array deployment activities. Moorings at these locations can potentially be deployed with biogeochemical sensors like those discussed above (see also Appendix IV).

The IO Argo float program can also provide a physical context for carrying out comparative process studies in the AS and the BoB. The density of Argo floats in the IO is now sufficient to provide broad-scale characterization of physical variability on seasonal to interannual time scales; indeed the data density in the IO is now sufficient to allow for performing objective analyses on a weekly basis (cf., Gaillard et al., 2009). Differentiation between the two regions' stratification conditions can be characterized, as well as their response to climate-related variability (e.g. IOD and ENSO). Any comparative process study of the AS and the BoB should start with a focused comparative analysis of the physical characteristics of the two basins. This analysis could be augmented with the deployment of Argo floats with oxygen and optical sensors, focusing in particular on deployments in the OMZ in the AS and a comparable location in the central OMZ waters of the BoB.

A comparative study of the AS and the BoB could be augmented with surface measurements from ships of opportunity. Potential routes include ferry services between Chennai and Port Blair, between Kolkatta and Port Blair, and between Lakshwadeep and Kochi. Glider surveys should also be carried out, focusing on the coastal OMZ in the AS and a comparable location in the BoB, e.g. off Visakhapatnam or on the IndOOS repeat XBT line in the BoB (**Fig. 24**). Deployment of only two gliders, one in each basin, would provide crucial information on subsurface processes including the OMZ, the deep chlorophyll maximum and subsurface productivity. For such glider deployments, data handling, storage and distribution issues need to be worked out to make these data widely available to the oceanographic community in a timely manner. CPR surveys should also be motivated. As discussed below, efforts are already underway to establish routine surveys from India to Oman. A comparable transect should also be considered for the BoB.

The ongoing WAIMOS monitoring program along the coast of western Australia provides further opportunity for initiating an international SIBER process study. WAIMOS efforts focus on shore-based and remote observations using satellites, CODAR (Coastal Ocean Dynamics Applications Radar) and glider technologies along with high-resolution coastal modeling (OFAM/BLUELink), but ship time is limited. Establishing an offshore international time series station and process study would provide an ideal complement to these coastally-oriented observations, as well as endpoints for onshore-offshore transects and sustained measurements of the oceanic end-member properties. The maintenance of an international time series/monitoring station could also provide much-needed ship time to support the WAIMOS coastal monitoring network. A study of at least five years duration is recommended. Relevant questions have been primarily defined in Theme 1, but quantification of the seasonality of chlorophyll distributions and primary production, as well as temporal and spatial distributions of nutrients and nutrient limitations (Theme 4) should also be targeted.

Targeted process studies should also be motivated at specific sites and times that focus on the general scientific questions identified in Themes 4-6. One obvious potential study would be the hypothesized iron limitation or co-limitation and/or potential grazing control of phytoplankton production in the AS during the SWM in coastal and open ocean waters (Theme 4). In addition to basic measurements of hydrography, optics, nutrients, dissolved organics, etc., such investigations might include a suite of core measurements:

- Phytoplankton biomass and composition (Chla, HPLC pigments, flow cytometry and microscopy)
- Size-fractionated primary production (^{14}C uptake)
- Growth rates of different phytoplankton functional groups (dilution, pigment labeling)
- Phytoplankton physiological indicators (e.g. fast repetition rate fluorometry)
- Community metabolism (O_2 production and consumption, net auto-/heterotrophy)
- Micro- and mesozooplankton grazing (dilution, gut fluorescence, experimental)
- Export flux (sediment traps, thorium deficit)
- Bioassay experiments to assess limitation by Fe, Si and N
- Stable isotope measurements

These studies should embrace new technologies and instruments like gliders (discussed above) and also the moving vessel profiler (MVP), a versatile sampling platform with CTD, fluorometer, optical plankton counter, etc., that can be efficiently deployed from a moving vessel at full speed. Such an instrument can undertake high-resolution gridded surveys of mesoscale variability around specific experimental sites or investigate fine-scale distributional patterns associated with targeted features like filaments and eddies.

Process studies are potentially important for investigating specific regions and processes. However, in general, they should play a relatively minor role in the investigation of the effects of climate change and anthropogenic impacts on the IO and its marginal seas. Rather, in this context, the role of monitoring should be emphasized along with leveraging of existing infrastructure to orchestrate long-term biogeochemical and ecosystem observations.

Benthic studies

Benthic biogeochemical processes and benthic-pelagic coupling have important roles in global bioelement cycles and as controls on ocean productivity and climate, but have received only limited focus as part of JGOFS and other previous coordinated research programs in the IO. By including benthic process studies, and linking these to parallel pelagic studies, the SIBER program intends to address these previous shortcomings in a basin where benthic processes are particularly significant. The IO, and especially the AS and BoB, exhibit extreme monsoon-driven variability in productivity (i.e. benthic food supply) and mid-water oxygen depletion that creates the largest expanse of reducing margin sediments (and associated suboxic benthic processes and fluxes) on earth. Moreover, major contrasts exist in both productivity and oxygen depletion between the AS and BoB, and both of these, as well as benthic biogeochemical processes, are subject to climate change and other anthropogenic impacts.

Common sets of systematic *in situ* and shipboard studies are needed that will include:

- Assessments of benthic microbial and faunal communities and sediment geochemistry

- Characterisation and quantification of microbial processes
- Determination of the cycling and burial of bioelements
- Determination of benthic fluxes of dissolved nutrients, organic matter, gases and metals and their significance to ocean inventories
- Tracer studies of benthic organic matter cycling and trophic interactions, and of bioturbation and sediment irrigation

These need to be conducted in the AS and BoB, but also in other selected IO regions, from the abyssal plain to the continental shelf (spanning the OMZ), and should include seasonal comparisons (monsoon versus intermonsoon and interannual).

Benthic sampling and experiments should be integrated with pelagic process studies to provide information on the amounts and nature of organic matter delivered to the sea floor (sediment traps) and to elucidate relationships and mechanisms in benthic-pelagic coupling. The logistical impediments to such integrated efforts (e.g. compatible cruise track and strategy, wire-time constraints, ship berthing capacity, etc.) can be significant and the time scales for studying surface-ocean phenomena and benthic community response are quite different. Therefore, pelagic-benthic collaborations that can be placed in the context of time series investigations at specific locations or exploit common infrastructures (e.g. instrumented mooring sites) stand the greatest chance of achieving success.

For assessing organic matter losses between euphotic zone export and the underlying benthos, respiration rates in the mesopelagic realm are almost completely unknown. This is especially true in the OMZs, where extremely low dissolved oxygen concentrations make direct measurements of O_2 changes virtually impossible. All available rates are instead based on the indirect index of O_2 utilization, electron transport system (ETS) activity (Naqvi and Shailaja, 1993; Naqvi et al., 1996). New methods, like non-invasive eddy correlation techniques (Berg et al., 2003) for estimating benthic O_2 flux, should be adopted

Similarly, respiration rates need to be measured in deep sea sediments and in shelf/slope waters that are in contact with the OMZs. It is possible to determine O_2 consumption in sediments under low O_2 conditions (e.g. Law et al., 2009), however, new technologies and sensors are required. These include provision for better/constant power supply (long-life batteries) to power underwater monitoring and sampling devices. Results from such efforts have to be incorporated into new budgets for organic matter production and consumption for OMZ waters to better determine magnitudes and to resolve imbalances in previous budget calculations.

Zooplankton studies

Intensive process-oriented studies of zooplankton in the IO have mostly been focused in the AS (Smith, 2005), although reports on zooplankton distribution in the BoB (Fernandes, 2008; Jyothibabu et al., 2008) and Southern IO (Cornelia et al., 2009) have recently appeared and mesoscale eddies in the LC off west Australia have also been an area of recent study (Strzelecki et al., 2007; Waite et al., 2007). Within the AS, additional studies are needed to understand how zooplankton populations interact with and tolerate the OMZ and how these interactions might impact biogeochemical cycling. Are significant fluxes of elements (C, N and P) generated as a result of active zooplankton migrations in and out of the OMZ? More generally, studies also need to be undertaken in the AS and elsewhere in IO basins to characterize species composition and seasonality of the resident populations. As discussed in Theme 4, the degree and spatio-temporal variation in grazing control of phytoplankton production in the AS remains an open question that needs to be addressed. In fact, the role of grazing is potentially an open question over vast areas of the southern tropical and subtropical IO, where modeling and remote sensing studies suggest that iron limitation may be an important limiting factor for phytoplankton growth (Behrenfeld et al., 2009; Wiggert et al., 2006). Process studies focusing on lower levels of the food web (i.e. microzooplankton and mesozooplankton) are typically in the order of 2-4 weeks duration, and their shipboard equipment requirements are relatively modest. These requirements include MOCNESS sampling capability, with multiple opening and closing nets and acoustical instruments designed to detect zooplankton and other organisms of the deep scattering layer (e.g. the TAPS, Tracor Acoustic Profiling System).

Long-term monitoring of specific zooplankton species has been carried out at certain stations (e.g. off Cochin on the southwestern coast of India through voluntary efforts). In addition, India's Marine Research and Living Resourses (MRLR) program collected zooplankton from 1998 to 2005 from India's EEZ, which includes jellyfish enumeration. The data is archived at NIO, Kochi with copies at the Department of Ocean Development (now Ministry of Earth Sciences - MOES), that funded the program. There needs to be an effort to digitize, further analyze and publish these data, which are potentially available (through Dr. Shetye Director, NIO or Dr. Sanjeevan, Director, MOES) together with all the ancillary environmental and primary production data that were also collected. There are also collections from the Andaman Sea but these are not as complete as the MRLR data.

Long-term time series with the trained/paid personnel needed to deal with species collections should be formally established for the Cochin station (where significant changes in zooplankton species composition have been observed), and for Masirah Island in the northern AS, where another time series station has been established by Oman, and elsewhere in the IO. For long-term quality control, for consistency in identification or to prove the introduction of new species, voucher collections in museums will be required. Training of young taxonomists in this region is crucial. Many of India's taxonomists have retired and have not been replaced, and Oman relies on the help of experts from the Institute of Biology of the Southern Seas in Sevastopol, Ukraine. There needs to be a meeting of regional experts to enable exchange of expertise and validation, and perhaps also to initiate new avenues of investigation of cryptic species with modern molecular techniques.

In addition to monitoring at specific stations, ship of opportunity CPR surveys should be established in the IO as in the Atlantic and Pacific Oceans. Transects have been proposed for the AS and across the entire IO from Australia (Perth) to Oman (Muscat). The latter, which would be a 4000 nautical mile tow, is feasible if every 4th sample is analyzed as is currently done in long Pacific CPR transects. One tow would generate 100 samples. The diversity of plankton along a transect of this length in the IO is likely to be high and so the analysis would be more labor intensive than a normal North Atlantic sample. Experienced analysts would be required for this work. The Sir Alister Hardy Foundation for Ocean Science (SAHFOS) has expressed interest in establishing CPR surveys in the IO as part of SIBER. In addition, India has a CPR at NIO that could potentially be deployed in the AS and the BoB.

Higher trophic level studies

Fisheries surveys are labor intensive because substantial manpower and expertise are required to sort and identify species in trawl samples. A crucial issue of concern is developing sufficient expertise to support fish trawl surveys. Any extensive field program targeting higher trophic levels motivated under SIBER will have to provide training and employment for technicians. In addition, special preparation and preservation techniques are needed, i.e. massive quantities of ethanol are required for each cruise. Identification of resources to cover the costs of applying these techniques is crucial. For example, New Zealand fisheries experts provided a year-long survey of Oman's fisheries resources along the AS coast at significant expense. However, the local expertise required for this type of study is scarce and ships are generally not available except from India.

In addition to basic survey work on stocks and biomass distributions, physiological studies need to be undertaken for converting measured concentrations into rates. The sampling strategy for carrying out physiological studies is very different from surveys because specimens need to be captured and brought back alive to either shipboard or land-based laboratories. Mesopelagic species pose handling challenges due to the elevated pressures of their natural environs; both temperature and pressure must be maintained when deep-living organisms are collected and transported to the laboratory. Some physiological studies can be focused on surface-collected animals, where night sampling can be employed to take advantage of vertical migrations to the upper ocean undertaken by a number of species. However, not all myctophid species, for example, are diel migrants, so this strategy will not work for studying all species of interest or for investigating rates under ambient conditions at depth. Physiological rate measurements might also be made in mid-depth traps, e.g. traps deployed *in situ* that measure O_2 consumption of captured fish. But there are also challenges associated with making such measurements in the OMZ realm, since determining small O_2 changes under conditions where the ambient concentrations approach anoxia is problematic.

In addition to crustacean zooplankton and fish, other forms that need to be sampled and considered are the gelatinous taxa (e.g. tunicates, coelenterates, cnidarians). Presumably, these are important components of the epipelagic and mesopelagic food webs, yet very little is known about the ecological function of these organisms in the food webs of the IO. In extensive cruises during the NEM and SIM (Spring Intermonsoon) of 1980 and 1990 in the open AS, tunicates and coelenterates contributed 36% and 14%, respectively, of the identifiable macroplankton species in mid-water trawls with 0.9 and 1.4 mm mesh in the cod ends. In addition, remains of gelatinous forms made up between 20-50% of the total wet weight (Ignatiev, 2006). Since trawl samples with large catches of jellies are often discarded, a first step would involve keeping such net collections, and then estimating the volume of jellyfish sampled. Contributions of shrimp to the pelagic food web also need to be considered and can nominally be assessed using trawl sampling surveys. Data mining efforts must be undertaken to extract existing observation data sets of pelagic shrimp and other species as has already been done with myctophids. The end-to-end food web modeling approaches described earlier could also be employed as a means of assessing the biogeochemical roles of jellyfish, shrimp and other species in the IO.

Acoustic sensors can now also be employed on gliders for autonomous deployment. These glider-deployed sensors could be very powerful for carrying out epipelagic and mesopelagic regional surveys. The caveat with this technology is that actual samples are needed in order to interpret the acoustic information, so glider surveys have to be validated by ship-based trawl surveys. Novel combinations of new and old sampling technologies should be actively studied and pursued in any programs motivated under SIBER.

Finally, it should be noted that the mapping of temporal changes in biodiversity is a targeted outcome of the Census of Marine Life (CoML). Identification of key species and their distribution and abundance has been undertaken as part of this effort. With the exception of the central eastern IO and ITF regions, the IO regional node of the CoML (IO-CoML) encompasses most of the IO domain being targeted by SIBER. Effort should be made to coordinate SIBER activities with the products and outcomes derived from the CoML. Guidance from CoML participants has to how SIBER can best leverage their complementary efforts should be sought, potentially in the form of organized collaborative workshop(s).

Ship availability

The establishment of the NIO time series station and the IndOOS and IMOS programs have been hampered by limited ship time. It is crucial that ship availability for maintaining time series and carrying out process studies is secured. There are several vessels that are or could be used for SIBER-related studies: The NIO has a new 80m vessel with adequate stern working area for carrying out a wide variety of oceanographic and fisheries-oriented studies. The Indian Ministry of Earth Sciences (MOES) has a ship that surveyed the Indian EEZ out of Kochi which is capable of mid-water trawling. The ASCLME operates the 57m *Dr. Fridtjof Nanse* Norwegian oceanographic research vessel in the western IO approximately 300 days per year. Its 23 berths could accommodate scientists focusing on SIBER-related activities, e.g. RAMA mooring and biogeochemical sensor deployment. However, additional vessels that have long-range, open ocean sampling capabilities are needed and these will have to be contributed by other countries (e.g. Japan, China, France, Germany, the U.K. and the U.S.A.). To address this need, the Indian Ocean Panel has established the IndOOS Resources Forum (IRF) to assist IndOOS/RAMA, IOGOOS and SIBER in securing ship time for mooring support/ maintenance and sampling.

Opportunity may also exist to piggyback nutrient determinations and bioassays on major large-scale survey cruises that are being carried out under WOCE and GEOTRACES. Such measurements could help to better characterize basinwide nutrient distributions and provide information on dissolved iron concentrations and limitation patterns. Discussions should be initiated with these programs to find ways to leverage SIBER-relevant biogeochemical and ecological observations.

Piracy

Piracy has become an increasingly significant problem in the western equatorial IO over the last decade, particularly in the Gulf of Aden and the coastal and open ocean waters off Somalia. As a result, many countries do not allow research vessel operations in this region at present. The National Science Foundation (NSF) cancelled a research project in the AS and ASCLME efforts to deploy RAMA moorings with biogeochemical sensors in the western IO were also cancelled due to piracy concerns. The piracy issue must be considered when developing any SIBER-related programs in the western IO and the AS for the foreseeable future. Alternative sampling methods using, for example, gliders are being considered by the IOP as a means to obtain data from the western equatorial IO where it is currently unsafe to deploy and retrieve RAMA moorings. This approach should also be considered for biogeochemical and ecological sampling in these waters. For additional details on piracy impacts in the western IO, see Appendix V (Regional Piracy Update).

SIBER METHODS FOR DATA SYNTHESIS AND MANAGEMENT AND MODELING

METHODS FOR DATA SYNTHESIS AND MANAGEMENT

SIBER will develop a data management policy under the guidance of IMBER and IOGOOS, that will be published on the SIBER website. The SIBER Data Policy will facilitate the use of all available data resources (including raw and processed field and laboratory data and model output), thus reducing fieldwork and research duplication, while respecting the intellectual property rights of the contributors.

SIBER intends to work closely with data management teams from different countries and projects to promote availability and interoperability of datasets where possible. Linking and collaborating with other national and international ocean science programs will add significant value to data mining and syntheses. For example, linking predator and food web community data to programs, such as CLIOTOP, would facilitate analysis of their distributions in relation to satellite-observable features.

SIBER will promote linkages with all international programs operating in the IO to share historical data and achieve the goals of each program. Its activities will contribute to the CoML, CLIVAR, SOLAS, IOCCP-GCP, GEOTRACES, GOOS/IndOOS, etc. SIBER data management and mining efforts will integrate with modeling and fieldwork activities. For example, modeling efforts will benefit from the identification, compilation and synthesis of existing datasets to produce regional and basinwide physical, biogeochemical and biological distributions for model initialization, calibration and verification (see integration section below).

FIELDWORK COORDINATION AND DEVELOPMENT

It is logistically difficult to work in the IO because it is so vast, and the southern IO open ocean is particularly remote. This problem is compounded by the limited availability of research vessels. SIBER aims to improve the integration of existing and planned field studies by promoting cross-cutting science activities and the exchange of personnel, expertise, methodologies, data and equipment. This should increase the efficiency and scientific value of the outcomes of the individual programs. It will require increased cooperation among the many nations and regional programs operating in the IO to streamline scientific objectives, integrate physical, biogeochemical and ecological data, identify key gaps and ensure effective future planning. SIBER's role will be to: 1) facilitate the fieldwork coordination among nations and programs to address these issues; 2) identify knowledge gaps from historical data analysis, remote sensing and modeling; and 3) maximize subsequent international efforts to begin to fill these gaps. These fieldwork efforts will be an integral part of the parallel initiatives of data syntheses and model development.

Existing field activities encompass only a small portion of the different biogeographic areas of the IO, with national programs often targeting restricted geographical regions and the coastal zone. A particular focus of SIBER will be to promote an international effort to improve geographical coverage of the IO, in both coastal and open ocean areas. This will be facilitated by increasing the use of satellite data and through deployment of remote instrumentation. The latter will include both fixed location devices, such as oceanographic moorings, and those on mobile platforms, such as ship of opportunity measurements, oceanographic (Argo) drifters and gliders.

In terms of planning future field efforts, regions that have been the focus of a number of national and international efforts (such as the AS) and have proved to be of significant interest, will continue to provide data for synthesis and modeling. Other less studied regions (such as the BoB, the equatorial waters and the open ocean areas of the southern IO) should be the focus of future coordinated field efforts.

INTEGRATION

PLANNING AND INTEGRATING ACTIVITIES

At the core of SIBER is the integration of ecosystem, biogeochemical and climate research in order to address the program's long-term goal of understanding the role of the IO in global biogeochemical cycles and the interaction between these cycles and marine ecosystem dynamics, both of which are subject to climate influences. The research will be structured under the six scientific themes described in the previous section. Models will provide the basis for integrating IO biogeochemical and ecosystem data and generating and testing relevant hypotheses. Modeling will help to focus the research by identifying gaps in available data, clarifying important areas of uncertainty and determining the most efficient and effective data collection strategies.

Modeling efforts will also benefit from the compilation and synthesis of existing *in situ* datasets and remotely sensed data, to produce both regional and basinwide physical, chemical and biological distributions for model initialization, calibration and verification. Remotely sensed data will be particularly important at the outset to produce basinwide maps of physical and biogeochemical quantities (e.g. SST, SSH, SSS and chlorophyll).

During the development stages of SIBER it will be important to establish links between scientists involved in modeling and observational/data mining activities and those involved in planning field studies (including process studies and survey and monitoring programs). Electronic communications, meetings and workshops will help to identify gaps and prioritize field sampling and monitoring efforts. Working groups will be formed for each scientific theme (see below). Workshops, organized by theme, will unite members of the IO science communities to address specific aspects of the science as SIBER develops.

Later in the program, a Synthesis Working Group will be established and a focused integration and synthesis phase will be started. This will draw together observations and results from the six science themes to develop a basinwide synthesis. The SIBER SSC will take the lead in guiding the integration process. This requires the early development of a framework to facilitate effective interaction between the SSC and the thematic working groups. This should focus on enabling the effective interaction between SIBER participants, working groups and national and regional programs. Ensuring that IO biogeochemical and ecosystem research under SIBER is developed in parallel with global efforts, as part of IMBER and GOOS, is imperative.

LINKAGES

SIBER has been developed in conjunction with GOOS, IGBP and SCOR. Directed jointly by IMBER and IOGOOS, with close links to CLIVAR's Indian Ocean Panel (IOP) and through national and international program activities, it is envisaged that SIBER will further the understanding of how the biogeochemical and ecosystem dynamics of the IO respond to physical forcing as part of the Earth system. SIBER will generate multidisciplinary links between biological, chemical and physical oceanographers, biogeochemists, climatologists and fisheries scientists from the international community, building upon the research experience of past projects such as the JGOFS Arabian Sea Process Study, and the monitoring experience of ongoing projects such as the CLIVAR/IOGOOS Indian Ocean Observing System (IndOOS). Indeed, substantial progress has already been made toward this goal through the process of developing the SIBER program.

In the earlier stages, SIBER will lead and coordinate its research with the IOP. Collaboration between the members of the SIBER SSC and the IOP offers a unique opportunity to mobilize the multidisciplinary, international effort that is required to develop a new level of understanding of the physical, biogeochemical and ecosystem dynamics of the IO in the context of the global ocean and the Earth system. As detailed in the implementation plan, SIBER will leverage several regional LME and GOOS programs and will form linkages with other national programs and organizations (**Fig. 25**).

Collaboration with other relevant programs is vital to SIBER's success and so it must be cognizant of the activities of other IO research programs and integrate with them where appropriate. As indicated in the implementation strategy, SIBER will collaborate with international and national monitoring programs such as IndOOS and IMOS to leverage, augment and integrate with their efforts. Limitations to our understanding of atmospheric transport, nutrient and trace metal cycling, and deposition processes will be improved by developing linkages with SOLAS and GEOTRACES. The primary task of the Indian Ocean Census of Marine Life (IO-CoML) is to strengthen the IO coastal and marine biodiversity database. SIBER collaboration with IO-CoML participants will promote capacity building and create opportunities for multi-institutional research on coastal and marine biodiversity. Establishing linkages with CLIOTOP and ESSAS will enable SIBER to leverage comparative studies aimed at developing an end-to-end understanding of marine ecosystems in the IO and elsewhere. SIBER will also seek to establish strong linkages with SANCOR, the ASCLME, the BOBLME and WIOMSA in an effort to help promote the educational, scientific and technological development of all aspects of marine sciences throughout the IO.

Understanding the connections between the changes that are being observed in the IO and other ocean basins is essential to determine the global ocean's response to climate change and potential feedback effects. Some of the strongest low latitude regional expressions of global climate change have occurred in the IO and these are predicted to continue or even increase. Developing links with Atlantic, Pacific and Southern Ocean physical, biogeochemical and ecosystem scientists and programs is important from SIBER's perspective, particularly in developing comparative analyses and models. SIBER has begun this process by working to coordinate efforts with the IOP, CLIOTOP, ESSAS and ICED. Linking with scientists and groups from other regions is also important in areas such as model development where certain concepts and methods will be applicable or adaptable regardless of geographic focus. This will be achieved in the first instance by inviting non-IO scientists from relevant fields to participate in the SIBER thematic working groups, meetings and workshops. There are many other examples of linkages and collaborations detailed and mentioned throughout this document. An important role for SIBER scientists will be to ensure that the biogeochemical and ecological dynamics of the IO are adequately and correctly represented in Earth system models.

Structure of SIBER

The SIBER Scientific Steering Committee (SSC) will have overall responsibility for the direction and management of SIBER activities on behalf of IMBER and IOGOOS. An interim SSC has been in operation since the first workshop, convened in Goa in 2007. The first official SSC was formally appointed by IMBER and IOGOOS in 2010. It comprises active scientists who have specific and broad expertise in the major disciplines covered by the SIBER Science

Plan and who provide broad geographical representation and gender-balance. The SSC will change periodically over the life span of SIBER following protocols established by IOP. The SSC will meet annually back-to-back with the IOP. A sub-set of the SSC will form an Executive Committee (EC). Flexible and interactive working groups (WG) will focus on and lead the research for each of the six SIBER science themes. A synthesis and integration WG will also be formed to promote the exchange of information amongst the six SIBER WGs and other programs. The SSC, EC and WGs, lead by the SSC Chair, will organize the SIBER work program to maximize efforts in securing the necessary financial resources, international expertise and time to achieve the program objectives. Terms of reference for the SSC, EC and WGs will be drafted. It is envisaged that SIBER will develop funding bids as the program develops, particularly through coordinated efforts with both national and international programs.

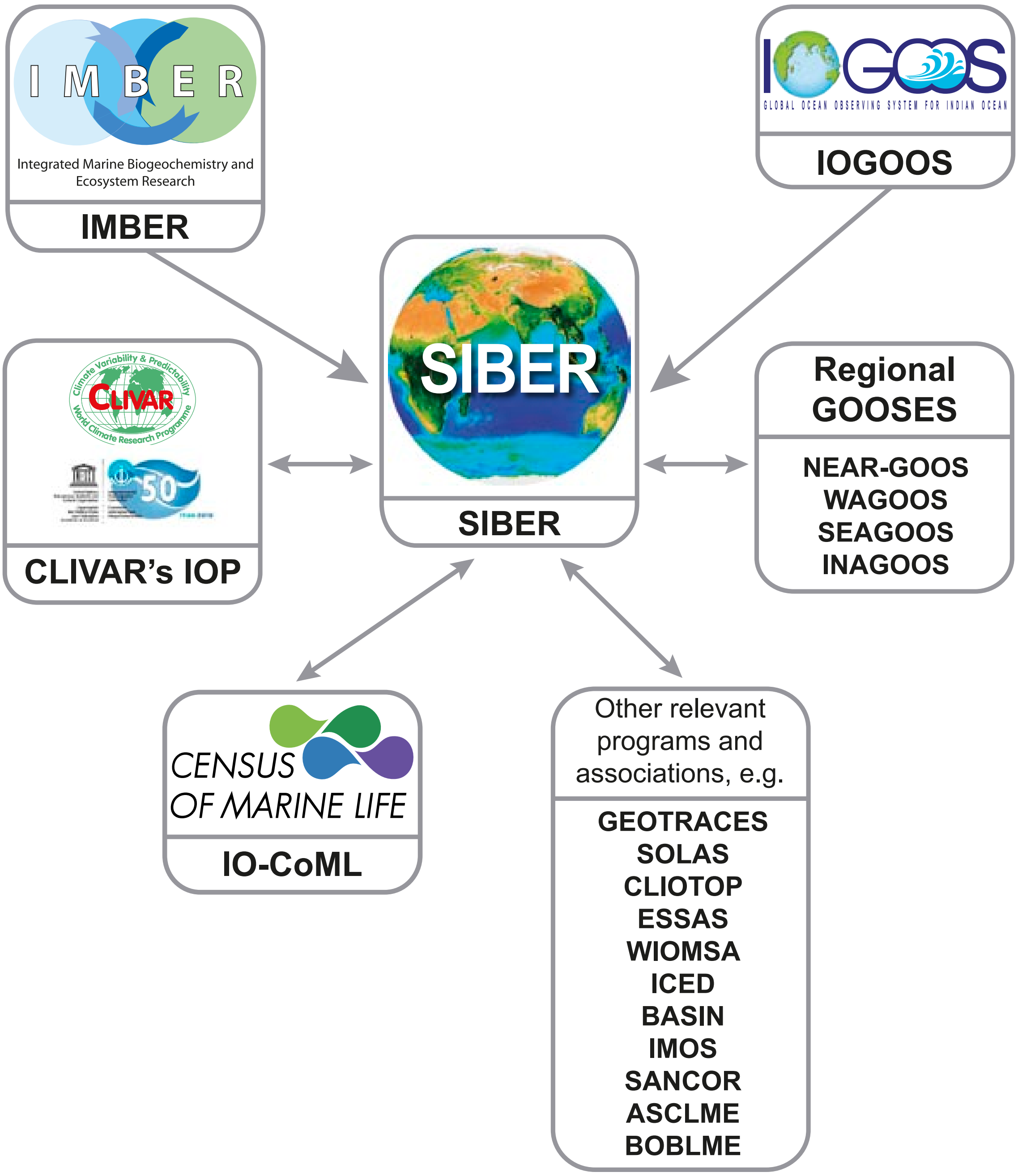

Figure 25 Collaboration with other relevant programs is vital to the success of SIBER. Directed jointly by IMBER and IOGOOS, SIBER will generate multidisciplinary links between biologists, oceanographers, biogeochemists, climatologists and fisheries scientists from the international community.

Communication

Given the international nature of SIBER, communication is fundamental to its success. In order to facilitate communication a SIBER website has been established through IMBER (see http://www.imber.info/SIBER.html). The development of a more comprehensive website is under development through IOGOOS. These sites will be used to coordinate and publicize the activities of SIBER and associated programs, provide the latest news and information on projects and progress, and provide a forum for communicating SIBER science to the widest possible audience.

SIBER will contribute articles to international newsletters, such as those of IOGOOS and IMBER. SIBER has already developed the format for a newsletter that will, in due course, be distributed electronically on a semi-annual basis. A series of workshops focusing on SIBER's six science themes is planned and these will be important for the development, implementation and integration of the program. Reports from the workshops will be published.

To develop and maintain communication with the wider IO research community, SIBER science meetings and sessions will be organized. These may be linked to, for example, IOGOOS, IMBER, AGU and EGU conferences and meetings, as well as separate SIBER meetings when the program becomes more established. The first SIBER Open Science Conference was held in Goa, India in October 2006. The second will be held in 2015 at NIO in conjunction with the 50th anniversary celebration of the International Indian Ocean Expedition (IIOE), which is especially noteworthy as the need for a regional facility to support IIOE activities was the motivation for establishing NIO in Goa (**Fig. 26**).

SIBER science results will be published in scientific journals and reports. However, SIBER will endeavor to ensure that the main results will also be accessible to a wider audience, including policy makers, managers and the public. Input will therefore be required to produce summary fact sheets or brochures.

Training and education

SIBER will help to stimulate research capacity in the international community and especially among developing IO rim nations by promoting training courses to develop multidisciplinary science skills, workshops, summer schools and a program of personnel exchange.

SIBER will promote public outreach and provide the opportunity to experience IO science through school activities, the internet, special events and exhibitions. The biogeochemical and ecological dynamics of the IO are unique and highly variable due to the influence of the monsoon winds. This variability impacts some of the most populous regions in the world. SIBER will provide a platform from which to address issues such as climate change: not only how it will impact the monsoon winds, coral reefs, the IO coastal zone and human populations, but also wider impacts on a global scale.

SIBER will ensure that its activities reach as wide an audience as possible and have the greatest possible impact.

SIBER program outputs and legacy

As this document has outlined, the IO is changing rapidly as a result of anthropogenically-driven effects. These changes could have profound consequences for populations, species, biodiversity and ecosystem structure and function. They affect biogeochemical cycles and influence the development of management strategies for fisheries. These anthropogenically-driven changes are already impacting human populations in the coastal zones of the IO and these impacts will increase with time. To fully understand the impacts of variability and change requires a basinwide approach and an integrated end-to-end analysis of IO biogeochemical cycles and ecosystem dynamics. The IO rim countries are, for the most part, developing countries, which means SIBER will provide an important vehicle for capacity building through its activities. Indeed, the success of SIBER is going to depend on the involvement of the rim countries.

It has been noted throughout this document that there are a wide range of distinct scientific questions concerning coastal waters, inland seas and the open ocean that the SIBER community needs to address. Ultimately, the goal is to achieve a greatly improved understanding of the large-scale operation of the whole IO basin. However, as this plan articulates, this goal can be best achieved by promoting regional studies (Themes 1-3) and motivating research that addresses key overarching scientific questions (Themes 4-6). The synthesis phase of the program will bring these studies together in order to provide an improved basinwide understanding. While a significant amount of data collection and modeling studies have been undertaken, there are still many gaps in our understanding and vast regions where little or no data have been collected and only a few modeling studies carried out. What is currently lacking is a basinwide, multidisciplinary effort to fill the gaps in our understanding. This forms the central focus of SIBER and the basis for its outputs and legacy.

Over the next decade SIBER will work towards determining the major controls on the biogeochemical cycles and ecosystem dynamics of the IO and the potential for feedbacks to the Earth system. Emphasis will be on evaluating and predicting the effects of climate change and other anthropogenic impacts on IO ecosystems. To do this, SIBER's major focus will be on integrated regional and basinwide analyses that extend from the benthos and coral reefs to the highest trophic levels, and how these impact, and are impacted by, biogeochemical cycles. The main activities will include regional and basinwide: 1) remote sensing studies; 2) modeling studies; and 3) *in situ* observational and monitoring studies. All these efforts will be aimed at characterizing how physical forcing drives biogeochemical and ecological response in coastal zones, inland seas and the open sea, and at examining long-term, large-scale ecosystem functioning, variability and change.

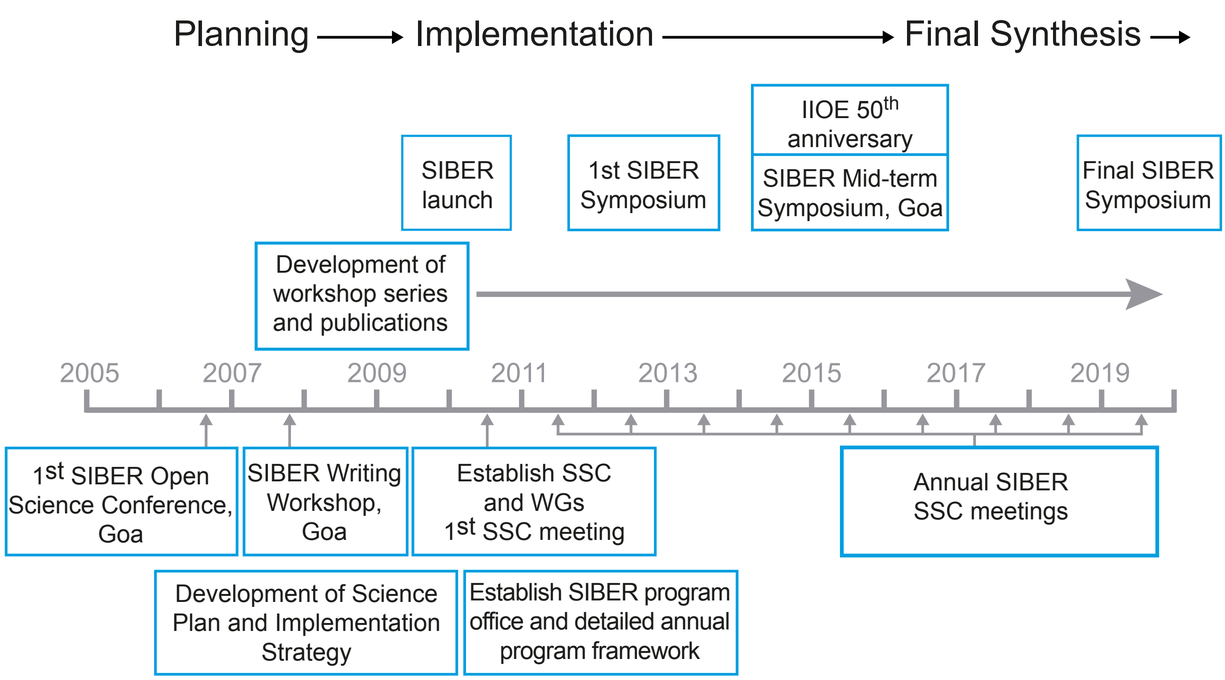

Figure 26 Timeline for the SIBER program.

SIBER is currently building a multidisciplinary network of experts that will grow throughout the program. Through the SSC and WGs, SIBER will convene regular meetings, workshops, scientific sessions and ultimately scientific conferences. A preliminary timeline is shown in **Fig. 26**.

The annual SSC meetings will serve to develop aspects of the work plan for each of the six SIBER themes. Subsequent events will build on these to develop new approaches and to advance the integration process. These events will occur at regular periods as noted in the timeline (**Fig. 26**). Other activities such as direct research, development of online tools, publications and model development will take place throughout the program and will feed into the workshops and meetings as appropriate. Some of the specific research questions and foci envisaged are listed here as a guide (for further details see the Science Background and Scientific Themes sections in the Science Plan):

How are marine biogeochemical cycles and ecosystem processes in the IO influenced by boundary current dynamics? For example, what are the ecological and biogeochemical impacts of:

- Seasonally reversing currents in the northern IO
- Poleward flowing currents in the southern hemisphere
- Mesoscale eddies and filaments in the AS and BoB

SIBER will seek to motivate studies on the unique boundary current systems in the IO focusing on how they mediate interactions between open ocean and coastal environments. These studies will provide new insights for identifying and understanding fundamental interactions between marine biogeochemical cycles and ecosystems.

How do the unique physical dynamics of the equatorial zone of the IO impact ecological processes and biogeochemical cycling? Potential core focus areas include:

- Forcing and response in the Southern Tropical Indian Ocean
- Seasonal variability in the equatorial zone
- Intraseasonal variability in the equatorial zone
- Impacts of the Indian Ocean Dipole

SIBER will seek to motivate studies in the equatorial zone of the IO (including the southern tropics and Indonesian Throughflow) that focus on understanding how this highly anomalous and fluctuating physical environment might lead to unique adaptations and/or species complements and how these in turn influence biogeochemical variability in comparison to the other oceanic basins.

How do differences in natural and anthropogenic forcing impact the biogeochemical cycles and ecosystem dynamics of the AS and the BoB? Potential core focus areas include quantifying differences between the AS and the BoB in terms of:

- Natural and anthropogenic forcing in the OMZ
- Export flux variability and impacts
- Anthropogenic impacts on food web structure and export
- Role of the marginal seas

The overarching question is what controls the mid-water oxygen concentration and how sensitive are these controlling mechanisms to global change? SIBER will seek to motivate studies focused on the physical, biogeochemical and ecological contrasts between the AS and the BoB, aimed at answering this question (and many other related questions) to shed light on the role of how wind and freshwater forcing drive biogeochemical cycles and ecosystem dynamics in marine systems, and how these might be altered by anthropogenic forcing.

What factors control phytoplankton production and export in the IO? What water column and benthic biogeochemical processes are driven by export from the euphotic zone? How do these processes and environmental controls vary across the IO and with season? For example, characterizing and quantifying the:

- Regional differences in controls on phytoplankton production
- Basinwide production and export flux variability
- Impacts of organic matter export on mid-water and benthic communities and processes

SIBER will seek to motivate studies focused on quantifying the relative roles of light, nutrient and grazing limitation in controlling phytoplankton production in the IO and how these vary in space and time, as well as determining the fate of this production after it sinks below the euphotic zone. Quantifying the influences of top-down versus bottom-up control and their impacts on biogeochemical cycles and ecosystem dynamics are a high priority. This question also encompasses the issue of how benthic biogeochemical processes are driven by production that sinks from the euphotic zone and how these processes and environmental controls vary in space and time across the IO.

How will human-induced changes in climate and nutrient loading impact the marine ecosystem and biogeochemical cycles? For example, impacts of:

- Warming and acidification on biogeochemical cycles and ecosystem dynamics
- Human activities in the coastal zone
- Increasing human populations in the future

For each driver there is a unique set of issues to explore. SIBER will seek to motivate studies focused on understanding the effects of these phenomena and how natural climate variability and extreme events impact marine biogeochemical cycles and ecosystems. These studies will provide crucial information for understanding how the IO (and other ocean basins) will be impacted by global warming and anthropogenically-induced change.

To what extent do higher trophic level species influence lower trophic levels and biogeochemical cycles in the IO and how might this be influenced by human impacts (e.g. commercial fishing). Potential study areas include:

- Lower trophic level food web dynamics and cycling
- Higher trophic level food web dynamics and cycling
- Human (fisheries) impacts

SIBER will motivate studies focused on understanding the influence of higher trophic level species on lower trophic levels and biogeochemical cycles in the IO and what the effects of human impacts might be.

CONCLUSIONS AND LEGACY

SIBER will develop a coordinated, basinwide approach to determine the major controls and feedbacks between biogeochemical cycles and ecosystem dynamics in the IO and potential feedbacks as part of the Earth system.

SIBER will focus on using remote sensing and models to improve our understanding of how the unique physical processes of the IO drive biogeochemical cycles and ecosystem dynamics. Models will also be used to improve predictions of future ecosystem dynamics in the IO, including responses to climate change and other anthropogenic impacts.

SIBER will work towards integrating and analyzing existing process studies and monitoring datasets to facilitate investigation of long-term, large-scale changes in physical processes, biogeochemical cycles and ecosystem dynamics.

SIBER will help to coordinate international research and monitoring programs, identify priority areas for research and monitoring, and develop coordinated field and monitoring studies to fill spatial and temporal gaps in IO data.

SIBER will provide an important vehicle for capacity building in IO rim nations.

The integration and coordination of IO biogeochemical and ecosystem research and analysis through SIBER will improve our predictions of the impacts of global change on IO ecosystems and human populations, creating a lasting legacy on which future research can build. Much of what is learned will also be transferable to other regions and research areas. The reports and papers produced will inform scientists in the international community and provide a focus for future research on important regional, basinwide and global issues. These outputs will also be presented in forms that provide policy makers with a sound scientific basis upon which to make decisions on how to mitigate anthropogenic impacts in the IO. In the global context, SIBER will complement IMBER and IOGOOS programs in facilitating the development of research and monitoring infrastructure and human resources in the IO and also by inspiring a new generation of international, multidisciplinary oceanographers and marine scientists to study and understand the IO and its role in the global ocean and the Earth system.

Appendix I. Glossaries

Scientific glossary

AATSR	Advanced Along-Track Scanning Radiometer
AS	Arabian Sea
ASCAT	Advanced Scatterometer
AVHRR	Advanced Very High Resolution Radiometer
BoB	Bay of Bengal
CPR	Continuous Plankton Recorder
CPUE	Catch Per Unit Effort
CTD	Conductivity/Temperature/Depth
CZCS	Coastal Zone Color Scanner
EEZ	Exclusive Economic Zone
ENSO	El Niño Southern Oscillation
GIS	Geographic Information Systems
HNLC	High-Nutrient Low-Chlorophyll
IO	Indian Ocean
IOD	Indian Ocean Dipole
ITF	Indonesian Throughflow
MERIS	Medium Resolution Imaging Spectrometer
MJO	Madden-Julian Oscillation
NEM	Northeast Monsoon
MODIS-Terra MODIS-Aqua	Moderate Resolution Imaging Spectroradiometer Terra – Earth Observing System - AM Satellite Aqua – Earth Observing System - PM Satellite
OCM	Ocean Color Monitor
QuikSCAT	Quick Scatterometer
RA-2	Radar Altimeter 2
SCTR	Seychelles-Chagos Thermocline Ridge
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SMOS	Soil Moisture and Ocean Salinity
SSH	Sea Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
STIO	Southern Tropical Indian Ocean
SWM	Southwest Monsoon
TOPEX/Poseidon (T/P), Jason	Satellite Altimeters that measure SSH
TRMM	Tropical Rainfall Mapping Mission

Project, program and organizational glossary

ASCLME	Agulhas and Somali Current Large Marine Ecosystems
BLUELink	Australian oceanic forecasting model http://www.cmar.csiro.au/bluelink/
BOBLME	Bay of Bengal Large Marine Ecosystem
CIRENE	French project: Center of Initiative and Research on Energy and the Environment.
CLIOTOP	Climate Impacts on Oceanic Top Predators http://www.imber.info/cliotop.html
CLIVAR	Climate Variability and Predictability
CoML	Census of Marine Life
CSIR	Council for Scientific and Industrial Research, India
CSIRO	Commonwealth Scientific and Research Organization, Australia
ECMWF	European Centre for Medium-range Weather Forecasts
ESA	European Space Agency
EUR-OCEANS	European Network of Excellence for Ocean Ecosystems Analysis (now the EUR-OCEANS Consortium (EOC))
GEOTRACES	An international study of marine biogeochemical cycles of trace elements and their isotopes. http://www.geotraces.org
GLOBEC	Global Ocean Ecosystem Dynamics
ICED	Integrating Climate and Ecosystem Dynamics
IGBP	International Geosphere-Biosphere Programme
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research http://www.imber.info/
IMOS	Australian Integrated Marine Observing System
INAGOOS	Indonesian Global Ocean Observing System
IndOOS	Indian Ocean Observing System
IOCCP	International Ocean Carbon Coordination Project
IO-CoML	Indian Ocean Census of Marine Life
IOGOOS	Indian Ocean Global Ocean Observing System
JCOMM	Joint Committee for Oceanography and Marine Meteorology
JGOFS	Joint Global Ocean Flux Study
MOES	Ministry of Earth Sciences, India
NASA	National Aeronautics and Space Administration
NEAR-GOOS	Northeast Asia Regional Global Ocean Observing System
NIO	National Institute of Oceanography, India
NOAA	National Oceanic and Atmospheric Administration
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction
SAHFOS	Sir Alistair Hardy Foundation for Ocean Science
SANCOR	South African Network for Coastal and Oceanic Research

SCOR	Scientific Committee on Oceanic Research
SEAGOOS	South-East Asian Global Ocean Observing System
SIBER	Sustained Indian Ocean Biogeochemical and Ecosystem Research
SOLAS	Surface Ocean-Lower Atmosphere Study
SOOP	Ship of Opportunity Program
WAGOOS	Western Australian Global Ocean Observing System
WCRP	World Climate Research Program
WIOMSA	Western Indian Ocean Marine Science Association
WOCE	World Ocean Circulation Experiment

APPENDIX II. SIBER WORKSHOPS AND PARTICIPANTS

Participants in the SIBER Science Planning Conference, National Institute of Oceanography, Goa, India, 3-6 October 2006.

Name	Country	Organization
S. Wajih A. Naqvi	India	NIO
Satish Shetye	India	NIO
B. N. Goswami	India	NIO
M. Dileep Kumar	India	NIO
Rajesh Agnihotri	India	NIO
Prasanna Kumar	India	NIO
Rengaswamy Ramesh	India	PRL
Ramaiah Nagappa	India	NIO
Man Mohan Sarin	India	PRL
V. V. S. S. Sarma Vedula	India	NIO
Baban Ingole	India	NIO
P. N. Vinayachandran	India	Indian Institute of Science
Balasaheb Kulkarni	India	The Institute of Science
Rohit Srivastava	India	PRL
V. S. N. Murty	India	NIO
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Appendix III. Issues to be considered in SIBER model development

This appendix is based upon recommendations put forward in Appendix III of the ICED Science Plan and Implementation Strategy (Murphy et al., 2008). SIBER will therefore adopt a strategy for model development that is consistent with ICED.

One of the first challenges to address is to define the theoretical and technical process required to model whole ocean biogeochemical cycles and ecosystem dynamics. It is imperative to identify the main areas and building blocks that will provide the underlying understanding required to inform and evaluate these models. Some key science areas and associated model requirements are listed below.

Objective 1: To understand the structure and dynamics of biogeochemical cycles and ecosystem dynamics in the Indian Ocean and how they might be affected by climate change and anthropogenic impacts
The development of models of IO biogeochemical cycles and ecosystem dynamics is still at an early stage and much of the work undertaken to date has been of restricted geographical or trophic scope. There are major questions regarding the criteria that should be used to develop realistic models of IO ecosystems. Model development should involve consideration of the following issues:

1. The development of integrated biogeochemical and ecosystem models must be done in conjunction with experimental and field studies to provide the basis for model parameterizations.

2. A range of approaches to food web representation is required, involving models with different spatial, temporal and trophic complexity. Specific issues include the effects of horizontal advection of chemical and biological materials (see below) and the effects of behavioral processes, such as vertical migration of plankton or predator-prey interactions. The importance of energy transfer from phytoplankton to upper trophic levels in structuring food webs, and the spatial and temporal resolution required for coupling lower trophic level models with those developed for top predators are important issues, as are regional differences and the links between benthic and pelagic systems, particularly in coastal regions.

3. The development of coupled physical-biological models will require close collaboration with physical modeling groups. As a basis for SIBER modeling efforts physical models that provide outputs relevant to the scales of operation of the biological processes under consideration are required, for example such models may include: basinwide atmosphere-ocean models (e.g. OFAM/BLUElink), coupled models for key regions of the IO, such as the AS, the BoB, the equatorial zone, and the Leeuwin and Agulhas Current systems, and high resolution mesoscale (10s-100s km) models of shelf and cross-shelf, island and frontal regions and processes.

4. Sub-decadal physical fluctuations are crucial for determining interannual to decadal dynamics of biogeochemical and ecological systems and provide an important and tractable scale for examining biogeochemical and ecosystem responses to physical variation. Models are therefore, required that include large-scale physical interactions (atmosphere-ocean and inter-basin) and their connections with global climate-related processes (e.g. the IOD, ENSO and the Antarctic Oscillation). Clarifying the interactive nature of these physical processes is required to determine the drivers of biogeochemical and ecological change.

5. Models predicting future climate-driven change in the global ocean have suggested that atmospheric warming will increase monsoon wind and precipitation variability. Increased variability in current speeds may result from increased wind speeds, and changes in freshwater budgets associated with precipitation changes will affect water column stability. However, a high degree of uncertainty is involved. This needs to be accounted for in simulating future change scenarios in relation to biogeochemical and ecological systems.

6. A wider network of physical and biological monitoring of oceanic systems is required to provide data for the robust development and testing of large-scale models. This could be achieved in conjunction with the IndOOS/RAMA mooring and observational network and by expanding and linking with IOGOOS measurements networks.

7. Circulation models at global and basin scales (such as the OFAM/BLUElink Project) and regional scales are valuable as stand-alone systems for examining circulation effects on biogeochemical and ecological systems. However, large-scale models may not capture key aspects of regional variation, which will be crucial in determining biogeochemical and ecosystem responses. For example, dynamic biogeochemical models that provide realistic simulations at regional scales are needed to better understand boundary current dynamics and oxygen minimum zone development in the AS and the BoB and responses to climate change.

8. High-resolution models that include adaptive vertical mixing schemes, the ability to handle steep topography, tidal effects, and processes over shelves are needed.

Objective 2: To understand how ecosystem structure and dynamics affect biogeochemical cycles in the IO

Development of biogeochemical models for the IO is advancing and models that simulate basinwide biogeochemical distributions are just becoming available. Acquisition of datasets that can provide evaluation of such model results will be an important focus for the next generation of IO research programs. Biogeochemical-based models have been developed for selected regions of, and across, the IO, for example, the AS (e.g. Hood et al., 2003; McCreary et al., 2001; McCreary et al., 1996), and the BoB (Vinayachandran et al., 2005). Wiggert et al. (2006) used a coupled physical-biochemical model to simulate nutrient limitation dynamics across the entire IO basin. These models provide very important insights as a basis for SIBER modeling studies. Model development should involve consideration of the following issues:

1. A focus for SIBER is to foster the development of regional coupled circulation-biogeochemical models, especially for areas identified as priority regions for field studies.

2. Understanding the influence of seasonally reversing boundary and open ocean currents on regional biogeochemical processes is crucial and presents methodological modeling challenges. Nested model structures can provide the space and time resolution for local scales as well as maintaining the larger scale connections between regions. A basinwide view could be developed by embedding high-resolution regional biogeochemical models into larger-scale circulation models.

3. Development of basinwide and regional watershed models, especially for land areas surrounding the BoB, needs to be promoted. The importance of river-derived inputs of nutrients to material cycling in the IO has not been examined in models. Inclusion of sediment transport into circulation models, especially for coastal and continental shelf regions, also needs to be considered.

4. Development of generic models to determine how ecosystem structure influences biogeochemistry will be useful because potential feedbacks and control processes need to be specifically explored before attempts are made to construct complex simulations.

5. The importance of iron in regulating primary production should be incorporated into models of IO primary production (Wiggert et al., 2006) to begin to address questions regarding links between biogeochemical cycles and food web structure.

6. Impacts of ocean acidification and warming will require a specific focus on impacts at different levels of the ecosystem: stress on organisms through pH and temperature changes, alterations in calcification rates of autotrophic species (hence impacts on production and phytoplankton community composition) and changes in calcification rates and bleaching of coral species. Models are required that quantitatively assess these impacts and examine potential food web effects.

7. The next generation of biogeochemical models should include explicit food web dynamics. Validation and testing of such models will require appropriate data (that are not often collected simultaneously) at the required scales. This presents a challenge for the development of field programs.

8. Most biogeochemical models developed for the IO focus on the euphotic zone. Depth-related vertical links in food webs, for example links to the mesopelagic layer and its role in controlling biogeochemical cycles and benthic production are largely unexplored in model studies. The biogeochemistry and ecosystem dynamics of this large and important environmental regime known as the mesopelagic zone, where organic material is remineralized, are poorly understood.

9. Coupling of pelagic-based biogeochemical models to benthic models will be important for some IO coastal regions to develop a more complete picture of pelagic-benthic coupling processes.

Objective 3: To determine how ecosystem structure and dynamics should be incorporated into management approaches to sustainable exploitation of living resources in the Indian Ocean

Model development should involve consideration of the following issues:

1. Much of the management-related modeling has tended to focus on single species harvesting-based models. In recent years there has been an increasing emphasis on the ecosystem-based approach, incorporating food web interactions and environment links.

2. SIBER will complement and contribute to the work of IO island and rim nation fisheries management efforts in developing modeling approaches for sustainable management of IO resources, providing a broad ecological perspective. A range of models have been developed to examine upper trophic level food web interactions with a particular focus on the effects of harvesting (see for example Hill et al., 2006).

3. SIBER will investigate how the structure and dynamics of IO ecosystems should be represented in ecosystem models used in resource management. The complexity of these

ecosystems, as well as the uncertainty in our understanding of their functioning should be reflected in the preparation and delivery of management advice. Additionally, the principles are required to utilize data from ecosystem monitoring programs as part of developing management strategies should be articulated.

4. A key aspect for SIBER will be addressing the appropriate scales at which biological populations/metapopulations need to be managed. This will be an ongoing and iterative process involving explicit consideration of the implications of model uncertainty within the context of delivering management advice.

APPENDIX IV.
SCIENCE AND IMPLEMENTATION PLAN FOR BIOGEOCHEMICAL SENSOR DEVELOPMENT AND DEPLOYMENT ON RAMA MOORINGS

Deployment of biogeochemical sensors on autonomous vehicles and moored physical sensor arrays is the next logical and essential step toward developing a global ocean physical-biogeochemical observing system. The ongoing deployment of the Indian Ocean Observing system (IndOOS) and the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) mooring array (McPhaden et al., 2009) presents a unique opportunity to combine physical and biological sensor deployment through the collaborative efforts of IndOOS, RAMA, IOGOOS and the emerging SIBER program. This unique collaboration has been facilitated by CLIVAR's Indian Ocean Panel (IOP), which recognizes the importance of fostering physical, biogeochemical and ecological research in the IO.

This appendix provides specific guidance for developing and deploying biogeochemical sensors on RAMA moorings in the IO. It is hoped that the realization of this plan will benefit from the momentum of the IndOOS, RAMA, IOGOOS and SIBER programs.

OBJECTIVES

The overarching objectives that provide the motivation for deployment of biogeochemical sensors on RAMA moorings in the IO are as follows:

1. To provide data for defining biogeochemical variability in key regions of the IO and for understanding the physical, biological and chemical processes that govern it.

2. To provide data for developing and validating models of ocean-atmosphere-biosphere interactions.

3. To provide baseline data for assessing the impacts of climate change on oceanic primary productivity and air-sea CO_2 exchange.

SITE SELECTION

Biogeochemical measurements should be made where they make the most scientific sense. The RAMA mooring array design/deployment team has identified eight sites for air-sea observatories (Flux Reference Sites, **FIG. A4.1**). Because of the comprehensive suite of co-located complementary measurements they would provide, these sites would also be logical places for biogeochemical sensors.

These sites include, for example, 16°S 55°E; 80°S 67°E in the Seychelles-Chagos Thermocline Ridge (SCTR) region and in the subduction zone in the SE tropical IO (97°E 26°S). These are regions of biogeochemical interest where additional measurements would enhance the planned physical and air-sea flux measurements.

Site selection for biogeochemical sensors is informed by remotely sensed chlorophyll variability. An animation of this variability (provided by Pete Strutton at http://www.imber.info/SIBER_downloads.html) shows climatological monthly chlorophyll with the eight RAMA Flux Reference Sites plotted as black circles. These animations show that the AS and BoB Flux Reference Sites are crucial locations for deploying biogeochemical sensors on RAMA moorings. These locations will also potentially have the further benefit of nearby sediment trap moorings (Prasanna Kumar, personal communication).

At the western SCTR site (8°S 67°E) some interesting phytoplankton iron-stress indications are suggested by biogeochemical model results (Wiggert et al., 2006) and MODIS-obtained chl-fluorescence, as recently reported in Behrenfeld et al. (2009). Moreover, the site is influenced by the IOD, with the subsurface biological response being difficult to perceive with remote sensing platforms, thus making moored *in situ* observations a paramount need (Vialard et al., 2009).

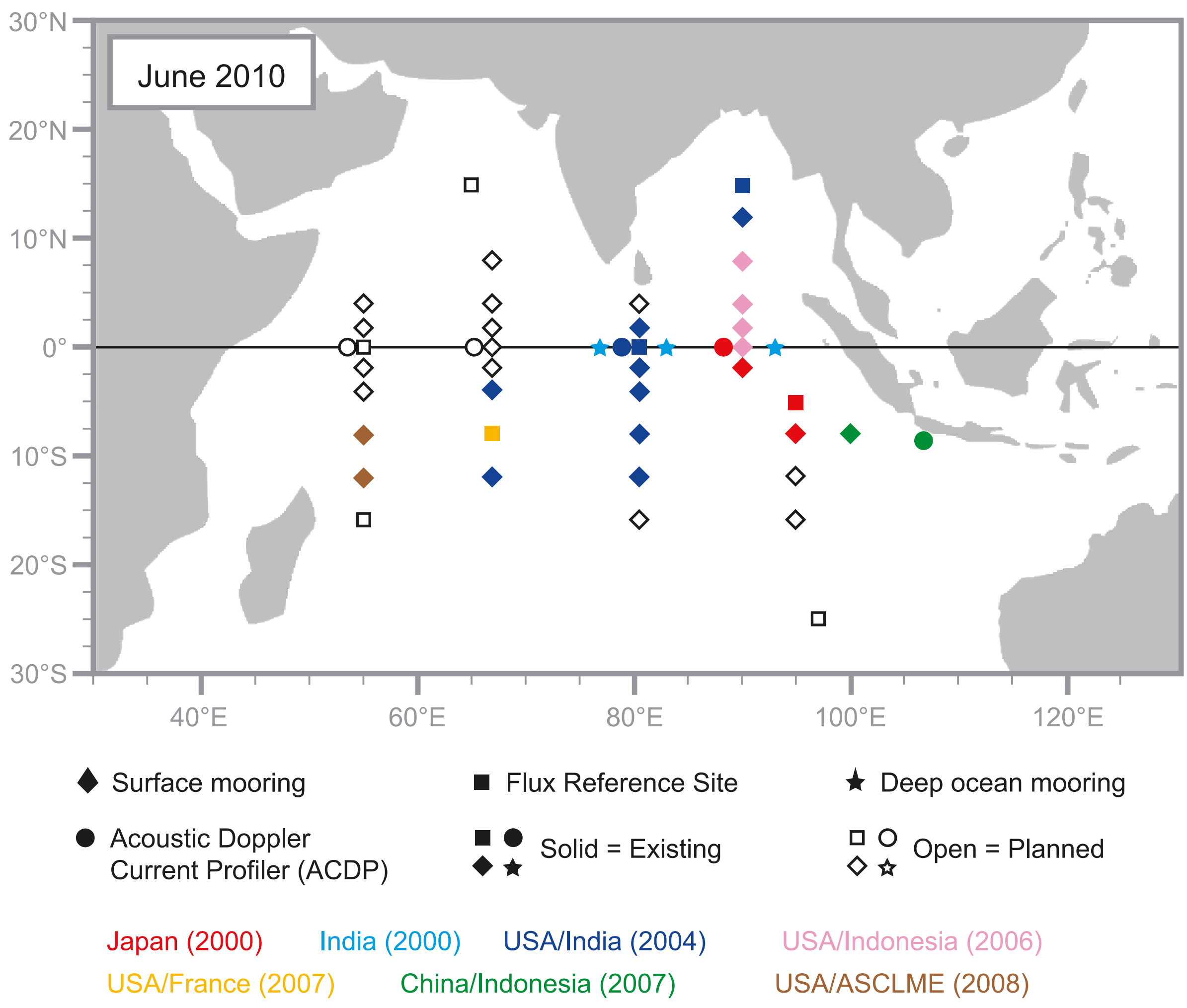

Figure A4.1 Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA). Note that the filled symbols represent assets deployed as of June 2010.

Reproduced with permission from McPhaden et al. (2009)

The site off SW Indonesia (5°S 95°E) would be the flux site most strongly impacted by the IOD, with the eastern tropical IO undergoing significant biogeochemical alteration during these events. A recent analysis of satellite-observed interannual chlorophyll variability, combined with ocean color based estimates of net primary production (NPP), reveals that the eastern IO from the equator down to ~ 8°S realizes significant enhancement of phytoplankton biomass (Wiggert et al., 2009). The NPP estimates show that local production rates can attain up to a 100% increase, with an overall regional increase of >40% recorded during the 1997/98 IOD.

The time series of climatological chlorophyll is plotted for each of the eight Flux Reference Sites in **Fig. A4.2** (note that the y scale on the two plots is different). The upper panel shows the four western sites and the lower panel is the four eastern sites. The western sites are of general interest due to their high biological variability. By contrast, the eastern sites have much lower variability but are interesting for the reasons discussed above. In addition, while productivity appears low and invariant at the eastern sites in the monthly climatological maps, model results (Jerry Wiggert, personal communication) suggest that these sites should experience short-term pulses of physical and biological variability that are not revealed by these coarse resolution (monthly) climatologies. Higher temporal resolution measurements are required to validate these results.

In addition, one interesting aspect of the 26°S 97°E mooring is that numerous eddies come off the Leeuwin Current and the mooring might be able to capture the biogeochemical impact of these. Research is currently being carried out at Oregon State University (USA) focusing on these features, i.e. satellite analyses of the sea surface temperature and chlorophyll anomalies associated with these eddies (see animation provided by Pete Gaube and Dudley Chelton at http://www.imber.info/SIBER_downloads.html).
Given the preceding discussion, it is difficult to prioritize the RAMA Flux Reference Sites for

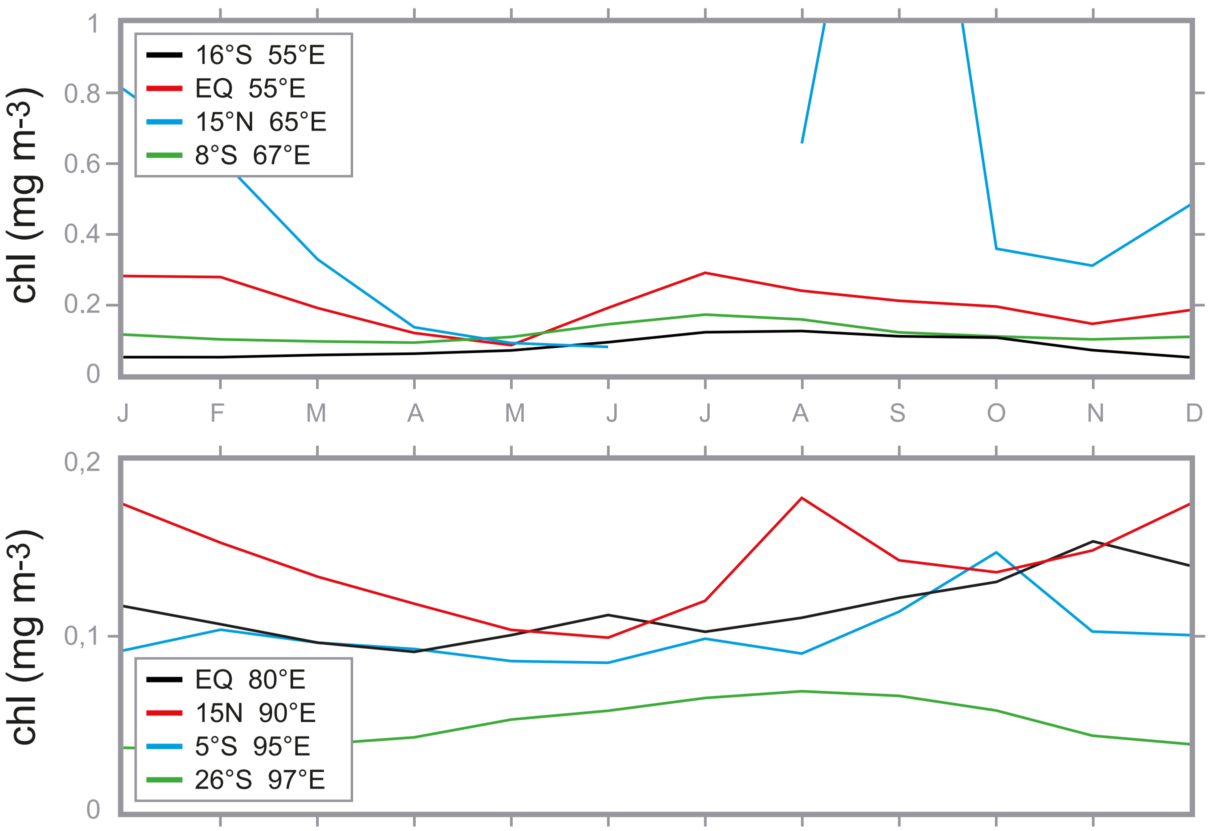

Figure A4.2 Time series of climatological chlorophyll plotted for each of the eight Flux Reference Sites. Note that the y scale on the two plots is different. The upper panel shows the four western sites and the lower panel the four eastern sites.

biogeochemical sensor deployment because all the sites are of interest, albeit for different reasons, and they all have fundamental open research questions to be addressed. Nonetheless, since it is likely that these eight locations will be instrumented in a stepwise fashion, mooring pairs have been identified and prioritized based on logistical as well as scientific considerations. The RAMA Flux Reference Sites in the AS and the BoB are ranked as having the highest priority for biogeochemical sensor deployment because they can provide crucial information about biogeochemical differences that arise due to differences in freshwater flux and monsoon influence and how this in turn impacts open ocean oxygen minimum zones. Near-term deployment of biogeochemical sensors in the AS and the BoB would complement India's plans to deploy biogeochemical sensors in the AS during 2012-2017 as part of a program on mineral dust flux, and in the equatorial IO as part of a program on climate change and variability.

The second priority pair of Flux Reference Sites is the RAMA western equatorial site (0°S 55°E) and the site off SW Indonesia in the southeastern tropical IO (5°S 95°E) for characterization of IOD influence. The third priority pair is the RAMA SCTR site (8°S 67°E) and the equatorial site south of Sri Lanka (0°S 80°E) for monitoring regions with and without potential phytoplankton iron-stress impacts. The fourth priority pair is the southern Indian Ocean Madagascar/Mauritius basin site in the west (16°S 55°E), and the Leeuwin Current ring-influenced region in the east (26°S 97°E) for assessing the influence of island wake and eddy effects on phytoplankton and carbon flux in regions where few measurements have been taken.

However, given the constraints imposed by piracy problems in the western equatorial IO, it is recommended that deployment of the second highest priority pair (the RAMA western equatorial site (0°S 55°E) and the site off SW Indonesia in the southeastern tropical IO (5°S 95°E)) be delayed indefinitely until the security situation improves.

Potential sensors, installation options and priority

NOAA has expressed interest in deploying CO_2 sensors on RAMA moorings in the IO (Chris Sabine, personal communication). The NOAA MAPCO_2 sensors are now being manufactured by Battelle Incorporated, USA, so they can be purchased commercially. The cost of each sensor is around $40,000 USD (Battelle contact representative, Mark Davis). NOAA personnel can collect and process the data and post it on the web in near real-time for the RAMA, IndOOS, IOGOOS and SIBER groups to use (Chris Sabine, personal communication).

In addition to CO_2, several other biogeochemical sensors can be deployed on RAMA moorings. For example, chlorophyll can be estimated by measuring fluorescence. There is likely considerable diel, physiological variability in the relationship between chlorophyll and fluorescence, so measuring either a daily average fluorescence value or the average of a two-hour window around midnight is recommended, which can then be correlated with extracted chlorophyll concentrations to estimate absolute chlorophyll concentration from fluorescence.

WETLabs Inc. makes fluorescence sensors that are combined with backscatter sensors. The latter measurements can be correlated with particulate organic carbon to give estimates of POC, given sufficient *in situ* comparison samples. See: http://wetlabs.com/products/eflcombo/flntu.htm for a detailed description. These sensors include an optional copper wiper/shutter to minimize fouling, and there are also self-powered and/or self-logging options. They cost approximately $8,000 USD. Ideally (depending on the funding available), one surface and one subsurface instrument should be deployed on each biogeochemical mooring site. In addition, it is desirable to have these instruments engineered so they report data in real-time. These sensors are about the size of the inductive T pods on the TAO moorings. One of these sensors was deployed at the EQ, 80°E mooring on 22 May 2010 as an unfunded pilot program to demonstrate the feasibility of such deployments. The site was selected for logistical reasons, i.e. this buoy was being serviced and therefore deployment of the sensors was easily achieved.

It is also entirely feasible and highly desirable to deploy oxygen sensors on the RAMA moorings. Installing a Sea-Bird (SBE) 16 (or 19) sensor on the mooring bridle would provide ports for several additional sensors, such as chlorophyll, turbidity and dissolved oxygen. In addition, the software for the CO_2 instrument mentioned above has recently been upgraded to make it compatible with the SBE 16 (or 19) system, i.e. it can be plugged in and all the data (including chlorophyll, turbidity and dissolved oxygen) can be transmitted back in real-time with the CO_2 data. This would provide an excellent option for powering, data logging and real-time data transmission, and would probably reduce the cost of the WETLabs Inc. fluorescence/ backscatter sensors discussed above, to about $7,000 USD per unit. The total cost of an SBE-16 including fluorescence, backscatter and oxygen is $20,000 USD.

Deploying this suite of sensors would provide a powerful set of highly complementary biogeochemical measurements (chlorophyll, particulate organic carbon, O_2, and CO_2) with physical data for context. The estimated overall cost of this sensor package is $60,000 USD, plus $10,000 USD for buoy modifications and mounting hardware.

To fully constrain the carbon systems and assess ocean acidification, ocean pH could also be measured on the moorings with a SAMI-pH system (Sunburst Sensors; http://www.sunburstsensors.com/). The SAMI-pH can also be plugged directly into the $MAPCO_2$ system so the data can be transmitted back to the lab in near real-time. The approximate cost of these systems is $20,000 USD.

Another biogeochemical sensor that should be considered is one that can be deployed to measure nutrients, like a Satlantic NO_3 sensor. These are, however, relatively expensive, costing ~$30,000 - $40,000 USD each, and may not be suitable for long-term deployments.

In terms of sensor priority, CO_2 and pH are the highest, given their relevance to the global carbon cycle. The next would be fluorescence and backscatter. It would be very beneficial to have oxygen for comparison with CO_2 and the biological measurements. The ranking for the full suite of measurements/sensors from highest to lowest priority is CO_2/pH, fluorescence/ backscatter, O_2 and then NO_3. NO_3 is ranked lowest due to the high cost and the absence of a track record of long-term deployments of these instruments in the open ocean.

Longevity of instruments

Fouling will probably compromise the data of the fluorescence/backscatter instrument first. Good data have been logged off the Oregon coast for four months where fouling is fairly intense (Pete Strutton, personal communication). In low-to-moderate productivity regions of the IO, six-month deployments should be feasible, perhaps more (this estimate is based on successful deployments in the equatorial Pacific which experiences comparable productivity and hence fouling). It is therefore, essential to consider the mooring servicing schedule to determine the feasibility of deploying biogeochemical sensors on the RAMA moorings. The current RAMA service schedule is one year and it is unlikely, in most cases, that this could be reduced to six months on a regular basis. The CO_2 systems should last for a year; but there may be some degradation in the fluorescence and backscatter data towards the end of deployments.

Implementation, servicing and program duration

Given the previous discussion, initial surface and subsurface deployments of CO_2 and optics, plus pH at the surface only, are recommended at an approximate instrument cost of $128,000 USD per system (see **Table 1**). A different CO_2 sensor (SAMI-CO_2) would be used for the subsurface location since the $MAPCO_2$ can only be used at the surface. The subsurface sensor set would only store data internally. Buoy modification and hardware for attaching sensors is estimated to be $10,000 USD. This gives a total instrumentation and hardware cost of $138,000 USD per system. Two systems will be required per mooring to maintain continuous measurements (one deployed while the replacement system is prepared on shore). Therefore, the total cost is $276,000 USD per mooring.

Given the current uncertainties in ship availability and maintenance schedules it would be prudent to deploy sensor pairs in a stepwise fashion as recommended above, with the deployment of the first pair providing a feasibility test. Once it has been established that these biogeochemical sensors can be deployed, serviced and recovered and that high quality data can be retrieved, additional sensors can be deployed.

Table 1 Total per system (note two systems per mooring): $138,000

Sensor	Depth	Parameters	Cost (USD)
$MAPCO_2$	Surface	Air-sea CO_2 flux	$40,000
Optics + SBE 16 CTD	Surface	Fluorescence, backscatter, O_2, T, S	$20,000
SAMI pH	Surface	pH	$20000
Optics	Subsurface	Fluorescence, backscatter	$8,000
SAMI CO_2	Subsurface	CO_2	$40,000
Mooring modification and hardware			$10,000

A simple timeline for deployment would be one sensor pair every 18 months over the next 4.5 years, beginning with the first deployment in 2012. In the context of SIBER, which is a 10-year program, the goal would be to maintain deployment of these sensors for 10 years. The annual maintenance and hardware replacement costs are estimated to be $125,000 USD per year after the initial deployments.

It should be emphasized, however, that much will be determined by logistics and other practicalities, such as which countries will support the measurements. It is doubtful that a single country will undertake all the deployments. For example, southern African countries might ascribe a higher priority to the western sites than the BoB, simply because they have more of a scientific interest in that region and it is where their ships travel. It should also be emphasized that a basin scale perspective is needed, and all the key regions should be measured. Therefore, the overarching goal is full implementation of biogeochemical sensors on the RAMA Flux Reference moorings, recognizing that the pace and sequencing of deployments will be determined by a range of factors such as availability of funding, ship time, national interests, etc., and that above all, there must be close international cooperation to ensure that instruments are deployed and the array maintained in the most efficient manner.

Data policy

Data collected as part of this effort, once calibrated and quality controlled, will be freely available on the internet.

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Summary and key questions that need to be addressed

Deploying a suite of biogeochemical sensors on the RAMA moorings in the IO is an exciting prospect. Indeed, it could revolutionize our understanding of biogeochemical variability in this under-sampled basin. Moreover, the ongoing deployment of IndOOS and the RAMA mooring array presents a unique opportunity to combine physical and biological sensor deployment through the collaborative efforts of IndOOS, RAMA, IOGOOS and SIBER. Having CO_2 sensors co-located with pH, fluorescence/backscatter and oxygen sensors deployed at two depths on a given mooring string and targeting the sites that will be instrumented as air-sea flux observatories would provide a powerful set of combined physical and biogeochemical observations that can help improve our understanding of the relationship between physical forcing and carbon/biogeochemical cycle response. Successfully deploying and retrieving useable data sets from these sensors would also be a major accomplishment.

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Appendix V.
Regional piracy update

From the Indian Ocean Piracy Discussions at the IOP-8, SIBER-2 and IRF-2 Joint Meeting in Chennai, India from 25-29 July 2011.

Piracy is a global problem, but heavily concentrated in the northwestern Indian Ocean (**Fig. A5.1**). Piracy in this region is extremely serious, and it is becoming impossible to arrange research cruises in the northwestern region of the basin. Piracy is adversely impacting Indian Ocean climate research, observations, modelling and consequently the world's ability to address the impacts of climate variability and climate change.

There have been several press reports recently on the Indian Ocean piracy problem and specifically how it is impacting science in the region, for example:

- "Pirates Scupper Monsoon Research", Nature, 7 July, 2011.

"Piracy is stopping oceanographers and meteorologists from collecting data vital to understanding the Indian monsoon…"

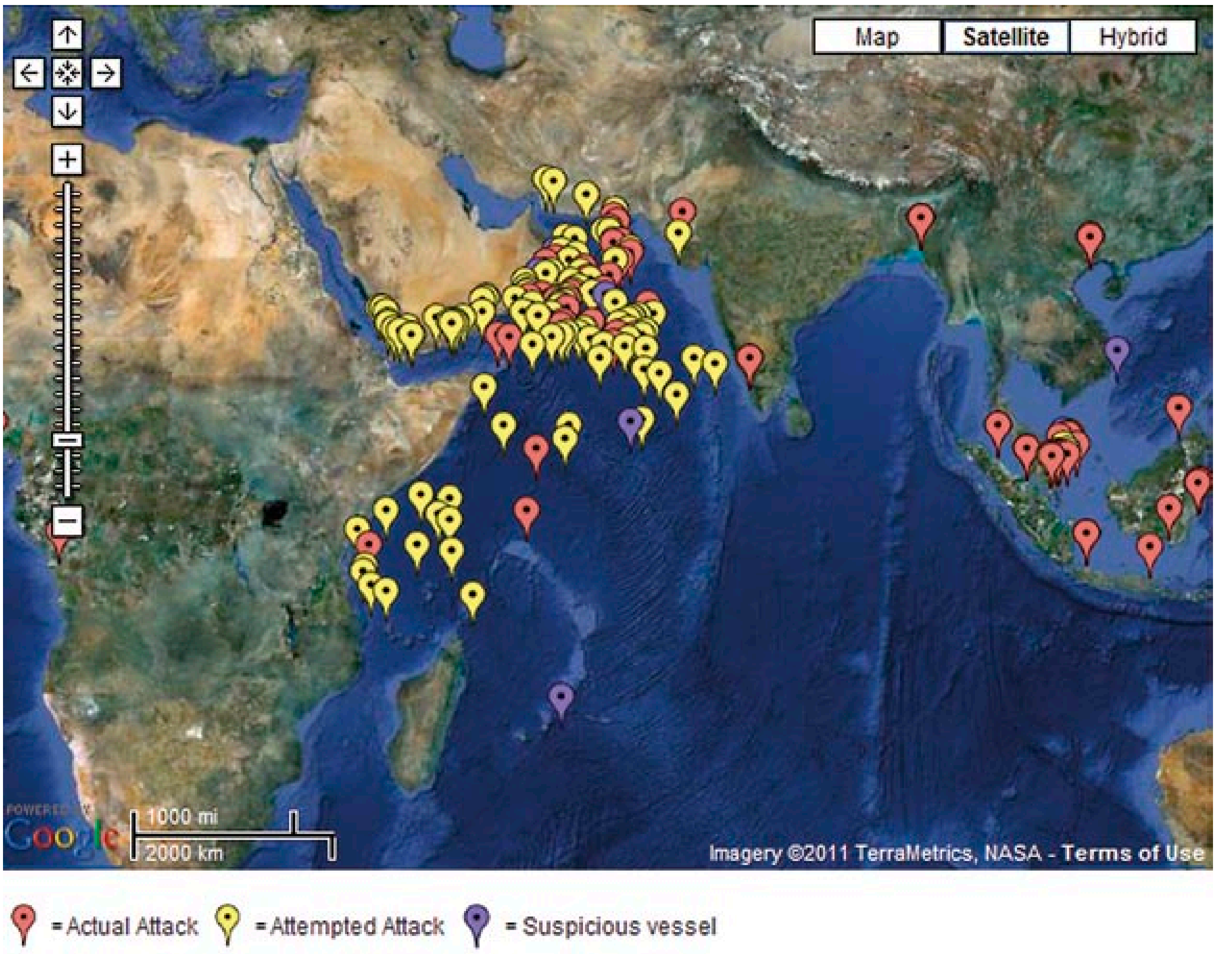

Figure A5.1 Indian Ocean piracy events in 2011

- "Navy to help climate scientists in pirate-infested waters", New York Times, 14 July, 2011.

"About a quarter of the Indian Ocean is now off limits to climate scientists trying to complete a global network of deep ocean devices that gather data crucial to climate change studies and weather forecasts."

In response to numerous piracy incidents in the western Indian Ocean, Lloyds of London declared an Exclusion Zone (EZ) (**Fig. A5.2**) within which additional insurance premiums are required for merchant vessels. In early 2011 the eastern border of the EZ was extended from 65°E to 78°E. The EZ includes most implemented and planned RAMA sites along 55°E and 67°E (green dots are surface RAMA moorings).

In the past six years, 30 of the 46 planned buoys have been installed (**Fig. A5.2**); 13 of the 16 remaining RAMA Sites are in the EZ (open green circles). Red dots signify sub-surface moorings. Red and yellow markers show pirate events for the period January 2010 - May 2011. Pirate events along the coast of Africa and Arabia have not been included as they are far from the mooring sites. Note the lack of piracy incidents in the SE portion of the EZ.

The information in Appendix V was compiled by Sidney Thurston, International Coordinator of the NOAA Climate Program Office.

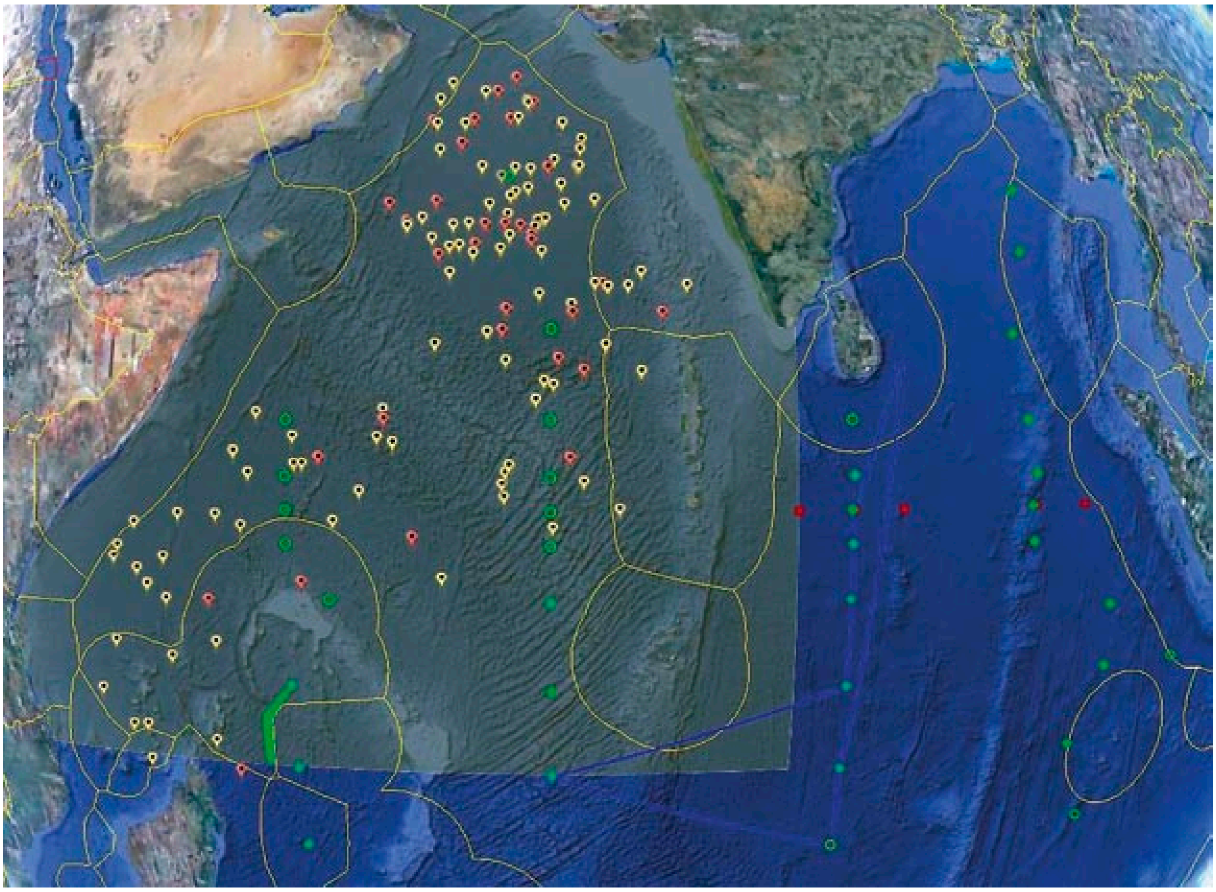

Figure A5.2 Updated Piracy Exclusion Zone

Appendix VI. SIBER-related publications, web sites and products

Publications and articles (ordered by date of publication)

Hood, R.R., Naqvi, S.W.A., Wiggert, J. and Subramaniam, A., 2007. Biogeochemical and ecological research in the Indian Ocean. Eos Transactions AGU, 88(12): 144.

Hood, R.R., Naqvi, S.W.A., Wiggert, J., Goes, J., Coles, V., McCreary, J., Bates, N., Karuppasamy, P.K., Mahowald, N., Seitzinger, S. and Meyers, G., 2008. Research opportunities and challenges in the Indian Ocean. Eos, Transactions, American Geophysical Union, 89(13): 125-126.

Hood, R.R., Wiggert, J. and Naqvi, S.W.A., 2009. Indian Ocean Research: Opportunities and challenges. In: Indian Ocean Biogeochemical Processes and Ecological Variability, Wiggert, J., Hood, R.R., Naqvi, S.W.A., Brink, K.H. and Smith,S.L. (Eds.), AGU Monograph Series, American Geophysical Union, Washington, D.C., pp. 409-428.

Hood, R.R., Wiggert, J. and Naqvi, S.W.A., 2010. Sustained Indian Ocean Biogeochemical and Ecological Research SIBER has taken off! IMBER Update, No. 15.

Hood, R.R., Wiggert, J. and Naqvi, S.W.A., 2010. SIBER: A new basinwide, international program in the Indian Ocean. Ocean Carbon and Biogeochemistry News, 3(3): 5-8.

Wiggert, J., 2010. Indian Ocean biogeochemical processes and ecological variability. Eos, Transactions, American Geophysical Union, 91(44): 409.

Web sites

IMBER/SIBER website: http://www.imber.info/SIBER.html

Products

SIBER News: Winter 2008 (view at http://www.imber.info/SIBER_downloads.html)

SIBER Monograph: Wiggert, J.D., Hood, R.R., Naqvi, S.W.A., Brink, K.H. and Smith, S.L., 2009. Indian Ocean Biogeochemical Processes and Ecological Variability. AGU Monograph Series, American Geophysical Union, Washington, D.C. (can be viewed and purchased at: http://www.agu.org/cgi-bin/agubooks?book=BIGM1854757).

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