THE SECOND INTERNATIONAL INDIAN OCEAN EXPEDITION (IIOE-2)

A Basin-Wide Research Program

Draft Science Plan

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Preface

The Second International Indian Ocean Expedition (IIOE-2) Science Plan, described in this document, is motivated by the need to advance understanding of geologic, oceanic and atmospheric processes and their interactions in the Indian Ocean, and to determine how these dynamics affect climate, marine biogeochemical cycles, ecosystems, and fisheries both within the region and globally. This understanding is required to predict the impacts of climate change, pollution, and increased fish harvesting on the Indian Ocean as well as the influence of the Indian Ocean on other components of the Earth System. New understanding is also fundamental to policy makers for the development of management strategies for the Indian Ocean. The improved understanding that IIOE-2 will bring to fundamental physical, biogeochemical and ecological processes also has strong relevance to the ecology and human societies of island and Indian Ocean rim communities.

IIOE-2 has been developed with joint sponsorship from the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO, with support from the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program, the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program and the Indian Ocean Global Ocean Observing System (IOGOOS), providing strong relevancies to IOC's High Level Objectives, which span the generic themes of marine hazards, climate change, ecosystem protection and associated marine natural resource management. IIOE-2 also has strong links with the Indian Ocean Panel (IOP) sponsored by the Global Ocean Observing System (GOOS) and 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 builds upon concepts and strategies formulated and discussed at three IOC-sponsored planning meetings (convened in Hyderabad, India in May 14-15, 2013; in Qingdao, China in November 20-21, 2013; and in Mauritius in March 6-7, 2014), a SCOR-sponsored workshop (in Bremen, Germany in September 12-13, 2014) and also national planning efforts in India, Australia, Germany, the United States and the United Kingdom. These meetings included scientists from Indian Ocean rim nations, eastern Asia, 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 implementation plans for specific aspects of the program as it progresses. Two IIOE-2 websites have been established to provide program updates on a regular basis, hosted by SCOR (http://www.scor-int.org/IIOE-2/IIOE2.htm) and by IOC (http://www.iocperth.org).

The IIOE-2 Science Plan is ambitious and broad. It encompasses geological, atmospheric and oceanographic research from coastal environments to the deep sea and trophic levels ranging from microbes and phytoplankton to top predators including fish and humans. This plan identifies important scientific themes for consideration as potential research foci for national and international studies in the Indian Ocean, while also recognizing the coastal and regional interests of many Indian Ocean rim countries that seek to pursue research under IIOE-2.

We encourage scientists from all relevant fields to collaborate and implement the IIOE-2 Science Plan to ensure that major questions about the Indian Ocean and Earth System are addressed in a fully integrated manner.

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EXECUTIVE SUMMARY

Although there have been significant advances in our ability to describe and model the Earth System, our understanding of geological, oceanic and atmospheric processes in the Indian Ocean is still rudimentary in many respects. This is largely because the Indian Ocean remains under-sampled in both space and time, especially compared to the Atlantic and Pacific. The situation is compounded by the Indian Ocean being a dynamically complex and highly variable system under monsoonal influence. Many uncertainties remain in terms of how geological, oceanic and atmospheric processes affect climate, extreme events, marine biogeochemical cycles, ecosystems and human populations in and around the Indian Ocean. There are also growing concerns about food security in the context of global warming and of anthropogenic impacts on coastal environments and fisheries sustainability. These impacts include sea level rise, which leads to coastal erosion, loss of mangroves, and loss of biodiversity. There is a pressing need for ecosystem preservation in the Indian Ocean for both tourism and fisheries.

More than 50 years ago the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO motivated one of the greatest oceanographic expedition of all time: the International Indian Ocean Expedition (IIOE). In the 50 years since the IIOE, fundamental changes have taken place in geological, ocean and atmospheric science. These have revolutionized our ability to measure, model, and understand the Earth System. Thanks to these technological developments we can now study how the ocean changes across a wide range of spatial and temporal scales, and how these fluctuations are coupled to the atmosphere and topography. Moreover, compared to the IIOE era, which relied almost exclusively on ship-based observations, new measurement technologies, in combination with targeted and well-coordinated field programs provide the capacity for a much more integrated picture of Indian Ocean variability.

SCOR and IOC are coordinating a new phase of international research focused on the Indian Ocean beginning in late 2015 and continuing through 2020. The goal is to assist ongoing research and stimulate new initiatives in this time frame as part of the second International Indian Ocean Expedition - IIOE-2.

The overarching goal of IIOE-2 is to:

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

The IIOE-2 Science Plan is structured around six scientific themes. Each theme comprises a set of core questions fundamental to our need to understand the forcings, processes, and resultant variability of the Indian Ocean and to develop the capacity to predict how this variability will impact human populations in the future.

- **Theme 1: Human Impacts** *(How are human-induced ocean stressors impacting the biogeochemistry and ecology of the Indian Ocean? How, in turn, are these impacts affecting human populations?)*

- **Theme 2: Boundary current dynamics, upwelling variability and ecosystem impacts** *(How are marine biogeochemical cycles, ecosystem processes and fisheries in the Indian Ocean influenced by boundary currents, eddies and upwelling? How does the interaction between local and remote forcing influence these currents and upwelling variability in the Indian Ocean? How have these processes and their influence on local weather and climate changed in the past and how will they change in the future?)*

- **Theme 3: Monsoon Variability and Ecosystem Response** *(What factors control present, past and future monsoon variability? How does this variability impact ocean physics, chemistry and biogeochemistry in the Indian Ocean? What are the effects on ecosystem response, fisheries and human populations?)*

- **Theme 4: Circulation, climate variability and change** *(How has the atmospheric and oceanic circulation of the Indian Ocean changed in the past and how will it change in the future? How do these changes relate to topography and connectivity with the Pacific, Atlantic and Southern oceans? What impact does this have on biological productivity and fisheries?)*

- **Theme 5: Extreme events and their impacts on ecosystems and human populations** *(How do extreme events in the Indian Ocean impact coastal and open ocean ecosystems? How will climate change impact the frequency and/or severity of extreme weather and oceanic events, such as tropical cyclones and tsunamis in the Indian Ocean? What are the threats of extreme weather events, volcanic eruptions, tsunamis, combined with sea level rise, to human populations in low-lying coastal zones and small island nations of the Indian Ocean region?)*

- **Theme 6: Unique geological, physical, biogeochemical, and ecological features of the Indian Ocean** *(What processes control the present, past, and future oxygen dynamics of the Indian Ocean and how do they impact biogeochemical cycles and ecosystem dynamics? How do the physical characteristics of the southern Indian Ocean gyre system influence the biogeochemistry and ecology of the Indian Ocean? How do the complex tectonic and geologic processes, and topography of the Indian Ocean influence circulation, mixing and chemistry and therefore also biogeochemical and ecological processes?)*

Programmatic Linkages

This IIOE-2 Science Plan has been developed with the sponsorship of the Scientific Committee on Oceanic Research (SCOR). The plan relies significantly on regional input from the IIOE-2 Reference Group meetings sponsored by the Intergovernmental Oceanographic Commission (IOC) of UNESCO. The IIOE-2 will coordinate with international research efforts such as the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program, the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program, the Surface Ocean – Lower Atmosphere Study (SOLAS), the Indian Ocean Global Ocean Observing System (IOGOOS), GEOTRACES (a global survey of trace elements and isotopes in the ocean), the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), the International Ocean Discovery Program (IODP), InterRidge (an international project that promotes interdisciplinary, international studies of oceanic spreading centers), and others. IIOE-2 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), the Southern Ocean Observing System (SOOS) and several regional GOOS programs. To develop a broader understanding of the Indian Ocean ecosystem IIOE-2 will coordinate its efforts with the Western Indian Ocean Marine Science Association (WIOMSA), the South African Network for Coastal and Oceanic Research (SANCOR), the Strategic Action Programme Policy Harmonization and Institutional Reforms (SAPPHIRE) project, and the Bay of Bengal Large Marine Ecosystem (BOBLME) program. As the IIOE-2 develops it is envisaged that the number of participants, institutes and programs involved will increase. IIOE-2 will provide the innovation, direction and coordination required to build a critical mass of multidisciplinary science and scientists to mount this ambitious and globally important expedition.

Legacy

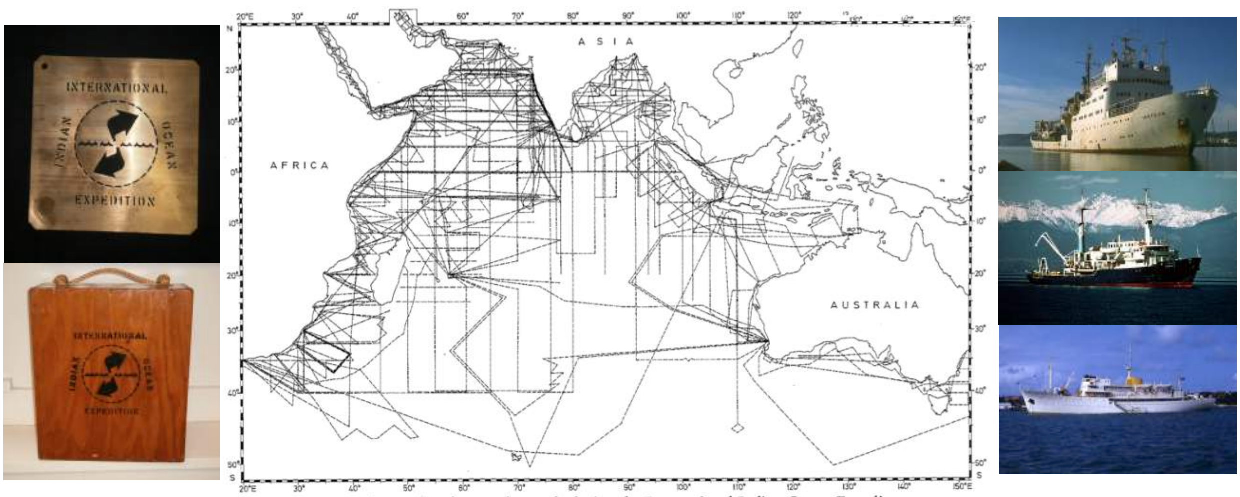
The motivation, coordination and integration of Indian Ocean research through IIOE-2 will advance knowledge, increase scientific capacity, and enable international collaboration in an under-sampled, poorly understood, yet important region. IIOE-2 will promote awareness of the significance of Indian Ocean processes and enable a major contribution to their understanding, including the impact of Indian Ocean variability and change on regional ecosystems, human populations, and global climate. The legacy of IIOE-2 will be to establish a firmer foundation of knowledge on which future research can build and on which policy makers can make better informed decisions for sustainable management of Indian Ocean ecosystems and mitigation of risk to Indian Ocean rim populations. IIOE-2 will leverage and strengthen SCOR and IOC by promoting coordinated international, multidisciplinary research among both developed and developing nations, hence increasing scientific capacity and infrastructure within the Indian Ocean rim and neighboring nations.

The success of IIOE-2 will be gauged not just by how much it advances our understanding of the complex and dynamic Indian Ocean system, but also by how it contributes to sustainable development of marine resources, environmental stewardship, ocean and climate forecasting, and training of the next generation of ocean scientists from the region. If this vision of success is realized, IIOE-2 will leave a legacy at least as rich as the original expedition.

INTRODUCTION

MOTIVATION

More than 50 years ago the Scientific Committee on Ocean Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) carried out one of the greatest oceanographic expeditions of all time: the International Indian Ocean Expedition (IIOE) (Figure 1). The expedition was motivated by the need to explore one of the last great frontiers on Earth. It dramatically advanced the understanding of monsoon dynamics, describing for the first time the northern Indian Ocean's response to monsoon forcing and provided a more detailed picture of the complex topography of the Indian Ocean basin that helped establish the theory of plate tectonics. However, 50 years later the Indian Ocean remains one of the most poorly sampled and overlooked regions of the world ocean, with significant gaps in the observing system for this basin. As a result many important scientific questions remain unanswered (see Science Plan below).



Cruise tracks of research vessels during the International Indian Ocean Expedition. Based on information from the Office of Oceanography, UNESCO Paris

Figure 1: Center: Map of the Indian Ocean showing the cruise tracks of research vessels during the International Indian Ocean Expedition. Left: Logo and field instrument case from the IIOE. Right: Three oceanographic research vessels that participated in the IIOE, from Germany (Meteor II), The US (Atlantis II) and the UK (Discovery).

Many pressing societally relevant questions have emerged since the IIOE. Today, more than 16% of the world's population lives around the northern Indian Ocean and the population of most Indian Ocean rim nations is increasing rapidly: India's population increased more than 75% between 1970 and 2000 (UN, 2004). Population increase contributes to multiple stressors on both coastal and open ocean environments, including eutrophication, deoxygenation, atmospheric and plastic pollution, and overfishing. These regional stressors, combined with warming and acidification due to global climate change, are resulting in loss of biodiversity in the Indian Ocean, as well as changes in the phenology and biogeography of many species.

In addition, the impacts of climate change on ocean circulation, sea level rise, extreme events, and monsoon variability are a growing concern. Rising sea level threatens to inundate the world's most heavily populated, low-lying areas in the Bay of Bengal (Figure 2). The very existence of some Indian Ocean island nations and deltaic coasts is in question. The severity of extreme events are projected to increase around the Indian Ocean, including an increase in flooding and droughts and in tropical cyclone intensity and associated rainfall. These projections, combined with the high exposure and vulnerability of many developing nations, suggest that negative human consequences from extreme events will dramatically increase for nations in and around the Indian Ocean in the coming decades.

There are also concerns about food security and fisheries and direct anthropogenic impacts on the coastal environments of the Indian Ocean. The declining state of both artisanal and industrial fisheries is of particular concern for Indian Ocean rim nations, who are among the world's least developed countries and whose inhabitants are dependent on fisheries for food and employment. Direct anthropogenic impacts on coastal environments, including coastal erosion, loss of mangroves, and degradation of coral reefs, are causing a pressing need for ecosystem preservation in the Indian Ocean in order to safeguard both tourism and fisheries.

Figure 2: Flooding in Bangladesh. Top: picture of a flooded village in Bangladesh, from *emel*, Issue 7, October 2004 (see: http://www.emel.com/article?id=8&a_id=1810). Bottom: Map of Bangladesh between India and Burma from http://www.bbc.co.uk/schools/gcsebitesize/geography/water_rivers/river_flooding_management_rev6.shtml.

In conclusion, increased human-environmental pressures and global climate change present an urgent need to understand and predict changes in the Indian Ocean, yet the necessary measurements are lacking. Hence, there is a demand for a second Indian Ocean Expedition.

GENERAL BACKGROUND

The Indian Ocean is a remarkable place (Figure 3). Unlike the Pacific and Atlantic oceans, it has a low-latitude land boundary to the north and the Indian subcontinent partitions the northern basin. The Eurasian landmass to the north is distinguished by the fact that much of it is extremely arid (i.e., the Thar Desert of NW India 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 Indian Ocean has no subtropical or temperate zones. As a result, high-latitude cooling of surface waters and subsequent ventilation of intermediate and deep water masses does not occur. A second unusual feature of the Indian Ocean is the low-latitude exchange between the Indian and the Pacific oceans known as the Indonesian Throughflow (ITF). The third striking feature of the Indian Ocean is the submarine topography, which is dominated by three meridional ridges (the Macarene Plateau, the Chagos-Laccadive Plateau and the Ninety East Ridge), and a triple junction where three spreading centers (the Southwest Indian Ridge, the Mid-Indian Ridge and the Southeast Indian Ridge) meet. Thus, by comparison with the Atlantic and Pacific, the Indian Ocean is highly asymmetrical, both zonally (with deep water, high-latitude exchange happening only to the south) and meridionally (with shallow water exchange along the eastern rim), and it has unusually complex submarine topography (with several major ridges influencing circulation, chemistry and biology).

As a result of the proximity of the Eurasian land mass and the heating and cooling of air masses over it, the northern Indian Ocean is subject to strong monsoonal wind forcing that reverses seasonally. That is, the SW Monsoon (SWM) blows from the SW towards the NE in the boreal summer (June-August) and the NE 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 and the Bay of Bengal, and their effects are clearly apparent down to ~ 10ºS. As a result of the monsoonal wind forcing, all of the boundary currents in the northern Indian Ocean reverse seasonally, driving upwelling circulations during the SWM and downwelling circulations during the NEM. These changes have profound impacts on biogeochemical cycles and ecosystem response. The northern Indian Ocean is also biogeochemically unique, in having one of three major open-ocean oxygen minimum zones (OMZs) in the north (the others are located in the eastern tropical Pacific, one on each side of the equator). Intermediate water (~100-800 m) oxygen concentrations decline to nearly zero (e.g., Morrison et al., 1999), with profound biogeochemical impacts.

Another important aspect of the northern Indian Ocean is the large dust and aerosol inputs that occur year round. The various dust source regions around northern Indian Ocean include the Arabian Peninsula, the African continent (Somalia) and Asia

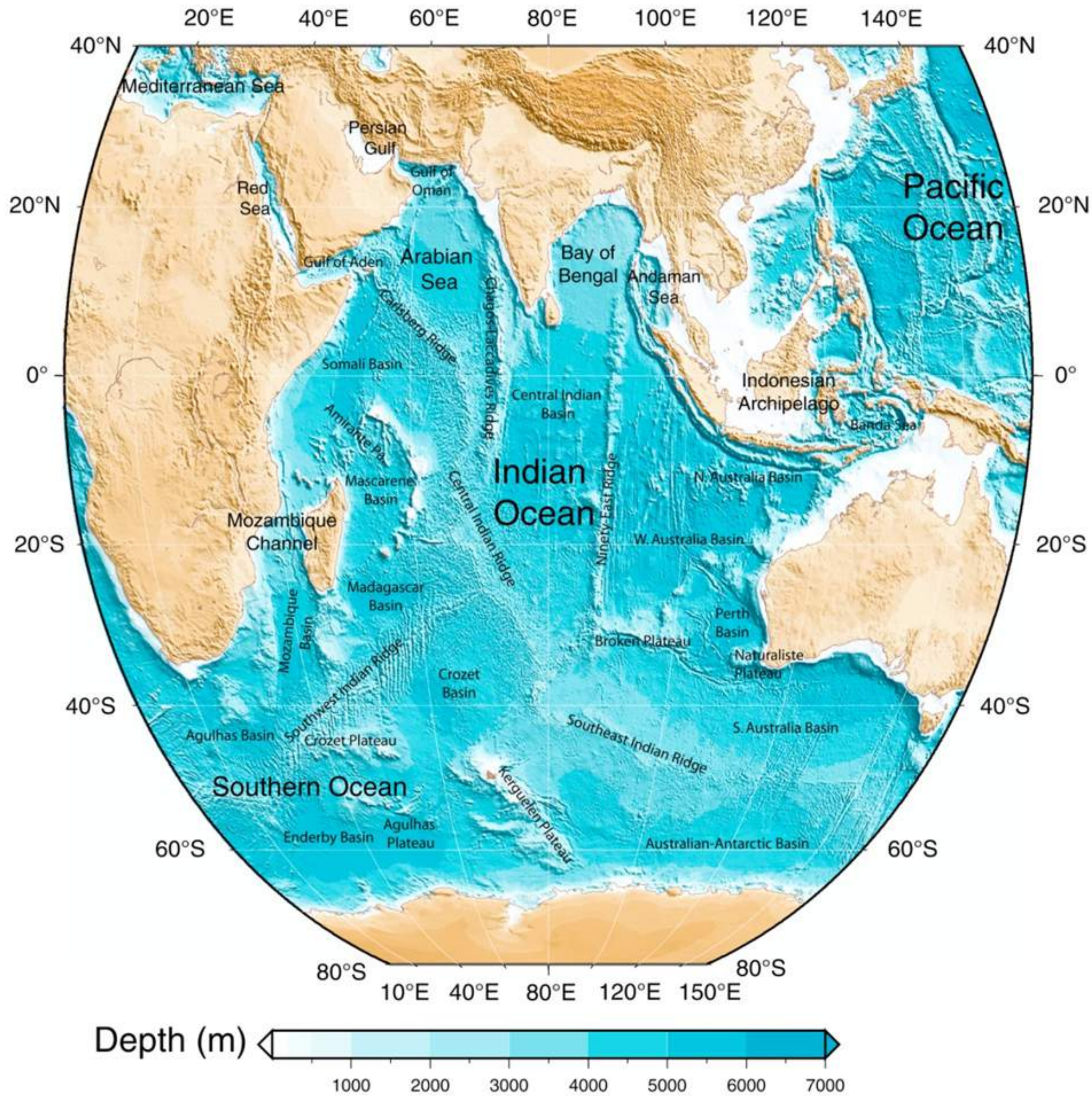


Figure 3: Indian Ocean topography (From Talley et al., 2011)

(Pakistan/India) (Pease et al., 1998; Leon and Legrand, 2003). Human-derived inputs are also prevalent, particularly the brown haze that lingers over the Arabian Sea, the Bay of Bengal and the southern tropical Indian Ocean from industrial pollution and biomass burning on surrounding continents (Lelieveld, 2001; Ramanathan et al., 2007). Finally, the northern Indian Ocean is ecologically unique in a variety of ways. One striking ecological feature is the presence of the largest mesopelagic fish stocks in the world (myctophids) in the Arabian Sea (Gjosaeter, 1984). These fish are specially adapted to the intense OMZ, where they reside during the day to escape predation.

In the Southern Hemisphere of the Indian Ocean the downwelling-favorable Leeuwin Current flows poleward along the west coast of Australia. The poleward direction of the

Leeuwin Current is unique among eastern boundary currents and it has the largest eddy kinetic energy among all mid-latitude eastern boundary current systems. As a result, it sheds anomalous high chlorophyll, warm-core, downwelling eddies that transport productive diatom communities and coastal fish and invertebrate larvae westward into open ocean waters. On the other side of the basin the Agulhas Current flows southwestward along the southeast coast of Africa. It is very large, with sources derived from the Mozambique Channel, the East Madagascar Current and the southwest Indian Ocean sub-gyre. Mesoscale eddies have a profound and complex impact on upwelling and downwelling circulations in the Mozambique Channel and therefore also on productivity and higher trophic levels. The Agulhas Current is upwelling favorable. However, significant surface expressions of upwelling are largely controlled by local wind and topographic forcing, that is, meanders and eddies in the current propagate alongshore and interact with seasonal changes in the winds and topographic features. This gives rise to seasonally variable localized upwelling and downwelling circulations with commensurate changes in primary production and higher trophic level responses.

Perhaps the most important consideration is that a significant fraction of the world’s population lives in the coastal and interior regions of Indian Ocean rim countries and they are directly impacted by the variability of the monsoons and associated rains. Moreover, many of these populations reside in low-lying coastal zones and island nations and are therefore threatened by tropical cyclones and sea level rise, both of which accelerate coastal erosion and the degradation of coastal ecosystems. Many other Indian Ocean 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 interactions between geological, ocean and atmospheric processes that give rise to the complex physical dynamics of the Indian Ocean region, and to determine how those dynamics affect climate, extreme events, marine biogeochemical cycles, ecosystems and human populations.

HISTORICAL BACKGROUND

In comparison to the Atlantic and the North Pacific oceans the Indian Ocean 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 Indian Ocean – the John Murray Expedition - was focused on the Arabian Sea in 1933-34 (Sewell, 1934), during which the intense mesopelagic oxygen deficiency was first recorded. During preparation and execution of the International Geophysical Year (1957-58), oceanographic exploration of the southern Indian Ocean was carried out by Australian, French, Japanese, New Zealand and Soviet researchers. Nevertheless, the Indian Ocean was one of the least known seas when the Scientific Committee on Oceanic Research started planning the International Indian Ocean Expedition (IIOE).

THE INTERNATIONAL INDIAN OCEAN EXPEDITION

The IIOE emerged from a remarkable cascade of events. The International Geophysical Year of 1957-1958 proved the value of coordinated multinational efforts and the formation of SCOR was dedicated to stimulating international cooperation in ocean sciences. At its first meeting in 1957, SCOR members identified the Indian Ocean as the least known region of the global ocean and envisioned exploration of the Indian Ocean as one of its first tasks (Deacon, 1957). After two years of dedicated planning, SCOR hired its first project coordinator, Robert G. Snider to lead the effort. The IIOE project office, located in New York City, was funded by the U.S. National Science Foundation (NSF) through the U.S. National Academy of Sciences and was overseen by the NAS Committee on Oceanography (one of the predecessors of the current Ocean Studies Board of the National Research Council). IIOE became the first project of the IOC, which assumed management responsibilities for the project in mid-1962. Berhman (1981) provides a popular account of the expedition, including personal reflections of many participants. Much historical information about the IIOE can be found on the SCOR Web site at: http://scor-int.org/IIOE-1/History.htm.

Figure 4: Indian Ocean Standard developed for the International Indian Ocean Expedition.

The IIOE was a monumental mid-20th century oceanographic research program that motivated an unprecedented number of hydrographic surveys covering the entire Indian Ocean basin (Figure 1). It was an interdisciplinary endeavor embracing physical oceanography, chemical oceanography, marine biology, meteorology and marine geology and geophysics. Planning for the IIOE began in 1957 and the project officially continued through 1965, with forty-six research vessels participating under fourteen different national flags. IIOE proved to be a remarkable success, providing much of the scientific foundation for our modern understanding of the Indian Ocean. Among its many legacies, the IIOE led to the publication of the first oceanographic atlas of the basin (Wyrtki et al., 1971) and a detailed map of the Indian Ocean bathymetry (Heezen and Tharp, 1966). It also revealed the existence of an equatorial undercurrent in the Indian Ocean (Knauss and Taft, 1964) and it contributed to the realization that old, grid-like traverses of the ocean needed to be complemented with phenomena-based experiment design (Stommel, 1963).

The planners of the IIOE recognized the importance of standardization and intercalibration: an Indian Ocean Standard Net (IOSN) (Figure 4) was adopted for plankton hauls (Currie, 1963) and intercalibration exercises were carried out for biological and chemical parameters. The

Indian Ocean Biological Centre was established at Cochin, India to process the biological samples collected with the IOSN, leading to the establishment of India's National Institute of Oceanography (NIO) in Goa (Figure 5), which marked the beginning of the development of India's considerable modern-day oceanographic research capacity.

Figure 5: India's National Institute of Oceanography in Goa.

Remarkably, most of the IIOE stations were positioned based on sun and star sighting and dead reckoning. During the IIOE, navigation was done much the way Captain Cook did two centuries earlier. The IIOE also led to capacity building in the region, particularly in India. Over subsequent years, research at NIO has led to marked improvement of our understanding of oceanographic processes in the Arabian Sea and the Bay of Bengal.

The end of 2015 will mark the 50th Anniversary of the completion of the IIOE. In the 50 years since the IIOE, three fundamental changes have taken place in ocean science. The first is the deployment of a broad suite of oceanographic and meteorological sensors on Earth-observing satellites that have dramatically improved the characterization of both physical and biological oceanographic variability and the atmospheric forcing of that variability. The second is the emergence of new components of the ocean observing system, most notably Argo floats and, in the Indian Ocean, the deployment of the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) and the tsunami detection network. The third fundamental change is the development of ocean modeling in all its facets from short-term forecasting to seasonal prediction to climate projections. In addition, improvements in our analytical techniques have made new and better measurements possible in all oceanographic disciplines. Other fundamental changes, not specific to oceanography but nonetheless highly consequential, are the advances in global positioning for precision navigation, advances in real-time data collection and transmission, and advances in communications (e.g., the World Wide Web) that have enormously facilitated data sharing and scientific collaboration. These advances have revolutionized our ability to measure, model, and understand the ocean. Moreover, compared to the IIOE era, which relied almost exclusively on ship- and aircraft-based observations (Figure 1), new measurement technologies in combination with targeted and well-coordinated field programs provide the capacity for a much more integrated picture of the Indian Ocean variability. Indeed, it is remarkable how much oceanography has advanced in the last 50 years. Thanks to these technological developments we can now study how the ocean changes across a wide range of spatial and temporal scales, and how these fluctuations are coupled to the atmosphere.

SUBSEQUENT RESEARCH

Subsequent research has built on work of that expedition (for further summary of early Arabian Sea efforts, see Wiggert et al., 2005). The next coordinated international study was the Indian Ocean Experiment (INDEX, 1979), which investigated the physical response of the Somali Current in the Arabian Sea to the summer monsoon (Swallow et al., 1983) and provided a first look at the associated biological and chemical distributions (Smith and Codispoti, 1980). Ships also crossed the Indian Ocean to collect information on mineral resources of the continental shelves and the deep ocean floor as part of the Deep Sea Drilling Project (1968 – 83). Two institutes in Ukraine (Marine Hydrophysical Institute and Institute of Biology of Southern Seas) undertook ten expeditions mostly in the 1980s (Goldman and Livingston, 1994).

The next cycle of coordinated investigations began with the Netherlands Indian Ocean Program (NIOP, 1992-1993; see review by Smith, 2005), which formed part of the international Joint Global Ocean Flux Study (JGOFS). Due to the uniqueness of the monsoon variability, the Arabian Sea was selected as one of four regions for detailed process studies. These investigations during the 1990s focused on the biogeochemical dynamics of the central and eastern Arabian Sea and were largely limited to the upper 500 to 1000 m of the water column. Paleoceanographic research focused on the Western Arabian Sea, with depth transects along the slopes of Somalia, Yemen, Oman and Pakistan. At the same time, the World Ocean Circulation Experiment (WOCE) had a much wider geographical coverage, with zonal and meridional sections criss-crossing the entire Indian Ocean basin. Since then, there have been several expeditions mounted by individual countries (India, France, Germany, Japan, UK, and the US), focused largely on physical processes, such as the Bay of Bengal Process Studies (Madhupratap et al., 2003). And the CLIVAR and GO-SHIP programs have continued the regular hydrographic surveys started by WOCE. However, the level of investigation in the Indian Ocean has fallen far behind studies in the Pacific, Atlantic, and even Southern oceans.

Almost two decades have passed since the last major international research program in the Indian Ocean. Efforts to mount a new program need to be initiated. This need is made even more pressing by the fact that important questions that emerged from the JGOFS, WOCE and IODP programs have not yet been addressed and some exciting new questions have arisen in recent years (see below). Moreover, many new pressing societally relevant questions have emerged since the JGOFS era related to anthropogenic impacts on the Indian Ocean and how these, in turn are influencing human populations.

SCIENTIFIC BACKGROUND AND MOTIVATION

GEOLOGICAL SCIENCE DRIVERS

The paleoceanography of the Indian Ocean is the most complicated of the three major ocean basins, yet it is among the least well-explored basins from a geological perspective. The Indian Ocean was formed as a result of the breakup of the southern supercontinent Gondwana about 150 million years ago (Norton and Sclater,1979). This breakup was due to the movement to the northeast of the Indian subcontinent about 125 million years ago. The Indian subcontinent collided with Eurasia about 50 million years ago. This coincided with the western movement of Africa and the separation of Australia from Antarctica about 53 million years ago. The Indian Ocean had taken on its approximate present configuration by approximately 36 million years ago. However, it first opened about 125 million years ago and most of the Indian Ocean basin is less than 80 million years old.

The oceanic ridges in the Indian Ocean are part of the worldwide oceanic ridge system where seafloor spreading occurs. The ridges form a remarkable triple junction in the shape of an inverted Y on the ocean floor of the Indian Ocean (Kennett, 1982; Figure 3). Starting in the upper northwest with the Carlsberg Ridge in the Arabian Sea, the ridge turns due south past the Chagos-Laccadive Plateau, and becomes the Mid-Indian (or Central Indian) Ridge. Southeast of Madagascar the ridge branches into the Southwest Indian Ridge, which continues to the southwest until it merges into the Atlantic-Indian Ridge south of Africa, and the Southeast Indian Ridge which extends to the east until it joins the Pacific-Antarctic Ridge south of Tasmania. The fracture zones associated with these ridges include the Owen, Prince Edward, Vema, and Amsterdam, with the Diamantina Fracture Zone located to the southwest of Australia (Figure 3). These tectonically complex and active spreading centers have significant impacts on deep ocean chemical distributions (Nishioka et al., 2013; Vu and Sohrin, 2013) and, they support diverse hydrothermal vent deep-sea communities (see http://www.interridge.org/WG/VentEcology), yet they are among the least well-explored in the world ocean.

In addition, there are several prominent aseismic ridges in the Indian Ocean (Figure 3). Perhaps the most striking is the Ninety East Ridge. It is the straightest and longest ridge in the world ocean. It runs northward along the 90° E meridian for 4,500 km from the zonal Broken Ridge at latitudes 31° S to 9° N. Other important aseismic ridges in the

Indian Ocean include the Madagascar, Chagos-Laccadive, and Mascarene plateaus. These ridges, which extend to the surface to form island chains in many places, have a profound impact on both surface and deep circulations in the Indian Ocean. They have been shown to dramatically enhance biological productivity in the surface waters of the Indian Ocean in regions where surface currents interact with topographic features and island chains, which can lead to nutrient and/or trace metal fertilization and pronounced island-wake effects (Strutton et al., 2015). For the most part, however, the topographic forcing of circulation and biological productivity has not been extensively studied, except using satellite-measured topography and ocean color (e.g., Gaube et al., 2013; Strutton et al., 2015).

The deep Indian Ocean basins are characterized by relatively flat plains of thick sediment that extend from the flanks of the oceanic ridges (Figure 6). The Indian Ocean's ridge topography defines several separate basins that range in width from 320 to 9,000 km across. They include the Arabian, Somali, Mascarene, Madagascar, Mozambique, Agulhas, and Crozet basins in the west and the Central Indian Ocean, and the Wharton and South Australia basins in the east (Figures 3 and 6).

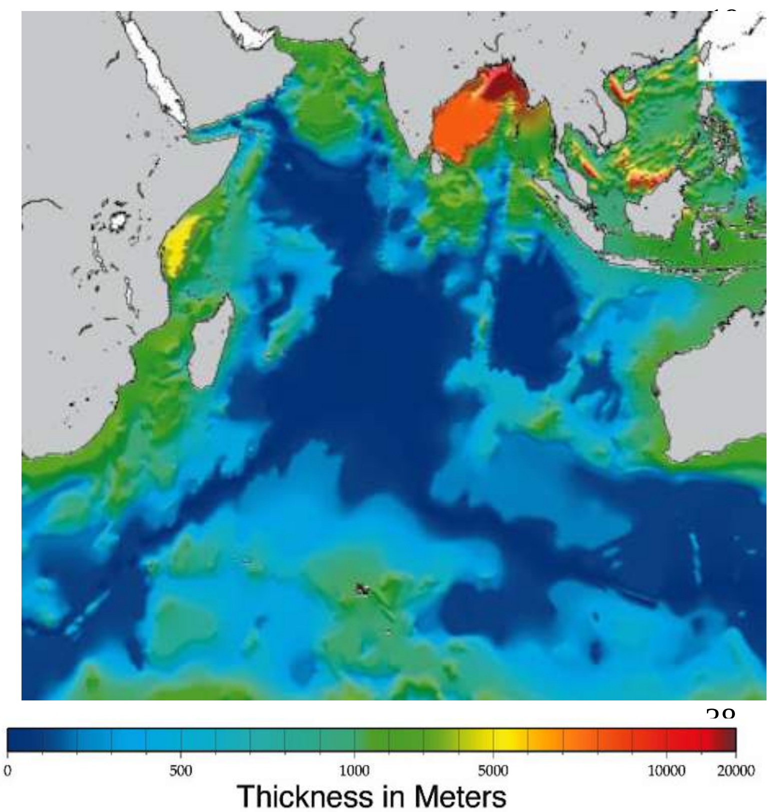


Figure 6: Total sediment thickness in the Indian Ocean (Divins 2003).

The continental shelves in the Indian Ocean are, for the most part, relatively narrow, extending to an average width of only 120 km (Talley et al., 2011; Figure 3). The widest shelves are found off India near Mumbai (Bombay) and northwestern Australia. The shelf break is typically found at a depth of about 150 meters. The Ganges, Indus, and Zambezi rivers have carved particularly large canyons into the shelf breaks and slopes in the Bay of Bengal, Arabian Sea and off off Mozambique, respectively.

The load of suspended sediments from the rivers emptying into the Indian Ocean is the highest of the three oceans and approximately half of this load derives from the Indian subcontinent (Schott, 1939; Ewing et al., 1969; Kidd and Davies, 1977; Kolla and Kidd, 1982). These sediments are deposited mostly on the continental shelves, slopes, and rises, and they extend far into the abyssal plains of the Indian Ocean in some places (Figure 6). Sediments more than one mile thick are found in the Bay of Bengal, the Arabian Sea, and the Somali and

Mozambique basins (Figure 6). The oldest sediments in the Indian Ocean are found off northwestern Australia in the Wharton Basin. In the Ganges-Brahmaputra sediment cone in the Bay of Bengal, the sediments are more than seven miles thick in some places and they extend to 10° S (Figure 6). Although the IODP has collected deep-sea cores through these sediments in many locations, the sampling in the Indian Ocean is relatively sparse. Several IODP expeditions to the Indian Ocean are planned, although sampling in national Exclusive Economic Zones may be problematic because of access restrictions.

In contrast, relatively little sediment has accumulated in the North Australian Basin off Java and Sumatra because the Java Trench traps sediment near the coast (Figure 6). Rather, silicic volcanic ash is found in this region due to the active volcanism associated with the subduction zone (see below). In deep sea regions far away from islands and continents between 10° N and 40° S the sediments in the Indian Ocean are dominated by brown and red clay. Calcareous and siliceous oozes are abundant in the productive equatorial zone. Beneath the Antarctic Convergence (roughly 50° S) diatomaceous oozes are found as in the South Pacific and South Atlantic. The principal mineral deposits in relatively shallow Indian Ocean waters (40 to 400 mters) are phosphorites. At greater depths (1000 to 2500 meters) ferromanganese crusts predominate. In the deep Indian Ocean (> 3000 meters) ferromanganese nodules are found in the abyssal plains whereas hydrothermal metalliferous sediments predominate at the crests of the Carlsberg and Central Indian ridges. These deposits have potential commercial value. Indeed, India's network of government-sponsored marine science programs has already undertaken studies of the seabed and carried out test mining in the northern Indian Ocean. It should be emphasized, however, that the distributions of these mineral deposits have not been well-characterized throughout the Indian Ocean.

Finally, it should be noted that the tectonic activity associated with subduction zones of the Java Trench and the Sunda Arc trench system has generated numerous tsunamis and volcanic eruptions over geologic time (Kennett, 1982), which have had widespread impacts in the Indian Ocean. Most recently, the Indian Ocean Tsunami of December 26, 2004 claimed more than 283,000 human lives in fourteen countries, inundating coastal communities with waves up to 30 meters high (Lay et al., 2005). This tsunami was one of the deadliest natural disasters in recorded history. Indonesia was the hardest-hit country, followed by Sri Lanka, India, and Thailand. Moreover, the geography of Indonesia is dominated by volcanoes that are generated by these subduction zones. As of 2012, Indonesia has 127 active volcanoes and about 5 million people have activities within the volcanic danger zones. The most active volcanoes are Kelut and Merapi on Java Island, which have been responsible for thousands of deaths in the region. Improved understanding of the geological processes that give rise to tsunamis and volcanic eruptions is needed to develop better warning systems and evacuation plans to reduce loss of life.

PHYSICAL OCEANOGRAPHY AND ATMOSPHERIC SCIENCE DRIVERS

GENERAL CIRCULATION AND ITS INFLUENCE ON BIOGEOCHEMISTRY AND ECOLOGY

The general circulation of the Indian Ocean is the least well understood of all of the open ocean basins. This is due to the fact that the Indian Ocean surface and deep currents are more complex and variable and they are less well-studied (both observationally and in terms of modeling) compared to the other ocean basins. As discussed above, the complexity is due to the influences of the monsoon winds (and associated planetary waves that are generated by these winds), the ITF (and the global thermohaline circulation surface return flow through the Indian Ocean), and topographic forcing.

As a result of the seasonal monsoon forcing, all of the northern Indian Ocean boundary currents reverse seasonally, which has profound biogeochemical and ecological consequences (see next section). Beyond the seasonal monsoon dynamics that can extend southward of 10°S, the equatorial and southern regions of the Indian Ocean are strongly 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 westerly winds (Han et al., 1999; Wyrtki, 1973). These jets depress the thermocline/nutracline in the eastern side of the basin upon their arrival in May and November and reduce primary production. However, they also interact with seamounts and islands along the Chagos-Lacadive Ridge in the central equatorial Indian Ocean, where they produce dramatic island wake effects that can be seen sweeping high chlorophyll concentrations eastward and also westward during the intervening NEM and SWM periods (Strutton et al., 2015). Although it has been suggested that the equatorial wind regime precludes development of tropical instability waves and associated biological responses that are common to the equatorial Atlantic and Pacific (Chelton et al., 2000; Strutton et al., 2001), recent work suggests that planetary wave phenomena may have significant biological impacts in the central equatorial Indian Ocean (Strutton et al., 2015).

In the southern tropical Indian Ocean (STIO), seasonally varying advection associated with the ITF and its connection to the western Pacific plays an important 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 30-60 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 Indian Ocean Dipole (IOD), is characterized by anomalous upwelling in the eastern Indian Ocean, 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 which contribute to prominent ecosystem anomalies that manifest throughout the basin (Resplandy et al., 2009; Wiggert et al., 2009).

A striking contrast exists between equatorial biological distributions in the Indian Ocean versus those in the Pacific and Atlantic oceans. The former typically exhibits elevated chlorophyll concentrations in the west and highly oligotrophic conditions in the east that results from the westward shoaling of the thermocline and nutracline. While equatorial band physical processes of the Indian Ocean have been relatively comprehensively investigated, the associated biogeochemical and ecological variability has not, and there are only a few examples of either observational or modeling efforts (Wiggert et al., 2006; Hanson et al., 2007; Waite et al., 2007; Resplandy et al., 2009). A region that is especially affected by MJO and IOD is the Seychelles-Chagos Thermocline Ridge (SCTR, Vialard et al., 2009), which is characterized by a shallow mixed layer (~30m) across the Indian Ocean within the 5-15^{o}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 wind curl distribution. 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 (Resplandy et al., 2009; Vialard et al., 2009).

The ITF connects the Pacific and Indian ocean basins, providing an estimated input to the Indian Ocean of up to ~20 Sv (Gordon and Fine, 1996; McCreary et al., 2007). This influences water mass properties of the Indian Ocean through exchanges of heat and freshwater. Indeed, it has been suggested that ITF waters propagate across the STIO and into the Arabian Sea via the Somali Current during the SWM (Song et al., 2004). Exchange and transport of nutrients, plankton and even larval fish via the ITF should influence biogeochemical and ecological variability, especially in the southeastern IO, but the extent of these impacts are largely unexplored. Although there have been numerous studies aimed at quantifying the transport through the ITF, only two studies have attempted to quantify the nutrient fluxes (Talley and Sprintall, 2005; Ayers et al., 2014). Talley et al. (2005) show that ITF nutrient inputs significantly impact biogeochemical properties (silicate) in the South Equatorial Current (SEC). Ayers et al. (2014) show that the total nutrient flux (nitrate, phosphate and silicate) contributed by the ITF can support a significant fraction of the new production in the tropical Indian Ocean. It remains to be seen whether or not these nutrient inputs have larger scale impacts. Do they influence, for example, the nutrient concentrations in the Leeuwin Current or the intensity of the northern Indian Ocean oxygen minimum zones?

Similar to the situation in the Atlantic and Pacific oceans, there is a broad westward zonal flow in the Indian Ocean within the latitude range of approximately 12–25°S (the South Equatorial Current or SEC), driven by the Southeast Trades, which supplies the western Indian Ocean boundary currents. Just east of Madagascar at about 17°S, the SEC splits into northward- and southward-flowing branches. The northern branch, known as the Northeast Madagascar Current, flows past the northern tip of Madagascar and feeds into the East African Coast Current (EACC). The southern branch, known as the Southeast Madagascar Current, flows past the southern tip of Madagascar and feeds the Agulhas Current (Schott and McCreary, 2001).

The southern central gyre of the Indian Ocean is one of the least well-studied regions of the global ocean. As in the Atlantic and Pacific, this gyre is characterized by a westward intensified anticyclonic circulation. But this gyre is unique due to the influence of the ITF (as discussed above) and submarine topography, that is, the Ninety East Ridge. The latter is a striking topographic feature that generates surface eddies that propagate hundreds of kilometers from east to west and it profoundly influence both surface and deep currents. The biogeochemical and ecological impacts of these topographically generated eddies and circulations are largely unknown.

Finally, it should be noted that the Indian Ocean overturning cells are important for redistribution of heat and other properties (Schott et al., 2002). The Indian Ocean has the world's largest meridional heat transport (Bryden and Beal, 2001; Lumpkin and Speer, 2007), with an estimated 1.5 PW exiting the basin across 32°S, associated with net heat gain from the atmosphere and vigorous diffusive heating and upwelling of deep and bottom waters. This transport balances heat loss in both the Atlantic and Southern oceans (Talley, 2013) and is likely linked to decadal variability of SST (Han et al., 2014) and CO_2 fluxes which influence climate around the Indian Ocean, yet it is poorly constrained and nothing is known about its variability.

BOUNDARY CURRENT DYNAMICS AND UPWELLING VARIABILITY

Boundary currents mediate the fluxes of biogeochemical properties and planktonic ecosystems between major oceanic biomes and these currents are dynamically coupled with upwelling and downwelling circulations in the coastal zone and thus impact higher trophic level productivity, behavior and recruitment. Due to the unique geomorphology of the Indian Ocean basin the boundary currents and the upwelling and downwelling circulations associated with them are complex and unique in many respects.

In the northern Indian Ocean, several boundary current systems are seasonally reversing (e.g., the Somali Current, West and East India Coastal Currents, and the Java Current) (Figure 7). These reversing surface currents are unique to monsoon-driven systems and they have profound biogeochemical and ecological impacts. The changes in upwelling and downwelling associated with the Northern Indian Ocean wind and boundary current reversals are dramatic. Upwelling is associated with the winds and the anticyclonic boundary current circulations that develop throughout the northern Indian Ocean during the SWM, though the intensity and surface manifestation varies from place to place. The strongest upwelling response is observed in the western Arabian Sea off Somalia and Oman, where near-surface nutrient concentrations increase to > 15 μmole/L (Morrison et al., 1998) and surface temperatures become as low as 16^{o}C (Swallow and Bruce, 1966). Although less pronounced, the southwest monsoon winds and the southward-flowing West Indian Coastal Current promote upwelling that outcrops at the surface along the west coast of India. In contrast, in the Bay of Bengal the effects of the winds and the currents tend to be more cryptic in part due to the influence of large freshwater inputs from rivers to the north, with upwelling sometimes occurring below but not outcropping at the surface (Gomes et al., 2000; Vinayachandran et al., 2005). Upwelling effects are strongly manifested as cold water at the surface along the south coast of Java in association with the northwestward-flowing upwelling-favorable Java Current and upwelling-favorable southeast monsoon (June through October) winds (Sprintall et al., 1999, Figure 7).

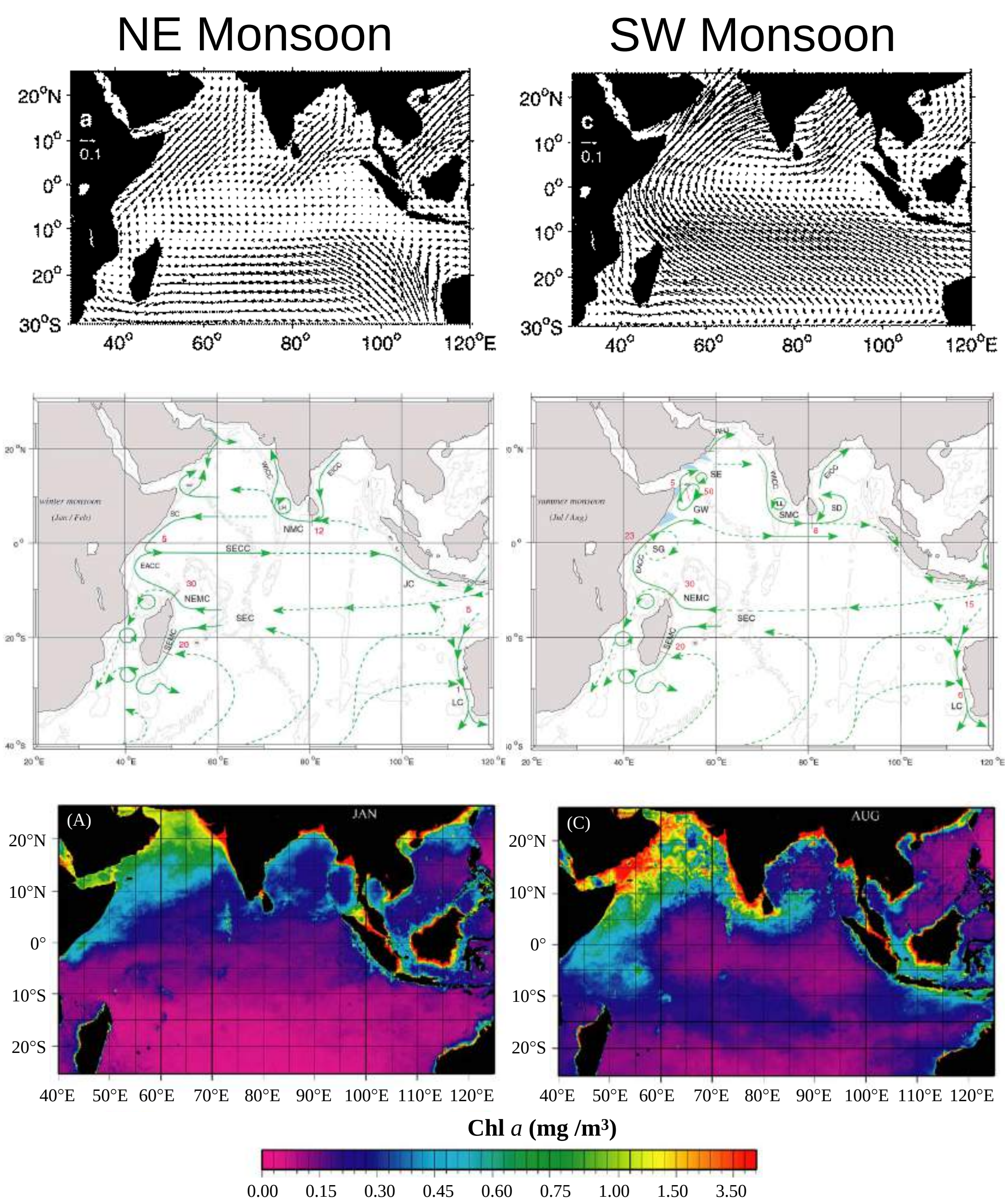


Figure 7: Comparison of (upper) winds, (middle) surface ocean circulation, and (bottom) satellite-derived chlorophyll concentration between the (left column) January-February and (right column) July-August periods in the Indian Ocean. The wind and circulation fields are from Schott and McCreary (2001), and the satellite chlorophyll concentrations are reproduced from Wiggert et al. (2006).

The Leeuwin Current (Figure 7) is downwelling-favorable because the Coriolis Effect on the southward flow in the southern hemisphere forces the current eastward toward the coast (Smith et al., 1991; Hanson et al., 2005ab). This tends to suppress upwelling. However, local wind forcing can override this general tendency and drive upwelling and current reversals near the coast (Hanson et al., 2005ab). The transport of the Leeuwin Current is relatively small, but the poleward direction is unique among eastern boundary currents and it has the largest eddy kinetic energy among all mid-latitude eastern boundary current systems. As a result, it sheds anomalous high chlorophyll, warm-core, downwelling eddies that transport productive diatom communities westward into open ocean waters (Waite et al., 2007). Variations in the Leeuwin transport, upwelling and eddy generation impact larval recruitment and the fate of many higher trophic level species.

Mesoscale eddies have a profound and complex impact on upwelling and downwelling circulations in the Mozambique Channel (Figure 7) and therefore also on nutrients and phytoplankton distributions (Jose et al., 2014; Lamont et al., 2014; Roberts et al., 2014). Counter to conventional wisdom, modeling studies in the Mozambique Channel indicate that cyclonic upwelling eddies sometimes have low concentrations of chlorophyll at their cores and vice versa (Jose et al., 2014). These eddies also mediate lateral transport of nutrients and chlorophyll from the coasts of Africa and Madagascar (Jose et al., 2014; Lamont et al., 2014; Roberts et al., 2014). These results suggest that phytoplankton growth within both cyclonic and anticyclonic eddies in the Mozambique Channel often occurs in response to lateral nutrient injection into the euphotic zone by advection from the coastal zones rather than upwelling and downwelling induced by the eddies themselves. In contrast, coastal upwelling in the East Madagascar Current is observed where the flow diverges from the shelf. This brings cold, nutrient-rich water to the surface, which stimulates primary production (Lutjeharms and Machu, 2000; Ho et al., 2004; Quartly and Srokosz, 2004). This upwelling and its impacts are enhanced in austral winter and in austral summer (Ho et al., 2004).

Like other western boundary currents, the Agulhas Current is “upwelling favorable” in that the Coriolis effect in the Southern Hemisphere is directed away from the coast. As a result, the dynamic balance associated with the flow causes the isopycnals and the nutricline to tilt up toward the surface along the inshore side of the flow. However, significant surface expressions of upwelling are largely controlled by local wind and topographic forcing (Lutjeharms, 2006a). Shelf-edge upwelling is observed primarily in association with specific headlands and topographic features along the coast (Pearce et al., 1978). Upwelling is enhanced southward (downstream; Figure 8) where increased meandering of the current and interactions with topography combine with wind forcing to lift deep water up toward the surface and onto the widening shelf (Lutjeharms, 2006a). Upwelling in this region is most intense in the austral summer in response to upwelling-favorable prevailing winds from the northeast and it is revealed by marked temperature variability at the coastline (Goschen et al., 2012) . Upwelling is also observed over the eastern Agulhas Bank (Figure 8) where it is confined almost exclusively to prominent capes and headlands (Schumann et al. 1982; Goschen and Schumann, 1995).

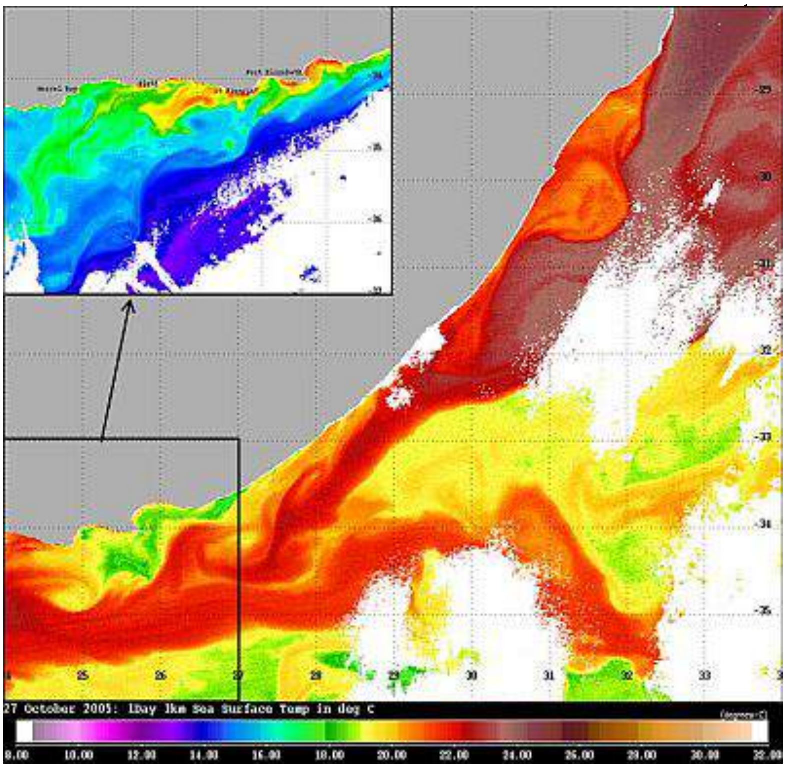


Figure 8: MODIS temperature and chlorophyll (inset) along the southeastern coast of Africa captured on October 27, 2005 (From http://www.csir.co.za).

In the equatorial zone, monsoonal rather than steady trade wind forcing at low latitudes of the Indian Ocean means that, unlike in the Pacific and Atlantic oceans, there is no permanent upwelling centered on the equator. Instead, water subducted at higher latitudes is upwelled in a variety of off-equator locations, including the Somali Coast, the Seychelles-Chagos Thermocline Ridge (SCTR), and the Sri Lankan Dome. Upwelling in these regions is strongly modulated seasonally by monsoon wind forcing. Interannually, large variations in upwelling also occur in the SCTR and off Java and Sumatra associated with the IOD and ENSO.

Many Indian Ocean fisheries are closely tied to boundary current dynamics and upwelling variability and so these features of physical oceanography have direct societal impacts. It is therefore important to understand these dynamics, their variability and their ecosystem impacts on time scales ranging from weeks to years. Longer time scale forecasts are also needed in order to predict how these boundary currents and the upwelling associated with them might change in the future and, in particular, how they will respond to climate change and global warming.

MONSOON VARIABILITY AND PREDICTABILITY

As a result of the proximity of the Eurasian land mass and the heating and cooling of air masses over it, the Indian Ocean is subject to strong monsoonal wind forcing that reverses seasonally (Figure 7). In the northern Indian Ocean the warm and moist Southwest Monsoon (SWM) blows from the SW towards the NE in the boreal summer (June-August) and the cool and dry NE Monsoon (NEM) blows in the opposite direction in the boreal winter (December-March). Along the eastern side of the basin these forces drive the SE monsoon winds that blow from the SE toward the NW in the boreal summer (June through October) (for a review see Schott and McCreary, 2001). These winds profoundly impact both the Arabian Sea and the Bay of Bengal, and also the entire eastern side of the Indian Ocean basin including Southeast Asia and Oceania, and their effects are clearly apparent down to ~ 10ºS.

Besides having the largest annual amplitude of any subtropical and tropical climate feature, the monsoons also exhibit considerable variability on a wide range of time scales. Within the annual cycle there are large-scale and high-amplitude variations of the monsoon. Perhaps the most important subseasonal phenomenon of the monsoon is the onset of the monsoon rains. The first rains of the monsoon occur over Burma and Thailand in middle May and then progress generally to the northwest, so that by mid-June, rains have advanced over all of India and Pakistan. However, during any given monsoon season the dates of the beginning of the monsoon in a particular location are quite variable (Webster et al., 2012). On time scales longer than the annual cycle the monsoon varies with biennial, interannual, and interdecadal rhythms. Biennial variability is manifested as a two- to three-year oscillation in rainfall of Indonesia and East Asia as well as Indian rainfall (Mooley and Parthasarathy, 1984; Yasunari and Suppiah, 1988; Tian and Yasunari, 1992; Shen and Lau, 1995). Interannual variability in the monsoon is observed on 3- to 7-year time scales and this variability can be related to other major features of the coupled ocean-atmosphere system. Specifically, there is a significant relationship between drought in India and ENSO; that is, when the Pacific Ocean SST is unusually warm, the Indian rainfall is often diminished in the next year (Shukla and Paolina, 1983). Interdecadal variability has been manifested as a change in this relationship between ENSO and the Indian monsoon in recent decades (e.g., Parthasarathy et al., 1988; 1992; 1994).

Agricultural practices around the northern Indian Ocean rim are closely tied to the annual monsoon cycle. The regularity of the warm and moist, and cool and dry, phases of the monsoon cycle is ideal for agricultural societies. This regularity, however, makes agriculture susceptible to small changes in the annual cycle. Fluctuations in the amount and timing of rainfall can have significant societal consequences. Weak monsoon years, with significantly less total rainfall than normal, generally result in low crop yields. In contrast, strong monsoon years usually result in abundant crops, although devasting floods can result from too much rainfall. The subseasonal variability (e.g., the timing of the onset or decline of the monsoons and the lulls or breaks in between) is also important. An early or late onset of the monsoon or an unexpected lull in the monsoon rains can have devastating effects on agriculture, even if the mean annual rainfall is normal (Webster et al., 2012).

As a result, forecasting monsoon variability on time scales ranging from weeks to years is an issue of considerable urgency. Longer time scale forecasts are also needed in order to predict how the monsoons will vary in the coming years and, in particular, how they will respond to climate change and global warming. Empirical seasonal forecasts of the monsoon have been made with moderate success. However, more recent mechanistic modeling efforts have not been successful. Even simulation of the mean structure of the Asian monsoon has proven elusive and the observed relationship between ENSO and monsoon variability has been difficult to replicate (Webster et al., 2012). As a result, there is currently low confidence in projections of both short-term (weeks to years) variability and long-term (biennial, interannual, and interdecadal) rhythms and changes in the monsoon rainfall and circulation (IPCC, 2014).

EXTREME EVENTS

The extreme events that are of particular concern in the Indian Ocean include tropical cyclones, flooding, drought, and tsunamis. What are the impacts of these events on coastal ecosystems and human populations and how will these impacts be affected by climate change and sea level rise?

Models project substantial increases in temperature extremes by the end of the 21st Century (IPCC, 2014). It is almost certain that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in and around the Indian Ocean. It is also likely that the length, frequency, and/or intensity of warm periods or heat waves will increase over most land areas surrounding the Indian Ocean rim.

The frequency of heavy precipitation will likely increase in the 21st Century over many land areas around the Indian Ocean (IPCC, 2014). This is particularly the case in tropical regions. Heavy rainfall associated with tropical cyclones and average tropical cyclone maximum wind speed is likely to increase in the Indian Ocean with continued warming. Droughts are projected to intensify in the 21st Century in some seasons and areas around the Indian Ocean rim, due to reduced precipitation and/or increased evapotranspiration.

Mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future (IPCC, 2014). Locations around the Indian Ocean rim that are currently experiencing adverse impacts—such as coastal erosion and inundation—will continue to do so in the future due to increasing sea levels. The contribution of mean sea level rise to increased extreme coastal high water levels, coupled with the projected increases in tropical cyclone maximum wind speed, is a major concern for tropical small island nations in the Indian Ocean. The frequency of tsunamis in the Indian Ocean is not expected to increase in the 21st Century. However, their impacts (coastal erosion and inundation) will be exacerbated in the future due to sea level rise.

The character and severity of impacts from climate extremes depend not only on the extremes themselves but also on exposure and vulnerability. Adverse impacts are considered disasters when they produce widespread damage and cause severe alterations in the normal functioning of communities or societies. Climate extremes, exposure, and vulnerability are influenced by a wide range of factors, including anthropogenic climate change, natural climate variability, and socioeconomic development (Figure 9; IPCC, 2012). More than 95% of deaths from natural disasters have occurred in developing countries, many of which are located around the Indian Ocean rim. In small exposed countries in the Indian Ocean, particularly small island developing nations, losses have been particularly high, exceeding 1% of GDP in many cases and 8% in the most extreme cases (IPCC, 2012). The frequency and/or severity of these natural disasters are projected to increase. It is therefore imperative to develop a better understanding of the dynamics of extreme events and their impacts on ecosystems and human populations in the Indian Ocean, and determine how these are likely to change in the future due to climate change in order to improve predictive capabilities and provide guidance for adaptation and mitigation strategies.

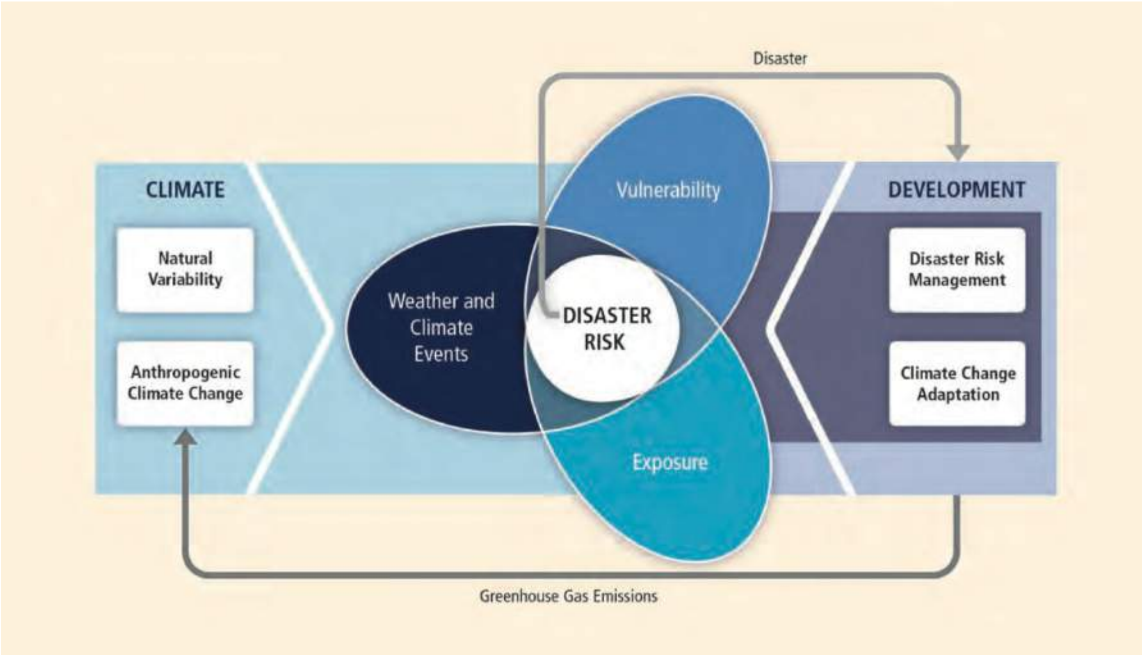


Figure 9: Assessment of how exposure and vulnerability to weather and climate events determine impacts and the likelihood of disasters (disaster risk). From IPCC (2012).

BIOGEOCHEMICAL AND ECOSYSTEM SCIENCE DRIVERS

OCEAN STRESSORS

Among the most important threats facing marine ecosystems today is the combined impact of multiple stressors (see Halpern et al., 2012 for maps of stressors). Stressors in marine and estuarine ecosystems have a large number of forms and sources. Most stressors represent the extremes of normal environmental variation that have increased in frequency or severity as a consequence of human activities (Breitburg and Riedel, 2005). Given their ubiquity, several stressors often simultaneously affect organisms, populations and communities. Marine ecosystem stressors that are of particular concern in the Indian Ocean include warming, sea-level rise, deoxygenation, acidification, eutrophication, atmospheric and plastic pollution, coastal erosion and overfishing. These stressors, combined with other physical consequences of human activities, are affecting marine biological processes from genes to ecosystems, over scales from rock pools to ocean basins, impacting ecosystem services and threatening human food security. The rates of physical change in the Indian Ocean are unprecedented in some cases (Brierley et al., 2009).

Warming

Recent research has documented a number of climate warming impacts on Indian

Ocean ecosystems. 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 Arabian Sea (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 Arabian Sea and the Bay of Bengal and these, in turn, will impact human populations, especially in coastal areas. Increasing temperatures will also have direct impacts on marine ecosystems in the Indian Ocean, likely altering food web dynamics, species distributions and the incidence of disease (Hoegh-Guldberg and Bruno, 2010). This warming trend will be amplified by the solar absorption caused by biomass burning and fossil fuel consumption (Ramanathan et al., 2007). Coastal and estuarine productivity in the Indian Ocean will change in response to alteration in the timing and amount of freshwater, nutrients, and sediment delivery. Higher water temperatures and changes in freshwater delivery will alter estuarine stratification, residence time, and eutrophication. Ocean warming is also expected to cause poleward shifts in the ranges of many marine organisms, including commercial species in the Indian Ocean, and these shifts may have secondary effects on their predators and prey (Scavia et al., 2002).

Acidification

The uptake of anthropogenic CO_2 by the global ocean induces fundamental changes in seawater chemistry that could have dramatic impacts on upper ocean ecosystems. Estimates based on the Intergovernmental Panel on Climate Change (IPCC) business-as-usual emission scenarios suggest that atmospheric CO_2 levels could approach 800 ppm near the end of this century (Feely et al., 2009). This global trend of increasing atmospheric and oceanic CO_2 concentrations will lead to lower pH and acidification of the Indian Ocean over the coming decades, with potential negative impacts on coral reefs and other calcifying organisms (Doney, 2010). The large-scale coral bleaching events of 1998 and 2005 caused by high sea-surface temperatures highlight the susceptibility of the Indian Ocean to warming and changes in ocean circulation (McClanahan et al., 2007), and ocean acidification has the potential to cause similar negative impacts on coral reef areas. For example, 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). A study on modern planktonic foraminifera of Somalia suggests that human-induced ocean acidification reduced the rate at which foraminifera calcify, resulting in lighter shells (de Moel et al., 2009). These studies have started to explore climate and human impacts on the IO, but much more research is needed to help mitigate the impacts and to assist adaptation to the changing environment.

Eutrophication

The population of most countries proximal to Indian Ocean river basins is increasing rapidly. Between 1970 and 2000 India's population increased by more than 75% (UN, 2004). The input of N and P fertilizers increased 7-8 fold between 1970 and 2000 (FAO, 2008) and has led to dramatic increases in nutrient inputs to surface waters. In addition, 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. Taken together, these river-borne nutrient loadings have often altered the stochiometric 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, with dominance of flagellated algae including noxious bloom-forming communities (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 fish harvests and human health.

Deoxygenation

Dead zones in coastal ocean areas have spread exponentially since the 1960s and have serious consequences for ecosystem functioning (Diaz and Rosenberg, 2008). The formation of dead zones has been exacerbated by the increase in primary production and consequent worldwide coastal eutrophication fueled by riverine runoff of fertilizers and the burning of fossil fuels. Enhanced primary production results in an accumulation of particulate organic matter, which encourages microbial activity and the consumption of dissolved oxygen in bottom waters. Dead zones have now been reported from many Indian Ocean coastal zones, and are probably a key stressor on marine ecosystems. Indeed, 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 (Helly and Levin, 2004), which is expected to expand and significantly impact benthic biogeochemical and ecological processes (Naqvi et al., 2006). Yet we know comparatively little about these low oxygen impacts at this time (Cowie, 2005). Similar impacts and concerns exist for the relatively pristine western coastal environments of Australia and also in African coastal waters. There is also evidence suggesting that the open ocean oxygen minimum zones in the northern Indian Ocean are expanding in response to increased stratification associated with global warming (Stramma et al., 2008; Doney, 2010; see next section).

Atmospheric and plastic pollution

Another important aspect of the Indian Ocean is the large dust and aerosol inputs that occur year-round. The various dust source regions proximal to the northern Indian Ocean include the Arabian Peninsula, the African continent (Somalia) and Asia (Pakistan/India) (Pease et al., 1998; Léon and Legrand, 2003). Inputs from human activities are also prevalent, particularly the brown haze that lingers over the Arabian Sea, the Bay of Bengal, and the southern tropical Indian Ocean from industrial pollution and biomass burning on the surrounding continents (Lelieveld et al., 2001; Ramanathan et al., 2007). Viewed from satellite photos, a giant brown cloud hangs in the air over much of South Asia and the Indian Ocean every year between January and March. The cloud is associated with the Northeast Monsoon, during which there is no rain to wash pollutants from the air.

Over the past five to six decades, contamination and pollution of the world's enclosed seas, coastal waters and the wider open oceans by plastics and other synthetic, non-biodegradable materials has been an ever-increasing phenomenon. The sources of these polluting materials are both land- and marine-based, their origins may be local or distant, and the environmental consequences are many and varied. The more widely recognized problems are typically associated with entanglement, ingestion, suffocation and general debilitation of marine organisms and seabirds (Gregory, 2009). The Indian Ocean garbage patch (Figure 10), discovered in 2010, is a gyre of marine litter suspended in the upper water column of the Indian Ocean Southern Gyre (Lebreton et al., 2012; van Sebille et al., 2012). As with other patches in each of the five oceanic gyres, the field constitutes an elevated level of pelagic plastics, chemical sludge, and other debris.

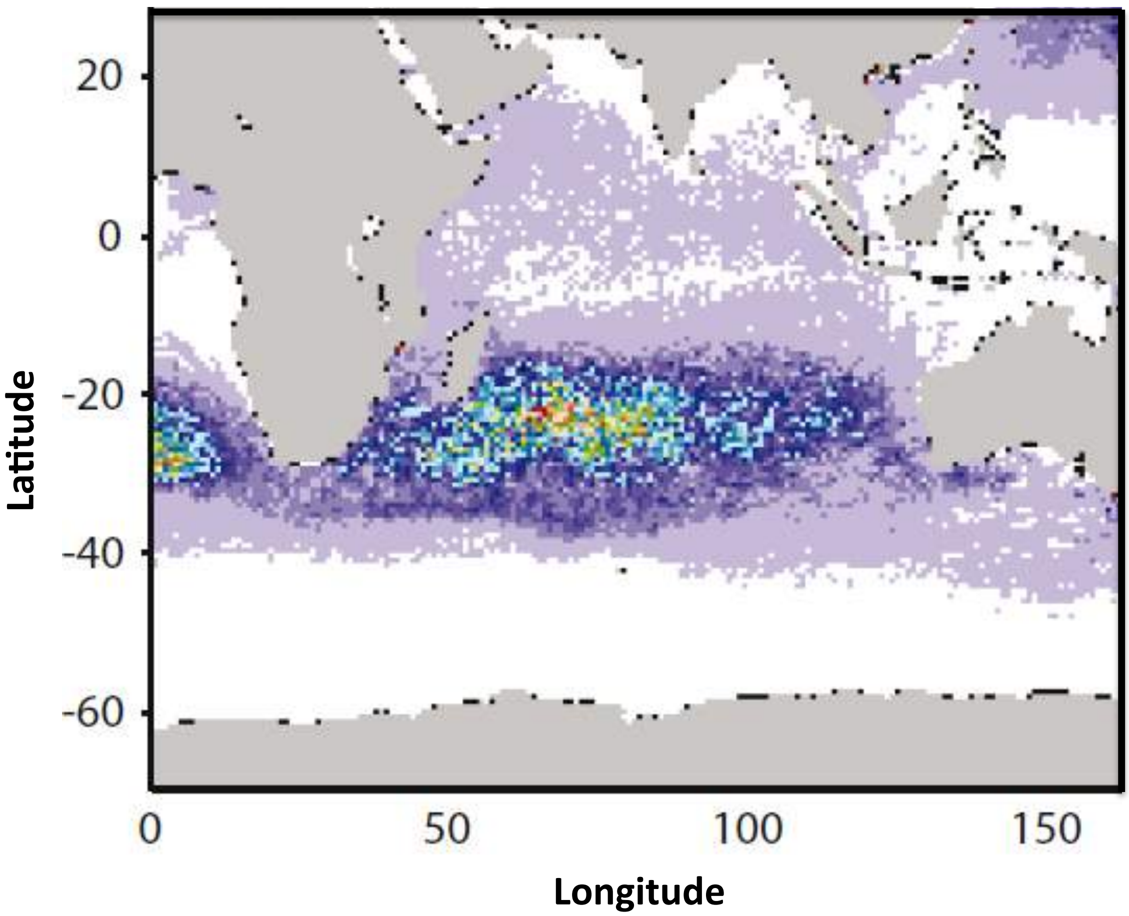


Figure 10: Model-predicted location of the Indian Ocean garbage patch. Modified from http://sciengsustainability.blogspot.com/2013/03/garbage-patch-in-oceans.html

Overfishing

Profound indirect ecosystem effects of overfishing have been shown for coastal systems such as coral reefs and kelp forests (Scheffer et al., 2005). Elimination of large predatory fish can cause marked cascading effects on the pelagic food web. Overall, the view has emerged that, in a range of marine ecosystems, the effects of fisheries extend well beyond the collapse of the exploited stocks. This is of particular concern in the Indian Ocean where overfishing in both coastal and open ocean environments has emerged as a pressing issue. For example, industrial long-line fishing for tuna and billfishes has contributed to the depletion of the abundance of these large oceanic predators by 90% (Myers and Worm, 2003; Polacheck, 2006).

BIODIVERSITY LOSS, CHANGES IN PHENOLOGY AND BIOGEOGRAPHY

Biodiversity is being threatened at an unprecedented scale by global environmental change brought about by human activities. Population-level shifts are occurring because of physiological intolerance to new environments, altered dispersal patterns, and changes in species interactions. Together with local climate-driven invasion and extinction, these processes result in altered community structure and diversity, including possible emergence of novel ecosystems (Doney et al., 2012). Ecological theory and a growing body of data suggest that certain general trends are emerging at local scales: positive interactions tend to become more prevalent with warming, and top trophic levels are disproportionately vulnerable. In addition, important ecological changes result when the geographic overlap among species changes, and when the seasonal timing of life history events of interacting species falls into or out of synchrony (Kordas et al., 2011).

The potential impacts of climate change and variability will vary from one region to another in the Indian Ocean and they will be superimposed upon, and in many cases intensify, other ecosystem stresses (pollution, harvesting, habitat destruction, invasive species, land and resource use, extreme natural events), which may lead to more significant consequences. Addressing this important issue will require improved understanding of marine ecosystems, targeted observations to monitor and detect change, and mechanistic model simulations to investigate different impact scenarios. Key directions for future Indian Ocean research include identifying demographic transitions that influence population dynamics, predicting changes in the community-level impacts of ecologically dominant species, incorporating populations' ability to evolve (adapt), and understanding the scales over which climate will change and living systems will respond.

THE INDIAN OCEAN'S ROLE IN THE GLOBAL NITROGEN AND CARBON CYCLES AND THE INFLUENCE OF IRON LIMITATION

The Indian Ocean is also biogeochemically unique, in having one of three major open-ocean oxygen minimum zones (OMZs) in the north (the others are located in the eastern tropical Pacific, one on each side of the equator). Intermediate water (~200-800 m) oxygen concentrations decline to nearly zero in the Arabian Sea (e.g., Morrison et al., 1999), with profound biogeochemical impacts. Low oxygen concentrations are also found in intermediate water in the Bay of Bengal. However, there are important physical and biogeochemical differences between the Arabian Sea and the Bay of Bengal (Figure 11). The Arabian Sea 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 (Figure 11). 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 – 800 meters) in the eastern-central Arabian Sea (Figure 11) and contributes ~ 20% to global open-ocean denitrification (Codispoti et al., 2001).

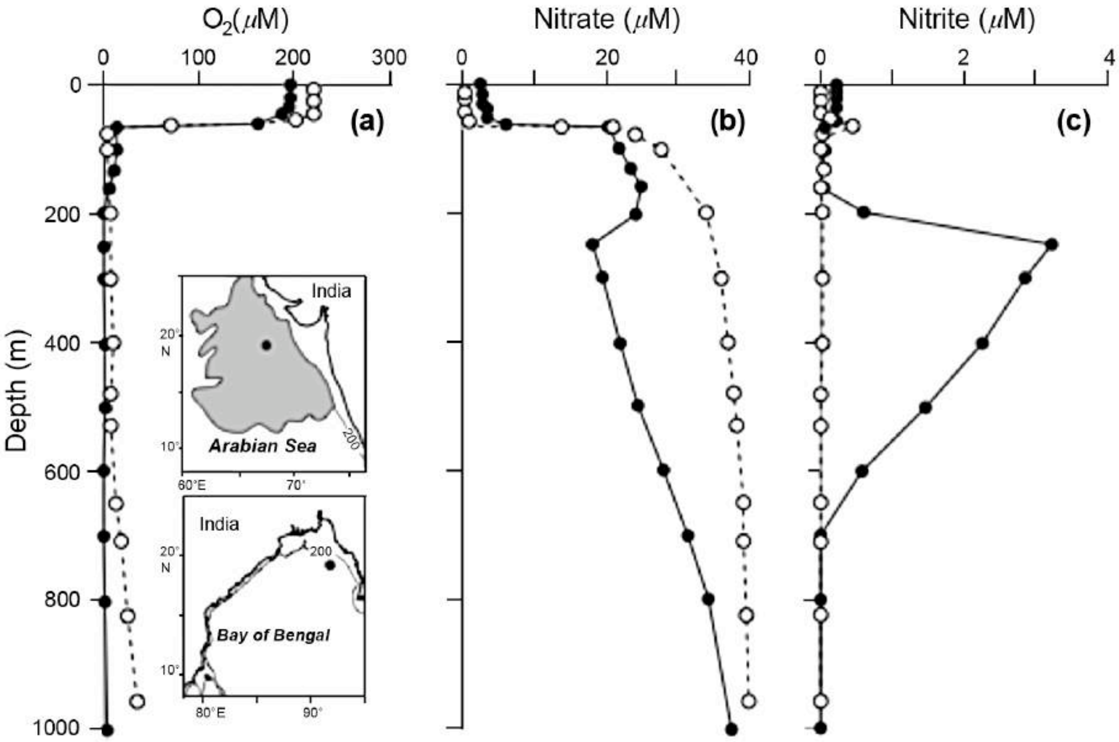


Figure 11: Comparison of vertical profiles of (a) oxygen, (b) nitrate and (c) nitrite in the AS (filled circles) and BoB (open circles). Station locations are shown in insets. The AS inset also shows limit of the denitrification zone to the eastern-central basin. Reproduced from Naqvi et al. (2006).

In contrast, mesopelagic dissolved oxygen concentrations in the Bay of Bengal are slightly higher so it remains poised just above the denitrification threshold (Figure 11). Questions still remain regarding 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. Modeling studies suggest that OMZs will expand in response to global warming (Stramma et al., 2008; Doney, 2010) but uncertainties in model predictions are large, especially in the Indian Ocean where global simulation models fail to reproduce the observed oxygen distributions (McCreary et al., 2013).

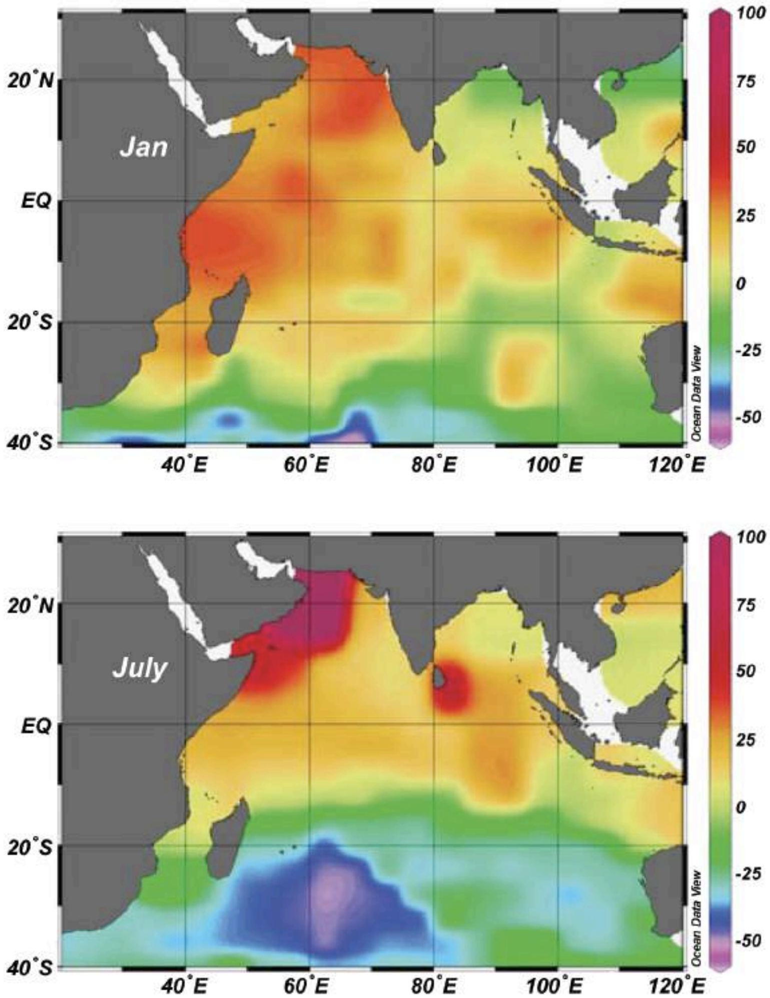


Figure 12: Air-sea pCO_2 difference (matm) between atmosphere and ocean for January and July from the climatology of Takahashi et al. (2002). Data are averaged over 4º x 5º areas and corrected to 1995. Regions with negative and positive values are, respectively, ocean sinks or sources for atmospheric CO_2. Figure reproduced from International CLIVAR Project Office (2006).

The Indian Ocean 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 Arabian Sea 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). But we have very few direct N_2 fixation rate measurements in the Indian Ocean. Thus, while it is agreed that the Indian Ocean plays important roles in the global N cycle and budget, we still do not have enough information to quantify the net atmosphere-ocean N flux in this basin.

Overall, the Arabian Sea is a source of CO_2 to the atmosphere because of elevated pCO_2 within the SWM-driven upwelling (Figure 12). Whether the Bay of Bengal 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 Indian Ocean 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 that chemical and biological factors are important (Piketh et al., 2000; Wiggert et al., 2006). For example, there is mounting evidence which suggests that iron limitation plays an important role in controlling phytoplankton production, and also carbon export to depth, over large areas of the Indian Ocean basin (Piketh et al., 2000; Wiggert et al., 2006). Iron limitation is believed to occur throughout the Southern Ocean due to lack of input from continental sources (Boyd et al., 2007). Presumably, this Fe limitation extends into the Indian Ocean sector (30° – 120° E) of the Southern Ocean. 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). Nonetheless, the extent of Fe depletion and Fe limitation in the Indian Ocean sector of the Southern Ocean and its northward extension into the southern Indian Ocean basin remains an open issue.

FISHERIES: RECRUITMENT, PRODUCTIVITY AND LINKS TO BIOGEOCHEMISTRY AND PHYSICS

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. 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, mammals, and 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 Arabian Sea and the Bay of Bengal.

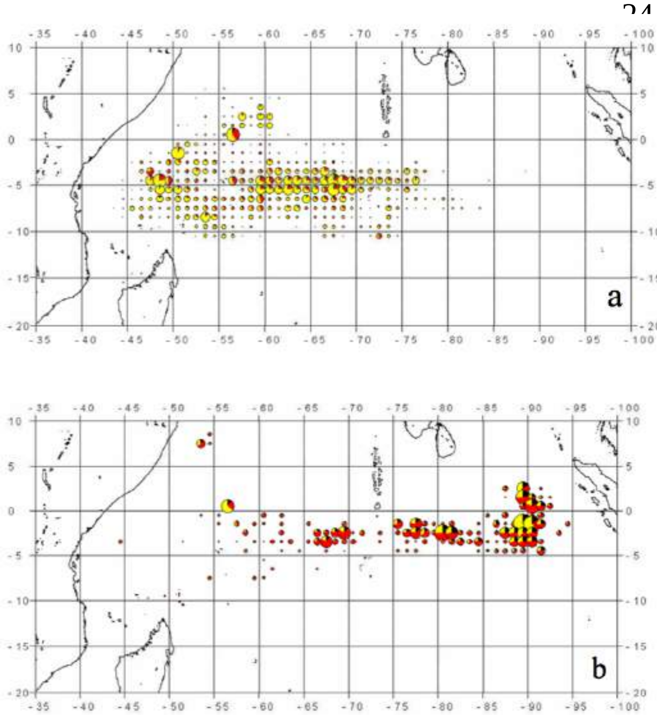


Figure 13: Tuna catch in the Indian Ocean during the 1997/1998 IOD event (bottom panel) compared to catch in normal years (top panel; From Marsac et al., 2006).

The Indian Ocean is ecologically unique in a variety of ways. One striking ecological feature is the presence of the largest mesopelagic fish stocks in the world (myctophids) in the Arabian Sea (Gjosaeter, 1984). These fish are specially adapted to the intense OMZ, where they reside during the day to escape predation. 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 needs to be quantified. Almost nothing is known about the role these fish play in the ecological and biogeochemical dynamics of the Arabian Sea. There are also many questions about how these myctophids interact with and tolerate the OMZ; about commercial harvest impacts; and how climate change, including ocean acidification, might affect the population.

Migrations of tuna in equatorial waters of the Indian Ocean are strongly influenced by the anomalous forage distributions that result in response to climate phenomena like the Indian Ocean Dipole (IOD) (Marsac et al., 2006). Indeed, natural climate variability associated with phenomena such as the IOD have influences that manifest strongly not only at the equator but also into the Arabian Sea and the Bay of Bengal, changing patterns of phytoplankton surface productivity (Wiggert et al., 2009) as well as distributions of commercially important top predators such as tuna (Figure 13; Marsac et al., 2006). These influences have also been linked to dramatic changes in sardine (*Sardinella leumuru*) catch and (presumably) production in Bali Strait (see Ghofar, 2005; Sartimbul et al. 2010 and references cited therein).

The influence of natural climate variations have been observed to impact fisheries recruitment and productivity in many other Indian Ocean coastal regions. For example, variations in the transport of the Leeuwin Current associated with ENSO have long been linked with the distribution and transport of biota along the west coast of Australia and this variation plays a crucial role in controlling recruitment of many coastal fish and invertebrate species (e.g., Hutchins and Pearce, 1994; Waite et al., 2007c; Caputi, 2008; Feng et al., 2010). It is well know that mesoscale eddies in the Mozambique Channel play a key role in marine ecosystem dynamics and higher trophic level behavior influencing, for example, the foraging patterns of Great Frigatebirds (*Fregata minor*). It has been suggested that interannual changes in large-scale remote forcing by the South Equatorial Current associated with the IOD and ENSO could potentially have profound effects on the number or intensity of eddies in the Mozambique Channel and the transport of the East Madagascar Current and therefore could potentially have profound effects on top predators like the Great Frigatebirds (Hood et al., 2015). It has been shown that, due to the strong influence of the Agulhas Current, most neritic fish species in southeast Africa coastal waters have evolved highly selective reproductive patterns for successful retention of planktonic eggs and larvae (Hutchings et al., 2002). Natural fluctuations in the transport of the Agulhas Current are therefore very important in controlling the productivity and recruitment variability in these species. 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?

SOCIETAL DRIVERS

FOOD SECURITY AND FISHERIES

Fisheries in developing countries in the Indian Ocean are a particularly important source of protein. Fisheries and fish products provide direct employment to millions of people in the Indian Ocean region (FAO, 2004). The state of both artisanal and industrial fisheries is of concern, as many people depend on their existence for food and employment, with many fisheries being overexploited. A substantil decline of catch per unit effort has been observed in the open Indian Ocean (Myers and Worm, 2003). Issues related to sustainability of these fisheries and food security need to be addressed. For example, is fishing on tuna stocks in equatorial waters in the Indian Ocean sustainable? Will commercial harvest of myctophids, as recently begun by Iran, be large enough to impact the stocks? There is also widespread concern about decreases in the mackerel population over the western continental shelf of India (Kochi, 2007). This could cause far-reaching socioeconomic problems in the coastal states.

Coral reefs in the Indian Ocean have been used by humans as a source of food and other products for thousands of years and more recently as places for recreation and tourism. Although the effects of humans on coral reefs are not well understood, it is clear that few reefs in the Indian Ocean remain unaffected by man, even at very remote sites. And the diversity, frequency, and scale of human impacts on coral reef ecosystems are increasing (Figure 14). Overfishing has reduced fish and invertebrates at most reefs, including those within marine protected areas (Hodgson, 1999). Moreover, projected increases in carbon dioxide and temperature over the next 50 years exceed the conditions under which coral reefs have flourished over the past half-million years. Although the impacts of these changes are still uncertain, it is very likely that they will lead to increased coral reef stress. Integration of management strategies that support reef resilience and the fisheries associated with them need to be vigorously implemented (Hughes et al., 2003), based on scientific knowledge.

Impacts of global climate change present significant challenges for societies and economies in Indian Ocean rim nations and island states that are reliant on fish for dietary protein (Allison et al., 2009). Tropical Asian countries (e.g., Bangladesh, Cambodia, Pakistan, and Yemen) are particularly vulnerable due to the combined effects of predicted warming, the relative importance of fisheries to national economies and diets, and limited societal capacity to adapt to potential impacts. Many of these vulnerable countries in the Indian Ocean are also among the world's least developed countries whose inhabitants are among the world's poorest and therefore more dependent on fishing. Although the precise impacts and direction of climate-driven change for particular fish stocks and fisheries are uncertain, research suggests that climate change impacts are likely to lead to either increased economic hardship or missed opportunities for development in countries that depend upon fisheries but lack the capacity to adapt (Allison et al., 2009).

Human impacts are expected to increase during the next decades due to increasing population density, especially around the Arabian Sea and the Bay of Bengal, and as a result of climate change. 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 human-induced fish kills, and the potential impacts of overfishing needs to be assessed. End-to-end models need to be developed that can predict the long-term consequences of climate change on marine ecosystems and fisheries. What are the human impacts of these losses and their potential feedbacks to pelagic and benthic food webs?

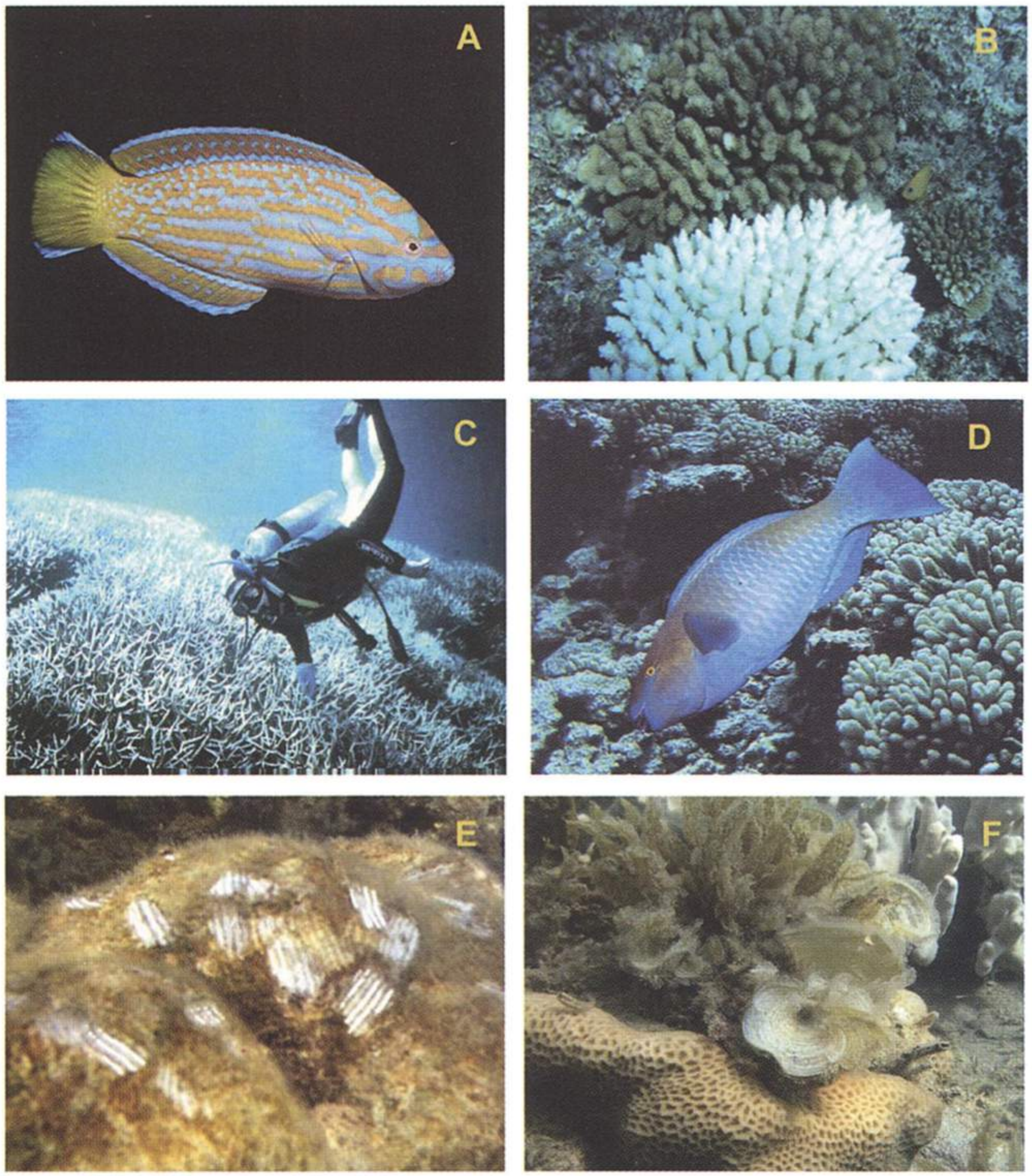


Figure 14: (A) Aquarium fish, such as *Anampses lennardi* from northwest Australia, are often endemic species and susceptible to overharvesting. (B) A bleached colony of *Acropora nasuta* (bottom), and unbleached *Pocillopora meandrina* (top), showing contrasting responses to thermal stress. (C) A bleached monospecific stand of the staghorn coral *Acropora formosa*. (D) Parrotfishes, such as *Scarus ferrugineus*, are important herbivores. (E) Parrotfish grazing-scars. (F) Macroalgae (top) and overgrowth of corals (bottom) are promoted by overfishing of herbivores and degraded water quality. Figure and caption from Hughes et al. (2003).

CHANGES IN COASTAL ENVIRONMENTS

Coastal ecosystems are among the most productive ecosystems in the world and provide many services to human society. In the Indian Ocean they provide supporting services in the form of a wide range of habitats. Estuaries, mangroves, lagoons, seagrasses, and kelp forests serve as nurseries for both inshore and offshore fish and other species, many of which are commercially significant (UNEP, 2006). Other habitats—such as beaches, dunes, saltmarshes, estuaries, and mudflats—play an important role in the life cycle of, for example, fish, shellfish, and migratory birds. By mixing nutrients from upstream and tidal sources, estuaries are one of the most fertile coastal environments. However, in the Indian Ocean many of these ecosystems have become degraded.

Coastal environments in the Bay of Bengal are particularly vulnerable due to high river nutrient loadings in surrounding countries that are also experiencing rapid increases in population density and economic growth (Millenium_Ecosystem_Assessment, 2005). Cholera in Bangladesh has already been linked to changes in sea surface temperature and height (Lobitz et al., 2000). Increases in nutrient loading will impact not only biogeochemical cycles, but also the coastal marine food web, which will, in turn, directly impact human activities including commercial and subsistence fishing. Large coastal infrastructure projects, increases in urban development, and the tremendous growth in human populations along the shores are posing a great danger to the marine environment in the countries of the Persian Gulf in particular.

Inundation from sea level rise will heavily impact low-lying areas around the Indian Ocean rim, where millions of people live within one meter of mean sea level and are at increased risk in the coming decades. The very existence of some Indian Ocean island states and deltaic coasts is threatened by sea level rise. An additional threat affecting some of the most heavily developed and economically valuable areas will come from an exacerbation of sandy beach erosion. The underlying rate of long-term sandy beach erosion is two orders of magnitude *greater* than the rate of rise of sea level, so that any significant increase of sea level has dire consequences for coastal inhabitants (Leatherman et al., 2000). Destruction of mangrove forests is also contributing to coastal erosion in the Indian Ocean. For example, 60% of the southern Thailand coast was formerly occupied by mangroves. During the past three decades, these mangrove areas have been reduced to about 50%, with less than 10% left on the east coast, which has led to an intensification of erosion during the past decade (Thampanya et al., 2006).

How, in general, are coastal erosion and coastal development affecting marine ecosystems around the Indian Ocean rim? How do these pressures and impacts differ in the coastal environments of different countries, for example in developing (e.g., Bangladesh and the northern Indian Ocean) versus developed countries (e.g., Western Australia in the southern Indian Ocean). 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. Coastal development also usually involves changes in land use. What will be the impacts of changes in land use (e.g., agriculture, deforestation, desertification) on coastal marine ecosystems in the Indian Ocean? What are the potential human consequences?

HUMAN IMPACTS OF CLIMATE CHANGE, EXTREME EVENTS AND MONSOON VARIABILITY

Human-induced global climate change has profound implications for marine ecosystems in the Indian Ocean and the economic and social systems that depend upon them. Recent work has revealed that both abiotic changes and biological responses in the ocean will be complex (Harley et al., 2006). For example, changes in ocean chemistry (e.g., acidification) may be more important than changes in temperature for the performance and survival of many organisms. Indian Ocean circulation, which drives larval transport, will also change, with important consequences for population dynamics. Furthermore, climatic impacts on one or a few key species may result in sweeping community-level changes. Finally, synergistic effects between climate and other human-induced, particularly fishing pressure, will likely exacerbate climate-induced changes.

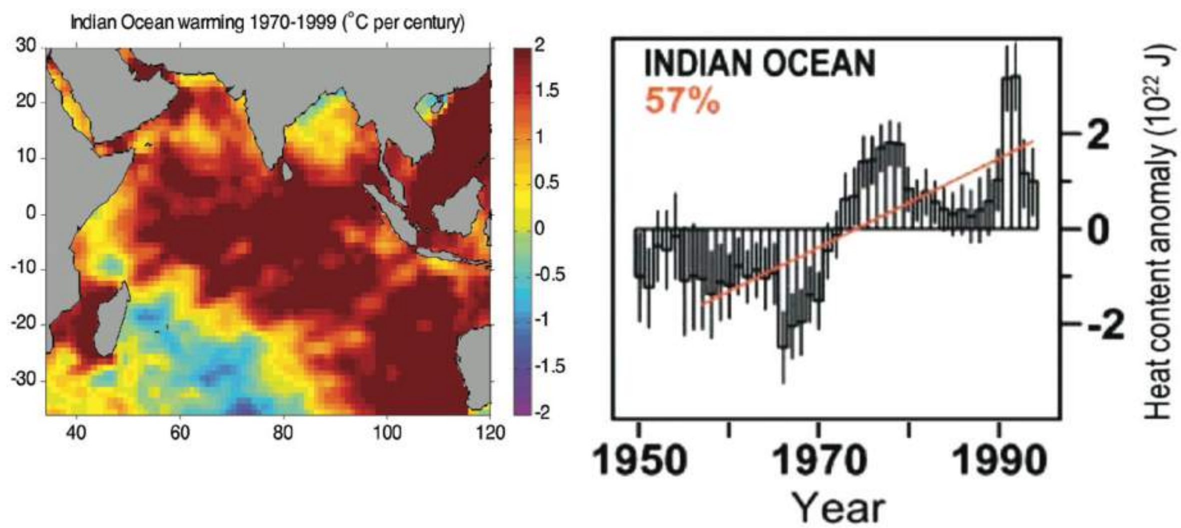


Figure 15: Indian Ocean warming (in °C) per century as assessed from satellite sea surface temperature data (left, from International Clivar Project Office, 2006). Indian Ocean total heat content anomaly trend from approximately 1950 through 1995 (right, from Levitus et al., 2000).

Because of its rapid warming (Alory and Meyers, 2009; Alory et al., 2007; International_CLIVAR_Project_Office, 2006) the Indian Ocean may provide a preview of how climate change will affect the biogeochemistry and ecology of other ocean basins and also human health (Figure 15). As discussed above, 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 Arabian Sea (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 Arabian Sea and the Bay of Bengal and these, in turn, will impact human populations, especially in coastal areas. Increasing temperatures will also have direct impacts on marine ecosystems in the Indian Ocean likely altering food web dynamics, species distributions and the incidence of disease (Hoegh-Guldberg and Bruno, 2010). Increased frequency of coral bleaching events in the Indian Ocean is also expected, which will lead to significant negative socioeconomic impacts (Wilkinson et al., 1999).

As discussed above, the frequency and/or severity of extreme events are also projected to increase in the Indian Ocean. High exposure and vulnerability to extreme events are generally the outcome of skewed development processes associated with environmental degradation, rapid and unplanned urbanization in hazardous areas, failures of governance, and the scarcity of livelihood options for the poor. These problems are particularly acute in many developing nations around the Indian Ocean rim and in small island nations. Countries can more effectively manage disaster risk if they include considerations of it in national development plans and if they adopt climate change adaptation strategies. Adaptation and mitigation can complement each other and together can significantly reduce the risks associated with extreme events.

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 Indian Ocean and they will be directly impacted by climate change, extreme events and monsoon variability. Many other Indian Ocean processes, such as seasonal variations in oceanic circulation and the biogeochemical and ecological responses associated with them, will also directly and indirectly impact these populations. Efforts to manage and conserve living marine systems in the face of climate change will require improvements to the existing predictive framework. Important directions for future research include identifying key demographic transitions that influence the population dynamics of marine species, predicting changes in the community-level impacts of ecologically dominant species, incorporating populations’ ability to evolve (adapt), and understanding the scales over which climate will change and living systems (including humans) will respond.

BIODIVERSITY LOSS AND ECOSYSTEM PRESERVATION FOR TOURISM AND FISHERIES

Biodiversity is being threatened in the Indian Ocean at an unprecedented scale by global environmental change brought about by increasing human population. In addition to the many moral reasons to preserve biodiversity for its own sake, it provides numerous ecosystem services that are crucial to human well-being (Millennium_ Ecosystem_Assessment, 2005). These services include both food supply and economics (e.g., fisheries, both subsistence and commercial, and tourism). Conserving habitats is essential for conservation of biodiversity. Habitat conservation is one of the most important issues facing Indian Ocean rim nations today — both in the ocean and on land. Habitat destruction is caused by: 1) Destructive fishing activity (e.g., bottom trawling and dynamiting coral reefs that destroy entire ecosystems); 2) Coastal development (e.g., marsh dredging for real estate development, increased soil runoff and erosion, nutrient pollution from fertilizers and domestic sewage and oxygen depletion); and 3) Industrial pollution (industrial development near coastal waters leading to release of toxic substances, such as industrial chemicals, pesticides, and oil, into coastal marine habitats). In addition, dredging ship channels resuspends and releases accumulated sediment and pollutants into the water. Dredging can also destroy seagrass beds and other habitats that provide food, shelter, and breeding grounds for marine species. (For an overview and additional readings see: http://www.seaweb.org/resources/briefings/marinebio.php).

Although habitat destruction in the Indian Ocean has been increasing for many years, the protection of marine habitats has only recently become an issue of critical importance to conservation efforts and local and national governments. Coastal regions around the Indian Ocean rim are experiencing intense pressure due to rapidly increasing coastal populations. Efforts need to be undertaken to raise awareness of the need for habitat conservation to prevent further damage from occurring.

IIOE-2 SCIENCE

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

INTRODUCTION TO IIOE-2

SCOR and the IOC are working to stimulate a new phase of coordinated international research focused on the Indian Ocean for a 5-year period beginning in late 2015 and continuing through 2020. The goal is to help to organize ongoing research and stimulate new initiatives in this time frame as part of a larger expedition. International programs that have research ongoing or planned in the Indian Ocean during this time include the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, the Climate Variability (CLIVAR) project, the Indian Ocean component of the Global Ocean Observing System (IOGOOS), GEOTRACES (a global survey of trace elements and isotopes in the ocean), the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), International Ocean Discovery Program (IODP), InterRidge (an international organization that promotes interdisciplinary, international studies of oceanic spreading centers) and others. Many countries, including Australia, China, Germany, India, Indonesia, Japan, the United Kingdom, and the United States, are planning cruises and other activities in this time frame, and new regional research programs in the Indian Ocean are under development. These programs and national cruises will serve as a core for the new Indian Ocean research focus, which has been dubbed “IIOE-2.”

The overarching goal of IIOE-2 is to advance our understanding of interactions between geologic, oceanic and atmospheric processes that give rise to the complex physical dynamics of the Indian Ocean region, and to determine how those dynamics affect climate, extreme events, marine biogeochemical cycles,

ecosystems and human populations. This understanding is required to predict the impacts of climate change, pollution, and increased fish harvesting on the Indian Ocean and its rim nations, as well as the influence of the Indian Ocean on other components of the Earth System. New understanding is also fundamental to policy makers for the development of sustainable coastal zone, ecosystem, and fisheries management strategies for the Indian Ocean. Other goals of IIOE-2 include helping to build research capacity and improving availability and accessibility of oceanographic data from the region.

SCIENTIFIC THEMES

To address this overarching goal the IIOE-2 will structure its research around six scientific themes. Each of these include a set questions that need to be addressed in order to improve our understanding of the physical forcing that drives variability in marine biogeochemical cycles, ecosystems and fisheries in the Indian Ocean and develop the capacity to predict how this variability will impact human populations in the future.

THEME 1: HUMAN IMPACTS

BACKGROUND

Human activities are changing the environment of the Earth with an unprecedented speed on both regional scales and on the global scale (see Halpern et al., 2012; IPCC, 2013; Rockström et al., 2009). Major human- induced global changes include: significant increase of greenhouse gases (such as carbon dioxide, CO_2, nitrous oxide, N_2O, and methane, CH_4) in the atmosphere; enhanced input of nutrients (namely nitrate, NO_3^-, phosphate, PO_4^{3-}, and silicate, SiO_2) to the coastal and open oceans (i.e., eutrophication); pollution of the ocean, land and atmosphere with chemical compounds; and the pollution of ocean and land with (micro)plastic debris.

These ongoing environmental changes are directly and indirectly affecting the global ocean ecosystems and biogeochemical cycles (Doney et al., 2012; Hoegh-Guldberg et al., 2014; Figure 16) with largely unknown consequences for the socio-economic development (Mora et al., 2013; Figure 17a) and human health (European Marine Board, 2013; Figure 17b).

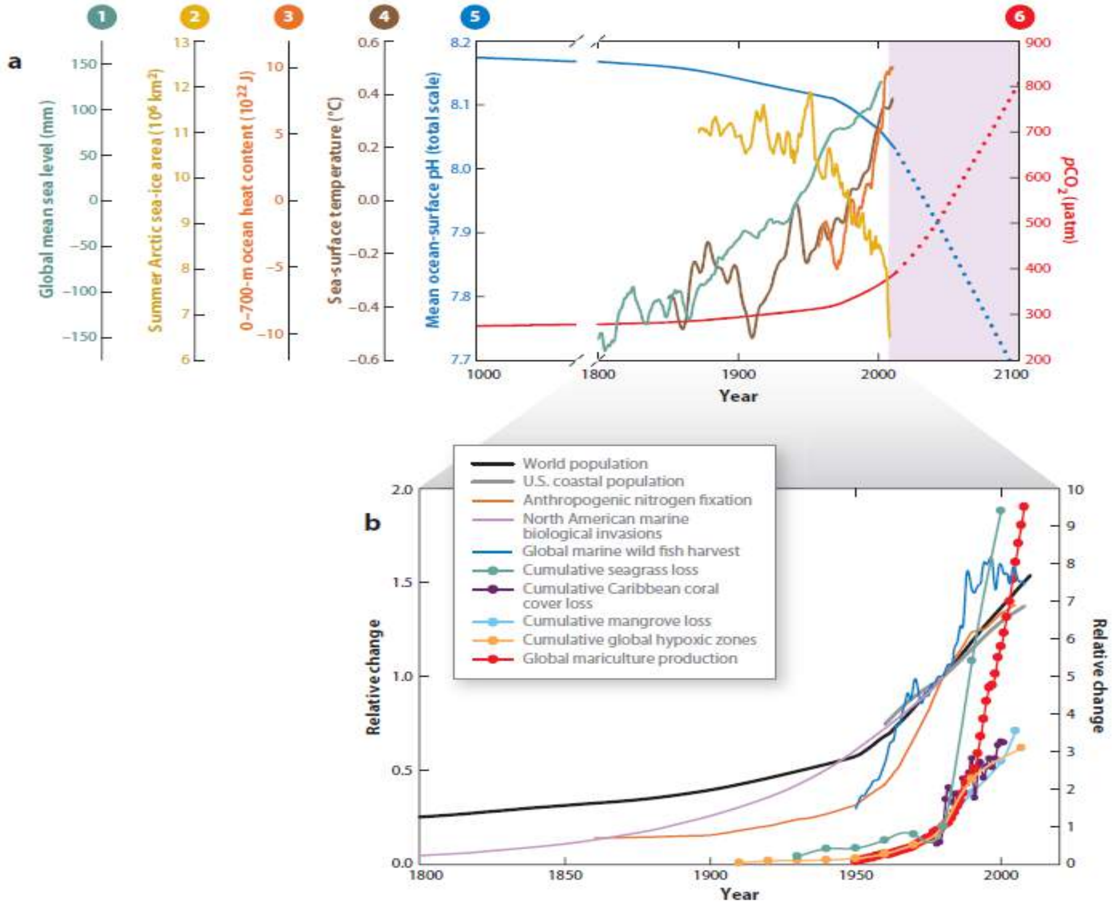


Figure 16: Summary of (a) global changes in mean sea level, summer arctic sea–ice area, 0-700 meter ocean heat content, sea-surface temperature and mean ocean surface pH and anthopogenic drivers (b) including: changes in world population, U.S. coastal population, anthropogenic nitrogen fixation, North American marine biological invasions, global marine wild fish harvest, cumulative seagrass loss, cumulative Caribbean coral cover loss, cumulative mangrove loss, cumulative global hypoxic zones and global mariculture production. From Doney et al., (2012).

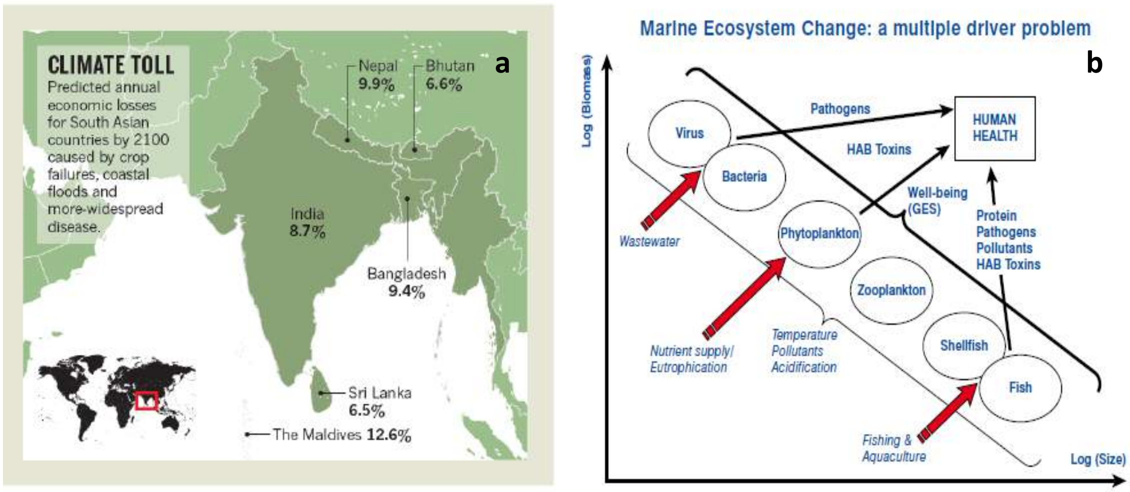


Figure 17: Predicted annual economic losses for South Asian countries by 2100 caused by crop failures, coastal floods and more widespread disease (left panel (a) from Mora et al., 2013) and a schematic diagram illustrating the multiple dirvers underlying the various processes contributing to the interactions between marine ecosystems and human health (right panel (b) form European Marine Board, 2013).

Climate Change

The increase of atmospheric CO_2, which started with the onset of the Industrial Revolution about 200 years ago, is the cause of both global warming and acidification of the ocean (Gruber, 2011; Bijma et al., 2013). Global warming, in turn, is leading to changes in the wind fields, enhanced stratification of the water column and changes in ocean circulation patterns, rising sea-levels and melting ice sheets (Bijma et al., 2013; IPCC, 2013) that affect biogeochemical processes, biological productivity and fisheries in coastal and open oceans (Doney et al., 2012; Jennerjahn, 2012). One of the indicators of a changing global oceanic environment, which has received increasing attention during the last years, is the observed loss of dissolved oxygen (deoxygenation) which is resulting from a combination of changes in ocean ventilation and stratification, decreased solubility of oxygen and enhanced microbial respiration caused by eutrophication (Diaz and Rosenberg, 2008; Keeling et al., 2010; Andrews et al., 2013).

Direct anthropogenic changes

Only recently the occurrence of (micro)plastic debris in almost all parts of the global ocean (Cózar et al., 2014) has been recognized as an increasing global threat for a wide range of marine organisms (zooplankton, fish, seabirds and mammals) because of its potential for physical and toxic harm (Law and Thompson, 2014; UNEP, 2014). significant accumulation of surface plastic debris in the Indian Ocean are only found in its southern gyre system at around 25°S because of the Indian Ocean’s unique geographic conditions (Cózar et al., 2014). The concentration of surface plastic in the Indian Ocean is the lowest of the three major ocean basins and is comparable to the remote South Pacific Ocean gyre (Cózar et al., 2014).

Urbanization of coastal zones

Mumbai and Kolkata (India), Dhaka (Bangladesh) and Karachi (Pakistan) are so-called coastal mega-cities and belong to the group of 21 urban agglomerations with more than 10 million inhabitants (see von Glasow et al., 2013 and reference therein). With the exception of Dhaka, which is only indirectly influenced by the coast, these megacities are directly located at the coast. In general, coastal megacities affect the ocean via high atmospheric pollution/aerosol load and the subsequent deposition of nutrients and contaminants to the ocean as well as sewage outflow and eutrophication of the coastal ocean (von Glasow et al, 2013). Thus, emissions and discharges from megacities have a high potential to influence biogeochemical cycles, ecosystems and fisheries in the adjacent coastal zones (von Glasow et al., 2013).

Human pressure on coastal ecosystems and the competition for land for aquaculture, agriculture, infrastructure and tourism are often high and are the major causes of the loss of mangrove ecosystems (FAO, 2007). The global loss rate of mangroves over recent decades has been significant, but seems to have slowed during the period from 2000 to 2005 (FAO, 2007). In Indian Ocean rim countries like Pakistan, Madagascar, Indonesia and Malaysia, the loss is high. However, Pakistan succeeded in reducing the loss rate. In the Sundarbans (Bangladesh), part of the largest mangrove area in the world, the mangrove area is even increasing because of effective protection measures (FAO, 2007).

ENVIRONMENTAL STRESSORS AFFECTING THE INDIAN OCEAN SYSTEM

The major environmental changes (so-called stressors) affecting the Indian Ocean system are warming, acidification, eutrophication, atmospheric pollution, and deoxygenation (Figure 18), which are briefly outlined in the following sections.

Warming

Global average sea surface temperatures (SST) have increased since the beginning of the 20th Century. The average SST of the Indian Ocean has increased by 0.65°C in the period from 1950 to 2009 and is the highest warming rate of the major ocean basins (IPCC, 2013).

Cyclones observed in the northern Indian Ocean show a significant increase in maximum wind speeds, which is in line with worldwide observations of a warming-induced increase of intensity of tropical cyclones (Elsner et al., 2008).

Global sea level is rising mainly as a result of the thermal expansion of the warming ocean and freshwater addition from glaciers (IPCC, 2013). A significant sea level change has been detected in the Indian Ocean: In general sea levels increased except in the western equatorial Indian Ocean. This pattern has been attributed to changes in both surface winds and atmospheric overturning circulation caused by the ocean warming (Han et al., 2010; Figure 19).

If the warming trend continues, the projected sea level rise will increase the environmental stress on beaches, coral reefs and mangroves, with far-reaching socio-economic consequences (tourism, fishing, ecosystem services such as coastal protection) (Hoegh-Guldberg et al., 2014). Moreover, coral reefs in the Indian Ocean are vulnerable to both the ongoing warming (-> increased frequency of mass coral bleaching and mortality) and acidification (see next section) (Hoegh-Guldberg et al., 2014). And warming-induced stratification will reduce the upwelling of nutrients from deeper in the ocean to surface layers, decreasing biological production by reducing nutrient supply.

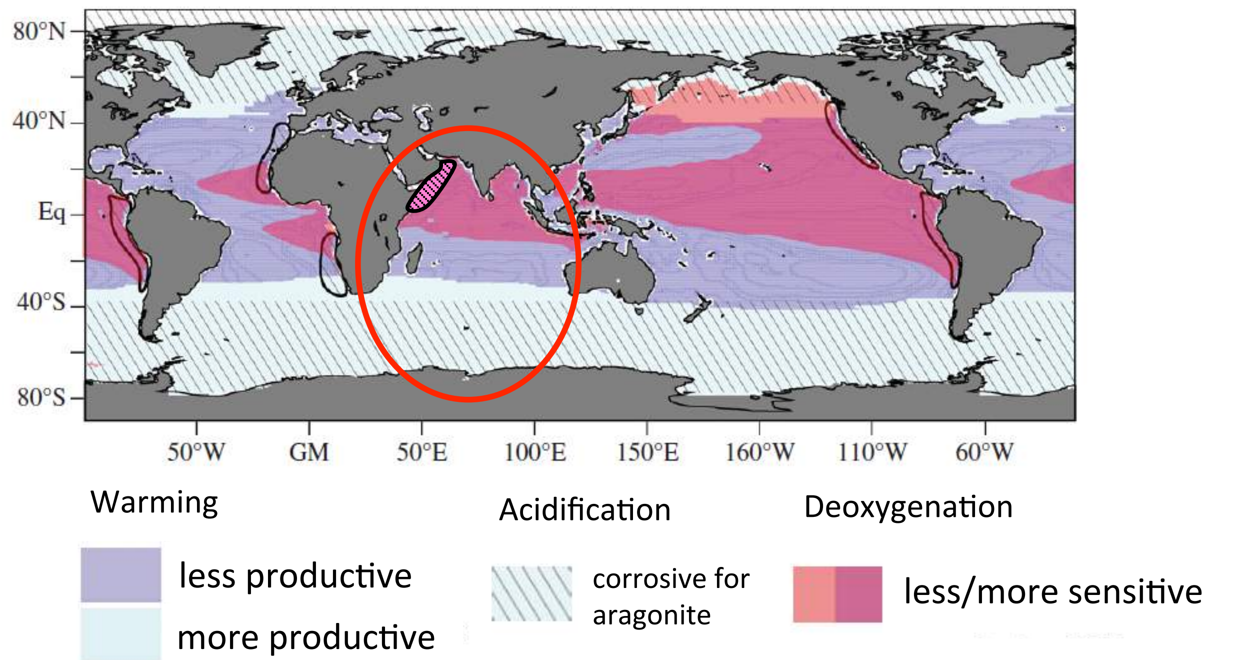


Figure 18: Regions of particular vulnerability to three of the main stressors in marine systems: ocean warming, acidification and deoxygenation. From Gruber (2011).

Acidification

Acidification of the surface ocean is caused by the uptake of anthropogenic CO_2 from the atmosphere, which results in a decrease of pH. The overall uptake of anthropogenic CO_2 in the Indian Ocean is low compared to the other major ocean basins because of its comparably small area and its special geographic condition (resulting in the absence of deep water formation areas) (see e.g. DeVries, 2014). The pH for the northern (20°E-120°E, 0°-24.5°N) and southern Indian (20°E-120°E, 0°-40°S) oceans in 1995 were 8.068 +/- 0.03 and 8.092 +/- 0.03, respectively (Feely et al., 2009). Thus, the average surface pH of the Indian Ocean is the lowest of the major ocean basins. The lower pH in the northern Indian Ocean results from areas of high productivity that are found, for example, in the upwelling regions of the Arabian Sea. There are only a few studies on the ongoing acidification because of the lack of time-series measurements. The results of a recently published study from the eastern Bay of Bengal indicate, indeed, a decrease in pH of 0.2 in the period from 1994 to 2012 (Rashid et al., 2013).

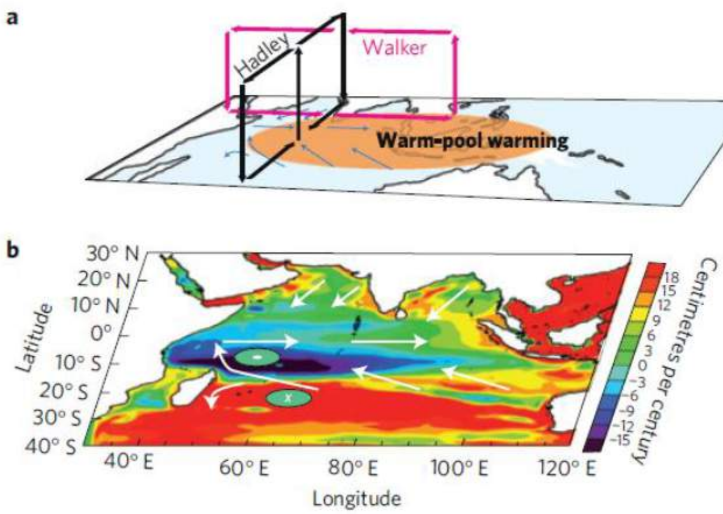


Figure 19: A schematic diagram showing the mechanisms for the Indo-Pacific warm pool warming that cause Indian Ocean sea-level change. Warming enhances the Indian Ocean Hadley and Walker cells (a). The two enhanced cells combine to form a specific pattern of surface wind exchange (arrows in (a) and (b)) together with the Ekman pumping velocity (see – and + in (b)) which drive the distinct sea-level pattern (contours in (b)). Figure and caption from Han et al. (2010).

Increasing CO_2 in the upper ocean could lead to increased primary productivity for some species (e.g., diazotrophs; Hutchins et al., 2007), altering the biogeochemistry of particulate organic matter respiration and impacting calcifying organisms (coral reefs, coccolithophorids) (Gattuso and Hansson, 2011). Decreasing pH shifts the chemical equilibrium from ammonia (NH_3) to ammonium (NH_4^+), which may alter key biological processes such as microbial nitrification and nitrogen assimilation by phytoplankton (Gattuso and Hansson, 2011). Commercially fished species (e.g., mollusks) are vulnerable to ocean acidification (Hoegh-Guldberg et al., 2014). Finally, the Southern Ocean sector of the Indian Ocean could experience major disruptions in upper levels of pelagic food webs due to the effects of acidification on calcifying pteropods, which are the prey of many higher trophic level organisms (Bednarsek et al., 2012).

Eutrophication and atmospheric pollution

Eutrophication and increasing atmospheric pollution (including aerosol load) of the Indian Ocean are caused by the rapid increase of the population density of the Indian Ocean rim countries, which results from intensified industrial and agricultural activities (see background section above).

Riverine inputs of dissolved nutrients (i.e., NO_3^-, PO_4^{3-} and SiO_2) are the major source of eutrophication in the coastal ocean. Major river systems such as the Indus, Narmada, Ganges/Brahmaputra and Irrawaddy Rivers as well as the Zambezi River are draining into the northern and southwestern Indian Ocean, respectively. The annual river discharge from the Indus River to the Arabian Sea has declined substantially from 150 km^3 to <10 km^3 since the early 1960s because of the construction of the Mangla and Tarbela dams (Milliman and Farnsworth, 2011; Figure 20) implying a significantly reduced input of riverine nutrients to the Arabian Sea. In contrast, the river discharge of the Ganges/Brahmaputra River is still high (Milliman and Farnsworth, 2011). Consequently, the indicator of coastal eutrophication potential (ICEP) caused by riverine nutrient inputs is low for the northwestern, southwestern and southeastern Indian Ocean whereas it is high for the northeastern Indian Ocean (i.e., Bay of Bengal) (Seitzinger et al., 2010).

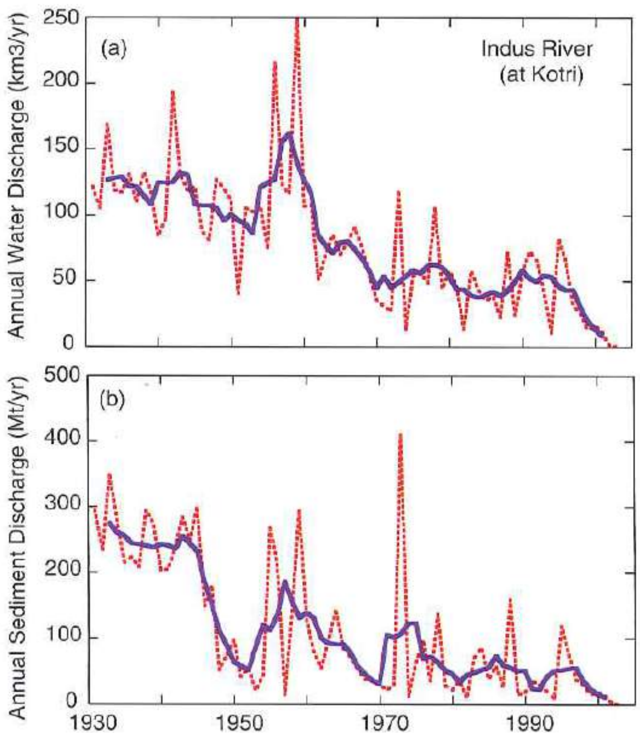


Figure 20: Annual water (a) and sediment (b) discharges from the Indus River from 1931-2002. Annual values are shown as dashed red lines; solid blue lines represent 5-yr running means. From Milliman and Farnsworth (2011).

Local eutrophication of coastal waters can lead to harmful algal blooms: For example, a significant increase of the number of harmful algal blooms (HAB) has been observed in the coastal waters of Arabian Sea and Bay of Bengal in the past three decades (Padmakumar et al., 2012). Moreover, open ocean waters of the Arabian Sea and Bay of Bengal also are experiencing an increase of harmful algal blooms, which may be attributed to the ongoing warming and eutrophication (Padmakumar et al., 2012). Frequently occurring harmful algal blooms are also reported along the coasts of East Africa and Indonesia (Sidharta, 2005).

In comparison to upwelled nitrate, the atmospheric nitrate input to the Arabian Sea is only of significance for the productivity in the central Arabian Sea during the intermonsoon periods (Bange et al., 2000). Srinivas et al. (2011) estimated that about 13% of primary productivity of the Bay of Bengal was supported by nitrogen input via aerosol deposition. During the NW monsoon season (January – April), aerosol deposition fluxes over the Bay of Bengal are generally higher than those observed over the Arabian Sea (Srinivas and Sarin, 2013a)

A brownish-grey atmospheric cloud frequently observed over the northern Indian Ocean (especially over the Bay of Bengal) has been identified as a huge aerosol plume, known as the “brown cloud” or “South Asian haze”, sometimes reaching as far south as 10°S (see, for example, Ramanathan et al., 2007; Figure 21). The large size of the plume is caused by very high atmospheric pollution and aerosol loads from land sources (i.e., biomass burning and fossil fuel combustion) in the northern Indian Ocean region. Satellite-derived time series measurements indicate that the annual aerosol load over the northern Indian Ocean is increasing significantly. This trend is more pronounced than in other oceanic regions worldwide (Hsu et al., 2012).

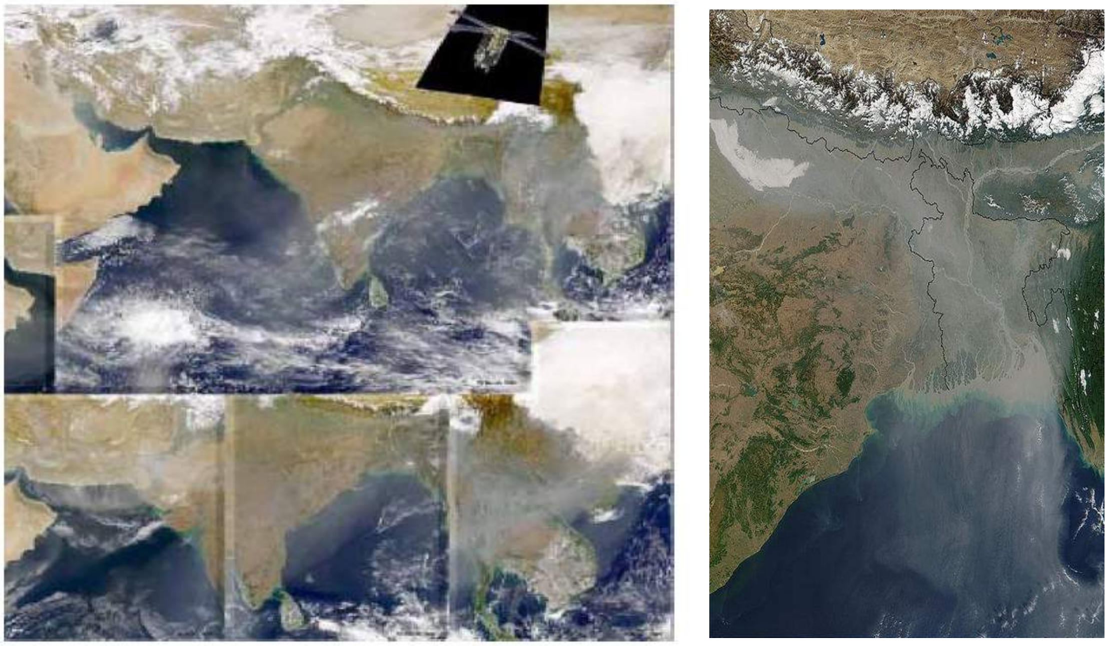


Figure 21: Atmospheric pollution ("brown cloud") over the Northern Indian Ocean (Jan-Mar 1999 and Dec 2001). Figures from NASA/INDOEX.

In addition, anthropogenic emissions from biomass burning and fossil-fuel combustion are significant sources of soluble/bioavailable Fe and other trace metals to the Bay of Bengal (Srinivas and Sarin, 2013b).

The increase of anthropogenic black carbon and sulphate aerosol emissions can also lead to a change in wind fields which, in turn, have been associated with the increase of the intensity of pre-monsoon tropical cyclones in the Arabian Sea in the period from 1979 to 2010 (Evan et al., 2011). Because the majority of the tropical cyclones in the Arabian Sea make landfall, the increasing cyclone intensity suggests increasing damage in coastal zone areas from these events.

The impact of the atmospheric pollution and aerosol load on the Indian Ocean's atmospheric chemistry, ocean biogeochemistry and ecosystems, as well its climate feedback, is largely unknown. An increasing number of harmful algal blooms will have negative effects on human health, fisheries and tourism. Increasing deposition of nitrogen-containing aerosols to the Arabian Sea may lead to a future increase of N_2O production in the intermediate layers of the central Arabian Sea (Suntharalingam et al., 2012).

Deoxygenation

The ongoing deoxygenation in the intermediate layers of the central Arabian Sea has been documented by a comprehensive analysis of dissolved O_2 measurements in the period from 1959 to 2004 (Banse et al., 2014). Moreover, by using O_2 concentration measurements from the period 1960 to 2010, Stramma et al. (2012a) were able to identify the northern Indian Ocean (i.e., from north of the Equator) as a region with a significant trend in decreasing O_2 concentrations in the intermediate layers (i.e., 300 meters; Figure 22). The maximum trend of decreasing O_2 concentrations in the Indian Ocean (~ -0.3 μmol O_2 kg^{-1} yr^{-1}) was computed for the region off Indonesia. (Interestingly, Stramma et al. (2012a) also identified zones with an increasing trend in O_2 concentrations in the Indian Ocean south of the Equator.)

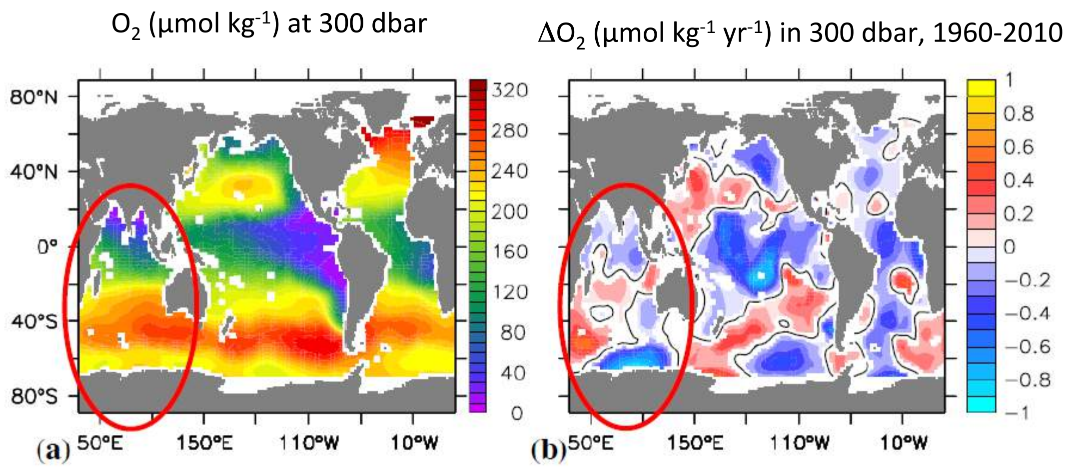


Figure 22: Global mean dissolved oxygen distribution at 300 dbar (a) and O_2 changes at 300 dbar from 1960-2010 (b). In (b) ares with O_2 increase are given in red and decrease are given in blue; changes with O2 < 95% confidence standard error interval are given in white. Figure and caption modified from Stramma et al. (2012b).

Deoxygenation may lead to an expansion of intermediate water layers with conditions favoring increased loss of bioavailable nitrogen under suboxic/anoxic conditions via denitrification and/or anammox reactions. Moreover, deoxygenation will enhance production of climate-relevant trace gases such as N_2O, CH_4 and dimethyl sulphide (DMS) (Naqvi et al. 2010; Shenoy et al., 2012), which are released to the atmosphere from the upwelling regions of the northern Indian Ocean. Finally, mesopelagic fish populations may be threatened by a reduction in suitable habitat as respiratory stress increases due to deoxygenation (Stramma et al., 2012b).

CORE QUESTIONS

1. **How are human-induced ocean stressors (for example, warming, sea-level rise, deoxygenation, acidification, eutrophication, atmospheric and plastic pollution, coastal erosion and overfishing) impacting the biogeochemistry and ecology of the Indian Ocean?**

2. **How, in turn, are these impacts affecting human populations?**

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

The on-going rise of CO_2 in the atmosphere causes both warming and acidification of the ocean. Warming-induced stratification may reduce the upwelling of nutrients from deeper in the ocean to surface layers resulting in decreasing biological production by reducing nutrient supply. Any changes in biological productivity will, in turn, affect webs and fisheries. Warming-induced sea level rise will increase the environmental stress on beaches, coral reefs and mangroves. Moreover, coral reefs are especially vulnerable to the ongoing warming. Increasing CO_2 (= decreasing pH) in the upper ocean will lead to an increase in primary productivity, altering the biogeochemistry of particulate organic matter respiration (including denitrification) and impacting calcifying organisms (coral reefs, coccolithophorids). Commercially fished species (e.g., mollusks) are vulnerable to ocean acidification. The Southern Ocean sector of the Indian Ocean could experience major disruptions in upper levels of food webs because of effects on pteropods, which are the prey of many organisms. **What is the effect of rising atmospheric CO_2 on biological productivity and fisheries as well as especially vulnerable coastal ecosystems (such as coral reefs, mangroves, etc.)?**

Eutrophication of coastal zones and the open ocean via rivers and atmospheric deposition, respectively, is suspected to cause an increasing number of harmful algal blooms and to enhance deoxygenation (i.e., loss of O_2). Deoxygenation, in turn, may lead to an expansion of intermediate water layers with conditions favouring increased loss of bioavailable nitrogen under suboxic/anoxic conditions via denitrification and/or anammox reactions with unknown consequences for the overall productivity of the Indian Ocean system. Moreover, deoxygenation may lead to enhanced production and release of climate-relevant trace gases such as N_2O, CH_4 and DMS. Mesopelagic fish populations may be threatened by a reduction in suitable habitat as respiratory stress increases due to deoxygenation. **How does eutrophication, atmospheric pollution and the loss of O_2 affect biogeochemical cycles, ecosystems and fisheries in coastal zones and the open ocean?**

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

Coastal waters receive large inputs of chemical and biological waste originating from land-based industrial, domestic and agricultural sources. Pollutants are also introduced by shipping activities, offshore oil and gas exploration and atmospheric deposition of particles from industrial origin. Sewage pollution of coastal waters by pathogens and toxic waste can cause illness and death. Aquaculture activities can lead to eutrophication (and deoxygenation) of coastal waters. In turn, eutrophication enhances the risk of harmful algal blooms (HAB) and the release of HAB toxins. **What are the consequences for human health caused by pollution, altered ecosystems and increasing aquaculture activities?**

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

THEME 2: BOUNDARY CURRENT DYNAMICS, UPWELLING VARIABILITY AND ECOSYSTEM IMPACTS

BACKGROUND

The geometry of the Indian Ocean basin, combined with monsoonal wind forcing, defines a unique and complex three-dimensional circulation in the tropical Indian Ocean (Schott et al, 2009). The monsoon domain in the Indian Ocean is usually defined as northward of 10°S, where the circulation is characterized by seasonal reversal along with the monsoon annual cycle. Even though the basin-scale upper circulation is becoming clear through several decades of research (Schott and McCreary, 2001; Schott et al. (2009), the boundary currents and upwelling processes in the Indian Ocean still remain far less well understood than in the Atlantic and Pacific.

The western/eastern boundary currents

An impressive western boundary current in the Indian Ocean is the Somali Current (SC), which is noted for its strength, seasonal reversal, and the associated eddies (Figure 7 and 23). Unlike its counterparts in the Pacific and Atlantic oceans, the Kuroshio and the Gulf Stream, respectively, the SC crosses the equator within a narrow zone during the boreal summer monsoon, which balances the southward Ekman transport. Furthermore, the Somali Current is closely connected with upwelling and strong eddies, through which it plays a significant role in the regional biogeochemical processes and climate. The Somali Current is reversed during the boreal winter monsoon and meets with the South Equatorial Current (SEC) to bring about the South Equatorial Counter Current (SECC) (Figure 7 and 23). By comparison, the eastern boundary current in the tropical EIO is the South Java Current (SJC), which is much weaker compared with the SC (Figure 23).

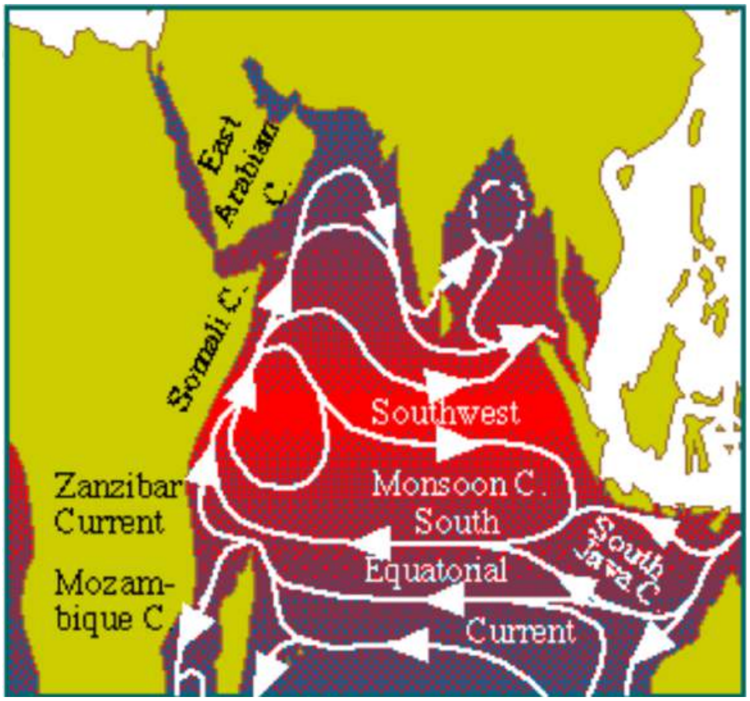


Figure 23: Surface currents in the tropical Indian Ocean during the Southwest Monsoon. From Tomczak and Godfrey (2003), downloaded and modified from http://www-pord.ucsd.edu/~ltalley/sio210/Indian/.

The southward flowing boundary currents (Agulhas and Leeuwin) of the Indian Ocean are associated with upwelling, downwelling and strong eddies, which are of vital importance to the adjacent coastal and open ocean ecosystems. The Agulhas Current is important because it connects the Indian Ocean with the Atlantic Ocean and through its leakage and plays an important role in the global overturning circulation (Beal et al., 2011; see also Themes 4 and 6 below). While a significant amount of research has been undertaken on the Agulhas Current, its dynamics, instability, and multi-scale variations still require more study. The source regions of the Agulhas Current, for example, the East Madagascar Current and flow through the Mozambique Channel, are also strongly associated with mesoscale activities and upwelling processes. In the eastern Indian Ocean, the Leeuwin Current (LC) is the only southward flowing eastern boundary current in the world's oceans and is strongly associated with mesoscale eddies which together with the main flow play a major role in supporting the marine ecosystem along the southeastern Indian Ocean. Many of these eddies propagate offshore into the eastern central Indian Ocean.

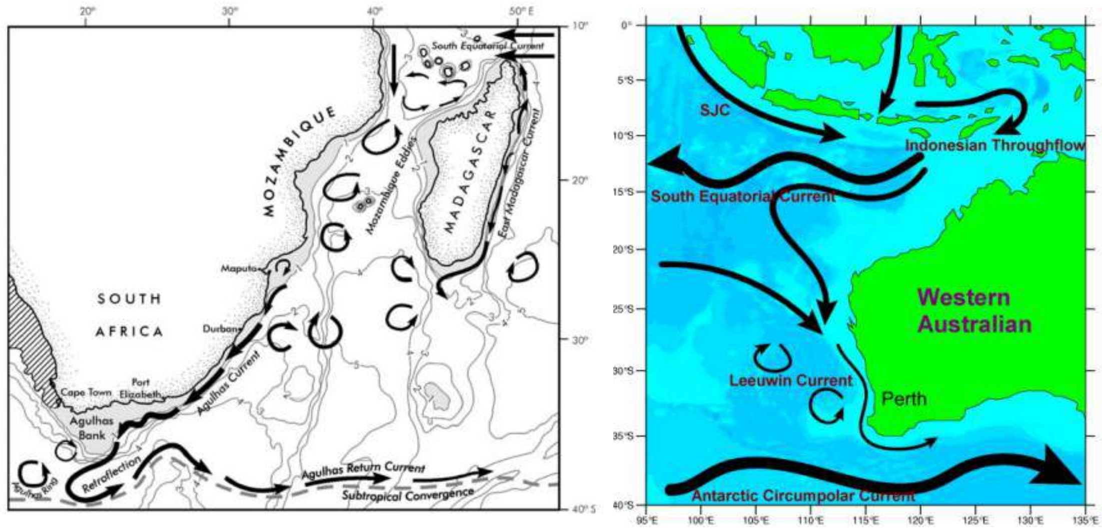


Figure 24: Source waters, eddies and coastal flow of the Agulhas Current (left panel; from Lutjeharms, 2006) and the Leeuwin Current (right panel, from www.per.marine.csiro.au).

The equatorial currents

The Indian Ocean Basin is also unusual in the equatorial region, given the seasonality of the currents and the reduced equatorial upwelling (Figure 7 and 23). The equator serves as the dynamic boundary separating the two hemispheres, which shares much similarity in dynamics with the lateral boundary. The eastward-flowing currents along and near the equator are worthy of attention since they link the two sides of the basin through the transport of large volumes of water, heat, salinity, oxygen and other substances. In that sense, the equatorial current plays a rather important role in the basin-scale circulation and biogeochemical processes.

At the surface, intense semi-annual eastward flows along the equator in boreal spring and fall—the Wyrtki jets (Wyrtki, 1973)—are generated by strong westerly winds in the transitions between the winter and summer monsoon. However, at the thermocline depth, there is no permanent eastward flowing equatorial undercurrent as in the Pacific and Atlantic oceans. The monsoonal forcing, rather than steady trade wind forcing at low latitudes of the Indian Ocean, drives a transient undercurrent that appears in March and again, with weaker amplitude, in September (Iskandar et al., 2009). Slightly away from the equator, the South Equatorial Counter Current exists during the boreal winter flowing eastward (Figure 7).

Due to the lack of steady trade winds, there is no permanent upwelling centered on the equator. Instead, water subducted at higher latitudes is upwelled in a variety of off-equatorial locations, including the coasts of Somali, Yemen and Oman, the Seychelles-Chagos Thermocline Ridge (SCTR; Figure 25), the Sri Lankan Dome, along the coasts of Java and Sumatra, and off the coast of Northwest Australia. Upwelling in these regions is strongly modulated seasonally by monsoonal wind forcing. Interannually, large variations in upwelling also occur in the SCTR and off Java and Sumatra associated with the IOD and ENSO. Cold sea surface temperatures (SSTs) in these upwelling zones stabilize the atmospheric boundary layer, affecting exchanges of heat and momentum across the air-sea interface (Vecchi et al, 2004).

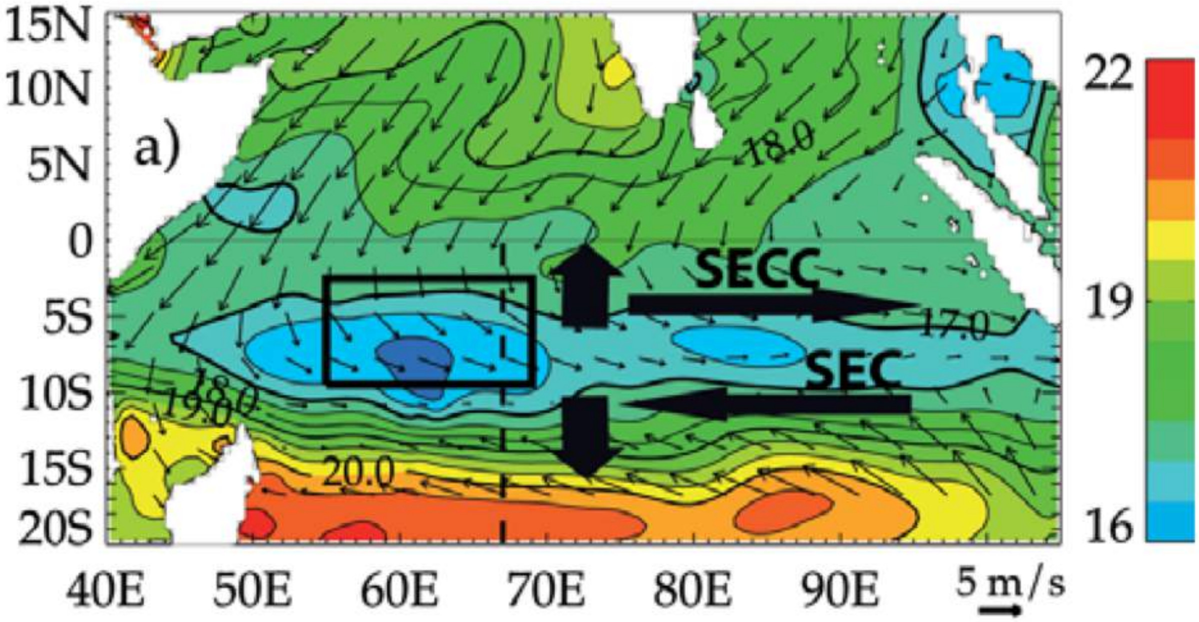


Figure 25: Climatological surface winds and 0–300-m average ocean temperature in Jan–Feb. The thick black arrows indicate the surface flow induced by wind that promotes upwelling and leads to the SCTR formation. The arrows marked SEC and SECC indicate the south equatorial current and south equatorial countercurrent. From Valiard et al. (2009).

Upwelling links the ocean interior with the surface, where the ocean and atmosphere interact and create remote impacts through teleconnections. Hence, coastal upwelling is not only a localized process, but also potentially couples with basin-scale circulation, regional climate and even beyond. Moreover, upwelling brings nutrients from below to support upper layer primary production and hence energy is transferred to the upper levels of the food web. Globally, eastern boundary upwelling systems occupy less than 2% of total ocean area, but they support 20% of global marine fish catches (Pauly and Christensen, 1995).

CORE QUESTIONS

1. **How are marine biogeochemical cycles, ecosystem processes and fisheries in the Indian Ocean influenced by boundary currents, eddies and upwelling?**

2. **How does the interaction between local and remote forcing influence these currents and upwelling variability in the Indian Ocean?**

3. **How have these processes and their influence on local weather and climate changed in the past and how will they change in the future?**

The boundary currents facilitate the inter-hemisphere (i.e., Somali Current), trans-basin (i.e., equatorial currents) and basin-scale (i.e., South Java Current, Agulhas Current and Leeuwin Current) transportation of water volume and nutrients, which underpin marine biogeochemical cycles. ***How do the multi-scale variations of boundary currents in the Indian Ocean, and particularly their strong annual cycle and decadal variability, mediate biogeochemical and ecosystem responses to the high and low frequency oceanic forcing, which is rare in other basins?*** Upwelling is another transport process, but vertically, linking the ocean surface with its interior. ***How does upwelling control the nutrient supply to the upper Indian Ocean and thereafter how are these nutrients redistributed by the horizontal currents and eddies? How do these complex biogeochemical and ecosystem processes support Indian Ocean fisheries?***

The boundary currents and upwelling in the Indian Ocean are driven by local as well as remote forcing. For the Somali Current, South Java Current and their associated upwelling processes, it is particularly important to gain deep insights into the dynamics of these systems. ***What can comparative studies tell us about the relative roles of the remote vs. local forcing in driving these currents and their associated upwelling and downwelling circulations and how does this influence nutrient supply and ecosystem dynamics? Addressing this question will also shed light on the role of the Somali Current and South Java Current in local and regional climate.*** The Agulhas Current is a more typical western boundary current with upwelling governed by topography and seasonal wind variability. Presumably, inter-annual to decadal variations in the strength of this current are closely tied with transport through the ITF and also with circulation variability in the Atlantic and Southern oceans. Yet, our understanding of Agulhas Current variability at these time scales and the forces that drive it are rudimentary at best. ***How does remote and local forcing interact to drive variations in Agulhas Current transport and upwelling and how does this, in turn, influence nutrient supply, larval transport and fisheries productivity?*** The Leeuwin Current is also strongly influenced by transport through the ITF and it receives remote forcing associated with ENSO and the IOD. In addition, local seasonal winds strongly influence upwelling and downwelling circulations and therefore also eddy generation, larval transport and nutrient supply. ***How does remote and local forcing interact to drive variations in Leeuwin Current transport and upwelling and how does this, in turn, influence nutrient supply, larval transport and fisheries productivity?*** A clearer dynamic picture of these currents and their upwelling variability is needed to understand their influence on the marine ecosystem and also climate variability and change.

Paleoceanographic and paleoclimate studies of the boundary currents and upwelling processes are still relatively limited in the Indian Ocean, with most of the effort to date focused on past changes in the strength of the summer monsoon in the Arabian Sea (Wang et al., 2005) and the Agulhas Leakage. There is a pressing need to expand paleoceanographic and paleoclimate research in the Indian Ocean and extend this research to other parts of the basin (see recommendation in Wang et al., 2005). ***How has the strength of the monsoons and associated upwelling and downwelling circulations changed in the past and how will they change in the future in response to climate change? How has the role of the Indian Ocean boundary***

currents in the global thermohaline circulation changed in the past and how might it change in the future? How have all of these processes influenced local weather and climate?

THEME 3: MONSOON VARIABILITY AND ECOSYSTEM RESPONSE

BACKGROUND

In this context the “monsoon” refers to the southwest boreal summer and northeast boreal winter monsoons that affect India and southeast Asia, and the southeast austral summer monsoon that affects the southern portion of the “Maritime Continent” and Australia (Maritime Continent refers to the region of Southeast Asia that includes Indonesia, the Philippines and Papua New Guinea) (Figure 26). These winds, which have the largest annual amplitude of any subtropical and tropical climate feature, profoundly impact both the Arabian Sea and the Bay of Bengal and the surrounding continents, and also the entire eastern side of the Indian Ocean basin including Southeast Asia and Oceania (Figure 7 and Figure 26).

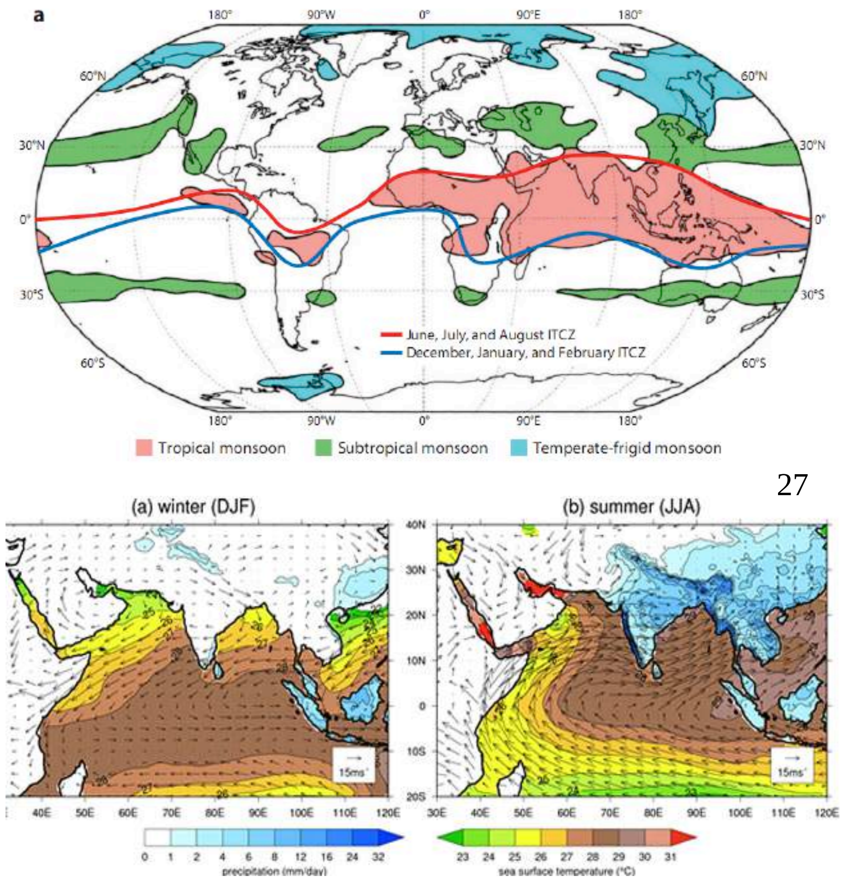


Figure 26: Top panel: The global monsoon distribution, where the Indian Ocean and its rim are under the regime of African-Asian-Australian monsoon (from Li and Zeng, 2005). Bottom Panel: Schematic diagram of boreal winter (December-February; left) and summer (June-August; right) daily mean precipitation, sea surface temperature (SST) and winds over the Indian Ocean and adjacent continents (from http://www.rmets.org/weather-and-climate/climate/indian-monsoon-changing-climate).

In the northern Indian Ocean the warm and moist Southwest Monsoon (SWM) blows from the SW towards the NE in the boreal summer (June-August) and the cool and dry NE Monsoon (NEM) blows in the opposite direction in the boreal winter (December-March) (Figure 7 and 26). Along the eastern side of the basin these forces drive the SE monsoon winds that blow from the SE toward the NW in the boreal summer (June through October; Figure 26) (for a review see Schott and McCreary, 2001). The summer monsoons are associated with convective, radiative, and sensible heat sources and sinks, with convective latent heating playing the most important role. During boreal summer, intense convection is observed in two regions: Over the Bay of Bengal–India–Arabian Sea and over the South China Sea–Philippine Sea (Wang et al., 2001). These two convection regions exhibit distinctive annual excursions (Figure 27). From September to March the maximum rainfall is observed west of Sumatra (5°S, 100°E). The convection center crosses the equator in May and moves into the southern Bay of Bengal (5°N, 92°E). Then, from May to June, the area of heavy rainfall jumps northward into the northern Bay of Bengal and remains there throughout the rest of summer.

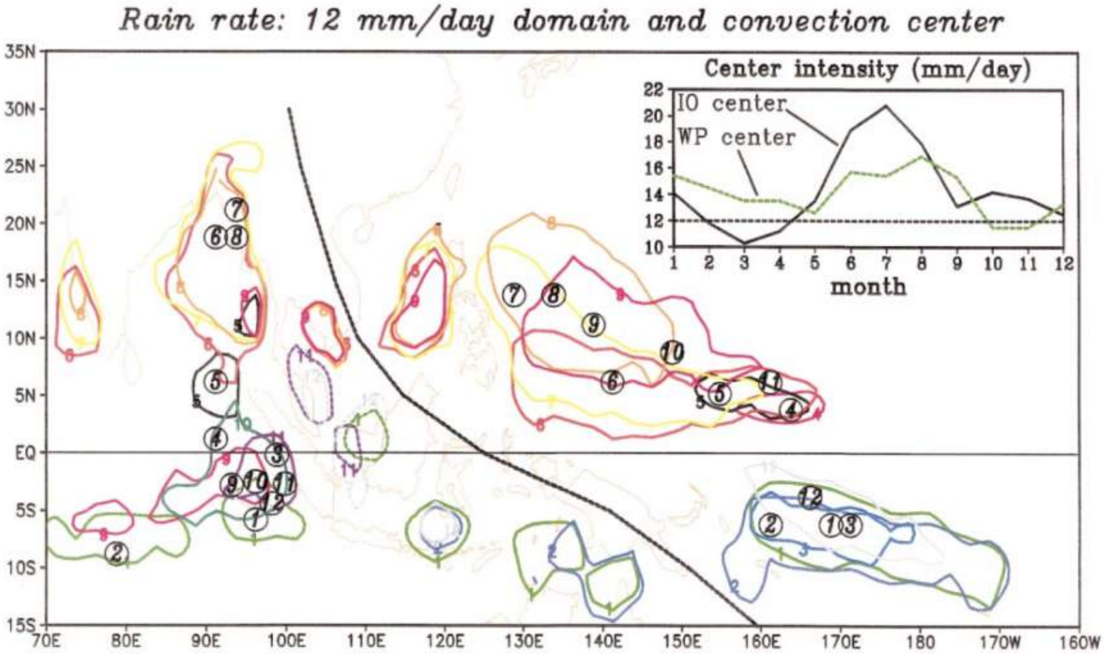


Figure 27: Annual march of the rain-rate centers over the Indian and the western Pacific Oceans. The contours denote rain rate of 12 mm/day. The locations of the maximum rain rate are indicated by circled bold italic. Intensities of the monthly mean maximum rain rate for the two centers are given in the plot at the upper-right corner. From Wang et al. (2001).

In addition to the annual cycle, the monsoons exhibit considerable variability on a wide range of time scales. Perhaps the most important intraseasonal phenomenon of the monsoon is the observed variability in the onset of the monsoon rains, that is, the dates of the commencement of the monsoon in a particular location are quite variable (Webster et al., 2012). Intraseasonal monsoon variability is also dominated by active-break cycles that are related to the influence of the MJO, which propagates from west to east along the equator during austral summer. During austral winter, intraseasonal variations are more complicated and have a strong poleward component, which is referred to as the Monsoon Intraseasonal Oscillation (MISO). On longer timescales the monsoon exhibits biennial, interannual, and interdecadal variations. Biennial variability is manifested as a two- to three-year oscillation in rainfall over Indonesia, East Asia and Indian (Yasunari and Suppiah, 1988; Tian and Yasunari, 1992; Shen and Lau, 1995;

Mooley and Parthasarathy, 1984). Interannual variability in the monsoon is observed on 3- to 7-year timescales and it can be related to other major features of the coupled ocean-atmosphere system (e.g., ENSO) (Shukla and Paolina, 1983). Interdecadal variability has been manifested as a change in the relationship between ENSO and the Indian monsoon in recent decades (e.g., Parthasarathy et al., 1988; 1992; 1994).

In the northern, western and eastern Indian Ocean (down to 10°S) the boundary currents reverse seasonally in response to the monsoon winds (Schott and McCreary, 2001b; Shankar et al., 2002; Schott et al., 2009) (Figure 7). These wind-forced current reversals are also associated with dramatic changes in upwelling and downwelling circulations. Indeed, the entire northern Indian Ocean, and particularly the western Arabian Sea, transitions to a eutrophic coastal upwelling system during the Southwest Monsoon as a result of the monsoon-driven switch to upwelling-favorable winds and currents (Wiggert et al., 2005b, and references cited therein; Figure 7). These monsoon-driven effects on biological productivity are also observed off Java on the eastern side of the basin (Figure 28) and Somalia on the western side of the basin. Coupled physical-biological modeling studies have suggested that reversals in the coastal currents and changes in upwelling intensity can cause significant shifts in nutrient stoichiometry (Wiggert et al., 2006).

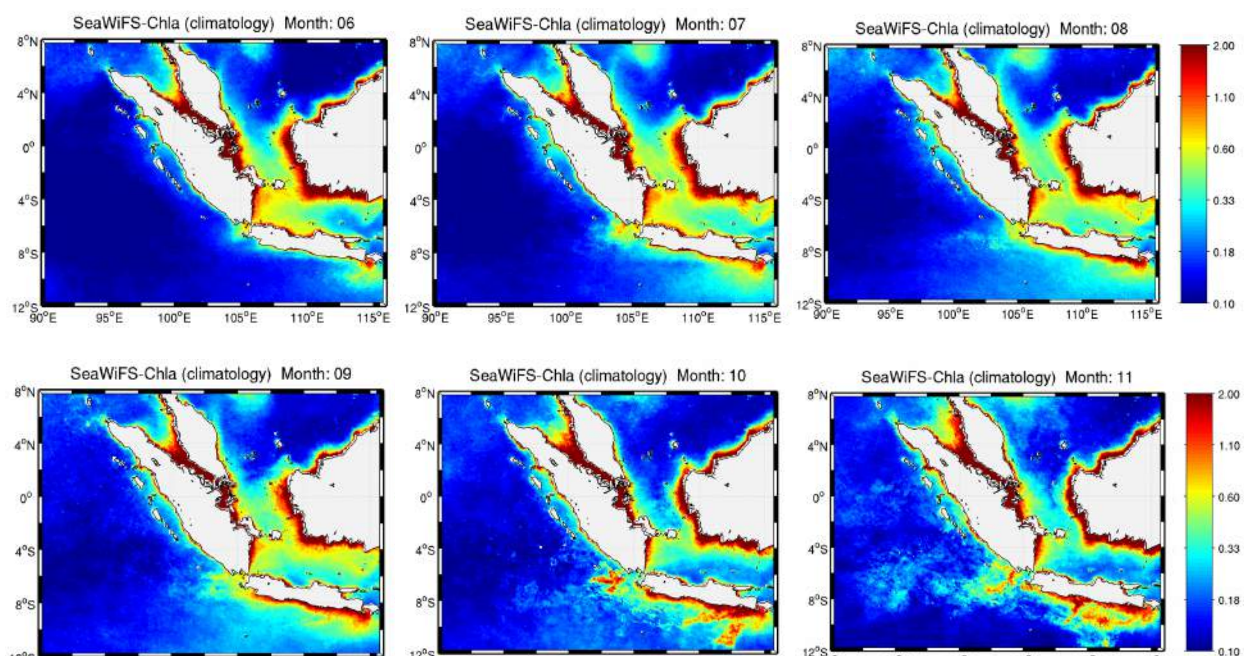


Figure 28: SeaWiFs-derived monthly chlorophyll-a climatologies for the eastern equatorial Indian Ocean in the vicinity of Java and Sumatra revealing increased productivity due to upwelling during the summer months driven by the Southeast Monsoon winds. Months 6 – 11 correspond to June – November. From Hood et al. (2015).

Monsoon-driven seasonal reversals in the coastal currents and associated changes in upwelling intensity also have profound impacts on oxygen concentrations and therefore higher trophic levels on the shelf off western India (Naqvi et al., 2000; Naqvi et al., 2006). These dramatic reversals in the boundary currents and associated changes in upwelling and primary production has led to the evolution of adaptive behaviors in higher trophic level species (e.g., Smith, 1992; Idrisi et al, 2004). Many coastal fish species in the northern Indian Ocean have undoubtedly evolved selective reproductive patterns for successful retention of planktonic eggs and larvae to ensure that progeny are retained or can enter nursery grounds along the coastline in the face of these seasonal changes in alongshore and offshore transport associated with the monsoon winds. We can also expect that fish species will have evolved reproductive strategies that maximize the overlap between first-feeding larvae and relatively predictable monsoon-driven periods of high productivity (Cushing, 1990). It follows that intraseasonal, to interannual and decadal variability in monsoon forcing must have profound impacts on ecosystem productivity, higher trophic level behavior and recruitment success and therefore also fisheries.

Figure 29: A submerged idol of Hindu Lord Shiva stands in the flooded River Ganges in Rishikesh in the northern Indian state of Uttarakhand, on June 18, 2013. Torrential monsoon rains caused havoc in northern India leading to flash floods, cloudbursts and landslides. From http://photo.sf.co.ua.

The regularity of the warm and moist and cool and dry phases of the monsoon cycle is ideal for agricultural societies. This regularity, however, makes agriculture susceptible to small changes in the annual cycle. Fluctuations in the amount and timing of rainfall can have significant societal consequences. As a result, forecasting monsoon variability on time scales ranging from weeks to years is an issue of considerable urgency. Forecasts are also needed on longer timescales in order to predict how the monsoons will vary in the coming years and, in particular, how they will respond to climate change and global warming. Unfortunately, recent mechanistc modeling efforts have not been successful. Even simulation of the mean structure of the Asian monsoon has proven elusive and the observed relationship between ENSO and monsoon variability has been difficult to replicate (Webster et al., 2012). Typical biases in coupled ocean-atmosphere models used for monsoon simulation and prediction produce results that are too cold in SST in Indian Ocean, too wet in the equatorial western Indian Ocean, and too dry over the continents. These biases result in the equatorial thermocline sloping upward to the east, whereas it should be relatively flat. This, in turn, results in a hyperactive Indian Ocean Dipole in the models. These biases are clearly coupled and not due solely to process in the Indian Ocean basin. Further, most models don't simulate the MJO/MISO very well and especially their interaction with the upper Indian Ocean. Clearly, reducing these biases would result in better models for monsoon simulation and prediction.

CORE QUESTIONS

1. **What factors control present, past and future monsoon variability?**

2. **How does this variability impact ocean physics, chemistry and biogeochemistry in the Indian Ocean?**

3. **What is the effect on ecosystem response, fisheries and human populations?**

Using all-India rainfall as index of overall Indian summer monsoon intensity, the relationship with local SST in the Indian Ocean is weak (no significant correlations in the Indian Ocean) but there is a modest remote relationship with La Niña. Regionally across India, rainfall west of the Ghat mountain range is related to local SST variations in the northern Indian Ocean (warm SST associated with more precipitation), whereas rainfall east of Ghats is more strongly related to ENSO in Pacific. Similarly, the Australian monsoon is more strongly related to remote forcing by La Niña during the pre-monsoon season (September, October, November) than during the monsoon. ***What causes this different sensitivity, especially the generally weak relationship of monsoon variability with Indian Ocean SST? From a modelling perspective, ENSO teleconnections to the monsoons are generally too strongly simulated in prediction/simulations models. Why?*** Monsoon-ENSO teleconnection has been observed to have weakened in the past 20 years. ***Is this a result of the cold phase of the Interdecadal Pacific Oscillation (IPO) or some other signature of global warming? What role is the Indian Ocean playing in the decadal variation of the monsoons, especially the variation of the ENSO-monsoon teleconnection?*** Monsoon variability is dominated by active-break cycles that are related to MJO and MISO. ***Some years the MJO/MISO accounts for majority of monsoon variability, but in others it is weak. Why? In general, what are primary factors, both local to the Indian Ocean and remote, that control monsoon intraseasonal-seasonal-***

decadal variability and how well are these mechanisms captured in prediction/simulation systems?

Intraseasonally, the MJO exhibits a range of air-sea interactions across the Indian Ocean basin, with strong impacts on SST (across the entire basin south of equator but most strongly on the NW shelf of Australia), equatorial surface currents, and coastal upwelling along Java/Sumatra. Most of the MJO-SST variability can be understood as the response to atmospheric surface fluxes, with a primary role for heat flux. However, the region of largest SST variation in the Indian Ocean (to the northwest of Australia) is also a region of limited observations (e.g., a big gap in the RAMA array) and the largest term in the heat budget for mixed layer in this region is the residual. ***Can we better constrain surface heat fluxes (e.g., by deploying additional moorings to NW of Australia) so as to close the heat budget for MJO events?*** Interannually, a strong Indian monsoon has been hypothesized to lead to a colder Indian Ocean, thereby delaying monsoon onset in the following year (i.e., leading to a biennial variation). ***What mechanisms lead to this cooling? How robust is this mechanism (i.e., how robust is the biennial peak)?*** The recent cold phase of the IPO has been implicated in the recent reduction in ENSO variability. ***But what role has the cold phase of the IPO played in ENSO-monsoon teleconnection? What are the implications for the circulation/temperature of the Indian Ocean? What is the role of remote forcing from Atlantic, especially with respect to interaction of the monsoons with the Indian Ocean? In general, how does monsoon variability interact with or otherwise impact the Indian Ocean and how does this interaction vary across time-scales from intraseasonal, to interannual and decadal?***

Monsoon forcing has well-documented and profound impacts on boundary current circulations, upwelling, and stratification throughout the northern Indian Ocean and therefore also nutrient supply, ecosystem productivity and higher trophic level behavior and recruitment success. These impacts, which extend to at least 10° S, are also manifested in the eastern equatorial Indian Ocean off Java/Sumatra and northwestern/western Australia, and in the Western Indian Ocean off Somalia. It follows that intraseasonal, to interannual and decadal variability in monsoon forcing also must have profound impacts on ecosystem productivity, higher trophic level behavior and recruitment success and therefore also fisheries. Yet, with the exception of the western/central Arabian Sea (e.g., JGOFS Arabian Sea Process Studies), remarkably few studies have been undertaken to understand the linkages between monsoon variability and ecosystem response and especially higher trophic level response. ***How does monsoon variability impact nutrient supply, ecosystem productivity and higher trophic level behavior and recruitment success in the Indian Ocean? How, in turn, does this variability impact fisheries and therefore human populations in Indian Ocean rim nations and island states that depend on fisheries for their food supply and/or income?***

Because agricultural practices around the northern Indian Ocean rim have traditionally been tied to the annual monsoon cycle, forecasting monsoon variability on time scales ranging from weeks to years is an issue of considerable urgency. However, the Indian Ocean is a region of relatively low seasonal forecast skill (both for rainfall and SST) especially relative to the Pacific Ocean. This is partly related to the lack of a mechanism for long “memory” of the physical system (i.e., there is no delayed oscillator in the Indian Ocean). But, the monsoon has also been postulated to play a self-limiting role. ***Can we better understand the limits of predictability of the monsoons and what this means for prediction of the upper Indian Ocean circulation? Would improved observations of the Indian Ocean (i.e., improved initial conditions) result in improved predictions? In general, what role does the ocean play in promoting or limiting monsoon predictability?*** Seasonal forecast skill for monsoon rainfall remains low. ***Is this because model biases in the Indian Ocean are acting to limit forecast skill or does it simply reflect the low upper limit of predictability in the monsoon? What are the key model biases and errors that are acting to limit accurate simulation and prediction of monsoon variability (intraseasonal to seasonal), including the associated variability in the upper ocean?*** Longer time scale forecasts (interannual and decadal) are also needed in order to predict how the monsoons and their associated rainfall will vary in the coming years and, in particular, how they will respond to climate change and global warming.

THEME 4: CIRCULATION, CLIMATE VARIABILITY AND CHANGE

BACKGROUND

The monsoon winds drive the seasonally reversing surface currents of the northern part of the Indian Ocean, a unique process in the world ocean. The southern part of the basin, south of 10^{o}S to the Subtropical Convergence, is centered on the zone of subtropical high atmospheric pressure, which form a continuous belt around the globe during the Southern Hemisphere winter. The seasonal variation in this area is small compared to the northern Indian Ocean.

The global thermohaline circulation includes transport of warm, relatively fresh upper-ocean waters from the Pacific passing through the Indonesian Seas to the Indian Ocean and then onward into the South Atlantic via the Agulhas leakage (Figure 30). Much of this transport through the Indian Ocean occurs in the tropics south of the equator in the South Equatorial Current (SEC) and is strongly affected by ENSO and the Indian Ocean Dipole (IOD). The latter causes pronounced variability in the thermocline (Qian et al., 2003) and includes propagation of upper-layer thickness anomalies by Rossby waves (Xie et al., 2002; Feng and Meyers, 2003; Yamagata et al., 2004) in the SEC. About 10-15 Sv of water flows through the ITF from the Pacific into Indian Ocean thermocline waters and the SEC. Thus, the ITF links upper ocean waters of the west Pacific and Indian Oceans, modulates heat and fresh water budgets between these oceans, and in turn plays an important role in global climate. Although long-term trends in ITF transport have not been reported, climatic phenomena such as the East Asian monsoon, the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO) exert a strong influence on the transport, water properties and vertical stratification of the ITF (Meyers, 1996; Wijffels and Meyers, 2004; Xu, 2014).

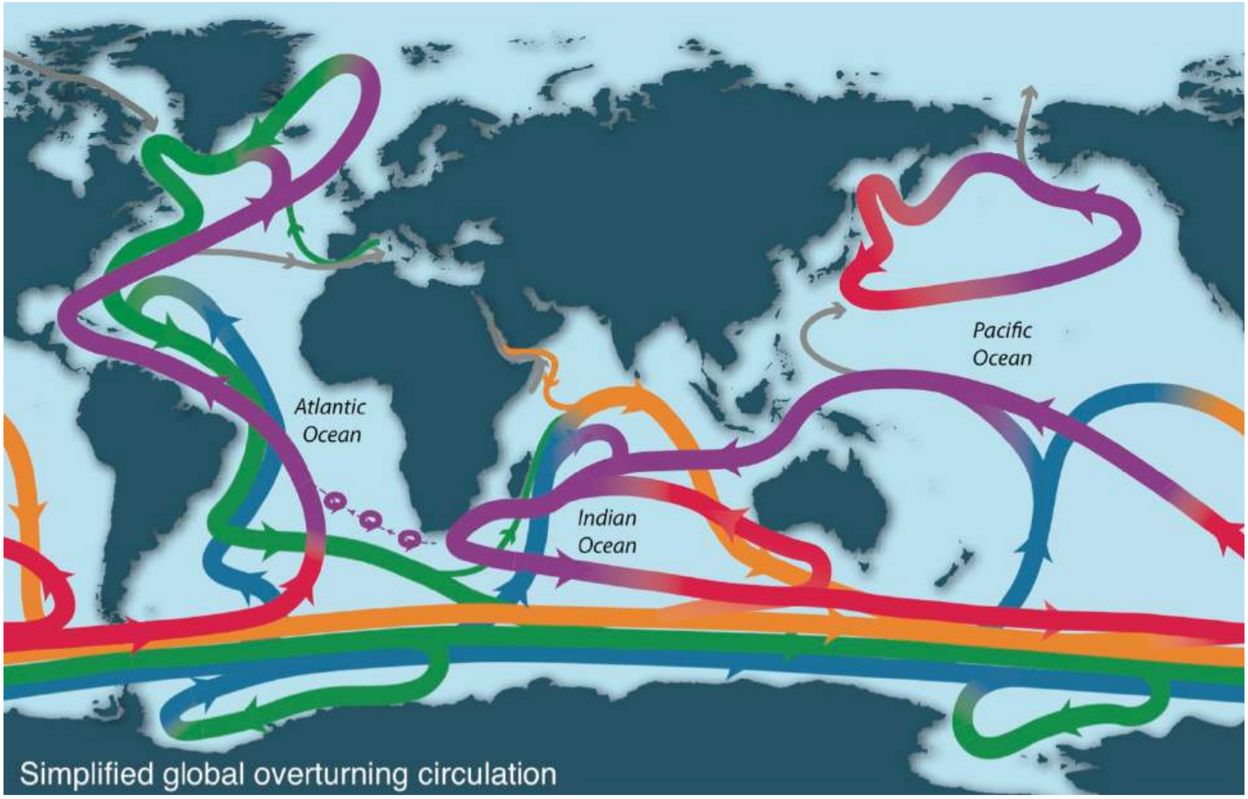


Figure 30: Simplified global thermohaline circulation showing roles of diapycnal upwelling and Agulhas and Tasman leakages in the Indian Ocean. From Talley (2013).

The South Equatorial Current feeds Indian Ocean heat into the Agulhas Current, which transports about 20 Sv of Indian Ocean water into the Atlantic Ocean. The Agulhas Current source water at its northern end is derived from the SEC via Mozambique Channel eddies (de Ruijter et al., 2002) and the East Madagascar Current, but the greatest source of water is recirculation in the southwest Indian Ocean sub-gyre (Gordon, 1985; Stramma and Lutjeharms, 1997). An interesting aspect of the Agulhas Retroflection (Figure 24) is that it periodically sheds anticyclonic rings >300 km in diameter at its westernmost extension. These rings enclose pools of relatively warm and saline Indian Ocean water whose temperature is more than 5°C warmer and salinity 0.3 psu greater than South Atlantic surface water of similar density (Gordon, 1985). The rings keep their distinctive thermal characteristics as far west as 5°E and as far south as 46°S, and they drift into the South Atlantic at approximately 12 cm s^{-1} (Lutjeharms and van Ballegooyen, 1988). This warm-water link between the Atlantic and Indian oceans is likely to have a strong influence on global climate patterns (Gordon, 1985; Beal et al., 2011).

The Indian Ocean overturning cells are important for redistribution of heat and other properties (Schott et al., 2002). The Indian Ocean has the world's largest meridional heat transport (Bryden and Beal, 2001; Lumpkin and Speer, 2007), with an estimated 1.5 PW exiting the basin across 32°S (Figure 31), associated with net heat gain from the atmosphere and vigorous diffusive heating and upwelling of deep and bottom waters. This transport balances heat loss in both the Atlantic and Southern oceans (Talley,

2013) and is likely linked to decadal variability of SST (Han et al., 2014) and CO_2 fluxes which influence climate around the Indian Ocean, yet it is poorly constrained and nothing is known about its variability.

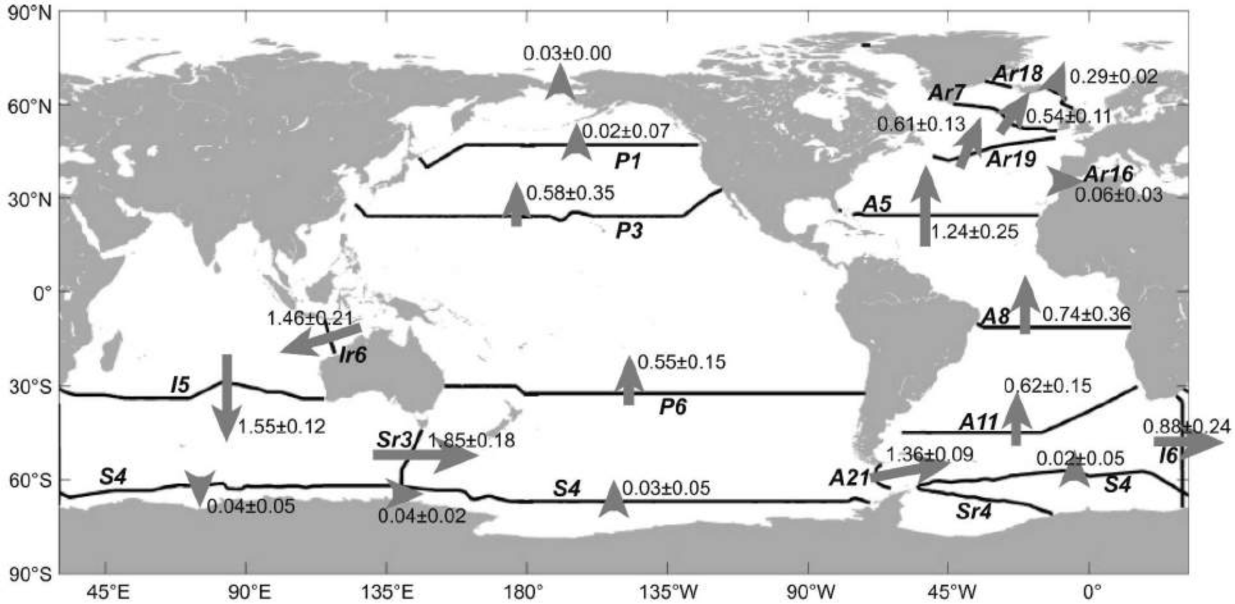


Figure 31: Global meridional heat flux estimates (in PetaWatts) showing the strongest heat transport in the south Indian Ocean. From Lumpkin and Speer (2007).

Several studies show that the near-surface waters of the Indian Ocean have been warming over the 20th Century (except in the South Equatorial Current; Figure 32), and it appears that the rate of warming has increased significantly in the latter part of the century, with some regions warming faster than 0.2°C per decade (IPCC, 2007). Models suggest that upper-ocean warming in the south Indian Ocean can be attributed to a reduction in the southeast trade winds and associated decrease in the southward transport of heat from the tropics to the subtropics (Lee, 2004). Warming in the northern Indian Ocean appears to be related to a reduction in the export of heat to the south across the equator, which is accomplished by a wind-driven, shallow cross-equatorial cell (Schoenefeldt and Schott, 2006).

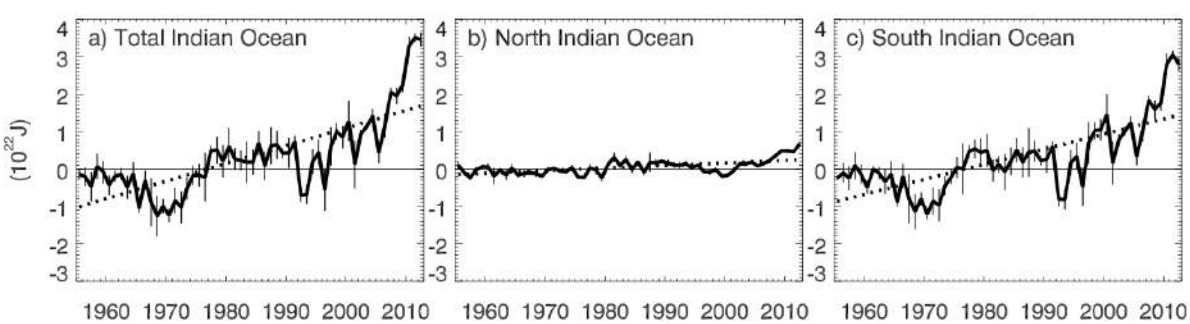


Figure 32: Decadal heat content change over the top 700 meters in the Indian Ocean. From Levitus et al. (2009).

Known changes in the Indian Ocean subtropical gyre circulation include a slowdown from 1962 to 1987 (Bindoff and McDougall, 2000) and a speedup from 1987 to 2002 (Bryden et al., 2003; McDonagh et al., 2005). During the slowdown the upper thermocline warmed, and it cooled during the speedup. Simulations of this region and the analysis of climate change scenarios show that these changes in the subtropical gyre circulation were part of a decadal oscillatory pattern (Stark et al., 2006).

On long timescales (centennial to millennial variability) relatively little is known about climate induced Indian Ocean variability (Figure 33). However, it has been shown that on the glacial/interglacial timescales two modes of operation prevailed (Peeters et al., 2004). During interglacial periods the Agulhas leakage functioned as a source of heat and salt for the meridional overturning of the Atlantic Ocean and may have contributed to the formation of North Atlantic Deep Water in terms of rate and magnitude. During glacial periods, the northward shift of the subtropical front passing the southern tip of Africa prevented Agulhas leakage. Hence, a pure retroflection mode prevailed during glacial periods, piling up heat and salt in the Indian Ocean. In addition, during glacial periods when sea level was lower transport through the ITF was reduced. When deglaciation re-started an initial pulsation of heat from the Indian Ocean to the Atlantic must have been very strong, gradually decreasing and reaching a constant rate and magnitude.

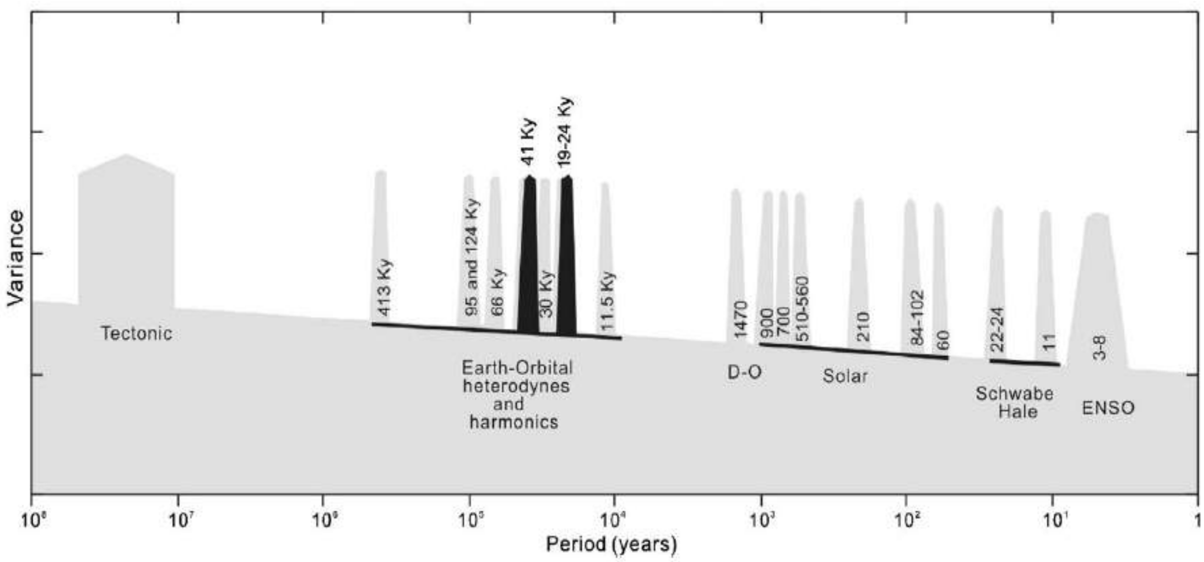


Figure 33: Conceptual spectrum of monsoon variability on the annual to techtonic time scale. Periods of spectral peaks are labeled. Relative concentrations of variance in these peaks are unknown. From Wang et al. (2005).

CORE QUESTIONS

1. **How has the atmospheric and ocean circulation of the Indian Ocean changed in the past and how will it change in the future?**

2. **How do these changes relate to topography and connectivity with the Pacific, Atlantic and Southern oceans?**

3. **What impact does this have on biological productivity and fisheries?**

The anticyclonic wind system over the southern Indian Ocean has expanded in response to global warming and ozone depletion, with a southward shift and strengthening of the Westerlies and a warming of the water column, most pronounced in the western subtropical gyre (Alory et al., 2007; Levitus et al., 2009). Similar warming and salinification events over the past 1 million years were accompanied by peaks in Agulhas leakage, which appear to have intensified the Atlantic Meridional Overturning Circulation and led to accelerated climate change (Peeters et al., 2004; Caley et al., 2011; Marino et al, 2013). **There is evidence that Agulhas leakage is currently increasing (Biastoch et al., 2009; Rouault et al., 2009), but will this trend continue (Beal et al., 2011; Le Bars et al, 2012Durgadoo et al., 2013)?** There is no consensus on variability and change of the Agulhas Current and its relationship to leakage beyond the recently observed seasonal cycle (Krug and Tournadre, 2012, Beal et al., 2014). **What can past changes in the strength and leakage of the Agulhas Current tell us about the future? How will the Agulhas Current/leakage and, indeed, the flow through the ITF and the global thermohaline circulation, change in response to global warming and sea level rise?**

The Indian Ocean Dipole (IOD) may shift towards a positive phase under climate change (Zheng 2013), with colder more salty waters in the eastern equatorial Indian Ocean and warmer, fresher waters in the western tropical gyre (Grunseich et al., 2011). These anomalies would lead to suppression of productivity in the Arabian Sea and western tropical gyre and enhanced productivity in the eastern equatorial Indian Ocean. The periodicity of IOD may have increased and the link with the Asian monsoon strengthened (Abram et al., 2008; Nakamura et al., 2009; Chu et al., 2014). Extreme positive IOD events are expected to increase due to the weakening of westerly equatorial winds and faster warming in the west (Cai et al., 2013; Chu et al., 2014), leading to more flooding in eastern Africa and droughts and forest fires in Indonesia and Australia (Ashok et al. 2003; Behera, 2005; Marchant et al. 2007; Cai et al. 2009; Ummenhofer 2009). Mesoscale activity in the Mozambique Channel and Agulhas system may also be affected by IOD/ENSO anomalies, which are propagated to the western boundary by Rossby waves (Wijffels and Meyers, 2004; Palastanga et al., 2006). **Can these changes be predicted with coupled ocean-atmosphere models? How will biogeochemical processes and ecosystem dynamics in the Indian Ocean respond to these IOD-induced changes in upwelling, stratification and productivity? What are the potential human consequences via changes in fisheries productivity and increased flooding in the west and droughts in the east?**

Interannual variability in the subtropics is dominated by a subtropical SST dipole, which influences rainfall over southern Africa and Australia and has complex, poorly understood links to IOD and ENSO (Reason, 2001; Zinke et al, 2004; England et al., 2006;). In the eastern subtropics, the Indonesian Throughflow and Leeuwin Current are strongly linked to Pacific equatorial winds and ENSO (England and Huang, 2005; Feng et al., 2010). Strengthening in easterly winds since the early 1990s appears to have led to a contemporary strengthening trend in both flows (Feng et al., 2011; Sprintall and Revelard, 2014), although they are expected to weaken in the long term in response to global warming (Sprintall et al., 2014). **How have these changes impacted biological productivity and fisheries in the eastern Indian Ocean? How will changes in the future associated with global warming impact human populations?**

As discussed above, the Indian Ocean has the world's largest meridional heat transport (Bryden and Beal, 2001; Lumpkin and Speer, 2007), with an estimated 1.5 PW exiting across 32° S, balancing heat loss in both the Atlantic and Southern oceans. Recent focus on wind-driven Southern Ocean upwelling and Atlantic overturning has overshadowed the essential role of deep diffusive heating and diapycnal upwelling of deep and bottom waters in the Indian (and Pacific) Ocean, where the associated overturning and heat transports are significant, but poorly constrained (Talley, 2013). Nothing is known about the variability of these transports, yet they are likely linked to decadal variability of SST (Han et al., 2014) and CO_2 fluxes across the Indian Ocean and therefore significant drivers of regional climate. **Can these overturning circulations and transports be better constrained? What are the biogeochemical impacts of these circulations and how do they influence global nutrient and carbon budgets?**

The submarine topography of the Indian Ocean is more complex than in any other ocean basin. **How does this topography influence the surface and deep circulations? For example, how does topography influence the return flow of the global thermohaline circulation between the Pacific and Atlantic oceans via the Indian Ocean? How have past changes in sea level influenced this flow and how might sea level rise impact it in the future and what are the global ramifications?** Topographic forcing has a strong influence on upwelling and mixing in the ITF (via the shallow Lombok and Ombai Straits and the Timor Passage), in the equatorial zone (e.g., the Ninety East Ridge) and in the western tropical Indian Ocean (e.g., the Mascarene Plateau). **How does this forcing impact biological productivity and fisheries and therefore human populations in Indian Ocean island states and rim nations?**

THEME 5: EXTREME EVENTS AND THEIR IMPACTS ON ECOSYSTEMS AND HUMAN POPULATIONS

BACKGROUND

Extreme events are rare natural occurrences that are far outside the norm for a particular place and time. They can have disastrous effects on vulnerable populations, both in terms of economic losses and the loss of life. There are many types of natural hazards that can, when they exceed a particular threshold, be categorized as extreme events. Often, extreme events are related to meteorological processes, for example, severe tropical storms, massive downpours, heat waves, and blizzards. Some involve both atmospheric and hydrological processes, such as flood and drought, which may be linked to extremes in climatic events like exteme IOD events (Cai et al, 2014). Extreme heat and drought combined can contribute to the spread of raging wildfires - another type of extreme event. Still other extreme events are geophysical in origin, such as volcanoes, earthquakes, and tsunamis.

Extreme events of oceanic character include, in addition to tsunamis, storm surge, coral bleaching, ocean acidification, harmful algal blooms (HABs), and deoxygenated “dead zones”. Storm surge involves wind-forced waves generated by tropical storms impinging on coastal zones, while tsunamis are the result of geophysical processes such as submarine landslides and earthquakes. HABs are a marine biogeochemical phenomenon in coastal and estuarine settings that can lead to fish kills, disrupt tourism, and cause human illness and death. A significant increase of the number of HABs has been observed in the coastal waters of Arabian Sea and Bay of Bengal in the past three decades (Padmakumar et al., 2012; Figure 34). Rising sea surface temperatures in the Indian Ocean as a consequence of anthropogenic greenhouse gas forcing, combined with climatic events like ENSO and the IOD, can push local temperatures over a threshold that leads to severe coral bleaching. Ocean acidification is increasing because of the uptake of CO_2 in the ocean, threatening biodiversity and adding an additional stressor to calcifying corals beyond the threats posed by pollution and bleaching.

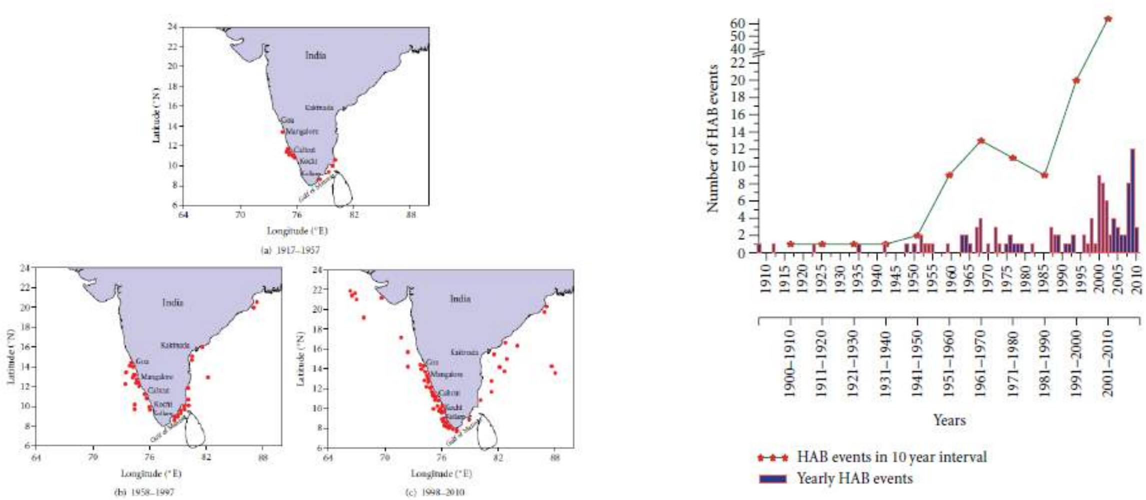


Figure 34: Trend figures indicating increasing incidence of harmful algal blooms in the Indian EEZ from 1917 to 2010 (left panels, red dots represent each algal bloom observed). Frequency of occurrence of harmful agal blooms during the last century (right panel). Figures from Padmakumar et al. (2012).

Extreme events occur all over the world. The Indian Ocean region is special though because of its unique oceanic and atmospheric circulation, geomorphology, and the vulnerability of populations living in the region. Many middle- and low-income countries with sizeable populations living in poverty rim the Indian Ocean. Extreme events expose these populations to great risk, since their ability to prepare for and mitigate the threats of natural hazards is limited. A few examples illustrate this point.

Cyclone Nargis in April-May 2009 developed over the warm surface waters of the Bay of Bengal and made landfall along the coast of Myanmar with wind speeds up to 210 km hr^{-1}, equivalent to a category 3-4 hurricane (McPhaden et al, 2009; Figure 35). The heavy rains and storm surge that inundated the low-lying and densely populated Irrawaddy River delta claimed 130,000 lives. The record for the deadliest tropical storm in history goes to Bhola, which hit what is now Bangladesh in November 1970. Storm surge on the low-lying and densely populated Ganges River delta claimed more than 500,000 lives. The Asian tsunami on 26 December 2004, triggered by the third largest earthquake ever measured, was the deadliest tsunami in recorded history, claiming 230,000 lives from island and coastal nations around the Indian Ocean (Lay et al, 2005). Severe droughts in India during the past decade (2002, 2004, 2009), caused by the failure of monsoon rains, led to billions of dollars in economic losses (e.g., Krishnan et al., 2006). Conversely, heavy summer monsoon rains led to historic flooding in Pakistan in July 2010 with up to a fifth of the country underwater at one time. Economic losses were in the billions of US dollars and more than 2000 people perished in the floodwaters.

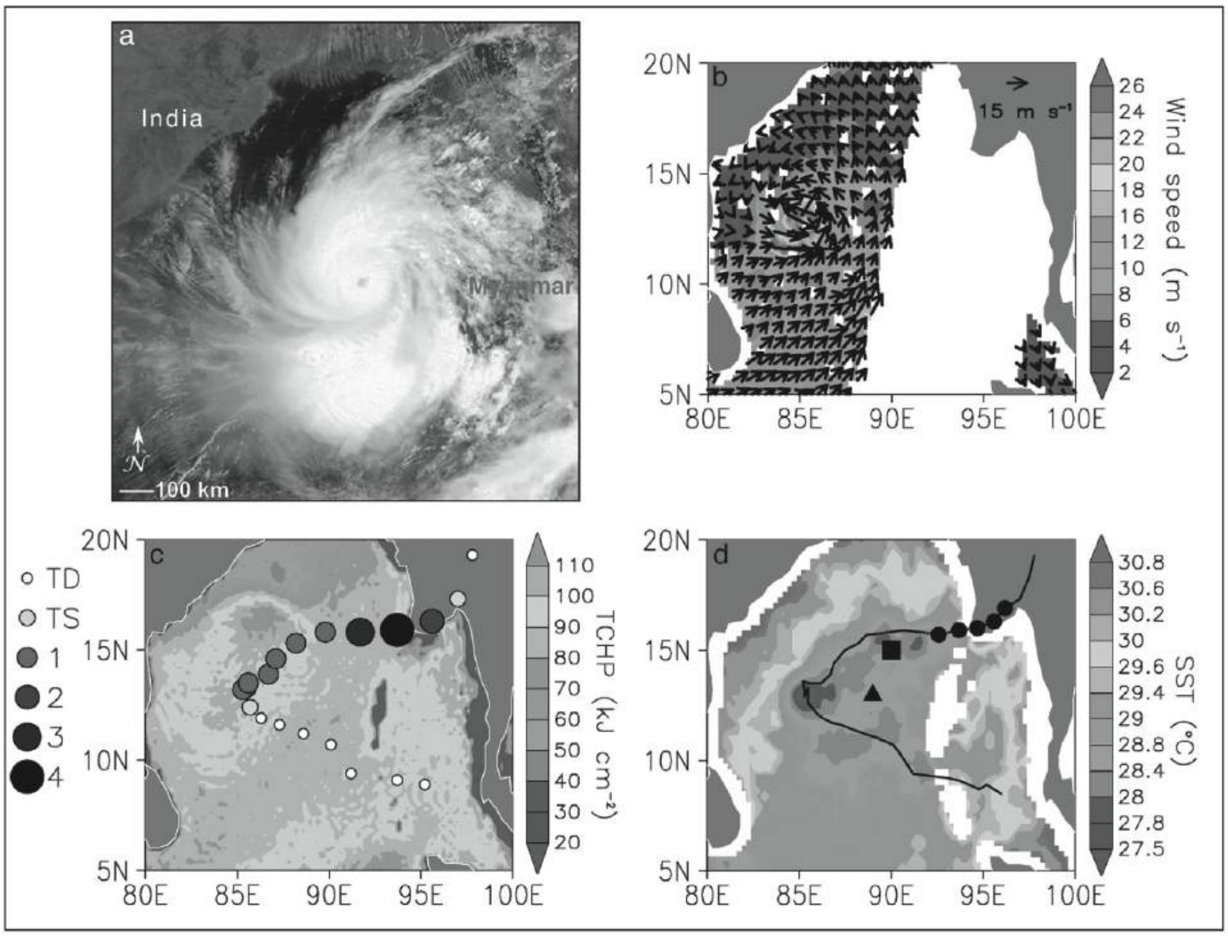


Figure 35: Cylone Nargis: (a) Moderate Resolution Imaging Spectroradiometer (MODIS) visible image, 1 May 2008 (Courtesy of NASA). (b) Quick Scatterometer (QuikSCAT) wind vectors and speeds for 28 April 2008. (c) Tropical cyclone heat potential (TCHP) climatology for April (in kilojoules per square centimeter). Composite image from McPhaden et al. (2009).

Extreme events are likely to increase over the course of the 21st Century as inferred from global climate change model projections (IPCC, 2012). It is virtually certain, for example, that in tandem with rising global temperatures, there will be more severe heat waves (for example, the 2013 austral summer heat wave over Australia (Figure 36) that led to destructive wild fires across the country). The most severe tropical storms are likely to increase in frequency even if the total number of storms remains constant or even decreases (Knutson et al., 2010). It is also likely that heavy rainfall events will increase in the future, since a warmer atmosphere can hold more moisture available for precipitation. Already, there are indications that heavy rainfall events are contributing a greater percentage of rainfall to Indian summer monsoon seasonal totals (Goswami et al., 2006). Droughts may also become more intense and prolonged in some regions of the globe by the end of the 21st Century.

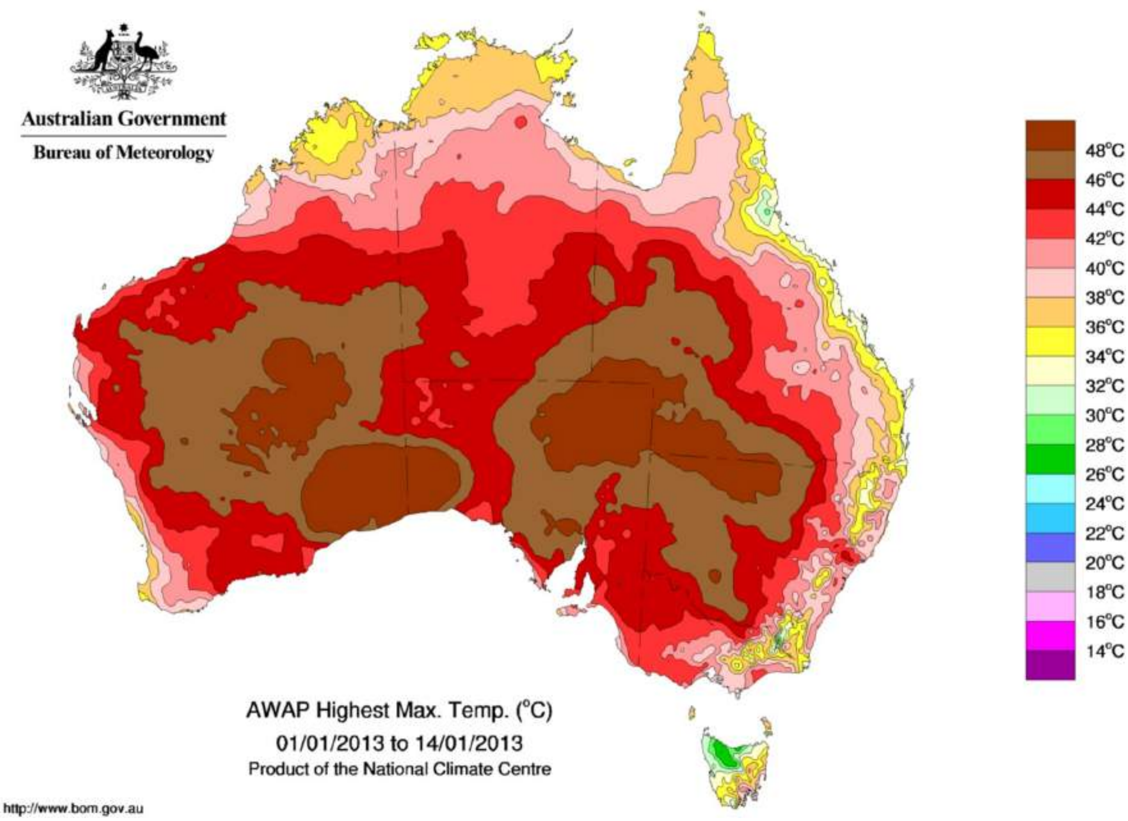


Figure 36: Highest maximum surface temperatures between 1/1/2013 and 1/14/2013 over the continent of Australia and Tasmania. From http://www.bom.gov.au.

Vulnerability to extreme events is also likely to increase in the 21st Century. Population growth, which is higher in the developing world, will expose more people from low- and middle-income countries to natural hazards. Also, there is demographic shift underway with more people migrating to coastal zones, where economic opportunities and living conditions are viewed as more favorable. Approximately 40% of the world's population today lives within 100 km of the coast and the number of people living in coastal zones is expected to double by 2025. Population density is also much higher in coastal zones, as is the concentration of wealth. Thus, coastal populations will be much more exposed to the increased threats from higher mean sea levels, more intense tropical storms, and more damaging storm surges resulting from elevated greenhouse gas concentrations in the atmosphere.

IIOE-2 can play a key role in assessing the risks associated with extreme events in the Indian Ocean region by providing fundamental new knowledge about the causes of these events. Meteorological, climatological and oceanographic processes that are the focus of IIOE-2 contribute to the genesis of all types of extreme events, with the exception of those that originate from geophysical processes. Research involving ocean-atmosphere interactions, ocean circulation, sea level rise, nutrient distributions, biological productivity and ecosystem dynamics will help to improve both the definition of these events and our ability to forecast them. This scientific knowledge can provide input to risk management strategies that minimize the adverse impacts of extreme events. It can also provide guidance for the development of adaptation strategies to make communities more resilient in the face of increasing threats from natural hazards in a warmer world.

CORE QUESTIONS

1. **How will climate change impact the frequency and/or severity of extreme weather events, tropical cyclones in the Indian Ocean?**

2. **How do extreme events in the Indian Ocean impact coastal and open ocean ecosystems?**

3. **What are the threats of extreme weather events, volcanic eruptions, tsunamis, combined with sea level rise, to human populations in low-lying coastal zones and small island nations of the Indian Ocean region?**

Tropical storms may increase in intensity in response to greenhouse gas forcing (Knutson et al, 2010), exposing vulnerable populations to even greater threats of flooding and hurricane force winds in the 21st Century. Sea level is rising globally due to both thermal expansion of the ocean and mass gain from runoff of glacial melt waters (IPCC, 2013). In addition, potential changes in the Indian Ocean monsoon and Walker circulations (Vecchi and Soden, 2007; Turner and Annamali, 2012) imprint regional structure to sea level rise (Han et al, 2010). Combined with the possibility that tropical storms may increase in intensity, inundation in low-lying coastal zones and island nations due to storm surge is likewise a growing threat. The frequency of extreme IOD events may increase in a warmer world, leading to more severe droughts and floods in Indian Ocean rim countries. ***Can we better represent modes of climate variability like the IOD and the effects that greenhouse gas forcing has on them in climate change models? How can we accurately downscale information on global and basin-scale processes to the regional and local scales of greatest relevance to affected populations? Can we reduce the uncertainty in future sea level rise projections for the Indian Ocean? Can we better represent the oceanic and atmospheric processes that give rise to severe tropical storms in climate change models?***

Ocean extremes related to sea level (e.g., storm surge and wind-waves) and their meteorological drivers (e.g., extreme weather events such as tropical cyclones and other storm events), coastal currents and extreme temperature events can have profound impacts on both coastal and open ocean ecosystems. The biological consequences of extreme events in the Indian Ocean are many and varied. Examples include the impacts of storm surges that combine with high waves, high tides and/or sea level rise (Shand et al., 2012), or high rainfall coinciding with high coastal sea levels (Zheng et al., 2013), to increase the frequency or extent of coastal flooding. In low-lying Indian Ocean rim nations and island states, these combined events can have devastating impacts on, for example, mangrove and coral reef-based coastal ecosystems. Extreme ocean temperatures events can also be disastrous for marine ecosystems (Feng et al., 2013; IPCC, 2013a). Temperature extremes can alter habitat, impact ecosystem health and cause changes in abundance of marine species through local extinctions. In the Indian Ocean, tropical marine species that are already living close to their upper thermal limits will be most affected. Interactions of temperature, ocean acidification, and hypoxia can enhance sensitivity to temperature extremes in organisms such as corals, coralline algae, mollusks, crustaceans, and fishes (IPCC, 2013a). Examples of recent ocean temperature extremes (Feng et al., 2013) and their impacts on marine biodiversity (Wernberg et al., 2014) have been recently documented. Research is needed to determine how future ocean temperature extremes might impact the unique marine ecosystems in the Indian Ocean and identify ecosystems that are particularly vulnerable and need protection. Development of improved forecast tools for extreme ocean temperature events to support management of reefs and fisheries is also needed. Historical changes in extreme sea levels and extreme waves and their impacts on coastal ecosystems need to be studied and better understood to gain insight into potential future impacts. ***How will shoreline erosion and deposition respond to sea level rise and extreme events such as storm surges and waves along different coastal types (e.g., sandy beach, rocky and coral reef coastlines, estuaries and coastal waterways?), and how will coastal ecosystems be impacted?***

The negative impacts of extreme events on coastal and open ocean ecosystems in the Indian Ocean can also have direct human consequences, for example, through reduced harvest in both coastal subsistence and open ocean commercial fisheries. These impacts can be serious in developing countries where food security often depends heavily upon fishing. Extreme events also have direct negative human consequences, for example, droughts, floods and storms can destroy property, reduce agricultural production, damage tourism and trade and cause loss of life. High exposure and vulnerability to extreme events are generally the outcome of skewed development processes associated with environmental degradation, rapid and unplanned urbanization in hazardous areas, failures of governance, and the scarcity of livelihood options for the poor. These problems are particularly acute in many developing nations around the Indian Ocean rim and in small island nations. ***How can these countries more effectively manage disaster risk? How can these countries be motivated to include disaster risk in national development plans and adopt climate change adaptation strategies?*** Adaptation and mitigation can complement each other and together can significantly reduce the risks associated with extreme events.

Finally, it should be noted that the Indian Ocean includes several countries that are particularly susceptible to extreme events associated with tectonic activity, that is, tsunamis and volcanic eruptions. The tectonic activity associated with subduction zones of the Java Trench and the Sunda Arc trench system has generated numerous tsunamis and volcanic eruptions over geologic time, which have had widespread impacts in the Indian Ocean. Most recently, the Indian Ocean Tsunami of December 26, 2004 was one of the deadliest natural disasters in recorded history. Indonesia was the hardest-hit country, followed by Sri Lanka, India, and Thailand. Moreover, the geography of Indonesia is dominated by volcanoes that are generated by these subduction zones. As of 2012, Indonesia had 127 active volcanoes and about 5 million people live and work within the danger zones. These volcanoes have been responsible for thousands of deaths in the region. Improved understanding of the geological processes that give rise to tsunamis and volcanic eruptions is needed to develop better warning systems and evacuation plans to mitigate loss of human life.

THEME 6: UNIQUE GEOLOGICAL, PHYSICAL, BIOGEOCHEMICAL AND ECOLOGICAL FEATURES OF THE INDIAN OCEAN

BACKGROUND

The exceptional phenomena exhibited in the Indian Ocean are the result of complex, both temporally and spatially variable, interactions among physical, chemical and biological processes. The phenomena are of major significance to ocean inventories of biologically important chemical elements and productivity, and are sensitive to and potential contributors to climate change, with broad teleconnections and societal relevance. However, the interactions remain poorly studied on multiple levels.

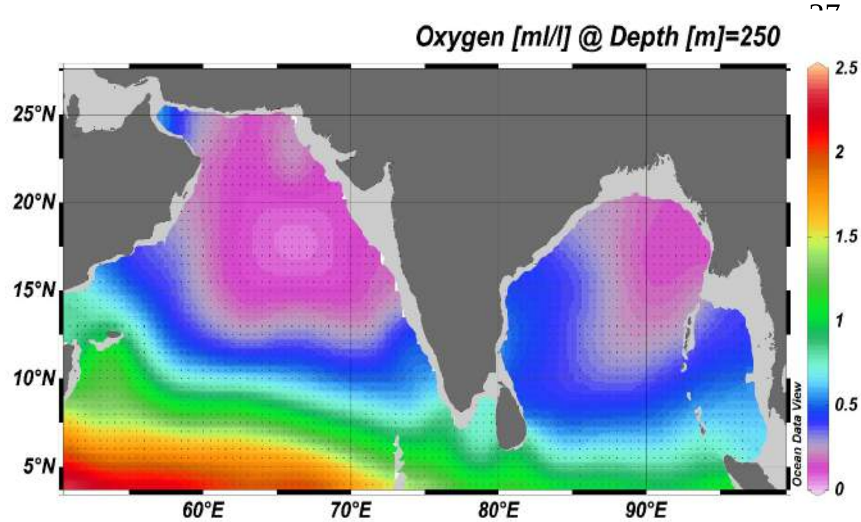


Figure 37: Dissolved oxygen concentration (ml/l) at 250 m depth in the Arabian Sea and Bay of Bengal.

As an important example, the Arabian Sea and Bay of Bengal contain the largest volume of open-ocean hypoxic waters on Earth (Figure 37) but, while both basins (unlike the Atlantic and Pacific) are landlocked to the north, they are fundamentally different in terms of the physical drivers of biological productivity and hypoxia. The seasonally reversing monsoons, which vary with the Indian Ocean Dipole (IOD), result in massive primary production in the Arabian Sea that, along with inputs from marginal seas and poorly ventilated subsurface flow, contribute to the intense mid-water oxygen minimum zone. Both productivity and hypoxia impact heavily on pelagic and benthic communities and processes. Yet, even

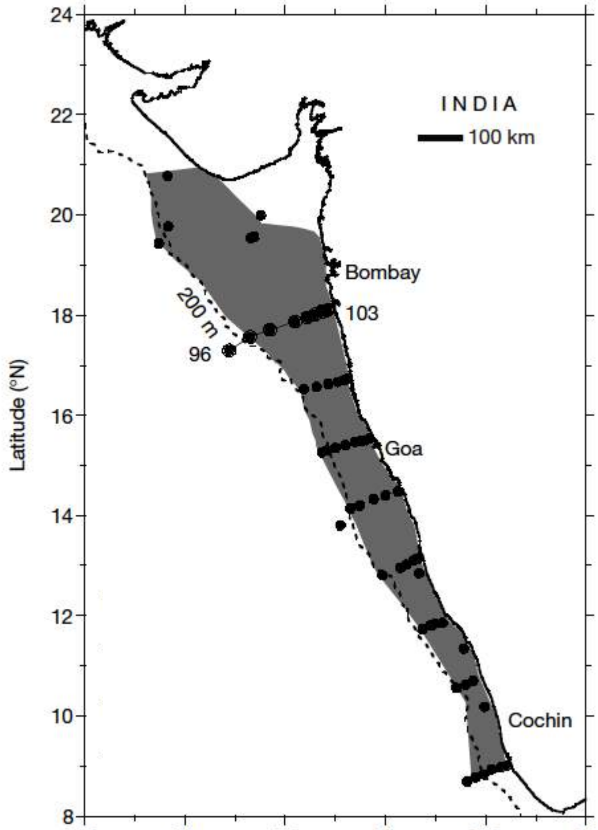


Figure 38: Zone of severe hypoxia on the western Indian shelf during September-October 1999 and locations of sampling sites. Zone of hypoxia is shown as shaded region (O_2 < 0.5 ml l^{-1}). Figure and caption modified from Naqvi et al. (2000).

within the Arabian Sea, striking regional (as well as seasonal) contrasts occur, in terms of coastal versus open-ocean upwelling and the intensity of mid-water oxygen depletion, and the associated particle fluxes and suboxic biogeochemical processes.

In the Bay of Bengal, monsoon-driven upwelling remains a factor, but midwater oxygen depletion is controlled primarily by stratification that results from Ganges-Brahmaputra runoff. The runoff and stratification again depend on the monsoons and the IOD, and there are also regional differences in productivity and oxygen depletion in the Bay of Bengal, but the stratification and river-born sediment load appear to create key differences in particle fluxes, organic matter turnover and oxygen depletion. Critically, open-ocean oxygen depletion in the Bay of Bengal remains slightly less intense than in the Arabian Sea, such that, for example, denitrification is not significant in the former area (Figure 11). However, oxygen depletion will increase with projected environmental change and/or with increased anthropogenic nutrient inputs. The potential biogeochemical consequences of the Bay of Bengal becoming fully hypoxic are immense, with respect to bioelement cycling and greenhouse gas emissions, and impacts on both pelagic and benthic ecosystems, resources (e.g., fish stocks) and large human populations. The expanding and intensifying seasonal hypoxia observed in recent decades on the Indian shelf (Arabian Sea, Naqvi et al., 2000; 2009; Figure 38), and sporadically in the Bay of Bengal, is evidence that these changes may already be underway. Fundamental questions remain about the mechanisms and variability of physical, biogeochemical and ecological interactions, about the causes for regional differences, about the roles of, and impacts on, biological communities – from microbes and higher trophic levels (e.g., mesopelagic fish stocks) – in hypoxic environments, and how ecosystem function may respond to future change.

Multiple other phenomena and interactions are of similar importance but remain poorly constrained. For example, in the equatorial Indian Ocean, the zonal thermocline and nutricline shoal toward the west rather than the east as in the Pacific and Atlantic oceans. The equatorial Indian Ocean 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 IOD. Many aspects of these unique physical dynamics, and their ecological and biogeochemical impacts, remain unclear.

Another example is the understudied southern subtropical gyre circulation of the Indian Ocean. As in the Atlantic and Pacific, this gyre is bounded by a westward intensified, poleward-flowing boundary current (the Agulhas), but the eastern side is bounded by the anomalous southward-flowing Leeuwin current (Figure 7), which has the largest eddy kinetic energy among all mid-latitude eastern boundary current systems. In addition, the northern side of the gyre is bounded by the SEC, which transports warm, nutrient-enriched freshwater from the ITF across the basin. These currents, combined with the topographic influence of the Ninety East Ridge, generate numerous westward-propagating eddies (Figure 39) and unusual circulation patterns that are not fully understood in terms of their physical or biogeochemical impacts.

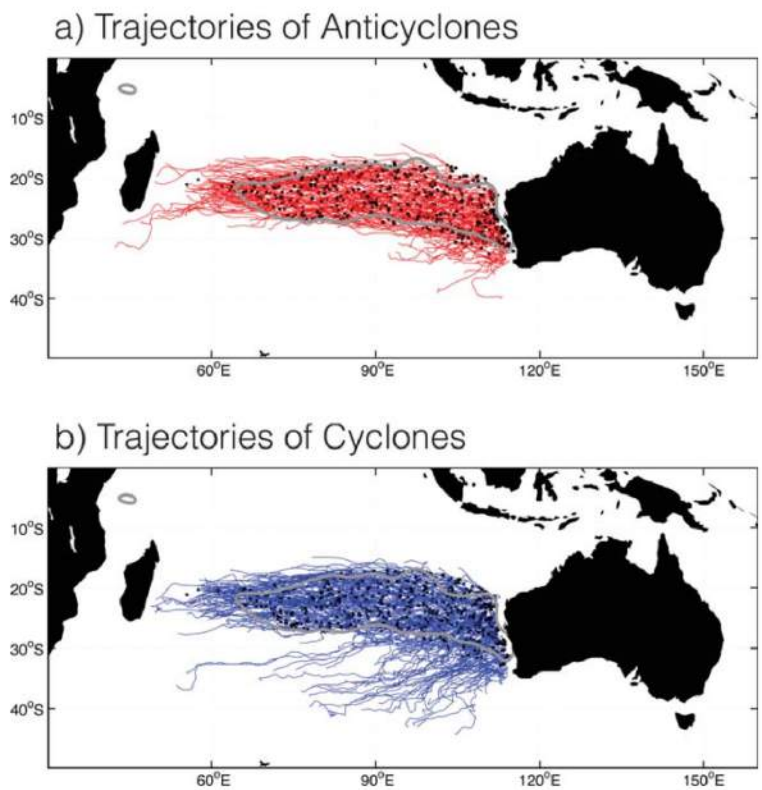


Figure 39: Trajectories of the (a) anticyclonic and (b) cyclonic eddies derived from satellite altimeter data. The start location of each eddy is marked with a black circle. The 0.2 contour of smoothed cross correlation between satellite-measured chlorophyll concentration and eddy- induced Ekman pumping velocity is shown in gray. From Gaube et al. (2013).

Finally, important questions remain unanswered about the physical, biogeochemical and ecosystem phenomena associated with the complex geology and topography in the Indian Ocean (Figure 3). Numerous seamounts, ridges and plateaus strongly influence circulation and mixing/upwelling, and give rise to unusual and contrasting productivity regimes that are atypical of surrounding deepwater areas. They must serve as important aggregation points for feeding and reproduction of commercially important fish species, but neither this function, nor their biogeochemical significance, have as yet received adequate research attention. These topographic features must also strongly influence the deep Indian Ocean circulation, but little is known about these impacts either. In addition, the tectonically active mid-ocean ridges and their associated hydrothermal vent circulations inject trace metals and reduced compounds into the deep ocean. The fate and impacts of these trace metals are largely unknown, though new insights are now emerging from the GEOTRACES program. The reduced compounds provide the energy to drive chemoautotrophic production, which supports diverse hydrothermal vent communities, yet these have received relatively little research attention compared to the Atlantic and Pacific.

CORE QUESTIONS

1. **What processes control the present, past, and future oxygen dynamics of the Indian Ocean and how do they impact biogeochemical cycles and ecosystem dynamics?**

2. **How do the physical characteristics of the southern Indian Ocean gyre system influence the biogeochemistry and ecology of the Indian Ocean?**

3. **How do the complex tectonic and geologic processes, and topography of the Indian Ocean influence circulation, mixing and chemistry and therefore also biogeochemical and ecological processes?**

The oxygen minimum zones (OMZs) of the present-day northern Indian Ocean are modulated by a complex interplay among factors controlling productivity and organic matter export, the age and ventilation of intermediate water inflow, and the extent of surface layer stratification. These factors vary both between and within basins, but in both basins hypoxia intensifies and the OMZ increases in thickness from southwest to the northeast, and margins experience markedly different redox conditions and processes (Figure 11). This regional trend does not map onto upwelling/primary productivity in either basin, clearly highlighting the complexity of controlling factors. Overall, intermediate waters of the Bay of Bengal are slightly more oxygenated than in the Arabian Sea, but are poised on the brink of becoming fully hypoxic. The causes for this subtle but critical difference remain uncertain. Seasonal coastal hypoxia, associated with upwelling and runoff-induced stratification, potentially compounded by increasing riverine nutrient inputs, is also an important phenomenon in both basins. In particular, it occurs along the entire western (Arabian Sea) shelf of India, forming the largest expanse of coastal hypoxic waters on Earth (Naqvi et al, 2000, 2009).

Biogeochemical processes occurring under hypoxic conditions in the water column and sediments across both basins have far-reaching biogeochemical importance. These include key source or sink terms in the global cycles of C, N and P, as well as important fluxes of greenhouse gases, together influencing ocean nutrient inventories, productivity and global climate. However, fundamental questions remain, especially in the relatively poorly studied Bay of Bengal, including ***How do factors controlling oxygen dynamics interact to result in the OMZs of the northern Indian Ocean and observed differences in oxygen depletion within and between basins? What roles do freshwater runoff and suspended sediment load play in modulating the oxygen dynamics of the Bay of Bengal relative to the roles of upwelling and productivity in the Arabian Sea? What controls development of coastal hypoxia and what are the relative influences of natural and anthropogenic factors? What are the threshold oxygen levels for key biogeochemical processes and fluxes associated with hypoxia? How do pelagic and benthic processes interact as controls on oxygen dynamics, and what are the net effects of progressive oxygen depletion on biogeochemical processes and bioelement source and sink terms*? What are***

the impacts of hypoxia, both mid-water and coastal, on pelagic and benthic communities and ecosystem function?

Sediment records have shown that oxygen depletion in the northern Indian Ocean, and associated biogeochemical processes, are temporally dynamic phenomena. For example, wholesale fluctuations have occurred in productivity and mid-water oxygen depletion (from fully aerobic to anoxic) in the Arabian Sea on both orbital and sub-orbital timescales (Reichart et al 1998; Schulz et al 1998; see also Wang et al., 2005 and literature therein). However, the nature and interplay of monsoon-driven upwelling and other mechanisms behind these fluctuations remain unclear, and the record is particularly uncertain for the Bay of Bengal. ***How have the degree and areal extent of hypoxia varied in the past, and in the Bay of Bengal relative to the Arabian Sea? What have been the relative contributions, over different timescales, of changes in upwelling and productivity, intermediate water circulation and freshwater runoff in modulating past oxygen dynamics in the two basins? What have been the consequences of past fluctuation in oxygen levels for ocean nutrient inventories, biogeochemical cycles and feedbacks on environmental change? Do past records permit predictions of how hypoxia and biogeochemical processes in the northern Indian Ocean will evolve in response to future environmental change?***

Oxygen depletion and associated biogeochemical processes and fluxes are expected to intensify with projected changes in temperature, circulation and surface ocean stratification, potentially compounded by direct anthropogenic forcing through eutrophication. The adaptations to pelagic and benthic hypoxia in the northern Indian Ocean, and the ecosystem roles played by higher organisms in hypoxic systems, are poorly characterized. While there is a threat of full-scale mortality – “dead zones” - with prolonged hypoxia, system response to partial oxygen depletion or short-term extreme events is less clear. Recent intensification of seasonal hypoxia on the western Indian shelf (Arabian Sea), as well as occurrences of coastal hypoxia in the Bay of Bengal, suggest that the expansion and intensification of hypoxia in the northern Indian Ocean may already be underway, with major potential consequences for biogeochemical cycling, fisheries and other marine resources, and for the food security of the large populations of northern Indian Ocean rim nations. ***How will benthic and pelagic communities and ecosystem function in coastal and open-ocean waters respond to seasonal or prolonged hypoxia in the future? What will be the impacts of future hypoxia on fish stocks, commercial fisheries and food security for IO rim nations?***

The southern central gyre of the Indian Ocean is one of the least well-studied regions of the global ocean. The surface circulation is dominated by westward and eastward propagating eddies. It is likely that both the deep and surface circulations of the gyre and eddy-generation processes are strongly influenced by the Ninety East Ridge, yet relatively little is known about these processes. In general, in situ, remote sensing and modeling studies need to be undertaken to better characterize the nature of surface, intermediate and deep-water flows and heat transport in the southern central gyre of the Indian Ocean. ***What role does the Ninety East Ridge play in modifying surface and deep currents? What are the physical and biogeochemical impacts of these***

ubiquitous eastward and westward propagating eddies?

The contribution from the southern subtropical gyre to the transport of the Agulhas Current is large (Stramma and Lutjeharms, 1997). In contrast, on the eastern side of the basin the exchange between the gyre and the ITF, SEC and the anomalous southward-flowing Leeuwin Current has not been fully quantified due to the complexity of the circulation patterns in this region (Domingues et al., 2007). These exchanges need to be better quantified. Information on the nature and dynamics of nutrient supply/limitation, plankton populations (phytoplankton community structure and grazing control etc) and higher food-web structure and fish stocks in this region are generally lacking. ***What are the consequences of the exchanges between the ITF, SEC, the Leeuwin Current and the southern subtropical gyre of the Indian Ocean for nutrient biogeochemistry, primary production and fisheries productivity in the southeastern Indian Ocean?***

There is emerging evidence from remote sensing that the southern central gyre of the Indian Ocean is expanding (e.g. Jena et al, 2012). Similar trends have been reported for the Atlantic and Pacific oceans (Polovina et al., 2008). The remote sensing data, however, do not go far back enough in time to determine the nature of this change (Rykaczewski and Dunne, 2010). ***Is this apparent expansion of the southern central gyre in the Indian Ocean indicative of a global warming-induced long-term trend or is it a manifestation of shorter time-scale (e.g., decadal) variability? How, in general has the southern central gyre circulation varied in the past in response, for example, to changes in sea level, and how is it likely to change in the future?***

It should also be noted that the surface and deep water exchanges between the southern central gyre of the Indian Ocean and the Southern Ocean are not well understood either physically or biogeochemically. ***What is the nature of surficial and deep exchanges between the southern subtropical gyre of the Indian Ocean with the Southern Ocean and how do these exchanges impact the heat, nutrient and oxygen budgets in the basin?*** We also know that the Southern Ocean sector of the Indian Ocean is iron-limited (Blain et al. 2003), but it is not known how far north this limitation extends into the southern central gyre. Piketh et al. (2000) have suggested that dust and iron transport from South Africa stimulate carbon fixation and create a carbon sink in a broad swath across the southern Indian Ocean, which is borne out by the strong autotrophy and net CO_2 sink found in the 20-35°S zone (Bates et al., 2006ab). Thus, spatio-temporal balances of iron-replete conditions, iron-limitation, and mineral dust enhancement of primary production and new nitrogen sources (through N_2-fixation) may play an important role in controlling the biological pump and the CO_2 source/sink balance in the southern central gyre of the Indian Ocean. ***What role does the southern central gyre play in the basin wide CO_2 dynamics of the Indian Ocean and, in general, global carbon cycling? What influence does iron transport and deposition play in modifying CO_2 sources and sinks in this region?***

In addition to the profound influence of the Ninety East Ridge, there are many other topographic features in the Indian Ocean that have a significant influence on physical, biogeochemical and ecological processes in the Indian Ocean (Figure 3). The Indian Ocean is home to large numbers of seamounts and ridges, as well as unique existence of large areas of shallow topography such as the Mascarene Plateau and Walter's Shoal. These topographic highs are important in terms of fisheries and biodiversity, as well as having far-reaching impacts on circulation, mixing and productivity. Yet the influence of these features remain poorly studied. The Chagos Islands are part of world's largest marine protected area (MPA). ***The physical, biogeochemical and ecological effects of shallow seamounts and ridges in the Indian Ocean and associated MPAs need to be assessed in relation to their contributions to Indian Ocean biodiversity and fisheries management.***

Finally, the deep Indian Ocean is crisscrossed by three tectonically active mid-ocean ridges, which form a remarkable triple junction on the ocean floor in the southern central Indian Ocean between 20° and 40° S (Figure 3). These ridges include the Carlsberg/Central Indian Ridge (which extends northward from the triple junction into the Arabian Sea and the Gulf of Aden); the Southwest Indian Ridge (which extends southwestward into the Southern Ocean and into the South Atlantic); and the Southeast Indian Ridge (which extends into the Southern Ocean and into the South Pacific). All of these ridge systems are poorly explored compared the mid-ocean ridges in the Atlantic and Pacific. The Southwest Indian Ridge is one the largest ultraslow spreading ridge systems in the world, with vents associated with both magmatic and amagmatic rifting. These spreading centers are almost certainly important sources of trace elements in the deep Indian Ocean and Southern Ocean and possibly also in the surface and the global ocean, but the element fluxes from these ridges have yet to be fully quantified. ***What is the contribution and impact of trace metals from Indian Ocean spreading centers to basinwide and global biogeochemistry and productivity?***

Moreover, as in the Atlantic, Pacific and Southern oceans, the hydrothermal vents associated with these spreading centers continuously inject reduced inorganic compounds into the water over the deep ridges, which supports chemautotrophic primary production on the bottom and in the overlying water column. This primary production, in turn, fuels remarkable hydrothermal vent communities, but the exploration and characterization of these vent communities in the Indian Ocean has been very limited to date. ***How similar are Indian Ocean hydrothermal vent communities to those that are found in the other ocean basins? Have alternative new chemautotrophic symbioses evolved in association with any of these spreading centers? How do these communities persist in the face of the ephemeral hydrothermal vents and how far can the larvae of these organisms travel along and between the ridges? Is there significant gene flow between the hydrothermal vent communities found in different parts of the basin? In general, the hydrothermal vent communities need to be explored and studied in the Indian Ocean.***

ONGOING AND PLANNED RESEARCH

A large part of IIOE-2, which is planned for 2015–2020, involves organizing ongoing research and stimulating new initiatives as part of a larger sustained expedition to the Indian Ocean. International programs that have research and observations ongoing or planned in the Indian Ocean during this time include the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, the Climate Variability (CLIVAR) project, the Indian Ocean component of the Global Ocean Observing System (IOGOOS), GEOTRACES (a global survey of trace elements and isotopes in the ocean), the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), the International Ocean Discovery Program (IODP), InterRidge (an international organization that promotes interdisciplinary, international studies of oceanic spreading centers) and others. Many countries, including Australia, China, Germany, India, Indonesia, Japan, the United Kingdom, and the United States, are planning research in the IIOE-2 time frame as well.

IIOE-2 RESEARCH INITIATIVES

In addition to organizing ongoing research, the IIOE-2 will work to initiate new geologic, ocean and atmospheric research projects and programs that are designed to address the core research questions articulated above. For example, planning efforts are underway to initiate upwelling research initiatives in the both the eastern and western Indian Ocean. These new initiatives, which are aligned with CLIVAR's interdisciplinary upwelling research theme, will be focused on understanding the interacting forces that drive upwelling variability in the Indian Ocean and the resulting biogeochemical and ecological responses.

Upwelling, used here in the general sense to imply the vertical movement of water and not necessarily outcropping, is an important mechanism in ocean dynamics that strongly influences coastal and open ocean regions. Although limited to a vertical movement of less than a few hundred meters, it underpins physical, atmospheric and biological processes in and above the ocean as well as in adjacent land masses. Not only is upwelling a key process that regulates ocean ecosystem functioning (i.e., through facilitation of the vertical flux of nutrients and biogeochemical tracers into the euphotic zone), but it also effects the depth of the mixed layer and at times sea surface temperature (SST) which both influence climate variability, and ultimately rainfall and drought over land. Upwelling also influences higher trophic level productivity and marine biodiversity and in many cases recruitment of species through its influence on food supply and through advection of eggs and larvae. Consequently fisheries are strongly related to upwelling.

In the open Indian Ocean, the trade winds, under the influence of the Coriolis Effect, cause a shoaling of the mixed layer in the form of the Chagos-Seychelles Thermocline Ridge (SCTR). This feature influences tropical cyclones and enhances productivity and is therefore an important enrichment feature for tuna feeding. In the central equatorial Indian Ocean the interaction of equatorial currents with the Chagos-Laccadive Ridge and seamounts induces island wake effects of which relatively little is known (Strutton et al., 2015). Similarly, little is known of the interaction between the South Equatorial Current and the high relief of the Mascarene Plateau where several channels give rise to topographic steering of the westward flow and where turbulence and mixing are induced.

The ultimate dependence of upwelling on wind and wind-driven currents implies that upwelling will be affected by global climate change with obvious socio-economic consequences.

THE EASTERN INDIAN OCEAN UPWELLING RESEARCH INITIATIVE

Planning for an Eastern Indian Ocean Upwelling Research Initiative (EIOURI) is already in an advanced stage. The main foci of this initiative will be on the upwelling regions that develop seasonally off Java, Sumatra, and northwestern Australia (Figure 40). However, the broader area of interest also includes upwelling in the eastern equatorial Indian Ocean, the Sri Lanka Dome and upwelling associated with boundary currents in the Bay of Bengal and Andaman Sea. and off western Australia associated with Leeuwin Current and the eddies it generates (Figure 40).

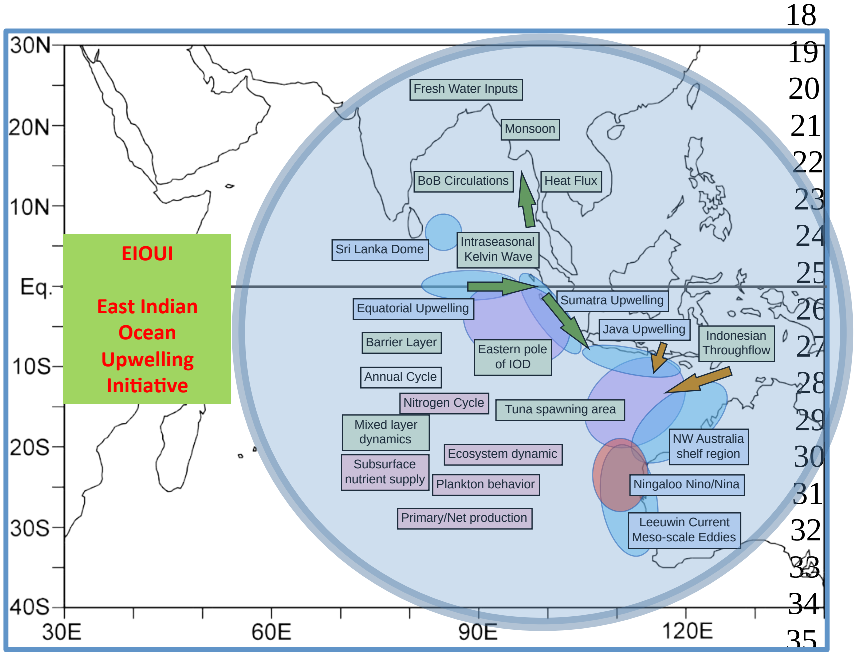


Figure 40: Regions and processes of interest in the Eastern Indian Ocean Upwelling Research Initiative.

The physical oceanography and atmospheric science drivers for this initiative include understanding the combined influences of local versus remote forcing on upwelling variability and also coastal–open ocean interactions. The study of local versus remote forcing includes consideration of ocean-atmosphere interaction, seasonal development and decay and intra-seasonal, and inter-annual variability in upwelling. This theme also covers the impacts of equatorial wave dynamic processes and local wind forcing, and the influence of the ITF on upwelling. The study of coastal–open ocean interactions in EIOURI includes consideration of the impacts of eddies and jets on onshore-offshore transport and also the broader influence of eastern Indian Ocean general circulation.

The biogeochemical and ecological science drivers for EIOURI include the need to understand the impact of the unique regional physical forcing in the eastern Indian Ocean upwelling regions on nutrient concentrations and stoichiometry related, for example, to the influence of the ITF, atmospheric inputs, nitrogen fixation and denitrification, and also how phytoplankton productivity and community composition responds to these nutrient inputs. ***What is the fate of this productivity response (recycling, transfer to larger consumers, aggregate export, transport offshore in filaments and eddies)? Are there differences in trophic transfer efficiency in eastern Indian Ocean upwelling regions compared to other eastern boundary upwelling centers, related, for example to differences in the food web dynamics? In addition, what are the biogeochemical and ecological impacts of lower oxygen and pH in upwelled water? Is this water advected onto to the shelf in these upwelling regions? What are the potential human consequences?***

THE WESTERN INDIAN OCEAN UPWELLING RESEARCH INITIATIVE

In addition to EIOURI, planning efforts have been initiated to develop a complementary upwelling research initiative on the western side of the basin. The western Indian Ocean contains a rich diversity of geophysical mechanisms that induce upwelling and make this region very different from the eastern Indian Ocean and, in fact, unique worldwide. The Asian-African monsoon produces one of the most intense upwelling regions in the Indian Ocean off Oman and Somalia (Figure 7). In the southwestern Indian Ocean, the influence of Madagascar on the SEC produces high turbulence in the Mozambique Channel in the form of mesoscale anticyclonic and cyclonic eddies. The latter have upward doming of the thermocline in their centers, which enhances productivity in the upper layer of the ocean while the anticyclones cause shelf edge upwelling along the Mozambican coast. To the south along the southeast coast of South Africa, the Agulhas Current, one of the most powerful western boundary currents on the planet, forces shelf-edge upwelling through divergence and generation of transient and fixed cyclonic eddies.

The varying upwelling systems in the western Indian Ocean can be grouped and distinguished into 9 systems — referred to as regional "upwelling" projects in the WIOURI (Figure 7 and Figure 24, left panel):

1. Agulhas Current-driven upwelling
2. Upwelling in the Mozambique Channel
3. Madagascar Ridge and seamounts
4. Upwelling in the East African Coastal Current (EACC) and influence of major islands (Mafia, Zanzibar, Pemba)
5. Upwelling in the Somalia Current system
6. Oman/Arabian Sea upwelling system
7. Chagos-Seychelles upwelling dome and Chagos Ridge
8. Mascarene Plateau-induced upwelling
9. Chagos-Laccadive Ridge-induced island wake effects

Capacity building and legacy are core themes of the IIOE-2 (see Training and Education below). An important feature of these upwelling initiatives is that the science is "down-scalable" from oceanic questions and observational systems towards the coastal areas of Indian Ocean rim countries so as to allow local research capacity to play a meaningful role. For example, simple Underwater Temperature Recorders (UTRs) can be deployed in the coastal areas to record upwelling events, which can be monitored by the regional scientific community. Two legacy projects anticipated from the WIOURI are the establishment of the School of Technical Oceanography (SOTO) in Cape Town and the replenishment and capacitation of the new Institute of Marine Science (IMS) in Zanzibar. SOTO is designed to produce new competent graduates in the technical side of oceanography including instrumentation, moorings, platforms, design, data analysis, visualization for the region, including upskilling of existing human resources through short courses. It also will underpin observational system support in the southwestern Indian Ocean region. The new IMS has the potential to become a central venue for science coordination via meetings, sabbaticals, and the hosting of the Western Indian Ocean Marine Science Association (WIOMSA) and its functions of support funding, publication and its biannual science symposium. It is hoped that these legacies of IIOE-2 could become a modern equivalent of the capacity building achievements of the original expedition which established, among other things, the National Institute for Oceanography (NIO) in Goa, India.

OTHER POTENTIAL IIOE-2 RESEARCH INITIATIVES

It is important to emphasize that EIOURI and WIOURI are just examples of two research initiatives that are already emerging under IIOE-2. Indeed, the scope of the Expedition is much broader than upwelling and embraces many other aspects of physical, chemical and biological oceanography and also geology and atmospheric science. Efforts will be undertaken to promote additional interdisciplinary initiatives under IIOE-2. These could include initiatives dedicated to any of the core themes articulated above. For example, Theme 3 (Monsoon Variability and Ecosystem Response) provides three overarching questions that could provide the foundation for a major IIOE-2 research initiative: What factors control present, past and future monsoon variability? How does this variability impact ocean physics, chemistry and biogeochemistry in the Indian Ocean? What is the effect on ecosystem response, fisheries and human populations?

In addition to the six themes, a major research initiative could be dedicated to exploring and better understanding the geophysical processes that have given rise to the complex submarine topography of the Indian Ocean. Such an initiative could potentially include exploration of how the complex tectonic and geologic processes, and topography of the Indian Ocean influence circulation, mixing and chemistry and therefore also biogeochemical and ecological processes at the surface and/or in the deep sea. Another potential topic could revolve around paleoceanography and one or more of the core questions articulated under research themes 2, 3 and 4: How have upwelling processes and their influence on local weather and climate changed in the past and how will they change in the future? What processes control the present, past, and future oxygen dynamics of the Indian Ocean and how do they impact biogeochemical cycles and ecosystem dynamics? How has the atmospheric and ocean circulation of the Indian Ocean changed in the past and how will it change in the future?

MONITORING, REMOTE SENSING AND MODELING

MONITORING

Long-term monitoring efforts are ongoing in several coastal and open ocean locations in the Indian Ocean. Studies motivated as a part of IIOE-2 should target and build upon this existing research infrastructure.

COASTAL MONITORING AND OBSERVATIONS

Australia's Integrated Marine Observing System (IMOS) is an example of a national observing system that is deploying high-technology sampling devices for making routine observations in its Indian Ocean coastal zone (Figure 41). Among other things, the Australian IMOS program is deploying long-term combined biological/physical moorings in shallow (< 200 m) waters off the south, west and northwest coasts of Western Australia. 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 south-eastern Africa; Oman's two cabled observatories on the shelf (off of Oman) in the northwestern Arabian Sea; and India has established open ocean time-series stations in the Arabian Sea and Bay of Bengal. All of this infrastructure could be leveraged and potentially expanded as part of IIOE-2.

Figure 41: Observational assets of Australia's Integrated Marine Observing System (IMOS).

In addition, the Bay of Bengal Large Marine Ecosystem (BOBLME) program could be engaged to help coordinate international research in the Bay of Bengal. The potential for leveraging ongoing programs is particularly strong in the Southern Hemisphere, for example, the Leeuwin Current and the Mozambique Channel, where there are few political impediments to carrying out research in the coastal waters. The international relevance is particularly strong in the western tropical Indian Ocean as the tuna fisheries off the east African coast are important to several countries.

OPEN OCEAN MONITORING AND OBSERVATIONS

CLIVAR and IOGOOS have developed a basin-scale observing system in the Indian Ocean (IndOOS) that is centered around the deployment of a mooring array (the

Research moored Array for African-Asian-Australian Monsoon Analysis and Prediction or RAMA, sponsored by the U.S. National Oceanic and Atmospheric Administration) along with repeated XBT lines, surface and subsurface drifters and ship-based hydrography through GO-SHIP (Figure 42). The moorings are capable of measuring key variables needed to describe, understand and predict large-scale ocean dynamics, ocean–atmosphere interactions and the Indian Ocean's role in global and regional climate. Efforts have also been undertaken to deploy biogeochemical sensors on the RAMA moorings (e.g., Strutton et al., 2015). Indeed, 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.

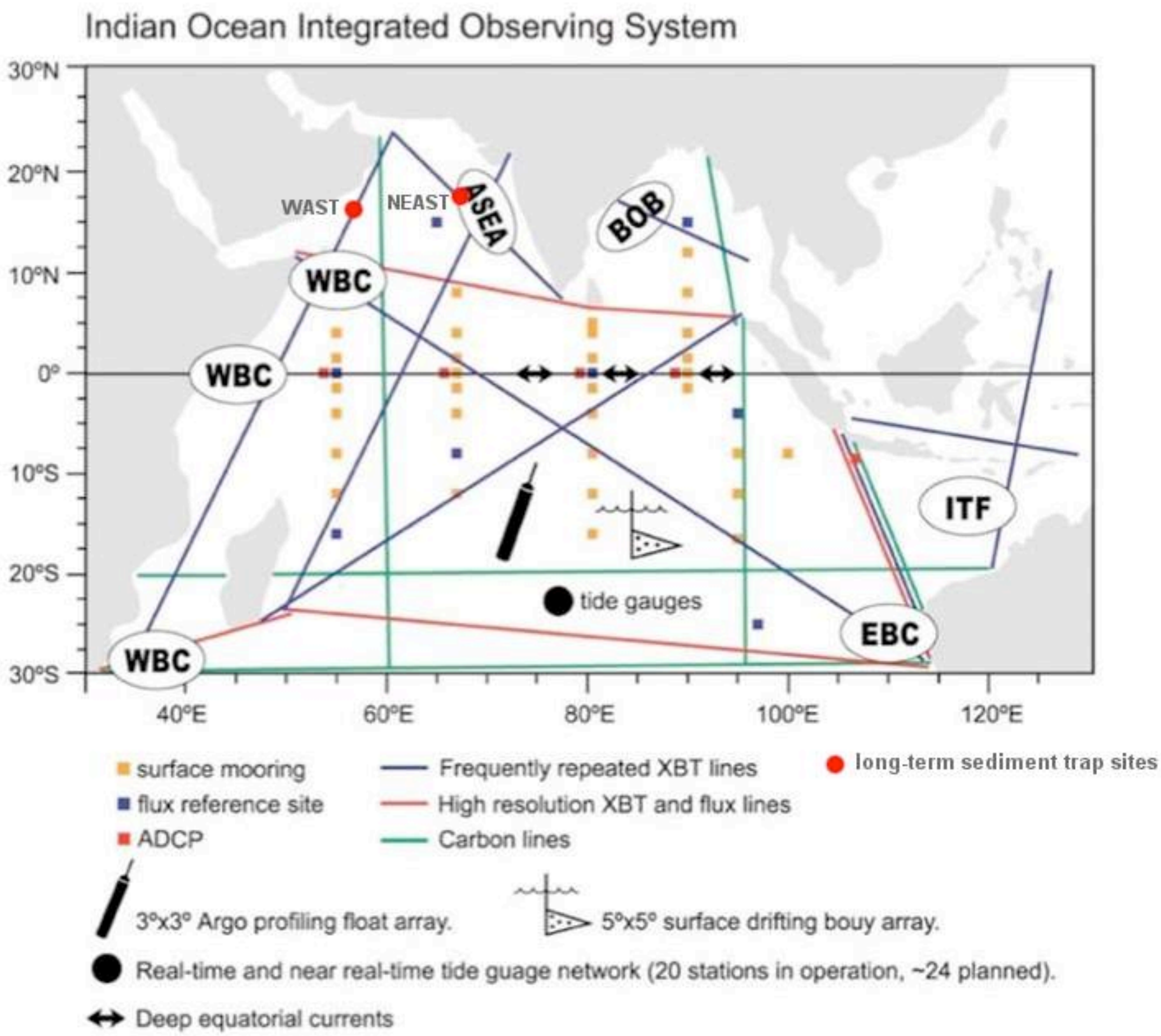


Figure 42: The integrated observing system, with basin-scale observations by moorings, Argo floats, XBT lines, surface-drifters and tide-gauges; as well as boundary arrays to observe boundary currents off Africa (WBC), in the Arabian Sea (ASEA) and Bay of Bengal (BOB), the Indonesian Throughflow (ITF), off Australia (EBC) and deep equatorial currents.

The mooring array is intended to cover the major regions of ocean–atmosphere interaction in the tropical Indian Ocean, namely the Arabian Sea, the Bay of Bengal, the equatorial waveguide, where wind-forced intraseasonal and semi-annual current variations are prominent; the eastern and western index regions of the Indian Ocean 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 southern tropical Indian Ocean, where wind-induced upwelling and Rossby waves in the thermocline affect SST; and the southwestern tropical Indian Ocean, 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 (Figure 42). Thus, the mooring array is ideally situated to study the physical, biogeochemical and ecological impacts of phenomena such as the IOD, MJO and Wyrtki Jets. However, due to piracy issues in the northwestern Indian Ocean and constraints on ship availability, the RAMA array has been only partially deployed. The IIOE-2 presents an important opportunity to complete the array and also motivate the deployment of additional biogeochemical and ecological sensors.

The ongoing Argo Program in the Indian Ocean is a continuation of the exploratory float measurements made during 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. The Indian Ocean 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 Indian Ocean. The potential for obtaining information about oxygen distributions is particularly valuable. At present, open-ocean oxygen concentration distributions are greatly under-sampled throughout the Indian Ocean (cf. Stramma et al., 2008). This is particularly true in equatorial and Southern Hemisphere waters. It is anticipated that the IIOE-2 will help motivate deployment of additional floats to meet the Argo network design criterion and also floats with biological and/or chemical sensors.

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 also are effective for monitoring specific areas, such as the upwelling zones of Java/Sumatra and the Seychelles-Chagos Thermocline Ridge (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 Indian Ocean and the tropical Pacific (Figure X). The XBT network is now largely operated by national agencies and is coordinated by the Ship of Opportunity 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). The XBT network in the Indian Ocean should be integrated into the IIOE-2. A potential opportunity also exists whereby the ships of opportunity used in the XBT deployments could be leveraged as platforms for carrying out parallel biogeochemical and ecological measurements, that is, 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). SCOR's OceanScope working group proposed a variety of new measurements that could be made from commercial ships (see http://scor-int.org/Publications/OceanScope_Final_report.pdf).

Hydrographic survey and mooring support cruises also provide potential leveraging opportunities for carrying out IIOE-2 motivated studies in the Indian Ocean. 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). Such mergers of buoy maintenance and targeted in situ studies are a cost-effective means of obtaining biological and chemical samples that helps justify the maintenance costs of the RAMA array. More generally, IIOE-2 planning must also include documentation of existing infrastructure around the Indian Ocean basin and synthesis of information on current/planned observational resources.

REMOTE SENSING

IIOE-2 studies in the Indian Ocean will take full advantage of remote sensing to characterize physical and biological variability in the ocean and on adjacent land masses. Relevant measurements, with corresponding representative mission(s) with NASA as a principal contributor, include satellite ocean color (retrospective SeaWiFS and MODIS-Aqua), 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 define and characterize the dominant scales of spatial variability and also to characterize interannual variability in the Indian Ocean, 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 Indian Ocean and also land-ocean interactions. In addition to studies based upon U.S.-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 Oceansat-2 provide physical (SST and winds) and ocean color measurements starting from 1999, though availability of high-resolution data to non-Indian scientists needs to be ensured. The European Space Agency (ESA) has also launched several satellite missions (e.g., ERS-1,2 and Envisat) that provide measurements of ocean color (MERIS), SST (AATSR), SSH (RA-2) and winds (ASCAT). In addition, since November of 2009, ESA's SMOS (Soil Moisture and Ocean Salinity) mission has been providing regular global mapping of sea surface salinity (SSS) (Berger et al., 2002). This remote sensing capability has been reinforced by the launch of NASA's Aquarius mission that also provides SSS measurements (Lagerloef et al., 2008). The continuous observations of SSS provided by SMOS and Aquarius can, among other things, help to improve understanding of the influence that the hydrological cycle exerts on the physical dynamics of the northern and eastern Indian Ocean.

Satellite observations can and should also play a central role in studying seasonal, intraseasonal and interannual biogeochemical variability of the Indian Ocean. Many of the phenomena discussed above are amenable to satellite studies, for example, 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 extreme events 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, that is, more than a 30-year record. This record has been used to demonstrate warming globally, including the prominent response observed in the Indian Ocean (Arguez et al., 2007). In the often cloudy regions of the Indian Ocean, 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., Harrison and Vecchi, 2001; Duvel et al., 2004). Satellite remote sensing can also be applied to study atmospheric transport, for example, transport of dust during the SWM and anthropogenic pollutants particularly during the NEM.

Ocean color data acquired by SeaWiFS, MODIS and other orbiting sensors extend from 1997 through the present, a record of more than 15 years duration. 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 (Wiggert et al., 2006; Lévy et al., 2007; Uz, 2007) and blooms associated with the MJO in the SCTR (Resplandy et al., 2009). 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). However, more comprehensive elaboration of Indian Ocean bloom dynamics and biogeochemical variability are needed. Ocean color measurements have also been used in studies of regional and basin-wide biological response to climate change (Goes et al., 2005; Gregg et al., 2005). Additional studies along these lines should be motivated.

MODELING

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 Indian Ocean. Eddy-resolving models are required in order to capture the physical and biological variability in Indian Ocean boundary current and upwelling systems. The eddy fields that are associated with these currents have been successfully modeled using, for example, the 1/16th degree resolution Navy Layered Ocean Model (NLOM) that assimilates SSH data (Smedstad et al., 2003) (Figure 43). 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 Indian Ocean under the auspices of BLUELink (see http://www.cmar.csiro.au/bluelink/). The current 1/10th degree implementation of OFAM in the coastal waters of Australia, successfully resolves the Leeuwin Current. OFAM's 1/10th degree implementation has recently been expanded to include the entire Indian Ocean (R. Matear, pers. comm.). OFAM is currently generating "nowcasts" and short-term forecasts in support of field studies, as well as retrospective studies. An important question in the context of boundary current and upwelling studies is how well these models represent cross-shelf exchange, which is unknown.

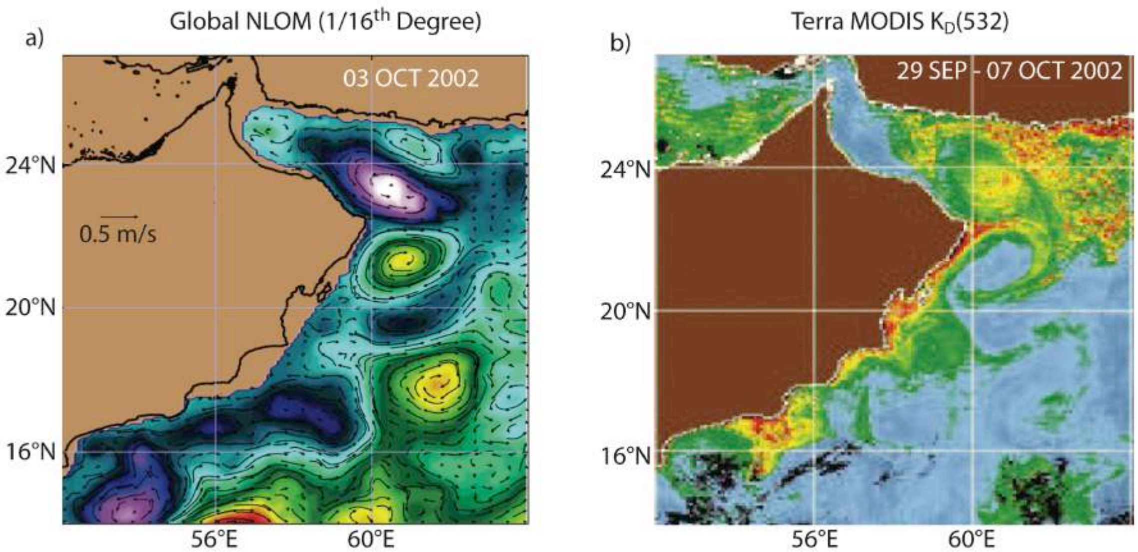


Figure 43: Comparison of 1/16th degree NLOM simulation snapshot of surface layer velocity and sea surface height with diffuse attenuation coefficient at 532 nm observed by the MODIS-Terra color sensor. Reproduced from Wiggert et al. (2005).

MODELING CIRCULATION, VARIABILITY AND CHANGE

Numerous modeling studies aimed at understanding the intense physical variability observed in the Indian Ocean have been undertaken (see reviews by Schott and McCrary, 2001; Schott et al., 2002; Schott et al., 2009) and this is still an area of active research. However, additional modeling studies need to be motivated to better understand how the atmospheric and ocean circulation of the Indian Ocean has changed in the past and how will it change in the future in response to climate change. In addition, both regional and basin-wide modeling studies need to be undertaken to better characterize both surface and deep circulation patterns and heat fluxes in the Indian Ocean and their variability, and how these relate to topography and connectivity with the Pacific, Atlantic and Southern oceans.

Long-term retrospective and climate forecast model simulations can be used to identify climate change impacts on the physical dynamics of the Indian Ocean. Model projections focused specifically on the Indian Ocean and its sub-regions should be run out to the year 2050 and beyond. Existing Earth System models can and be used to develop these projections. Downscaling techniques should also be applied, that is, 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 for engagement of scientists from outside the earth system modeling community that have specific expertise in Indian Ocean basin-scale and regional modeling. Emphasis here should also be placed on combining retrospective modeling with satellite observations (SST, SSH) to investigate climate change.

As discussed in Theme 3, the Indian Ocean is also a region of relatively low seasonal forecast skill (for both rainfall and SST) especially compared to the Pacific. Coupled atmosphere-ocean modeling studies need to be undertaken to better understand the limits of predictability of the monsoons and what this means for prediction of the atmosphere and upper Indian Ocean circulation variability. It has been suggested that well-known biases in coupled atmosphere-ocean models are, at least in part, responsible for this low forecast skill. Typical biases in coupled models used for simulation and prediction are too cold SST in Indian Ocean, too wet in the equatorial western Indian Ocean, and too dry over the continents. These biases typically result in the equatorial thermocline sloping upward toward the east, whereas it should be relatively flat. This, in turn, results in a hyper-active IOD. These biases are clearly coupled and not due solely to process in the Indian Ocean basin. In addition, most models don’t simulate the MJO/MISO very well and especially their interaction with the upper Indian Ocean. Modeling efforts need to be undertaken that are aimed at reducing these biases, which, presumably, will result in better models that can be used for simulation and prediction. In particular, modeling studies need to target identification of key model biases that arise from atmosphere versus the ocean in order to better understand what role atmosphere and ocean models are playing in generating these biases.

MODELING BIOGEOCHEMICAL PROCESSES

Much of the Indian Ocean biogeochemical modeling effort so far has consisted of regional applications that have focused on the northern basin or its two sub-regions (Swathi et al., 2000; Hood et al., 2003; Vinayachandran et al., 2005: Anderson et al., 2007; Sharada et al., 2008). Only recently have regions outside of the northern Indian Ocean been a focal point, with a primary example being a physical-biogeochemical modeling implementation that was applied to investigate how the MJO and IOD influence biological processes in the SCTR (Resplandy et al., 2009).

Satellites and coupled physical-biogeochemical models can both be applied to study planetary wave-induced chlorophyll and productivity responses in equatorial and subtropical waters similar to analyses focusing on other ocean basins and the SE Indian Ocean (e.g., White et al., 2004; Waite et al., 2007; Feng et al., 2008). Given the dramatic differences in the surface eddy kinetic energy between the Arabian Sea and the Bay of Bengal, modeling studies aimed at contrasting these two basins should provide good first-order information about dynamical differences. Here also, coupled physical-biological models can be applied to study biogeochemical and ecological responses to physical forcing (e.g, Lévy et al., 2007; Wiggert et al., 2006), though having sufficient resolution to resolve the observed variability, especially in the Arabian

Sea, is an issue here as well. 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 Arabian Sea and the Bay of Bengal.

Retrospective biogeochemical modeling studies that have addressed basin-wide variability are relatively few (Kawamiya and Oschlies, 2001; Kawamiya and Oschlies, 2003; Wiggert et al., 2006; Wiggert and Murtugudde, 2007; Kone et al., 2009). Forcing data are available to extend modeling simulations back to the late 1940s (Kistler et al., 2001). Retrospective studies that extend much further back in time could be used to investigate interannual and decadal biogeochemical variability, for example, how IOD events affected biogeochemical variability in the pre-SeaWiFS time frame. Similarly, long-term retrospective and climate forecast model simulations can be used to identify climate change impacts on the biogeochemical dynamics of the Indian Ocean. Biogeochemical model projections focused specifically on the Indian Ocean and its sub-regions should also 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 should be used to develop these projections.

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 Arabian Sea and the Bay of Bengal. Model simulations can be run with nutrient and freshwater fluxes that can be turned on and off to quantify the impact of these fluxes 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 Arabian Sea and the Bay of Bengal. Similarly, model simulations can and should be applied to study the influences of marginal seas, for example, the spreading and impact of Persian Gulf and Red Sea water in the Arabian Sea and the exchange of deep water between the Andaman Sea and the Bay of Bengal.

Modeling studies of atmospheric dust and pollution fluxes should also be undertaken because of the importance of dust in the Arabian Sea and other India Ocean regions to particle fluxes and sedimentation. Retrospective watershed modeling simulations should be motivated to simulate how riverine nutrient loads have changed in the past and that project how they will likely change in the future with increasing population density and associated changes in land use. These simulations can then be used to force coastal circulation and biogeochemical models to project these changes in the watershed to coastal biogeochemical cycles and ecosystem dynamics.

HIGER 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 being 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 are emerging from IMBER and other programs can and should be leveraged. IIOE-2 should motivate the development and use of new, alternative end-to-end modeling approaches; model structures that are adaptive and/or generate emergent behavior should be especially promoted. There are several recently developed alternative modeling approaches that are based on more fundamental ecological principles (e.g., Follows et al., 2007; Maury et al., 2007a; Maury et al., 2007b) that can capture such adaptive and/or emergent behaviors. Modeling efforts of this type, with specific application to the Indian Ocean, should be undertaken.

In addition, "offline" individual-based modeling (IBM) approaches can be applied to study higher trophic levels (e.g., Lehodey et al., 1998). More traditional food web modeling approaches (for example, EwE, see http://www.ecopath.org) may also be productively applied to study the dominant pathways of trophic interactions in ecological processes in the Indian Ocean, and their potential vulnerabilities to climate change.

INTERCALIBRATION

The planners of the IIOE recognized the importance of data standardization and intercalibration. For example, the Indian Ocean Standard Net (IOSN) was used for collecting all zooplankton samples (Currie, 1963) and was intercalibrated against other nets used at that time (Barnes and Tranter, 1965). The IOSN was designed specifically for the IIOE. Intercalibration exercises were also carried out for other biological and chemical parameters in an attempt to make samples comparable among stations. Although the attempt was not entirely successful, the effort highlighted how IIOE planners wanted to be able to combine data from different investigators into a data set that could be scrutinized to better understand basin-wide dynamics.

Planners for the IIOE-2 should determine whether there will be any variables measured basin-wide and, if so, intercalibration activities should be conducted, manuals of standard methods should be compiled, and training should be carried out. Such efforts will be necessary to make it possible to compare results from different cruises, and from different labs, can be compared in a meaningful way. Intercalibration activities can be a tool for capacity building, to ensure that laboratories in the region are using globally accepted procedures for sample collection, processing, and analysis.

INTEGRATION

LINKAGES

The IIOE-2 has been developed with joint sponsorship from SCOR and IOC. Directed jointly by SCOR and IOC with close ties to IMBER, GOOS (including IOGOOS) and CLIVAR, and through national and international program activities, it is envisaged that IIOE-2 will advance our understanding of interactions between geological, ocean and atmospheric processes that give rise to the complex physical, chemical and biological dynamics of the Indian Ocean as part of the Earth System.

IIOE-2 will generate multidisciplinary links among marine geologists, atmospheric scientist, biological, chemical and physical oceanographers, 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 World Ocean Circulation Experiment (WOCE). IIOE-2 will also build upon and leverage ongoing projects such as the CLIVAR/IOGOOS Indian Ocean Observing System (IndOOS), GEOTRACES (a global survey of trace elements and isotopes in the ocean), the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), the International Ocean Discovery Program (IODP) and InterRidge (an international organization that promotes interdisciplinary, international studies of oceanic spreading centers).

CLIVAR's Indian Ocean Panel (IOP), the Indian Ocean GOOS Regional Alliance (IOGOOS) and IMBER's Sustained Indian Ocean Biogeochemistry and Ecosystem Research Program (SIBER) already meet together on a regular basis and have undertaken joint efforts in support of the IIOE-2 planning phase. Collaboration among IIOE-2, IOP, IOGOOS and SIBER offers a unique opportunity to mobilize the multidisciplinary, international effort that will be required to develop a new level of understanding of the physical, biogeochemical and ecosystem dynamics of the Indian Ocean. In order to extend this effort and understanding to include geological processes and deep-sea ecosystems, strong linkages will also be established with organizations representing the marine geological research community (such as IODP), and the interdisciplinary research community focusing on oceanic spreading centers (InterRidge).

Collaboration with other relevant programs will be vital to the success of IIOE-2. IIOE-2 will need to be aware of the activities of many other Indian Ocean research programs and integrate with them where appropriate. For example, IIOE-2 will collaborate with international and national monitoring programs such as Australia's Integrated Marine Observing System (IMOS) to leverage, augment and integrate with their efforts. Limitations to our understanding of atmospheric transport and deposition and nutrient and chemical cycling would be improved by developing linkages with SOLAS and GEOTRACES. By establishing linkages to the Climate Impacts on Oceanic Top Predators (CLIOTOP) program, IIOE-2 would leverage global tropical studies that are aimed at developing an end-to-end understanding of marine ecosystems. IIOE-2 could also seek to establish strong linkages with the South African Network for Coastal and Oceanic Research (SANCOR), the Bay of Bengal Large Marine Ecosystems (BOBLME) program and the Western Indian Ocean Marine Science Association (WIOMSA) in an effort to help promote the educational, scientific and technological development of all aspects of marine sciences throughout the Indian Ocean.

It is becoming increasingly apparent that links need to be strengthened between scientists working in the Indian Ocean and other ocean basins, particularly the Pacific Ocean and the Southern Ocean. Some of the strongest low-latitude regional expressions of global climate change have occurred in the Indian Ocean and these are predicted to continue or indeed increase. Understanding the connections between the changes that are being observed in the Indian Ocean and other ocean basins is essential to determine the global ocean's response to climate change and potential feedback effects. Developing links with Pacific and Southern ocean researchers and programs is important from the IIOE-2 perspective, particularly in developing comparative analyses and models. IIOE-2 would benefit from coordinating its efforts with CLIVAR's Pacific Ocean Panel, IMBER's Integrating Climate and Ecosystem Dynamics (ICED) program and the Southern Ocean Observing System (SOOS).

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 could be achieved in the first instance by inviting non-Indian Ocean scientists from relevant fields to participate in the IIOE-2 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 IIOE-2 scientists will be to ensure that the unique geological, atmospheric and ocean dynamics of the Indian Ocean are adequately and correctly represented in Earth system models. This is achievable primarily through working with IODP, IMBER, GOOS and CLIVAR.

STRUCTURE OF IIOE-2

The structure of IIOE-2 management will be developed in the implementation phase, but past and current large-scale ocean research projects provide successful models (e.g., Figure 44). It is envisaged that the project would establishdd an international scientific steering committee (SSC) to oversee the implementation and prioritization of science activities in relation to the themes provided in this science plan. SCOR suggests that the SSC would be formally appointed by SCOR and IOC and its membership would be rotated following protocols established by SCOR and IOC. This committee would consist of active scientists

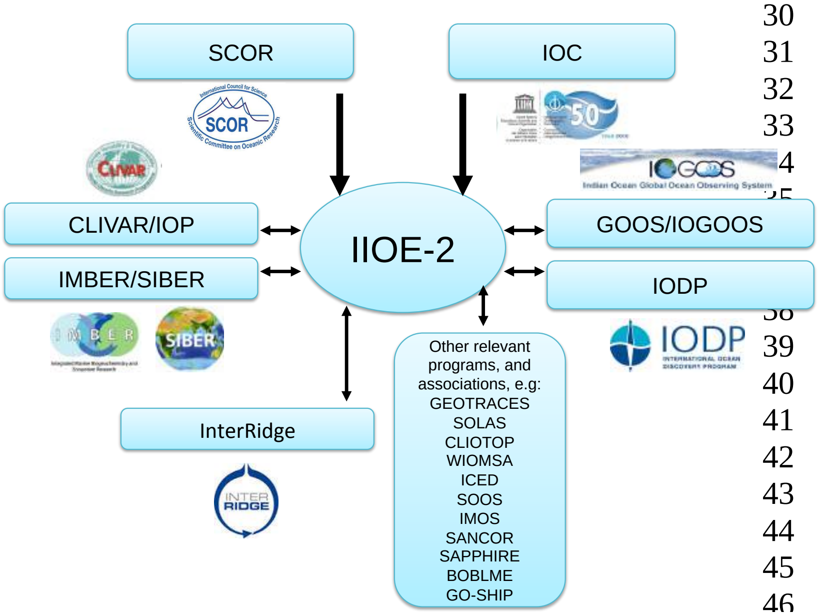


Figure 44: A proposed IIOE-2 management structure.

who have specific and broad expertise in the major disciplines covered by the IIOE-2 Science Plan and who provide broad geographical and national representation. An international project office (IPO) would also need to be established to handle administration and logistics for the expedition.

In respect to the science, flexible and interactive working groups (WGs) could be formed to focus on, and lead, the work for each of the six IIOE-2 research themes. A synthesis and integration WG would promote exchange of information among the six IIOE-2 WGs and with other programs.

COMMUNICATION

Given the international nature of IIOE-2, communication is fundamental to its success, and should be an important component of the project implementation plan. IIOE-2 communication could take many forms, including the following, based on experience with other international research projects:

- Website—To coordinate and publicize the activities of the expedition and associated national and international programs, provide the latest news and information on projects and progress, and provide a forum for communicating IIOE-2 science to the widest possible audience.
- Articles to international scientific magazines and newspapers—These could include the *CLIVAR Bulletin* and American Geophysical Union's *Eos*, and also to newsletters, such as those published by IMBER and IOGOOS. Regular updates and features on the IIOE-2 could also be published in the newly re-established *Indian Ocean Bubble-2* newsletter, which is focused exclusively on the IIOE-2.
- IIOE-2 science meetings and special sessions—These could be linked to, for example, IUGG, IAPSO, AGU, EGU, IOGOOS, WIOMSA, SANCOR and IMBER, conferences and meetings, as well as separate/dedicated IIOE-2 meetings when the program becomes established.
- Communication aimed beyond the scientific community—The results from IIOE-2 will be published in scientific journals and reports. However, it is envisaged (and felt fundamentally important) that the prospective IPO would endeavor to ensure that the main results be made accessible to a wider audience, including policy makers, managers and the public. Some effort should therefore be devoted to producing summary fact sheets or brochures.

DATA AND INFORMATION MANAGEMENT

METHODS FOR DATA SYNTHESIS AND MANAGEMENT

Data and Information synthesis and management is a critical issue for IIOE-2, to ensure that the data and information derived from IIOE-2 science are not only well curated, managed and quality assured, but also that they result in maximal use and benefit to Indian Ocean stakeholders. Therefore, explicit and dedicated emphasis will need to be assigned to data and information management in IIOE-2 from the outset of the program to ensure effective connections to and utilization of the range of available data and information management mechanisms and associated capacity building programs. These mechanisms and programs exist at national/institutional levels within the participating IIOE-2 countries and internationally at integrating levels across the spectrum of data and information management programs, facilities and institutional networks available under collaborative models.

It is envisaged that the IIOE-2 will develop a data and information management plan under the guidance of IOC and SCOR. This would be refined and published in due course on the IIOE-2 website. It is envisaged that such a plan would facilitate the full exploitation of data resources available to the program, while respecting the intellectual property rights of contributors and reducing duplication of fieldwork and research effort. The term 'data' includes raw and processed field and laboratory data and model output. It is envisaged that the development of the IIOE-2 data and information management plan will be overseen by the IIOE-2 Interim Planning Committee (Group of Experts) as signaled by the IOC's 47th Executive Council meeting Resolution on IIOE-2 (1-4 July 2014). With respect to the science planning process under SCOR, it is important for the scientific objectives and strategies of IIOE-2 that are being developed under the sponsorship of SCOR (i.e., this science plan) to be developed with due reference to and, where relevant, even early alignment to some key generic elements relevant to data and information management.

At the international level, the IOC's International Oceanographic Data and Information Exchange (IODE) provides a logical framework and infrastructure that can support IIOE-2 data and information management. Indeed, the IODE was established in 1961 (www.iode.org), during the time of the original IIOE. IODE's purpose is to enhance marine research, exploitation and development, by facilitating the exchange of oceanographic data and information among participating IOC Member States, and by meeting the needs of users for data and information products. The IODE network includes national, regional and global-scale systems through which the IIOE-2's scientifically generated data and informational products can be managed, curated and made accessible. Nationally, these include the National Oceanographic Data Centers; Associate Data Units (since 2013); Marine Libraries (with IODE national coordinators for marine information management); and OBIS Nodes (since 2010). Regionally, they include Ocean Data and Information Network (ODIN) hubs (with IODE regional coordinators); and OBIS Nodes (since 2010).

The ICSU World Data System and World Data Centers for Oceanography may also play a role in regard to IIOE-2 data.

It is important to emphasize that one of the virtues of the IODE framework is that the associated IOC Data Policy (2003, www.iode.org) encourages Member States to provide timely, free and unrestricted access to all data, associated metadata and products generated under the auspices of IOC programs. Data sharing is a major issue in the region and it will be important for success of the program that data from the entire region be shared more freely in the future than in the recent past.

In addition, the Ocean Data Portal (ODP: *http://www.oceandataportal.org*) provides a data and information-sharing framework that links data systems and allows searching across the network, as a distributed system. IIOE-2 and science generating partners within IIOE-2 could become nodes of the Ocean Data Portal. At the national/institutional level, the data and information generated by the IIOE-2 can link with facilities such as the Biological and Chemical Data Management Office (BCO-DMO) in the United States; IMOS in Australia; and regional IOC-related training centers such as ITCOceans in India and UNESCO Category 2 regional training centers (in Iran).

In the implementation phase, it should be determined whether a centralized data management system should be implemented for any of the core parameters. CLIVAR, Argo, GEOTRACES, the IIOE (for IOSN samples), and some other projects have implemented such centralized data management, which allows seamless integration of intercalibrated data from all samples and creation of merged datasets. Without centralized data management, it can take years after project completion to compile data (e.g., for the Joint Global Ocean Flux Study).

FIELDWORK COORDINATION AND DEVELOPMENT

The Indian Ocean is logistically difficult to work in due to its vast size, remoteness and the lack of availability of research vessels and as such is one of the least sampled regions on Earth. Ensuring that field activities are planned and undertaken in such a way as to facilitate their integration is a huge challenge requiring the cooperation of many nations operating throughout the Indian Ocean. Such cooperation is necessary to achieve improved geographical coverage of the Indian Ocean, streamlining of scientific objectives, integration of physical, biogeochemical and ecological processes, identification of key gaps, and effective future planning. The main role of IIOE-2 in this early phase will be to facilitate improved fieldwork coordination among nations and programs to address the core scientific questions identified in this plan.

During the program's early phases, IIOE-2 should try to improve the integration of existing and planned field studies. This includes increasing the promotion of cross-cutting science activities and the exchange of personnel, expertise, methodology, data and equipment. This should increase the efficiency and scientific value of integration of the outcomes of the individual programs.

Existing field activities encompass only a small fraction of the Indian Ocean basin, with national programs often targeting restricted geographical regions and the coastal zone. A particular focus of IIOE-2 should be promoting an international effort to provide improved geographical coverage of the Indian Ocean, both coastal and open ocean areas. This will be facilitated by increasing the use of satellite data and by remote instrumentation. Remote instrumentation will include both fixed-location devices, such as oceanographic moorings, and those on mobile platforms, such as ship of opportunity measurements and oceanographic (Argo) drifters.

In terms of planning future field efforts, regions that have been the focus of several national and international efforts (such as the Arabian Sea), and proved of significant interest, will continue to provide data critical for synthesis and modeling. Other regions, which have received much less attention (such as the Bay of Bengal, the equatorial waters and the open ocean areas of the southern Indian Ocean) and for which data are sparse, should be the focus of future coordinated field efforts. Toward this end, the IIOE-2 should promote the development of regional research initiatives that target less-studied regions, such as the Eastern and Western Indian Ocean Upwelling Research Initiatives described above.

TRAINING AND EDUCATION

A major aspect of the first International Indian Ocean Expedition (IIOE) was the enhancement of capacity for ocean science in the Indian Ocean region. This was accomplished through two lines of action: (1) participation of scientists from the region in IIOE cruises, on ships sent to the region by Australia, Japan, the United Kingdom, USSR, the United States; and (2) investments from outside the region and from India to create the Indian Ocean Biological Centre (IOBC) and the International Meteorological Centre at Bombay (http://mea.gov.in/bilateral-documents.htm?dtl/7106/Exchange+of+Notes+for+Establishment+ofan+International+Meteorological+Centre). These centers became major hubs for training of Indian scientists in taxonomy and meteorology and attracted cooperation from scientists from outside the region. Similarly, the IIOE-2 should be designed to stimulate research capacity in the international community and especially among developing Indian Ocean rim nations by promoting training courses to develop multidisciplinary science skills, workshops, summer schools and a program of personnel exchange. Morrison et al. (2013) provided advice for capacity building for research projects, which could serve as a foundation for capacity building within the IIOE-2.

The IIOE-2 should promote engagement across Indian Ocean scientists and associated institutions from developed and developing countries that are planning to undertake science activities in the region. The IIOE-2 should include capacity building components that will accomplish collaborative use of expertise and physical resources from within and outside the Indian Ocean region to accomplish training, joint research and analysis, and other activities. This motivation has been embraced by scientists from the region and beyond, and implementation of the project in this manner (logistical operations, data acquisition, management and processing, application of scientific results for societal benefit) should continue.

<u>Fundamentals for an IIOE-2 Capacity Development Plan</u>

A detailed capacity development (CD) plan will almost certainly be developed in the IIOE-2 implementation phase. The following points should be considered in development of the plan:

1. Focus CD on activities that will directly benefit IIOE-2 during the period 2016-2020.
2. Determine CD needs in the region related to IIOE-2.

3. Determine national and international resources related to the needs.
    a. What training centers exist in the region?
    b. Should new centers be developed for the period of the IIOE-2?
    c. What CD activities will exist from cruises to the region? Will there be empty berths on the cruises?
4. What CD opportunities are available from international organizations?

Several international and regional organizations are engaged in the development of IIOE-2 and their capacity building resources should be tapped during the implementation of the IIOE-2.

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (IOC)

The IOC's Strategic Plan for Capacity Building will provide insight into how the science community in developed countries can implement mechanisms that promote and enable capacity building during, and as a legacy of, their activities relating to science under IIOE-2. The IOC's International Oceanographic Data and Information Exchange (IODE) provides one convenient and logical institutional and programmatic framework to organize and implement IOC's capacity building activities under IIOE-2. IODE has significant experience in training, in-country, at IODE headquarters, and through distance learning techniques such as OceanTeacher (see http://classroom.oceanteacher.org/).

SCIENTIFIC COMMITTEE ON OCEANIC RESEARCH (SCOR)

SCOR has included a capacity building mission since its inception in 1957, including as part of the IIOE. SCOR's current activities in capacity building focus on travel support to scientific meetings, training in oceanographic observations (with the Partnership for Observation of the Global Oceans), and SCOR Visiting Scholars. SCOR-sponsored research projects—the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project, the Surface Ocean – Lower Atmosphere Study (SOLAS), and GEOTRACES—each has its own capacity building experience and approaches that could be applied to the IIOE-2. In particular, SOLAS and IMBER have significant experience in conducting summer schools, which could be an important approach for capacity building related to IIOE-2. SCOR has sent several Visiting Scholars to the Indian Ocean region so far, to Bangladesh, India, and South Africa.

PARTNERSHIP FOR OBSERVATION OF THE GLOBAL OCEANS (POGO)

POGO is a non-governmental consortium of oceanographic institutes. POGO uses several different capacity building approaches, including fellowships for ocean observations (with SCOR), Visiting Professorships, and a Centre of Excellence in Operational Oceanography.

The IIOE-2 could provide a platform from which to address issues such as climate change: not only how it will impact the monsoon winds, coral reefs, the Indian Ocean coastal zone and human populations, but also wider impacts on a global scale.

Recommended Capacity Building Actions

1. The IIOE-2 Interim Planning Committee should consider forming a capacity building subcommittee, whose members would be from countries planning IIOE-2 activities (from the Indian Ocean region and beyond) and international organizations with activities in capacity building for ocean science.
2. The IIOE-2 Subcommittee on Capacity Building should initiate its capacity building activities by convening a meeting of the major international and regional organizations that conduct capacity building, including IOC, SCOR, POGO, WIOMSA, etc. The purpose of this meeting would be to determine what each organization would contribute, and to develop a detailed capacity building plan for IIOE-2, including how funds will be developed for the plan.

IIOE-2 OUTPUTS AND LEGACY

As this document has outlined, the Indian Ocean is changing rapidly as a result of human-activities. These changes could have profound consequences for marine populations, species, biodiversity and ecosystem structure and function. They affect biogeochemical cycles and they influence the development of management strategies for fisheries. These human-driven effects are also modifying the frequency and severity of extreme events. The impacts of these changes on human populations in the coastal zones of the Indian Ocean are already evident and they will increase with time. To fully understand the impacts of variability and change requires a basin-wide, interdisciplinary approach and an integrated analysis to determine the major controls and feedbacks between geological, ocean and atmospheric processes that give rise to the complex physical, biogeochemical and ecological dynamics of the Indian Ocean region. The Indian Ocean rim nations are largely developing countries, which means IIOE-2 will provide an important vehicle for capacity building through its activities. Indeed, the success of IIOE-2 will depend on involvement by the rim countries.

It has been noted throughout this document that there are a wide range of distinct scientific questions that the IIOE-2 community needs to address, which span from coastal waters and inland seas to the open ocean. Ultimately, the goal is to achieve a greatly improved understanding of the large-scale operation of the Indian Ocean basin. However, as this plan articulates, this goal can be best achieved by motivating research that addresses key overarching scientific questions (themes 1-6). The synthesis phase of the expedition will bring these studies together in order to provide an improved basin-wide understanding. While a significant amount of data collection and modeling studies have already been undertaken, there are still very large gaps in our understanding and there are vast regions of the Indian Ocean where little or no data have been collected and only a few modeling studies have been carried out. What we currently lack is a basin-wide, multidisciplinary effort to fill in the gaps in our understanding. This forms the central focus of IIOE-2 and the basis for its outputs and legacy.

In IIOE-2 emphasis will be given to evaluating and predicting the effects of climate change and other anthropogenic and natural impacts on Indian Ocean ecosystems and human populations. To do this the major focus of IIOE-2 will be on integrated regional and basin-wide analyses that extends from the deep sea to coral reefs all the way up the highest trophic levels, including humans, and how these are impacted by geological, ocean and atmospheric processes. All of these efforts will be aimed at characterizing how geological and physical forcing drives biogeochemical and ecological response in inland seas, coastal zones, the open sea, and at examining long-term, large-scale ecosystem functioning, variability and change.

IIOE-2 is currently building a multidisciplinary network of experts that will grow throughout the program. The IIOE-2 may convene regular working group and steering committee meetings, scientific sessions, capacity building activities, and ultimately scientific conferences. A preliminary timeline is shown in Figure X. 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.

CONCLUSIONS AND LEGACY

IIOE-2 will motivate a coordinated, basin-wide expedition to determine the major controls and feedbacks among geologic, oceanic and atmospheric processes that give rise to the complex physical dynamics of the Indian Ocean region and potential feedbacks as part of the Earth System.

IIOE-2 will determine how these complex physical dynamics affect extreme events, marine biogeochemical cycles, ecosystems and human populations in the context of climate change and sea level rise.

IIOE-2 will address growing concerns about food security and fisheries and anthropogenic impacts in coastal environments, and the pressing need for ecosystem preservation in the Indian Ocean for both tourism and fisheries.

IIOE-2 will work towards integrating and analyzing existing process study and monitoring datasets to facilitate investigation of long-term, large-scale changes in geological and physical processes, biogeochemical cycles and ecosystem dynamics.

IIOE-2 will help to motivate and coordinate new 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 Indian Ocean data.

IIOE-2 will provide an important vehicle for capacity building in Indian Ocean rim nations.

IIOE-2 motivation, coordination and integration of Indian Ocean geological, oceanographic and atmospheric research 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, ecosystems and human populations, not only in the Indian Ocean, but in the Earth System, creating a lasting legacy on which future research can build. The reports and papers produced will inform scientists in the international community and provide a focus for future research on important regional, basin-wide and global issues. These outputs will also be presented in forms that provide policy makers with the sound scientific basis upon which to make decisions on how to mitigate anthropogenic impacts in the Indian Ocean. In the global context, IIOE-2 will provide a mechanism for carrying out SCOR and IOC programs aimed at facilitating the development of research and monitoring infrastructure and human resources in the Indian Ocean and also by inspiring a new generation of international, multidisciplinary oceanographers and marine scientists to study and understand the Indian Ocean and its role in the global ocean and the Earth System.

The success of IIOE-2 will be gauged not just by how much it advances our understanding of the complex and dynamic Indian Ocean system, but also by how it contributes to sustainable development of marine resources, environmental stewardship, ocean and climate forecasting, and training of the next generation of ocean scientists from the region. If this vision of success is realized, IIOE-2 will leave a legacy as rich as the original expedition.

APPENDICES

APPENDIX I. ACRONYMS

SCIENTIFIC ACRONYMS

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 Through Flow
MERIS	Medium Resolution Imaging Spectrometer
MJO	Madden-Julian Oscillation
MODIS-Terra MODIS-Aqua	Moderate Resolution Imaging Spectroradiometer (Terra – AM Equatorial Crossing; Aqua – PM Equatorial Crossing)
NEM	Northeast Monsoon
NWM	Northwest Monsoon
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 ACRONYMS

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	A French program that studied how strong air-sea interactions promoted by the shallow thermocline in the Seychelles-Chagos thermocline ridge (5°S to 10°S, 50°E to 80°E) results in marked variability at synoptic, intraseasonal and interannual timescales in the Indian Ocean. Leader: Jérome Vialard
CLIOTOP	Climate Impacts on Oceanic Top Predators, http://web.pml.ac.uk/globec/structure/regional/cliotop/cliotop.htm
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 Center for Medium Range Weather Forecasts

ESA	European Space Agency
EUR-OCEANS	European Network of Excellence for Ocean Ecosystems Analysis
GEOTRACES	A collaborative multi-national programme to investigate the global marine biogeochemical cycles of trace elements and their isotopes
GLOBEC	Global Ocean Ecosystem Dynamics project (SCOR, IGBP, IOC)
ICED	Integrating Climate and Ecosystem Dynamics in the Southern Ocean (IMBER)
IGBP	International Geosphere-Biosphere Programme
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research, http://www.imber.info/ (SCOR, IGBP)
IMOS	Integrated Marine Observing System (Australia)
INAGOOS	Indonesian Global Ocean Observing System
IndOOS	Indian Ocean Observing System
IOCCP	International Ocean Carbon Coordination Project (SCOR, IOC)
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 (SCOR, IGBP)
MOES	Ministry of Earth Sciences (India)
NASA	National Aeronautics and Space Administration (USA)
NEARGOOS	Northeast Asia Regional Global Ocean Observing System
NIO	National Institute of Oceanography (NIO)
NOAA	National Oceanic and Atmospheric Administration (USA)
RAMA	Research moored Array for African-Asian-Australian Monsoon Analysis and Prediction
SAHFOS	Sir Alistair Hardy Foundation for Ocean Science (UK)
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 (IMBER)
SOLAS	Surface Ocean-Lower Atmosphere Study (SCOR, IGBP, WCRP, iCACGP)
SOOP	Ship of Opportunity Program
WAGOOS	Western Australian Global Ocean Observing System
WCRP	World Climate Research Programme
WIOMSA	Western Indian Ocean Marine Science Association
WOCE	World Ocean Circulation Experiment (WCRP)

APPENDIX II. MEETING REPORTS, URLS AND CONTACT INFORMATION

IIOE-2 REFERENCE GROUP MEETING NO. 1 REPORT

http://iocperth.org/IOCPerth/images/stories/IIOE2_Reference_Group_Meeting_1_Report_10-4-13.pdf

IIOE-2 REFERENCE GROUP MEETING NO. 2 REPORT

http://iocperth.org/IOCPerth/images/stories/IIOE2_Reference_Group_Meeting_1_Report_10-4-13.pdf

IIOE-2 REFERENCE GROUP MEETING NO. 3 REPORT

http://iocperth.org/IOCPerth/images/stories/IIOE2_RG3_FinalReport_Mauritius_March2014_dated120614.pdf

IIOE-2 MEETING REPORT, KIEL GERMANY

Bange, H. W., and M. Visbeck (2014) Towards an Integrated German Indian Ocean Study 2015-2020 - From the seafloor to the atmosphere. 22/23 January 2014, GEOMAR Helmholtz-Zentrum für Ozeanforschung, Kiel Organized by: Prof. Dr. Hermann W. Bange and Prof. Dr. Martin Visbeck, GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel Düsternbrooker Weg 20 24105 Kiel, e-mail: hbange@geomar.de, mvisbeck@geomar.de

APPENDIX III. IIOE-2-RELATED PUBLICATIONS AND WEBSITES

PUBLICATIONS AND ARTICLES (ORDERED BY DATE OF PUBLICATION)

Hood, R. R., M. J. McPhaden and E. Urban (2014) New Indian Ocean program builds on a scientific legacy. *Eos*, 95(39): 349-360.

INCOIS (2014) The Indian Ocean Bubble 2. Issue No. 1, Available at: http://www.incois.gov.in/documents/IndianOceanBubble2.pdf

Hood, R. R., M. J. McPhaden, N. D'Adamo and E. Urban (2015) SCOR and IOC motivate a second International Indian Ocean Expedition. *Indian Ocean Bubble-2,* in press.

Meyers, G. (2015) The Indian Ocean Observing System and Ocean-reanalysis in IIOE2. *Indian Ocean Bubble-2*, in press.

WEBSITES

SCOR IIOE-1

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

SCOR IIOE-2 SCIENCE PLAN DEVELOPMENT COMMITTEE

http://www.scor-int.org/IIOE/IIOE_2_Research_Plan_Committee.htm

UNESCO IOC PERTH OFFICE IIOE-2

http://iocperth.org/IOCPerth/index.php?option=com_content&view=article&id=64:iioe-2&catid=16:iioe-2&Itemid=57

INDIAN NATIONAL CENTER FOR INFORMATION SERVICES

http://www.incois.gov.in/portal/iioe/index.jsp

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Alory, G., & Meyers, G. (2009). Warming of the upper Equatorial Indian Ocean and changes in the heat budget (1960-99). *Journal of Climate, 22*(doi:10.1175/2008JCLI2330.1), 91-113.

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