Chapter 36E. Indian Ocean

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1. Introduction

The Indian Ocean is the third largest ocean in the world. It is mostly surrounded by a rim of developing countries and island States, one of which is the fourth largest island in the world, Madagascar. The Indian Ocean is bound by Asia to the north, by Africa to the west, Australia to the east and Antarctica to the south. It has two major seas, the Red Sea between the Arabian Peninsula and Africa, and the Arabian Sea to the west of India; and the largest bay, the Bay of Bengal, to the east of India. Following the FAO statistical fishing areas, the Indian Ocean is divided into two major parts: the Western Indian Ocean (WIO) and Eastern Indian Ocean (EIO) (FAO, 1990-2015).

In terms of the oceanographic physical environment of the Indian Ocean, the major epipelagic atmospheric and ocean currents in relation to other global features are as depicted in Figure 1. The detailed seasonal characteristics of the reversing wind systems of the monsoon are shown in Figure 2. The system is important in the distribution of global heat, salinity and biogeochemical cycling of carbon and inorganic elements (Wajih et al., 2006). There are basically two monsoonal seasons, but it is common to have a third inter-monsoonal season: North East Monsoon (NEM), from February to May; South West Monsoon (SWM) from June to October and an Inter-Monsoon Season (IMS) from November to January.

[1]The members of the Group of Experts would like to thank Cosmas Munga, Melchzedeck Osore, and Nina Wambiji for their substantive input to this chapter.

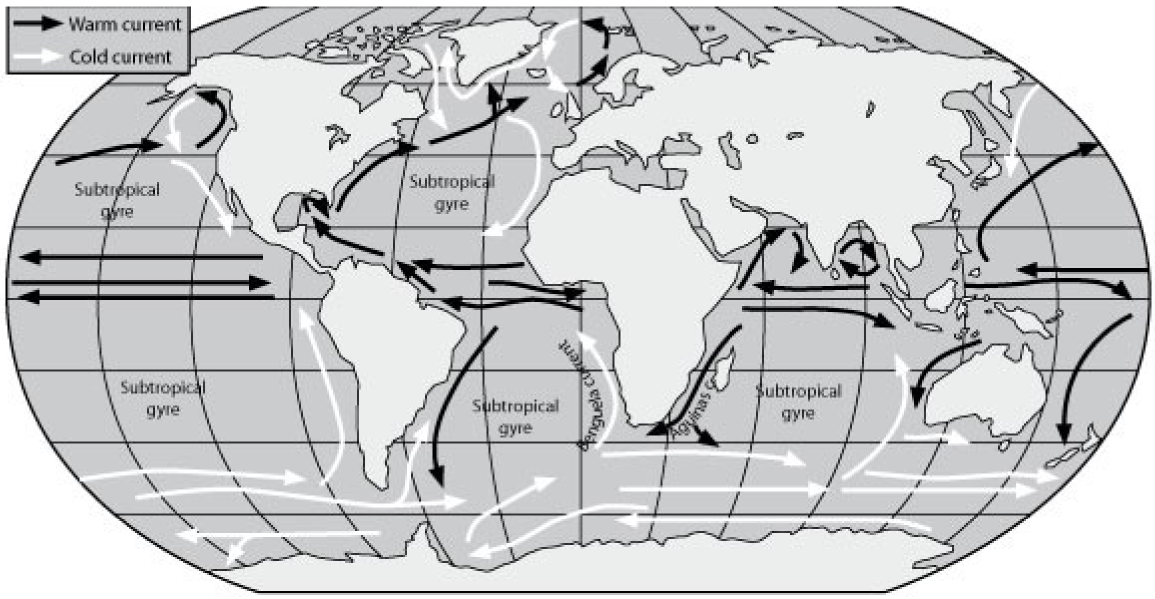

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Figure 1. Map to show the epipelagic water masses and current patterns in the Indian Ocean in relation to other global circulations in the world oceans (Source: Pierrot-Bults and Angel 2013).

It is noted that:

(a) From a wide geographical perspective, most of the major ocean area is under-sampled with regard to both coastal and oceanic environments. The oceanic areas are particularly unsampled and therefore the biological diversity is still incompletely described for most ecosystems;
(b) In terms of human scientific capacity, there is an extreme lack of taxonomists and therefore most of the species are still undescribed or are simply unknown;
(c) Much of the area has largely been studied using satellite technology, so observations are based on remote sensing and therefore driving forces at species and community level are relatively vague or unknown; there is a need to undertake ground truth sampling to support satellite data;
(d) Most studies are based on isolated collections in localized areas and are not continuous, making it difficult to discern possible trends;
(e) Coastal and offshore ocean sampling are rarely synchronized in space and time, increasing data gaps in data collection;
(f) At regional scales most of the sampling methods are not standardized making the data difficult to compare and a weak basis for describing status and trends or creating baselines for benchmarking. There is a need to form regional multidisciplinary research teams to address these needs. Such teams could create the necessary synergy to share research capacity in terms of both human skills and infrastructure, standardize research methodologies, synchronize sampling programmes and plans, establish sampling stations for continuous sampling and data generation for long-term research data requirements, and create databases.

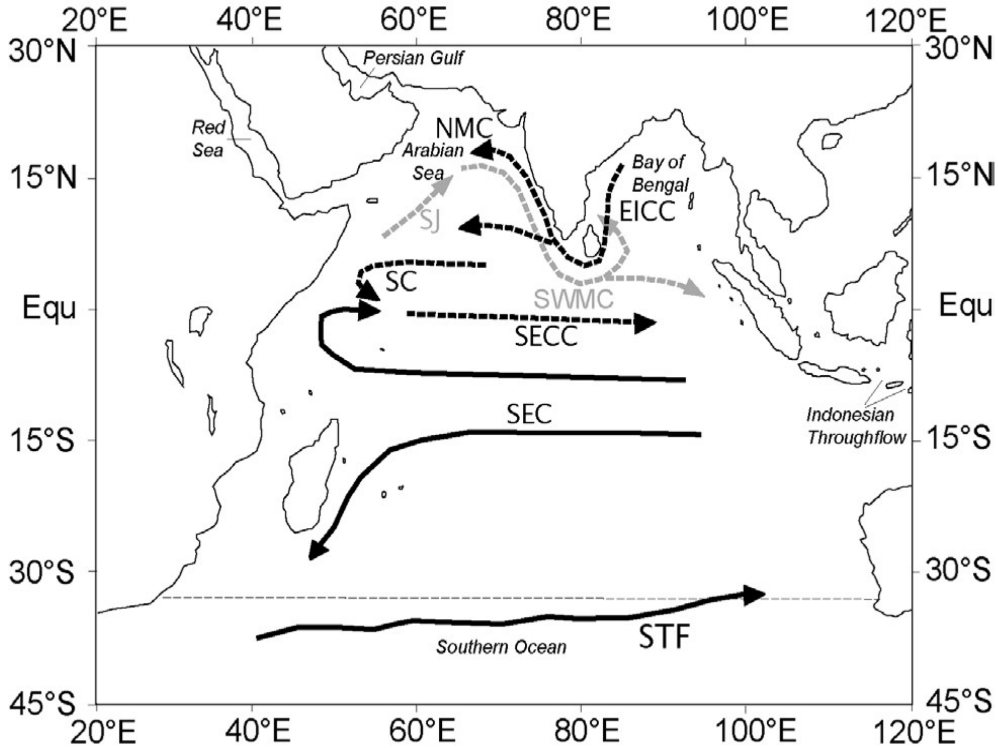

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Figure 2. Major features of the surface circulation in the Indian Ocean [after Schott and McCreary, 2001; Wajih et al., 2006]. The SEC (South Equatorial Current), SECC (South Equatorial CounterCurrent), and STF (Subtropical Front) are present throughout the year. Surface currents during the Northeast Monsoon include the NMC (Northeast Monsoon Current), SC (Somali Current), and EICC (East Indian Counter Current). Surface currents during the Southwest Monsoon include the SWMC (Southwest Monsoon Current) and SJ (Somali Jet). (Source: Bates et al., 2006).

2. Indian Ocean Biodiversity

The Indian Ocean covers about 30 per cent of the total global ocean area and being predominantly a tropical ocean, accounts for a significant part of tropical coastal biodiversity and deep-sea oceanic biodiversity in various marine ecosystems. It accounts for 30 per cent of the total global coral reef cover, 40,000km^2 mangrove cover, besides supporting various types of biodiversity found in its various ecosystems (Table 1). There has been progress in addressing marine and coastal biodiversity since the major surveys undertaken in the first International Indian Ocean Expedition (IIOE) (1960-1965) about 50 years ago (http://www.incois.gov.in/portal/iioe/aboutus.jsp). The present review of Indian Ocean biodiversity will address the long-term status, trends and research gaps in relation to:

(a) Marine fisheries including tuna, focusing on their exploitation and species diversity over wide geographic coverage;

(b) Threatened megafauna species, particularly: marine mammals, marine reptiles and seabirds, focusing on describing the status and trends including their associated drivers and general abundances and what dominant taxa groups exist;

(c) Description of phytoplankton production, zooplankton and benthos structures focusing on their abundance and diversity, including the drivers of change and possible effects of climate change; identifying hot spots for primary production in both coastal and deep sea over various time and geographical scales and major influences of seasonality.

Table 1: Types and area cover of marine ecosystems in the Indian Ocean (Source: Wafar et al., 2011)

ECOSYSTEM	Area (in million km^2)
Open ocean	
Oligotrophic	19.6
Transitional	23.8
Equatorial divergence	18.9
Coastal	
Upwelling zones	7.9
Other neritic waters	5.3
Other	
Coral reefs	0.2
Mangroves	0.04
Sandy and rocky beaches	0.004
Estuaries	-
Hypersaline water bodies/lagoons	<0.005

3. Fish Biodiversity

This section mostly presents information on marine capture fisheries, as reported by the FAO and the Indian Ocean Tuna Commission (IOTC).

3.1 Marine Finfish

The contribution of coastal and marine capture fisheries (finfish, shellfish and molluscs) from the Indian Ocean (average of 11.01 million tons annually) to the global landings is third after the Pacific Ocean (average of 48.3 million tons annually) and the Atlantic Ocean (average of 11.03 million tons annually) based on the 2003, 2011 and 2012 FAO estimates (FAO, 2014). This chapter describes the coastal and marine fisheries finfish production excluding tuna in the Indian Ocean, focusing on the status and trends in exploited species, long-term species surveys and different kinds of diversity indices over the FAO statistical areas of the EIO and the WIO. These areas have recorded increasing overall catch trends since 1950 (Figure 3) however, incidences of reduced catches have been reported in inshore areas. This increase in catches may be due to expansion of fishing to new areas or species, and the improved recording of fish landing statistics over time. The EIO and WIO together contributed 28 per cent of the total global marine catches of finfish, shellfish and molluscs in 2011 (FAO, 2014).

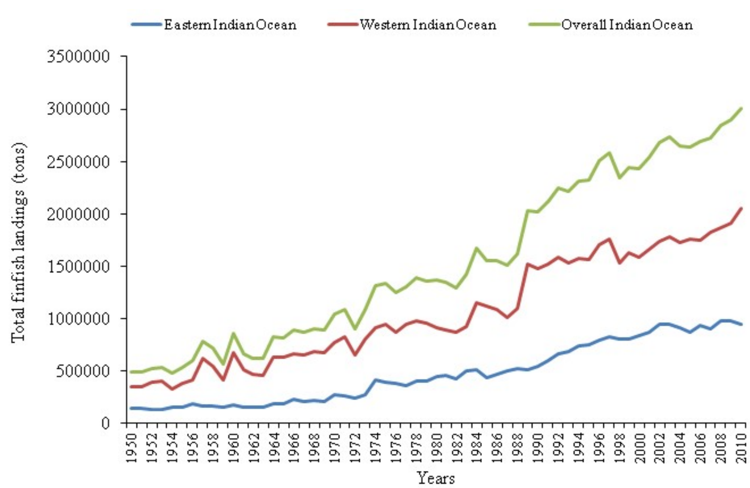

Figure 3. Long term trends in total finfish landings excluding tuna in the EIO, WIO and overall Indian Ocean (data source: FishstatJ – FAO Fishery and Aquaculture Global Statistics).

The EIO total finfish catches except tuna (Figure 3) are based on fish statistics from Australia and India. On the other hand, catches from the WIO are based on statistics from Kenya, Madagascar, Mauritius, Mayotte (France), Mozambique, Seychelles, South Africa and the United Republic of Tanzania. Although finfish total catches seem to be higher in the WIO, the EIO has recorded a higher growth rate in the overall catches (finfish, shellfish and molluscs), with a 17 per cent increase from 2007 to 2011, now totalling 7.2 million tons (FAO, 2014). The Bay of Bengal and Andaman Sea regions have seen total catches increase steadily with no signs of the catch levelling off. The highest catches both in the EIO and WIO are made up of the category "marine fishes nei", that is, "marine fish that are not identified" (Figure 4). This is a cause for concern as regards the need for monitoring stock status and trends. In the EIO alone, this category "marine fishes nei" makes up about 42 per cent of the catches (FAO, 2014). A group of small pelagic fish categorized as "clupeoids nei" also support high landings, as do sharks, rays and skates in the EIO. The decline in fish catches in the EIO, especially within Australia's exclusive economic zone, can be partly explained by a reduction in effort and catches following structural adjustment to reduce overcapacity and a ministerial direction in 2005 aimed at ceasing overfishing and allowing overfished stocks to rebuild (FAO, 2014).

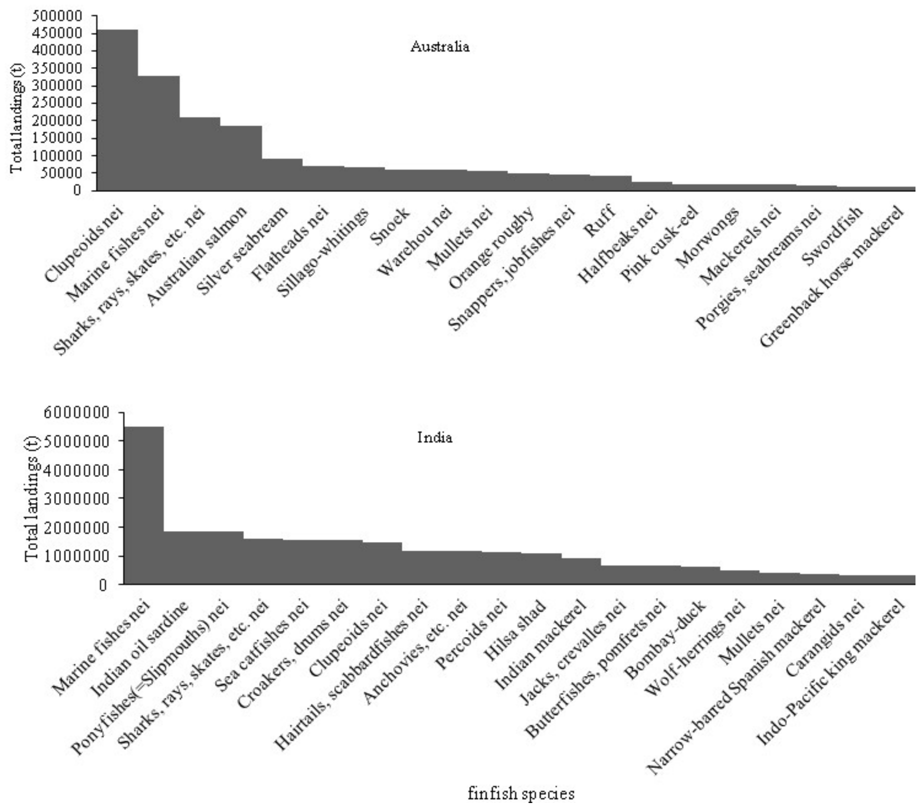

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Figure 4. Top twenty highest landed finfish species except tuna from the Eastern Indian Ocean based on total catches from 1950-2010 data in Australia and India (data source: FishstatJ – FAO Fishery and Aquaculture Global Statistics).

The WIO shows a similar scenario, in which the largest catches are made up of the category "marine fishes nei" followed by the small pelagic "Indian oil sardine", ponyfishes, and sharks, rays and skates. Total landings in the WIO reached a peak of 4.5 million tons in 2006, but then declined slightly, with 4.2 million tons in 2011 (FAO, 2014). A recent assessment has shown that the narrow-barred Spanish mackerel (*Scomberomorus commerson*) is overfished, and this species is among the 20 most highly landed (FAO, 2014; Figure. 6) in the WIO. Long term catch data in the Indian Ocean, especially the WIO, are often not detailed enough for stock assessment and species composition purposes, a situation aggravated by the lack of adequate resources to conduct scientific studies, monitoring and enforcement (McClanahan and Mangi, 2004). However, the Southwest Indian Ocean Fisheries Commission (SWIOFC) conducted stock assessments for 140 species in 2010 based on best available data and information (FAO, 2014). Overall, 75 per cent of fish stocks were estimated to be fully fished or under-fished, and 25 per cent fished at unsustainable levels. There are many other species in the Indian Ocean where the level of exploitation is unknown or is extremely difficult to determine. Long-term trend analysis by individual fish taxa indicates that catches of sharks, rays and skates together started to decline or level off from the mid-1990s in both the EIO and WIO (Figure 5a). In the late 1990s, a similar trend is observed with the narrow-barred Spanish mackerel in the WIO (Figure 5b).

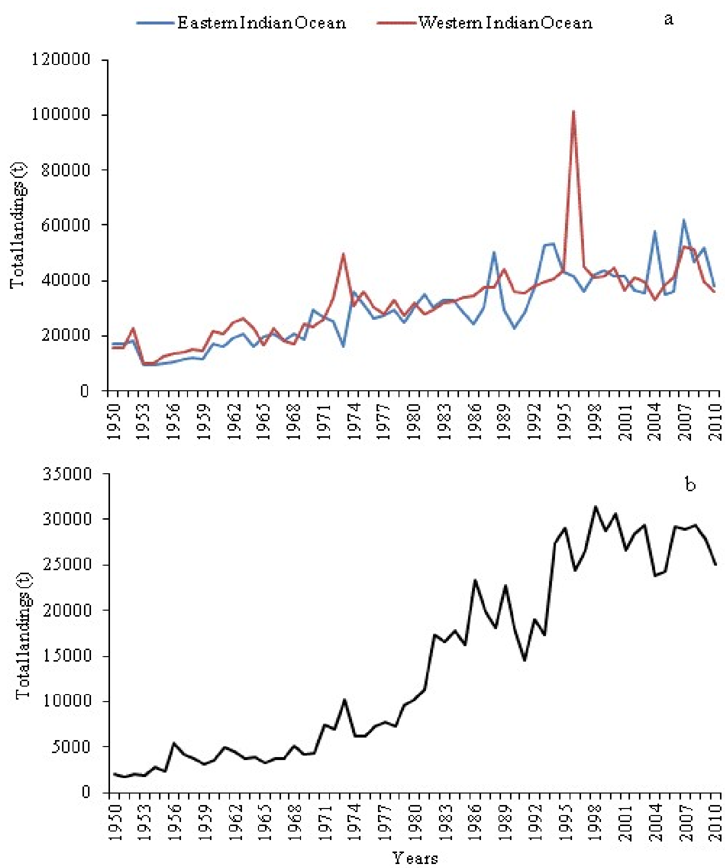

Figure 5. Long-term trends in total landings of (a) sharks, rays and skates in EIO and WIO, and (b) narrow-barred Spanish mackerel in the WIO.

Fish species diversity studies in the Indian Ocean, especially in the WIO are biased to coral reef areas. Fish diversity in relation to coral reefs in the region covering about 200 sites situated in Kenya, Madagascar, Maldives, Mauritius, Mayotte (France), Mozambique, Reunion (France), Seychelles, South Africa and the United Republic of Tanzania was studied (McClanahan et al., 2011). This study found that the region from southern Kenya to northern Mozambique across to northern eastern Madagascar and the Mascarene Islands and the Mozambique-South Africa border are areas with moderate to high fish diversity. The WIO fish fauna is one of the richest marine fish faunas in the world, with some 3,200 species or about 20 per cent of the world marine fish fauna. Despite considerable effort by ichthyologists over the past two centuries, the taxonomy of WIO fishes is ongoing. Of the 329 new marine species described between the years 2002 and 2012, 140 were from the WIO (http://www.saiab.ac.za/coastal-fishes-of-the-western-indianocean.htm).

Long-term fish species surveys are scanty in the Indian Ocean. The South African line fishery however, has been monitored since the late 1900's. This fishery is multispecies targeting over 200 species with about 50 being economically important. Due to concerns of overfishing, management measures were first introduced in the 1940s. Stock assessment of the line fishery has been based on both fishery dependent and independent data, as well as data from marine protected areas. Since 1985, the South African line fishery has been one of the largest spatially referenced marine line fishery data sets. After the introduction of management measures, monitoring results have indicated that, generally, the over-exploited line fish stocks are now slowly recovering except for *Polysteganus undulosus* which has remained significantly reduced (SWIOFC, 2012).

This chapter has identified key gaps in relation to the Indian Ocean fisheries, as follows:

- Total catch statistics data is mostly still poor in terms of temporal and spatial coverage, and catches are in many cases estimates of actual catches. This is attributed to lack of human and financial capacity as well as remoteness of some of the fish landing sites;
- Lack of a comprehensive species' composition data. To date, the largest proportion of catches is categorized as "unidentified". This is attributed mainly to the inadequate knowledge in fish taxonomy in the region;
- Long-term research surveys in the region are rare due to lack of professional expertise, infrastructure and financial capacity. Most of the research surveys are short term and sporadic depending on availability of donor funding. The International Indian Ocean Expedition, if regularly implemented could be the best source of long-term research survey data.
- The impacts of fishing gears on target fisheries, by-catches and habitats are hardly studied, and bottom contacting fishing gears are used indiscriminately in the region, resulting in biodiversity losses.

3.2 Tuna Species

Tuna and tuna-like species form the most important resources of the offshore pelagic fishery. In the Indian Ocean, both the EIO and the WIO, at least seven different tuna species, including tuna-like species, have been reported in the landing statistics. The four main commercially fished tuna species in the Indian Ocean are: albacore (*Thunnus alalunga*), skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*T. albacares*) and bigeye tuna (*T. obesus*). The other species are: frigate and bullet tunas (*Auxis* sp.), kawakawa (*Euthynnus affinis*), southern bluefin tuna (*Thunnus maccoyii*), and tuna-like species. Since 2010, after three years (2007–09) during which piracy negatively affected fishing in the WIO, tuna catches have recovered. During the 2007-2009 period, total tuna catches decreased by 30 per cent as piracy deterred fishing operations (FAO, 2014). Among the 23 major fish species in the global marine capture fisheries, skipjack tuna ranked third with increasing landings of 2.2 million tons in 2003, 2.6 million tons in 2011, and 2.8 million tons in 2012 (FAO, 2014). The yellowfin tuna was ranked eighth, however with variable landings of 1.5, 1.2 and 1.4 million tons in 2003, 2011 and 2012 respectively.

In the last 5 decades, total landings of tuna and tuna-like species in the Indian Ocean have been increasing (Figure 6). This is especially evident in the WIO region, whose global contribution in total tuna landings is 30 per cent. The increasing trend of total tuna and tuna-like landings in the EIO region is not pronounced as landings have remained just about 20 000 tons annually for a long time between 1982 and 2010. During this period, a total of 7 tuna species and tuna-like species were recorded in the Indian Ocean (Figure 7). The contribution of tuna and tuna-like landings for the WIO region in the last 5 decades came from India, Kenya, Madagascar, Mauritius, Mayotte (France), Mozambique, Seychelles, South Africa and the United Republic of Tanzania. On the other hand, landings for the EIO during the same period were reported from Australia, India, Madagascar and Seychelles.

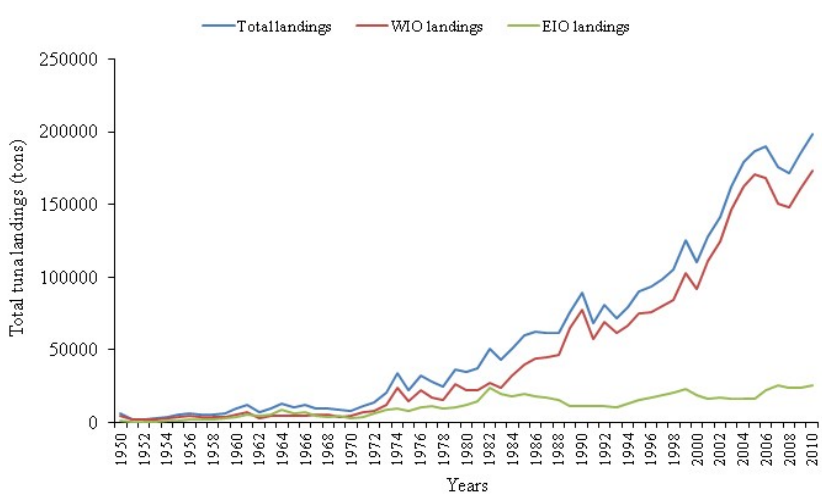

Figure 6. Long term trends in total tuna and tuna-like landings in the EIO, WIO and overall Indian Ocean (data source: FishstatJ – FAO Fishery and Aquaculture Global Statistics).

The landing statistics of tuna and tuna-like species in the last 5 decades in the Indian Ocean show a great variation in terms of species percent composition of total landings

(Figure 7). In this period, skipjacks, kawakawa and yellowfin tuna contributed the highest percent composition of 29 per cent, 24 per cent and 23 per cent respectively. The lowest percent composition was made up of albacore (0.4 per cent), tuna-like fishes nei (2 per cent), and bigeye tuna (4 per cent). The species frigate and bullet tunas, and southern bluefin tuna contributed intermediate percent composition of about 9 per cent each.

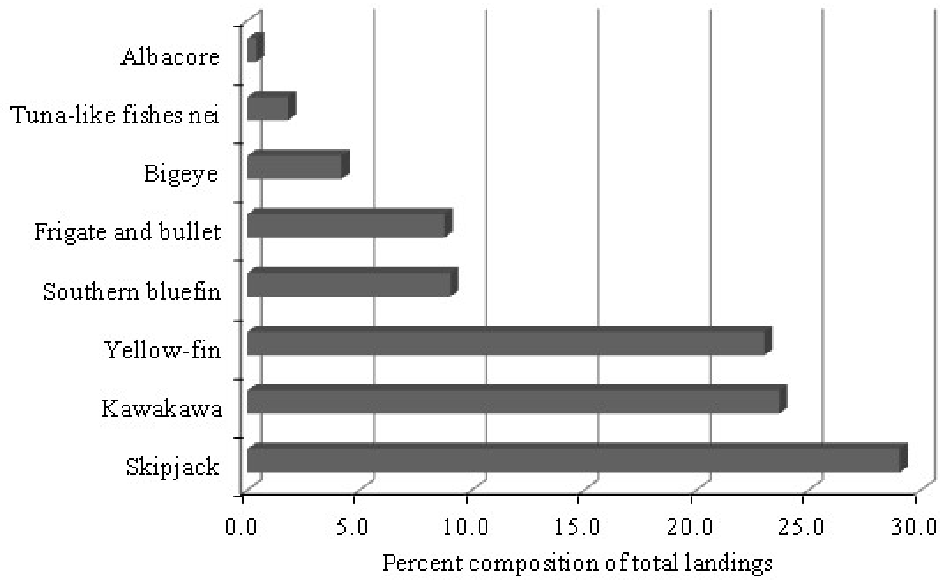

Figure 7. Species percent composition of total landings of tuna and tuna-like from the Indian Ocean based on total catch data from 1950-2010 (data source: FishstatJ – FAO Fishery and Aquaculture Global Statistics).

Recent stock assessment estimates from the Indian Ocean Tuna Commission (IOTC) indicate that yellowfin, bigeye tuna stocks, skipjack and albacore are not overfished and not subject to overfishing (IOTC, 2014). Estimates of the total and spawning stock biomasses show a marked decrease over the last decade, accelerated in recent years by the high catches of 2003-2006 (Figure 7). The Spawning Stock Biomass was estimated to be 57 per cent for the skipjack tuna, 38 per cent for the yellowfin tuna, 40 per cent for the bigeye tuna and 57 per cent for the albacore of the unfished level. However current fishing mortality has not exceeded the Maximum Sustainable Yield (MSY) level for these species (IOTC, 2014).

The estimated catches for the skipjack tuna was 455,000 tons in 2009 and 428,000 tons in 2010 with an average catch of 500,000 tons between 2005 and 2010 being lower than the median value of the estimated Maximum Sustainable Yield. IOTC recommended that catches should not exceed 500,000 tons. The MSY for yellowfin tuna for the whole Indian Ocean should not exceed 300,000 tons, while the MSY estimates for bigeye tuna is estimated at 102,664 tons. Based on available data, the major challenge in the region at large is declining spawning stock biomass and the possibility of recruitment overfishing.

3.3 Research gaps

There is a need to research the impacts of the target fish catches and fishing gear on non-target fish or bycatch, food chains cycles and overall on species biodiversity, especially focusing on various taxa over long-term periods in order to also account for climate change effects.

4. Plankton Diversity

The contribution of the Indian Ocean plankton data into the World Ocean Database (WOD) is still very minimal. Similarly, except for India and South Africa and to some extent Indonesia and Pakistan, very little research is undertaken by the countries of the Indian Ocean region. The national contribution of plankton data work in the WOD09 by the countries bordering the Indian Ocean is less than 1.5 per cent Likewise, among the major international oceanographic projects that contribute to the plankton data, only a minimum has involved the Indian Ocean.

4.1 Phytoplankton

Marine phytoplankton are an essential component in marine life as they play a fundamental role in the biodiversity and bio-productivity of the marine ecosystem. They are mainly microscopic plants that float passively throughout the pelagic zone, pushed by the dominant ocean current. They also play a crucial role in the food chains and food webs, as phytoplankton represent the primary producers of organic matter and zooplankton are the link between the phytoplankton and higher trophic levels. In addition, plankton play a crucial role in the biogeochemical cycle of numerous chemical elements in the ocean.

In a balanced ecosystem, phytoplankton provide food for a wide range of sea creatures including whales, shrimp, snails and jellyfish. During unusually high availability of nutrients, phytoplankton may grow out of control and form harmful algal blooms (HABs). These blooms can produce extremely toxic compounds that have harmful effects on fish, shellfish, mammals, birds, and even humans. The Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO) has supported effort towards the detection, identification and management of HABs in the WIO region but the data are still inadequate to generate trends.

Results from the Tyro Expedition in the WIO under the Netherlands Indian Ocean Programme (NIOP, 1991-1995) established that the seasonal change in monsoon regime affect the nitrogen nutrition of marine phytoplankton conspicuously (Wafar et al., 2011). Seasonal variation of phytoplankton abundance and diversity is a common occurrence in many bays and creeks of the Indian Ocean. This is driven by the interchanging monsoon regime almost every half year as well as by water quality as result of land based activities.

Research undertaken by India in its west coast, in the Arabian Sea, and east coast, in the Bay of Bengal, has demonstrated strong monsoonal seasonality using satellite and remote sensing technology and sampling cruises (Moharana and Patra, 2013) to measure chlorophyll and analyze patterns of distribution over time. The same technology has also been used to study the global impact of climate change on in primary production in oceans using chlorophyll concentrations (Gregg et al., 2003)

Climate change effects on primary production in the oceans have been a major subject of study globally. Using satellite technology to study chlorophyll records over 22 years, from 1980, in 12 major oceanographic basins (Figure 8), it has been established that the global annual ocean primary production has declined by 6 per cent since 1980. The question is whether the Indian Ocean has behaved similarly. The Indian Ocean is divided in three major oceanographic basins which are: North Indian Ocean, Equatorial Indian Ocean and South Indian Ocean. On the basis of the differences between the SeaWiFS (1997-2002) and CZCS (1979-1986), the analysis which not only involved primary production but also environmental parameters including surface sea temperatures, nutrients and wind stress in the 12 major oceanographic basins (Figure 9 and 10), is summarized in Table 2. It is clear from this analysis that primary production increases in the North and Equatorial Indian Ocean but decreases in the South Indian Ocean basin, which is at higher latitudes and close to the Antarctica basin, where also the primary production decreases. It was further noted that the highest increase occurs in the western portion of the Arabian Sea, in the west coast of India, and in the North Indian oceanographic basin, which experiences upwelling (Gregg et al., 2003). Chaturvedi et al., (2013) observing the chlorophyll behaviour around the coast of India, recorded that there was higher chlorophyll from December to March in the Arabian Sea whereas in the Bay of Bengal, the peak occurs in February to March.

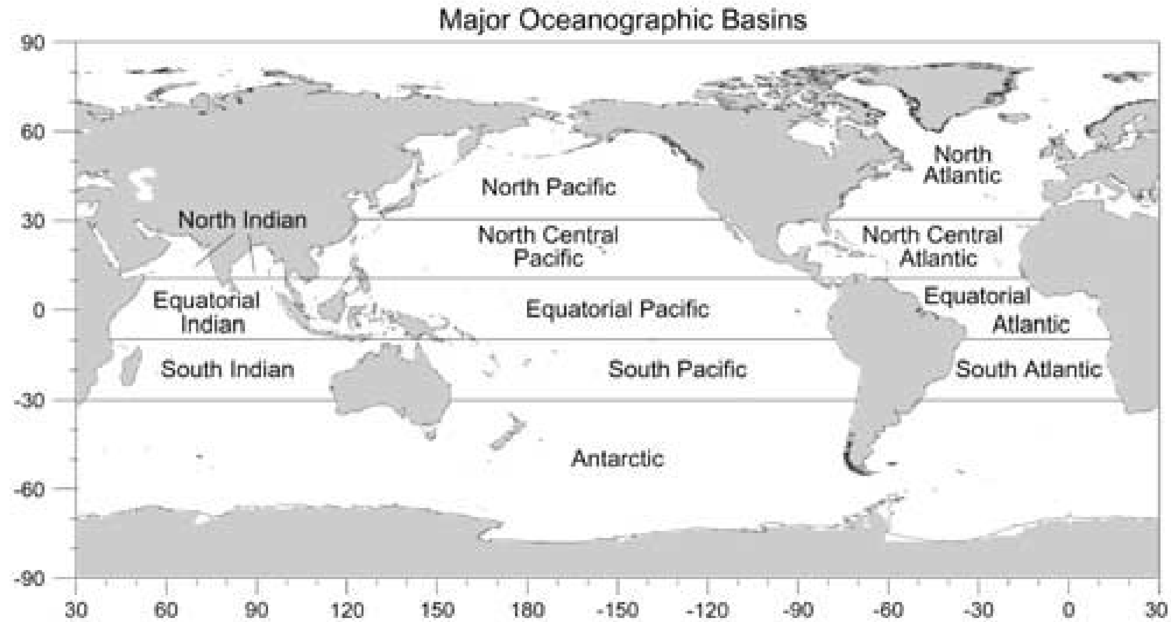

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Figure 8. Boundaries for the 12 major oceanographic basins (Source: Gregg et al., 2003).

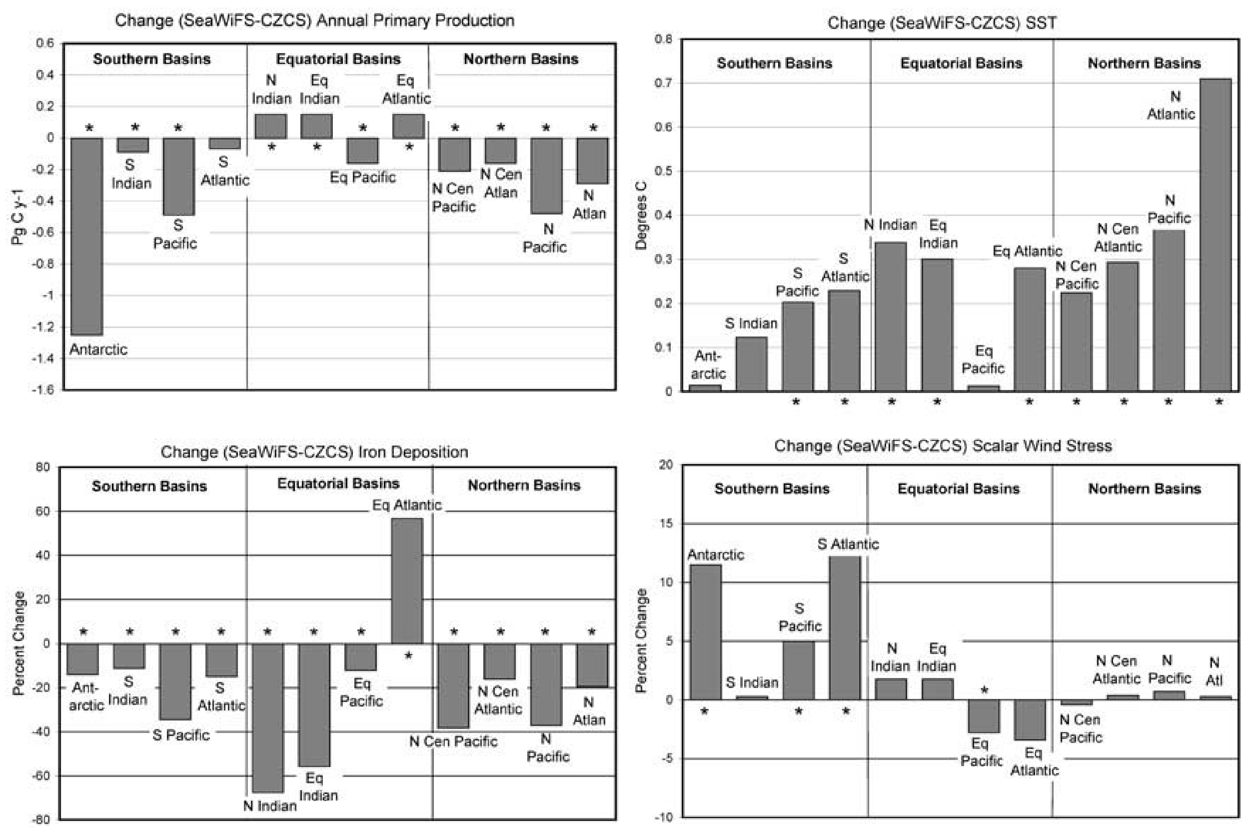

Figure 9. Differences between SeaWiFS (1997–2002) and CZCS (1979–1986) in the 12 major oceanographic basins. Differences are expressed as SeaWiFS-CZCS. Top left: Annual primary production (Pg C y_1). An asterisk indicates the difference is statistically significant at P < 0.05. Top right: SST (degrees C). Bottom left: iron deposition (%). Bottom right: mean scalar wind stress (%) (Source: Gregg et al., 2003).

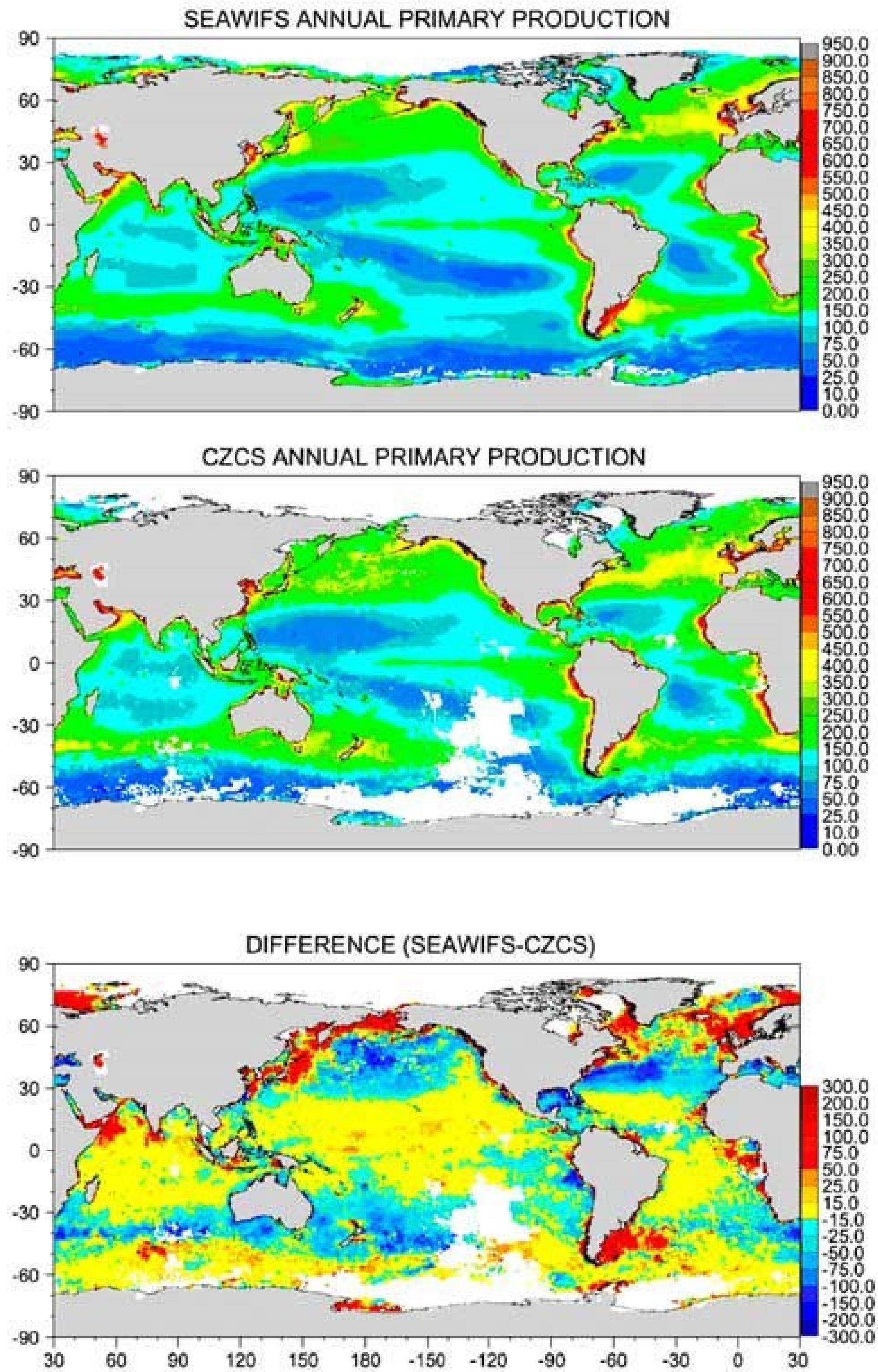

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Figure 10: Primary production distributions for the SeaWiFS era (1997-mid-2002), the CZCS era (1979-mid-1986) 327 and the difference. Units are $gCm^{-2}y^{-1}$. White indicates missing data (Source: Gregg et al., 2003).

Table 2: Percent change in ocean primary production (SeaWiFS-CZCS) by basin and surface area of the basins ($10km^{-2}$) where data from both SeaWiFS and CZCS were sampled (Source: Gregg et al., 2003).

OCEAN BASIN	AREA	CHANGE
N. Atlantic	1.83	- 6.7%
N.Pacific	2.32	- 9.3%
N.Central Atlantic	1.53	-7.0%
N. Central Pacific	3.22	-5,8%
N. Indian	**0.46**	**13.6%**
E. Atlantic	1.15	6.9%
E. Pacific	3.72	-3.8%
Eq. Indian	**1.37**	**8.8%**
S. Atlantic	1.20	-3.8%
S. Pacific	2.69	-14.0%
S. Indian	**1.77**	**-4.2%**
Antarctic	8.28	-10,4%
Global	29.73	-6.3%

329

4.2 Zooplankton

Implementation of the Indian Ocean chapter of the Census of Marine Life Programme (IOCoML) inaugurated in 2003 has vastly increased the knowledge of marine biodiversity of the Indian Ocean countries. Among the major achievement of IO-CoML is the discovery of more than 40 new zooplankton species including from groups of mysids, chaetognaths and sponges.

There are two types of zooplankton differentiated by aspects of their life cycles. There are categories of zooplankton that partly live as zooplankton, for example as larvae, and grow to sub-adults and then adults and leave the plankton community as they grow. Others live as zooplankton throughout their lives. Those that live partly as zooplankton are referred to as meroplankton, e.g. fish larvae, whereas those that live in planktonic form throughout their lives are known as holoplankton, e.g. copepods.

The biophysical factors that affect phytoplankton similarly affect zooplankton and their peaks tend to be in rhythm with a small time lag of 1-1.5 months because zooplankton depend on phytoplankton for food (Fabian et al., 2005). For vertebrate animals like fish the peak abundances are highly influenced by taxonomic category, since some taxa which are r-selected can produce eggs profusely throughout their short lives whereas k-selected tend to have fewer larvae which take long to mature and may not be in rhythm with other taxonomic groups. To discern these patterns, long-term research to cover various biophysical factors associated with seasonality, climate change, predation, pollution and eutrophication are essential and have to be multidisciplinary. These types of coordinated research protocols are lacking in the region, making it difficult to describe zooplankton status and trends.

Most studies are one-off events at short time intervals and can only be taken to represent season samples. Only in rare cases does sampling cover longer periods of the continuous cycles, although in most cases the abundance and species composition of the zooplankton vary considerably across seasons (Fazel et al., 2013). The situation is compounded by the lack of taxonomic expertise as well lack of taxonomic descriptions of many of the major zooplankton in the area (Chesalina et al., 2013). Since samples are rarely continuously collected for long-term monitoring, and most samples are collected to represent a part of a season, therefore the variances are high, making quantification of trends very difficult. This emphasizes the need to have permanent sampling platforms in the region for long-term continuous monitoring, preferably daily sampling to account for diel cycles also.

One of the clearest scenarios shown in the field relating to nutrient levels is the comparison of performance of production in the Arabian Sea and the Bay of Bengal. It is clearly observed that the production of zooplankton and phytoplankton shows a higher standing crop in the west coast of India, in the Arabian Sea, than in the east coast of India, in the Bay of Bengal. The difference is attributed to upwelling in the Arabian Sea whereas the Bay of Bengal depends only on nutrient inputs from the major rivers (Moharana and Patra 2013; Dorgham 2013).

4.3 Research gaps

The gaps identified requiring research in both phytoplankton and zooplankton are similar and therefore most efficiently addressed together as a plankton group, with emphasis appropriately made for either of the two groups when necessary. For regional and global comparisons of data and information to be effective the sampling methodologies need to be standardized, including equipment, and the time of cruises synchronized since plankton are highly affected by atmospheric processes and ocean currents which vary regionally and globally in time and space. There is therefore a need to establish the frequency and regular nature of sampling, number of sampling stations and their location, number of samples to be taken, methods of collection (net and/or water samples, depth of collection (surface and/or other defined and agreed depth as per sampling protocol)). Without such a coordinated research protocol approach the studies will remain fragmented and consequently the data and information will be difficult to use for comparative studies, or to provide baselines for documenting trends. The following specific needs should be addressed:

(a) Plan synchronized regular, multidisciplinary and comprehensive study for both phytoplankton and zooplankton and have a comprehensive database for the Indian Ocean;

(b) Identify exotic plankton carried in various areas by ship ballast;

(c) Collect detailed information about harmful algal blooms;

(d) Establish fixed stations for continuous regular plankton studies for time series analysis;

(e) Establish coastal fixed stations in water masses covering special benthic communities in critical habitats namely: Corals, seagrass, mangroves and intertidal zones;

(f) Undertake continuous special studies on dinoflagellates cysts to establish potential of harmful algal species; and

(g) Establish satellite networks for regional studies of primary production in relation to various environmental parameters in order to relate to climate change.

5. Benthos

Marine benthic organisms are organisms that live on or are associated with the seabed. Their usual mode of effective dispersal is through their planktonic larval or immature stages, transported by ocean currents. Key benthic habitats include: coastal water bottoms, mangrove habitats, coral reefs are benthic hot spots, seagrass beds, intertidal zones, deep water continental shelf and slopes or in the depth of ocean trenches. Since the initial IIOE in 1959-1965, there have been various other research expeditions to the northern part of the WIO that have yielded a substantial amount of results about the benthos. These have especially been conducted by the former USSR and also by the United States, the United Kingdom, Germany, France and the Netherlands. This region still lacks the capacity to support and execute research offshore. In fact the only States bordering the Indian Ocean that have demonstrated capability to conduct oceanographic research are Australia, India, Pakistan and South Africa. These countries have continued to conduct research even after the IIOE ended, especially in their own territorial waters.

As documented in Chapter 34, species diversity gradients exist across latitudes and from coastal waters to deep or oceanic water, such that there is an increase in species diversity from high to low latitudes and a decrease from shallow coastal waters to deep oceanic waters (Gray 1997, Chapter 34). However, little data and information exist in the Indian Ocean to describe these scenarios and establish how effectively this pattern could be applied for conservation purposes especially when interlinked with within – habitat or alpha diversity (Fisher et al., 1943; Whittaker, 1967) and between habitat or beta biodiversity (Whittaker, 1975, 1977) and at a larger regional scale seascape gamma diversity (Ray 1991). Due to scanty studies and many undescribed benthic species in the Indian Ocean, the reliability of species diversity indices for the Indian Ocean benthos is similarly poor due to the likely underestimation of species numbers (richness underestimated) and relative abundance of species, particularly less common species (evenness not accurately measured) (Wafar et al., 2011).

Further challenges are due to threats to benthic biodiversity occurring at different intensities with time and space. The coastal and oceanic benthic habitats and species diversity are threatened by habitat loss and perturbations or alteration especially due to mining, sediment deposits, fishing with bottom-contacting gears, and dumping of solid wastes. Other threats are due to climate change, overexploitation of benthic species which affect their feeding cycles and ecological balances. There is a tendency for opportunistic species succession resulting from ecological population imbalances and pollution, especially in shallow coastal habitats where eutrophication and toxicity from algal blooms may lead to loss of species biodiversity. Sand and coral mining, including dynamite fishing which blasts coral reefs, can lead to complete loss of habitat, with restoration often difficult, if possible at all, and costly. There is evidence of various degrees of continuous benthic habitat loss especially coral, seagrass and mangrove in various parts of the Indian Ocean (Gray 1997; Wafar et al., 2011).

Due to taxonomic limitations, the major taxa encountered in cruises have also been limited to common names or groups but identified to species levels, even for species that have been described. Consequently, it is difficult to provide even snapshots of species richness or species diversity of any given space and time in the region, even for relatively well sampled areas like the Bay of Bengal and the Arabian Sea. The results from the latter areas have contributed to demonstration of the existence of species gradients with depths. However the need for multidisciplinary approaches to describe the drivers of these gradients in an ecosystem context cannot be overemphasized. Based on meiofauna and macrofauna occurrence across shallow to deep sea, from 20m to 6km water depth, both groups showed a similar gradient pattern that the density and species variety of the meiofauna and macrofauna decreased significantly with increasing water depth. The taxon-specific depth affinities have also formed the basis for macrobenthic organisms to be selected as suitable indicator organisms for environmental stress, taking advantage of their sedentary habits, so changes in population abundance and species composition reflect changes in habitat quality (Dauer and Corner, 1980). There is also a positive significant correlation between chlorophyll concentration and macrobenthic density (Pavithran et al., 2009). In the Arabian Sea, the surface water chlorophyll a is higher due to upwelling than that of Bay of Bengal (Prasanna et al., 2002; and Madhuparatap et al., 2003).Therefore the macrobenthic density is also higher in the Arabian Sea than in Bay of Bengal (Parulekar et al., 1982; Mahapatro et al., 2011). This highlights the need for bringing interdisciplinary ecological relationships into focus through ecosystem approach rather than dealing with single factors in isolation.

5.1 Research Gaps

- There is a lack of, or there are relatively few, quantitative data on local species extirpations in the Indian Ocean region.
- Predatory gastropod snails are fished or collected to be used as souvenirs in various places and since they play key roles in controlling prey population their local extirpation can lead to major changes in biodiversity and this needs to be studied.
- Overexploitation of other benthic species is occurring and there is need to properly evaluate the status and trends in exploited benthos.
- Particularly where benthos are being over-exploited or suffering high stress from coastal inputs, there is a need to get better information about the rate and magnitude of loss of species and the implication of these losses for ecosystem processes, including trophodynamics.
- Coastal benthic critical habitats e.g. corals, seagrass and mangrove, are threatened by various anthropogenic activities e.g. overfishing, mining, dynamiting, pollution, beach seining and trawling. There is need to study the effect of these on latitudinal and longitudinal loss of biodiversity and species diversity focusing also on endemic species.
- There is a need to have coordinated rapid regional assessments of benthos to provide a baseline report on the status of species diversity in the various benthic habitats in the Indian Ocean.
- Taxonomic experts are generally lacking for the various numerous benthic taxa groups and there is need to train and create a critical number of taxonomists to develop accurate identification and complete databases for benthic species diversity.
- For deep-sea or ocean diversity, there is a need for scientific assessment of little-known benthic ocean species biodiversity, particularly because it is increasingly being threatened by various anthropogenic activities, especially ocean dumping, mining and climate change.
- There is an urgent need to undertake regional scale assessments and long-term monitoring of habitat loss and species loss, record and document it using Geographical Information Systems (GIS). The assessment methodology should be robust enough to discern effects due to climate change and seasonality that may cause habitat loss or disturbance that may cause species loss, abundance and population density.

- There is a need for monitoring marine litter disturbance of benthic habitats, especially intertidal zones due to dumping of solid wastes.
- There is a need for undertaking long-term regional assessments of root causes or causal chain analyses of habitat loss and degradation to combat loss of biodiversity.

6. Megafauna

The megafauna, namely marine mammals (cetaceans and the sirenians), seabirds, and reptiles (sea turtles and sea snakes) may be described characteristically as large species with low fecundity and productivity, slow growth, and late age at maturity. Such biological characteristics have important implications for their sustainability in fisheries, especially as by-catch because they can sustain only very low rates of mortality. Moreover, they typically depend on a healthy, stable environment and generally have limited capacity to sustain and recover from depleted populations, such as result from heavy fishing pressure.

The megafauna in marine ecosystems play a significant role in the structure and functions of the ecosystems and in the economic sector, especially in tourism. The representative groups in consideration are as follows: (a) marine mammals, (b) marine reptiles, and (c) seabirds. These groups have characteristic species whose lives are interconnected with maritime zones, coastal and shelf waters and deep sea oceanic habitats as grazers or primary consumers and predators or secondary consumers in the ecological food chain cycles. In these predator-prey relationships these megafauna groups play an important ecological role in regulation of marine biodiversity, species richness and environment quality. However, as much as they play their important roles, they face various challenges that threaten their lives and ability to play their roles efficiently and effectively. The major threats are primarily anthropogenic pressures, especially habitat loss and degradation, overexploitation or unsustainable exploitation, pollution and climate change, whose root causes are a major concern (Wafar et al., 2011; Chaturvedi et al., 2013; Bellard et al., 2014).

6.1 Marine Mammals

The entire Indian Ocean region has 31 species of marine mammals found in the pelagic shelf and near-shore waters (De Boer et al., 2003). Though well surveyed, with further surveys the number of species is likely to increase. The North Western Indian Ocean region has 25 species, the North Eastern Indian Ocean 28 species, the South Eastern Indian Ocean 30 species and the South Western Indian Ocean has 25 species (De Boer et al., 2003). Whales are known to be highly migratory over long distances, across the hemisphere, to their nesting and feeding grounds.

The marine mammals are threatened by various human activities especially fishing activities using gill nets, seine nets, beach seines and drift nets, in which they are caught as by-catch; habitat degradation and loss, as well as pollution, including marine debris. These threats lead to the destruction of their breeding and feeding grounds. A further threat is deliberate hunting for food. Being slow to grow and reach maturity, coupled with having low fecundity, overexploitation leads to population destruction and collapse, leading to extinction (Kiszka et al., 2008).

6.2 Research Gaps

(a) Although the taxonomy of marine mammals is fairly well known, there is a need to train and equip local scientists and equip local institutions to effectively collect and archive quality data in suitable databases, to enable accurate analysis of status and trend of stock status of marine mammals across various time scales in various geographical locations, in a regional way due to their migratory behaviours.

(b) The existing research studies are patchy and one-off event types and their data and information make it difficult to standardize and to generate trends. Therefore there is a need for coordinated long-term monitoring, using standardized multidisciplinary methodologies which will allow to document status and trends in time and space, including climate change impacts.

(c) For conservation of whales, it is important to undertake analysis of the biology and ecology of the various species of whales to protect and avoid polluting their habitats.

(d) Undertake regular by-catch research including the fishing gears that are used so that the impacts of fishing on whales are understood and appropriate mitigating measures can be undertaken.

(e) Genetic studies are also needed to be able to understand the interconnectedness and dispersal nature of the similar species over the wider geographical ranges that are encountered in the region.

6.3 Sea Turtles

Sea turtles are herbivorous or sometimes invertebrate-eating reptiles that play a very important role in marine ecosystems in the maintenance of healthy seagrass beds and coral reefs and assist in avoiding trophic cascades. As part of their life is spent on land to breed, sea turtles also play an important role in nutrient cycling from land to water and vice-versa (through their faeces).

In the coral ecosystems, sea turtles also forage on sponges which are known to compete aggressively with corals and can reduce coral growth. Where sponges can colonize aggressively and grow, they can limit the growth of corals and modify the overall structure of a given coral reef ecosystem. Sea turtle predation on sponges can prevent the expansion of sponges, and thus protect coral reefs. In terms of pelagic food webs, sea turtles predate on jelly fish and especially leatherback sea turtles which may be the dominant predator on jellyfish. Decline in this key predator may lead to jelly-fish population explosion, possibly leading to gradual replacement of once abundant fish species (Lynam et al., 2006, Purcell, J.E. et al., 2007).

The Taxonomy of sea turtles in the Indian Ocean is well known and they are represented by only a few species which migrate extensively to various oceans. According to WWF (2012), the sea-turtle taxa are:

- Leatherbacks (*Dermochelys coriacea*)
- Green sea turtles (*Chelonia mydas*)
- Hawksbills (*Eretmochelys imbricat~~e~~a*)
- Olive ridleys (*Lepidochelys olivecea*)
- Loggerhead (*Caretta caretta*)

According to the Convention on International Trade in Endangered Species of Wild Fauna and Flora[2] (CITES) and IUCN all the species of sea turtles in the Indian Ocean require protection from anthropogenically induced activities. Specifically, CITES lists all sea turtle species under its Appendix I meaning that commercial international trade in the species is prohibited (CITES, 2015). The explanation of CITES listing is as follows:

- Appendix I lists species that are the most endangered among which are those threatened with extinction and CITES prohibits international trade in specimens of these species except when the purpose of the import is not commercial.
- Appendix II lists species that are not necessarily now threatened with extinction but that may become so unless trade is closely controlled.
- Appendix III is a list of species included at the request of a Party that already regulates trade in the species and that needs the cooperation of other countries to prevent unsustainable or illegal exploitation.

The IUCN Red List of Threatened Species (IUCN Red List) classified the status of leatherback turtles globally as ‘Vulnerable’ (IUCN, 2015). Specifically, the Southwest Indian Ocean subpopulations are ‘Critically Endangered’, while the Northeast Indian Ocean subpopulations are ‘Data Deficient’. Green turtles and loggerhead turtles are listed in the IUCN Red List as globally ‘Endangered’, while Olive Ridley turtles are globally ‘Vulnerable’ and Hawksbill turtles are ‘Critically Endangered’. Further threats to sea turtles are also discussed in chapter 39.

[2] United Nations, *Treaty Section*, vol. 993, No. 14537.

6.4 Research Gaps on Sea Turtles

- There is a need to undertake research on bycatch intensity by taxa and gear type for effective conservation management;
- Methods of assessment of bycatch should be standardized so that the data and information can be comparable using GIS and reduce high variances especially at regional levels;
- There is a need for long-term multidisciplinary research study to understand the life histories and ecology of the various species of sea-turtles in the various regions, how they relate to seasonality and climate change;
- There is a need to deploy observers in industrial fishing vessels to collect all the essential information for management of bycatch;
- Nesting and feeding grounds at national and regional levels need to be mapped;
- The genetic connectivity of the various taxa groups needs to be known in order to understand the nature of regional connectivity of the sea turtles.

6.5 Seabirds

Seabirds are characterized by their nature and behaviour to live partly in a terrestrial environment and partly in marine littoral, pelagic and oceanic habitats. Essentially they exploit the terrestrial environment for reproduction strategies and the benthic coastal marine and pelagic oceanic environment for foraging or feeding, playing the role of a fisher like human beings (Burger 1988, chapter 38).

Seabirds, in terms of their species numbers, contribute significantly to the overall marine species biodiversity and they can play a significant role in the predator – prey relationships in the marine food webs. Global patterns and trends in seabird biodiversity, and threats to the populations, are discussed in chapter 38.

Information exists on the seabird taxa in the Indian Ocean. These families are mainly *Diomedeidae* (albatrosses), *Procellariidae* (petrels) *Hydrobatidae* (storm-petrels), *Pelecanoididae* (diving-petrels), *Phaethonidae* (tropic birds), *Sulidae* (gannets and boobies), *Fregatidae* (frigatebirds), S*tercorariidae* (skuas) *Phalacrocoracidae* (cormorants) and *Laridae* (gulls and terns). Most of these taxa are migrant seabirds from European and Asian regions and their most preferred habitats are the estuaries of large rivers along the African continent. There are many species of seabirds, but there is a low degree of endemism (Wanless, 2012). There are still very few studies on seabirds and these are mostly patchy. Long-term studies to analyze status and trends are lacking. There is a need to focus these studies on measuring the impacts of climate change and bycatch due to industrial commercial fishing, and their effects on biodiversity changes in the coastal, offshore and deep or open ocean ecosystems. Seabirds in the tropical Indian Ocean region are primarily migratory birds from breeding grounds in the Arctic, Antarctic and temperate regions that come wintering in the tropics, after travelling tens of thousands kilometres. Chapter 38 discusses the major global threats to seabirds, including bycatch mortality in fisheries, habitat degradation and loss, over-exploitation of their food supply, bioaccumulation of pollutants and toxins, and sea-level rise. Because the seabirds use the Indian Ocean for only part of their annual cycle, it is very difficult to distinguish the impacts of pressures in the Indian Ocean from other pressures on the same populations. Combined with the few targeted studies of seabirds in the Indian Ocean, particularly offshore, it is hard to evaluate status and trends of most seabirds in the Indian Ocean and many research gaps exist.

6.6 Research Gaps on Seabirds

There is a need to address the following research gaps:

- −Lack of comprehensive taxonomic knowledge of species of seabirds at national and regional levels in the various countries of the Indian Ocean region;
- −Lack of data and information of the bioaccumulation of toxic substances in seabirds arising from marine food chains and their impacts on species biodiversity;
- −Lack of comprehensive long-term biophysical impacts due to habitat degradation and loss including sea-level rise impacts on seabirds migration and their biodiversity at taxa levels;
- −Lack of comprehensive understanding of long-term bycatch impacts due to various fishing methods and gears on seabirds at taxa levels and different habitats ranging from coastal to open sea at various depths where the seabirds forage;
- −Need to create GIS maps for various migratory routes of the seabirds encountered in the region and their hotspots at taxa levels;
- −Need to undertake coordinated research using harmonized methodologies for improved quality of data and information and facilitate comparisons.

7. Conclusion

Compared to other world oceans, the Indian Ocean biodiversity is relatively still scarcely known in terms of the taxonomic composition of the species found therein and their geographical distribution, except for some continental shelf areas around the Indian Subcontinent, Southwestern Australia and Southern Africa. However, deep sea species remain the most unknown, hence the need for concerted research efforts to understand their ecological roles in the diverse ecosystems of the Indian Ocean where they may be encountered. It is known that fish taxa and their geographical distribution are comparatively fairly well known and documented but from a fisheries activity perspective, which also generates ecological bycatch concerns. Since fish do not live in isolation and are part of the ecological systems, their role in relation to other biological taxa including their interaction with the environment can be fully understood if comprehensive integrated ecological studies are undertaken across seasons and time scales.

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