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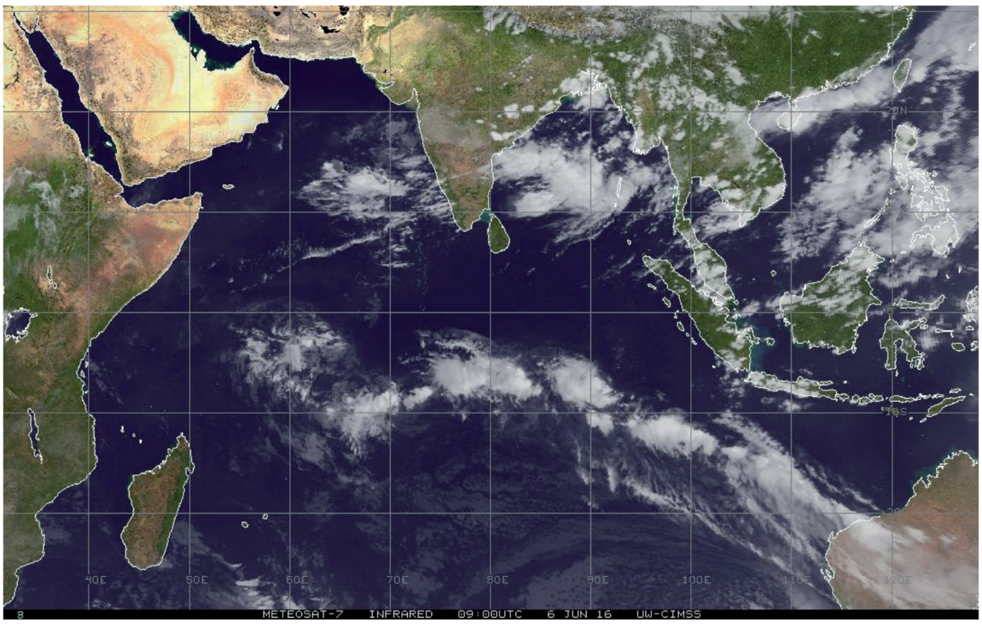
- From the seafloor to the atmosphere -

A possible German contribution to the
International Indian Ocean Expedition 2 (IIOE-2) programme
– A Science Prospectus –



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– A Science Prospectus –

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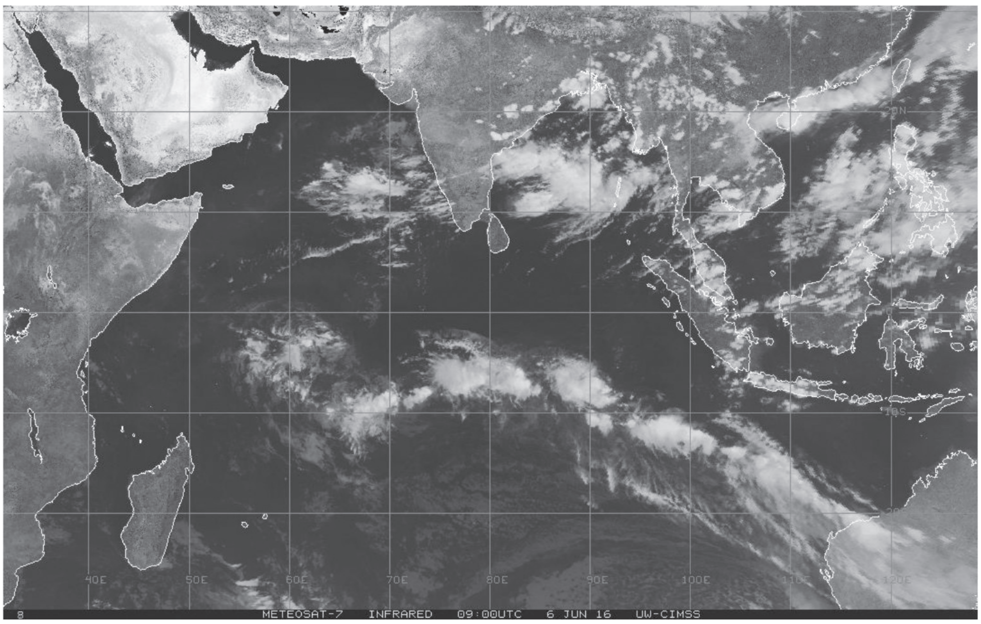

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Satellite (METEOSAT 7) view of the Indian Ocean on 06 June 2016, 09:00h UTC.
(Source: http://tropic.ssec.wisc.edu/real-time/indian/images/xxirm5bbm.jpg)

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CONTENT

Foreword

This document describes the 'Science Prospectus' for an 'Integrated German Indian Ocean Study (IGIOS) – From the seafloor to the atmosphere'.

IGIOS is the result of the discussions during a meeting which was held at GEOMAR, Kiel, 22/23 January 2014. This meeting was funded by the *Deutsche Forschungsgemeinschaft* (DFG) and more than 30 colleagues from all over Germany attended the workshop. The workshop presentations -covering various disciplines from seismology to stratospheric chemistry- and the enthusiastic discussions conveyed the obvious need of a joint research project for the Indian Ocean.

Germany has a long-standing tradition of Indian Ocean research which already began with probing the South Indian Ocean as part of the round the world trip of *SMS Gazelle* from 1874 to 1876. This was followed by the 'Deep Sea Expedition' of R/V *Valdivia* (1898/1899) to investigate the physical and biological oceanography of both the East Atlantic and Indian Oceans. In order to participate in the International Indian Ocean Expedition (IIOE, 1959-1965), which was one of the first modern multinational ocean programmes, the R/V *Meteor II* was built and commissioned in 1964. The first cruise of *Meteor II* went from Hamburg to the Arabian Sea and took place from Oct. 1964 to May 1965. 71 scientists and 21 technicians took part in the ten legs of the cruise. 11 working groups were involved covering disciplines such as physical and chemical oceanography, marine meteorology, marine geology, marine geophysics, planktology, marine botany, marine zoology, ichthyology, marine microbiology and ship building[*].

On the occasion of the 50th anniversary of IIOE, SCOR and IOC set up the 2nd IIOE (IIOE-2) in order to push Indian Ocean projects addressing the emerging scientific issues of the Indian Ocean in the 21st century. To this end the Science Plan and Implementation Strategy of IIOE-2 were launched on 04 December 2015 during the 'International Symposium on the Indian Ocean' held at the National Institute for Oceanography in Goa (India). The Science Prospectus of IGIOS described here is designed as a possible German contribution to the IIOE-2 programme and beyond that we hope to have articulated an exciting scientific framework for an integrated German research programme for the Indian Ocean.

Kiel, 24 May 2016

Hermann W. Bange

[*] for details see G. Dietrich et al., Reisebericht der Indischen Ozean Expedition mit dem Forschungsschiff Meteor 1964-1965, *„Meteor" Forschungsergebnisse Reihe A, Bd. 1*, 1-52, 1966.
The pictures show: a helicopter view of R/V *Meteor II* during her IIOE cruise; the deployment of an Indian Ocean Standard Net from *Meteor II* during the IIOE cruise; and a poster announcement of the conference on 'Biology of the Indian Ocean' held at University of Kiel, 31 Mar – 6 Apr 1971.

1 Executive Summary

There have been significant advances in recent years in our ability to describe and model the Earth system, but our understanding of geological, oceanic and atmospheric processes in the Indian Ocean region is still rudimentary in many respects. This is largely because the Indian Ocean remains under-sampled in both space and time, especially compared to the Atlantic and Pacific Oceans. The situation is compounded by the Indian Ocean being a dynamically complex and highly variable system under monsoonal influence. Many uncertainties remain in terms of how geological, oceanic and atmospheric processes affect climate, extreme events, marine biogeochemical cycles, atmospheric chemistry, meteorology, 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. One of the impacts of global warming is sea level rise, which leads to coastal erosion, loss of mangroves, and loss of biodiversity. Anthropogenic impacts include pollution, with water quality deterioration as a result of nutrient and contaminant inputs resulting in detrimental ecosystem effects such as eutrophication and deoxygenation. 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 expeditions of all time: the International Indian Ocean Expedition (IIOE: scor-int.org/iioe/iioe_history.htm). In the 50 years since the IIOE, fundamental changes have taken place in geological, ocean and atmospheric sciences. Novel measurement technologies, unprecedented computing capacities and new insights 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, the new technologies, in combination with targeted and well-coordinated field programmes (by making use of platforms such as ships, aircraft, satellites, autonomous observatories etc.) and advanced modelling studies provide the capacity for a much more integrated picture of the Indian Ocean system and its variability.

SCOR and IOC are coordinating a new phase of international research focused on the Indian Ocean (i.e. the 2nd International Indian Ocean Expedition, IIOE-2) that began in late 2015 and will continue through 2020 (see www.scor-int.org/IIOE-2/IIOE2.htm and www.iioe-2.incois.gov.in).

The outline of an Integrated German Indian Ocean Study (IGIOS) described here is designed as a possible contribution to the IIOE-2. The Science Plan of IIOE-2 has been released on 4 December 2015 during the International Symposium ‘Dynamics of the Indian Ocean: Perspective and Retrospective’ held at the National Institute for Oceanography in Goa (India) from 30 November to 4 December 2015. The IIOE-2 Science Plan is available from http://www.scor-int.org/IIOE-2/IIOE2_Science_Plan.pdf .

The overarching goal of IGIOS is to:

Advance our understanding of geological, oceanic and atmospheric processes and their interactions that shape the complex physical dynamics of the Indian Ocean region, and to determine how those dynamics affect climate, atmospheric chemistry, extreme events, marine biogeochemical cycles, ecosystems and human populations in response to regional and global environmental changes.

This understanding is required to assess the impacts of climate change, oceanic and atmospheric pollution, and increased fish harvesting in the Indian Ocean and its surrounding nations, as well as the influence of the Indian Ocean on other components of the Earth system. New understanding is also fundamental to policy makers for the development of sustainable coastal zone, ecosystem, and fisheries management strategies for the Indian Ocean. Other goals of IGIOS include helping to build research capacity and improving availability and accessibility of scientific data from the Indian Ocean region.

The IGIOS Science Prospectus is structured around four scientific themes. Each theme comprises a set of key questions fundamental to our need to understand the forcing, processes, and resultant variability of the Indian Ocean and to develop the capacity to assess how this variability will impact human populations in the future. The themes are sorted according to the IGIOS subtitle ‘From the seafloor to the atmosphere’.

Theme 1: Ocean Crust and Convergent Margins

- *What are the major processes shaping the Indian Ocean crust?*
- *How do fluid migration and tectonic processes interact in the Makran and Sunda subduction zones and what controls do they exert on megathrust earthquakes?*
- *To what extent do sediment/ocean fluxes from convergent margins contribute to water column biogeochemistry?*

Theme 2: Ocean Circulation and Ocean-Climate Interactions

- *What are the key processes that determine ocean circulation and climate in the Indian Ocean?*
- *What is the role of the Indian Ocean in the global Conveyor Belt circulation system and in global climate?*
- *What are the key elements that enable interannual, decadal or multidecadal predictability of the Indian Ocean system and how do they interact with global climate change?*
- *What are the key interactions between the ocean and atmosphere in the context of the Australasian and African monsoon systems?*

Theme 3: Biogeochemical Cycles and Atmosphere

- *Which processes determine the natural variability of the biogeochemical cycles, ecosystems and atmospheric chemistry over the Indian Ocean?*
- *What is the effect of the (long-range) transport of air pollution on ocean biogeochemistry, ecosystems, atmospheric chemistry and climate?*

Theme 4: Anthropogenic Impacts

- *How are human-induced stressors impacting the biogeochemistry and ecosystems of the Indian Ocean?*
- *How, in turn, are these impacts affecting human populations?*

The motivation, coordination and integration of Indian Ocean research through IGIOS will advance knowledge and increase scientific capacity. IGIOS will promote awareness of the significance of Indian Ocean processes and enable a major contribution to their better understanding, including the impact of Indian Ocean variability and change on biogeochemical cycles, ecosystems, human populations and global climate. The legacy of IGIOS will be to establish a firmer foundation of knowledge on which future research can build and which will enable policy makers to make better informed decisions for sustainable management of Indian Ocean ecosystems and mitigation of risks to the Indian Ocean populations. IGIOS will leverage and strengthen IIOE-2 and other programmes by promoting coordinated, multidisciplinary research among Germany and Indian Ocean nations, hence increasing scientific capacity and infrastructure within the Indian Ocean nations.

The success of IGIOS 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. IGIOS has the potential to leave a legacy at least as rich as the original German contribution to IIOE 50 years ago.

2 Introduction

2.1 Motivation

The International Indian Ocean Expedition (IIOE) -carried out between 1959 and 1965- was one of the first multinational, interdisciplinary joint programmes and marked a watershed in the pursuit of knowledge within the Indian Ocean region (scor-int.org/iioe/iioe_history.htm). Germany was invited to join the IIOE and significantly contributed to its success. German participation in IIOE also provided a community focus and the impetus to build the research vessel Meteor II.

The IIOE 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 bathymetry 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 understudied regions of the world’s ocean. As a result many important scientific questions remain unanswered (see Scientific Themes below).

Many pressing societally-relevant questions have emerged since the IIOE. Today, more than two-thirds of the world’s population lives in the adjacent continents of the Indian Ocean. The populations of most Indian Ocean nations are increasing rapidly: For instance, India’s population increased by about 240% from 380 million in 1951 to 1,300 million in 2015 (countrymeters.info/en/india). 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 ocean acidification due to the increase of atmospheric carbon dioxide, cause a loss of biodiversity in the Indian Ocean, as well as changes in the phenology and biogeography of many species.

Changes in the Indian Ocean temperature and circulation both in time and space strongly affect the atmospheric moisture content and its transport towards the surrounding continents, and ultimately impact the amount of rainfall over regions that are home to more than two-third of Earth's population. The warming of the Indian Ocean over the past decades is projected to continue in the future with uncertain implications for continental rainfall and its often catastrophic aspects such as floods, droughts, famine, and economic losses. A deeper understanding of the feedbacks associated with Indian Ocean temperature and circulation changes is thus critical to better project and mitigate the consequences of global warming.

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. The future existence of some Indian Ocean island nations and deltaic coasts is in question. The severity of extreme events is 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 protein supply 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.

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 observations are lacking. Hence, there is a strong demand for a second International Indian Ocean Expedition (IIOE-2).

2.2 General Scientific Background

The Indian Ocean (located between 20°E and 147°E and north of 60°S; Fig: 1) is the third largest of the major world's oceans. It contains about 20% of the water volume of all oceans on Earth (www.ngdc.noaa.gov/mgg/global/etopo1_ocean_volumes.html). 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 south-western Indian Ocean, respectively.

The outstanding features which determine productivity, cycling of elements and atmospheric chemistry in/over the Indian Ocean are its land-locked nature in the north, oxygen minimum zones in the Arabian Sea and Bay of Bengal, seasonal monsoon systems and its connectivity to the western Pacific Ocean via several shallow sills between the many Islands of South East Asia and Oceania. Many oceanographic features in the Indian Ocean are a direct result of the changing monsoonal wind pattern and are coupled to El Niño Southern Oscillation (ENSO) events in the Pacific Ocean.

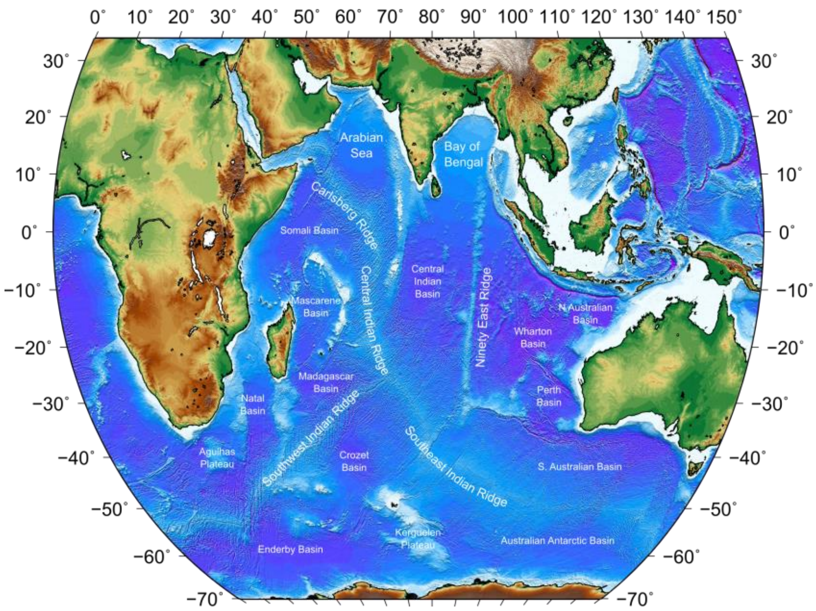

Fig. 1: Map of the Indian Ocean.(map provided by C. Berndt, GEOMAR; based on bathymetry data from Smith and Sandwell, Science, 277, 1956-1962, 1997).

The composition and chemistry of the atmosphere over the northern Indian Ocean region is dominated by the South Asian (Indian) monsoon circulation (Fig. 2): During the winter monsoon (November-March) near surface flow of air masses is mostly to the south, advecting gaseous and particulate pollution from the heavily populated and biofuel intensive regions of Southeast Asia out over the northern Indian Ocean. The Inter-Tropical Convergence Zone (ITCZ) forms a strong atmospheric boundary that results in a divide between the aerosol-rich northern Indian Ocean and the south Indian Ocean subtropical gyre which features a pristine atmosphere. Moreover, the atmosphere over the eastern Indian Ocean is the site of strong atmospheric convection leading to rapid transport of air masses from the surface into the upper troposphere/lower stratosphere.

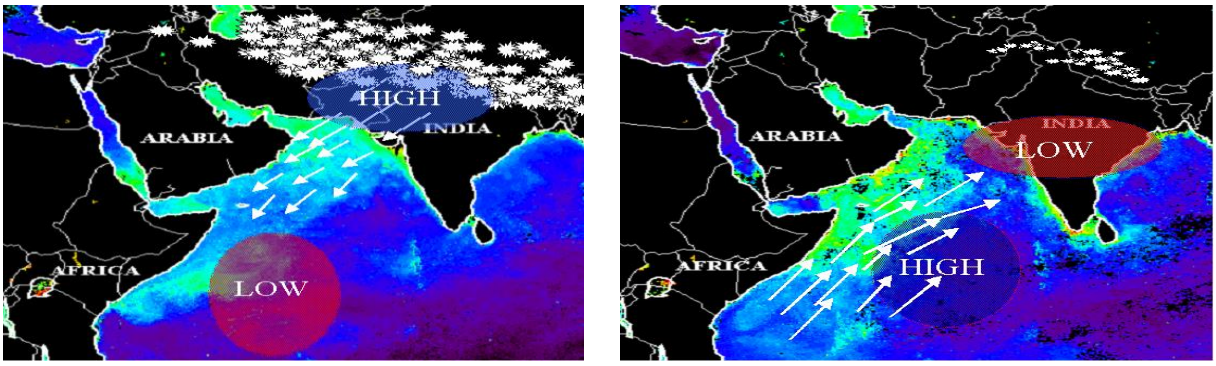

Fig. 2: The South Asian (Indian) monsoon system of the northern Indian Ocean (NE monsoon, during winter months, left; SW monsoon during summer months, right).
www.sciencedaily.com/releases/2005/04/050421204327.htm;
credit: Joaquim Goes,Bigelow Laboratory for Ocean Sciences.

The Indonesian Throughflow (ITF) and Agulhas Leakage play active roles in redistributing heat, moisture and salt along the return path of the conveyor belt circulation and therefore surface and subsurface currents in the Indian Ocean are considered instrumental in modulating global climate. There exists also a complex interplay between ocean currents and different oscillations unique to the Indian Ocean but operating at different time scales such as the Madden-Julian Oscillation, the Wyrtki Jets, the Australasian and African monsoon systems and the Indian Ocean Dipole.

The Indian Ocean is the youngest of the three major world's oceans and has active spreading ridges that are part of the worldwide system of mid-ocean ridges. The Indian Ocean features >15,000 km of mid-ocean ridges, including the slow to intermediate spreading Central Indian Ridge, the intermediate spreading Southeast Indian Ridge and the slow to ultra-slow spreading Southwest Indian Ridge. In addition there are numerous oceanic plateaus, such as the Madagascar Plateau, the Mascarene Ridge, or the Marion Rise, commonly interpreted as large igneous provinces.

Most continental margins around the Indian Ocean are passive, such as the margins along Africa, India and Australia. Two areas exist where accretionary wedges are formed in compressional regimes of plate tectonics: the Makran margin and the Sunda Arc. In both areas the convergence of plates is responsible for magnitude 8-9 megathrust earthquakes, which lead to disruptive tsunamis along the coast of the Indian Ocean. Those types of subduction zone earthquakes account for the largest portion of the seismic energy release, and represent the greatest natural hazard to life and property for major coastal populations.

3 Scientific Themes

The overarching goal of IGIOS is to

Advance our understanding of geological, oceanic and atmospheric processes and their interactions that shape the complex physical dynamics of the Indian Ocean region, and to determine how those dynamics affect climate, atmospheric chemistry, extreme events, marine biogeochemical cycles, ecosystems and human populations in response to regional and global environmental changes.

To address this overarching goal IGIOS will structure its research around four scientific themes. Each of these include a set of questions that need to be addressed in order to improve our understanding of the past and present Indian Ocean System and its variability and to develop the capacities to assess how this variability will impact human population in the future.

3.1 Ocean Crust and Convergent Margins

W. Bach (U Bremen), C. Berndt (GEOMAR, Kiel), G. Bohrmann (MARUM, Bremen),
K. Haase (U Erlangen) and U. Schwarz-Schampera (BGR, Hannover)

3.1.1 Ocean crust

The Indian Ocean features >15,000 km of mid-ocean ridges (MOR), including the slow to intermediate spreading Central Indian Ridge (CIR), the intermediate spreading Southeast Indian Ridge (SEIR) and the slow to ultraslow spreading Southwest Indian Ridge (SWIR) (Fig. 3, Seton et al., 2012). In addition there are numerous oceanic plateaus, such as the Madagascar Plateau, the Mascarene Ridge, or the Marion Rise, commonly interpreted as large igneous provinces (Fig. 3). The formation of the seafloor is thuoght to be due to mantle melting in response to asthenospheric upwelling underneath the spreading centres. Variable mantle temperatures (Klein and Langmuir, 1987) have been proposed to control the degrees of partial melting in the upper mantle along mid-ocean ridges. Episodic diapiric uprise of deeply rooted mantle plumes underneath the plateaus is also believed to be caused by excess heat (hot spot). Both notions have been challenged, however, by recent observations of (1) wide-spread non-magmatic accretion along the SWIR (Cannat et al., 2008; Sauter et al., 2013) and (2) exposure of mantle peridotite in the Marion Rise, suggesting a non-magmatic origin of the plateau (Zhou and Dick, 2013). Furthermore, the current conceptual model of seafloor formation predicts that regions of shallow seafloor are underlain by anomalously thick basaltic crust. However, the SWIR shows a large variation of water depths but the magmatic crustal thickness is thin everywhere (Cannat et al., 2008) and there appears to be no systematic variation of basalt composition with water depth. This would imply that mantle composition rather than temperature may have a large influence on ridge depth.

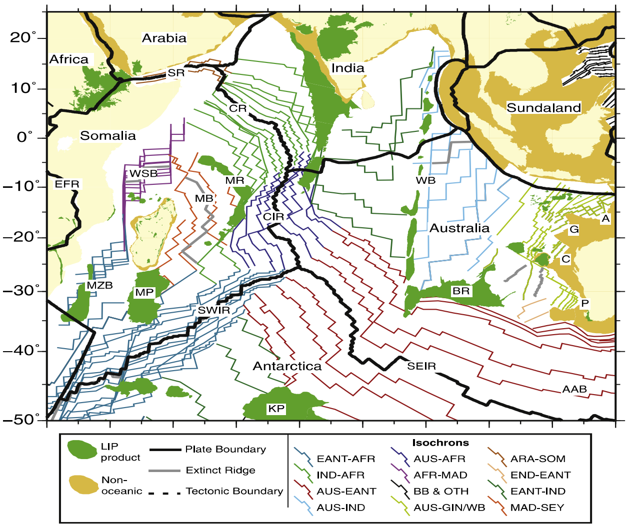

Fig. 3: Map of the evolution of the Indian Ocean (Seton et al., 2013).

Indian Ocean MORB is indeed different from the lavas erupting in the other oceans because large parts are apparently affected by an isotopically enriched component creating the so-called DUPAL anomaly (Hart, 1984) and this enriched material could represent recycled sediments (Rehkämper and Hofmann, 1997), recycled subcontinental lithosphere (Hanan et al., 2013), or lower continental crust (Hanan et al., 2004). The global upper mantle appears to be divided into several chemically and isotopically different regions with the region underlying the southern Indian Ocean having the most extreme isotopic composition. The origin of this unusual composition is unclear and it may either be that subducted material pollutes the upper mantle during transport into the lower mantle (Christensen and Hofmann, 1994) or that mantle plumes transport the enriched material from the lower mantle into shallower regions (Phipps Morgan et al., 1995). Although a transport of mantle material over 1000 km from the Réunion plume into the Central Indian Axis (CIR) was postulated (Mahoney et al., 1989; Morgan, 1978), a more detailed isotopic and geochemical study of CIR did not find a geochemical link to Réunion magmatism (Nauret et al., 2006). Consequently, the upper mantle beneath the Indian Ocean may have gained its unusual composition from recycling of lithospheric components. In this respect, the abundance of microcontinents like the Seychelles, Kerguelen and the Wallaby Plateau in the Indian Ocean may indicate that continental lithospheric material may have polluted the asthenosphere. Sampling of these submarine structures could yield insights into the recycling processes of continental material into the mantle. The composition of mantle peridotite should be the complement of the basalts above and should have the same isotopic composition. Few studies have addressed this question due to a lack of associated mantle and crustal rock samples (e.g. Cipriani et al., 2004). The SWIR offers the opportunity to study the relationship between the crust and underlying mantle.

Additional samples from the spreading axes of the Indian Ocean and of older MORB from the flanks of the axis as well as samples from intraplate volcanoes in the Indian Ocean will help to better define the origin and distribution of the unusual composition. The off-axis samples will help to resolve the temporal variation of magma sources. Off-axis volcanoes have been sampled along the East Pacific Rise and typically show more extreme compositions in terms of incompatible elements and radiogenic isotopes than the basalts at neighbouring spreading axes (e.g. Brandl et al., 2012; Niu and Batiza, 1997). Off-axis seamounts along the SWIR can hence be expected to show more extreme compositions than the SWIR MORB. These end-member compositions may help to determine the origin of mantle heterogeneities. Mapping of the triple junction area shows signs of off-axis volcanoes along the Indian Spreading Centres and whereas such structures have been sampled in the Pacific and Atlantic Oceans (e.g. Batiza and Vanko, 1984; Niu and Batiza, 1994; 1997) no such studies exist for the Indian Ocean. Sampling and analysis of the off-axis volcanoes will help to better define the geochemical variation in the upper mantle beneath the Indian Ocean which then should allow the distinction of the evolution of the mantle sources. Additionally, the comparison of on- and off-axis volcanism will lead to a better understanding of melting processes and melt distribution beneath a very slow-spreading axis, including using short-lived isotope systems that have successfully been used along the EPR.

The ultraslow spreading of large portions of the Indian Ocean spreading axes allows insights into the processes in this extreme tectonic setting and offers the possibility to frequently sample deep crustal and upper mantle rocks (Dick et al., 2003; Seyler et al., 2011). Thus, the relationship between oceanic magmas and their potential source mantle can be studied at the Indian spreading centres by detailed sampling of volcanic and plutonic rocks as well as mantle rocks in specific segments of the spreading axis. This can be very well combined with the high-resolution mapping and sampling carried out by the BGR on the SWIR and Rodriguez Triple Junction. The observation of a thin magmatic crust at the large oceanic plateau of the Marion Rise contradicts previous models of a simple relationship between oceanic crust thickness, magma composition and water depth (Klein and Langmuir, 1987) but implies that other parameters than mantle temperature must play an important role in the generation of such plateaus (Niu and O'Hara, 2008; Zhou and Dick, 2013). For example, an extremely depleted (Fe-poor) mantle may also contribute significantly to the formation of anomalously shallow spreading axes. Recently, a relationship between mantle peridotite composition and spreading rate was suggested and this model needs further testing using peridotites from mid-oceanic ridges with intermediate spreading rate like they occur in the Indian Ocean. Sampling of these ridges can provide better insights into the dynamics of mantle melting.

Exposure of mantle peridotite by detachment faulting is common along slow and ultraslow spreading ridges, where perhaps as much as 50% of the seafloor is made up by serpentinized peridotite and not basalt (Escartin et al., 2010). Denudation of mantle peridotite along long-lived detachments faults is associated with pronounced footwall rotation giving rise to core complex formation (Smith et al., 2012). Oceanic Core Complexes (OCCs) host hydrothermal systems that are markedly different from those associated with magmatically dominated crustal accretion. The latter are controlled by magmatic diking and the vent fluid chemistry is set by reactions between seawater and basaltic rocks. In contrast, the OCC-bound venting is controlled by deep faulting and seawater reacts with mantle peridotite to form serpentinite. Magmatic intrusions into the lithospheric mantle appear to play a key role in detachment faulting, both large intrusive bodies (Ildefonse et al., 2009) and small volume impregnations with highly evolved melts (Jöns et al., 2009). We hypothesize that hydrous alteration at the lithologic boundary between plutonic and mantle rocks initiates at higher temperatures than in peridotite. The alteration causes a mechanical weakening of the rock and will cause strain localization in this zone which, in turn, facilitates fluid ingress and more hydrothermal alteration. These coupled processes may help explain the longevity of oceanic detachment faults. Detailed mapping and sampling of the OCCs in the Indian Ocean would allow us to test this hypothesis

The ultraslow spreading (7 mm yr^{-1} half rate) SWIR west of the Rodriguez Triple Junction (RTJ) shows indications of expansive detachment faulting which has been the primary mode of seafloor formation along vast stretches of ridge for the past 11 Ma (Sauter et al., 2013).

Further west, along the obliquely spreading SWIR between 10°E and 16°E, volcanism is also scarce (Standish and Sims, 2010), but indications of hydrothermal venting are abundant, similar to other ultraslow spreading centres (Baker et al., 2004). Active hydrothermal venting in an area of detachment faulting has been confirmed for the Drag Flag area around 50°E on the SWIR (Tao et al., 2012; Zhou et al., 2013). Another OCC with associated hydrothermal venting has been identified in an area just north of the RTJ (Nakamura et al., 2009). Recent exploration along the CIR and SEIR in the vicinity of the RTJ has located more OCCs and vent fields related to pillow volcanoes (Schwarz-Schampera, unpublished).

Moderate-temperature, alkaline vent fluids with very high hydrogen and methane concentrations are related to serpentinization in OCC settings (e.g., Kelley et al., 2005), but hot and acidic vents can also form, perhaps during earlier stages of OCC development (McCaig et al., 2007). OCCs host rich deposits of magmatic chromite and seafloor sulphide are associated with melt- and fluid-facilitated mass transfers in the lithospheric mantle. The details, however, are poorly understood and our conceptual models are derived primarily from work in ophiolites. Metal contents and deposit size of sulphide accumulations are highly variable, but slow and ultraslow-spreading ridges appear to be larger and stronger enriched in base and precious metals than their fast-spreading counterparts (Hannington et al., 2011). It is unclear which role the magma budget and the basement composition play in determining metal enrichment and deposit size.

Secondary low-temperature processes facilitated by seawater percolation within these deposits and the associated microbial activity cause a drastic redistribution of metals, which can lead to supergeneous enrichment of nobel metals. These processes are expected to affect the different deposit types to different extents, but details about the actual processes and potential consequences for the fate of metals in seafloor massive sulphide deposits are not known. The microbial communities are also expected to be radically different between sulphide, peridotite, and basalt, since the metabolic energy landscape is very different in these substrates (Menez et al., 2012; Amend et al., 2011; Toner et al., 2012). For both geobiology and ore geology, systematic and detailed sampling of OCCs in the Indian Ocean would yield a wealth of samples of mantle rocks and hydrothermal deposits, which would go beyond what is possible from reconnaissance sampling of isolated occurrences.

3.1.2 Convergent margins

3.1.2.1 Introduction

Most continental margins around the Indian Ocean are passive margins along Africa, India and Australia. Two areas exist, the Makran margin and the Sunda Arc where accretionary wedges are formed in compressional regimes of plate tectonics. In both areas the convergence of plates are responsible for magnitude 8-9 megathrust earthquakes, which lead to disruptive tsunamis along the coast of the Indian Ocean. Those types of subduction zone earthquakes account for the largest portion of the seismic energy release, and represent the greatest natural hazard to life and property for major coastal populations. Within the range of seismic activities those largest earthquakes known as megathrust earthquakes happen less often, however, they are in some cases disastrous, like the tragedy in Indonesia in December 2004. We do not understand why some earthquakes grow into rare giant events whereas others in similar areas are much smaller. Hypotheses suggest that pore fluids and sediment frictional properties are providing fundamental controls on earthquakes, but to dates investigations on fluid circulation and pore pressure conditions are very rare in both accretionary wedges of the Indian Ocean. Other hazards are submarine landslides and the understanding of their controls on timing, size, nature and effects are important as well. Hydrodynamics along the margins may precondition certain systems to failure, methane hydrate dissociation driven by climate may generate landslides and slides may naturally recur, driven entirely by the internal dynamics of pore pressure and stress evolution.

3.1.2.2 Makran subduction zone

The Makran subduction zone is formed where the Arabian Plate subducts beneath the Eurasian plate with moderate rates of ca. 4 cm yr^{-1} offshore Pakistan and Iran (Demets et al., 2010). The accretionary wedge is the largest accretionary complex in the world and is thus an end-member globally, with its exceptionally high incoming sediment thickness of more than 7.5 km due to the high terrigenous sediment input from land. The offshore section is characterized by a narrow shelf and a steep, about 90-km-wide continental slope which is dominated by a structurally simple imbricate thrust belt. The tectonic segments are morphologically expressed as long, narrow and steep accretionary ridges separated by ponded slope basins and cut by erosive submarine canyons (Minshull and White, 1989; Kukowski et al., 2001; Smith et al., 2012).

Because of the subduction of the thick water-rich sediments from the incoming plate comprehensive dewatering and degassing happens during the compression within the accretionary wedge and extensive fluid and gas discharge was expected especially from that margin (von Rad et al., 2010). Findings for fluid discharge were initially moderate, however, due to the technical development of the ship-borne hydro-acoustic tools for detecting of gas flares in the water column, gas discharge became known to occur over the entire margin. Dives with the remotely operated vehicle QUEST 4000 proved various manifestations of cold seepage on the sea floor. Hydro-acoustically measured gas plumes originated from hydrocarbon seeps at water depths from the upper slope down to the nascent ridge in the abyssal plain (Römer et al., 2012). A widespread bottom simulating reflector interpreted as the lower boundary of gas hydrates has been identified from 2D seismic studies in the past which was extended over the whole Pakistan margin (Minshull and White, 1989; Smith et al., 2012) and indicate the extensive presence of gas hydrates and free gas in the Makran accretionary prism. In comparison to other subduction zones, seismicity in the Makran is generally low (Smith et al., 2012), however, the margin experienced an Mw 8.1 earthquake in 1945 which generated a significant tsunami of wave heights up to 10 m that killed 4,000 people locally (Heidarzadeh et al., 2008). Recent investigations of pore water profiles indicate a substantial upward flux of gas in the past, and the time of the event modelled by Fischer et al. (2013) was shown to be triggered by the Mw 8.1 earthquake 60 years ago.

3.1.2.3 Sunda Arc

The subduction zone following the Sunda Arc extends over 5,000 km from Burma in the northwest to Indonesian Island Sumba in the southeast. The India plate in the north and the Australia plate in the south, as well as their intervening diffuse oceanic plate boundary, subduct beneath the Sundaland plate in the east along the Java –Sumatra trench. The oblique subduction of the plates is accompanied by varying degrees of trench-parallel fore-arc translation (McCaffrey, 1991). The Subduction zone is a typical accretionary margin subducting variable age oceanic lithosphere (40-150 Ma; DeMets et al., 2010) with relatively low convergence rates (44-60 mm yr^{-1} at Sumatra and 60-73 mm yr^{-1} at Java Island) and oblique convergence along much of its length. Because of the huge sediment input by Ganges and Brahmaputra rivers that form the Bengal-Nicobar deep sea fan in the north, the trench is less deep in the north and is getting deeper to the south away from the sediment source. In addition, due to the sediment thickness in the north the accreted prism is influenced to southeast by increasing dominance of oceanic basement.

The margin has recently experienced a number of very large magnitude earthquakes including two of the largest ever recorded. The Mw 9.2 Aceh-Andaman Earthquake (26 December 2004) ruptured ca. 1,300 km of the plate-interface involving seismic slip close to the trench that triggered the disastrous Indian Tsunami (Ishii et al., 2007; Merrifield et al., 2005). Three months later the plate-boundary segment immediately to the southeast ruptured during the 2005 Sumatra Mw 8.7 earthquake. During this event, seismic slip did not extend as far seaward (Ishii et al., 2007) and the following tsunami was significantly smaller. Geersen et al. (2013) showed that a high fluid-pressured pre-décollement, likely enabled the 2014 rupture to reach the shallow plate-boundary, result from thermally controlled mineral transformation and liberation of fluids, most probably during smectite-illite transition, in the upper oceanic basement and overlying sediments. More recently research cruises of RV SONNE examined in detail the structure and morphology of the Sunda margin from North of Andaman Islands to westernmost Java in the south (McNeill and Henstock, 2014; Cook et al., 2014). Apart from the tectonic studies, research about the fluid flow and its changes along the 5,000 km long accretionary prism are missing.

At its northern termination of the Sunda Arc connects to the strike slip system of the Himalayan collision zone at the coast of Myanmar (Mukhopadhyay et al., 2010). Although strong earthquakes have occurred in this transition zone leading to uplift of large stretches of the coast, this region has not been studied for political reasons. Its tectonic setting and the influence of fluid migration from the thick Bengal fan deposits on seismicity will be crucial for assessing the risk of future earthquakes and their tsunami potential in this region.

Key Questions

1. **What are the major processes shaping the Indian Ocean crust?**
2. **How do fluid migration and tectonic processes interact in the Makran and Sunda subduction zones and what controls do they exert on megathrust earthquakes?**
3. **To what extent do sediment/ocean fluxes from convergent margins contribute to water column biogeochemistry?**

Specific Questions

- What is the relationship between crustal thickness (magma production), water depth, and mantle temperature at ultraslow-spreading ridges?
- What is the composition and origin of non-plume off-axis magmas in the Indian Ocean and how do these compare to the DUPAL end-members in Indian MORB and OIB?
- How does the mantle heterogeneity evolve with time in the Indian Ocean, i.e. do we observe compositional changes in older parts of the crust?
- How are the compositions of mantle peridotites and the overlying magmatic rocks linked in terms of geochemical and isotopic compositions?
- What is the origin of the Marion Rise and other plateaus in the Indian Ocean?
- What are the feedbacks between magmatism, deformation, and hydrothermal alteration in oceanic detachment faults?
- What controls the distribution of oceanic detachment faults in the Indian Ocean?

- How do mantle denudation and detachment fault processes determine metal accumulations at the seafloor?
- Why are basalt-hosted and peridotite-hosted hydrothermal systems so different from each other – mineralogically and biologically?
- Is the oxygen depletion of methane emissions of the Makran margin critical and is contributing the oxygen minimum zone of the Arabian Sea?
- Are there seeps at the passive margin in the gulf of Oman which contribute to the OMZ?
- To what extent does strike slip tectonics affect the offshore part of the marine termination of the Sunda Arc in the north?
- What processes control fluid and gas circulation in the Sunda accretionary prism and what are the manifestations on the seafloor?
- Are there major changes in fluid circulation along the 5,000-km-long Sunda collision zone, i.e. how does the pronounced decrease in sediment input from NW to SE and the distribution of gas hydrate affect the fluid migration patterns?
- What are the tectonic circumstances which lead to the large megathrust earthquakes in the Indian Ocean, and under which conditions tsunamis are generated?
- How are landslides involved in the accretionary processes of the Makran and Sunda zones and how is there relation to earthquake events?

3.2 Ocean Circulation and Ocean-Climate Interactions

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3.2.1 Introduction

Over the last decades the Indian Ocean has warmed faster than most regions in the Atlantic and Pacific with an accelerated warming since 1970 (Hoerling et al., 2012). Both, observational and modelling studies have shown a close relation between sea surface temperature (SST) variations and monsoon variability on seasonal, interannual and decadal scales (Waliser et al., 2000, Latif et al., 1999, Annamalai et al., 2005). Indian Ocean SST variability, beyond its regional impact on sea level, cyclogenesis, rainfall and the Indian Ocean monsoon systems, also plays a crucial role in modulating global climate variability.

Pronounced regional differences in the warming trend highlight the important role of ocean dynamics. The upper ocean circulation and the two associated shallow overturning cells, the cross-equatorial cell (CEC) and the subtropical cell (STC), drive the southward basin-wide ocean heat transport. Variability of their intensity, often associated with the Indian Ocean Dipole (IOD), generates SST and sea level variations in upwelling regions (Lee, 2004; Miyama et al., 2003; Schott et al., 2002) as well as anoxic events by variations in biological productivity (Currie et al. 2013). The Indonesian Throughflow (ITF), the only connection between major oceans in the tropics, varies on time scales from intraseasonal to decadal, thereby impacting the variability of the shallow overturning cells and interacting with El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD).

An improved understanding of ocean-climate variability will advance climate prediction efforts and has the potential to benefit a large percentage of the world's population living in countries surrounding the Indian Ocean and elsewhere around the globe. Yet, decadal variability of ocean circulation and its influence on the variability of heat content and SST is much less understood in comparison to the Atlantic and Pacific (Han et al., 2014).

Historically, most of the research in the Indian Ocean has been dedicated to the Australasian monsoon systems. Not surprisingly, the vast majority of the paleo-(oceanographic) study sites are located in the Arabian Sea and the Bay of Bengal in the northern Indian Ocean, and within the Indonesian Seas in the eastern Indian Ocean. However, there is increasing evidence that also southern hemisphere subtropical to high latitude ocean dynamics, which are fairly unexplored, play an important role for the atmosphere-ocean interaction with a crucial impact on continental climates in Africa, Madagascar, and Australia.

3.2.2 Circulation

3.2.2.1 Upper ocean circulation

The Asian continent as the northern boundary of the Indian Ocean leads to the strongest monsoon on earth. The monsoon winds generate a seasonally reversing upper ocean circulation in the entire basin north of 10°S, such as the intriguing annual reversal of the Somali Current (SC), the Southwest and Northeast Monsoon Current (SMC, NMC), the East Indian Coast Current (EICC) and the South Java Current (SJC) (Fig. 4).

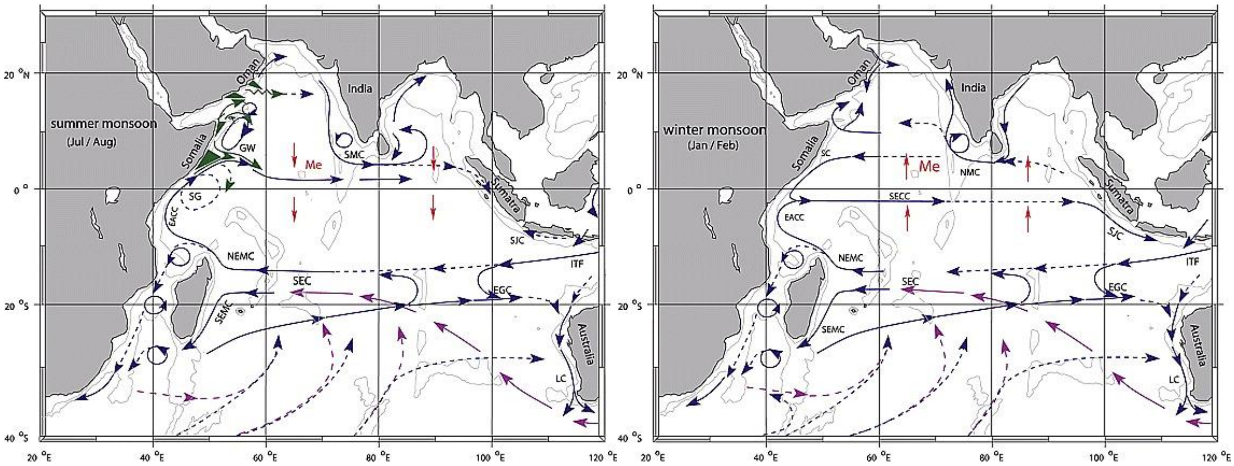

Fig. 4: Schematic representation of identified current branches in the Indian Ocean during the summer (left) and the winter (right) monsoon (Schott et al. 2009). See text for acronyms and details.

At the western boundary, the seasonal reversal of the SC is associated with the formation of large eddy structures prevailing during the summer monsoon, the Southern Gyre and the Great Whirl, driving upwelling processes (Fig. 5, Schott and McCreary, 2001). Throughout the year a northward undercurrent at thermocline depth (100-400 m) supplies the upwelling regions. There exist only sparse measurements of the unique western boundary current system whose dynamical development and impact on regional biogeochemical processes still remain unclear.

South of 10°S, the upper ocean exhibits a more persistent character. The Indian Ocean receives surface and intermediate water from the Pacific Ocean, and exports it into the South Atlantic Ocean. These inter-ocean exchanges vary on various time scales and play an active role in redistributing heat, moisture and salt along the return path of the conveyor belt circulation. From the Pacific, two uncorrelated routes exist north and south of Australia: the Indonesian Throughflow (ITF), playing a key role as it is the only connection between two major oceans in the tropics, and the Tasman leakage. The ITF communicates changes in Pacific forcing into the Indian Ocean (Wijffels et al., 2008), influencing sea level (Schwarzkopf and Böning, 2001) and upper ocean circulation (Feng et al., 2011). The variability of the ITF on seasonal (Sprintall et al., 2009), inter-annual (Meyers et al., 1996), decadal (Feng et al., 2010), and multi-decadal (Feng et al., 2011) time scales is related to the Asian-Australian monsoon, zonal wind anomalies over the equatorial Pacific and Indian Oceans, and climate variability (ENSO, IOD). Though somewhat smaller in magnitude, the Tasman leakage (Fig. 6) constitutes an important route of thermocline waters entering the Indian Ocean. It is associated with the supergyre which connects the major oceans (Speich et al., 2007) and does not appear to be correlated with the flow through the Indonesian Archipelago (van Sebille et al., 2014).

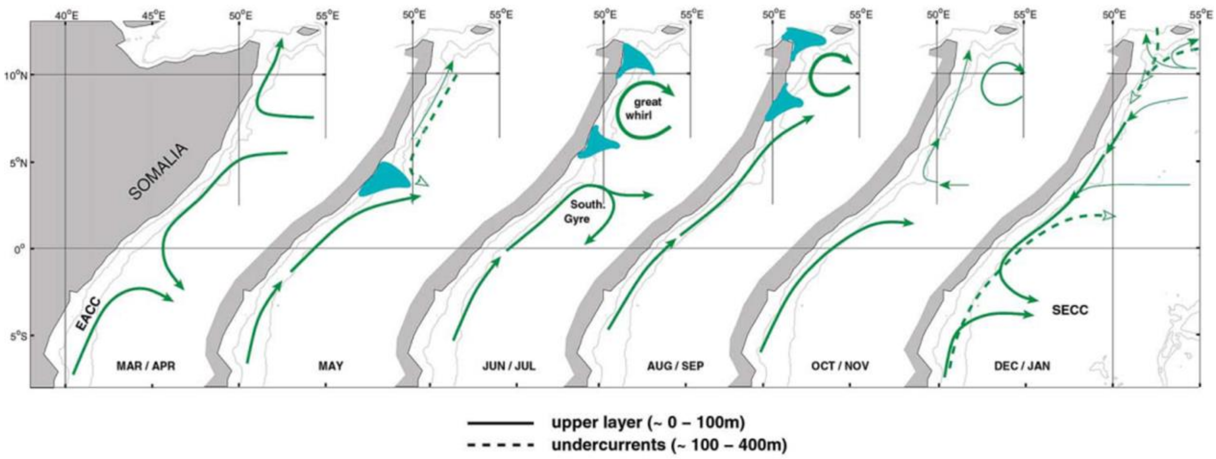

Fig. 5: Schematic diagram of the seasonal development of the Somali Current system (Schott and McCreary, 2001).

The export of Indian Ocean waters into the South Atlantic, known as Agulhas leakage (Richardson, 2007), is accomplished by the Agulhas Current which is fed by southward flow through the Mozambique Channel and the East Madagascar Current, both dominated by strong eddy activity. However, the connection to the source region in the western tropical ocean associated with mesoscale eddy and upwelling processes as well as southern hemisphere climate variability is still not well understood at many different time scales. Little is known about the role of the Indian Ocean circulation in communicating changes from the Pacific into the Atlantic via the Agulhas leakage. This is of particular importance since ocean models suggest an increase of Agulhas leakage over the past decades (Biastoch et al., 2015) and is projected to further increase under global warming conditions (Biastoch and Böning, 2013).

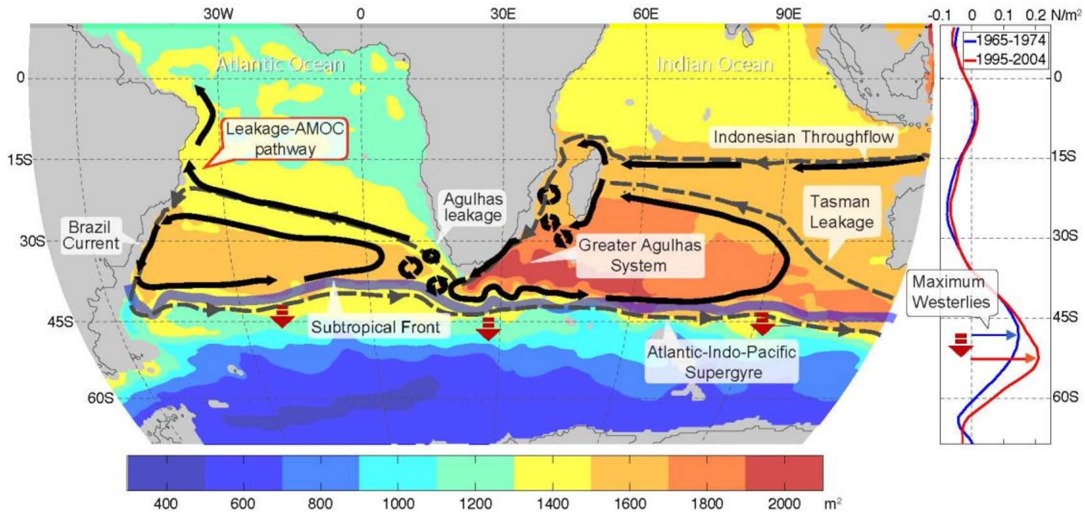

Fig. 6: Schematic of the greater Agulhas system embedded in the Southern Hemisphere super gyre (Beal et al., 2011).

3.2.2.2 Shallow meridional overturning cells

Two shallow meridional overturning cells exist in the Indian Ocean that accomplish the southward basin-wide heat transport, control the heat balance of the Indian Ocean and may play a key role in its decadal and multidecadal variations. The structure of both cells differs from those in the Atlantic and Pacific due to the lack of equatorial upwelling resulting from annual-mean equatorial westerlies. The cross equatorial cell (CEC) is driven by southward near-surface Ekman and Sverdrup transports, which is then subducted in the southeastern subtropics, including contributions from the ITF. Southward transport is balanced by northward cross-equatorial transport in thermocline depth within the Somali Current at the western boundary which is then upwelled in the Arabian Sea and the Bay of Bengal (Schott et al., 2002; Miyama et al., 2003) (Fig. 7). The subtropical cell (STC) connects the southern Indian Ocean subduction region with the open-ocean upwelling region in the thermocline ridge region (Yokoi et al., 2008) and is closed by southward Ekman transport (Lee, 2004) (Fig. 7).

Analysis of satellite data suggests that the strength of both shallow cells varies significantly on interannual to decadal time scales (Lee, 2004; Lee and McPhaden, 2008, Schoenefeldt and Schott, 2006). Advanced understanding of the dynamics and variability of the different branches of these cells is of particular importance. In upwelling regions along the Somalia-Oman coasts, interannual SST variability causes variability in monsoon rainfall (Izumo et al., 2008). Westward propagating Rossby waves that in part originate from the Pacific play a dominant role in SST variability within the open-ocean upwelling region (Xie et al., 2002), such as SST variability on different time scales, reaching from intraseasonal to interannual, with influence on cyclone genesis in the southwestern Indian Ocean (Xie et al., 2002) and summer monsoon rainfall (Annamalai et al., 2005; Izumo et al., 2008).

Weak subduction rates in the northern Indian Ocean are the dominant reason for the appearance of one of the main global Oxygen Minimum Zones (OMZs) in the world tropical ocean within the northern Arabian Sea and a somewhat weaker OMZ in the northern Bay of Bengal (McCreary et al., 2013). For the southern Indian Ocean, Karstensen and Quadfasel (2002, 2002b) suggested a significant increase of water mass subduction rates by as much as 70% over the period 1982 to 2000. To date, however, the impact of the increased ventilation has not been investigated.

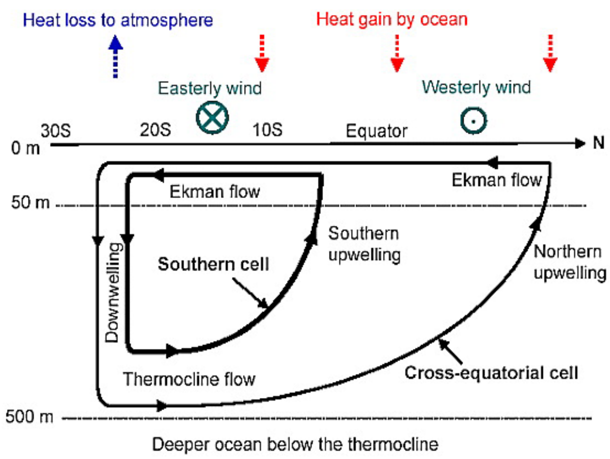

Fig. 7: Schematic diagram of the zonal and time-mean meridional overturning circulation of the upper Indian Ocean that consists of STC and CEC.

Furthermore, the CEC accounts for the northward transport of oxygen-rich thermocline water masses from the southern hemisphere across the equator into the poorly ventilated Arabian Sea and the Bay of Bengal. Variability of the CEC strength will thus impact biogeochemical cycling within the OMZs in the northern Indian Ocean. To improve climate-biogeochemical models, dedicated process studies aimed at a better understanding of the physical processes which occur within the coastal upwelling regions are required.

Paleoceanographic studies at interannual resolution exist for the western tropical Indian Ocean but cover only certain periods for the Holocene, mainly based on Seychelles and La Reunion corals. These records cover properly the seasonal cycle but it is still difficult to separate local ocean dynamics from those governed by changes in overall hemispheric insolation changes during the mid to late Holocene (Pfeiffer et al., 2004, 2006; Zinke et al., 2005, 2014). Temperature records covering interglacial-glacial climate variations in this equatorial upwelling region do not exist, except for one record (Kiefer et al., 2006) that has been criticized because of potential proxy bias due to carbonate dissolution effects in the deep-sea.

3.2.2.3 Intermediate and deep circulation

The Arabian Sea, where southern-source Central and Intermediate Waters mix with water masses from the ITF, the salinity characteristics of northern-source Red Sea Water and Persian Gulf Water are exceptionally strong. Knowledge about western boundary transport at thermocline and intermediate levels is fairly poor and the magnitude of interannual variability of this transport is currently unknown. At the equator, deep zonal jets appear to change direction on interannual time scales (Dengler and Quadfasel, 2002; Brandt et al., 2011), but their role in redistributing intermediate and deep water masses is unclear. A better understanding of the intermediate circulation describing the pathways of Red Sea Water and Persian Gulf Water within the Arabian Sea is utterly needed, particularly within the focus of advancing the understanding of climate-biogeochemical interactions within the northern Indian Ocean in respect to the OMZs.

Nevertheless, it is suggested that the amount of salt introduced by the RSW is balanced by the Agulhas Current export (Beal et al., 2000). As the outflow of the RSW is controlled by the monsoon on seasonal time scales, and sea-level on glacial-interglacial time scales, past variations in monsoon intensity and sea-level should have resulted in profound yet unexplored changes not only in upper ocean circulation of the western Indian Ocean but also in the strength of the shallow overturning cells. However, our limited understanding of the regional oceanography precludes a sound interpretation of any potential dataset arising from future coring campaigns. A similar connection can be drawn between the ITF and Agulhas leakage. Although Le Bars et al (2013) demonstrated that the mean inflow from the Pacific is directly passed to the Agulhas regime, it remains unclear how this relates to any decadal changes in the inflow (ITF, Tasman leakage) and outflow (Agulhas) regimes.

The deep Meridional Overturning Circulation (MOC) in the Indian Ocean describes an overturning cell involving northward flowing Antarctic Bottom Water (that here is historically called Circumpolar Deep Water) below 3500m depth and southward flowing Indian Ocean Deep Water from 3500m to 2000m depth (Ganachaud and Wunsch, 2000; Lumpkin and Speer, 2007). It is generally accepted that the deep MOC is driven by diapycnal mixing in the deep ocean. Due to the small temperature difference of the opposing abyssal flows, heat transport within the deep MOC is much smaller than the heat transport accomplished by the shallow cells. However, a remaining puzzle is the large overturning transport within the Indian deep MOC compared to the deep MOC of the Pacific, although the latter is several times larger than the Indian Ocean (Lumpkin and Speer, 2007). Also, due to the scarcity of intermediate and deep coring sites offshore the main upwelling centres in the Arabian Sea and the Bay of Bengal, state-of-the art paleo records for a 2-dimensional reconstruction of the Indian Ocean MOC in the late Pleistocene and Holocene are missing.

3.2.3 Ocean-climate variability and feedback mechanisms

The tropical Indian Ocean forms the major part of the largest warm pool on earth. Through interaction with the atmosphere, its variability plays a dominant role in both regional and global climate variability. Modes of climate variability exhibit a broad range of time scales, from intraseasonal, interannual, decadal and longer.

3.2.3.1 Tropical cyclones

A devastating demonstration of the destructive power of tropical cyclones in densely populated areas like the Bay of Bengal is the recent cyclone Nargis (Fig. 8). The category 3–4 hurricane made landfall in Myanmar on 2 May 2008 and brought vast amounts of rain and a storm surge to the low-lying and densely populated Irrawaddy River delta. In its wake, the storm left a death toll of more than 100,000 and caused more than $10 billion in economic losses (McPhaden et al., 2009). Shortly before landfall, the cyclone extracted vast amount of heat from the ocean mixed layer that fuelled intensification of the storm (Maneesha et al., 2012). Regions of cyclogenesis are the Bay of Bengal and to a lesser extend the Arabian Sea and the South Indian Ocean between 10°S and 25°S.

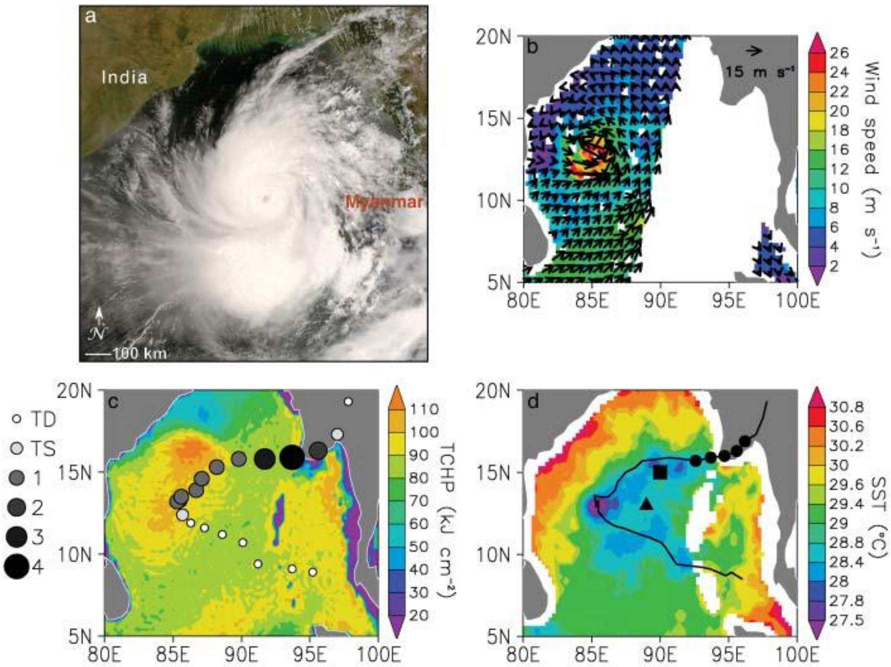

Fig. 8: Oceanic and atmospheric conditions during cyclone Nargis. a) Visible image (MODIS) from 1 May 2008. (b) Wind vectors (QuikSCAT) and speeds for 28 April 2008. (c) Tropical cyclone heat potential (TCHP) climatology for April (in kJ cm^{-2}). Storm intensity is shown by dots, TD - tropical depression, TS - tropical storm, numbers - equivalent hurricane strength). (d) Sea surface temperature showing the track of Nargis (from McPhaden et al., 2009).

Significant progress has been made in understanding the regulation of cyclogenesis by the seasonal cycle and its modulation by intraseasonal and interannual climate variability. Tropical cyclone activity over the Bay of Bengal is enhanced during La Nina events in the Pacific due to elevated zonal winds variance and lower vertical wind shear over the central and northern Bay of Bengal (Felton et al., 2013). Additionally, increased relative humidity during La Nina events contributes to enhanced cyclogenesis. Furthermore, the intensity of Madden-Julian oscillations modulate cyclogenesis in both hemispheres (Bessafi and Wheeler, 2006; Yanase et al., 2012). The response of the ocean to cyclone forcing is predominately by near-inertial motions that cool and deepen the ocean mixed layer by breaking and subsequent mixing (Wang and Han, 2014; Cuypers et al., 2013). Additionally, salinity stratification and mesoscale eddies can influence the cooling below tropical cyclones and potentially their intensity (Neetu et al., 2012; Yu and McPhaden, 2011). However, ocean feedback processes and their impact on cyclone development remain largely unexplored.

3.2.3.2 Intraseasonal oscillations

Intraseasonal oscillations with periods between 14 and 90 days are pronounced in the ocean as well as in the atmosphere. The most dominant form of intraseasonal variability in the tropical atmosphere is the Madden-Julian Oscillation (MJO, Madden and Julian, 1972). It is often initiated in the Indian Ocean (Zhang et al., 2013), and lateral moisture transport plays a leading role in the initiation process (Yoneyama, et al., 2013; Kerns and Chen, 2014). Apart from modulating cyclogenesis, it has far reaching impacts on weather and climate, affecting Indian, Asian and Australian monsoon rainfall, tropical storm formation, the evolution of El Niño events, and the North Atlantic Oscillation (Webster at al., 1998; Zhang, 2005; Cassou, 2008, Vitart and Molteni, 2010, Zhang, 2013).

Recent field programmes within the CINDY/DYNAMO project (Yoneyama et al., 2013) have highlighted the important role of the ocean feedback mechanisms during MJO initiation. In particular, barrier layers, wind- and shear-driven mixing, zonal advection, shallow thermoclines, and mixed-layer entrainment play essential roles in MJO initiation by controlling the upper-ocean heat content and SST, and thereby surface flux feedback (e,g., Moum et al., 2013; McPhaden and Foltz, 2013). Regions of particularly strong SST response to atmospheric intraseasonal variability are the open-ocean upwelling region between 5°S and 10°S (Saji et al., 2006; Izumo et al., 2010; Jayakumar and Gnanaseelan, 2012) and the northwestern Australian Basin (Vialard et al., 2013). Modelling studies demonstrate that the inclusion of air-sea coupling on intraseasonal time scales can improve the simulation and forecast of the MJO behaviours (Woolnough et al., 2007, Yang et al., 2012). Thus, a better understanding of the feedback processes is needed to enhance predictability of MJO events and their impact on climate.

Dynamically forced intraseasonal variability in the ocean is particularly elevated within the equatorial wave guide where intraseasonal winds excite Kelvin and Rossby waves (Nagura and McPhaden, 2012) that also effect the eastern boundary current system and upwelling off Indonesia (e.g. Vialard et al., 2009b; Chen et al., 2015). Oceanic intraseasonal variability resulting from instability processes within the ocean have been observed and modelled to modulate SST and upwelling intensity in the Arabian Sea (Brandt et al., 2003; Wirth et al., 2002; Vialard et al., 2012; Beal and Donohue, 2013) and to interact with the western boundary circulation in the Bay of Bengal (Girishkumar et al., 2013). Intense mesoscale eddies form in the southern Indian Ocean within the South Equatorial Current between 5°S and 15°S, favoured by the destabilizing effect of ITF water on the stratification (Zhou et al., 2008), at about 25°S due to baroclinic instabilities (Palastanga et al., 2007), in the

Mozambique channel and around south Madagascar (de Ruijter et al., 2004; Ridderinkhof et al., 2013). The impact of oceanic intraseasonal variability on climate variability and its influence on biogeochemistry needs further evaluation.

3.2.3.3 Interannual variability

The most pronounced modes of interannual variability in the Indian Ocean are ENSO, the IOD, the Tropical Biennial Oscillation and the subtropical dipole (e.g. Schott et al., 2009). The tropical Indian Ocean responds to a positive ENSO event with a gradual warming that lags slightly behind El Niño warming in the Pacific and can be explained by changes in surface heat fluxes due to the anomalous atmospheric conditions (Klein et al., 1999). Warming over the open-ocean southern hemisphere upwelling region, however, is caused by downwelling Rossby waves that are excited in the southeastern Indian Ocean (Xie et al., 2002). The Indian Ocean warming persists until the summer following the ENSO event, much longer than ENSO related SST anomalies in the Pacific. The so called “capacitor effect” (Annamalai et al., 2005) then causes remote interannual climate variability over the Northwest Pacific and East Asia (Huang et al., 2004) but maintains its regional impact, such as rainfall anomalies (Xie et al., 2009).

The tropical Indian Ocean typically exhibits warmer SSTs in the eastern part compared to the western part of the ocean. During IOD events that develop in June and peak in October, this zonal SST gradient is reversed (Saji et al., 1999), leading to enhanced rainfall over East Africa (e.g. Latif et al., 1999), while rainfall is weakened over the Australian continent. Between 1876 and 1999, about 50% of the IOD events co-occurred with a positive ENSO event (Meyers et al., 2007) but can also be internally triggered (Yamagata et al., 2004, Schott et al., 2009, Fig. 9). IOD events, particularly the associated warming in the thermocline ridge region between 5°S and 10°S, have important remote effects through atmospheric teleconnections. These influences are felt not only over the mid-latitudes (e.g. Annamalai et al. 2007), but are also thought to influence the evolution of ENSO although it is not clear if this influence is associated with the IOD (Izumo et al., 2010b) or the IO basin-wide warming (e.g. Kug and Kang, 2006).

The ITF shows significant interannual variability related to monsoon, ENSO and the IOD: surface (thermocline) flow is intensified during La Niña (El Niño) and positive (negative) IOD years (Gordon et al., 2003; 2010; 2012; Sprintall et al., 2009; Sprintall and Révelard, 2014). The most important implication of the variability in the vertical profile of the ITF transport is that a thermocline-intensified ITF cools the surface layer of the Indian Ocean and warms the Indian Ocean deeper layers, whereas a surface-intensified ITF warms the eastern tropical Indian Ocean SST (Gordon et al., 2012). Despite decades of research in this region, the complex feedback mechanisms along the ITF path and their implications for regional and global climate are still poorly understood.

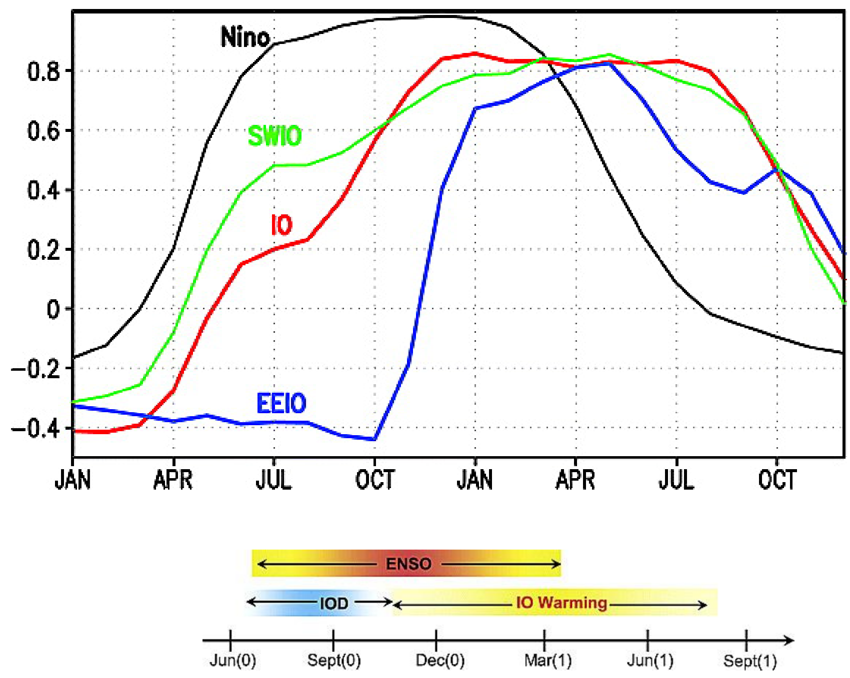

Fig. 9: Upper panel: Nino3 SST (eastern equatorial Pacific) correlation with SST averaged in the central equatorial Pacific (Nino, black), the tropical IO (IO, red), the southwest IO (SWIO, green), and the eastern equatorial IO (EEIO, blue). Lower panel: Seasonality of major interannual IO climate modes.

3.2.3.4 Variability on decadal and longer time scales

Decadal and long-term variability can be generated internally or externally and provides a potential predictability, which is important for societal management (Meehl et al., 2009). Indian Ocean SSTs are known to affect monsoon systems even in the Atlantic sector (Giannini et al., 2003), whereby its decadal variability is not limited regionally but rather globally (Han et al., 2014). During the 20th and 21st centuries, Indian Ocean SSTs have undergone a strong warming particularly since the 1950s (Ihara et al., 2008), with a stronger warming in the western tropical Indian Ocean (Roxy et al., 2014). The warming is accompanied by an increased radiative forcing due to enhanced greenhouse gases in the atmosphere. These trends, however, are superimposed by a decadal variability, which can be independent of the interannual variability (e.g. ENSO, IOD) or may modulate the interannual variability (Ashok et al., 2004).

Internal decadal variability in the Indian Ocean is weak compared to that in other ocean basins, where long-term internal modes of variability exist, e.g. Pacific Decadal Oscillation in the North Pacific and Atlantic Multidecadal Variability in the North Atlantic (Boer, 2010). Although the level of decadal variability is low, the predictability can be enhanced due to external forcing or influence from outside of the ocean basin. Indeed, Guemas et al. (2013) showed that the Indian Ocean is the region of highest skill of multi-year predictability in decadal prediction systems, which is mainly attributed to the long-term warming trend. Therefore, attributing the observed Indian Ocean SST evolution to external factors should be a subject of future study.

In addition to SST, oceanic heat capacity change is important because the Indian Ocean is located on an important path of the global thermohaline circulation, in particular, by its connection to the Pacific via ITF (Gordon and Fine, 1996) and to the Atlantic via Agulhas leakage (Beal et al., 2011). Strong decadal change has been observed in the inter-ocean exchange between the Pacific and Indian Ocean, in which wind-driven ocean dynamics are involved (Han et al., 2010; Schwarzkopf and Böning, 2011). It has also been shown that during the recent hiatus of global warming, large portions of heat received through the Pacific ocean surface were transported to the Indian Ocean (Lee et al., 2015), where the wind plays an important role. In this regard, variability of the Walker circulation and its response to global warming is crucial (Kociuba and Power, 2015), because it drives the spatial structures of Indian Ocean sea level and thermocline changes (Han et al. 2006). There is, however, no consensus on trends in equatorial Indian Ocean westerly winds and the Indo-Pacific Walker circulation over the past 50–100 yr. Some observational analyses indicate that the Indo-Pacific Walker circulation is weakening while others indicate its strengthening (Meng et al., 2012). Therefore, wind change and related wind-driven ocean dynamics and inter-ocean exchanges of heat and salt need to be considered for understanding decadal variability in the Indian Ocean.

3.2.3.5 Climate variability on longer time scales

In the Arabian Sea and the Bay of Bengal, the structure and characteristics of the water column show a strong, monsoon-related seasonality. The hitherto available proxy-based productivity and salinity reconstructions from these regions have been interpreted as changes in upwelling and precipitation and thus, the summer monsoon intensity (e.g. Reichart et al., 1998; Budziak et al., 2000; Anand et al., 2008; Marzin et al., 2013) with the first order variability occurring at millennial and not glacial-interglacial time scales.

The prime mechanisms controlling this variability and connecting the South Asian (Indian) monsoon and the North Atlantic climate regime are still debated. Both insolation forcing on precessional time scales (Budziak et al., 2000) and changes in the intensity of the Atlantic meridional overturning circulation (Schmittner et al., 2007; Ziegler et al., 2010) have been suggested to control the Arabian Sea biological productivity via atmospheric (e.g. Schulz et al., 1998) or oceanic (e.g. Hong et al., 2003) processes. Alternatively, local feedback processes involving snow and dust on the Tibetan plateau have been suggested to control the millennial cycles recorded in the South Asian (Indian) monsoon archives (Kudrass et al., 2001). A recently published study combining model and proxy data suggests that changes in the North Atlantic climate are transferred to the Indian Ocean realm during all seasons involving similar atmospheric teleconnection mechanisms (Mohtadi et al., 2014). One major caveat is that high-resolution records reflecting the glacial/interglacial and millennial-scale development of the winter monsoon are practically non-existent. Study of winter monsoon variations over the last glacial-interglacial cycles is thus essential to understand the monsoonal cycles and their forcing mechanisms.

The western Indian Ocean constitutes a climatic sensitive region with SST changes driven by monsoon seasonality and rain belt displacement and thus responding to changes in both Walker and Hadley circulations. Almost the entire paleoceanographic studies in existence have been devoted to African/Arabian/Indian monsoon reconstruction as recorded in wind, rainfall, and productivity proxies in marine and terrestrial climate archives (see e.g. reviews by Wang et al., 2005; Thomas et al., 2012). Surprisingly little is known about past changes in the Walker Circulation and their effect on the hydroclimate of the western Indian Ocean, which can be studied in marine archives between off Kenya and Madagascar, where changes in the Walker Cell are not entirely masked by the Hadley Cell and monsoon circulation changes. First results from paleo studies south of the equator still relate surface ocean variability at centennial and millennial time scales to insolation and northern hemisphere high-latitude climate forcing transferred via latitudinal movements in the ITCZ position (Bard et al., 1997) while paleo records for austral winter temperatures and/or subsurface mode waters in the western Indian Ocean suggest a more direct link to climate variability in the southern hemisphere (Wang et al., 2014). Hence, our paleoceanographic knowledge from the extratropical southern Indian Ocean is rudimentary at best owing to perpetual logistical constrains for sampling endeavours. Although this issue remains hard to overcome, data from this part of the Indian Ocean are invaluable for tracking the exchange between the southern high-latitudes and the tropics at surface (southward via Leeuwin Current and Southeast Madagascar Current) and at subsurface (northward via AAIW and SAMW) in order to decipher leads and lags, forcing and response, and their mechanistic link in paleoclimate data and model simulations.

3.2.3.6 Monsoon rainfall

Observation and model studies suggest that changes in the amount and pattern of sea surface temperature (SST) in the Indian Ocean strongly affect rainfall over the adjacent continents by modifying the atmospheric circulation and moisture content and thus, impact the economy and livelihood of more than two-thirds of the world's population (Mohtadi et al., 2016 and references therein). For southern Asia, the lag correlation between South Asian (Indian) monsoon (SAM) rainfall and preceding Indian Ocean SST anomalies in observations suggests that the Indian Ocean SST affects the SAM variability (Chang et al., 2011). An atmospheric general circulation model ensemble forced only in the Indian Ocean region also suggests that the Indian Ocean SST is contributing significantly to the decadal SAM rainfall variability (Kucharski et al., 2006). Here, cold (warm) equatorial SSTs induce low-level divergence (convergence) that in turn modifies the local Hadley cell and strengthens (weakens) the Asian monsoon circulation. Spatiotemporal changes in the Indian Ocean SST are also critical for the rainfall intensity and pattern over Asia: the springtime SST in the Indian Ocean leads to opposite changes in the SAM and the Southeast Asian monsoon (SEAM), reinforcing the out-of-phase relationship that appears often between the two monsoon components, with a warmer SST strengthening the SAM but weakening the SEAM. Instrumental data suggest that the southern Indian Ocean SST is related to the SAM more closely than the northern Indian Ocean SST (Yoo et al., 2006). In addition, southern Indian Ocean SST and the associated wind and circulation anomalies are particularly pronounced during strong El Niño years, and favor the subsequent development of La Niña conditions (Yoo et al., 2010). Model simulations of past rainfall changes suggest that Indian Ocean SST alone accounts for virtually all the variability in precipitation over the Indian subcontinent during abrupt climate changes (Pausata et al., 2011).

Model simulations indicate that enhanced East African 'short rains' (Oct-Nov) are predominantly driven by the local warm SST anomalies in the western equatorial Indian Ocean, which reduce sea level pressure over the western half of the Indian Ocean and lead to wind and moisture convergence and increased convective activity over East Africa (Ummenhofer et al., 2009). SST anomalies in the southwest Indian Ocean are central to southern African rainfall variability, in which positive events are associated with dry conditions over southern Africa and negative events with wet conditions (Kay and Washington, 2008).

Warm Indian Ocean SST anomalies also induce northwesterly flow towards Australia and increased moisture convergence and rainfall over the land (Chang et al., 2011). On the other hand, the boreal fall SST, especially in the north Indian Ocean, is strongly associated with the subsequent Australian summer monsoon (Yoo et al., 2006). Atmospheric general circulation model sensitivity experiments indicate a significant negative partial correlation between rainfall over the western and southern regions of Australia and the Indian Ocean Dipole (Ashok et al., 2003; Cai et al., 2009; Cai et al., 2011). The Indian Ocean Dipole (IOD) is the prominent coupled climate mode in the tropical Indian Ocean and is phase locked to the seasonal cycle (Saji et al., 1999; Webster et al., 1999). IOD is characterised by strong east–west SST anomaly gradient and favouring upwelling by alongshore winds in the southeastern tropical Indian Ocean from boreal spring which peak in September–November (Saji et al. 1999). Several studies have addressed the coupled atmospheric and oceanic response of IOD in terms of different indices such as SST anomalies over various regions (Webster et al., 1999). Cold SST anomalies prevailing west of the Indonesian archipelago during the positive IOD events introduce an anomalous anticyclonic circulation at lower levels over the eastern tropical and subtropical Indian Ocean, and over much of the Australian continent. Composite IOD reconstructions show that drought is a key feature associated with IOD events in western Indonesia and northern Australia (Abram et al., 2007).

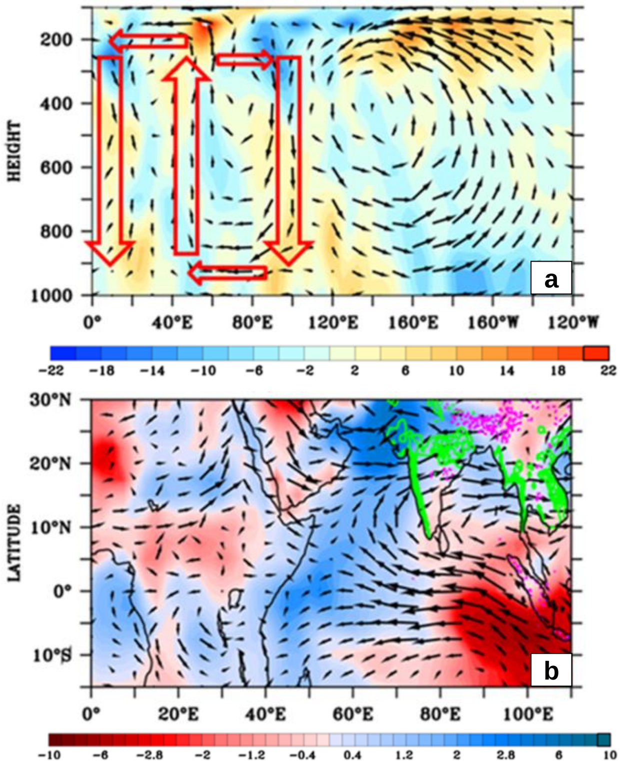

Fig. 10: Circulation and rainfall anomalies in the Indian Ocean realm caused by the IOD-related SST changes. a) depth–longitude plot of wind divergence anomalies (shaded, x 10^{-7} s^{-1}) overlaid with anomalous zonal (in m s-1) vertical (y-axis, in -10-2 Pa s-1) circulation averaged over 5°S–5°N. Red arrows indicate ascending and descending arms of the Walker circulation. b) Composites of precipitable water (shaded, kg m-2) overlaid with precipitation anomalies (green contours) and 850 mb wind anomalies (vectors) during June–August. Adapted from Deshpande et al. (2014).

Diagnostic analyses and atmospheric general circulation model simulations suggest that strengthening of monsoon flow and local Hadley cell associated with strong IOD events enhances precipitation over the Indian subcontinent (Deshpande et al., 2014) (Fig. 10). They also show a positive influence of IOD on snow cover over the Tibetan Plateau through a barotropic cyclonic anomaly north of India that transports the moisture from the tropical Indian Ocean together with the moisture from the Bay of Bengal and the Arabian Sea toward the Tibetan Plateau. This convergence of moisture over the plateau increases the possibility of precipitation and snow cover (Yuan et al., 2012).

Key Questions

1. **What are the key processes that determine ocean circulation and climate in the Indian Ocean?**
2. **What is the role of the Indian Ocean in the global Conveyor Belt circulation system and in global climate?**
3. **What are the key elements that enable interannual, decadal or multidecadal predictability of the Indian Ocean system and how do they interact with global climate change?**
4. **What are the key interactions between the ocean and atmosphere in the context of the Australasian and African monsoon systems?**

Specific Questions

- What drives the variability and dynamics of the shallow overturning cells?
- What ocean processes contribute to SST variability in the upwelling regions?
- How does the intermediate and deep circulation of the Indian Ocean determine the ventilation pathways and biogeochemistry of the northern Indian Ocean?
- Why and how does the Indian Ocean warm water transport between the western Pacific and the South Atlantic Oceans change on decadal and longer time scales?
- How does high latitude climate change contribute to the tropical Indian Ocean circulation through time and space?
- What is the effect of sea-level change on circulation and water mass characteristics in the eastern and western tropical Indian Ocean?
- Is there a long-term periodicity in the zonal ocean-atmosphere coupled systems within the Indian Ocean (IOD, ENSO) and how does it relate to the meridional (monsoon) systems?
- What is the impact of Agulhas leakage on the stability of the Atlantic thermohaline circulation?

3.3 Biogeochemical Cycles and Atmospheric Chemistry

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3.3.1 Introduction

Global change affects biogeochemical cycles and ecosystems, but ecosystem responses and associated feedbacks to the marine biogeochemical processes and climate are unknown. (Doney et al., 2012; Hoegh-Guldberg et al., 2014). The biological pump is the ecosystem function that controls the distribution of oxygen and nutrients in the water column, transfers climate signals into the sedimentary records, and influences the greenhouse gas concentrations in the atmosphere. Although it is known that marine ecosystems respond to global warming, ocean acidification, deoxygenation, eutrophication and probably also atmospheric pollution, our understanding of the functioning of the biological pump is still so poor that the extent and even the future direction of change are unpredictable. This lack of understanding confines the reliability of climate projections, which are essential especially in a region where a large part of the world's population depends on the summer monsoon rainfall.

3.3.2 Present Indian Ocean biogeochemistry and major nitrogen (N) losses

The South Asian (Indian) monsoon region of the northern Indian Ocean has a unique circulation and biogeochemistry. Primary productivity is highly seasonal in the northern Indian Ocean related to the seasonal reversal in South Asian monsoonal winds: During the southwest (SW) monsoon, upwelling driven productivity maxima occur along the Arabian Peninsula, Somalia and within the Sri Lanka Dome and SW monsoon current in the southern Bay of Bengal (Wiggert et al., 2006). During this season nitrate concentrations in the upwelling areas off the Arabian Peninsula and Somalia can exceed 15 µM (Morrison et al., 1998; Woodward et al., 1999) with filaments and plumes of enhanced nutrient concentrations and productivity spreading hundreds of kilometres to the east (Naqvi et al., 2003; Rixen et al., 2005). During the northeast (NE) monsoon, winter cooling leads to convective mixing and associated nutrient entrainment and enhanced productivities in the Arabian Sea (Rixen et al., 2005). Nitrate concentrations in the euphotic zone can reach 6 µM during this season (Morrison et al., 1998). Compared to the Arabian Sea, productivity is much lower in the Bay of Bengal. Upwelling is subdued by the large fresh water input from the Ganges Brahmaputra (Kumar et al., 1996) which reduces salinity in the surface waters to values <33 to 34 (Conkright et al., 2002).

The equatorial upwelling in the Indian Ocean is weak compared to other ocean basins and restricted to the western Indian Ocean (Murtugudde et al., 1999). In the Indian Ocean nitrogen fixation and the removal of nitrogen via denitrification and anammox are closely located. The OMZs of the Arabian Sea and Bay of Bengal cover areas of $2.5*10^6$ km² and $1.6*10^6$ km² (Fig. 11), respectively, with vertical extensions of 760 ± 340 m and 170 ± 30 m, respectively (Paulmier and Ruiz-Pino, 2009). While the Indian Ocean OMZ has the smallest area of all oceanic OMZ, it holds a significant core thickness with an intense mid-water oxygen minimum. Oxygen concentrations are below 100 µM at around 1000 m extending to 20°S (Conkright et al., 2002). In the Arabian Sea and Bay of Bengal oxygen concentrations have their minima between the oxycline at the base of the surface mixed layer and about 1000 m to 1200 m water depth.

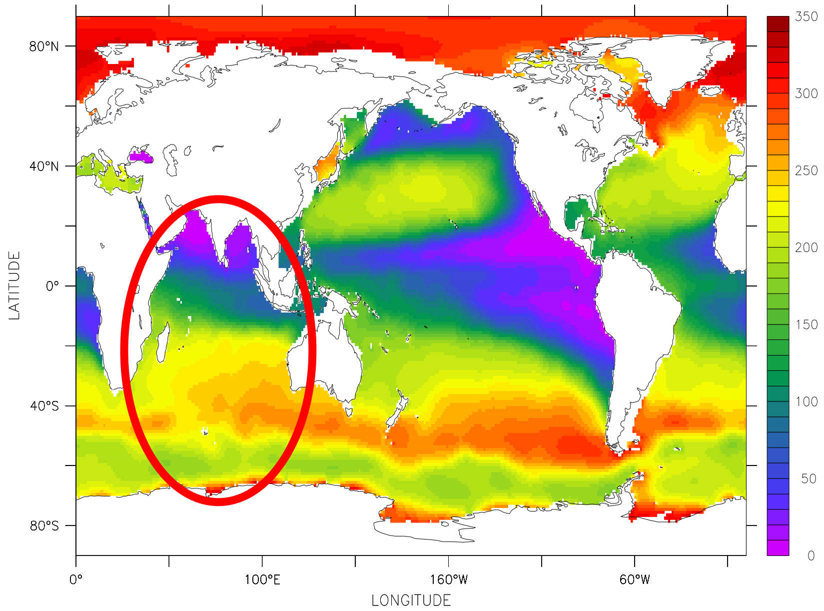


Fig. 11: O_2 (µM) at 400 m depth, data from World Ocean Atlas.

Ship based observations have shown oxygen concentrations below 1 µM in the core of the Arabian Sea OMZ and minima of about 3 µM in the Bay of Bengal (Rao et al., 1994; Rixen et al., 2014) (Fig. 11 and Fig. 12). There have been no reports of nitrite accumulation in the OMZ of the Bay of Bengal in off shore areas, whereas a large zone with a secondary nitrite maximum is permanently present in the northeastern Arabian Sea (Naqvi, 2008) (Fig. 12) suggesting that the threshold for nitrate reduction is below a concentration of 3 µM oxygen. The accumulation of nitrite in OMZs is classically regarded as an indication of active heterotrophic denitrification of nitrate with nitrite accumulating as intermediate (Naqvi, 1987). Nitrite re-oxidation may be closely coupled even at very low oxygen concentrations in the upper and lower denitrification zone (Gaye et al., 2013). Autotrophic anaerobic oxidation of ammonium with nitrite (anammox) as well as the dissimilatory nitrite reduction to ammonia (DNRA) have been detected in OMZs (Jensen et al., 2011; Lam and Kuypers, 2011) but the major loss of nitrogen in the Indian ocean is still considered to be denitrification (Ward et al., 2008; Ward et al., 2009).

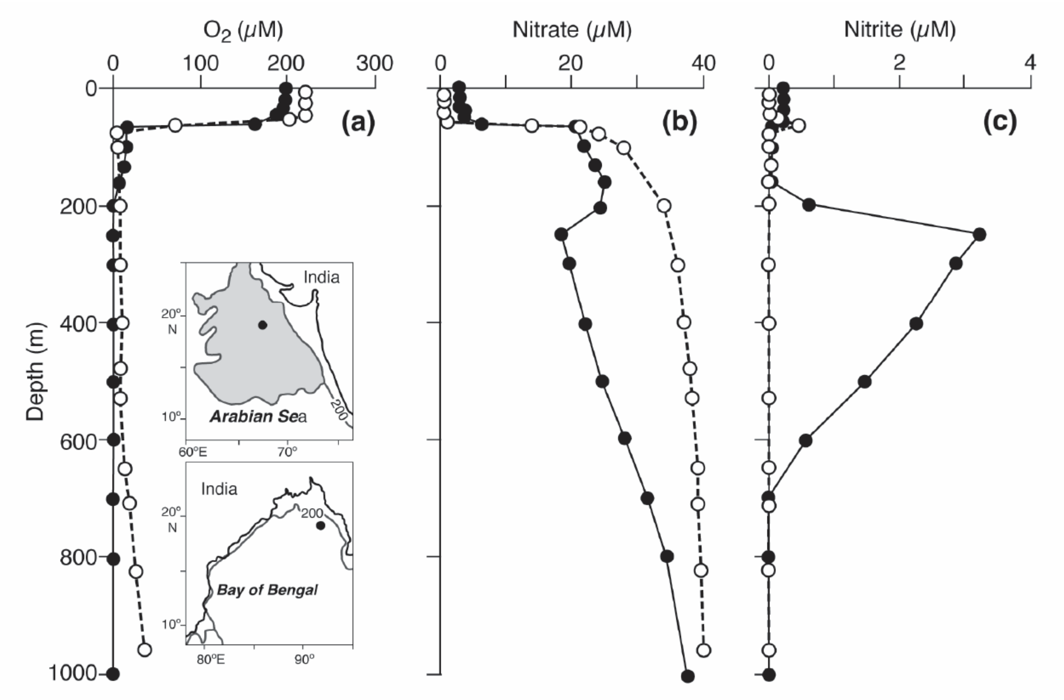


Fig. 12: Typical profiles of O_2, nitrate and nitrite from the Arabian Sea (filled circles) and the Bay of Bengal (open circles) (Naqvi et al., 2006).

As a result of the denitrification and anammox processes in the OMZ of the Arabian Sea, the Indian Ocean acts as a major sink of nitrogen (N) (Gruber and Sarmiento, 1997) (Fig. 13), with N:P ratios below Redfield and consequently depleted N* values (N* = $[NO_3^-]$ − 16 x $[PO_3^{4-}]$ µM).

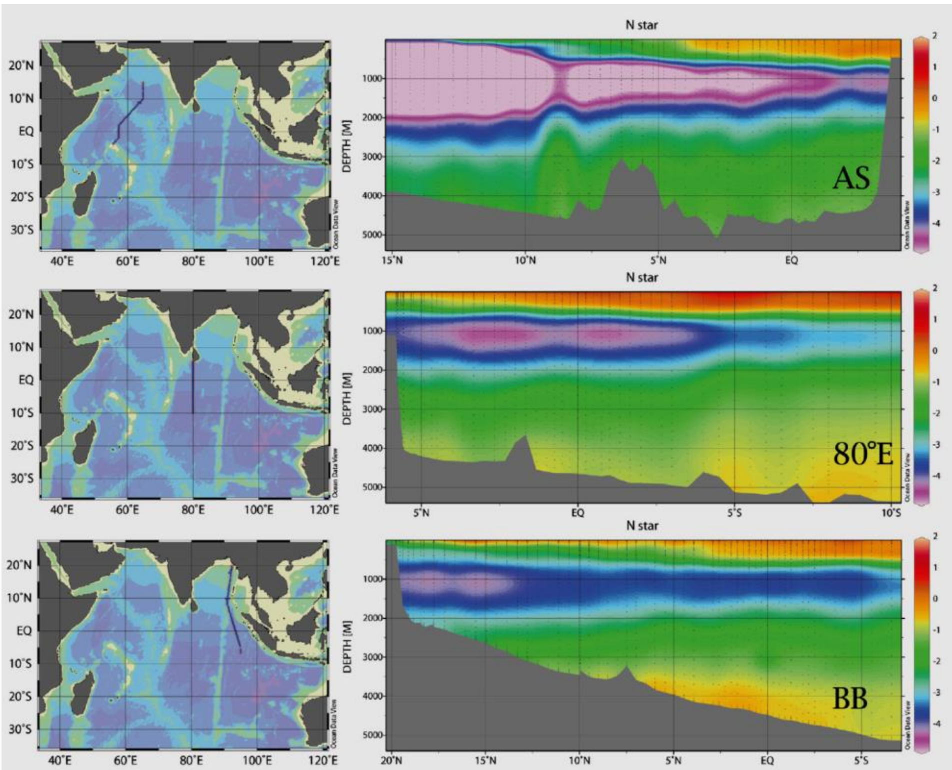


Fig. 13: N at selected transects in the northern Indian Ocean (Mulholland and Capone, 2009).*

Strongly negative N* values (< -5 µM) are observed in the deep waters of the subtropical South Indian Ocean, and a strong gradient with depth is apparent with N* close to zero in surface waters and the highest values in the SW Indian Ocean. This has been attributed to N supply by N_2 fixation (Gruber and Sarmiento, 1997), and emphasised by enhanced abundances of *Trichodesmium* and *Richelia/Rhizosolenia* symbionts in the Madagascar Basin (Poulton et al., 2009). Large blooms of *Trichodesmium spec.* have also been observed in the central Arabian Sea (Capone et al., 1998) above the Arabian Sea's OMZ where their biomass may support the oxygen removal when blooms sink (Montoya and Voss, 2006). Diazotrophs acquire Fe and P from limited dissolved seawater sources, whilst their N requirement can be met by fixation of abundant dissolved N_2 gas (Falkowski, 1997; Schlosser et al., 2014), with reported exudation of N (Mather et al., 2008). This diazotrophic supply of N is thought to fuel the massive phytoplankton blooms observed from space typically every other year in the SW Indian Ocean (Wilson and Qiu, 2008). While phosphate concentrations in surface waters of the subtropical South Indian Ocean are enhanced (up to 0.2 µM), the dissolved Fe concentrations are low, with values of ca. 0.1 nM recently observed along the 32˚S CLIVAR I5 transect. It has been hypothesized that the Fe is derived from island sources (Madagascar) or atmospheric dust inputs (Uz, 2007). Identification and quantification of the Fe sources and their stimulation of diazotrophy with subsequent biogeochemical consequences, including carbon export, is important and timely. Future changes in Fe source strength due to projected changing wind and rainfall patterns (e.g. Mahowald, 2007), and intensification and spread of OMZs (Stramma et al., 2008) may influence N_2 fixation and the fixed N inventory and consequently the productivity of the South Indian Ocean.

3.3.3 Sedimentary record and past Indian Ocean biogeochemistry

Paleoceanographic work revealed teleconnections between South Asian (Indian) monsoon driven oceanographic conditions in the Arabian Sea and North Atlantic climate (Sirocko et al., 1993; Schulz et al., 1998). Pleistocene climate follows the insolation record and shows millennial scale climate fluctuations known as Dansgaard-Oeschger events. The Younger Dryas and Heinrich events were periods of low productivity and absence of denitrification whereas a shift to high productivity and intense denitrification coincided with warm interstadials (Altabet et al., 2002; Möbius et al., 2011; Suthhof et al., 2001) (Fig. 14). Few records are available from the Holocene and suggest that it was a more stable period with ongoing denitrification since the Younger Dryas (Möbius et al., 2011). The denitrification maximum occurred in the western Arabian Sea during the Holocene climatic optimum (Pichevin et al., 2007). The late Holocene insolation driven cooling led to reduced upwelling and a strengthening of the NE monsoon which has evidently led to a shift of the denitrification maximum to its present position in the northeastern Arabian Sea (Böll et al., 2014; Pichevin et al., 2007). Millennial scale drops in upwelling and productivity were coupled with Bond events (Gupta et al., 2003) and could be related with droughts in India during historical time (Anderson et al., 2002). Land use changes and damming significantly impacted the river loads for at least the last century and caused productivity changes in the coastal areas such as off the Indus river mouth (Lückge et al., 2012) and along the Indian shelf (Naqvi et al., 2006).

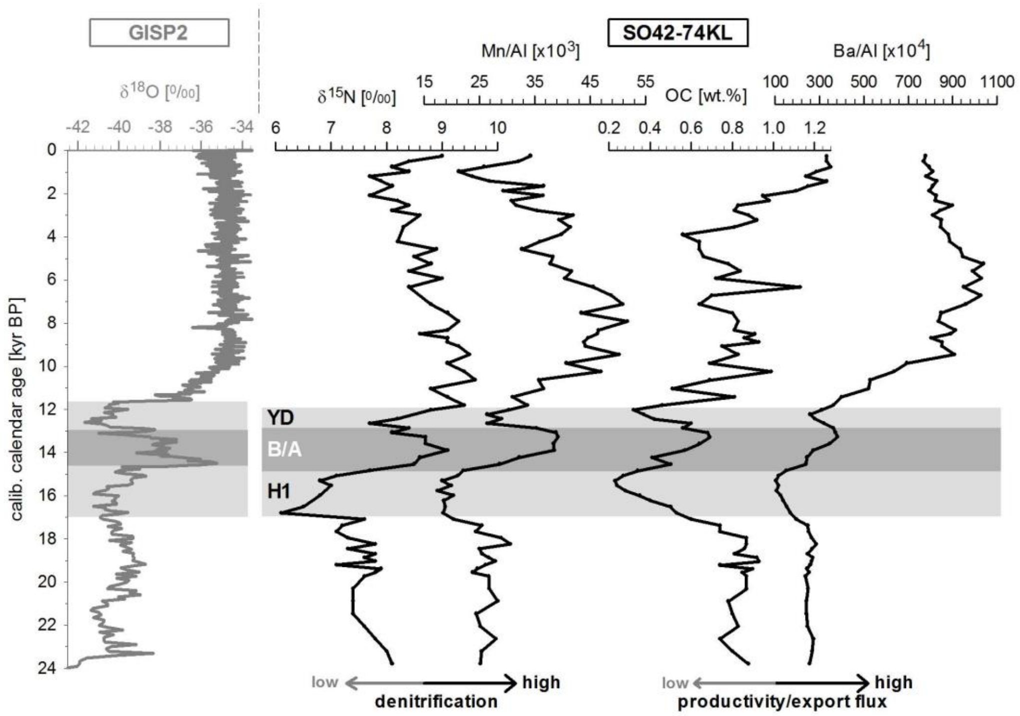


Fig. 14: Paleo records of denitrification and productivity/export flux from the western Arabian Sea (core SO42-74KL) and $\delta^{18}O$ record from core GISP2 (Greenland) (Suthhof et al., 2001).

3.3.4 The Indian Ocean OMZ under a changing climate

(see also Section 3.4.4.4)

Oxygen minimum zones are formed as a result of a low supply of oxygen from the surface ocean due to weak ventilation and sharp pycnoclines, and enhanced organic matter respiration rates (Stramma et al., 2008; Gilly et al., 2013). The OMZs geographically overlap with highly productive upwelling regions which supply the organic matter responsible for the enhanced oxygen consumption at depth, and are typically characterized by a sluggish horizontal transport (Luyten et al., 1983). Climate models suggest an overall decline in dissolved oxygen and an expansion of the OMZs with global warming (e.g. Matear and Hirst, 2003), however, decreasing oxygen concentrations could not solely be explained by physical processes (Oschlies et al., 2008).

Comparisons of dissolved oxygen observations in the Indian Ocean OMZs (Arabian Sea and Bay of Bengal) for the period 1960-1974 and 1990-2008, also indicate a decrease of up to 8 µmol kg^{-1} for the 200-700 m depth interval (Stramma et al., 2010). It is however difficult to quantify the interplay of the various physical oxygen supply and biological removal processes without extensive long-term observational datasets (Stramma et al., 2010) and process studies on the functioning of the biological pump. The expansion of the Indian Ocean OMZs will have biogeochemical consequences, with an increase in the benthic release of phosphorus and iron which may stimulate surface ocean productivity and diazotrophy, and also a potential increase in denitrification and anammox in the Arabian Sea resulting in N loss. Moreover, an expanding OMZ may lead to enhanced production and release of climate relevant trace gases such as N_2O (Naqvi et al., 2010).

The future Indian Ocean will face a multitude of changes, including deoxygenation, ocean acidification, warming and increased water column stratification, increases in aerosol inputs, and enhanced reactive nitrogen inputs (Gruber, 2011; Guieu et al., 2014). Combined effects of two or more of these future changes on biogeochemical cycles and ecosystems in the Indian Ocean are challenging to predict as additive, synergistic and antagonistic effects may occur in addition to transitions in oceanic microbial communities.

3.3.5 Interactions between ocean and troposphere

(see also Section 3.4.4.3.2)

The composition and chemistry of the atmosphere over the Indian Ocean region is dominated by the circulation of the South Asian (Indian) monsoon system: During the winter monsoon (November-March) near surface wind is mostly to the south, advecting gaseous and particulate pollution from the heavily populated and biofuel intensive regions of Southeast Asia out over the northern Indian Ocean. The resulting thick haze extends over millions of square kilometres to the ITCZ. Its initial proof of existence and characterisation has been a main achievement with Indian Ocean Experiment (INDOEX) (Lelieveld et al., 2000) but should be deepened and updated after nearly two decades. The influence of this huge atmospheric pollution phenomenon on the ocean itself should be further explored. Beyond the ITCZ to the south the air is pristine being influenced by the relatively small natural marine emissions. This phenomenon was first characterized during the 1999 INDOEX. Therefore, the Indian Ocean presents a globally unique, natural laboratory to the atmospheric scientist. The co-location over the ocean of the extreme large scale pollution directly adjacent to the clean air background conditions allows the photochemistry of both environments to be examined and contrasted without influence of terrestrial sources. During the summer Monsoon (June-September) the ITCZ migrates north bringing rains to northern India. The extensive rainfall removes soluble gases and aerosol particles, though with poorly known efficiency. The atmosphere over the northern and southern Indian Ocean is clean at this time and the surface wind is more northerly, see Fig. 15.

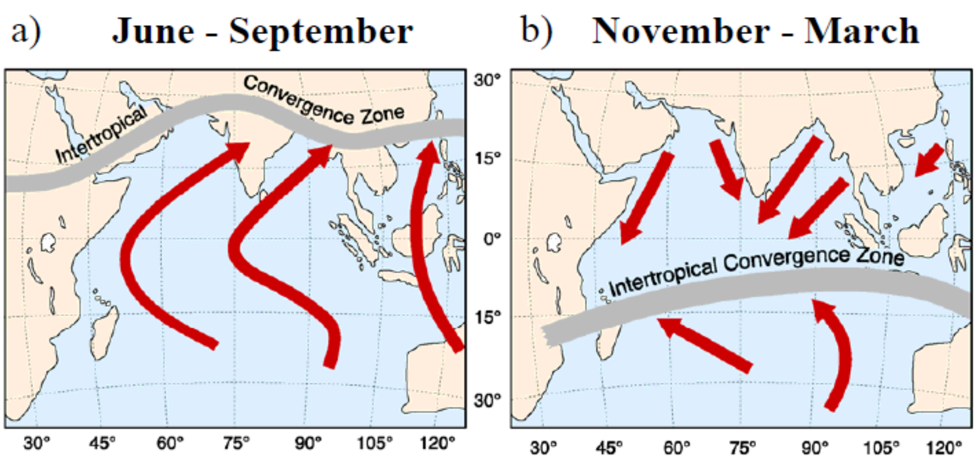


Fig. 15: Near surface transport pathways for the a) summer and b) winter monsoon of the South Asian (Indian) monsoon system (taken from Lawrence and Lelieveld, 2010)

Investigation of the aerosol particles during INDOEX revealed that organic carbon (OC) concentrations were typically more than one order of magnitude higher in the northern compared to the southern Indian Ocean (Neusüß et al. 2002). Specific organic tracer studies suggested that a large amount of the organic material was of secondary origin. However, low OC/elemental carbon (EC) ratios argued for the existence of primary OC (Neusüß et al. 2002). Detailed source studies of OC and EC in the Indian Ocean are strongly needed.

The South Asian (Indian) monsoon also influences atmospheric chemistry through vertical transport processes because the deep convective clouds associated with the ITCZ alter the vertical distribution of trace species, atmospheric radiation and humidity (e.g. Williams et al., 2000). Transport of emissions from the ocean surface into the upper troposphere and even the stratosphere can be effective in this region. The presence or absence of the aforementioned pollution-haze layer can profoundly affect the radiative balance leading to anomalous long term heating rates for the northern Indian Ocean (Levitus et al., 2000; Koren et al., 2014).

3.3.6 Ocean-troposphere-stratosphere chemical cycling

The Asian monsoon system is one of the most active components of the global climate system. The summer monsoon winds are characterized by a strong anticyclone with mean upward transport on its eastern side in the upper troposphere and lower stratosphere (Fig. 16), which provides a potential way of rapid vertical transport of very short-lived substances from the ocean as well as surface air from Asia, India, and Indonesia to the lower stratosphere (Randel et al., 2010). The effects of the monsoon circulation on chemical species can be seen for example as enhanced concentrations of water vapour, ozone, as well as carbon monoxide and other pollution tracers in the lower stratosphere from satellite as well as modelling studies (Park et al., 2007; Randel et al., 2015). The monsoon system is therefore relevant to scales and processes bridging regional air quality, climate change, and global chemistry-climate interactions.

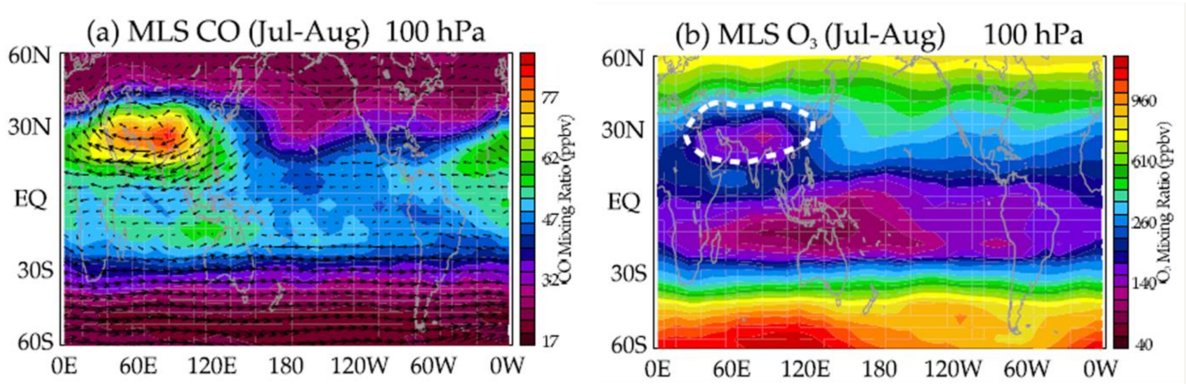


Fig. 16: Horizontal structure of July–August 2005 average (a) carbon monoxide (ppbv) and NCEP horizontal wind fields (vectors) at 100 hPa. (b) Ozone (ppbv) and the 400 m^2s^{-1} streamfunction (Ψ) contour (thick dashed line) defining the monsoon anticyclone at 100 hPa (from Park et al., 2007).

Key Questions

1. **What processes determine the natural variability of the biogeochemical cycles, ecosystems and atmospheric chemistry of the Indian Ocean?**
2. **What is the effect of the (long-range) transport of air pollution on ocean biogeochemistry, ecosystems, atmospheric chemistry and climate?**

Specific Questions

- How does natural and anthropogenic forcing influence the functioning of the biological pump and what are the consequences for the greenhouse gas emissions and the OMZ in the Arabian Sea and Bay of Bengal?
- Which processes are maintaining the productivity in the subtropical South Indian Ocean?
- How do atmospheric inputs of nutrients and trace metals and its anthropogenic components modify productivity?
- How do human-made compounds influence the self-cleaning (oxidation) capacity over the Indian Ocean?
- How is marine background atmospheric chemistry perturbed with regards to species budgets and conversions in the gas and aerosol phases?
- What role does the deep convective atmospheric mixing over the eastern Indian Ocean play for the stratospheric element budgets and chemistry?

3.4 Anthropogenic Impacts

H.W. Bange (GEOMAR, Kiel)

3.4.1 Introduction

Human activities are changing the Earth's environment at an unprecedented rate on both regional scales and the global scale (see Halpern et al., 2012; IPCC, 2013; Rockström et al., 2009) (Fig. 17). The perturbance of the Earth system by Man is so large that it has been proposed to name the present epoch "the anthropocene" (see e.g. Williams and Crutzen, 2013). 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^-, and phosphate, PO_4^{3-}) to the coastal and open oceans (i.e., eutrophication);
- pollution of the ocean, land and atmosphere with chemical compounds; and
- pollution of ocean and land with plastic debris.

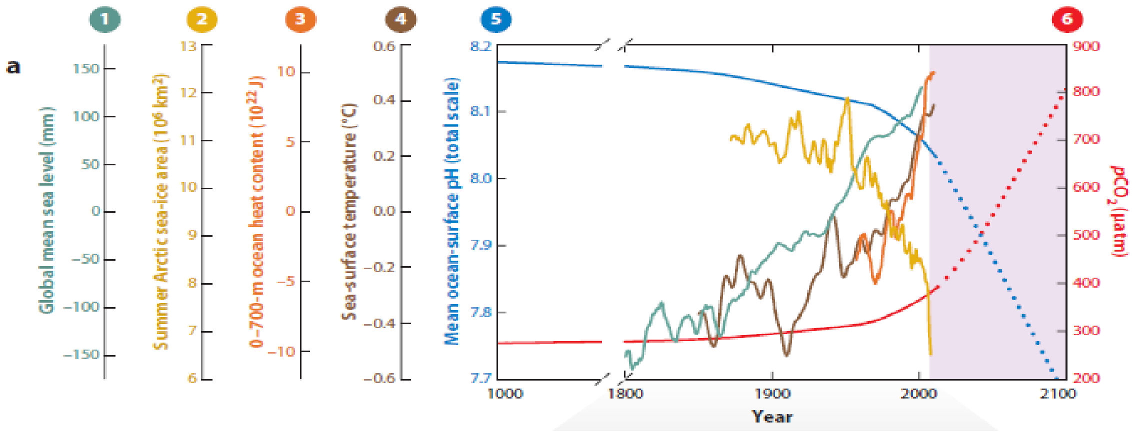
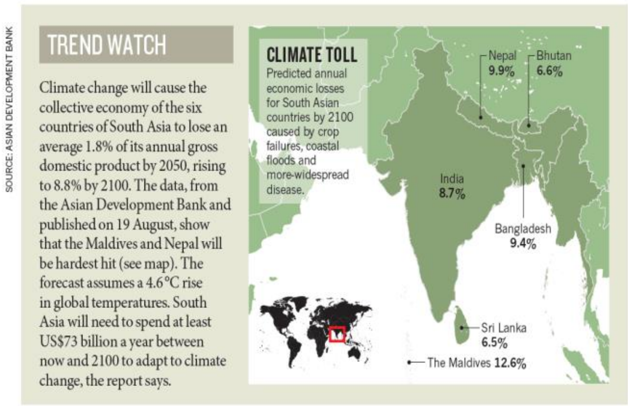


Fig. 17: Global changes in the anthropocene (Doney et al., 2012)

These environmental pressures are directly and indirectly affecting the global ocean ecosystems and biogeochemical cycles (Doney et al., 2012; Hoegh-Guldberg et al., 2014) with largely unknown consequences for the socio-economic development (Mora et al., 2013) and human health (European Marine Board, 2013) (Fig. 18).



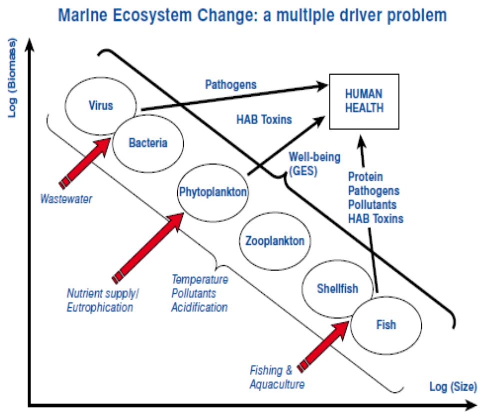


Fig. 18: Left: predicted annual economic loss for South Asian countries by 2100 (Fig. from Nature, 2014). Right: stressors of ecosystems (European Marine Board, 2013)

The increase in atmospheric CO_2, which commenced 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 is leading to changes in the wind fields and causes 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 and increase of coastal hypoxia) which is resulting from a combination of changes in ocean ventilation and stratification, decreased solubility of oxygen (O_2) and enhanced microbial respiration caused by eutrophication (Diaz and Rosenberg, 2008; Keeling et al., 2010; Zhang et al., 2010; Andrews et al., 2013).

3.4.2 Plastic debris

In recent years 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 micro plastic debris in the Indian Ocean is 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 micro plastic (<5 mm) in the surface 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). However, the results of a recent study which took into account a wider spectrum of plastic debris size classes (from 0.3 to > 200 mm) indicated that the southern Indian Ocean "appears to have a greater particle abundance and weight count than the South Atlantic and South Pacific Oceans combined" (Eriksen et al., 2014). Reasons for this are not yet clear.

3.4.3 Urbanization of coastal zones

Mumbai and Kolkata (India), Dhaka (Bangladesh) and Karachi (Pakistan) are 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 industrial and household sewage outflows 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 countries like Pakistan, Madagascar, Indonesia and Malaysia, however, the loss is high. Even though, 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 efficient protection measures (FAO, 2007).

3.4.4 Environmental stressors affecting the Indian Ocean system

The major environmental pressures (so-called stressors) affecting the Indian Ocean system are warming, acidification, eutrophication, atmospheric pollution, and deoxygenation (Fig. 19), which are briefly outlined in the following sections.

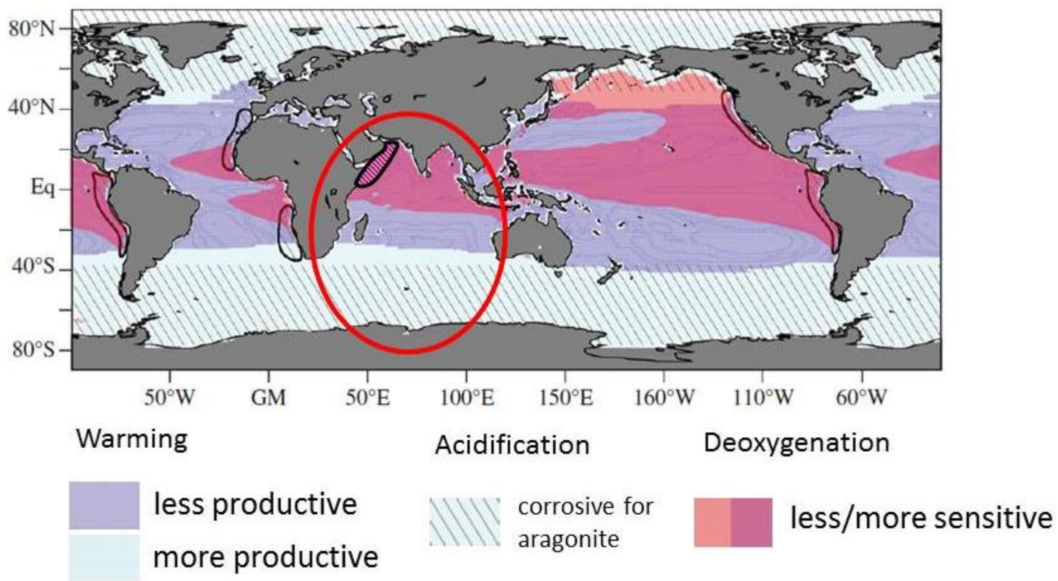


Fig. 19: Regions of particular vulnerability to the three main stressors, i.e. warming, acidification and deoxygenation (modified from Gruber, 2011)

3.4.4.1 Warming

The global average sea surface temperatures (SST) increased since the beginning of the 20th Century. The average SST of the Indian Ocean Basin has increased by 0.65°C, in the period from 1950 to 2009, which is the highest warming rate of the major ocean basins (Hoegh-Guldberg et al., 2014). The trend is driven by the warming of the Indian Ocean sub-tropical gyre. Warming-induced stratification will reduce the upwelling of nutrients from deeper in the ocean to surface layers, decreasing biological production by reducing nutrient supply.

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 the intensity of tropical cyclones (Elsner et al., 2008). 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 (see also Section 3.2.3.1).

Global sea level is rising 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 ocean warming (Han et al., 2010) (Fig. 20). However, the resulting changes in regional sea level as a direct consequence of changes in the ocean circulation remain uncertain (Schwarzkopf and Böning, 2011).

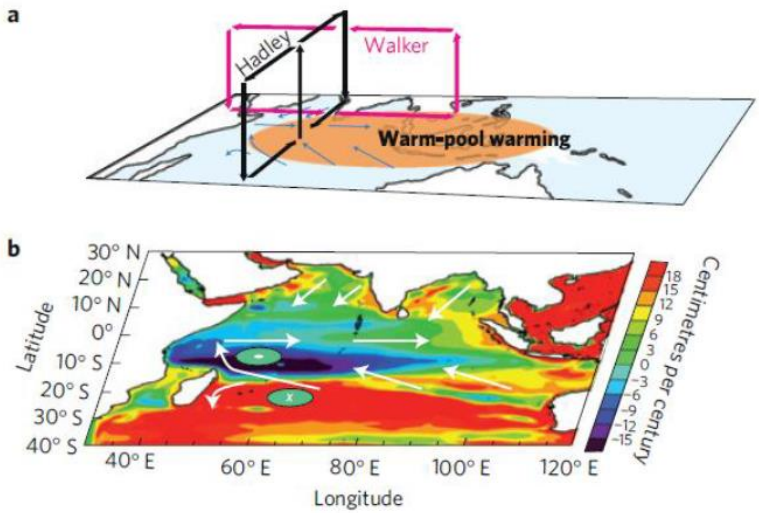


Fig. 20: A schematic diagram showing the mechanisms for the Indo-Pacific warm pool warming to cause the Indian Ocean sea level rise (Han et al. 2010).

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 on tourism, fishing, and other ecosystem services including coastal protection (Hoegh-Guldberg et al., 2014). Especially countries like the Maldives and Bangladesh are under threat because of the rising sea levels. Moreover, coral reefs in the Indian Ocean are vulnerable to both the ongoing warming (resulting in increased frequency of mass coral bleaching and mortality) and acidification (see next section) (Hoegh-Guldberg et al., 2014).

3.4.4.2 Uptake of anthropogenic carbon dioxide and acidification

The overall uptake of anthropogenic CO_2 (i.e. the storage of CO_2 in the entire water column) 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 in the northern Indian Ocean) (see e.g. DeVries, 2014). The anthropogenic CO_2 signal is found down to 1500 m in the SW Indian Ocean and is associated with the formation of mode and intermediate water masses (Alvarez et al., 2009, 2011).

Acidification of the ocean is caused by the uptake of anthropogenic CO_2 from the atmosphere, which results in a decrease of pH. The surface pH for the northern (20°E-120°E, 0°-24.5°N) and southern Indian (20°E-120°E, 0°-40°S) Ocean in 1995 were 8.068 +/- 0.03 and 8.092 +/- 0.03, respectively (Feely et al., 2009). Thus, the average surface pH (and other carbon chemistry properties such as total alkalinity, total CO_2 and Ω) of the Indian Ocean is the lowest of the major ocean basins. The causes for these differences are not understood (Takahashi et al., 2014). Seasonally occurring very low surface pH (<7.9) off the Arabian Peninsula are resulting from upwelling of (lower pH) subsurface waters during the SW monsoon (Takahashi et al., 2014). There are only a few studies on the temporal evolution of ocean 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).

Increasing CO_2 in the upper ocean could lead to increased primary productivity for some species (e.g., diazotrophs; Hutchins et al., 2007; 2013), 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).

3.4.4.3 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 countries, which results from intensified industrial and agricultural activities (see background section above). Tightly connected to the increasing industrial and agricultural activities is a strong increase of the ship traffic during the last 20 years which, in turn, implies an enhanced anthropogenic pollution of the open ocean regions especially in the Arabian Sea and the Bay of Bengal.

3.4.4.3.1 Eutrophication

Riverine inputs of dissolved nutrients (i.e., NO_3^- and PO_4^{3-}) 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) implying a significantly reduced input of riverine nutrients to the Arabian Sea (Fig. 21). In contrast, the river discharge of the Ganges/Brahmaputra River is still high (Milliman and Farnsworth, 2011).

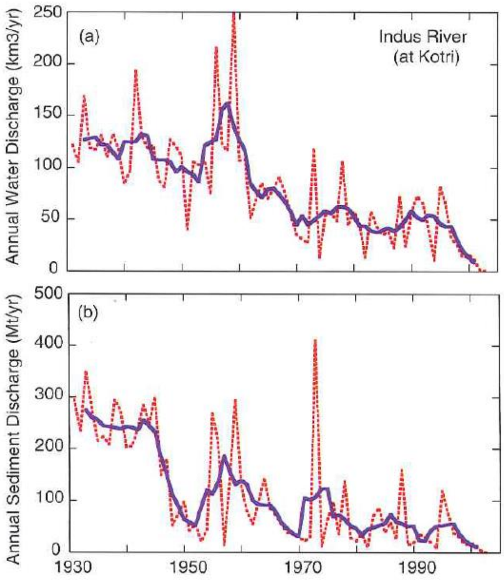


Fig. 21: Annual water (a) and sediment (b) discharges from the Indus River 1931-2002 (Milliman and Farnsworth, 2011).

Consequently, the indicator of coastal eutrophication potential (ICEP) caused by riverine nutrient inputs is low for the north-western, southwestern and south-eastern Indian Ocean whereas it is high for the north-eastern Indian Ocean (i.e., Bay of Bengal) (Seitzinger et al., 2010) (Fig. 22).

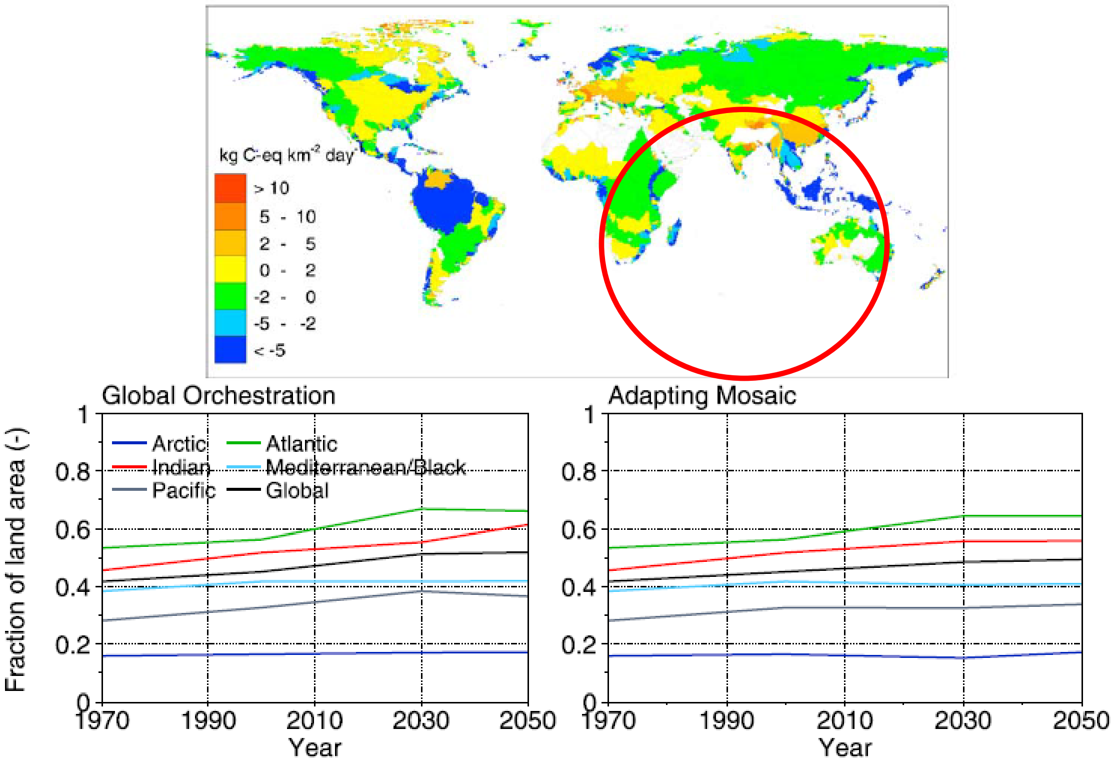


Fig. 22: Indicator of coastal eutrophication potential (ICEP) calculated for (top) the year 2000 and fraction of land area with river basins draining into the world's oceans with ICEP > 0 for 2000–2050 for (bottom left) Global Orchestration and (bottom right) Adapting Mosaic scenarios. (Figure from Seitzinger et al., 2012).

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 the Arabian Sea and Bay of Bengal in the past three decades (Padmakumar et al., 2012) (Fig. 23). 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).

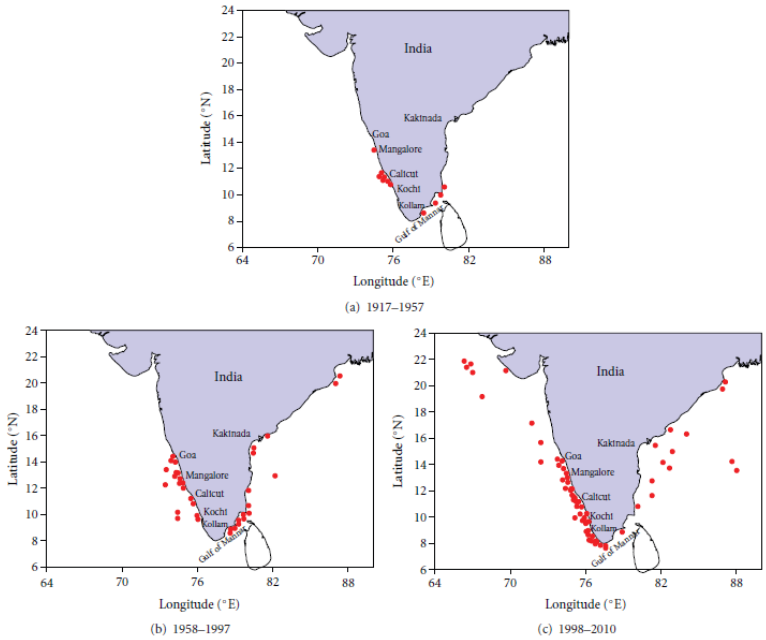


Fig. 23: HAB in the northern Indian Ocean. (a) 1917-1957, (b) 1958-1997 and (c) 1998-2010 (Padmakumar etal, 2012).

In comparison to upwelled nitrate, the atmospheric nitrogen 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).

3.4.4.3.2 Atmospheric pollution

(see also section 3.3.5)

Considerable amounts of sulphur and nitrogen oxides are emitted from ships' diesel engines and are deposited to the ocean along the ship tracks. Thus, ship emissions represent a major anthropogenic input to the open ocean. A detailed study of the global ship traffic in the period from 1992 to 2012 revealed a fourfold increase. The largest growth rates of ship traffic were indeed observed for the Indian Ocean (particularly for the Arabian Sea and Bay of Bengal) (Tournadre, 2014). The increasing ship traffic was also visible by the increase of atmospheric nitrogen dioxide (detected by remote sensing) along the main ship track in the southern Bay of Bengal (Tournadre, 2014).

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) (Fig. 24). 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).

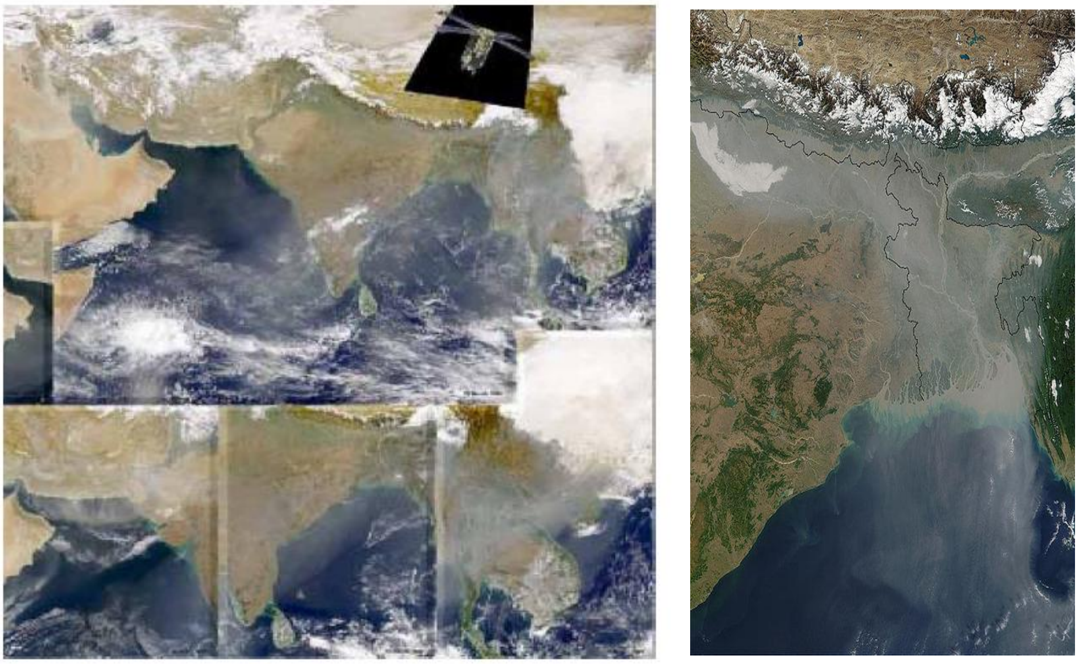


Fig. 24: The ‘Brown Cloud’ over the northern Indian Ocean (Pic. from NASA and NOAA).

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).

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).

3.4.4.4 Deoxygenation

(see also section 3.3.4)

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) (Fig. 25). The maximum trend of decreasing O_2 concentrations in the Indian Ocean (~ -0.3 µM O_2 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).

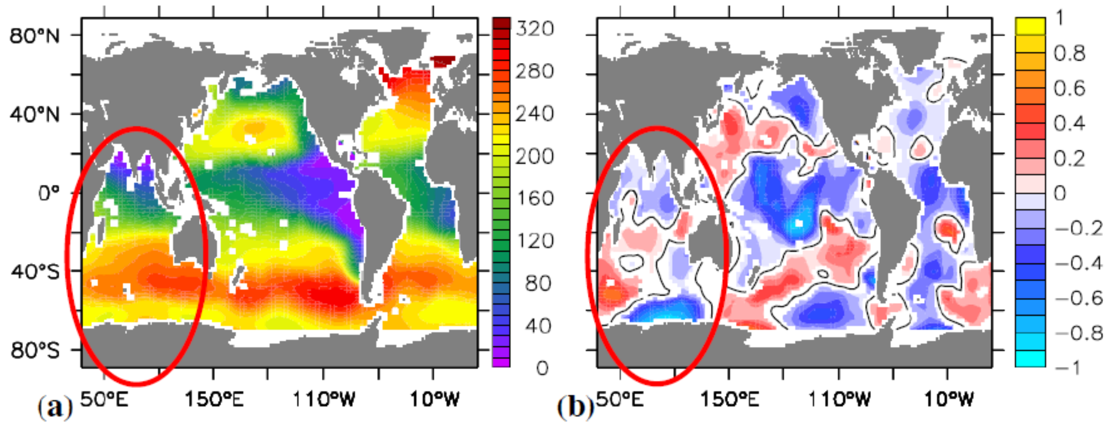


Fig. 25: Deoxygenation in the Indian Ocean: (a) O_2 concentrations (µmol kg^{-1}) at 300dbar; (b) Annual loss rates ΔO_2 (µmol kg^{-1} yr^{-1}) 1960-2000 (Stramma et al., 2012a).

Deoxygenation 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. 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).

Key Questions

1. **How are human-induced stressors (e.g. warming, sea-level rise, deoxygenation, acidification, eutrophication, atmospheric and oceanic pollution, coastal erosion and overfishing) impacting the biogeochemistry and ecosystem of the Indian Ocean?**
2. **How, in turn, are these impacts affecting human populations?**

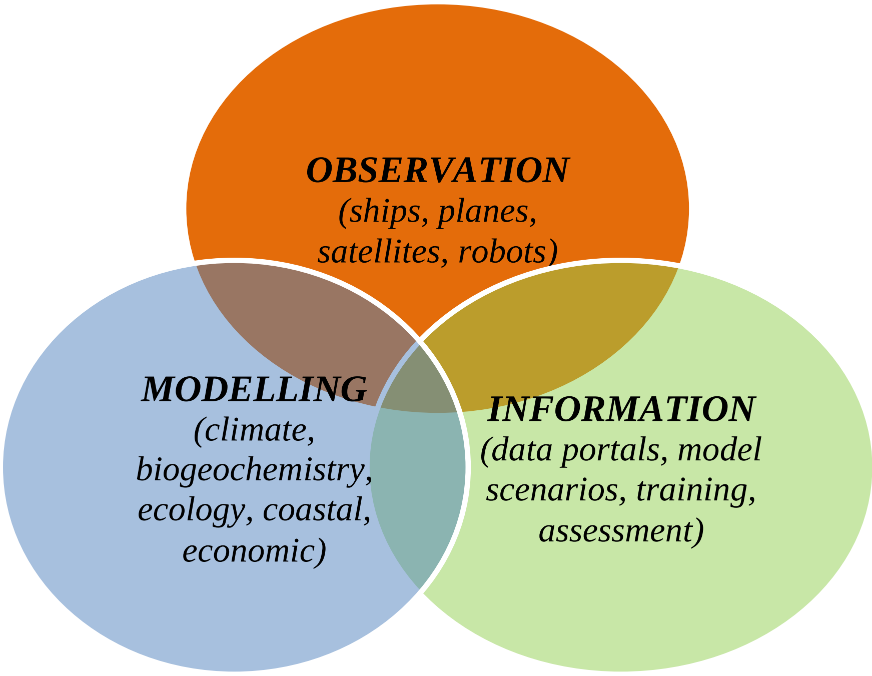
Specific Questions

- 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)?
- 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)?
- How do eutrophication, atmospheric pollution and the loss of O_2 affect biogeochemical cycles, ecosystems and fisheries in coastal zones and the open ocean?
- What are the socio-economic consequences of altered biodiversity and changing food webs (including fisheries)?
- What are the consequences for human health caused by pollution, altered ecosystems and increasing aquaculture activities?
- 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 and sea level rise?

4 Implementation Strategy In Brief

The IGIOS implementation strategy is designed to conduct science in support of a sustainable development of the Indian Ocean and to address the scientific Key Questions outlined in the IGIOS Themes 1-4 as described above. Therefore, the IGIOS implementation strategy may consist of three major components which are tightly linked:

- Observation,
- Modelling and
- Information.



Suggested scheme of the IGIOS Implementation Strategy.

IGIOS will make use of the already existing world-class observational and modelling infrastructures as well as databases and outreach/training capabilities of the oceanic and atmospheric communities in Germany. The following provides a brief summary of the three main components of the IGIOS implementation strategy.

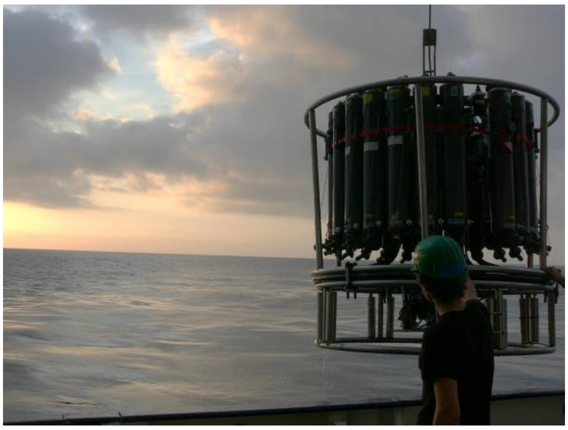
4.1 Observation

4.1.1 Ocean crust

Improved understanding of the links between fluid migration and tectonic processes in subduction zones requires high-quality imaging of (a) the tectonic structures such as the decollement and the location and type of faulting, and (b) fluid migration pathways from the decollement through the overburden and up to the seafloor. Previous seismic cruises have investigated the Makran and Sunda arc subduction zones, but these surveys where either aimed at imaging the deep-crustal structures or the upper crustal gas hydrate systems only. As a result the existing data are not sufficient for studying the link between fluid migration and earthquake activity, and integration of the existing data sets requires collecting geophysical data that can bridge the gap between them. This can only be achieved through dedicated scientific cruises. Such cruises are also necessary for the study of key areas in which existing scientific seismic data is sparse such as the northern termination of the Sunda Arc.

4.1.2 Physical oceanography and marine biogeochemistry

Essential for carrying out the goals of IGIOS is a modern, state-of-the-art sea-going infrastructure, in particular ships such as the R/V *Sonne* and R/V *Meteor*. Furthermore, ship-based surveys are also being increasingly extended through the use of robots such as fleets of gliders to carry out sampling, in situ measurements and high-resolution water column sampling. Major advances in sensor, platform and communication technology have opened up exciting new possibilities for marine sciences. Finally, drifting profiling floats within the international ARGO consortium are currently sampling the upper global ocean on a weekly basis (see www.argo.ucsd.edu). This network, which measures temperature and salinity, also has the potential to grow in scope, including measurements of dissolved oxygen, nutrients, and other parameters. Targeted observational campaigns using robots and supported by research vessels should be used to investigate interactions between physical and biogeochemical processes within mesoscale variability, open ocean upwelling and subduction regions as well as large-scale circulation variability.



Deployment of CTD/Rosette from R/V Meteor off Peru. (Photo H. Bange, GEOMAR)

In general, next to more comprehensive syntheses of existing and new ocean observations via satellites, floats and glider deployments, long-term series of mooring deployments designed to measure specific physical, chemical and biogeochemical parameters are required to assemble a reliable synoptic picture of the currents, their variability and different water masses. The mooring could ideally be equipped with sediment traps that collect samples of sinking particles at several depths in order to quantify their fluxes and their link to seasonal and interannual climate variability. Such campaigns are clearly needed to monitor the zonal and meridional transport in the Indian Ocean, especially at the western boundary, the variability of the subtropical and cross-equatorial cell and its relation to different climate phenomena such as IOD and ENSO. Analyses of the sediment trap data will significantly improve our knowledge of different organism or biogeochemistry-based proxies in Indian Ocean paleoceanography and their applicability to new sediment archives to be taken at hotspots of surface and deep Indian Ocean circulation.

CO_2 float in the eastern tropical North Atlantic Ocean off the Cape Verde Islands.
(Photo A. Körtzinger, GEOMAR)

Further research efforts in the Indian Ocean on the effects of multiple stressors on marine biogeochemical cycles and ecosystems is required, and will have to include laboratory experiments, mesocosm studies and also oceanic observational studies conducted across physical and biogeochemical gradients. Probing of the sea surface microlayer as a source for aerosol constituents will be performed. Additionally, satellite remote sensing provides maps of surface variables such as temperature, sea surface height, sea surface winds, sea surface salinity and ocean color, parameters for estimating air-sea momentum, heat and fresh water fluxes.

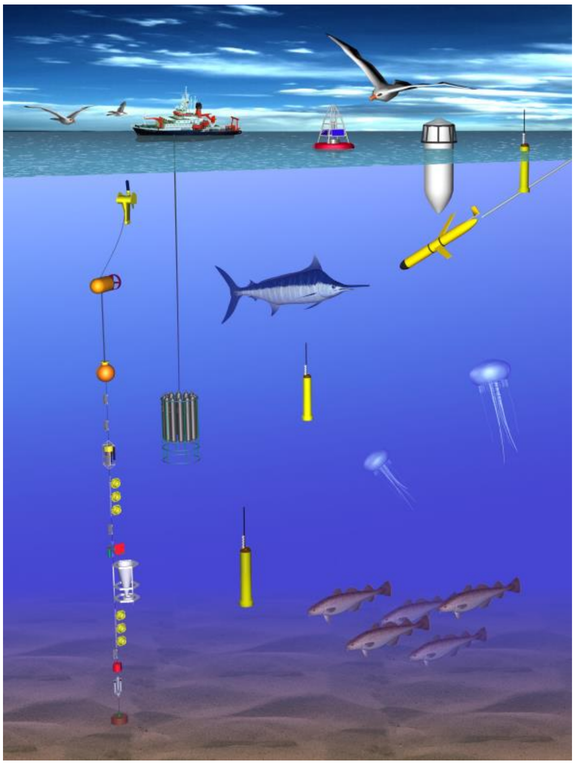


Illustration of multidisciplinary measurement platforms and robots (Illustration M. Müller, GEOMAR).

4.1.3 Atmospheric chemistry

The chemistry and deposition processes of this region under monsoon conditions need to be investigated to advance atmospheric chemistry and climate models, leading to improved air quality and climate change projections. Field measurement campaigns investigating the atmosphere over the Indian Ocean will address the "self-cleaning capacity" of the atmosphere from research ships, aircraft, and ground based platforms. The focus will be on atmospheric oxidation mechanisms and radical chemistry in the atmosphere over South Asia particularly during the summer monsoon. These chemical mechanisms control the self-cleaning capacity and convert natural and human-made pollutants into more soluble products that can be removed by rain. This is critical for air quality and climate change regionally and worldwide considering the rapidly growing pollution emissions, especially in Asia.

Joint measurement campaign of R/V Sonne and the research aircraft Falcon in the South China Sea in Nov. 2011. (Photo T. Bierstedt, R/V Sonne)

Intensive measurement campaigns will aim to determine the rates at which natural and human-made compounds are converted by oxidation processes in the atmosphere, which in turn affect the lifetime and the global distribution of many air pollutants and greenhouse gases, including tropospheric ozone (O_3). Measurement campaigns will quantify reactive species, including radicals, and their major chemical sources and sinks to evaluate model calculations. The campaigns will be predominately performed during the summer monsoon (July-August) when convective cloud mixing, rain and photochemistry are most intense, although some cruises and ground based data will be needed for contrast.

HALO (i.e. the German High Altitude – Long-range research aircraft) and Caribic could serve as major platforms for airborne campaigns in IGIOS. Caribic (Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container), is a powerful system for obtaining detailed atmospheric composition data. This aircraft package regularly crosses the monsoon region with a comprehensive measurement package (http://www.caribic-atmospheric.com/2005/gen_inf.htm).

HALO, the German High Altitude – Long-Range research aircraft. (Photo from www.dlr.de/dlr/desktopdefault.aspx/tabid-10658/#gallery/1725)

4.2 Modelling

Through the underlying theoretical equations *Ocean General Circulation Models* (OGCM) provide a physically consistent framework for the understanding of the circulation and hydrography. In addition, OGCM aid to interpret and dynamically interpolate observations.
Owing to the strong influence of the adjacent oceans on the large-scale circulation, OGCM configured for Indian Ocean research should explicitly simulate inflow (ITF, Tasman leakage) and outflow (Agulhas) conditions and also cover the transport of water masses (AAIW, AABW) through the open boundary towards the Southern Ocean. This can be handled with global models, either at uniform resolution or with a specific Indian Ocean focus through regional grid refinement. Horizontal grid resolution is an important criterion for an OGCM setup; because of the tropical/subtropical focus, a 1/10° Mercator grid resolves the important mesoscale over most of the Indian Ocean. However, for an inclusion of sub-mesoscale dynamics a resolution of 1/20° or more is required. A sufficient vertical grid resolution is needed for a proper simulation of the stacked equatorial jet system; modern OGCM will resolve the vertical with 100 levels or more.

Important for an interpretation of the observed interannual to decadal variability of water masses are reliable and consistent atmospheric boundary conditions. The international ocean model community provides data and recipes for the atmospheric forcing through Coordinated Ocean-ice Reference Experiments (COREs). A series of ocean model intercomparisons under joint forcing data of the past 60 years has been published, and an intercomparison for the Indian Ocean is underway. New atmospheric forcing data sets such as JRA-55 will continuously be kept up to date and allow a better temporal coverage between recent observations and model simulations. What-if scenarios, e.g. with spatially varying atmospheric forcing, allow to distinguish local versus remote influences and to isolate specific physical processes. Finally, OGCM also provide a consistent physical setting for the application of biogeochemical models.

In contrast to the hindcast character of OGCM simulations, future and paleo conditions can only be simulated by including active atmospheric components. These Atmosphere Ocean General Circulation Models (AOGCM) include the feedback to the atmosphere and allow to simulate changes in air-sea fluxes, e.g. under changing greenhouse gases or solar cycles. In particular studies of the overturning circulation, both in the Indian Ocean and the Atlantic Ocean further downstream, require to include these active feedbacks between the ocean and the atmosphere. AOGCM can also be used to interpret changes in the atmospheric circulation (e.g. Walker Cells).

Models of the marine biogeochemistry (OBGCM) combine numerical descriptions of the marine carbon cycle components and a simplified ecosystem. Results from OGCM -either in stand-alone, CORE style experiments or in coupled AOGCM mode- provide the necessary information to advect and diffuse the biogeochemical tracers. Albeit with much coarser resolution than envisaged for the physical ocean model, such models can be used to aid in the interpretation of observations, and to test the impact of changing climate and changed nutrient input on the biogeochemistry of the Indian Ocean. Fluxes of climate-relevant gases across the ocean-atmosphere boundary can be computed to estimate the impact of changed oceanic conditions on atmospheric chemistry.

The interpretation of ocean observations is often guided by assimilation products. The assimilation of observational data (satellite and *in situ* data) into ocean models is usually claimed to reach a certain degree of realism. While simple assimilation schemes work well for the upper ocean, the more sluggish water mass transport and any calculation of heat or freshwater budget requires the use of consistent data which can only come from ocean state estimations that utilize optimal assimilation schemes. Particular caution has to be taken when interpreting long-term variability and trends for overturning components from assimilation products.

4.3 Information

Communication. Communication is fundamental to the success of IGIOS. In order to facilitate communication an IGIOS website/portal will be established. This site will be used to coordinate and publish the activities of IGIOS, provide the latest news and information on projects and progress, and provide a forum for communicating IGIOS science to the widest possible audience. IGIOS will contribute articles to international newsletters, such as those of IIOE-2, SCOR, Future Earth, IMBER, SOLAS etc. To develop and maintain communication with the wider IGIOS research community, science meetings and sessions will be organized. IGIOS results will be published in scientific journals and reports. However, IGIOS will endeavour to ensure that the main results will also be accessible to a wider audience, including policy makers, managers and the public by producing summary fact sheets and/or brochures.

Training and education. IGIOS will help to build up research capacity in the international community and especially among developing Indian Ocean nations by promoting training courses to develop multidisciplinary science skills, workshops, summer schools and a programme of personnel exchange. IGIOS will promote public outreach and provide the opportunity to experience Indian Ocean science through various activities such as school activities, the internet, and special events (e.g., contribution to exhibition).

Data management. IGIOS intends to work closely with data management teams on national (such as PANGAEA: www.pangaea.de) as well as international level to secure availability and long-term storage of all kind of biological, biogeochemical, atmospheric and geological data from IGIOS. Effective use of resources requires integration of all existing data: Collaboration with other national and international ocean/atmosphere science programmes will add significant value to data mining and syntheses. IGIOS will contribute to international programmes operating in the Indian Ocean to share historical data. IGIOS data management and mining efforts will be an integral part of both modelling and fieldwork activities. For example, modelling and remote sensing efforts will benefit from the identification, compilation and synthesis of existing datasets to produce regional and basin-wide distributions of physical, biogeochemical and biological parameters for model initialization, calibration and verification. Data from ocean and climate model simulations will be made available to the wider community. This will help to identify weaknesses in the simulations; it also ensures a wider range of analyses across the different disciplines.

5 References

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