DRAFT

Indian Ocean and Red Sea (FAO 51, 57)

Economic Impacts of Ocean Acidification on Fisheries and Aquaculture in the Western Indian Ocean: Current Knowledge and Recommendations

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I. The Indian Ocean

Geography

The Indian Ocean (Figure 1) comprises 20% of the World's surface water, has an austral to tropical temperature gradient, is bounded to the east by the African continent, to the north by the Asian land mass (which includes semi-enclosed seas - the Red Sea, Arabian Gulf, Gulf of Thailand and Bay of Bengal), and to the West by SE Asia (Thailand, Malaysia, Indonesia, Timor L'Este and Australia). The throughflow between the Indian and Pacific Oceans is known as the Australasian Mediterranean Sea (Tomczak and Godfrey, 2003).

Atmospheric conditions driving the weather and climate across the Indian Ocean are strongly tied to processes that originate across the Indian Ocean (both north and south of the equator), and in the Pacific Ocean that are transmitted into the Indian Ocean through the Indonesian Throughflow (ITF) and El Niño/La Niña. The primary, relevant climatic phenomena affecting the tropical zone of the Indian Ocean are the El-Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), both of which have direct impacts on rainfall patterns and sea surface temperature.

During the austral winter (May-October) the southeast (SE) Monsoon is dominant as a result of the (boreal summer) heating of the large landmasses of the Indian Subcontinent and Asia. During the austral summer (November-April), the SE trade winds are weaker and the monsoon reverses due to significant (boreal winter) cooling of the Indian Subcontinent and Asia giving rise to the weaker northeast trade winds.

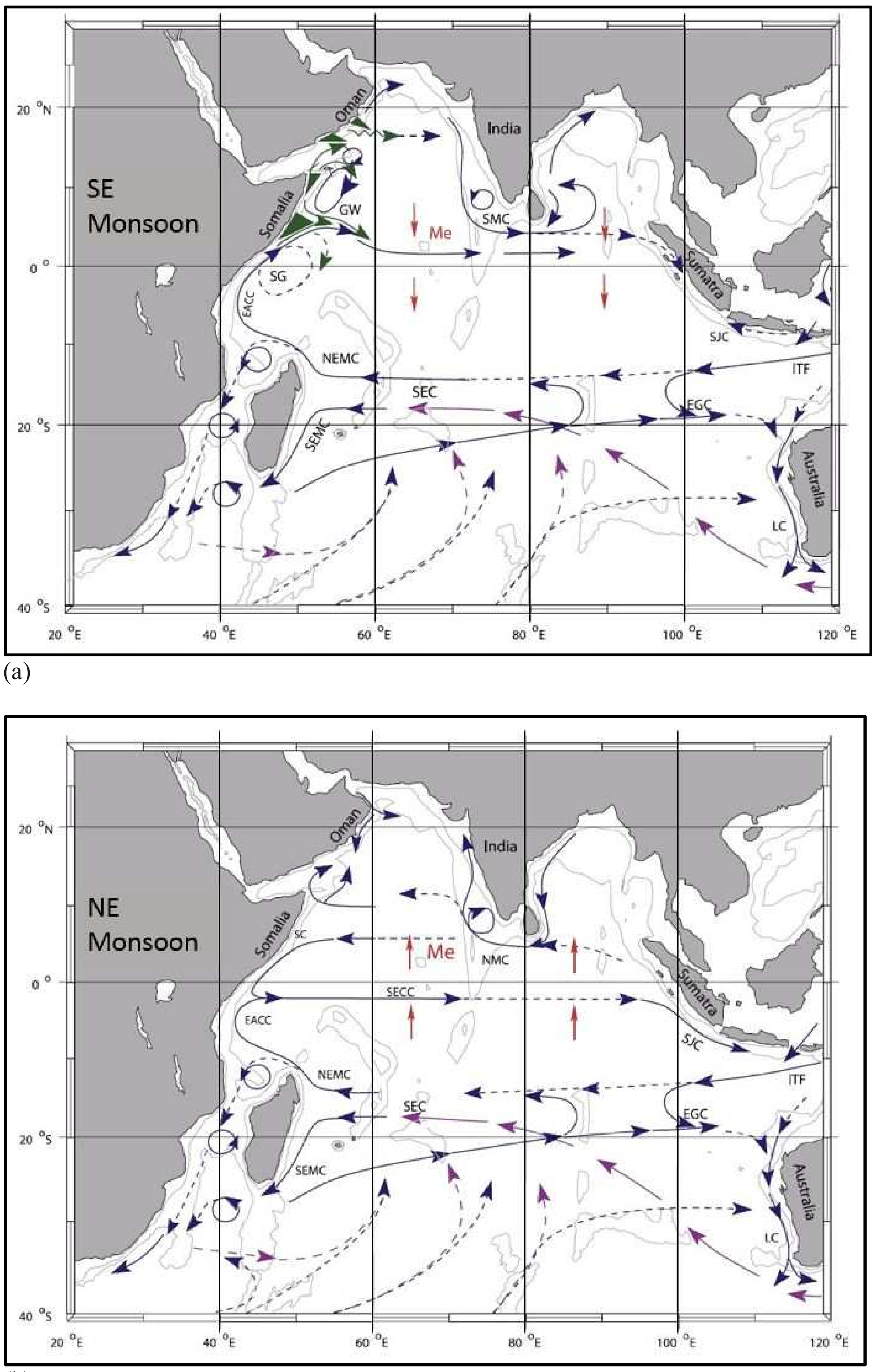
The principle ocean currents of the WIO are presented in Figure 1. The major current, running throughout the year, is the westward-flowing South Equatorial Current (SEC) located in a band around approximately 15-20^{o}S. The SEC is driven by a number of processes including forcing by the ITF and, through the SE Trades, by atmospheric processes associated with the heating of the Indian/South Asian landmass, as well as by equatorial oceanic heating and the formation of the Hadley Cells (Han et al., 2006; Schott et al., 2009).

Deep water circulation is controlled primarily by inflows from the Atlantic Ocean, the Red Sea, and Antarctic currents. The minimum surface temperature exceeds 28°C (82 °F) in the northeastern Indian Ocean. North of 20° South latitude the minimum surface temperature is 22°C (72°F). Southward of 40° South latitude, sea surface temperatures drop quickly to below 4°C (40°F).

Surface water salinity ranges from 32 to 37 parts per thousand, the highest occurring in the Arabian Sea and in a belt between southern Africa and south-western Australia. Pack ice and icebergs are found throughout the year south of 65° South latitude. The average northern limit of icebergs is 45° South latitude.

The main area of sea shelf is the Northwest Australasian Shelf, through SE Asia and the Bay and Bengal. Fringing reefs, mangrove and seagrass habitats are the dominant form of shallow-water environment in the tropical and sub-tropical zones.

The main riverine inputs are from the South Asian landmass - the Shatt-Al Arab and Indus draining into the Persian Gulf and Arabian Sea, respectively, and the Ganges/Brahmaputra and Irrawaddy rivers into the Bay of Bengal. From tropical and sub-tropical Eastern and Southern Africa flow the Tana, Rufiji, Zambezi and Limpopo rivers.



(a)

(b)

Figure 1: The Indian Ocean and its currents during the a) South East Monsoon and b) NE Monsoon (Schott et al., 2009).

Much of this review is focused on the Western Indian Ocean (WIO) region which lies within FAO statistical area 51 and comprises ten countries: Somalia, Kenya, Tanzania, Mozambique, South Africa, Madagascar, Comoros, Seychelles, Mauritius and the dependent Rodrigues, and the French dependent territory of La Réunion (France). The region has a mainland coast that extends over 11,000 km (with over 3000km in

Somalia) and a coastal population of over 20 million which is projected to double as a result of migration and birth, reaching 40 million by 2020 (Olsen et. al. 1999).

The marine ecosystems of the WIO are typified by coral reefs through the tropical zone merging with sandstone marginal reefs in South Africa; extensive mangrove forests and seagrass beds on the African mainland and in Madagascar; sandy beaches, muddy bays, rocky shores, fossil coral reef coastlines and islands (e.g. Zanzibar); granitic and volcanic oceanic islands (Seychelles, Comoros) and atolls. This diverse array of coastal resources in the WIO region provides for key livelihood activities including fisheries and tourism. Others are aquaculture, shipping, mineral exploitation including most recently oil and gas, agriculture and forestry. There are marked differences between countries in terms of development and fisheries: the highest dependence on fisheries is found in Quirimbas, northern Mozambique and Andavadoaka, Madagascar, with over 80% of households in each of these areas dependent on marine resources for food and income (Lopez et al. 2008).

Main Stressors

Quality of life of coastal communities in the WIO region is inextricably linked to the quality of coastal resources. Over the past decade, trends in socio-economic indicators have declined (Lopez et al 2008). The main regional drivers of change include: destructive and unsustainable pelagic and coastal fishery practices (dynamite and overfishing), climate change, land-based sedimentation, watershed pollution and soil run-off, population growth, poorly planned infrastructure, tourism and shipping activities. Increase in human pressure on coastal and marine resources in the WIO region is evident from decreasing fish catches, increasing use of destructive fishing practices and by the increasing volume of untreated sewage and nutrient runoff released into near-shore areas. The main stressors for this area have local, regional and global sources:

- Eutrophication & land-source pollution from nutrients and sewage;
- Sediment impacts on reefs;
- Hypoxia and ‘dead zones’ (e.g. in Bay of Bengal);
- Overharvesting, overcapacity of marine resources, illegal and destructive fishing;
- Mangrove deforestation;
- Impacts of rising sea surface temperature, UV light, & doldrums on coral reefs (Maina et al. 2008, 2011);
- Climate change impacts (sea level rise, rainfall and primary productivity changes, coral bleaching) shifting distribution & productivity of fish stocks;
- Decreasing aragonite saturation and ocean pH, surface water warming, increased stratification of the water column resulting in nutrient limitation and decreasing productivity and deoxygenation are projected to continue in this ocean area this century (Figure 2, Gruber 2011).

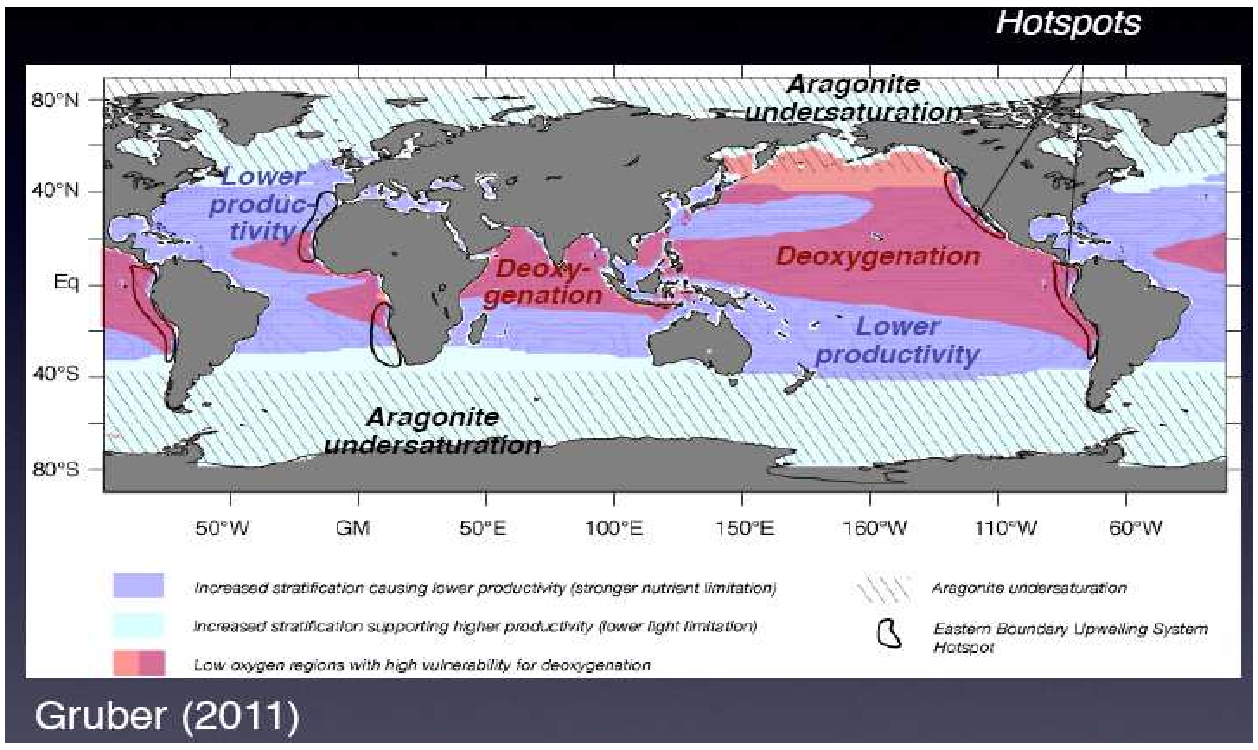


Figure 2.

General socio-economic aspects of the area

Twelve of the 20 countries with the highest rates and prevalence of child malnutrition border the Indian Ocean (Figure 3, Black et al. 2008).

Fisheries of the WIO countries can be categorised into two different types: i) coastal artisanal fisheries fished by local fishers (in territorial waters) and ii) offshore commercial or industrial scale fisheries (in EEZ waters) fished largely by foreign fishing fleets, though this varies considerably between countries (Everett et al. 2010). This overview focuses on national artisanal fisheries as these play a more direct role in the socio-economics of each country.

Artisanal fisheries of the WIO are the mainstay of over 20 million coastal peoples' livelihoods, providing a vital source of protein and income (Olsen et al. 1999). To our knowledge there has been no specific research on the impacts of ocean acidification on these fisheries, and hence on the people who depend on fishing for their livelihoods. The socio-economic impacts of ocean acidification on coastal communities in the WIO have not been studied and the biological and ecological impacts of ocean acidification on fisheries in the WIO are also unknown.

The WIO artisanal fisheries harvest a diverse range of species including: molluscs, lobster, octopus, sharks, pelagic fin-fish such as mackerels and tunas, both near and offshore, and demersal fish including coral reef fish and those from other habitats. The relative contribution of these fisheries varies considerably between countries.

Fish species targeted by fisheries of the WIO

The fish species targeted by fisheries of the WIO include the following:

> Hakes, Cape rock lobster, Yellowfin tuna, Cape horse mackerel, Bigeye tuna, Skipjack tuna, Porgies, Panga sea bream, South American pilchard, Natantian decapods, *Penaeus* shrimps, Indian oil sardine, Drums or Croakers, Bombay duck, Indian mackerel, Herrings, Perch-likes, Cutlass fishes, Anchovies, Jacks and Pompanos, Emperors, Narrow-barred Spanish mackerel, Groupers, Lizard fishes, Snappers, *Sardinella*, Indian mackerel, Rabbit fishes, Seer fishes, Wrasses, and Halfbeaks.

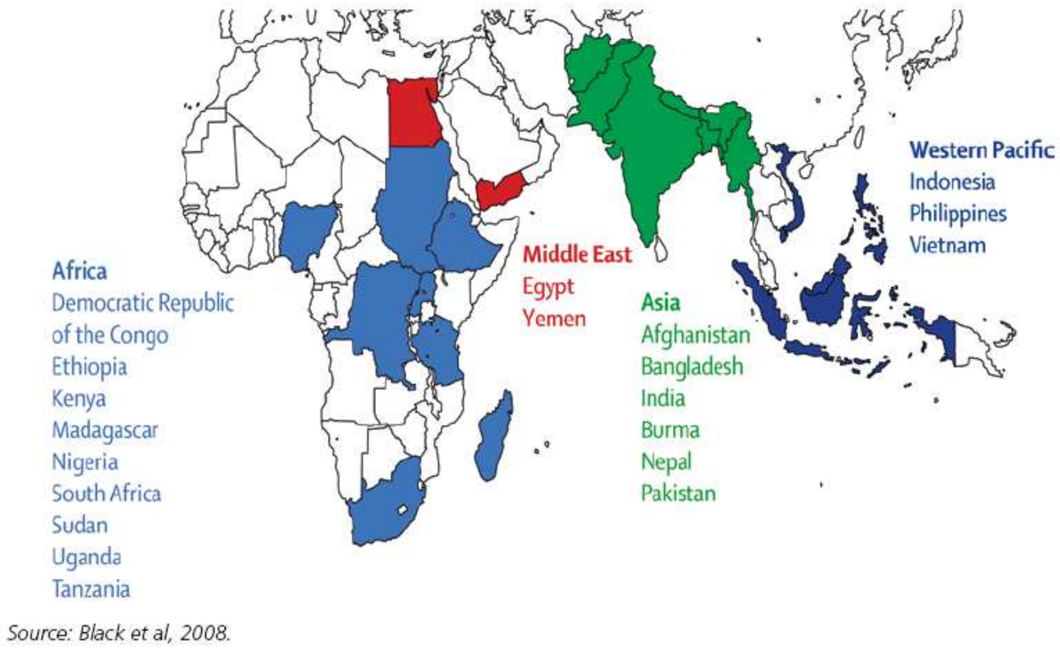


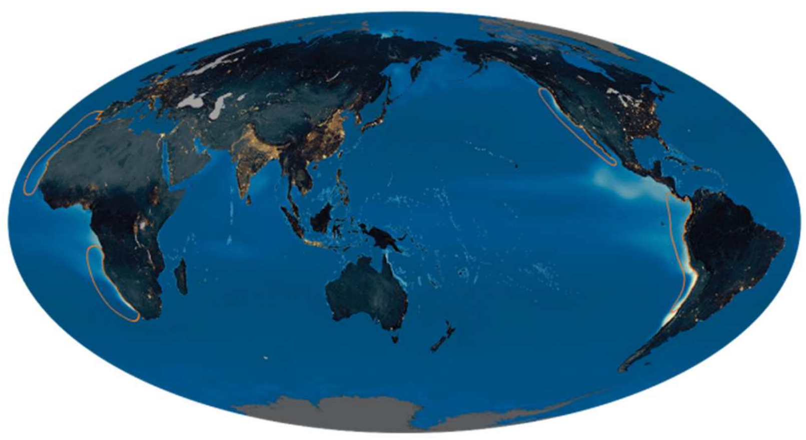
Figure 3. The 20 countries with the highest burden of under-nutrition: countries with stunting prevalence ≥20% in children under the age of 5 years that together account for >80% of the world's undernourished children. Colour denotes region (Black et al. 2008).

II. Biological Impacts of Ocean Acidification

From studies elsewhere we know the ocean acidification impacts on these different taxa are likely to vary substantially. This WIO context therefore provides an ideal experimental situation for modelling and quantifying the socio-economic impacts of ocean acidification on coastal artisanal fisheries. The implications of the results will be critical for determining mitigation and adaptation measures.

Individual level and Population/community level:

No experimental studies on acidification impacts have been conducted in the region to date, the only available data are from similar species in other regions. Projections of aragonite saturation from global models are available for the Indian Ocean (Figure 4), but projections from regional and coastal models are not yet available. The global projections show that ocean acidity (pH) has already declined across the global ocean by 30% (0.1 pH unit) and by the end of this century will decline by 100-150% (0.3-0.4 pH unit) if CO_2 emissions continue at the same rate.



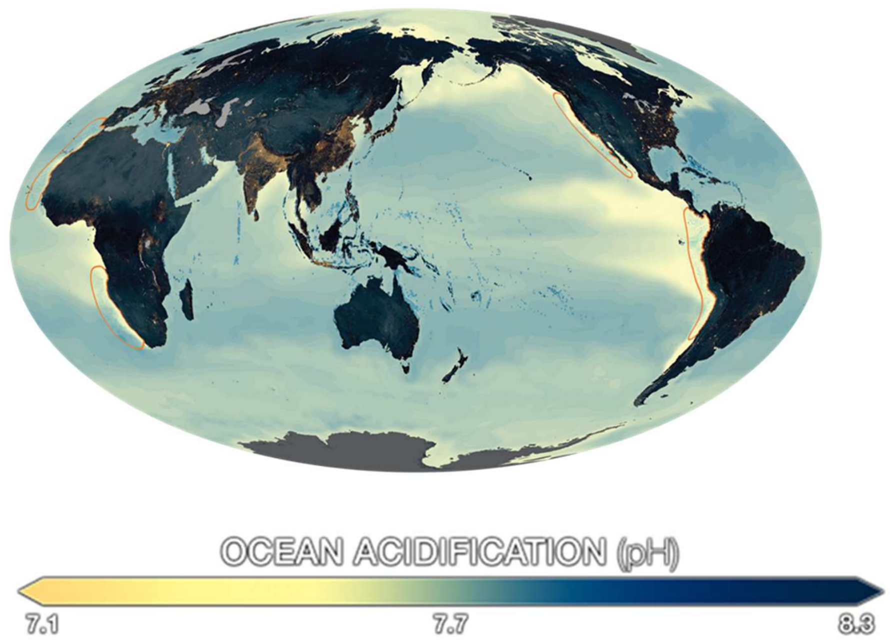


Figure 4: Projections of decrease in ocean pH from start of the industrial revolution (upper figure) to 2100 (lower figure) (from IGBP, IOC, and SCOR (2013) Ocean Acidification Summary for Policy Makers).

The following lists current status of observational data:

- pH monitoring studies are beginning in India, elsewhere there is little monitoring so there is no long term observational pH data available;
- Fisheries and aquaculture production data are available from ‘Sea around us’ project and catch-reconstructions;
- Contribution of marine resources to human nutrition, employment and revenues are available from FAOSTAT.

Consequences at the socio-economic scale

No observational or direct experimental data or studies on acidification impacts have been conducted in the region so we use data on similar species from other regions (average effect-sizes of impact, from meta-analysis).

Table 1. Summary of main effects of likely future ocean acidification on different groups of marine organisms, mostly based on experimental studies from around the world. Note that none of the data is from this region. Table from Williamson, P. and Turley, C. (2012) Ocean acidification in a geoengineering context: Phil. Trans. R. Soc. A 370, (1974), 4317–4342. doi:10.1098/rsta.2012.0167.

Group	**Main acidification impacts**
Warm water corals	A relatively well-studied group. The great majority of experiments show that increasing seawater CO_2 decreases adult coral calcification and growth, and suppresses larval metabolism and metamorphosis (Kleypas et al. 2006; Cohen et al. 2009, Nakamura et al 2011. Although most warm water coral reefs will remain in saturated waters by 2100, saturation levels are predicted to decline rapidly and substantially; thus coral calcification is unlikely to keep up with natural bioerosion (Cao & Caldeira 2008; Hoegh-Guldberg et al, 2008, Feely et al. 2004; Silverman et al, 2009). Interactions with other climatic and anthropogenic pressures give cause for concern (Fischlin et al. 2007; Veron et al, 2009).
Cold water corals	The long-lived nature of cold-water corals, and their proximity to aragonite saturation horizons, makes them vulnerable to future shoaling of the ASH. Around 70% of known cold water coral locations are estimated to be in undersaturated waters by the end of this century (Guinotte et al. 2006, Turley et al. 2007). Experiments found the effect of pH change on calcification was stronger for fast growing, young polyps (Maier et al. 2009).
Molluscs	Significant effects on growth, immune response and larval survival of some bivalves (Berge et al 2006; Bibby et al 2008, Talmage & Gobler, 2009), although with high inter-specific variability (Gazeau et al. 2007, Miller et al, 2009: Parker et al, 2010). Pteropods seem particularly sensitive (Orr et al, 2005; Comeau et al, 2009 & 2010) and are a key component of high latitude food webs. Molluscs are important in aquaculture,, and provide a small yet significant protein contribution to human diet (UNEP 2010).
Echinoderms	Juvenile life stages, egg fertilization and early development can be highly vulnerable, resulting in much reduced survival (Kurihara & Shirayama, 2004; Dupont et al 2008, Clark et al. 2009). Adult echinoderms may increase growth and calcification; such responses are, however, highly species specific (Dupont et al, 2010).
Crustaceans	The relative insensitivity of crustaceans to ocean acidification (e.g. Kurihara & Ishimatsu, 2008, Arnold et al, 2008, Ries et al 2009) has been ascribed to well-developed ion transport regulation and high biogenic content of their exoskeletons (Kroeker et al, 2010). Nevertheless, spider crabs show a narrowing of their range of thermal tolerance by ~2˚C under high CO_2 conditions (Walther *et al.* 2009).
Foraminifera	Shell weight sensitive to CO_3^{2-} decrease in the laboratory (Bijma et al, 2002) with field evidence for recent shell-thinning (Moy et al, 2009; de Moel et al, 2009).
Fish	Adult marine fish are generally tolerant of high CO_2 conditions (Ishimatsu et al, 2008; Melzner et al 2009a,b). Responses by juveniles and larvae include diminished olfactory ability, affecting predator detection and homing ability in coral reef fish (Munday et al, 2009, 2010) and enhanced otolith growth in sea bass (Checkley et al, 2009).
Coralline algae	Meta-analysis (Kroeker et al, 2010) showed significant reductions in photosynthesis and growth due to ocean acidification treatments. Elevated temperatures (+3°C) may greatly increase negative impacts (Martin & Gattuso, 2009). Field data at natural CO_2 vents show sensitivity of epibiont coralline algae (Hall-Spencer et al., 2008; Martin et al., 2011).
Non-calcified macro-algae; sea grasses	Both groups show capability for increased growth (Hendricks et al., 2010; Kroeker et al., 2010). At a natural CO_2 enrichment site (Hall-Spencer et al 2008), sea grass production was highest at mean pH of 7.6.
Coccolitho-phores	Nearly all studies have shown reduced calcification in higher CO_2 seawater, as first found by Riebesell et al. (2000). However, the opposite effect has also been reported (Iglesias-Rodriguez et al, 2008),and ocean acidification impacts on coccolithophore photosynthesis and growth are equivocal, even within the same species. This variability may be due to the use of different strains (Langer et al 2009) and/or experimental conditions (Ridgwell et al 2009).
Bacteria	Most cyanobacteria (including *Trichodesmium*, a nitrogen-fixer) show enhanced photosynthesis and growth under increased CO_2 and decreased pH conditions (Hutchins et al, 2007, 2009). Heterotrophic bacteria show a range of responses with potential biogeochemical significance, including decreased nitrification and increased production of transparent exopolymer particles (affecting aggregation of other biogenic material and its sinking rate) (Liu et al, 2010). Adaptation by bacteria to a high CO_2 world may be more rapid than by other groups (Joint et al, 2010).

Potential <u>direct</u> impacts of acidification on Indian Ocean fisheries and aquaculture:

- *Negative effects on small-scale fisheries:*
  - SE Asia, S Asia, E&S Africa, Madagascar; S Australia scallop fishery;
  - Small effect relative to over-exploitation and habitat change;
  - Local acidification could be regulated by better coastal/habitat management.

- *Negative effects on mollusc mariculture:*
  - Abalone farms (Australia, South Africa);
  - Oyster farming (throughout the region);
  - Asian moon scallop (*Admusium*) – SE Asia;
  - Pearl oyster farming (Zanzibar, Indonesia).

- *Positive impacts on seaweed farming and fishing for sea-grass dependent species:*
  - Enhanced growth of fleshy seaweeds, flourishing algal and sea grass habitats (but may be at the expense of other species);
  - Benefits of seaweed culture productivity increases to household livelihoods and SME development.

Potential <u>indirect</u> impacts of acidification on Indian Ocean fisheries and aquaculture:

- *Capture fisheries:*
  - Ornamental fisheries for corals and reef fish (small niche industry for aquaria);
  - Fish production, diversity, value of reef fish may be affected by reductions in reef area or habitat structure.
  - Unknown but potentially significant impacts on cephalopod, echinoderm and finfish fisheries;
  - Concerns for food security are small-pelagic and near-shore sea-shelf and reef-associated fisheries (throughout the region);
  - Macro-economic concerns are for large pelagic fisheries, particularly tuna fisheries (Maldives, Seychelles, Sri Lanka, Indonesia).

- *Unknown but potentially significant Impacts beyond fisheries and aquaculture:*
  - Reductions in reef quality and extent affects reef based tourism and associated livelihoods and economic benefits (e.g. Maldives, Seychelles, East African Coast, Andaman Coast of Thailand);
  - Reduction in reef formation may reduce coastal protection from storms and increase erosion and storm damage;
  - Positive benefits to seagrass dominated coasts.

III. Economic Impacts of Ocean Acidification

Current data:

Fish landings and landed values from fisheries of the WIO[1]

The following graphs summarises landings and landed values of fish caught in the WIO, split according to the various large marine ecosystems [the Red Sea, Somali Coast, Agulhas Current, Arabia Sea and the High Seas] within the WIO.

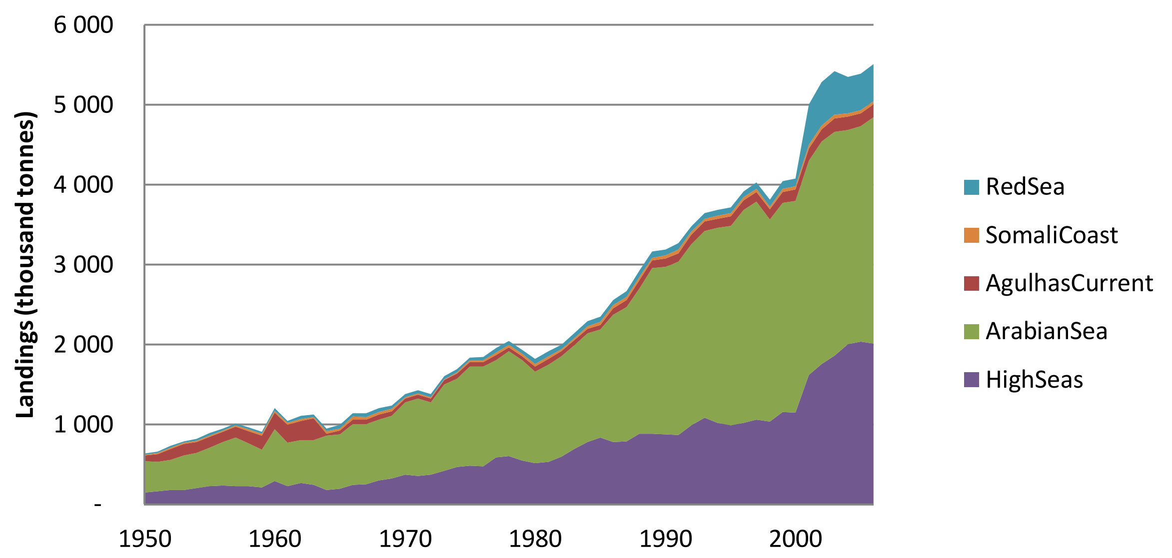


Figure 5: Marine fish landings from the Western Indian Ocean by marine ecosystem.

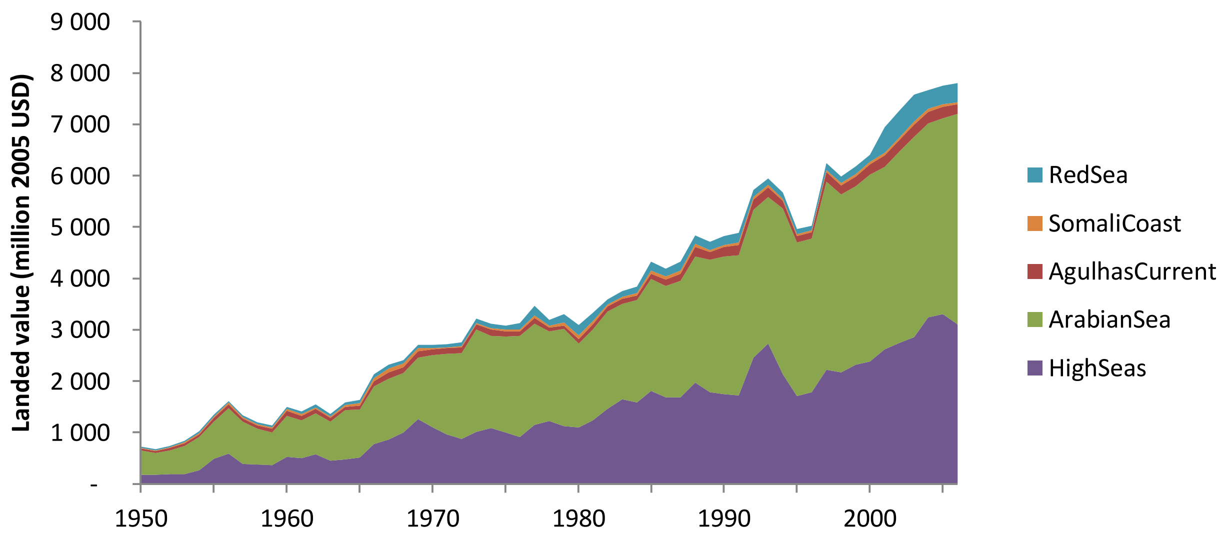


Figure 6: Marine fish landed values from the Western Indian Ocean by marine ecosystem.

Because tuna is a very important commercial group of fish species caught in the WIO, tuna landings and landed values are presented in Figures 7 & 8.

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[1] The data used to draw these graphs are taken from the *Sea Around Us* project website (www.seaaroundus.org) whose basis are reported in Watson, R, Kitchingman, A., Gelchu, A. & Pauly, D. Mapping global fisheries: sharpening our focus. Fish and Fisheries. 5(2), 168-177. (2004); and Sumaila, U. R., Marsden, A. D., Watson, R., & Pauly, D. A global ex-vessel fish price database: construction and applications. Journal of Bioeconomics, 9(1), 39-51. (2007).

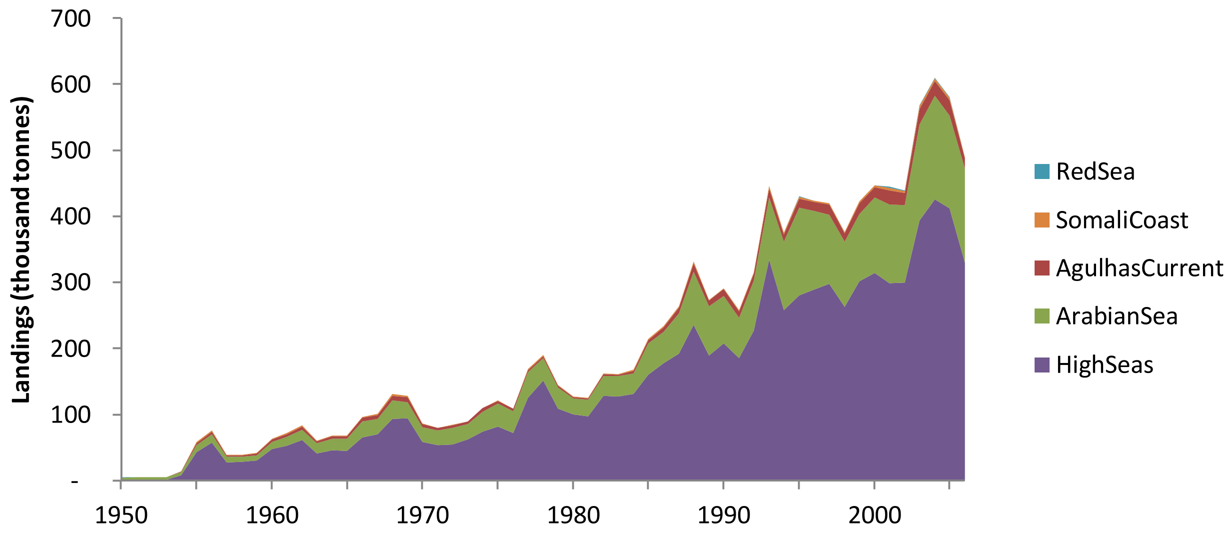

Figure 7: Tuna landings from the Western Indian Ocean by marine ecosystem.

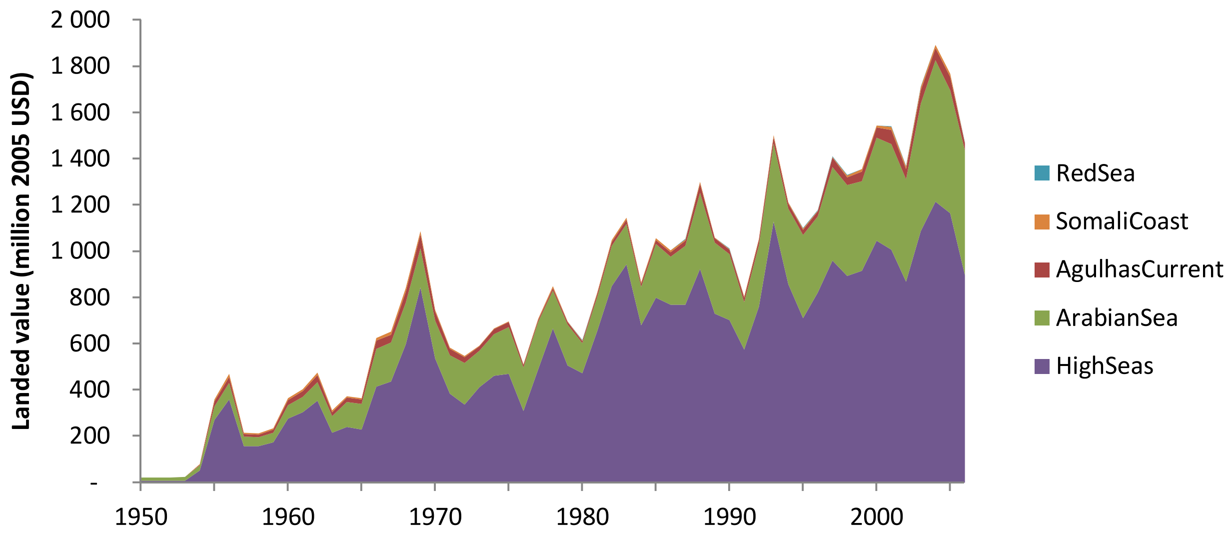

Figure 8: Tuna landed values from the Western Indian Ocean by marine ecosystem.

Role of fisheries in the economy

To demonstrate how important the fisheries of the WIO are to the people (especially small-scale fishers) of the region, the following describes the contribution of small-scale fisheries and mariculture operations in the following countries of the region: Comoros, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, South Africa, Somalia, and Tanzania.[2]

[2] This section draws on the work reported in the "Overview of Coastal Livelihoods in the Western Indian Ocean" Report prepared by Dr. Tim Andrew and his collaborators.

Mauritius

Small-Scale Fisheries

The Fisheries in Mauritius employ an estimated 11,000 people and contributes 1.5% to GDP. Artisanal fishers have an income level of around Rs300[3] per day, while monthly consumption expenditures for all fishers are, on average, above Rs 4,000. Total domestic catch in the sector is valued at Rs 1 billion. However, catch by the artisanal sector dropped by nearly 360 tonnes between 2004 and 2008, which correlates to the declines in total catch during the same period.

The fisheries sector employs an estimated 2,000 people, 78% of whom are between the ages of twenty to forty five. The number of fishers increased between 2005 and 2008, while production in the sector, unlike Mauritius, increased during the same period. The artisanal sub-sector supplies the majority of fish caught domestically, however, 60% of all domestic fish consumption is imported.

Mariculture

Only one mariculture farm is active in Mauritius and Rodriguez, with cage culture being utilized to produce gold-lined sea bream, red drum and cobia in Mahebourg. The farm produces both for domestic consumption and export, employing 65 people and, in 2008, produced an estimated 750 tonnes of fish. The sector is not yet a major part of the country's economy, however, six mariculture licenses have been granted as of 2009 and the government has identified the sector as having great potential for growth, thus, activity is likely to increase in the near future.

Madagascar

Small-Scale Fisheries

The small-scale fishery in Madagascar made up of subsistence, artisanal/traditional and recreational fishing, is largely concentrated on the country's west coast. This sector employs 36% and 27% of the workforce in the provinces of Toliara and Mahajanga, respectively. Traditional fishing, undertaken mostly by canoe, represents nearly 68% of total fish catch, largely focusing on export products, such as crustaceans, holothurians and cephalopods. Men make up 97% of the workforce. In 2003, the small-scale fisheries, as a whole, contributed nearly 26% of the total tonnage of fisheries export and nearly 9% of the total value of exports, worth an estimated $142 million USD.

Mariculture

Mariculture is a developing sector in the Madagascan economy. There is currently on-going research and pilot projects studying the feasibility of farming mud crab, sea cucumber, blue-green algae, oyster and eel. There are also commercial activities present, seen with the large scale farming of prawn for export and domestic consumption, as well as small-scale production in seaweed. Prawn farming, in particular, has been very successful in providing employment for rural communities, supplying 4,325 permanent and 30,000 part time jobs in 2003. The sub-sector has a strong export component worth an estimated $62 million USD.

South Africa

Small-Scale Fisheries

It has been estimated that nearly 100,000 people are directly involved in the sector, while upwards of 28,000 households are dependent on subsistence fisheries. The commercial fishery contributes 0.5% to GDP and brings in R80 billion annually. Commercial fisheries include some aspects of the small-scale sector (for example west coast rock lobster and traditional line fish). As a whole, small-scale fishing along the east coast has traditionally focused on shore-based activity as a means of livelihood, while small-scale fishers along the west coast have normally been drawn into the commercial fishery.

[3] 100 Mauritian rupees = 3.66 U.S. dollars as at May 8, 2011.

Mariculture

Medium and large-scale mariculture activity is well established in South Africa, with commercial farming prevalent in abalone, seaweed, mussels and oysters, and pilot commercial projects underway in dusky Kob, silver Kob and yellowtail finfish. Research is also ongoing for the production of clownfish, white margined sole, west and east coast rock lobster, scallops and bloodworms. Small-scale production is, however, scarce in the country, as most projects are being developed by the private-sector with an emphasis on pump ashore systems. This lack of small-scale production has been attributed to several factors, including poor environmental conditions, inadequate participatory approaches, poor fish growth, very low returns, lack of interest and neglect. Medium and large-scale farms are, nevertheless, providing employment outside urban areas, particularly in the Eastern and Western Cape.

Seychelles

Small-Scale Fisheries

The small-scale fishery in Seychelles, which includes the artisanal and semi-industrial sub-sectors, contributes between 1% and 2% to GDP annually, while the fisheries sector, as a whole, contributed 7.7% in 2008, an increase of 1.3% from 2004. Seychelles has very limited land-based opportunities, thus, the fishery is a vital source of income, employment, food security and foreign exchange in the country. Reliance on the sector is most evident in the fact that 17% of the total population is employed in the fishery, 30% of which are active in the small-scale sector, while 10% of the population is directly dependent on the small-scale sector.

Mariculture

Few mariculture activities are currently operational in Seychelles, with only prawn, giant clam and pearl oysters being produced in small-scale commercial operations.

Prawn and clam production has also been decreasing in recent years, with clam production falling from 1,960 tonnes in 1996 to 585 tonnes in 2006 due to weak demand, while prawn production fell from 1175 tonnes in 2004 to 704 tonnes in 2006.

Farming of clam and pearl oysters are not labour intensive practices, thus, little employment has been generated around the sub-sectors, and while the prawn farm on Coëtivy Island employs 350 people, only 18% are actually native Seychellois.

Comoros

Small-Scale Fisheries

The small-scale fisheries in Comoros employ 6% of the country's population, with women mainly being employed in post-catch operations, while 30% of the population is dependent on the fishery. The sector contributes 8% to GDP, 24% to agriculture GDP and also makes up 5% of total foreign exchange annually, making fishing not only a net supplier of foreign exchange, but also a key component of the country's balance of payments. The small-scale fishery is, in this respect, a vital link to the global economy for the Comoros.

Mariculture

With no designated mariculture zones, limited fresh or brackish water resources, and limited areas suitable for culture, there are currently no operating mariculture activities in the country.

Somalia

Small-Scale Fisheries

There is an operative small-scale fishery in Somalia with approximately 50 fishing centers and an estimated 30,000 people from coastal communities engaged. Despite rich biodiversity and an extensive coastline, exports of fishery products only account for around 3% of total exports and contribute about 2% to GDP, though it is difficult to verify these figures. Household income in the sector also fluctuates by season, with fishers earning US$1.5 per day during monsoon season and an estimated US$40 per day during fishing season.

Mariculture

A dedicated report on mariculture has not been included in this country report due to the current difficulty in obtaining detailed information on the potential of this sector in Somalia.

Kenya

Small-Scale Fisheries

The small-scale fisheries in Kenya, defined as artisanal in the country report, employs 10,000 people and supplies 95% of the country's total marine catch, generating an estimated US$ 3.2 million per year and accounting for between 2% and 6% of total fish production in the country. An estimated 60,000 coastal residents depend on the sector, wherein, the level of dependence is higher in regions with low development, less salaried employment and high poverty rates. Hence, while the entire fisheries sector only contributes 0.5% to national GDP, it is nevertheless a vital component to economic activity in the coastal regions.

Population growth, along with high levels of poverty in the coastal regions, has contributed to increases in the number small-scale fishers, with a 34% increase documented between 2004 and 2008. This has, in turn, placed great strain on fish stocks along the coast, resulting in the over-exploitation of fisheries resources. This has subsequently resulted in an overall decline in small-scale landings, evident in the 50% decrease in demersal coral reef fish yields through the 1990s. Rabbit fish and emperor fish, which make up nearly 40% of the small-scale fishers' landings, declined by 40% in the 1990's. The catch of tuna has been declining since 2004. Destructive fishing techniques, such as the use of seine nets have facilitated these declines; however, population growth and poverty in the coastal regions have been documented as the key contributing factors.

Mariculture

There are several mariculture activities currently in the experimental stage along the south coast of Kenya. This includes eight finfish farms, six crab farms and four prawn farms, all of which are currently producing for domestic consumption. This development is a reflection of not only the high-quality seawater in the coastal region, but also the enthusiasm of coastal communities to develop mariculture activities. Many mariculture operations, particularly crab and finfish, are also being developed as community-based initiatives, again a testament to the willingness of coastal residents to become involved in the sector. Thus, despite inadequate coordination and planning in the sector, mariculture is a developing field in the Kenyan economy.

Tanzania

Small-Scale Fisheries

The small-scale fisheries in Tanzania accounts for 98% of total fish production, 1.3% of GDP and makes up 9.9% of fish exports worth an estimated $12.4 million USD. While its contribution to GDP may appear marginal, the sector is a vital source of food security, employment and income for coastal communities, which subsequently stabilizes the five coastal regions which, when including all sectors, make up 32% of Tanzania's GDP.

Mariculture

Mariculture is clearly a vibrant sector in the Tanzanian economy, with finfish, seaweed and mud crab being farmed in all coastal regions, and pearls and prawns also being farmed in Mafia and Tanga. Regulation and infrastructure development has lagged behind in this sector, however, high quality seawater, large numbers of candidate species and existing research and support capacity highlight the untapped potential in the sector.

Mozambique

Small-Scale Fisheries

Comprised of subsistence, semi-industrial and artisanal fishing, the small-scale fishery in Mozambique employs over 351,700 people, 2% of which are women. It accounts for 93% of the country's total marine catch, 91% of which is caught by the subsistence and artisanal fishers and 2% by the semi-industrial sub-sector. Income levels in the small-scale fisheries are largely dependent on position within the sector, whereby, three broad positions are classified in the report; Boat and gear owners, crew (employees) and fishing by foot/collectors. Income in the sector is dependent on region, and subsequently distances to market.

Mariculture

Mariculture employs 2,000 people in commercial seaweed farming, 80% of which are women, and 1,000 people in commercial prawn farming, and is thus a strong developing sector in the Mozambican economy. There are also experimental projects underway in finfish and mud crab, which highlight the opportunities for further development in the sector. The country's high quality seawater, its ideal environment for prawn farming, along with its large areas identified as suitable for mariculture development, should only accentuate these growing opportunities.

Forecast (or scenarios):

Economic studies of the effects of ocean acidification on fisheries in general are very scarce, and such studies for the WIO are virtually non-existent. We can, however, learn from more general studies on this issue in the literature.

It is very likely that the impacts of ocean acidification on fisheries, in general, will take place along with other environmental stresses (e.g. warming, deoxygenation, eutrophication) and non-environmental stress (e.g. overfishing). An increase in ocean acidity would add more stress to the marine ecosystem and the human communities that depend on them.

Increasing dissolved CO_2 in the ocean is very likely to lead to reduced growth of calcifying marine species such as molluscs, which would, in turn, affect the economics of the fisheries that depend on them. Cooley & Doney (2009)[4] estimated substantial revenue declines, job losses, and indirect economic costs in the United States by assuming that the reductions in calcification rate or growth equate to the corresponding decline in molluscs fisheries productivity and revenues. A subsequent study was conducted to identify countries with the most vulnerable to ocean acidification-driven decrease in landings of molluscs (Cooley et al. 2011)[5]. Narita et al. (2012)[6] also estimated the global and regional economic costs due to loss in the production of molluscs under ocean acidification using partial-equilibrium modelling, estimating a loss of about 6 billion USD.

It is also very likely that ocean acidification will impact coral reefs and the marine species associated with them. An increase in ocean acidity may reduce coral calcification, favour highly invasive non-native algal species, and reduce the biodiversity associated with the reefs. Brander (2007)[7] estimated that the economic impact of ocean acidification on coral reefs will escalate over time under the Intergovernmental Panel on Climate Change (IPCC) CO_2 emission scenarios. The study estimated the economic loss due to the impact of ocean acidification on coral reefs by combining both the impact of CO_2 on coral reef cover and the projected economic value of coral reef using a meta-analysis (Brander 2007).

Although there is still no detailed study on the economic impact of ocean acidification on global fisheries, it seems reasonable to assume that the direct impacts associated with ocean acidification might eventually

[4] Cooley, S.R., H.L. Kite-Powell and S.C. Doney 2009. Ocean acidification´s potential to alter global marine ecosystem services. Oceanography 22(4): 172-181.
[5] Cooley, S.R., S.C. Doney. (2009). Anticipating ocean acidification's economic consequences for commercial fisheries. Environmental Research Letters. 4: doi:10.1088/1748-9326/4/2/024007.
[6] Narita, D., Rehdanz, K., Tol, R.S.J. 2012. Economic costs of ocean acidification: a look into the impacts of global shellfish production. Climate Change, DOI: 10.1007/s10584-011-0383-3.
[7] Brander, K. M. 2007. Global fish production and climate change. PNAS 104, 19709–19714.

impose costs in the order of 10% of marine fishery production, perhaps something in the order of $10 billion/year (Kite-Powell 2009)[8].

Clearly, work is needed to help reveal the potential impact of ocean acidification on the fisheries of the WIO, in particular, and all the world's large marine ecosystems, in general.

A comprehensive, broad-based approach for understanding the impact of ocean acidification on the marine ecosystem, fisheries, and eventually the socio-economic dimensions, is still scarce (Hilmi et al. 2012)[9]. One approach to estimating these impacts is to use "Economic Valuation" based on changes in ex-vessel prices, fishing costs and projected catch under different ocean acidification scenarios. Other than the change in landed value or total revenue, ocean acidification may also affect the cost of fishing by changing the fishing effort needed to catch the same amount of fish, the number of fishing days, travel distance, gear to be employed, etc., when the distribution and abundance of target species are affected by ocean acidification. The wages earned by fishers may also be affected. Since fisheries are a primary or base industry, change in catch potential may also indirectly affect other economic sectors, from boat building to international transport (Dyck and Sumaila 2010)[10]. Thus, it is crucial for us to take these induced and indirect economic activities into account when assessing the full economic impact of ocean acidification on fisheries.

IV. Case Studies or Empirical Evidence (if any)

No experimental studies on acidification impacts have been conducted in the region, the only available data are from similar species in other regions (Table 1). Considering the vulnerability of the populations bordering the Indian Ocean to food security, this is a major finding of this study, and requires urgent attention.

V. Policy Recommendations

1. Ocean acidification will have direct impacts on select fisheries and aquaculture systems that are of economic importance and will impact food security.

> *Recommendation*: The need to implement best fishery and ecosystem based management practices is even more urgent.

2. Aquaculture likely to be more impacted by ocean acidification than wild harvest because it targets species that are directly impacted by ocean acidification.

> *Recommendation:* Shift away from reliance on wild-caught seed; breed for acidification tolerance.

3. Indirect impacts of ocean acidification on habitats (e.g. coral reefs) and processes (e.g. food webs) are likely to be even more important than direct impacts.

> *Recommendation:* Investment in long-term research and monitoring; choose sentinel sites in countries likely to be impacted.

4. Marginalised and vulnerable groups likely to be negatively affected and be unable to take advantage of opportunities, such as increased seaweed production.

> *Recommendation:* Build adaptive capacity of marginalised and vulnerable coastal communities.
>
> *Recommendation:* Share best practices, information and adaptation options.

5. Recognise the potential for blue carbon value of coastal ecosystems, e.g. seagrass and mangroves.

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[8] Kite-Powell, H.L. 2009. Economic considerations in the design of ocean observing systems. Oceanography 22(2):44–49, http://dx.doi.org/10.5670/oceanog.2009.37.

[9] Hilmi, N., Allemand, D., Dupont, S., Safa, A., Haraldsson, G., Nunes, P.L.D, Moore, C., Hattam, C., Reynaud, S., Hall-Spencer, J.M., Fine, M., Turley, C., Jeffree, R., Orr, J., Munday, P.L., Cooley, S.R. 2012. Towards improved socio-economic assessments of ocean acidification's impacts. Marine Biology, doi:10.1007/s00227-012-2031-5).

[10] Dyck, A. J., & Sumaila, U. R. 2010. Economic impact of ocean fish populations in the global fishery. J Bioecon. 12:227–243. DOI 10.1007/s10818-010-9088-3.

Recommendation: This is a knowledge gap that needs to be addressed through research, but in the meantime, protect these habitats, for example through multi-habitat protected areas, banning of destructive gears (such as, beach seines).

VI. Suggestions for further research needed to fill the gap between natural sciences and economics.

This study has highlighted the scarcity of ocean acidification observational data (of both carbon chemistry and biological impacts) in this region, the lack of studies of vulnerability of socio-economically important species and ecosystems to acidification, the risk these changes may impose on the peoples in this region, and the ability of these societies to adapt to changes. There are currently only two projects completing climate change and fishery risk assessments for species in Western Australia and Northern Australia.

- *Recommendation:* Develop long-term ocean acidification monitoring sites in coastal regions and societies likely to be most vulnerable to ocean acidification to give early warning and forecasting to facilitate societal adaptation.
- *Recommendation:* Address knowledge gaps between both direct ocean acidification impacts on aquaculture and wild harvest target species and the indirect impacts on habitats (e.g. coral reefs) and processes (e.g. food webs) as the latter could likely be more important that direct impacts.
- *Recommendation:* Further research on potential for blue carbon value of coastal ecosystems (e.g. seagrass and mangroves).

<u>Proposed new economic analysis</u>

Base case analysis:

- Determine the impact of ocean acidification increase on species biomass and therefore impact on catch potential;
- Use catch data to compute the potential catch changes for this ocean, in general, and for countries fishing in it;
- Translate the potential economic effects of the projected catch changes (indicators: total revenues, economic impact; income impacts); and
- Assess the impact of catch changes on food security by looking at catches for domestic use and exported fish.