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Frontline Observations on Climate Change and Sustainability of Large Marine Ecosystems

Large Marine Ecosystems
Volume 17

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Frontline Observations on Climate Change and Sustainability of Large Marine Ecosystems

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FOREWORD

The growing risks and impacts of climate change and the accompanying loss of ecosystem services require the world to urgently invest in a new development paradigm. Development, climate change and ecosystem sustainability issues are increasingly interlinked, requiring a rethinking of traditional development assistance in order to remain relevant to human needs.

UNDP has fully embraced the new development paradigm – a unique strategic approach for each economy - to help countries achieve development targets while meeting the needs of their citizens in the face of growing challenges of climate change.

As the UN's global development network, UNDP recognizes the increasing urgency of mainstreaming climate change into sustainable development planning at all levels, linking development policies with the financing of solutions and helping countries move towards less carbon intensive economies. During the present period of global warming, a firm scientific basis is essential to develop options for mitigation and adaptive actions.

The Large Marine Ecosystem (LME) approach recommends a baseline of information at the LME management scale on changing states of productivity, fish and fisheries, pollution and ecosystem health, and socioeconomic and governance conditions. This time-series information provides data to assess the extent of overfishing, nutrient over-enrichment, habitat loss, and progressive rates of surface water warming in LMEs around the globe. Through the GEF's Transboundary Diagnostic Analysis/Strategic Action Programme (TDA/SAP) approach, this LME data set can inform issue prioritization, strategic planning and adaptive management of LMEs towards sustainability.

This volume is a key contribution to advancing LME management in a changing climate. The authors describe the impacts of climate change on LME sustainability in Africa, Asia, and Latin America. Important information is provided on the key role the GEF has played in mobilizing financial support crucial to developing countries committed to carrying forward an ecosystem based approach to sustain LME goods and services. UNDP wishes to express its sincere thanks to the distinguished group of contributors to this volume for their leadership and commitment to sustainable human development.

Yannick Glemarec
Executive Coordinator
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INTRODUCTION

The United Nations Conference on Environment and Development (UNCED) convened in 1992 in Rio focused attention on the need for reversing decades of environmental degradation and moving the world toward sustainable development. Follow-on targets prompted by UNCED and the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg included addressing the effects of climate change on the world's coastal areas and ocean ecosystems.

One of the world's international financial institutions, the Global Environment Facility (GEF), was reorganized following UNCED, to provide financial assistance to developing countries committed to environmentally sustainable development. In addition to serving as the financial mechanism for the Biodiversity and Climate Change Conventions, the GEF committed to support efforts to protect and restore the world's most important marine and freshwater transboundary waters systems through its International Waters focal area. Since 1991, the GEF has provided $4.1 billion in grants, leveraged World Bank investments, and co-financing support for projects to recover, sustain, and develop the goods and services of Large Marine Ecosystems (LMEs) off the coasts of over 100 developing countries around the world.

On the occasion of UNCED's 20th anniversary and the 2012 Rio+20 Earth Summit, we are pleased to introduce this volume authored by marine experts engaged in carrying forward GEF supported projects. Their contributions consider the effects of climate warming on the trillions of dollars worth of both market and non-market goods and services provided by LMEs in Africa, Asia, and Latin America.

In the first chapter, Hume and Duda describe the **role of the GEF** in supporting LME projects. The authors focus on the GEF's International Waters portfolio and the distribution of financial assistance provided to over 100 countries participating in LME sustainable development projects around the globe.

The following two chapters examine the relationships among small pelagic fish species and describe how physical forcing controls the strength of upwelling in the Canary Current and the Benguela Current LMEs. Recent effects of climate change are resulting in shifts in distribution patterns of fish populations. For the **Canary Current**, Sambe assesses changes in maximum levels of sardine biomass and observes that shifts in movement of the stocks are in synchrony with wind direction, velocity, and plankton production. For the **Benguela Current**, Hampton and Willemse report on a major shift, likely due to climate change, of pelagic sardine and mackerel fisheries biomass south and eastward, from the coast of Namibia, toward the Cape of Good Hope and beyond.

The **Guinea Current**, like many LMEs, is already stressed by fisheries losses, pollution and the degradation of coastal ecosystems. As a result, project experts are striving to develop a regional management network to sustain the resources in the GCLME. Climate change is an additional stress, especially the expected degradation to coastal fishing communities from sea level rise. The authors review the present problems in the GCLME as well as the projected issues related to climate change. They also discuss mitigation actions and governance mechanisms, most notably the formation of the Guinea Current Commission, to address these threats and promote sustainable development of GCLME goods and services.

The focus of the UNDP-GEF **Agulhas and Somali Current LME** (ASCLME) project has been to acquire scientific data to support policy decisions for the benefit of the nations who rely on the goods and services of both LMEs. Climate change appears to be influencing distribution patterns of sardine, anchovy, lobster and horse mackerel in the ASCLME. The authors review how the eddies and dipoles affecting the ASLME relate to Western Indian Ocean circulation.

Vivekanandan, Hermes, and O'Brien, reporting observations from the FAO/GEF **Bay of Bengal LME** project, describe the impact of climate warming in producing higher intensity monsoons and lowering salinity levels in the waters of the BOBLME. The resulting increase in thermal stratification could lead to a long term negative effect from lowered primary production and a subsequent decline in fisheries yields.

In the **Humboldt Current LME**, the authors Serra, Akester, Bouchon and Gutierrez focus on climate forcing and how it is changing abundance levels of two small, but extremely abundant pelagic fish species - the anchovy and sardine. The annual production of these species is equal to 20 percent of the world's recent average marine fisheries catch. The authors illustrate the complex interactions between shifting oceanographic regimes and annual levels of fisheries yields in the HCLME.

The **Gulf of Mexico LME** chapter by Mendoza-Alfaro and Alvarez-Torres outlines climate observations for the Gulf of Mexico LME within the context of an ecosystem under stress from overfishing, pollution, nutrient over enrichment, and gas and oil exploration and production. Climate change is creating more intense hurricanes in the GoMLME and this in turn has ramifications for the populations of finfish, shellfish (oysters) and crustacean (shrimp) fisheries. The authors also discuss the impact of climate change and sea level rise on habitats (mangroves, seagrasses) and human populations.

In the penultimate chapter on the **Yellow Sea LME**, Professor Qisheng Tang and Dr. Jianguang Fang review the variable states of productivity and biomass yields under the influence of climate change and anthropogenic forcing. They indicate that in response to overfishing, fishing effort in the Yellow Sea was reduced. In order to replace the loss of capture fisheries in the YSLME, the UNDP-GEF supported YSLME program initiated a pilot project using an innovative integrated multitrophic aquaculture (IMTA) approach. The IMTA technology includes the production of algae (kelp), mollusks (abalone) bivalves (bay scallop), and echinoderms (sea cucumber) to help close the fisheries protein gap, while capture fisheries recover to sustainable levels. Preliminary results suggest that the IMTA pilot should be expanded throughout the YSLME and into other Asian LMEs, where applications could provide job opportunities and food security. The pilot IMTA project proved to be highly energy efficient and optimized the carrying capacity of coastal embayments while improving water quality, increasing protein yields, and, through carbon capture, contributing to mitigation of the effects of climate change.

In the last chapter, Oliver, Widdicombe, and Laffoley outline how increasing levels of carbon dioxide from global climate warming, contribute to **acidification in LMEs**. This in turn limits the calcification process for organisms such as corals, shellfish and calcifying plankton. The authors review how continued acidification of the world's oceans will impact primary production, fisheries and overall ecosystem health. They also consider the socioeconomic effects of acidification in LMEs.

The Editors

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This volume was made possible through the cooperation of eight GEF LME projects, the International Waters team of the Global Environment Facility (GEF), the GEF Unit of the United Nations Development Program (UNDP), the US National Oceanic and Atmospheric Administration (NOAA), and the International Union for the Conservation of Nature (IUCN). Special thanks go to GEF Agency and LME programme partners including the United Nations Environment Programme (UNEP), the United Nations Industrial Development Organization (UNIDO) and the Food and Agriculture Organization of the UN (FAO).

In October 2011, the GEF included an LME climate change workshop during the 6th GEF Biennial International Waters Conference in Dubrovnik, Croatia. In recognition of the excellent quality of the papers presented, a select number of presenters were invited to submit manuscripts for peer review and publication consideration. We are indebted to the authors who patiently, and with considerable diligence and insight, contributed extended analyses first elaborated in Dubrovnik, and now included in this volume. Their names and affiliations are listed on pages vi-ix. We acknowledge the chairpersons of the workshop – Marie Christine Aquarone and Galen McGovern of NOAA for their expert summary of the workshop and archiving of the Power Point materials.

Special thanks for financial and other contributions made to support the production of this volume are also extended to UNDP, GEF, the Gordon and Betty Moore Foundation, IUCN, and US-NOAA.

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GLOBAL ENVIRONMENT FACILITY STRATEGY FOR ASSESSING AND MANAGING LARGE MARINE ECOSYSTEMS DURING CLIMATE CHANGE

Andrew C. Hume and Alfred M. Duda

LMES AND THE GEF

The International Panel on Climate Change's Fourth Assessment Report in 2007 presented a grim view of the coastal environment encompassing the world's 64 Large Marine Ecosystems (LMEs). In particular, the report noted that "Coasts will be exposed to increasing risks such as coastal erosion due to climate change and sea-level rise" and "Increases in sea-surface temperature of about 1-3 °C are projected…", and perhaps most dire, that, "Many millions more people are projected to be flooded every year due to sea-level rise…." (IPCC 2007). What is noticeably absent from this and many other IPCC reports is an assessment of the effects of climate change on marine organisms, most notably on commercially important marine species and their habitats. While there is still much to learn about how climate change and variability will affect the marine environment, some disturbing trends are already taking shape.

Climate change is one of the most acute threats to LMEs and their coasts. Continued over-fishing in the face of scientific warnings, fishing down food webs, destruction of habitat, and accelerated pollution loading—especially nitrogen export—have resulted in significant degradation to coastal and marine ecosystems of both rich and poor nations as shown by Duda and Sherman (2003) and others (Pauly et al. 1998). Fragmentation among institutions, international agencies, and disciplines, lack of cooperation among nations sharing marine ecosystems, and weak national policies, legislation, and enforcement all contribute to serious environmental, social, and economic disruption. Nothing less than the security of coasts and oceans is at stake as degradation and depletion impact coastal economies, communities, and food security (Duda, 2005).

In the Yellow Sea LME (YSLME), a proactive approach is well underway in an effort to produce protein from mollusks and other invertebrates to offset lower fishing yields, while at the same time minimizing marine pollution. In the YSLME, overfishing, pollution, nutrient over enrichment, habitat degradation and climate change are the major issues affecting fishing yields. Even with the agreement by the People's Republic of China and the Republic of Korea to reduce fishing effort by 33% in the coming years (in an effort to recover depleted capture fisheries stocks), the fish protein needs for the growing population of the region are increasing.

In recognition of lower fisheries yields, during the fish stock recovery period, both countries are ramping up newly developed mariculture technology (integrated multi-trophic aquaculture (IMTA) methodology) in the annual production of shellfish (mollusks) and marine benthic invertebrates (sea cucumbers). IMTA is adaptive and efficient. Buoys with strings of lantern nets are placed in strategic locations creating extensive buoy fields over large coastal embayments. Fishermen travel to these fields in a convoy of up to eight interconnected boats towed by a single, motorized boat. In turn, the mature *Laminaria*, abalone and bay scallops are returned to the shore-side facility for processing and market destinations.

This scenario is a win/win solution to meet protein needs, minimize habitat degradation, and combat global warming – all while allowing capture fisheries time to rebuild. In addition to providing needed protein, the IMTA process sequesters an estimated 3.8 M mt Cy^{-1} annually (Tang, Q. et al. 2011, Sherman and McGovern, 2011).

Transferring innovative IMTA methodology to GEF-supported LME assessment and management projects around the globe would contribute toward the goals of the Cancun declaration and green energy initiatives aimed at reducing excess levels of atmospheric $CO_{2.}$

ROLE OF THE GLOBAL ENVIRONMENT FACILITY

Since the mid-1990s, developing countries have approached the Global Environment Facility (GEF) in increasing numbers for assistance in improving the management of large marine ecosystems (LMEs) shared with neighboring nations. LMEs serve as place-based, ecologically defined areas for integrating national and multi-country reforms and international agency programs for introducing ecosystem-based management (EBM). GEF assistance is addressing site-specific ocean concerns, issues in adjacent coastal areas, and linked freshwater basins using EBM practices.

The GEF is best known as the financial mechanism supporting a number of global environment conventions signed at the Rio Earth Summit in 1992, including the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD). The GEF's mandate is to provide financial assistance to address global environment issues including: climate change, biodiversity and concerns in international waters—which cover both transboundary freshwater and marine systems. GEF projects were implemented originally through a partnership among the United Nations Development Program (UNDP), the United Nations Environment Program (UNEP), and the World Bank (International Bank for Reconstruction and Development and the International Finance Corporation). More recently, seven additional organizations have been added to the partnership. These include the African Development Bank (AfDB), the Asian Development Bank (ADB), the European Bank for Reconstruction and Development (EBRD), the Food and Agriculture Organization of the United Nations (FAO), the Inter-American Development Bank (IDB), the International Fund for Agricultural Development (IFAD), and the United Nations Industrial Development Organization (UNIDO). Policies are set by a Council representing 182 developing and developed nations that balance the interests of all.

In its first two decades, the GEF has allocated $US 10.7 billion, supplemented by more than $US 50 billion in co-financing, for 2,900 projects in 165 developing countries and countries with economies in transition. For the International Waters focal area, 220 transboundary water projects have been funded with 149 different cooperating countries totaling over $US 8.5 billion in total cost and $US 1.3 billion in GEF grants. The GEF is clearly a significant funding source for transboundary systems—especially marine ecosystems. In 1995, the GEF Council included the concept of LMEs in its Operational Strategy as a vehicle to foster ecosystem-based management of coastal and marine resources in the International Waters focal area. Eighty percent of the global marine fisheries catch comes from the 64 LMEs located along the coastal margins of the continents. The LMEs represent multi-country, EBM units. This geographic approach represents a pragmatic way to implement the "ecosystem approach" and includes GEF transboundary considerations, especially with mobile living resources. To date, GEF is providing support to 19 of the world's 64 LMEs along the coasts of developing countries and one LME equivalent project is the southwest Pacific Warm Pool (Figure 1).

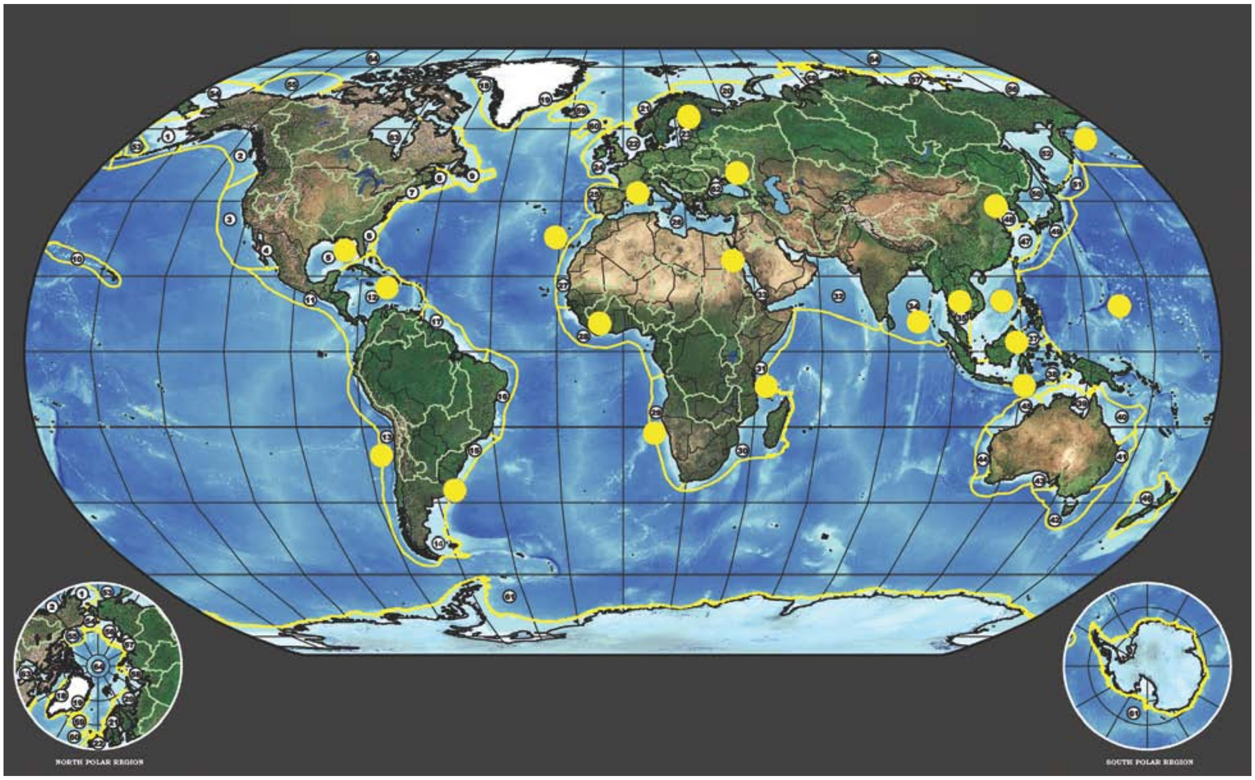


Figure 1. GEF support for LMEs is global and projects are depicted by yellow dots in the following LMEs: Gulf of Mexico, Caribbean Sea, Humboldt Current, Patagonian Shelf, Canary Current, Guinea Current, Benguela Current, Mediterranean Sea, Baltic Sea, Black Sea Red Sea, Agulhas/Somali Current, Bay of Bengal, West Bering Sea, Yellow Sea, Gulf of Thailand, South China Sea, Sulu/Celebes Sea, Indonesian Sea, and the Pacific Warm Water Pool.

TWENTY YEARS OF GEF SUPPORT FOR LMES

GEF LME projects are piloting and testing how integrated management of oceans, coasts, estuaries, and freshwater basins can be implemented though an EBM approach. The GEF continues to provide substantial funding to support country-driven LME projects for introducing multi-sector, ecosystem-based assessment and management practices. At present, 110 GEF recipient countries and 20 non-recipient countries are collaborating on LME projects. Figure 1 identifies those 19 LMEs and one LME-equivalent (the Pacific Warm Water Pool) of the Western and Southern Pacific) in which countries have requested and received funding for GEF LME projects.

The connectivity of LMEs through drainage basins and estuaries to terrestrial landscapes, which often extend far inland, reflect how the GEF addresses transboundary marine issues. In order to have an impact on these complex issues, GEF interventions are made at one or more of four management scales: 1) the LME scale; 2) integrated coastal management (ICM) provincial or municipal scale; 3) The land-based pollution reduction scale, and; 4) the global scale. By using a multi-scaled approach, investments target root problems, such as municipal pollution and nutrient over enrichment of LMEs, through reforms in governance at one scale, as well as improvements in infrastructure and conservation programs at another. In this way issues are addressed from the watershed to the river delta and ultimately downstream to LMEs.

LME SCALE

The five-module indicator approach to assessment and management of LMEs (e.g. (i)productivity, (ii) fish and fisheries, (iii) pollution and ecosystem health, (iv) socioeconomics, (v) governance) has proven useful in ecosystem-based projects in the United States and groups of nations sharing an LME. The modules are adapted to LME conditions through a transboundary diagnostic analysis (TDA) process to identify key issues, and a strategic action program (SAP) to remediate the issues. These processes are critical for integrating science into management in a practical way, and for establishing appropriate governance regimes to change human behavior in different sectors.

The shared commitment and vision for action embodied in the TDA - SAP process has proven essential in GEF projects for developing partnerships that can sustain commitment to action. Countries cooperate in establishing adaptive management structures as part of GEF monitoring and evaluation requirements for establishing indicators. This has led countries to adopting their own LME-specific ecosystem targets in response to the 2002 Johannesburg World Summit on Sustainable Development and to establishing partnerships with different bilateral, multilateral, and UN agencies for better coherence by development assistance agencies.

Overall, GEF has provided $US 380 million in grants that have accompanied $US 2.35 billion in investments from countries, GEF agencies, and public and private organizations for the protection of LMEs. The cumulative investment in LMEs through GEF projects along with project co-financing is shown in Figure 2 for the 20 year period of the GEF (1992 – 2012). When added to the pollution reduction projects at the coast, the total rises to $700 mil GEF and 4.1 billion in co-financing.

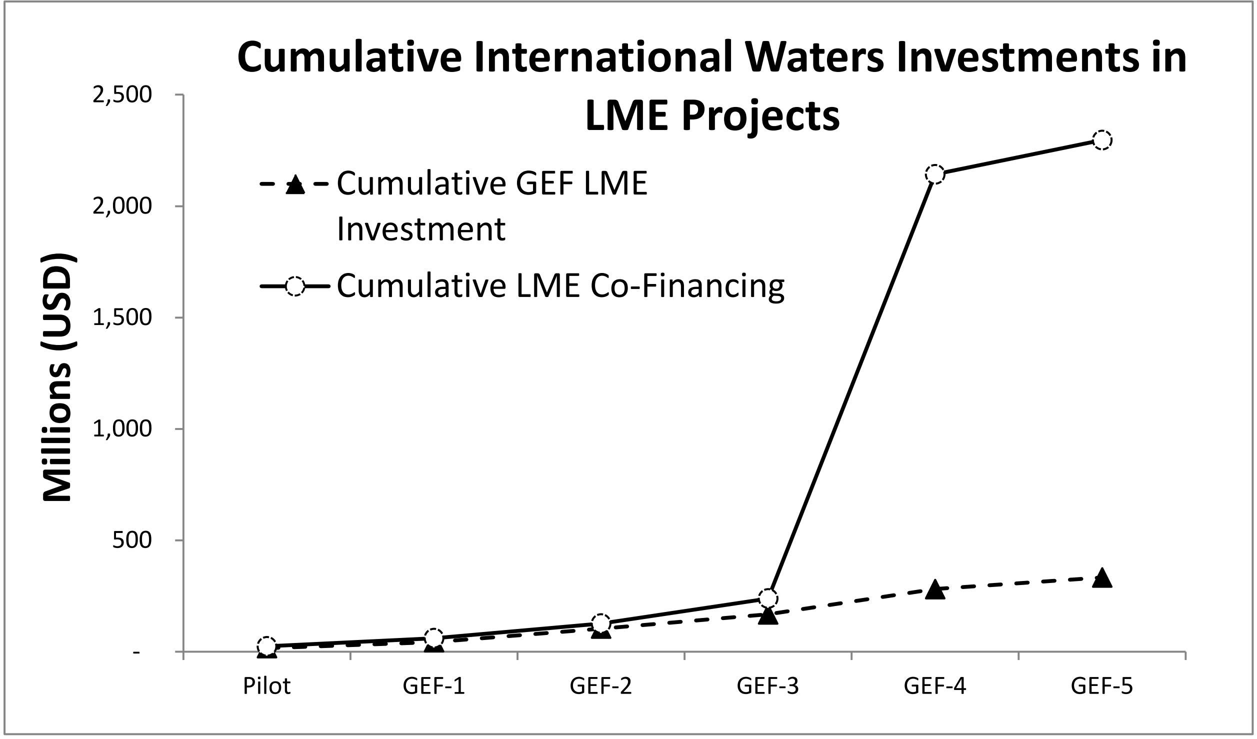
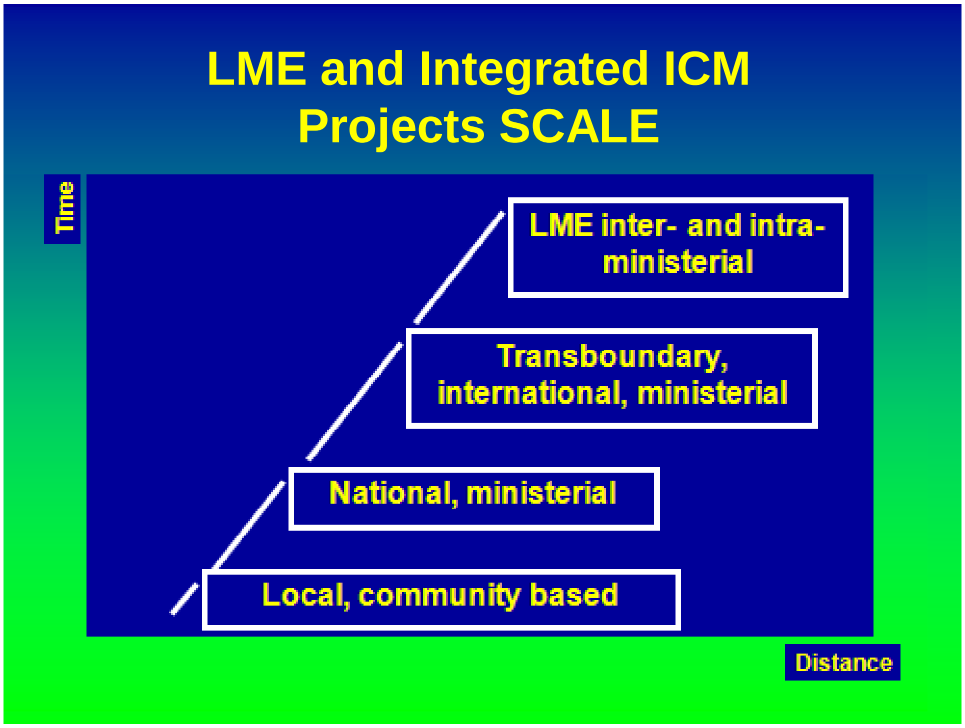


Figure 2. Cumulative Amount of GEF financing and co-financing for GEF LME Projects (1992-2012).

INTEGRATED COASTAL MANAGEMENT (ICM) WITHIN LMEs

When moving down in scale, LME geographical units are enhanced with political units within the boundaries of the LME such as counties or provinces and cities. Here management regimes such as ICM are utilized as described by Duda (2005). One of the most successful examples of ICM from GEF's portfolio is the Partnerships in Environmental Management for the Seas of East Asia (PEMSEA) program. Through the work of GEF and UNDP, the countries of Cambodia, China, Democratic People's Republic of Korea, Indonesia, Japan, Laos, Philippines, Republic of Korea, Singapore, Timor-Leste, Vietnam have worked together to better manage sources of marine pollution in the seas of East Asia. In addition to the creation of high level multilateral agreements, dozens of ICM pilot projects were established, including projects in Xiamen, China and the Batangas Bay, Philippines. In the case of Batangas Bay, the pilot catalyzed efforts to address marine pollution problems in the Straits of Malacca, one of the busiest shipping lanes in the world.



LME and Integrated ICM Projects SCALE

LME inter- and intra-ministerial

Transboundary, international, ministerial

National, ministerial

Local, community based

Figure 3. LME and Integrated ICM Projects.

Pilot projects like these are instrumental for successful scaling up of ICM programs within LMEs at the municipal and national levels. Another case is the zoning of sea use space in China. Once the government experienced this, it passed a national law requiring replication up and down the coast of China. Various examples of GEF support for ICM are included in the GEF publication entitled "*From Ridge to Reef: Water Environment, and Community Security"* (Duda et al. 2009). LME tools, indicators, and methodologies in LME-ICM projects are utilized at a smaller scale to foster integration, participation, and reform processes for implementation. Instead of labeling these tools TDAs or SAPs as they are at the LME level, they are named other, more locally appropriate processes. Establishment of ICM programs can have a positive, cascading effect in transforming deficient small scale governance, improving awareness of important ecosystem services and social values, and serving as a reform for spurring additional private sector involvement.

LAND-BASED NUTRIENT POLLUTION REDUCTION in LMEs

Pollution from land-based sources is a constant transboundary threat to LMEs and can only be addressed in a coordinated fashion by all states. However, coordination at this scale is not easy. Fortunately, the GEF learned early about the importance of coordination through the success of the Black Sea/Danube River Basin program. Land-based nitrogen pollution leading to accelerated eutrophication was identified by Black Sea LME States in their GEF-supported SAP as the top priority for interventions to begin restoration of the world’s most transboundary LME. A series of GEF/UNDP projects in the Danube Basin, Dnieper Basin, and the Black Sea States were designed to bring basin and coastal States together. These were followed by the Strategic Partnership for Nutrient Reduction in the Danube River and Black Sea Investment Fund with the World Bank, UNDP and UNEP which mobilized more than $US 450 million in co-financing. This supplemented the $US 106 million from GEF to help enact policy, legal, and institutional reforms and demonstration investments in the agriculture, municipal, and industrial sectors and in wetland restoration to reduce nitrogen pollution in the Black Sea watershed. Through the GEF, political commitments were garnered from the 17 involved States and nutrient reduction projects were initiated by the non-recipient states of Austria and Germany. The Partnership among GEF agencies, donors, and the 17 States is now bringing coordinated support and benefits to the transboundary basin and its linked marine environment under the Bucharest Convention and the Istanbul Convention and has fostered an adaptive management approach.

Land-based sources of pollution can cause significant disruptions to global nutrient cycles. Excess loading of nitrogen and phosphorus pollution from agriculture, human sewage, and industry can lead to large areas of eutrophication which can create dead zones of severely degraded coastal water quality (Diaz and Rosenberg, 2008). The water in these areas becomes unusable, and is a hazard to ecosystems and human health. Communities can lose their sources of income and food from fisheries, and ecosystems can experience a phase change causing loss of services that coastal communities rely on to survive (Hume et al. 2011). These dead zones seem to be expanding and projections of future degradation are alarming. The Danube Delta and the Black Sea have experienced this degradation at an alarming rate and GEF investments aim to reduce agriculture, municipal, and industrial sources of nutrient pollution. Thanks to the early investment from the GEF and the hard work and cooperation of the many public and private organizations and States, the Black Sea is showing remarkable signs of recovery. Measurable improvements have been observed in the Danube and Black Sea ecosystems over the last decade and a half. Nitrogen and phosphorus pollution has been reduced and reversed the documented dead zone of oxygen depletion in the Black Sea’s Northwest shelf. Algal blooms declined throughout the Northwest Shelf during the 1990s, and continuing reductions have been recorded since then. The number of benthic species observed in the early 2000s was nearly two times higher than levels found in the late 1980s. While the series of GEF International Waters projects in the Danube and Black Sea basin since 1991 cannot take overall credit for the reductions in nutrient emissions and measured improvements in ecological health and water quality, all countries and partners acknowledge the catalytic role of these projects in focusing national awareness on the needed technology to reduce nitrogen and phosphorus pollution. Ultimately, the GEF-funded actions in the Danube-Black Sea basin demonstrate how countries can work together to reduce land-based pollution and dead zones. Additional information on this and other examples is presented by the GEF (Duda et al. 2009).

Like other projects targeting land-based pollution, these interventions contribute to the countries’ responsibilities under the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA). Many countries have taken out loans to help reduce sources of pollution to dead zones. Similar requests have been received from East Asian and Mediterranean countries to reduce dead zones. Figure 4 outlines cumulative GEF investments in LMEs and the GPA to benefit LMEs. Note the progressive increase in GEF amount and co-financing over the 20 year period. Countries have asked for assistance in this area and the GEF has responded. Since the adoption of the GPA in 1995, the GEF has invested $US 357 million in GPA projects, with more than $US 4 billion in co-financing.

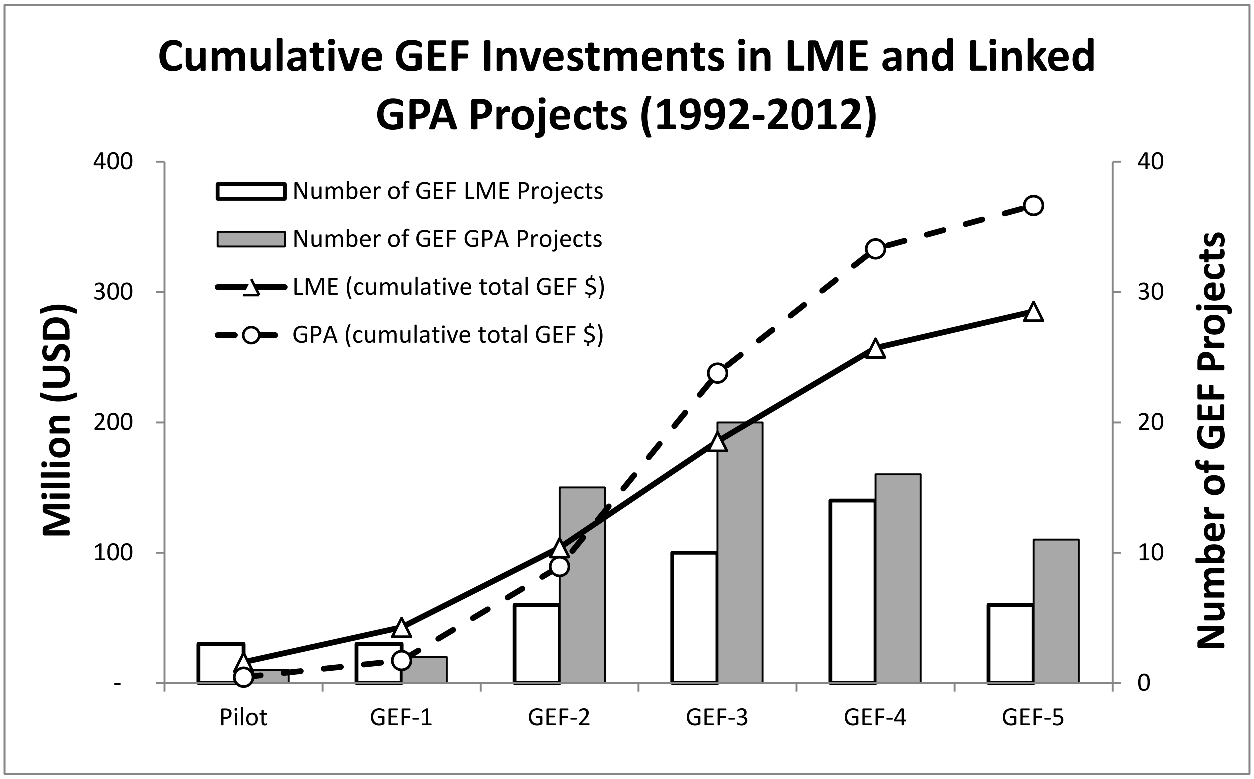


Figure 4. Cumulative GEF Investments in LME and linked GPA Projects (1992-2012).

GLOBAL SCALE GEF PROJECTS AFFECTING LMEs

Global projects can provide international attention and solutions to marine issues that may affect individual LMEs, but which also plague coastal environments around the globe. The GEF has invested over $US 72 million in global marine projects over the last twenty years. One of the many successful global projects is the “Reduction of Environmental Impact from Tropical Shrimp Trawling through the Introduction of By-catch Reduction Technologies and Change of Management” project implemented by FAO and UNEP. Shrimp exploitation by tropical trawl fisheries generates millions of tons of non-shrimp by catch, with some estimates placing the ratio of up to 20 kg by catch for every kg of shrimp caught. Although by catch has become an important source of income and contributes to food supply in some countries, the capture of juveniles of economically valuable and ecologically important fish and other organisms constitutes a threat to the sustainable fisheries and ecosystem health. Extensive removal of non-target fish can also be a threat to the biodiversity. If the introduction of fishing technologies and practices that reduce the capture of juveniles is successful, it can be assumed that such technology and practices can be transferred and adopted by other trawl fishing countries, which are also experiencing problems with by catch. For example, Cameroon recently passed a law which made the use of Turtle Exclusion Devices (TEDs) and By catch Reduction Devices

(BRDs) a stipulation for receiving a commercial fishing license, while six other nations have already made TEDs mandatory for parts of their fisheries. Costa Rica adopted modifications of its fishing gear, while Venezuela introduced a complete trawl ban in March 2009. Further, By-catch Reduction Devices have become mandatory in notable segments of some national fisheries, including those of Cuba, Indonesia, Iran, and Mexico.

Broad based upstream and downstream cooperation with the industry played an important role in the success of this project, and the major achievements of the project were intimately related to the close collaboration between the fishing industry, the research institutes and the governments. The project used practical demonstration workshops and discussion forums for industry representatives which sometimes included more than 250 key persons. These sessions had a considerable impact on the industry engagement and the adaptation of by-catch reduction devices. The cooperation established by the project between the different countries resulted in by-catch reduction technologies previously only available for more developed nations.

GEF 5 STRATEGY INCORPORATES CLIMATIC VARIABILITY AND CHANGE

With the loss of economic, environmental, and community security that accompanies the degradation and depletion of coastal and marine waters, climate variability and change has shown to add unprecedented complexity (Lehodet et al. 1997). Governments still have much work left to undertake to reverse the depletion of ocean fisheries, restore and conserve critical coastal habitat, improve river flows to sustain deltas, and reduce pollution sources that create coastal dead zones. Having an accurate understanding of how climate change will influence these ecosystems and their services is imperative for policy makers. Such accurate information comes from good science and environmental and socio-economic assessments.

Together with NOAA, UNDP, UNEP, UNIDO, FAO, IOC-UNESCO and other partners, GEF has supported an assessment of the changing states of coastal oceans and LMEs due to climate variability and change. This assessment documents an alarming warming of sea-surface temperatures (SSTs) over the last 25 years as recorded from satellites. A recently published report details this ocean warming along with depletion of ocean fisheries and accelerated nutrient pollution resulting in coastal dead zones. One of the key findings of the report is that warming rates are much faster than scientists have suspected (Sherman and Hempel, 2008, Sherman et al. 2009, and Belkin 2009). As Figure 5 shows, the dark red areas are warming on average at the most rapid rate. Such rates of more than one degree Centigrade over 25 years are unprecedented. Together with the lighter red shaded LMEs, more than one-quarter of the planet’s LMEs are warming at an alarming rate.

As previously mentioned, the warming of LMEs is forcing fish stocks to move. Such trends have become a direct threat to food and national security for some coastal communities, and include the loss of investments and jobs related to fish processing. Increased insecurity in coastal areas only fuels tension that exists among neighboring countries over disputed areas of oceans, islands, fish stocks, oil/gas reserves and pollution loading.

The warming of marine waters has serious implications for GEF International Waters support for countries that wish to collaborate in sharing benefits from LMEs on their transition to environmental, economic, and social sustainability. As this paper has shown, many of these countries have made decisions to collectively manage their LMEs with management institutions at different scales from local ICM to LME-wide collective management. These investments in collective management are clearly threatened now by the unprecedented changes in the coastal and marine systems. An increased GEF effort and scaling-up is essential if these nascent LME initiatives are to be transformed into adaptive management institutions capable of incorporating new stresses, including ocean warming, sea-level rise, coastal storm vulnerability and saline water intrusion into coastal drinking water supplies.

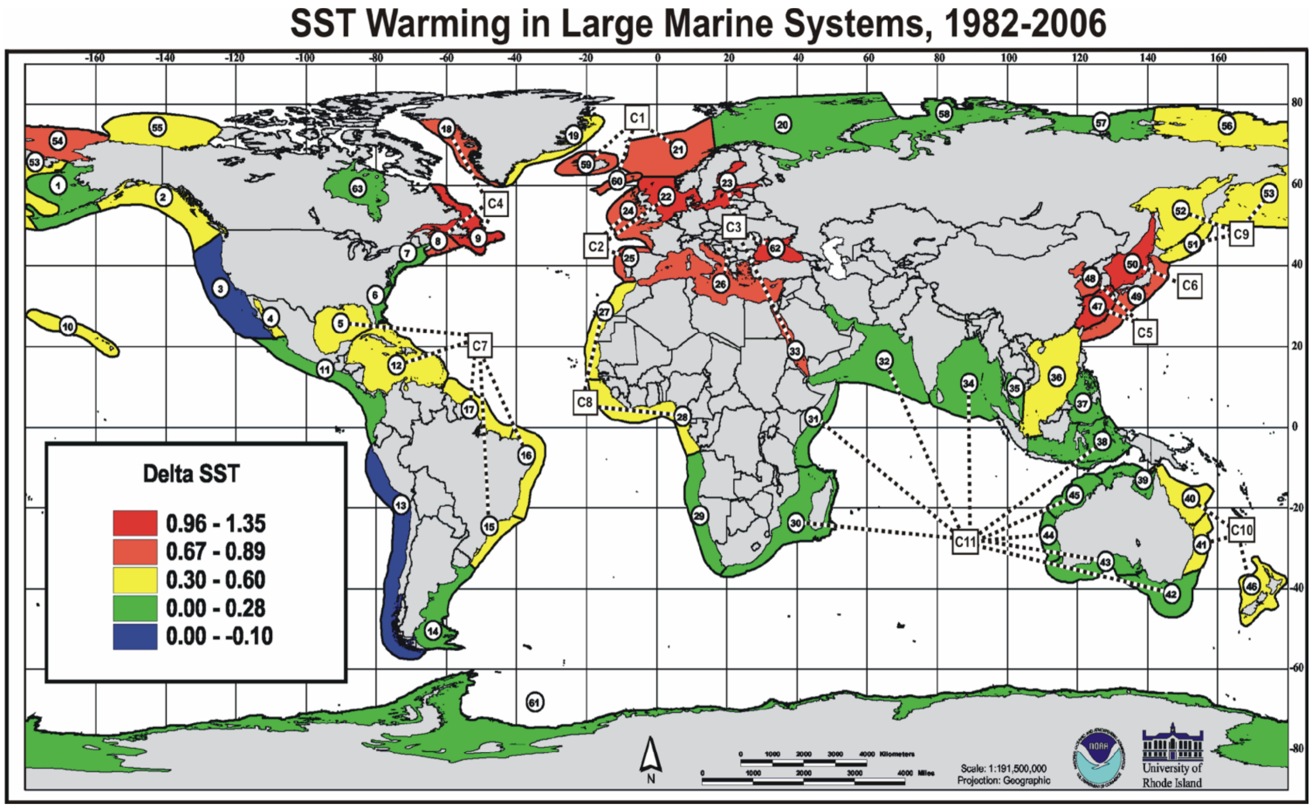


Figure 5. Warming Clusters of LMEs in Relation to SSTs, 1982-2006 (Sherman and Hempel, 2008 and Belkin, 2009).

FAST WARMING:

C1 Northern European Cluster; **C2** Southern European; **C3** Semi-Enclosed European Seas; **C4** of the NW Atlantic; **C5** Fast Warming East Asian LMEs; **C6** Kuroshio Current and Sea of Japan/East Sea LMEs.

MODERATE WARMING:

C7 Western Atlantic LMEs; **C8** Eastern Atlantic LMEs; **C9** NW Pacific; **C10** SW Pacific. Several **Non-Clustered, Moderate Warming LMEs** are moderate warming: NE Australia, Insular Pacific Hawaiian, Gulf of Alaska, Gulf of California; South China Sea, East Greenland Shelf

SLOW WARMING:

C11 Indian Ocean and Adjacent Waters.

Non-clustered, Slow Warming LMEs include the U.S. Northeast Shelf, the U.S. Southeast Shelf, the Barents Sea, East Bering Sea; Patagonian Shelf, Benguela Current and Pacific Central American Coastal LMEs.

Since its inception, the GEF has placed human needs at the center of priorities in transboundary water systems. The GEF approach has provided opportunities for states wishing to address transboundary water-related disputes and resolve national development priorities across transboundary systems in a collective manner. To adapt to the changing priorities of international agreements, every four year period, a specific strategy is developed to identify priorities for future GEF funding.

GEF 5th REPLENISHMENT

Currently, the GEF is in its fifth four-year replenishment (GEF-5) which started in 2010 and will conclude in 2014. The International Waters focal area strategy for GEF-5 relies on multi-state commitments to collectively manage transboundary action. This strategy builds on the work accomplished in GEF-3 and GEF-4 replenishments and proposes to scale-up national and local action given sufficient resources. GEF operations help catalyze implementation of multi-State SAPs with shared visions for specific transboundary surface and groundwater systems or LMEs.

In order to reflect the urgent need for the International Waters focal area to address issues of climate change, the GEF-5 IW strategy incorporates capacity building and knowledge generation to address climatic variability and change into Objective Two. In Objective Two, GEF funds are used to rebuild marine fisheries and reduce pollution by utilizing multi-state cooperation, all while considering climatic variability and change. Achieving cost effectiveness and producing benefits that contribute to Millennium Development Goals and World Summit on Sustainable Development targets dictate that multiple stresses must be addressed and multiple uses must be balanced. This multifaceted approach is applied to GEF projects on LMEs and their coasts. Concerns related to coastal climatic variability, sea-level rise, ocean warming, protection of coastal carbon sinks ("blue forests") and ecosystem resilience are addressed through governance reforms at multiple scales. Past GEF IW capacity building projects show that including climatic variability and change is an essential transboundary concern along with the other drivers that cause depletion and degradation.

Loss of coastal habitat has multiple impacts on marine ecosystems, community livelihoods, food security and reduced capacity to sequester carbon. Recent studies suggest that these marine-related carbon sinks are at least as important as terrestrial forests in the global carbon cycle, but they are reportedly being lost four times more rapidly than rainforests while the majority of funding goes to rainforest protection. When coupled with the expansion of dead zones from increasing nutrient pollution from agriculture and sewage, habitat loss poses a grave threat to living resources that cross borders. And now, new multiple risks related to climatic variability and change are becoming clear such as coastal flooding with sea-level rise, storm vulnerability, warming oceans, ocean acidification, food chain disruption, and salt water intrusion into groundwater supplies. Before our planet's ocean ecosystems lose more of their capacity to provide protein, livelihoods, and services, such as sinks for excessive emissions of carbon, further degradation must be prevented now before irreversible conditions develop.

The GEF's focus on results-based management means that the multiple stresses on coastal and marine systems encompassed by LMEs must be addressed collectively for communities to benefit in terms of livelihoods, access to safe water sources, and improved socio-economic status. Initiatives addressing one issue, such as sustainable fisheries, will fail to produce community results if excessive pollution from agriculture or human sewage results in a dead zone that impairs sustainable fisheries or if the increase in sea surface temperatures causes the fish stocks to move elsewhere.

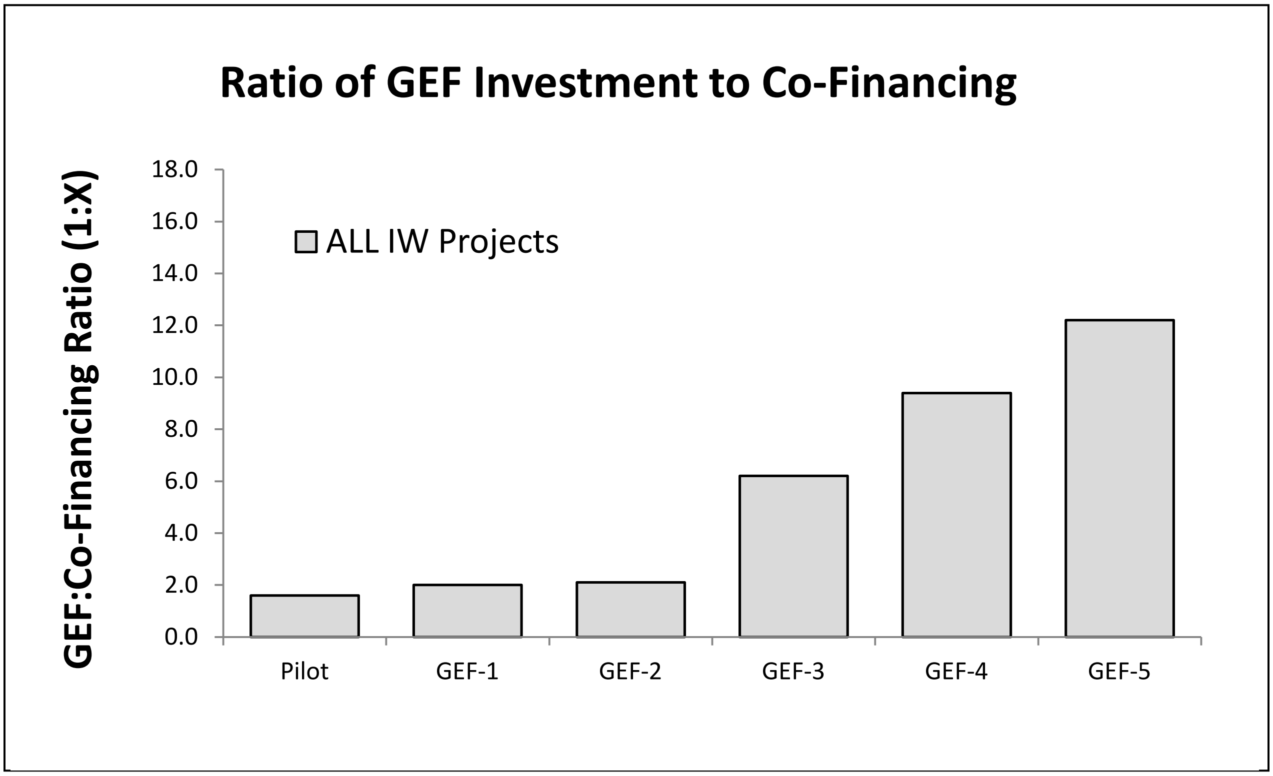


Figure 6. Time trend of the ratio of GEF investments to co-financing in GEF Projects.

In order to minimize the vulnerability from sea-level rise, displaced fisheries, and other concerns from climatic variability and change, GEF support for LMEs and ICM plans and actions within the natural boundaries of LMEs will begin to consider risks related to these issues, as future action programs are implemented and new ones formulated. Up to $US 100 million is programmed in the GEF-5 replenishment to help countries address climatic variability and change along with traditional issues in LMEs. One of the GEF's greatest strengths is its ability to leverage co-financing. Figure 6 depicts the ratio of GEF financing of international waters projects versus co-financing by participating countries, over time. Note that the ratio has increased as time progresses and GEF LME projects move from planning to implementation. This illustrates that the countries can mobilize more resources as they move from planning to implementation and this bodes well for increases in future funding. Very large investments in ICM within the boundaries of LMEs will be necessary for adaptive management measures to address sea-level rise, coastal storms, and coastal flooding. The GEF must ensure that this ratio continues to move upward as countries work harder to incorporate LME and linked ICM governance concerns into their national budget programs.

NEW GEF MULTI-FOCAL PROGRAMS CATALYZE ACTION

Climatic variability and change are modifying the distribution and productivity of marine organisms of all sizes and have already started affecting biological processes and altering food webs. Fishers, fish farmers and coastal inhabitants will bear the full force of these impacts through less stable livelihoods, changes in the availability and quality of fish for food, and rising risks to their health, safety and homes. Many fisheries-dependent communities already live a precarious and vulnerable existence because of poverty, lack of social services and essential infrastructure. The implications of climate variability and changes in food security and livelihoods in small island states and many developing countries are profound.

Fisheries and aquaculture contribute significantly to food security and livelihoods and depend on healthy aquatic ecosystems, but this often goes unrecognized or undervalued at the policy level. A key in being able to incorporate climatic variability and change into GEF projects during GEF-5 will be integration and cooperation across GEF focal areas. Because of the ambitious scope of many of these programmatic approaches, funding is often combined from two or more focal areas. GEF has invested in seven programmatic approaches the last 10 years to have a larger, more integrated impact on outcomes for sustaining LMEs and their coasts. They range from the original Danube/Black Sea LME Basin to the Mediterranean Sea LME, to LMEs of East Asia, the LMEs constituting the Asia Coral Triangle, and even LMEs in the Arctic.

Coral Triangle Initiative

A good example of a cross focal area project is The Coral Triangle Initiative on Coral Reefs, Fisheries and Food Security (CTI). At the confluence of the Indian and Pacific Oceans, spanning Indonesia, Malaysia, Papua New Guinea, Philippines, Solomon Islands and Timor-Leste, the 1.6 billion acre Coral Triangle supports: (a) five commercial tuna species which spawn there and migrate to the Indian and Pacific Oceans - where 90% of the world’s catch occurs, (b) the highest numbers of coral, crustacean, mollusk, and marine plant species and 3,000 species of fish – twice that of any other region, (c)51 of the world's 70 mangrove species and 23 of the 50 sea grass species, and (d) 120 million people. The Coral Triangle is not only a source of food but also a way of life fostered across generations by a close dependence on the marine environment. The Triangle supports the largest tuna fishing industry in the world, which generates billions of dollar in global income each year and its reefs also buffer coastal communities from cyclones and tsunamis.

GEF funding from the International Waters, Biodiversity and Climate Change adaptation focal areas were pooled together in order to achieve integrated actions. The CTI, spearheaded by the six heads of States/Governments of Indonesia, Malaysia, Papua New Guinea, Philippines, Solomon Islands and Timor-Leste, was an unprecedented regional GEF program that focused on the conservation of essential natural resources to ensure food security for coastal populations. This Initiative, led by the ADB, focused on the management, conservation and adaptation to climate change of the tuna fisheries and coral ecosystems in the western Pacific region. It hinged on high-level political commitments and proactive implementation by governments, and was supported by multilateral and bi-lateral agencies, non-governmental organizations, and private sector partners. The CTI was approved with $US 62 million in GEF grants accompanied by $US 220 million in co-financing. The assessment and management activities of the CTI countries will support LME projects in the region presently in planning and implementation phases, including the Indonesian Sea LME and the Sulu-Celebes LME.

Sustainable Fisheries for the LMEs of Sub-Saharan Africa

The GEF and the World Bank are assisting countries sharing the LMEs of Sub-Saharan Africa to secure community livelihoods, food security and foreign exchange proceeds from selling of licenses to distant fishing fleets. Nowhere is the crisis in global fisheries more evident, and the need to implement both the fisheries and poverty reduction targets set by the World Summit on Sustainable Development greater, than in the five LMEs that cover the coastal waters of Sub-Saharan Africa (SSA). These LMEs possess a wealth of globally significant marine biodiversity and habitats that provide the coastal countries of SSA with some of the world's most productive fishing grounds, many of which are transboundary in nature. In most coastal countries in SSA, the fishing sector is a major contributor to rural income and employment, attracts considerable local and foreign investment, contributes significantly to food security, and in many countries is a substantial source of foreign exchange and funding for public budgets. The FAO has estimated that nearly 2.7 million people in the region are engaged in coastal and inland fishing activities on a full or part-time basis and fishing provides up to 70 percent of the daily animal protein intake in some coastal countries in the region. In terms of foreign exchange earnings, the value of net exports of fish products for the continent as a whole reached the equivalent of roughly $US 1.7 billion in 2001, exceeding the net foreign exchange income reported for any other agricultural commodity.

However, as significant as fishing is for the livelihoods and economies in many countries in the region, and for continued poverty reduction efforts, the LMEs of SSA are beginning to feel the cumulative effects of growing populations and over-fishing. The total marine production from these LMEs has leveled off since the early 1990s, and the number of overexploited and depleted stocks is rising throughout the region. Regional fisheries management organizations lack adequate funds to assist individual coastal countries to implement the needed governance reforms in fisheries. Thus, in many coastal countries of SSA, governments still do not have the capacity to take control of their own resources and prevent overexploitation, and specifically to regulate access to these resources and protect the critical habitats that support them. Further, because many of the SSA countries lack the capacity for effective fisheries management based on an ecosystem approach, both local and foreign fleets operate in *de facto* open access conditions along most of the continent.

GEF and the World Bank have committed to reducing poverty, increasing food security, conserving habitat and reforming fisheries with assistance from FAO and WWF. These mostly single country projects complement the five regional LME projects and empower the African Union through a GEF project linking the regional and national operations. The first programmatic approach was approved by the GEF Council in fall 2005 for $US 11 million and over $US 124 million in co-financing. Now that the first pilots are completed, GEF approved $US 25 million more in grants in fall 2011 to accompany an additional $US 138 million in co-financing for five operations to scale up initiatives and expand these to cooperating countries.

TURNING THE TIDE TOWARD ADAPTIVE MANAGEMENT OF LMEs FOR THE FUTURE

Future GEF investments in transboundary issues of international waters must address many of the most pressing issues facing the planet. This is especially true in the coastal and marine environment of LMEs, where issues such as diminishing fish stocks, increased population pressure, coastal development, and subsequent pollution, and of course, climate change, are threatening food and national security of both developing and developed countries alike. The future of GEF investments will not address these issues piecemeal. Rather, just as the LMEs and species targeted for conservation are interconnected, so too are many of the issues that threaten them. Any mechanisms that aim to manage these interconnected and complex issues will need to be dynamic, adapting to changes brought on by multiple threats.

In fact, many of these threats are not future problems, but serious issues that threaten livelihoods today. These include changes in coastal water dynamics like the Benguela Current LME. Here, economically important fish species are migrating from the territorial seas of one country to neighboring ones (as described by Hampton and Willemse in Chapter 2). Fortunately, the Benguela Current Commission was formed in 2007 to address transboundary problems of their shared LME. This joint Commission is managed by government ministers of Angola, Namibia and South Africa and their foresight has led to unprecedented cooperation among the countries as they jointly and adaptively manage fish stocks. The Commission enables the three countries to follow an EBM approach to address issues such as environmental variability, pollution, impacts, health and sustainability. Like much of the African continent, the Benguela Current LME has been impacted by the effects of climate change, including warming of surface waters and changes in the abundance and distribution of the major fisheries such as sardines, anchovies, and hake.

The Benguela Current Commission grew out of the resounding success of the GEF funded Benguela Current Large Marine Ecosystem (BCLME) Program. In this project, UNDP and other partners helped the three countries manage the shared living resources of the highly productive Benguela Current LME, where mixing of warm and cold currents generate an abundance of fish, seabirds and marine mammals. This nutrient-rich LME is subject to a range of public and private interests, including fisheries, seabed mining, oil and gas exploration and production, and tourism and coastal development. The resources found within the waters of the Benguela Current are vital for the food security of over 22 million coastal residents. Since the program's inception in 2002, the BCLME program has initiated over 75 projects addressing one or more of three broad goals: 1) the sustainable management and utilization of living resources; 2) the assessment of environmental variability, ecosystem impacts and improvement of predictability; and 3) maintenance of ecosystem health and management of pollution. The BCLME program has been a model of success for other transboundary marine resources, demonstrating the need for support all the way from the community to the cabinet levels of government. The Benguela Current Treaty has been negotiated and heads of states of the three countries are set to sign and their parliaments plan to ratify shortly.

As the BCLME project and Commission demonstrate, adaptive management is essential to addressing the mounting challenges that face the coastal and marine environments. But adaptive management would not be possible without the spirit of cooperation among neighboring countries to solve complex international waters problems. Management will not be effective unless commitments are authorized by legal frameworks. GEF is committed to assist countries who wish to work together on their shared LMEs and coasts not only on traditional concerns of pollution or overfishing, but also on climatic variability and change. While the challenge is large, inaction is not an option if communities and their economies are to survive in times of global change.

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2

POTENTIAL EFFECTS OF CLIMATE CHANGE AND ENVIRONMENTAL VARIABILITY ON THE RESOURCES OF THE BENGUELA CURRENT LARGE MARINE ECOSYSTEM

Ian Hampton and Nico E. Willemse

ABSTRACT

This chapter considers the possible effects of environmental change on the physical, chemical and biological elements of the Benguela Current Large Marine Ecosystem (BCLME), with emphasis on the system's commercially important living marine resources. The main features and functioning of the ecosystem are briefly reviewed, followed by an examination of the variability and decadal–scale changes in the biophysical environment over the past 50 years. The most salient points are that a) the extreme natural variability of the system makes it difficult to distinguish long-term trends brought about by climate change, b) that there has been a major regime shift in the northern BCLME brought about primarily by the virtual removal from fishing of the sardine and anchovy populations in the 1970s and 1980s and c) that over the past few decades there has been a widespread warming of surface water at both the northern and southern boundaries of the system and in the northern Benguela, but a general cooling inshore along the west and south coasts of South Africa. There is evidence of a general increase in upwelling-favorable winds in summer throughout the system, but little to suggest that this has resulted in large-scale changes in primary production. There is some evidence of an increase in the frequency of anomalous intrusions of warm, nutrient and oxygen-poor water from southern Angola, which can severely affect marine life in the northern Benguela, but it is not clear whether this trend is continuing. The abundance of copepods has increased by at least an order of magnitude in both the northern and southern Benguela over the past 40 years, accompanied by a change in their size structure, possibly due to a change in predation pressure rather than in primary production.

Figure 1. Location of the Benguela Current LME.

In the southern Benguela, a pronounced eastward shift in the distribution of both sardine and anchovy in the early 2000s (thought at the time to herald a regime shift) now appears to be reversing. We note that few of the postulated links between the environment and resource

dynamics have been established well enough for use in resource management, emphasizing the need for greater research effort into the effects of incipient climate change, however caused, on the region's major marine resources. A particularly important question appears to be the effect of the leakage of Agulhas current water into the Southeast Atlantic. Recent evidence suggests the leakage is increasing due to anthropogenically-induced global warming, with potentially profound effects on the BCLME's upwelling regime. We conclude that the recently-established Benguela Current Commission is the most appropriate body to co-ordinate and facilitate this work, preferably through a focused regional program on the effects of climate change on the ecosystem and on ways of adapting to it.

BACKGROUND

The BCLME (Figure 1) is one of the world's four eastern boundary upwelling systems and is defined as the part of the Southeast Atlantic between about 14° S and 37° S, east of the 0° meridian, encompassing the coastal upwelling regime, frontal jets and the eastern part of the South Atlantic gyre. The wind-driven coastal upwelling system, which is the most powerful in the world, is characterized by strong annual upwelling along the coast of southern Namibia and seasonal upwelling to the north and south. The northern boundary of the upwelling region coincides with the Angola Benguela Frontal Zone (ABFZ) where the warm Angola Current meets the cool Benguela upwelling regime. The southern boundary is considered to be the Agulhas current retroflection area, which typically lies between 36 and 37°S. The upwelling system is thus bounded at both extremities by warm water regimes, making it unique in that respect. The Benguela current itself flows northwards along the coasts of the three nations bordering the BCLME: Angola, Namibia and South Africa (Figure 2).

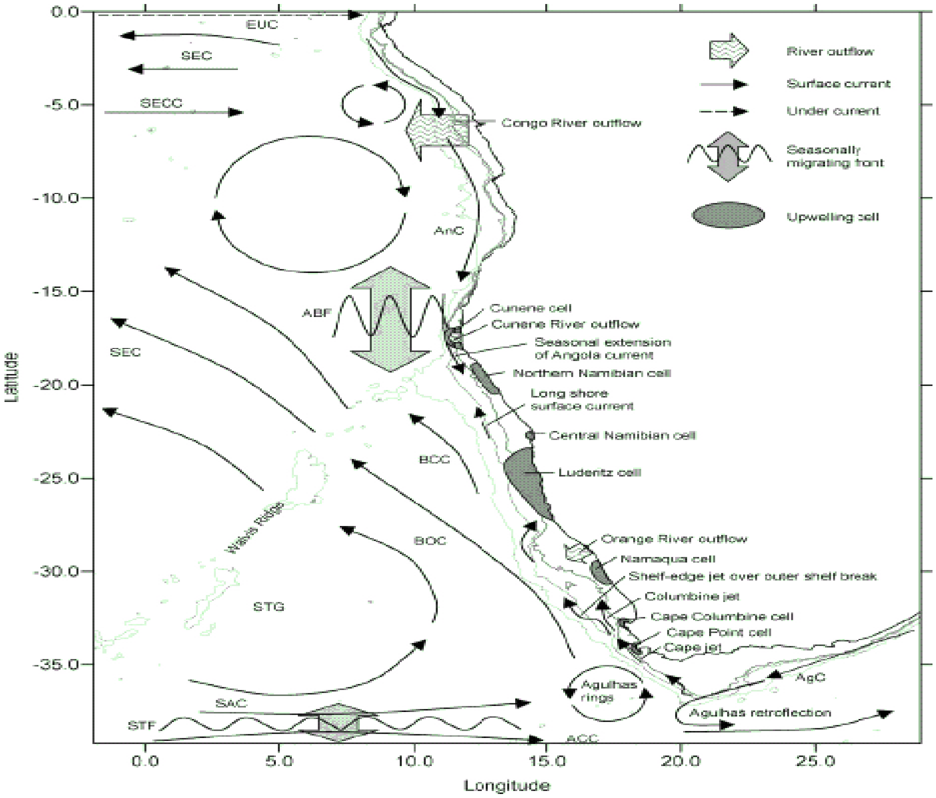

Figure 2. The Benguela Current Large Marine Ecosystem and salient physical features of Southeast Atlantic (adapted from Hardman-Mountford et al. 2003).

Primary production estimates from satellite imagery rate the BCLME as a Class I (high biological productivity) ecosystem (>300 gC $m^{-2}yr^{-1}$). For many decades, the system has supported valuable commercial fisheries for small pelagic species, demersal fish (mainly hakes), horse mackerels, rock lobster and a variety of other species. In Namibian waters, over-fishing by local and distant-water fleets prior to Independence in 1990 (Nichols, 2004) severely reduced the stocks of most of these species, from which the system has not recovered, possibly indicating a major regime shift there.

Pollution is mainly localized in small harbor environments, but all major forms of pollution and ecosystem degradation do exist, including excessive nutrient inputs into coastal waters, hazardous wastes from mine tailings, dredge spoils, deforestation of coastal mangroves, soil erosion, oil spills, marine debris and invasive species (UNEP 2006).

The BCLME is primarily driven by climate, making the system susceptible to change and increased variability as a consequence of change and greater variability in global climate (UNEP 2006). Of particular concern are possible teleconnections between the Benguela Current and large scale ocean-climate processes in the North Atlantic and the Pacific (including *El Niño* events), which mounting evidence suggests are altering and becoming more variable due to global climate change.

THE BCLME AND CLIMATE CHANGE

The BCLME is dominated by a highly productive coastal upwelling system. The system is complex, and displays substantial variability which impacts on its living resources over a wide range of temporal and spatial scales. The effects of the ecosystem's natural variability have been, and continue to be, compounded by heavy exploitation of some of the region's major fish stocks.

The living resources of the BCLME and adjacent areas may be particularly sensitive to long-term climate change as the region is situated at the choke point in the global ocean climate "conveyor belt", where warm surface waters from the Indo-Pacific pass around Africa into the Atlantic. Consequently, it may well be a site for the early manifestation and detection of global climate change.

Concerns about the effects of climate change on the BCLME, and consequently on its living marine resources, were first articulated through a number of papers at the Conference on Geosphere-Biosphere Change in Southern Africa in 1989 (Crawford *et al.*, 1990, Shannon *et al.*, 1990 Siegfried *et al.*, 1990). Siegfried *et al.*, (1990) speculated on the consequences for selected fisheries of the region of four possible scenarios of global warming- induced climate change, namely increased intrusion of warm water from the Angolan region in the north and the Agulhas Current in the south, altered wind stress, and general warming of surface waters throughout the system. They argued that all four could potentially have dramatic, although largely unpredictable, effects on the fisheries considered, while stressing that all the scenarios were purely speculative due to great uncertainty about the nature, extent and likelihood of the postulated environmental changes (Shannon *et al.*, 1990), and the nature, and even the sense, of biological responses to such changes (Crawford *et al.*, 1990).

Shannon et al. (1990) noted the naturally high variability on intra- and inter-annual scales in the Benguela and Agulhas Current systems and the Subtropical Convergence area, and concluded that all these areas appear to be sensitive to the changes in wind fields. Among the large-scale changes which they hypothesized could be caused by a poleward shift in the hemispherical wind belts induced by global warming was a southward shift in both the northern and the southern boundary of the Benguela, the displacement of the upwelling centers, and an increase in the exchange of Atlantic and Indian Ocean water to the south of the continent, all of which would almost certainly have major effects on the marine environment. They noted however that these scenarios were highly speculative, and should not be treated as predictions because of inadequacies in the general circulation models (GCMs) in use at the time.

More recently, Clark (2006) explored the implications of global climate change for fish stocks and their management off southern Africa, specifically with regard to projected changes in ocean temperature, pressure/wind fields, CO_2 levels, rainfall, mean sea level and UV radiation. He noted the common view that changes in pressure fields and hence wind stress over southern Africa are likely to have a greater effect on marine biota (and thereby fisheries) than the other effects, and paid particular attention to Bakun's (1990) global prediction that an increase in greenhouse gases in the lower atmosphere is likely to lead to intensification of onshore-offshore pressure gradients, and hence to stronger alongshore winds and increased upwelling. However, he noted that the link between increased upwelling and changes in fish production in the BCLME (whether positive or negative) is extremely tenuous, citing contradictory evidence from the region on the response of the ecosystem to apparent changes in upwelling intensity. Some other factors which he considered were the effect of changing wind fields on turbulence, hypoxia and harmful algal blooms, shifts in fish distribution due to changes in temperature, the detrimental effects of acidification on plankton with calcium carbonate skeletons, increased UV-B radiation on primary production, and the effects of sea level rise and reduced fresh water discharge on coastal areas. He pointed out that these effects complicate an already unclear picture, making it very difficult to predict outcomes, but concluded nonetheless that there is no room for complacency regarding the possible effects of climate change on the region's fisheries, and outlined a number of steps for dealing with the effects if and when they become manifest.

Roux (2003), in speculating on the possible effects of global warming on Namibia's marine environment, singled out changes in the frequency and amplitude of tropical intrusions and modifications in upwelling resulting from changes in the wind field as the most important potential effects. He speculated on the effects on the ecosystem and the fisheries of four possible scenarios (namely reduction in coastal upwelling intensity, an increase in average summer wind stress, an increase in the frequency and severity of warm-water intrusions from the north, and gradual responses to climatic changes of low amplitude) and suggested possible adaptive action in each case. He too emphasized the uncertainties in the processes and magnitude of the physical and biological effects considered, and pointed out that because of these uncertainties timely management action to reduce the effects of adverse environmental conditions had up to that time not been possible.

In this article earlier reviews of the BCLME and its functioning are re-visited and updated, drawing on articles in the scientific literature and particularly the report on the expert workshop on the Changing State of the BCLME, held in Cape Town in May 2007 under the aegis of the Benguela Current Large Marine Ecosystem (BCLME) Programme (Veitch, 2007).

BIOPHYSICAL FEATURES OF THE BCLME

Physical environment

Lying to the north of the BCLME is the Angolan subtropical zone, which is essentially a transition zone between the wind-driven upwelling system to the south and the Equatorial

Atlantic, from where the seasonal cycle is remotely driven (e.g. Hutchings *et al.*, 2009). The northern boundary of the upwelling region coincides with the Angola Benguela Frontal Zone (ABFZ) where the warm Angola Current meets the cool Benguela upwelling regime. The front is a permanent feature at the surface, moving seasonally over a narrow band of latitudes, characteristically between 14^{o}S and 17^{o}S. The southward movement of the front is most pronounced during summer, when long shore wind stress and upwelling in the northern Benguela is reduced.

The major wind-driven upwelling zone is situated between Cape Frio in the north and Cape Agulhas in the extreme south. Powerful perennial upwelling centered on Lüderitz in southern Namibia, which causes high offshore advection and strong turbulent mixing, partially separates the zone into northern and southern regions, hereafter referred to as the northern and southern BCLME. The South Atlantic high pressure system and its seasonal shift facilitate the upwelling-favorable wind regime, which is dominant during the summer in the southern BCLME and throughout the year in the northern BCLME. The periods of maximum upwelling intensity in the northern and southern BCLME are out of phase, with the northern peaking in late winter/early spring and the southern in summer. This is due to the seasonal shift in the pressure system, which results in a higher frequency of westerly (i.e. non-upwelling) winds in the south, particularly in winter.

The southern boundary is considered to be the Agulhas retroflection area. This warm southern boundary moves during the year as tropical Agulhas Current water leaks into the South Atlantic, mostly in the form of rings which are shed from the Agulhas current as it retroflects to the east. The Agulhas Bank itself displays the characteristics of both an upwelling and a temperate shallow shelf system, with seasonal stratification and mixing, shelf-edge and dynamic upwelling, moderate productivity and a well-oxygenated shelf (Hutchings et al. 2009).

The area experiences episodic warming events, known locally as *Benguela Niño*s (Shannon et al. 1986) similar to the seasonal *El Niño* Southern Oscillation (ENSO) in the eastern Pacific. These events, which are probably linked to, but are not necessarily in phase with, the ENSO, occur when extreme warming takes place in the tropical eastern Atlantic and warm water is advected southwards and east along the Namibian coast. Florenchie et al. (2003) concur with earlier suggestions by Horel (1986) that *Benguela Niño*s are generated by a sudden change in the zonal wind stress in the western tropical Atlantic and propose that this excites an eastward propagating Kelvin wave-like disturbance that continues southward and northward as a coastally trapped wave upon reaching the coast. They provide evidence that the warm anomaly is a subsurface feature as it travels southwards along the African coast, outcropping at the surface off Angola when it reaches the BCLME upwelling regime. They note that the timing of warm anomalies appears to be a crucial factor in the development of *Benguela Niño* events, which tend to occur in February/March.

The extent and intensity of coastal upwelling throughout the BCLME is primarily determined by the wind/pressure field. Atmospheric pressure over the continent changes markedly from a well-developed low in summer to a weak high in winter, with resultant seasonality in the long shore pressure gradient and hence upwelling intensity. In the southern BCLME, cyclones approaching from the west give rise to coastal lows which migrate in a clockwise direction around the subcontinent. Wind relaxation or reversals associated with the passage of these cyclones modulate the upwelling in the south over periods of three to ten days during the upwelling season.

The South Atlantic high pressure system and its seasonal shift facilitate the upwelling-favorable wind regime, which is dominant during the summer in the southern Benguela and throughout the year in the northern Benguela. The primary perennial centre of upwelling-favorable winds lies near Lüderitz (26^o 30'S), with a secondary centre near Cape Frio (18^o 30'S). The periods of maximum upwelling intensity in the northern and southern Benguela are out of phase, with the former peaking in late winter/early spring and the latter in summer. This is due to the seasonal shift in the pressure system, which results in a higher frequency of westerly (i.e. non-upwelling) winds in the south, particularly in winter.

The Lüderitz upwelling cell, which is characterized by weak stratification and high turbulence, is the most concentrated and intense found in any upwelling system on earth. This cell, and its interaction with the local topography, effectively divides the BCLME into two semi-independent parts, and is believed to act as an environmental barrier separating a number of commercially-important species. The upwelling cells in the extreme south tend to be more ephemeral and seasonal, and tend to have less effect on the distribution of plankton and nekton in this region.

Between Cape Frio and Cape Point there is a well-developed long shore thermal front, or series of fronts, which in summer extend eastwards around Cape Point. The front, which is meandering in nature, coincides approximately with the seaward boundary of the general upwelling area. South of Lüderitz it is single and usually well defined, but further north its surface manifestation is more diffuse, and multiple fronts are sometimes evident. Associated with the front in the south are upwelling filaments which have a lifespan of days to several weeks. These are generally oriented perpendicular to the coast, causing the front to become highly convoluted in places.

Important circulation features affecting the life cycles of commercially-important marine species within the upwelling region include offshore Ekman-transport at the surface driven by winds travelling towards the equator, a poleward undercurrent over the shelf and in deeper water adjacent to the shelf throughout the region, and the growth and decay of frontal jets into meanders, eddies and filaments. Of particular importance to the transport of pelagic fish eggs and larvae from spawning to nursery grounds is the strong northwards flowing shelf-edge jet that connects the Cape Peninsula to Cape Columbine (e.g. Shelton and Hutchings, 1982, Fowler and Boyd, 1998).

Oxygen

Central water in the Southeast Atlantic commonly contains between 4.8 and 5.2 ml l^{-1} of dissolved oxygen, and is about 80-85 percent saturated. In contrast, the shelf waters of the BCLME frequently contain lower levels of oxygen, and at times are anoxic, with considerable impact on the living resources of the southern African west coast.

The formation of low oxygen water (LOW) depends on physical as well as biogeographical processes. A primary source of LOW in the northern and central BCLME is the Angola Gyre area of the Southeast Atlantic, where the primary production, stratification and retention processes facilitate the maintenance of LOW in the area. The Angola Gyre feeds the Angola Current which deepens as it moves southward to form the Benguela Poleward Undercurrent, which extends to about 27^{o}S, where it forms the boundary of advected LOW for the northern and central parts of the BCLME.

While southward advection of oxygen-deficient (< 2 ml l^{-1}) and oxygen-depleted (< 5 ml l^{-1}) water from the north via the poleward undercurrent is important in controlling the spatial and temporal distribution of the water on and adjacent to the shelf, local processes over the Namibian shelf are probably more important determinants of oxygen dynamics in the BCLME as a whole. In the southern BCLME, the formation of LOW is largely driven by a combination of local physical (stratification, recirculation and advection) and biochemical (upwelling-driven new production) factors. Hypoxic water occurs sporadically in a narrow inshore strip, but seldom reaches the extreme levels of depletion experienced in the northern BCLME.

Monteiro and van der Plas (2006) have identified three different regimes of LOW in the BCLME system:

1. the northern BCLME, in which the LOW is controlled entirely by the advection of LOW from the Angola Gyre, and is strongly linked to the upwelling which peaks between June and August,

2. the central BCLME (off Namibia) in which fluctuations in LOW are controlled by complex interactions between remotely forced shelf processes, seasonal thermocline variability and biogeochemical carbon fluxes, and

3. the southern BCLME (off South Africa), where the generation of LOW is primarily driven by local seasonal winds, with little remote influence.

In a more detailed investigation into the sources and variability of hypoxia in the central BCLME, Monteiro et al. (2008) concluded that while seasonal variations in the hypoxia in this region can be explained by the interaction of seasonally- varying advective and biogeochemical processes, the latter do not seem to influence the variability on inter-annual/decade scales. From a study of temperature, salinity and oxygen data between 1981 and 1999 they proposed that long term variations in hypoxia on the Namibian shelf are driven by a combination of advection in the first half of the year of hypoxic equatorial water from the north, and ventilation in the second half of the year by the upwelling of aerated South Atlantic Central Water from the Lüderitz upwelling center. They postulated that the degree and extent of the hypoxia depends on whether these forcing factors tend to reinforce or counteract each other, and on differences in amplitude and phase between the upwelling at Lüderitz and Cape Frio.

Off Namibia, the break-down of organic matter under anoxic conditions by sulphate-reducing bacteria often leads to eruptions of hydrogen sulphide which can extend over large areas, not only the coastal zone, as once thought (Weeks et al. 2002, 2004). The full extent and toll on marine life of this phenomenon, which is unique to Namibia, has yet to be established (e.g. Brüchert et al*.* 2009).

Phytoplankton and primary production

Brown et al. (1991) have estimated that the total primary production in the northern BCLME (15^o – 28^oS), southern BCLME (28^o – 34^oS) and the Cape South Coast (34^o 30'S – 27^oE) is about 80 tons C yr^{-1}. This is similar to that in the Peruvian system, but substantially greater than off California.

The BCLME is generally regarded as a diatom dominated system, although small flagellates are also important, particularly in warmer, lower density water further offshore (e.g. Barlow et al. 2005, 2006). Phytoplankton assemblages are similar in the northern and southern BCLME, with *Chaetoceros, Nitzchia, Thalassiosirs* and *Rhizoselenia* being common throughout the region. There are however essential differences between the north and the south, some of which are due to differences in the atmosphere and ocean dynamics (e.g. nutrient supply, turbulence and stratification) in the two regions. The abundant diatom *Delphineis karstenii* is restricted to the north, while *Skeletonima costatum* is particularly abundant in the south. Large-cell *Coscinodiscus spp*. are common in areas of high turbulence. Over the Agulhas Bank the species assemblages are more cosmopolitan than on the West Coast. Algal blooms occur throughout the region, especially during quiescent periods following upwelling as the water ages and stratification increases. These so-called red-tides can be harmful to marine life through depletion of oxygen as the organisms decay, and some are toxic to humans, fatalities having occurred.

Despite the obvious connection between primary production and the upwelling of nutrient-rich water over short time scales, de Villiers (1998) concluded from a study of ocean color imagery from the South African West Coast and the Agulhas Bank between 1979 and 1986 that inter annual variability in phytoplankton biomass (at least in the southern BCLME) is more likely associated with large-scale oceanic circulation features and forcing mechanisms, than with localized upwelling events. She suggested that the most probable driver in the southern BCLME is the anomalous advection of warm surface water from the Agulhas retroflection in the south.

Zooplankton

Estimates of zooplankton standing stock in the upwelling area off the Cape Peninsula reveal a distinct seasonality, associated with the upwelling cycle, with values ranging from a winter minimum of about 1.5 g dry mass m^{-2} to a summer maximum of roughly twice this figure. Superimposed on the seasonal cycle is substantial short-term variability driven by pulses of upwelling, the dynamics of phytoplankton blooms and the life histories of the various zooplankton groups affected.

Less is known about patterns of zooplankton abundance and zooplankton dynamics in the northern BCLME. Peaks in abundance appear to coincide with periods of maximum phytoplankton abundance – i.e. from November to December and between March and May. The former occurs in the main upwelling season and the latter during periods of moderate upwelling when summer stratification weakens. In both cases the zooplankton tends to be more abundant offshore of the phytoplankton, which occurs in a band closer inshore following the coastline.

Living marine resources

As in the Californian, Humboldt and Canary Current systems, the high primary productivity of the BCLME supports large commercial fisheries for a variety of epipelagic, demersal and midwater species. There are three major resource groups: 1) pelagic fish such as sardine *Sardinops sagax*, anchovy *Engraulis encrasicolus,* round herring *Etrumeus whiteheadi* and (in Angola) the sardinellas *Sardinella aurita* and *S. madarensis* 2) the hakes *Merluccius capensis* and *M. paradoxus* caught by trawl and long line in Namibia and South Africa, and 3) the Cape and Cunene horse mackerels, *Trachurus trachurus capensis* and *T. trecae,* caught by purse seine when juvenile and by midwater trawl and (less frequently) bottom trawl as adults. These groups are similar to those found `in the other eastern boundary upwelling systems. Since 1960 they have together contributed close to 90% of the total catch of finfish and shellfish from the region as a whole. Other important commercial fisheries in the region are those for West Coast rock lobster *Jasus lalandii* in Namibia and South Africa, and hook and line fisheries for species such as snoek *Thyrsites atun* and tuna, particularly albacore *Thunnus alalunga*, yellow fin tuna *T. albacores* and skipjack tuna *Katsuwonus pelamis*. There are also important recreational fisheries for a variety of species, whose value in terms of the tourist revenue which they generate greatly exceeds that of the catch itself. In Angola there is an extremely important artisanal fishery which exploits a wide variety of species, ranging from small shoaling pelagic fish to demersal fish, sharks, invertebrates and large pelagic predators. This fishery provides valuable food and employment for a large number of people along the entire Angolan coastline. The artisanal fishery is less important in South Africa and even less so in Namibia because of the low population density along the coast.

The pelagic resources in Namibia and South Africa support large populations of apex predators such as the Cape fur seal *Arctocephalus pusillus pusillus* (which is commercially exploited in Namibia) and various seabirds such as the Cape gannet *Morus capensis*, Cape cormorant *Phalacrocorax capensis* and the African penguin *Spheniscus demersus.*

The food web and carbon budget

Probyn (1992) has estimated from stable isotope analysis that in the southern BCLME, new production (which determines the productivity of high trophic levels) is relatively low, being only one half to one third of that in the Californian and Peruvian upwelling systems. This, plus the removal of an unusually large proportion of the production of small phytoplankton by microheterotrophs (estimated at 38% by Moloney, 1992) helps to explain why the BCLME as a whole yields considerably less fish annually than would be expected from a simple short food-chain system.

It is clear from mass-balance and other models of the ecosystem (e.g. Heymens et al. 2004, Watermeyer et al. 2008a) that the northern BCLME ecosystem and its trophic functioning are now very different in character from that in the 1970s when sardines (the most important wasp-waist[1] species in the ecosystem) were abundant. Pelagic fish are scarce, horse mackerel (a mid-water species) are abundant, and recent acoustic surveys, using techniques developed by Brierley et al. (2005) suggest that the biomass of the jellyfish *Chrysoara hysoscella* and *Aequorea forskalea (aequorea)* is now of the order of 10 million tons (Gibbons et al. in Hampton et al. 2009), far exceeding that of pelagic finfish in the region. It also appears that the biomass of pelagic goby *Sufflogobius bibabartus* has increased since the collapse of the sardine, and that it is now a uniquely important keystone species in the ecosystem (Utne-Palm et al. 2010). It is believed that a greater part of the production is now being used by benthic organisms, entering the bacterial loop as detritus. Some species might have benefited from these changes (e.g. goby and jellyfish), but they are not fulfilling the role of wasp-waist species, are of low energetic value to the rest of the food web and are of no economic value. Dependent species (e.g. penguins and gannets) are declining and are facing local extinction. Other predators (hakes, seals, snoek, etc.) have also been negatively affected by the change in ecosytem functioning.

VARIABILITY in the BCLME

Like other upwelling systems, the BCLME exhibits a large degree of natural, environmentally-driven variability over spatial and temporal scales ranging from the decadal (driven by long term changes in global/regional weather patterns) to daily or even hourly variability resulting due to small scale upwelling. Within the major upwelling region, event-scale variability is often dominant, particularly in the upwelling centers. There is further variability on larger spatial and temporal scales from seasonal modulation of upwelling winds in the northern and southern

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[1] Wasp-waist species are those which play a critical role in the ecosystem both as predators (in this case on plankton) and as prey.

boundaries of the system, which are characterized by intense mixing and high variability (Hutchings et al. 2006).

Due to the variability in their environment, fish populations which inhabit the Benguela ecosystem are subject to a high degree of variability in enrichment, retention and concentration processes, which are believed to be dominating factors in determining recruitment, particularly during the early life-history stages (Bakun, 1996), thus exercising a “bottom-up” control over recruitment and ultimately distribution and abundance. These effects have been exacerbated by depletion of some of the system’s major resources through commercial fishing, directly affecting their abundance and distribution (a form of “top- down” control), and more indirectly, the ecosystems of which they are an integral part, through changes in the structure and functioning of the food web.

In the following the most evident variability which has been recorded over past decades is examined, working from the environment, through the major commercial resources to the ecosystem as a whole.

Winds

From an analysis of wind data from the Southeast Atlantic between 1948 and 1989, Shannon et al. (1992) concluded that during the 1950s, 1960s and 1970s there was a trend towards increased equatorward wind stress in both the southern and northern BCLME, and also further offshore, with a markedly strong increase in both regions from 1975. There was also an increase in easterly winds over the study period, consistent with an extended decadal scale southward shift in the mean position of the South Atlantic Anticyclone, which Taunton-Clark and Kamstra (1988) have proposed sets up strong equatorward winds and low coastal SSTs when south in summer and the opposite when further north in winter.

Subsequently, Hardman-Mountford et al. (2003) investigated the winds of the Southeast Atlantic from the equator to the Cape South Coast on the basis of model outputs for the period 1982 to 1999 obtained from the European Center for Medium-Range Weather Forecasts. The models indicated a pronounced increase in westerly surface wind anomalies up until 1997 at the equator and off Angola, followed by a marked return to normal conditions towards the end of the time series in both areas. There was a general increase in equatorward anomalies at the equator for the whole time period and off Angola up until 1992. After this there was a sudden increase in poleward winds, which continued until the end of the time series. No conspicuous inter-annual or longer term trends in either zonal or meridional wind stress in the northern or southern BCLME, or in the area south of the continent, were suggested by the models.

From an analysis of NCEP wind data Rouault (in Veitch, 2007) mapped the trends (assumed to be linear) in wind speed and direction per season over the southern African continent and adjacent ocean areas for the period 1982 to 2005. He found that the strongest trends occurred over the ocean in summer (January-March), particularly off the Namibian coast (which was dominated by an increase in equatorward winds); with a secondary maximum off the Cape Peninsula, where it appears that there has been an increase in southeasterly winds. There are no obvious trends in the mapped winds over the southern BCLME compared to the northern BCLME through the rest of the year, except in autumn (April-June) when there is a fairly strong tendency towards increasing easterlies south of the African continent and in the Agulhas retroflection area. Although Rouault’s maps are based on low-resolution (1^o x 1^o) data, and the assumption of linearity in the trends is questionable, they are valuable in that they give a sense of the large scale fluctuations in the wind field that have occurred in the region over a long time period up until fairly recent times.

In a more recent analysis of similar data from around the South African coast between 1982 and 2009, Rouault et al. (2010) confirmed the increase in upwelling-favorable southeasterly and easterly winds in the southern BCLME in the first half of the year during this period, evident from their earlier analysis. They found furthermore that the upwelling-favorable winds were on average weaker during *El Niño* ENSO events and vice versa for *La Niña* events, which supports earlier hypotheses of a tele-connection between climatic events in the Southeastern Pacific and the southern BCLME.

Wind monitoring stations at a number of locations between Lobito in Angola and Cape Point have provided relatively long time series of wind speed and direction, but because of the high degree of variability in the data at all scales, and the frequent lack of coherence between time series from stations a relatively short distance apart (e.g. Cape Point and Cape Columbine), it has proved difficult to extract long time series from these data. Nonetheless, some coherent patterns are evident; for example a marked reduction in upwelling favorable winds at both Cape Point and Cape Columbine during the 1980s, following an *El Niño* event in 1982/83 (Hutchings, in Veitch, 2007). This pattern was consistent with changes in three month averages of offshore Ekman volume transport (a proxy for upwelling-favorable wind stress) at Cape Columbine over this period, which Johnson and Nelson (1999) extracted from the Cape Columbine wind record for the period 1957 to 1992. Their averages showed that upwelling at this site is perennial over this time scale with peaks and troughs occurring roughly every seven years, although there was a marked reduction in upwelling after the *El Niño* in 1983, which only increased again in 1990. Note that the decrease in upwelling-favorable winds in 1983 agrees with the finding of Rouault et al. (2010) of an apparent connection between *El Niño* events in the Southeast Pacific and reduced upwelling in the southern BCLME. Recent evidence of an impact on upwelling-favorable winds on the west and south coasts of South Africa of a dramatic shift in *La Niña* conditions in the Southeast Pacific in mid-2010 (G. Brindrit, *pers. comm.)* is further evidence of this connection.

In the northern BCLME, plots of cumulative north-south wind anomalies based on data from the Lüderitz and Möwe Point (19^o 20' S) weather stations from 1960 at Lüderitz and from 1979 at Möwe Point, show a broad increase in upwelling-favorable winds from around 1980 and a decline since the early 1990s in both areas, with a slight increase around 2000, particularly at Lüderitz. NCEP data on the zonal and meridional components of the wind off Lobito over the 32 year period between 1967 and 1999 show low wind speeds throughout the period, with no obvious long-term trends in speed. There was however a switch from in-phase to out-of-phase fluctuations in the zonal and meridional components between 1982/83 and the early 1990s which implies a change in wind direction during this period.

Sea Surface Temperature

From an analysis of monthly mean SSTs between 1948 and 1989, Taunton-Clark and Shannon (1988) and Shannon et al. (1992) found that there was a general increase of about 1^oC in surface temperature over the areas offshore of the northern and southern BCLME. They noted no trend in the coastal areas other than a period of sustained cooling in the mid-1980s, particularly in the near-shore areas of the southern Benguela. The time series from the various areas studied, which extended from 10^oS to 35^oS and to about 1000 km offshore, show a reasonable degree of coherence, particularly in warm anomalies, which occurred in all areas every eight to 10 years on average.

Time series of high-resolution (4.5 km) satellite data for the period 1982 to 1999 compiled by Hardmann-Mountford et al. (2003) show that the warming trend noted by Shannon et al. continued into the next decade, being most pronounced near the equator and progressively less so towards the south. There is obvious coherence between the time series, particularly in the north, with the warm anomalies in 1985 and 1995 (*Benguela Niño* years) being particularly noticeable there, and considerable variability, which is greater variability in the tropical regions than in the areas further south. Of particular importance is evidence of a warming trend in the southern BCLME and Agulhas regions since 1995. This has been more consistent in the Agulhas region than in the southern BCLME, which implies that the cross-shelf SST gradient in that area has intensified, with possible implications for the transport of ichthyoplankton from the western Agulhas Bank to the West Coast nursery grounds since it could affect the strength and position of the northward-flowing jet current along the shelf edge.

Veitch et al. (2006) worked with the same data set and found that the warming trend in the region of the ABFZ was relatively uniform over the time period, suggesting that the position and intensity of the thermal front remains relatively stable except during major warm and cool anomalies. Monteiro et al. (2008) provide further evidence of the general warming of the ABFZ over the last two decades from an analysis of optimally-integrated NCEP SST data from the frontal region between 1982 and 2005.

Rouault (in Veitch, 2007) mapped seasonal trends in SST for the oceans adjacent to the southern African continent over the past 25 years from 1^o x 1^o resolution, optimally interpolated NCEP Reynolds data for the period 1982 to 2007. His maps reveal that the most intense warming has occurred at the northern and southern boundaries of the Benguela upwelling system throughout the year, and that there has been cooling in a narrow strip along the south and southwestern coasts. Warming has occurred offshore of this strip and throughout the rest of the BCLME upwelling region. This broad picture, and particularly the intensification of the SST gradients to the south of the continent, is in accordance with the findings of Hardman-Mountford et al. (2003).

Rouault et al. (2010) extended this analysis to include recent years, concentrating on South Africa and the region to the south of the continent. Their results clearly show the general warming of the Agulhas current and the cooling of the inshore area along the west and south coasts over the past two decades (Figure 3).

They found a statistically significant cooling trend of up to 0.50 ^{o}C per decade along the West Coast from January to August and one of lesser magnitude along the South Coast between May and August. These trends were attributed to the increase in upwelling-favorable southeasterly and easterly winds, noted earlier. A warming trend of up to 0.55^{o}C per decade throughout the year was detected in most parts of the Agulhas Current system. This was attributed to an intensification of the Agulhas Current in response to a poleward shift of westerly winds and an increase in trade winds in the South Indian Ocean at relevant latitudes. They also found a statistically significant positive correlation between warm events along the west and south coasts from February to May and *El Niño* events in the south east Pacific, in accordance with the apparent connection between the ENSO and upwelling-favorable winds in this region, previously noted. A further significant (negative) correlation was found between *El Niños* and warm events in the Agulhas Current south of 36^{o}S.

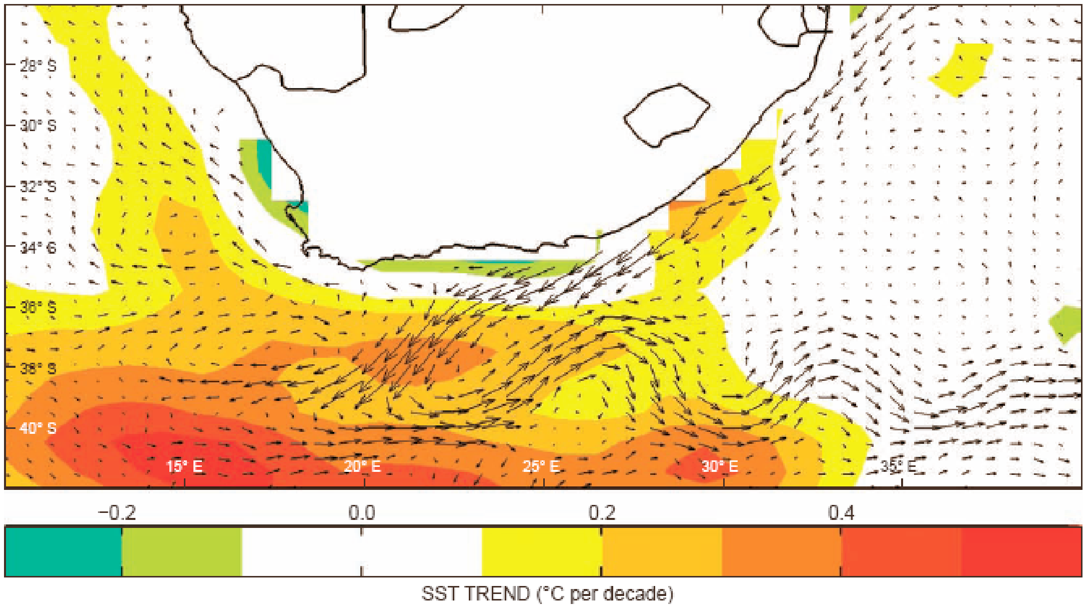

Figure 3. Linear trend in 1° x 1° Reynolds SST south of the African continent between 1985 and 2009 (from Rouault et al. 2010).

Major anomalies

The major environmental anomalies which have been recorded in the BCLME since the start of the data collection are of particular interest, especially in respect of any long term changes in their frequency, intensity or nature which may be symptomatic of recent global or regional changes in climate.

By far the most prominent anomalies in the data record are the *Benguela Niño* events, whose generation and connection to ENSO events in the Pacific was briefly outlined above. In their analysis of SST data extending from 1906 to 1985, Taunton- Clarke and Shannon (1988) concluded that these events, which result in a very conspicuous southward displacement of warm water in the northern BCLME in late summer and early autumn, have occurred throughout the environmental record about every 10 years on average since the start of the 20th century. Three such events (in 1963, 1984 and 1995) were clearly evident in temperature records from Walvis Bay between 1958 and 2004. A moderate, but very persistent warm episode between 1972 and 1974, evident in the same data set, is also generally considered to have been a *Benguela Niño*, and was categorized as such by Shannon et al. (1986). Other, less prominent, intrusions of warm water from the north, manifest as a southward shift in the ABFZ Benguela Frontal Zone have occurred more frequently. These can be seen in Figure 3, which shows satellite-derived SSTs along the entire Namibian coast between January 1982 and March 2004 (from Bartholomae and van der Plas, 2007).

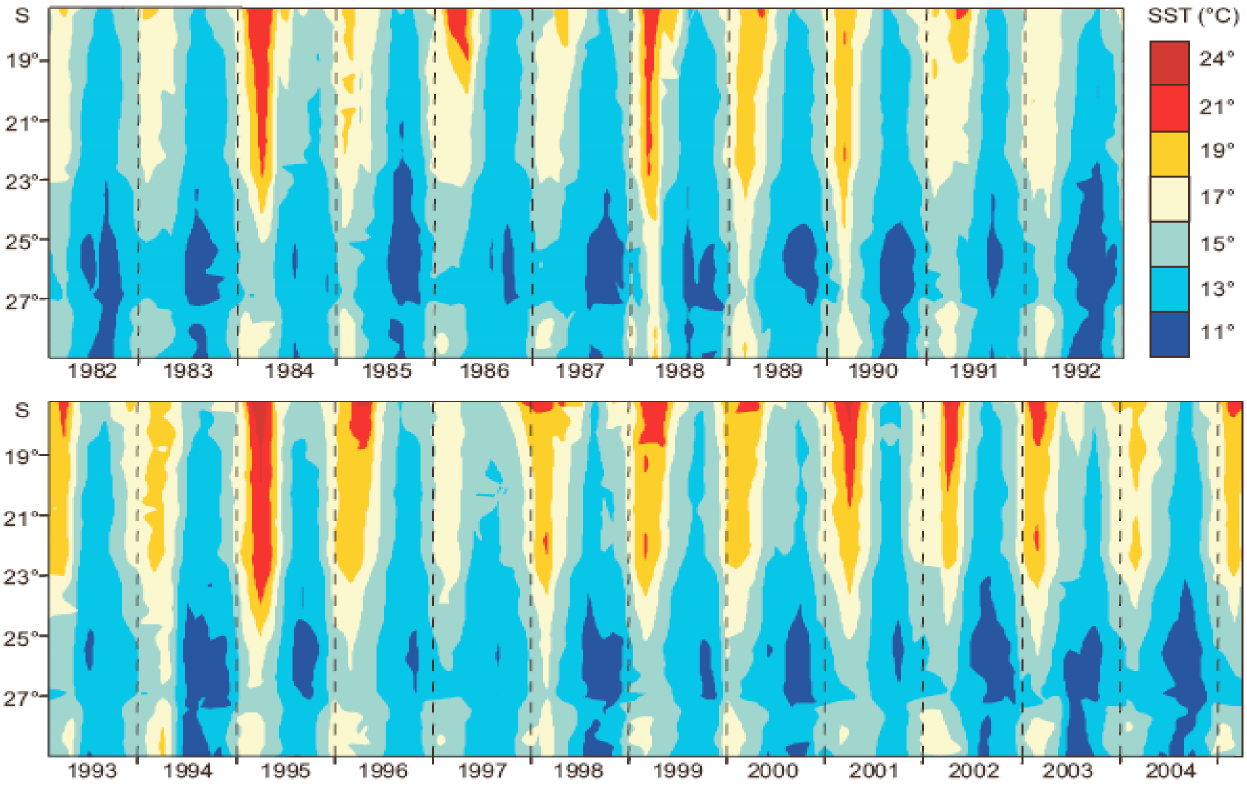

Figure 4. Monthly satellite-derived plots of SST along the Namibian coast between 1982 and 2004, averaged over 60 km-wide strips (from Bartholomae and van der Plas, 2007).

It appears from Figure 4 and other information in Bartholomae and van der Plas (2007) that these intrusions have increased in frequency since the early 1990s, although none have occurred in the past four years according to the most recent records. The general warming is consistent with a time series of satellite-derived SST measurements for the region between 10^o and 20^oS, east of 8^oE (Reason and Rouault, 2006). This suggests a warming tendency in this region since the beginning of the 1980s. Figure 4 shows that the extent of the warming in northern Namibia/southern Angola is to some degree inversely related to the extent and intensity of upwelling further south in summer. There is however no obvious correlation between the SSTs around 26^oS and the cumulative north/south wind anomalies at Lüderitz since 1982, suggesting a more complex relationship between wind strength and upwelling than is often assumed.

The southern BCLME is beyond the range of the southernmost excursions of the Angola Benguela Frontal Zone, which can therefore be assumed to have little direct influence on this region. The major large-scale temperature and associated anomalies here appear to stem from anomalous injections of warm water from the Agulhas Current retroflection area into the Southeast Atlantic (e.g. Mann 1992, de Villiers 1999), which there is evidence to suggest originate from processes in the northern Agulhas current on a mesoscale and forcing from the equatorial Indian Ocean on a larger scale (Reason and Rouault, 2006). Unlike the *Benguela Niño* events in the northern BCLME, the long term records of ENSO events in the Pacific and SST variability in the Tropical Atlantic, there are no long-term time series capturing these anomalies to discern any long term trends in their frequency, nature or intensity.

Of particular interest and importance are recent studies which have shown that the leakage of warm, saline Agulhas current water into the South Atlantic is a crucial component of the global climate system (even reaching the North Atlantic and possibly counteracting the cooling of the Gulf Stream), and that the leakage has increased in the past decades in response to a progressive poleward migration of westerlies south of the African continent, which has been linked to anthropogenic warming (Biastoch et al. 2009, Beal et al. 2011). It seems reasonable to suppose that because the leakage occurs immediately offshore of the southern BCLME upwelling region, further increases in its extent as a result of continuing anthropogenic warming may have a great effect on the upwelling region, with dramatic consequences for the southern BCLME as a whole.

South of the African continent, pressure anomalies associated with the Antarctic Oscillation produce wind anomalies over the Southeast Atlantic, particularly in spring, which Reason and Rouault (2006) postulate well influence the BCLME. However, as with the anomalies in the penetration of Agulhas current water into the South Atlantic, there are no long term data series to examine influences on the southern Benguela system.

Sea level

Brundrit (1984) and Brundrit et al. (1987) reported changes in sea level from tide gauge measurements at a number of sites between Swakopmund and Mossel Bay on the Cape South Coast between 1959 and 1985. They recorded anomalies in excess of 5 cm above or below the long term, particularly at Lüderitz. They noted that the nature of the sea level variability was similar to that in the eastern Pacific Ocean and that as in that region, sea level and SST were apparently correlated. While they did not extract an estimate of the long term increase in sea level over the study period, it is evident from the greater frequency of positive anomalies at all of the sites, that there was probably a general rise in sea level throughout the region over these years.

From satellite data between 1993 and 1999, Hardman-Mountford et al. (2003) showed that sea level anomalies between the equator and the southern BCLME during this period seemed to be in phase with one another, decreasing in amplitude from north to south. Their data show an overall rise of about 40 mm over the 7 year period (i.e. ca. 6 mm yr^{-1}) in the equatorial region, dropping to about half this in the northern BCLME, and no obvious rise in the southern BCLME.

In Veitch (2007), the mean rate of sea level rise in the BCLME upwelling region (period unspecified) was on the order of the global average (ca. 1.8 mm yr^{-1} according to the 2005 IPCC Report). While this rate is not considered to be a threat to persons or infrastructure along the south west African coast because of the relatively few low-lying developments there, Brundrit (*pers. comm*.) pointed out that the combined effects of sea level rise and the intensification of storm events due to the general warming of the ocean could cause a breach in the Pelican Point sand spit which shelters Walvis Bay, threatening both the town and the harbor. (Sand spits elsewhere on the coast have been permanently breached in recent years).

Upwelling/Ekman transport

In most of the studies, anomalies in upwelling at various localities have been expressed in terms of variation in the speed of the north and south components of the coastal wind, averaged over time periods typically of the order of a month (e.g. Shannon et al. 1992, Hutchings et al. 2006, Bartholomae and van der Plas 2006). An exception is the work of Johnson and Nelson (1999), who estimated the average rate of total Ekman transport at Cape Columbine for three-monthly intervals between 1957 and 1990 from hourly records of wind strength there. Their time series shows a peak and a trough approximately once every seven years up to 1983, followed by a sharp fall-off in volume continuing until the early 1990s. (Preliminary results suggested wind strength returned to its pre-1979 magnitude after 1995). As previously noted, the reduction in upwelling between 1983 and 1990 is consistent with a marked reduction in upwelling favorable winds at both Cape Point and Cape Columbine during the 1980s, following an *El Niño* event in 1982/83, reported by Hutchings (in Veitch 2007).

Since no estimates of long term changes in Ekman transport in the BCLME have been made since Johnson and Nelson’s study, long term trends in the extent and intensity of upwelling in the BCLME over the past two decades can only be inferred indirectly from the changes in the wind field, as previously discussed.

Low Oxygen Water

Long-term variations in the extent of low oxygen water (LOW) have differed in the three oxygen regimes (northern, central and southern) defined by Monteiro and van der Plas (2006). Their data and those of Hutchings et al. (2009) suggest that there has been an increase in the frequency of LOW events on the Angolan shelf since 2000, with a particularly strong event in mid-2002. A similar but more obvious trend is evident in the central BCLME. Seasonal fluctuations in LOW in this region are not in phase with upwelling intensity since the LOW is formed by a number of physical and biogeochemical processes which are not directly linked. Monteiro et al. (2008) have confirmed the importance of advected rather than biogeochemically-generated oxygen fluxes in determining seasonal-decadal variability in LOW in the central BCLME, and have hypothesized that it is the coupling of ocean-shelf boundary conditions and the advection of these conditions onto the shelf that are responsible for most of the inter annual variability in hypoxia there. They identified two long-term influences on hypoxia variations in their data set: changes in the lag between seasonal warming at Cape Frio and peak ventilation from Lüderitz (the timing of the former being the more important), and the long-term warming of the ABFZ. They detected a general increase in lag between 1981 and 1999 from 11 to 16 weeks with much shorter lags in the *Benguela Niño* years of 1984 and 1995.

In the southern BCLME there is a strong contrast in oxygen regimes between an aerated period in the 1980s and an oxygen deficient/hypoxic period in the 1990s, which Monteiro et al. (2006) attributed to a change from relatively weak wind fields in the 1980s to strong upwelling conditions in the 1990s. Figure 5 shows a significant declining trend in oxygen levels below the thermocline in St. Helena Bay since the early 1980s, while data in Hampton et al. (2009) indicate a marked increase in the offshore extent of LOW off St. Helena Bay since 2005. All indicators, including an increasing frequency of rock lobster walk-outs in Elands Bay since the 1980s (caused by anoxic conditions on the bottom) suggest a general decline in oxygen concentration below the thermocline in the southern BCLME over the past two decades.

Primary production/phytoplankton

It is generally assumed that long term shifts in upwelling-favorable winds will lead to changes in upwelling, and consequently, to changes in primary production and phytoplankton biomass on similar scales. There is little evidence to suggest that this has happened in recent decades in the BCLME, but there is evidence of substantial inter-annual changes in phytoplankton production at a number of times and locations in both the northern and the southern BCLME, as detailed below.

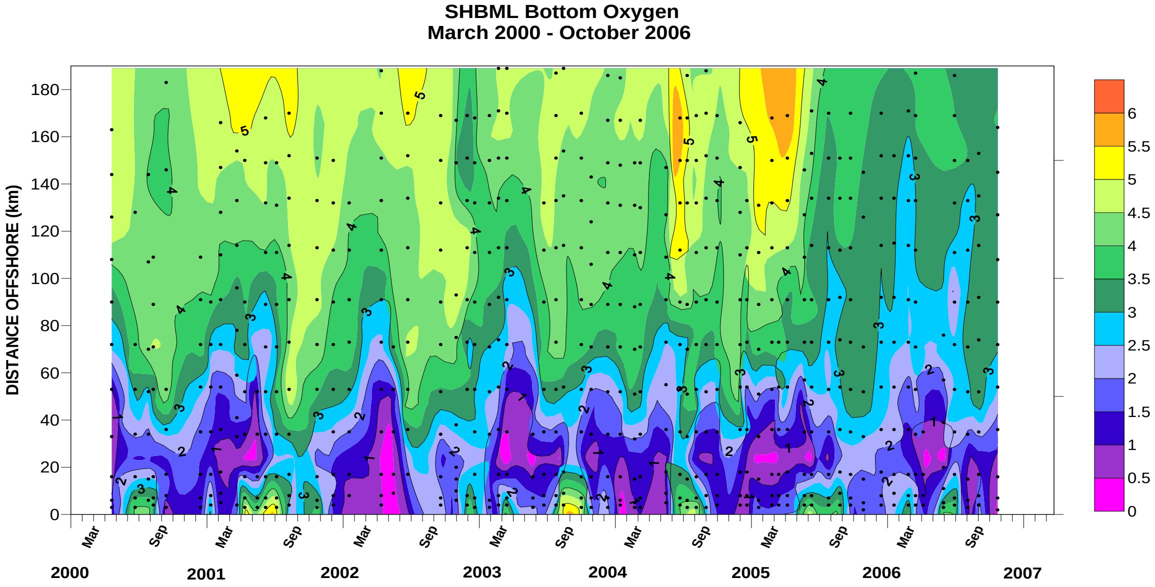

Figure 5. Concentration of dissolved oxygen at the bottom on the St. Helena Bay Monitoring Line, March 2000 – October 2006 (in Hampton et al. 2009).

From an analysis of chlorophyll data from the NASA Coastal Zone Color Scanner between 1979 and 1986, de Villiers et al. (1998) found that there were marked inter-annual variations in phytoplankton biomass off Cape Columbine and the Cape Peninsula during this period. However, these seemed to be more related to large-scale oceanic circulation features and forcing mechanisms (particularly the advection of warm Agulhas Current water into key regions of the Southeast Atlantic) than to seasonal variations in upwelling. Verheye (2000) found an increase in the mean concentration of chlorophyll *a* at the surface in the St. Helena Bay region in the early to mid-1990s, which was accompanied by a pronounced increase in phosphate, nitrate and silicate concentrations there over the same time period. An index of integrated chlorophyll for the same area between January 2000 and July 2003, derived by Barlow et al. from satellite imagery (in Hampton et al. 2009) suggests that although there were marked peaks in production in some months, there was no overall trend over this period akin to that in the first half of the 1990s. The same index for the northern BCLME suggested decreasing integrated chlorophyll levels off Walvis Bay between 2001 and 2007.

A time series of integrated chlorophyll a for the whole west coast shelf of Southern Africa between 1997 and 2007, derived from SeaWiFS data (Figure 6) confirms that there were substantial seasonal and inter-annual variations in concentration along the coastline during this period. But the time series does not show any obvious, broad changes in chlorophyll distribution or biomass over the region which might be indicative of a regional response to large scale climate changes.

In the long term, anthropogenically-induced increases in water temperature, carbon, and perhaps nitrate concentration, could bring about large scale changes in primary production (e.g. Riebesell et al. 2007, Tamelander et al. 2010), and in the efficiency of carbon uptake by phytoplankton and of carbon movement from the atmosphere to marine sediments. The likely net effect of these processes on the BCLME is unknown at present, but could be considerable.

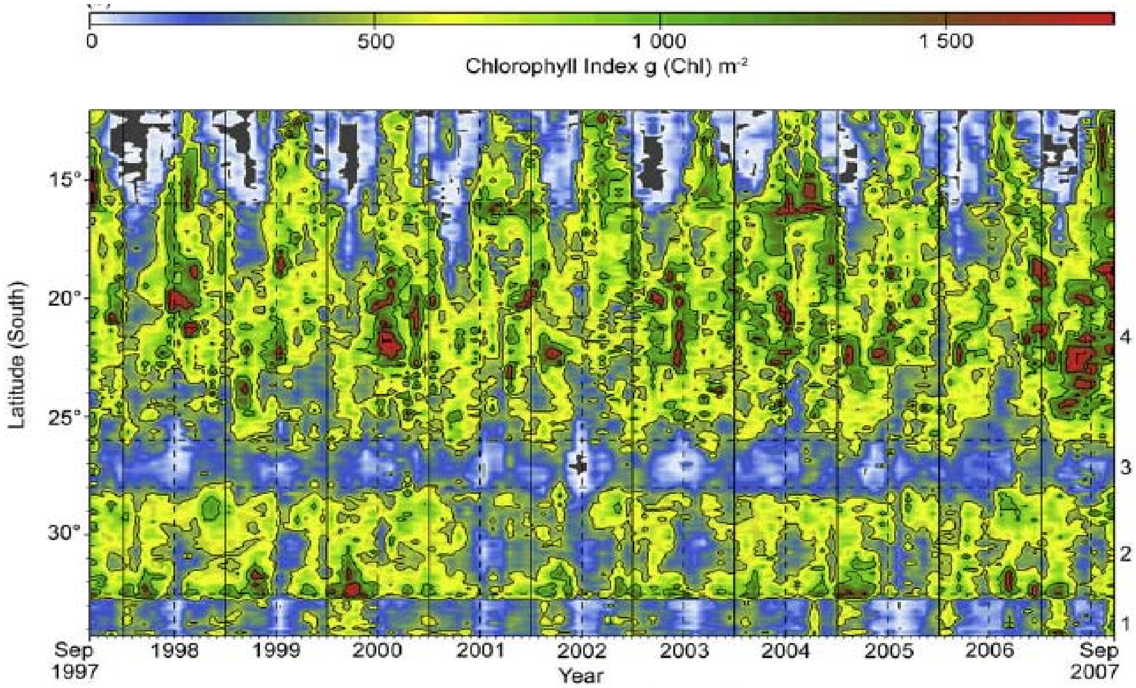

Figure 6. Monthly averages of chlorophyll *a* concentration between 10 and 40 °S, estimated from SeaWiFS data collected between October 1997 and September 2007 (In Hutchings *et al.*, 2009, updated from Demarcq *et al.*, 2007). The measurements have been integrated between the coast and the 1 mg m^{-3} offshore limit.

Zooplankton

From the 1950 to 2006 time series of zooplankton biomass in St. Helena Bay, Verheye and colleagues deduced that between the early 1950s and the mid-1990s there was a 100-fold increase in the biomass of crustacean zooplankton (primarily copepods) in this area, followed by an approximately 10-fold decline over the remainder of the time series. In earlier work on this data set, Verheye et al. (1998) observed that the larger copepods declined in abundance from the early 1990s to the end of 1996, coincident with the decline in total copepod biomass during this period. Figure 7 (upper panel), which extends the time series to 2004, does not indicate a further decline in the southern BCLME in more recent years.

An important question is whether the changes in the southern BCLME were caused by changes in the upward-propagating effects of oceanographic and biological processes (i.e. control from the "bottom-up") or from the "top down" by the impact of predators, particularly sardine and anchovy. These small pelagic fish are abundant in the St. Helena Bay area, feed on different size fractions of the zooplankton, and have undergone major changes in abundance and relative abundance over the time period due to heavy fishing pressure. In support of the bottom-up hypothesis, Verheye (2000) presents evidence of parallel decadal-scale changes across lower trophic levels in the southern BCLME, which he attributes to a long-term increase in wind stress. However, he also notes that the long-term increase in zooplankton biomass following the onset of commercial fishing in the early 1950s. The differences in the size structure of the copepod community between periods when sardine dominated the catches (1951 to 1967) and the 1980s when catches were dominated by anchovy, are evidence for a measure of top-down control as well. Negative correlations between the abundance of large copepods (the preferred prey of anchovy) and acoustic estimates of anchovy recruits on the West Coast in autumn and

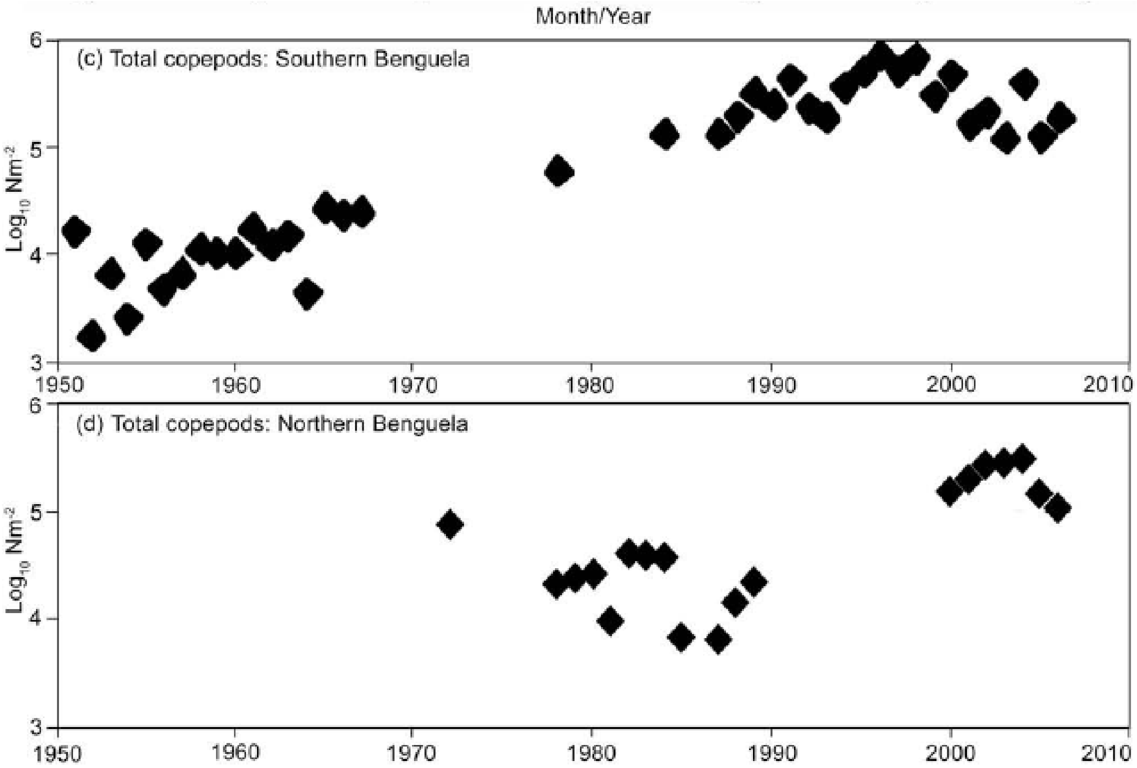

Figure 7. Trends in zooplankton abundance in the northern and southern BCLME, 1950 – 2004 (from Hutchings et al. 2009, updated from Verheye and Richardson, 1998).

spawners on the South Coast in early summer (in Hutchings et al. 2006) are further evidence of top down control of the zooplankton by anchovy.

A comparison by Verheye (2007) between copepod abundances in the northern BCLME between 1972 and 1990 and from more recent monitoring off Walvis Bay, shows a roughly 10 fold increase in copepod abundance over the past three to four decades, with a decline after 2007 (Figure 6, lower panel). He found that these changes were also accompanied by long-term changes in zooplankton community structure. In this region there is a much less obvious relationship between copepod biomass and pelagic fish catches, although the increase in 2000 could be at least partly related to the effective disappearance of anchovy from Namibian waters in the mid-1990s (Boyer and Hampton, 2001). In all, it seems reasonable to conclude that although top-down control of zooplankton biomass may well have occurred in the northern BCLME up until the collapse of pelagic fish stocks there in the 1970s, it is unlikely to have been a significant controlling factor there since then because of the persistently low abundances of the major zooplanktivorous pelagic fish species off Namibia in the past three decades.

It is tempting to see the decadal-scale changes in zooplankton biomass and community structure over the whole BCLME as a response to a common long term change in ocean climate over this period. However, because of the confounding effects of the different histories of pelagic fishing in the northern and southern BCLME, probable regional differences in the degree of top-down vs. bottom-up control over zooplankton communities, and the lack of independent evidence of a long-term environmental change over the time period of the zooplankton record, this comparison could not be justified.

Commercial resources

The important commercial resources of both the northern and southern BCLME have suffered heavy declines in the second half of the twentieth century due to over-exploitation. Some of the trends in the catches over this period are illustrated in Figure 8 for Angola and Figure 9 for Namibia and South Africa.

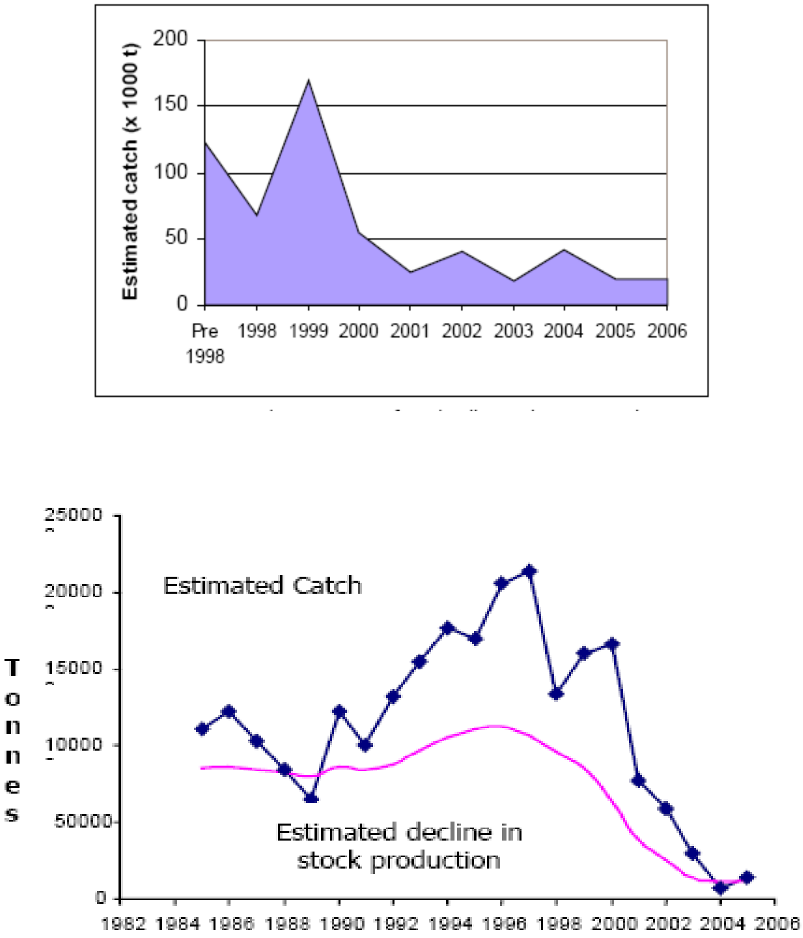

Figure 8. Estimated catches of both species of sardinella (top) and horse mackerel (bottom) off Angola over past few decades (from Japp et al*.* 2007).

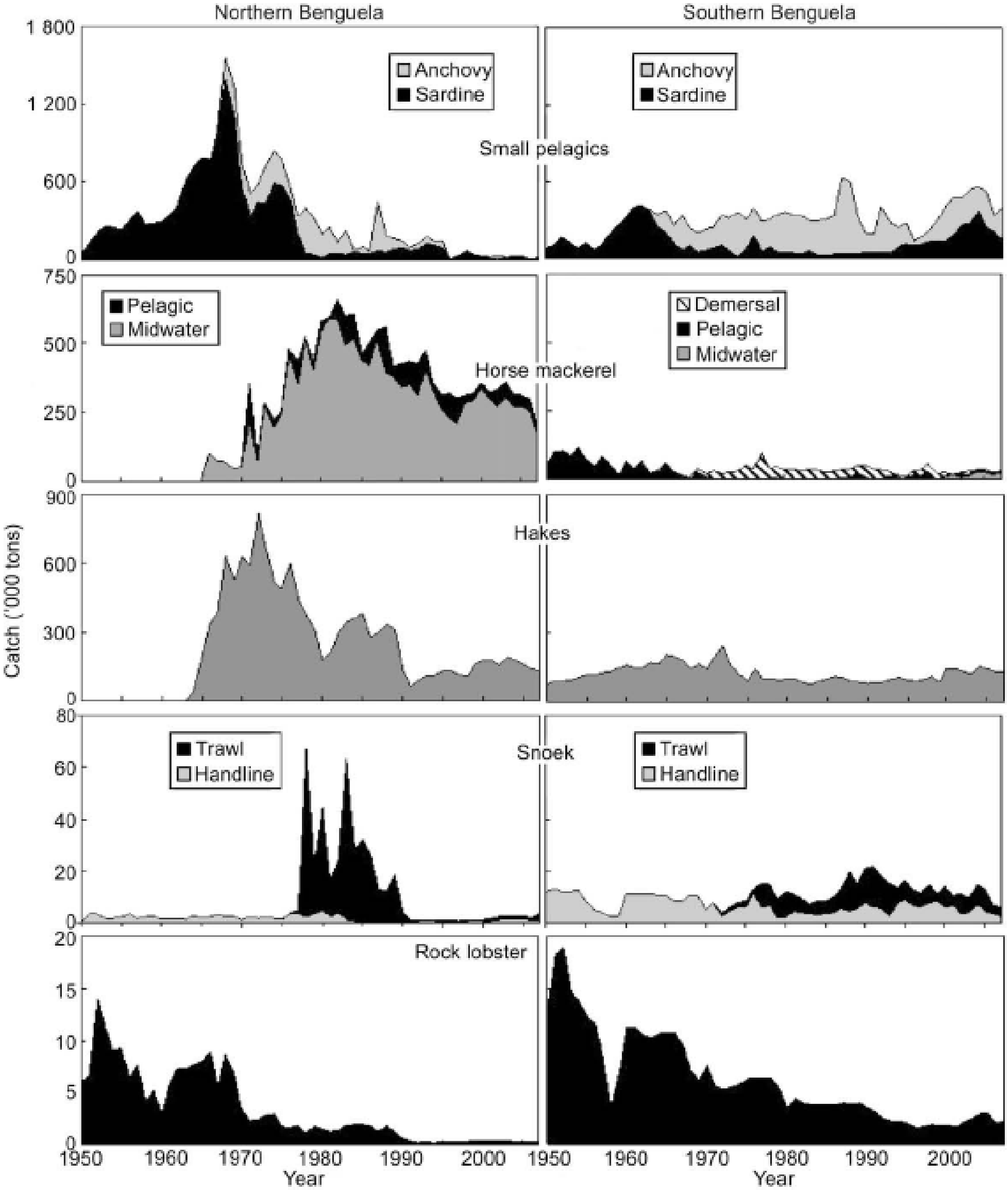

Figure 9. Changes in catches of major fish resources in the northern and southern Benguela (from Hutchings et al. 2009, updated from van der Lingen et al. 2006).

Notable features in Figure 7 are the sharp reduction in catches of horse mackerel and sardinella towards the end of the 1990s. Figure 8 shows that In Namibia and South Africa the most dramatic declines have been in the catches of sardine in Namibia since the early 1970s and of anchovy since 1990, sardine in South Africa in the mid 1960s, hakes in Namibia since the early 1970s, and West Coast rock lobster in both countries following the initial large catches in the 1950s. The only resource to show a sustained increase in recent decades is the sardine resource in the southern Benguela, where catches have at times been comparable with those at the height of the fishery in the 1960s. These catch trends are generally consistent with stock estimates from surveys and population modeling.

As pointed out in Section 3.3, the virtual removal of sardine and anchovy from the northern BCLME in the 1970s and 1980s due to over-fishing has resulted in a shift to a less efficient and less environmentally robust regime, with no sign of a recovery despite low fishing pressure on these two species over the past two decades. In the southern BCLME the most obvious change in the ecosystem over the past few decades has been the eastward shift in the distribution of sardine, anchovy and rock lobster to the Agulhas Bank in the late 1990s (e.g. Coetzee *et al.*, 2008, Cockcroft et al*.* 2008). The reasons for this are poorly understood but believed to be at least partly environmental (e.g. Roy et al. 2007). This shift is not seen as far-reaching or irreversible as in the northern Benguela. There is already evidence of a return westward in the distribution of sardine and anchovy, and of their spawning, in recent years (J. C. Coetzee, *pers. comm*.).

Environmental influences on commercial resources

There are many competing processes within the BCLME which make it extremely difficult, if not impossible, to predict the response of the major resources to any particular change. For example, an increase in upwelling could improve feeding conditions for small pelagic fish but increase offshore advective loss of their ichthyoplankton. Or an increase in the extent of low oxygen water on the shelf may inhibit recruitment of both species of hake, but because of differences in their tolerance to hypoxia. This could reduce the degree of overlap between distributions of the two species and the predation of *M. capensis* on *M. paradoxus*, which is a major source of mortality in the latter. On a lower trophic level, a change in the size and species structure of zooplankton communities could benefit or inhibit pelagic fish production, depending on many factors such as the distribution of the predators and prey, turnover rates and inter-specific competition for food. Nonetheless, it is possible to speculate broadly on the possible effects of environmental changes on the major fisheries in each of the three countries.

Angola

In Angola, a significant and protracted change in the position and/or characteristics of the ***Angola-Benguela Frontal Zone*** could have a major effect on the ecology of the northernmost reaches of the BCLME and on the distribution and abundance the species which inhabit this region. The extensive, seasonal spawning migrations of the two sardinella species could be disrupted. An increase in the frequency of *Benguela Niños* could have a strong effect on the distribution, and abundance, of pelagic fish species.

Namibia

Off Namibia, an increase in the intensity and/or frequency of *Benguela Niños* and other intrusions of warm, nutrient and oxygen-poor water from southern Angola could alter the vertical distribution of both hake species making them less available to the trawl and long-line fleets. In extreme cases, such as the prolonged and intense warm event in 1994/95 (e.g. Gammelsrød et al*.* 1998), recruitment itself could be severely affected. Such intrusions could also severely reduce sardine egg production and spawning success by shifting the spawning area and the dispersal of the eggs and larvae to less favorable environments. The impact on Namibian fisheries and other possible changes in the environment such as large-scale changes in primary and secondary production are difficult to predict since the processes involved and the connections between them are complex. Nonetheless, there can be little doubt that large-scale environmentally-driven changes in primary and secondary production could have profound effects on many of the resources of the region and the fisheries and communities that depend on them.

South Africa

The environmental perturbations that appear likely to cause the most damage for the major fisheries in South Africa are a) a persistent, large-scale change in upwelling-favorable winds in summer, b) increases in the amount of low oxygen water on the bottom and c) environmental changes that may have been responsible for the eastwards shift in the distribution of pelagic fish and rock lobster away from the traditional West Coast fishing grounds in the past decade. We consider these briefly in turn.

Major, long-term changes in the upwelling regime could result in large-scale changes in the production, distribution and species composition of the phyto- and zooplankton communities on which pelagic fish feed, with potentially severe effects on these resources. However, it is not at all clear whether the outcome would be positive or negative because of the uncertainty concerning the nature and extent of such changes and the possibility of conflicting responses to them.

A persistent increase in the extent of low oxygen water on the shelf could make the valuable hake resource less available to the deep sea trawl fleet and reduce catchability by forcing the fish further off the bottom. Although since oxygen levels in bottom water on the West Coast seldom reach the low levels experienced on the Namibian shelf, and there is no convincing evidence to suggest that oxygen levels will have a strong influence on hake catch rates on the South African coast. These may be relatively benign effects. In contrast, the West Coast rock lobster resource would probably be severely affected by an increase in the frequency and/or extent of anoxic water close to the coast. These conditions have caused large scale walk-outs in the past, particularly in the St. Helena Bay area.

Long-term environmentally-induced changes in the proportion of the sardine, anchovy and rock lobster populations west and east of Cape Agulhas will reduce their availability to the West Coast-based fisheries. Such changes are also likely to affect the locality, extent and intensity of sardine and anchovy spawning, the survival and dispersal of their ichthyoplankton, and movement of the pre-recruits into the inshore nursery areas on the West Coast. All of these factors will affect the annual recruitment strength essential to these short-lived species.

Arguably, the greatest long-term new environmental threat to the resources of the southern Benguela is the possibility of further increases in the amount of Agulhas current water leaked into the Southeast Atlantic (Biastoch et al*,* 2009, Beal et al*.* 2011). It seems reasonable to suppose that because the leakage occurs immediately offshore of the upwelling region, further increases in its extent may have a great effect on the upwelling region, with dramatic consequences for the southern BCLME, and possibly for the northern BCLME as well.

Regime shifts

An important question is whether any of the long-term ecosystem changes that have been observed in the BCLME since the start of comprehensive data collection constitute regime shifts as defined, for example, by de Young et al. (2004): *a rapid change from a quantifiable state, representing substantial restructuring of the ecosystem, acting over large spatial scales and persisting for long enough that a new quasi-equilibrium state can be observed*.

The changes in the trophodynamics of the northern BCLME following the collapse of the pelagic fisheries there in the 1970s and 1980s clearly constitute a regime shift which was in all likelihood caused primarily by overfishing. Watermeyer et al. (2008a) calculated that between 1967 and 1990 the mean trophic level (MTL) of the catches in the northern BCLME increased, as did the weighted trophic level of the community (excluding detritus and plankton) after the collapse of the small pelagic stocks. They attributed these increases in MTL to the declines in biomass of the small pelagic fish and the increase in the relative importance of horse mackerel catches during this period, rather than seeing them as being indicative of a healthy ecosystem. It is less certain whether the prolonged hypoxia and warming events in 1994 and 1995, and the subsequent severe effect on many of the resources, resulted in a regime shift, since there is no conclusive evidence to suggest that the ecosystem now is functioning any differently from the manner in which it functioned prior to these events. Watermeyer et al. (2008a) pointed out that, in line with Odum's (1985) hypothesis on the increased vulnerability of stressed ecosystems to environmental change, these events could well have had a greater negative influence over the already depleted stocks than previous such events, and hindered attempts to rebuild stocks by reducing fishing pressure on them. If so, it would mean that the present system is more sensitive to changes in the physical and biological environment than in earlier times, particularly before the onset of commercial fishing. It could be increased sensitivity to environmental perturbations, together with the reduced efficiency with which primary production is now being passed on to higher trophic levels, that has prevented the system from returning to a more productive state despite the greatly reduced catches of small pelagic fish in the past two decades.

Changes in the southern BCLME since the beginning of the 1950s have not been as drastic as those which occurred in the northern BCLME in the 1970s and 1980s. Nonetheless, two long term changes which qualify as regime shifts have been identified by Howard et al. (2007). The first occurred in the late 1950s, when horse mackerel were replaced by sardine in the pelagic fishery, possibly coincident with the period of increased upwelling identified by Shannon et al. (1992). The second occurred in the late 1990s and early 2000s, when sardine and anchovy biomass was simultaneously high, and the populations and spawning areas of both species were concentrated more on the South Coast than the West Coast. Howard et al. attributed the first shift to fishing (with some environmental influence) and the second primarily to the environmental changes on the Agulhas Bank described by Roy et al. (2007).

Calculations by Watermeyer et al. (2008b) indicate that the MTL of the catch changed little between the 1960s and the 2000s, although this may not be true of the ecosystem as a whole (see recent criticism by Branch et al. (2010) of the use of the MTL in catches as an indicator of the trophic structure of an ecosystem). The other fluctuations in the distribution and abundance of small pelagic fish and their prey which have occurred since the start of the sardine fishery in the 1950s are not thought to be indicative of regime shifts since they have been highly variable, reversible and often of short duration. In that sense, even the major shift in the distribution of sardine to the South Coast in the late 1990s and early 2000s could be questioned as indicative of a regime shift since there is evidence of a recent shift in the distribution of the fish and their spawning back to the West Coast. Whatever the reasons for the fluctuations in abundance and distribution of sardine and anchovy since the 1960s, at no stage have both species effectively disappeared from the ecosystem (as in Namibia). This fact suggests that they continued to act as a wasp-waist species in the ecosystem even with the effects of commercial fishing. According to Odum's (1985) hypothesis, the southern BCLME should therefore at present be less sensitive to environmental change than the northern BCLME at present.

Summary

The following conspicuous, long term trends in the environment were identified at the BCLME Workshop on the Changing State of the BCLME in 2007, listed in Veitch (2007):

- The most obvious and long-lasting documented changes in the BCLME in the past half-century have been the drastic declines in the abundance of many of the major resources, all of which have been primarily due to over-fishing rather than environmental effects.

- There has been widespread warming of surface water at both the northern and southern boundaries of the system and in the northern BCLME over the past few decades, but a general cooling of inshore waters of the west and south coasts of South Africa over the same period. The latter has led to an intensification of cross-shelf SST gradients in the southern BCLME.

- The events with the most obvious consequences for marine life in the northern BCLME are *Benguela Niños* and other such intrusions of warm, nutrient and oxygen-poor water from southern Angola. Over the past decade the frequency of these events, and consequently the extent of low oxygen water in Namibian shelf waters, appears to have increased, although the time series is still be too short to assess whether these are continuing, long term trends or not.

- Averaged over the past few decades there has been a general increase in upwelling-favorable winds in the northern and southern BCLME in the summer months, although these trends have been subject to considerable decadal-scale modulations. Notably, there is little evidence to suggest that there have been large-scale inter-annual changes in primary production in response to changing wind fields, contrary to expectation.

- All indicators suggest a general decline in oxygen concentration below the thermocline in the southern BCLME over the past two decades, consistent with the general increase in upwelling-favorable winds in the southern BCLME over this period.

- The abundance of copepods (the major zooplankton group) has increased by at least an order of magnitude in both the northern and southern BCLME over the past 40 years or so, accompanied by a substantial reduction in the proportion of larger copepods (the preferred prey of anchovy). These changes have been attributed to a combination of increased primary production and the reduction of predation by small pelagic fish removed from the system through heavy fishing pressure. Since the late 1990s there has been a reduction in copepod biomass in the southern Benguela, coincident with the substantial increase in the biomass of both the sardine and the anchovy in the southern BCLME at that time. Because of the uncertainty regarding the relative importance of bottom up vs. top-down control of zooplankton biomass, and the lack of clear evidence of a region-wide, long-term increase in primary production, it would be premature to attribute the apparent increase in copepod biomass in both the northern and southern BCLME primarily to a general increase in primary production in the region.

- The virtual removal of the wasp-waist species sardine and anchovy from the northern BCLME ecosystem in the 1970s and 1980s has resulted in a shift to a less efficient and less environmentally robust regime, believed now to be dominated by gobies, jelly fish and horse mackerel, with no sign of a recovery despite low fishing pressure on sardine and anchovy over the past two decades. In the southern BCLME the most obvious change in the ecosystem over the past few decades has been the shift in the distribution of sardine, anchovy and rock lobster to the Agulhas Bank in the late 1990s. The reasons for this are poorly understood but are believed to be at least partly environmental. This shift is presumed to be localized and reversible compared to the northern BCLME.

PREDICTABILITY/FORECASTING

In this section, we explore the possibility of predicting change in the BCLME on the basis of current information and understanding the system's functioning. Model-based forecasts of environmental responses to anticipated changes in global climate are considered, and various possible scenarios regarding the way biota respond to such changes are discussed.

Model predictions of environmental change

There has been a general warming of the earth's lower atmosphere in recent decades, at least partly due to anthropogenic effects, particularly the build-up of greenhouse gases. The likely effects of continuing atmospheric warming on the world's oceans are less clear, due partly to deficiencies in the current Global Circulation Model and in models linking the atmosphere and the ocean on regional scales.

Although numerical modeling of large scale interactions between the atmosphere and the ocean in the BCLME, and of physical and chemical responses in the ocean environment has advanced rapidly over the past decade (e.g. Shillington et al. 2006, Monteiro et al. 2006a), it is probably true that none of the existing models is capable of predicting the effects of atmospheric warming on the hydrodynamics of the BCLME with an adequate degree of certainty. This is partly due to a shortage of not only ocean data, but also the land surface and atmospheric data needed to improve the models and validate their outputs (Reason et al. 2006). This is a problem which is likely to persist for some time.

Shillington et al. (2006) pointed out that the potential for forecasting large scale variability in the BCLME depends mainly on how well the processes that transfer remote signals from the equatorial region and the Agulhas retroflection area to the Benguela are understood. They identified a number of processes which have been characterized well enough to be built into an early warning/forecasting system for the BCLME. The best prospects for a forecasting system are variations in equatorial upwelling intensity, timing of trade winds, movement of the ABFZ and ring shedding from the Agulhas retroflection.

Certain extreme events in the BCLME, notably *Benguela Niños*, the formation of low oxygen water and hydrogen sulphide eruptions, do appear to be predictable to some extent. Florenchie et al. (2003 and 2004) postulate that *Benguela Niños* may be anticipated about two months in advance by tracking the oceanic disturbance resulting from the sudden change in zonal wind stress in the western equatorial Atlantic as it crosses the Atlantic and then travels polewards along the coast. Note however that modulating influences from local processes such as variations in upwelling intensity and the intrinsic variability in the ABFZ (Colberg, 2006) may weaken the strength of any such predictions. Monteiro et al. (2006b) noted that the two month lead time would also apply to the prediction of large scale intrusions of LOW from the north which is associated with *Benguela Niños* events. (By implication, hydrogen sulphide eruptions off the Namibian coast, which are associated with LOW intrusions, may also be predictable this far ahead). They also considered that LOW events leading to the walk-out of rock lobster in certain areas in the southern BCLME such as St. Helena Bay could be forecast about a week ahead of time on the basis of a two phase wind-driven model of the development of harmful algal blooms in the region. Bernard et al. (2006) have considered the monitoring requirements for such a forecasting system.

Predicting response of resources to environmental change

Predicting the response of marine resources to environmental changes has been the goal of long term intensive environmental research in the region for many years, particularly in the southern BCLME. For example, attempts have been made to predict anchovy and sardine recruitment there on the basis of environmental information since the early 1980s. However, despite a wealth of information on environmental conditions, the physiological condition of the fish, the distribution and abundance of all life history stages, and success in the prediction of anchovy recruitment over a relatively short time period (e.g. Roy et al. 2001), no recruitment predictors robust enough to be consistently used in management have yet emerged. Recruitment prediction for most other species (even for hake, where the data series are even longer, although not as comprehensive) and of adult survival rates has been equally problematic. The inevitable conclusion is that even if changes in the marine environment can be forecast sufficiently far in advance, difficulties in predicting the response of marine resources to such changes are likely to limit the use of this information in management. We can construct plausible scenarios of changes in the ecosystem due to climate change. A number of these (with potentially negative consequences for the resources of the northern BCLME), were presented to the BCLME Climate Change Workshop by Roux and Kreiner (in Veitch, 2007), and are listed below:

- Widespread reduction in coastal upwelling leading to a warm, tropical and low productivity system with disastrous effects on current fisheries for temperate species;

- Enhanced upwelling leading to enhanced productivity, increased turbulence and offshore advection. Negative consequences of this would include an increase in the local production of LOW through biogeochemical processes, and therefore an increased risk of hydrogen sulphide eruptions;

- An increase in the severity and frequency of *Benguela Niños*, leading to a decrease in productivity, and increased vulnerability of fish stocks to over-exploitation;

- A non-linear response of the ecosystem to general, low-amplitude changes in the ecosystem induced by gradual climate change, producing a succession of rapid regime shifts between semi-stable states. It was postulated that such shifts would have the most impact on the pelagic fisheries of the region.

It must be emphasized that these scenarios are purely conjectural, and that their likelihood (or that of alternative scenarios) cannot be quantitatively assessed from current information. Note too that they have been limited to negative outcomes for the resources of the region, whereas a number of positive outcomes (which may be just as likely) could possibly be envisaged.

Brundrit (2010) has put forward the following possible scenarios which would or could affect the South African fishing negatively:

- General warming of the surface waters leading to their eventually becoming more tropical in nature;
- A continuation of the shift in pelagic fish distribution to the South Coast;
- Decreased oxygen concentrations in the St. Helena Bay region, and in the poleward transport of LOW from Namibia;
- Increased frequency of storms and extreme winds;
- Increased acidification of surface waters.

He speculated on the general effects which might be expected from such changes in the environment, but not on their likelihood or the possible rate at which they could occur.

Use of predictions in management

Although much progress has been made in understanding the functioning of the BCLME since the speculations on its possible response to climate change by Siegfried et al., Shannon et al. and Crawford et al. in 1990, much has still to be learned before any predictions based on new understanding can be used in management of the region’s marine resources. The net effect on resources in the retroflection of the Agulhas Current (believed to be a major driving force in the southern BCLME) is still totally unpredictable at present despite the greatly increased understanding of its dynamics and the ease with which its surface expression can be monitored through satellite imagery. This area deserves particular attention considering recent evidence of anthropogenically-generated increases in the leakage of Agulhas current water into the South-East Atlantic, and of the great importance of the Agulhas current in the global climate system.

THE ROLE OF THE BENGUELA CURRENT COMMISSION

The Benguela Current Commission (BCC) came into being in August 2008 in Windhoek, Namibia with the appointment of an Executive Secretary. The Commission formalizes almost two decades of trust building, cooperation and collaboration at technical and scientific levels between Angola, Namibia and South Africa (e.g. Hampton and Sweijd, 2008), and many initiatives in capacity building and empowerment in marine science and governance the region. The BCC is mandated to give science-based advice on the optimal use, conservation and protection of the BCLME to the Ministers of the three countries, through its Management Board. It is in a prime position to coordinate collective efforts by the three countries to address the observable and predictable effects of climate change on the BCLME.

While both independent and collaborative research in the region has been focused on a wide range of specific environmental questions, the Commission itself has only recently become formally involved in climate change issues. When the Strategic Action Program (SAP) for the BCC was being developed, in the late 1990s, the issue of climate change and its effects was not a priority and was not specifically addressed. There is now a pressing need for the BCC to have a position on climate change, adaptation and mitigation. In November 2011, in partnership with the FAO, the BCC hosted a regional workshop on *Climate Change Implications for Fisheries of the Benguela Current Region: Making the Best of Change*. As a result, the BCC initiated the development of a joint proposal to the GEF for a regional project on climate change and its effects on the BCLME entitled, *Anticipating and adapting to climate variability and change in the social-ecological marine fisheries systems of the Benguela Current Large Marine Ecosystem (regional).*

The BCC is expected to play an important role in the climate change arena within the region by a) improving capacities to deal with climate change and adaptation, b) improving monitoring and assessment of climate related parameters and processes through the fostering of research partnerships, c) establishing a formal regional policy on climate change that supports that of SADC and the AU, d) sourcing and securing the expertise needed to improve knowledge and understanding of climate change and its effects, and e) lobbying at regional and international levels for increased support for work in LMEs to counter the negative impacts of climate change.

To maximize and sustain the goods and services that emanate from LMEs, effective governance institutions are needed (e.g. Olsen et al. 2006). Such institutions need to operate at various levels to cope with the uncertainty and dynamics associated with ecosystems, climate change and anthropogenic impacts. Governance of LMEs requires integration at all levels and sectors from local to national and from project to program. Conventional institutional models which are based on centralized command and control are often ineffective when dealing with complex ecosystems such as LMEs. LME governance systems should include a variety of institutional types and have an array of decision rules and tools to enhance access to information, improve incentives, monitor resource use and foster compliance. Thus the role of the institution should be to consider and reconcile the differing values of user groups and the general public, and propose the best means of implementing selected objectives for the general good (Olsen et al. 2006).

The BCC currently enjoys commendable political support in the BCLME region, which is crucial if such an institution is to be seen as relevant and needed. This support facilitated the development of a multilateral, inter-sectoral and legally binding LME Convention. Politicians generally understand the role of science in the region but need to be fully engaged to improve the state of the ecosystem. Fortunately, Ministers in the three countries increasingly understand how much of a “lifeline” the BCLME is to the region and have amply recognized its present and potential future role in overcoming contemporary social challenges posed by poverty, food insecurity, lack of education and HIV/Aids. In September 2010, Ministers at the BCC’s Ministerial Conference pledged their full support for the full institutionalization of the Commission, the finalization, signing and ratification of the Convention, the full implementation of the Strategic Action Program, and agreed to support National Action Planning. At the same meeting they requested that the Angolan and South African Ministries of Transport be included in the Commission given the importance of maritime transport issues in the region.

While the BCC does not at present have the mandate to make decisions on the use of shared resources, it will this year, in collaboration with the ACP EU Fish II Program, support Angola and Namibia in the development of a joint management plan for shared stocks of Cape and Cunene horse mackerel. This would be the first step towards jointly assessing and making decisions on the sharing of these resources. The Commission will also investigate means of harmonizing the collection of data on stocks of Cape hakes *Merluccius capensis* and *M. paradoxus* shared by Namibia and South Africa, and ways of standardizing survey methods to produce integrated sets of data on these species for stock identification and joint management. Furthermore, through a Strategic Environmental Assessment, the Commission will be integrating the economically highly important mining sector into its work program. Finally, in collaboration with national and local government structures, the BCC has started the process of identifying local sites in all three countries for demonstration projects aimed at securing income and improving conservation.

As chair of the Africa LME Caucus during Oceans Day at COP 17 in Durban, December 2011, the BCC was instrumental in presenting the observable effects of climate change on these LMEs. In 2012 it will develop a policy position on climate change, based on the statement on climate change which representatives from the world’s LMEs delivered at Oceans Day.

Although the Commission is a fairly new institution, it has made commendable strides in becoming an appropriate mechanism for LME management, and has made notable attempts to draw all levels of society and sectors into the debate, from local to national and from projects to programs. An important consequence is that through increased stakeholder involvement, the BCC has garnered more buy-in and secured increased regional ownership.

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3

RESPONSE OF EPIPELAGIC SPECIES TO CLIMATE CHANGE IN THE CANARY CURRENT LARGE MARINE ECOSYSTEM

Birane Sambe[1]

INTRODUCTION

The Canary Current Large Marine Ecosystem (CCLME) extends southwards from the Atlantic coast of Morocco to the Bijagos archipelago of Guinea Bissau and westwards to the Canary Islands (Spain). The countries within the recognized limits of the CCLME are Spain (Canary Islands), Morocco, Senegal, The Gambia and Guinea Bissau. Cape Verde and the waters of Guinea are considered adjacent areas within the zone of influence of the CCLME (Figure 1).

CCLME is one of the world's eastern boundary current LMEs and includes important upwelling areas.

The coastal and estuarine areas provide vital goods and services including critical fish habitat and wood harvest areas in mangrove forests, and profitable tourism locations. The CCLME is an important source of food and economic resources for much of Western Africa. However, fish resources in the Canary Current are on the decline and the region is also experiencing degradation of several important habitats. Causes of this degradation include overfishing, weak fisheries management, over-harvesting of wood, salinity changes, sedimentation and trawling.

Figure 1. Location of the Canary Current LME.

The impacts of climate change are likely to aggravate these issues by affecting the intensity and seasonality of upwellings, coastal currents, salinity and acidity levels. This, in combination with ocean sea-level rise, coastal erosion and increasing occurrences of extreme weather events would cause further decreasing water quality, changes in fish species distribution and

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[1] *This work has been prepared primarily from materials of the FAO Working Group on the assessment of pelagic stocks in the northern region of West Africa and reports of the Project Protection of Large Marine Ecosystem of the Canary Current.*

production seasonality, deterioration of mangrove and other coastal habitats, damage to coastal infrastructure and increasing risks for coastal communities and fishermen (Niang, 2010).

This chapter deals with the impact of climate change on pelagic species. Indeed, various studies have highlighted the impact of hydro-climatic fluctuations on the abundance of coastal pelagic stocks such as sardine, sardinella, horse mackerel and mackerel. Indeed one of the characteristics of pelagic stocks is that these species mainly colonize upwelling zones which are one of the most productive regions of the oceans. The pelagic species account for enormous biomass but they are also known for their sensitivity to environmental fluctuations, resulting in variability in their abundance and availability to fishing interests.

PRODUCTIVITY

The seasonal movement of the anticyclone Azores, Saharan depression and the intertropical convergence zone determines the swing of the trade winds and therefore the position of and intensity of upwellings along the West Coast of Africa (Wooster et al., 1976; Parrish et al., 1983).

The circulation of water over the continental shelf of northwest Africa is largely dependent on the wind regime that is generally directed toward the south and the Canary Current LME. This coastal current, engendered by trade winds from Morocco to Senegal, unites this vast region. The Canary Current water flowing on the surface, from north to south, is constantly renewed from the North Atlantic Central Water (NACW), north of Cape Blanc and the South Atlantic Central water (SACW), south of this Cape. These water mass upwellings are associated with terrigenous rivers (there are seven major estuaries and river systems including the Casamance, Senegal River and Gambia) and are sources of nutrients enriching CCLME productivity. Indeed, the coast has conditions for abundant photosynthesis with plentiful nutrients and high irradiance.

The Canary Current LME is a Class I, highly productive ecosystem (>300 g C/m2/year), based on SeaWiFS global primary productivity estimates (Sherman and Hempel, 2008).

Temperature variability, indicative of upwelling and therefore addition of nutrients, has a clear impact on fisheries resources of the entire food web.

FISH AND FISHERIES

The CCLME is characterized by important biological diversity. Fisheries resources include coastal pelagic fishes (e.g. sardines, sardinella, and the mackerels), demersal fishes (e.g. sea breams, groupers) and oceanic pelagic species (e.g. tunas, sailfishes). Artisanal, semi-industrial, and industrial fisheries all harvest these fish species.

COASTAL PELAGIC FISHES

The coastal pelagic fish, based on tonnage landed, are the most important marine resource in the region. They are shared among CCLME countries due to their migratory behavior. These coastal pelagic fish account for millions of tons of biomass and are particularly sensitive to climate variability.

The most important pelagic resources in the region are the sardines off Morocco and Mauritania, and the sardinellas, mackerels, and horse mackerels mainly distributed from Mauritania to Guinea.

The coastal pelagic resources that are exploited consist mainly of *Clupeidae*, *Engraulidae, Carangidae,* and *Scombridae.* The clupeidae are mainly composed of round sardinella or *Sardinella aurita*, flat sardinella or *Sardinella maderensis* and Sardine or *Sardina pilchardus*. Round sardinella are found in cold upwelling areas while the flat sardinella usually live in less saline coastal waters, often at the mouths of rivers. Flat sardinella are less migratory than round sardinella. Sardinella are mainly found in temperate waters of Canary Current to the north. The Shad razor or *Ilisha africana* and Ethmalosa or *Ethmalosa fimbriata* both live in estuaries and coastal lagoons, prefer warm and turbid water and also belong to this same order.

The Engraulidae are represented by common anchovy or *Engraulis encrasicolus*, and are present especially when the water is very cold.

The exploited Carangidae are the Cunene horse mackerel or *Trachurus trecae*, the Atlantic horse mackerel or *Trachurus trachurus* and scad or *Decapterus rhonchus*. The white horse mackerel seems to have an affinity for temperate waters and is rarely found in southern Mauritania.

The Spanish mackerel or *Scomber japonicus* reported throughout the west African coast and the Atlantic mackerel or *Scomber scomberus* are the main Scombridae in the region.

Mullet and croakers are being targeted for exploitation in coastal countries. More than six species of mullet in landings in Mauritania were identified, including the black mullet (*Mugil capurrii*) which is the dominant species. Mullet and croaker (*Argyrosomus regius*) are species that have a very wide range and are located mostly on the west coast of Africa, where, in the area of Mauritania, Senegal, their area of distribution is similar. Both species gather in large schools and migrate to spawning areas where water conditions are favorable.

Some of the secondary coastal pelagic species include: the Bigeye grunt (*Brachydeuterus auritus*), the Atlantic bumper (*Chloroscombrus chrysurus*), and the hairtails (*Trichiurus lepturus*). The sompat grunt (*Pomadasys jubelini*) shows strong abundance especially in the transition season and remains a target for fisheries.

In Cape Verde, exploited coastal pelagic resources are *Selar crumenophthalmus* and *Trachurus spp*. (horse mackerel), the *Decapterus macarellus* (mackerel scad), *Decapterus punctatus* (chub mackerel), and *Sardinella maderensis* (flat sardinella) are also caught in small quantities.

FISHERIES

The description of fisheries in the CCLME is listed in a report by the FAO / CECAF Working Group on the assessment of small pelagic fish off the coast of northwest Africa (FAO, 2006b; Sambe, B. 2002 ; FAO, 1994).

Artisanal and industrial fisheries are exploiting the coastal pelagic resources in the northern region of West Africa.

The majority of landings in Senegal are from the artisanal sector while the industrial sector dominates in Morocco and Mauritania.

Artisanal fisheries

Artisanal fishers use canoes of sizes ranging from three to 25 meters. Large canoes are powered by outboard motors of 40 hp and smaller canoes by motors of 5 to 20 HP. The number of fishermen per boat varies from four to seven depending on the countries/region. The crews of large vessels over 15 meters may exceed 10 people. Table 1 presents some characteristics of the artisanal fleet in the countries.

	Number of fishermen	**Number of boats**	**Engine %**
Morocco (2011)*	170,000	14,225	+90%
Cape Verde (1997)	3,108	1,036	74
Mauritania (2008)	12,100	3,495	n.a.
Senegal (2005)	59,428	13,903	75
Gambia (2006)	6,000	1,785	84
Guinea (2001)	25,000	3,636	29
Guinea Bissau (2007)	11,000	3,500	12

Table 1. Number of fishermen and boats, and percentage of engines in the artisanal fisheries listed by country (Salah BEN CHERIFI and Majida MAAROUF, 2011 and B. Sambe 2009).

The sub-sector of artisanal fishing has grown in the number of fishermen and boats in recent years but also in production and exports. The fishery is characterized by considerable heterogeneity. The fishing techniques used are quite diverse depending on the target species and change with the fishing grounds and seasons. The gears and fishing techniques most commonly used to catch coastal pelagic fish used were described in detail by Gruvel (1913), Postel (1960), Seck (1980), Boely (1978) and Freon (1988). The most common techniques are: bottom lines, swordfish lines, purse seines, gillnets, beach seines, gillnets, trammel nets, long lines, pots and traps. And between countries and even regions, there are many variations.

Pelagic industrial fisheries

The fishery has different characteristics in different countries and includes pelagic trawlers and purse seiners. Industrial fisheries are dominant in Morocco and Mauritania. They are described by the FAO Working Group on the assessment of coastal pelagic stocks in the northern region of West Africa (FAO, 2008).

The industrial fishing vessels that exploit small pelagic fish are purse seine and pelagic trawlers. Most of these industrial fishing vessels come from home ports in Eastern Europe and operate in all CCLME countries. In Senegal, semi-industrial fisheries also operate. After the breakup of the Soviet Union, the size of the industrial fleet has been reduced but remains in the region. The largest industrial coastal pelagic fishery among the countries in the CCLME is in the Moroccan and Mauritanian exclusive economic zones (EEZ).

In Morocco, foreign, industrial fleets operating under fishing agreements or under charters almost exclusively exploit pelagic fish. In 2010, sardine fishing in the Moroccan EEZ was accomplished by a fleet composed of heterogeneous coastal traditional seiners, modern vessels equipped with means of conservation (refrigerated seawater - RSW) and pelagic freezer trawlers. These trawlers also fish for other pelagic species, within the framework of fisheries agreements between Morocco, the EU, and Russia.

In Mauritania, industrial fleets that have exploited these resources are almost exclusively foreign. In addition to the fleets of the European Union, including the Netherlands, Russia and Ukraine, coastal pelagic fish are harvested by foreign and domestic fishers based in Nouadhibou. The main coastal pelagic species caught by commercial fishing in Mauritania are the round sardinella (target of the Dutch fleet) and the black horse mackerel (target of the Russian and Ukrainian fleet).

In Senegal, the coastal industrial pelagic fleet is comprised of Russian trawlers and small purse seiners or small "sardinier dakarois." In Gambia, there is no industrial coastal pelagic fishery.

In Guinea, the industrial pelagic fishery targets horse mackerel, mackerel, and flat sardines and constitutes 46% of industrial catches. From 1995 to 2005, there were between three to six foreign trawlers from Russia, Ukraine, Belize, Comoria and Guinea.

In Guinea Bissau, there are no domestic vessels. The only pelagic vessels are chartered and these boats catch mainly horse mackerel, sardinella and mackerel with the mackerel being the most important, especially the scad (carapau). In Cape Verde, the small pelagic fishery was developed (particularly in the 90s) as a fisheries development project. Industrial fishermen or associations commonly use purse seine nets targeting black mackerel. The catches are intended for local consumption or processing industries. Industrial fishing for coastal pelagic fish is practiced by about fifty boats from 11 to 22 meters in length with gross registered tonnage (GRT) ranging from 14 to 126 GRT using the purse seine. These fleets operate in the entire EEZ except for an area of 3,000 nautical miles reserved for artisanal fishing.

Variability in the abundance and distribution of coastal pelagic stocks

These coastal pelagic resources are important both for food security and job creation. The fluctuation of abundance of these species will have a considerable socio-economic impact on the state of development of the CCLME countries.

The important decline of sardine stock in 1997, 2006 and 2010 and the migration of sardinella to the north was related to the impacts of climate change according to scientists and policy makers (Orbi, 2011).

Since 1995, these resources are subject to regular evaluation by the Norwegian research vessel R/V Dr. Fridtjof Nansen through regional acoustic surveys covering the area from southern Senegal to Cape Cantin in Morocco. This activity is undertaken within the framework of a program of cooperation between the countries, FAO and the "Nansen Programme." The acquisition of national research vessels with acoustic equipment initiated a transition for the national vessels to take over the responsibility for the acoustic surveys carried out by the R/V Dr. Fridtjof Nansen. To achieve this, several parallel surveys and intercalibration exercises were carried out to ensure comparable results between the national vessel (national vessels Cherif Al Idrissi of Morocco, Al Awam of Mauritania, and Itaf Deme of Senegal) and the R/V Dr. Fridtjof Nansen, using the latter as a reference. Changes in the survey results were used to estimate sardine biomass (millions of tons) over time - illustrated in figures 2 and 3.

Sardine biomass showed a significant decline in 1997 and 2006 (Figure 2). These years also had remarkable temperature anomalies. In 2006, lesions were observed on the same number of samples of sardine as 1997.

In 2010, the abundance of sardine was estimated in the regional survey coordinated between the national R/Vs of the region: Al Amir Moulay Abdellah from Morocco and Al Awam from Mauritania. The indices calculated were translated using the coefficient of inter-calibration between the boats and the R/V Dr. Fridjtof Nansen - calculated for 2006 for Al Amir Moulay Abdellah Al Awam and 2005 (FAO 2008).

The total biomass of sardine in the northern region of West Africa was estimated at 2,314 thousand tons - 99% of which were caught north of Cape Blanc. Biomass has declined by 48% compared to the levels in November 2009 (nearly 5 million tons). The decrease in biomass is particularly marked between Cape Cantin and Cape Boujdor, with the peak going from 1,105 thousand tons to 94 thousand tons. The biomass in the area between Cap Boujdor and Cap Blanc also declined by 30 percent. This decrease is attributed to the hydrological conditions due to the weakening of upwelling in the summer of 2009.

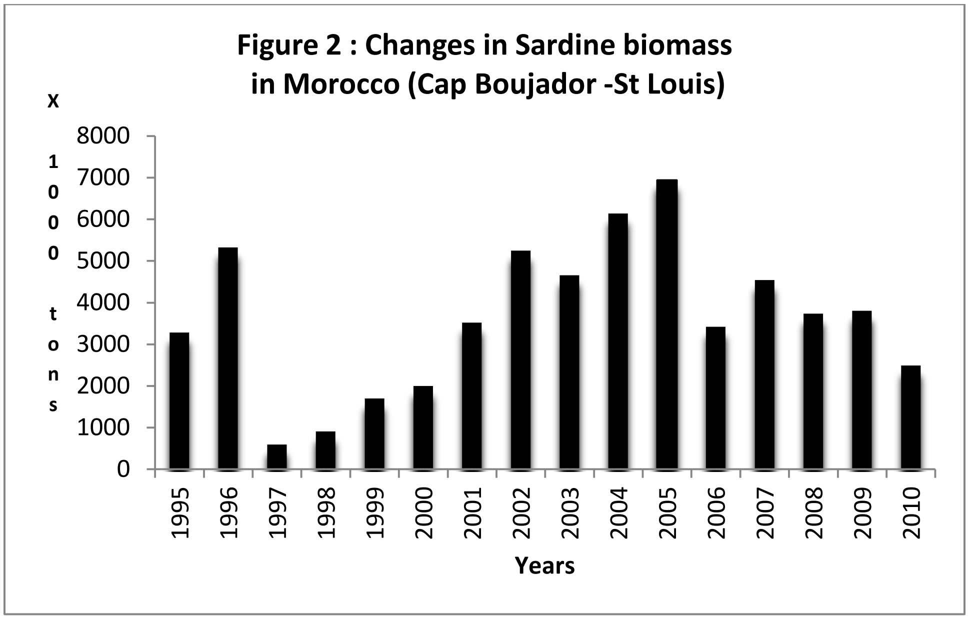


Figure 2. Changes in Sardine biomass in Morocco (Cap Boujador-St. Louis).

Annual changes in sardinella biomass, based on survey results, is presented for the areas of Morocco, Mauritania and Senegal and Gambia (Figure 3). These species, generally located in the south, were found in abundance during the survey period in the north or in the Moroccan zone.

The total biomass of sardinella was estimated at 1,720 thousand tons, of which 1200 thousand tons were *S. aurita* and 460 thousand tons were *S. maderensis*. Seventy-three percent of the *S. aurita* was found between Cap Timiris and St. Louis, and 19 percent between Cap Blanc and Cap Boujdor. The flat sardinella was detected mainly between Cap Blanc and Cap Boujdor, where 96% of the total biomass was found.

The biomass of *S. aurita* in 2010 declined by 52% from November 2009. The decline was 12 percent between St. Louis and Cap Blanc, and 84 percent between Cap Blanc and Cap Boujdor. At the same time, the fish extended towards the north, where 47 thousand tons were estimated between Cap Boujdor and Cap Cantin.

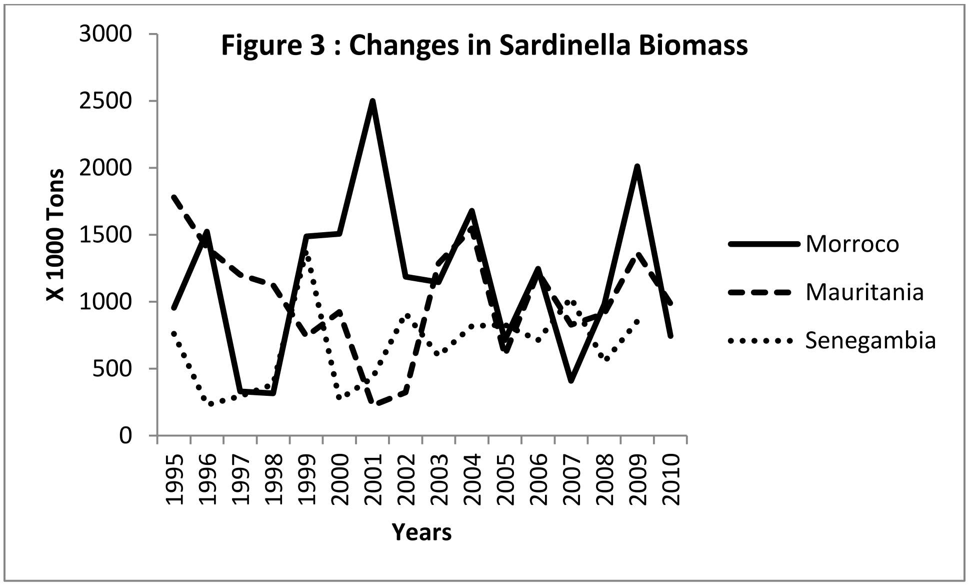


Figure 3. Changes in Sardinella biomass.

Changes in abundance are extreme from year to year and are partly related to recruitment variability of this short-lived species. Current theories focus on examining two assumptions relating to trophodynamics and reproductive health.

(1) Coincidence or non-coincidence between the presence of an appropriate planktonic food, when the larvae begin to feed (Cushing, 1982). Larval mortality depends on the ability of the larvae to access appropriate plankton prey, especially during a critical phase.

In areas of upwelling, plankton blooms depend on episodes of wind, and the amount of plankton food available is related to the intensity of the wind generation of upwelling. This follows a nonlinear relationship: increasing up to a threshold, then decreasing. Indeed, the limiting factor for plankton production is initially the supply of nutrients, and this transitions to the stability of the water column in a second phase (Cury and Roy, 1989). Belvèze (1984) indeed observed that the recruitment of sardines changes with the variance of the wind.

(2) The ability for an individual sardine, not only to survive in isolation, but also to participate in the reproduction and recruitment of the population, and the need to find partners in a state of sexual maturity at the time of spawning (Sinclair, 1988).

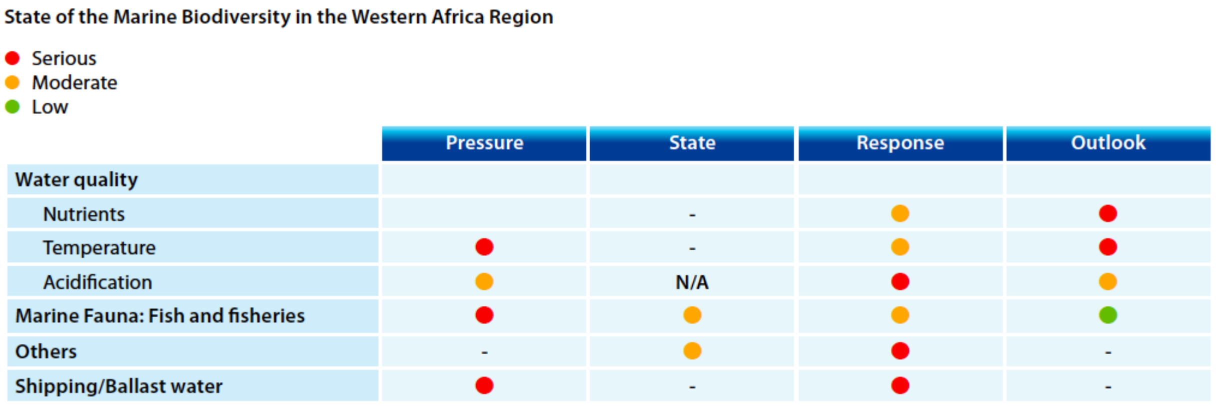
These two hypotheses are complementary, and indicate the importance of the climatic factor.

POLLUTION AND ECOSYSTEM HEALTH (INCLUDING HABITAT CONSIDERATIONS)

Fish resources in the Canary Current are on the decline. Many of the important demersal resources are overexploited and it is necessary to ensure the application and intensification of appropriate fisheries management measures to avoid a possible collapse of these stocks. The pelagic resources are in general fully exploited, but some show signs of overexploitation. These stocks are also highly influenced by environmental factors. Many of the stocks in the region are shared between two or more countries and need to be managed in this context (FAO/CECAF, 2010; Caramelo, 2010).

Some of the underlying causes of the declining fish resources include the overcapacity of fishing fleets (both industrial and artisanal); ecosystem complexity and variability; weak management and monitoring; lack of adequate control and surveillance; insufficient scientific and technical capacity for management; and poor stakeholder participation in management decisions. The magnitude of the illegal, unreported and unregulated catches adds another management challenge (Caramelo, 2010).

The impact of climate change is likely to aggravate these issues by affecting the intensity and seasonality of upwellings, coastal currents, salinity and acidity levels. This, in combination with ocean sea-level rise, coastal erosion and increasing occurrences of extreme weather events will cause further decreasing water quality, changes in fish species distribution and production seasonality, deterioration of mangrove and other coastal habitats, damage to coastal infrastructure and increasing risks for coastal communities and fishermen (Niang, 2010).



State of the Marine Biodiversity in the Western Africa Region

🔴 Serious
🟠 Moderate
🟢 Low

	Pressure	State	Response	Outlook
Water quality				
Nutrients		-	🟠	🔴
Temperature	🔴	-	🟠	🔴
Acidification	🟠	N/A	🔴	🟠
Marine Fauna: Fish and fisheries	🔴	🟠	🟠	🟢
Others	-	🟠	🔴	-
Shipping/Ballast water	🔴	-	🔴	-

Table 2. State of the Marine Biodiversity in the Western Africa Region (UNEP 2010 and Bamba 2010).

SOCIOECONOMICS

The impacts of climate change could hamper the economy surrounding the exploitation of pelagic resources. Hydroclimatic conditions unfavorable to recruitment or to the availability of resources as well as high fishing pressure are serious threats to employment, food security, income from fisheries agreements and the creation of wealth (H. Diop, 2011).

In fact, the fisheries in the CCLME are of major economic and social importance in that they provide sustainable livelihoods, fish-protein and revenue for the coastal populations and States of the region. National economies among the countries depend on a range of sectors, but all countries depend on the economic and social resources of coastal and marine areas. The region is characterized by the presence of important fish resources. Fisheries support an estimated one million jobs (FAO, 2009), including more than 150,000 artisanal fishermen (Sambe, 2009). Coastal artisanal fishermen undertake substantial migrations within the region, and fish and fish products are traded extensively across national borders.

Throughout the last decades, the national fisheries of CCLME coastal states have developed. Total landings reported to FAO in the CCLME area have increased from 22 to 69 percent between 1970 and 2008 (FAO FishStat Plus, 2010; Caramelo, 2010).

The post-harvest sector (unloading, processing and marketing) of fish products is also economically important. Statistics on the economic contribution of this sub-sector to the countries' GDP or the number of people (primarily women) employed in this sector are however very difficult to determine. According to the World Travel and Tourism Council (2010), around 900,000 people are employed by the tourism sector in the CCLME countries. For some countries, like Cape Verde and the Gambia, tourism is one of the main sources of foreign exchange and contributes strongly to the economic performance of the country.

Table 3 shows the contribution of fisheries and tourism (much of it coastal) sectors to the economies of the CCLME countries (Sambe et al. 2011).

Statistics	**Cape Verde**	**Gambia**	**Guinea**	**G-B**	**Mauritania**	**Morocco**	**Senegal**
Population (million)	0.5	1.6	9.6	1.5	3.1	31.2	11.9
GDP per capita (USD)	2,705	377	487	211	847	2,434	900
HDI ranking (1 to 182)	121	168	170	173	154	130	166
Fisheries contribution to GDP (%)	1.25	2.2	3.6	3.7	6[2]	2.5	1.9
Tourism contribution to GDP (%)	11.3	5.1	2.7	x	x	7.7	4
Average fish consumption (kg/pers/yr)	16-22	25-28	12	2.1	17.5	8.7	26.8

Table 3. Socio-economic statistics in the CCLME countries.

Apart from fisheries and tourism; marine, coastal and estuarine zones are highly important for other economic sectors including energy, onshore and offshore petroleum exploitation, agriculture (irrigated flood plains), human settlement and urbanization, transport (both land and sea), industry, and trade. Coastal and estuarine ecosystems provide vital goods and services

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including fresh water (ground water, river water), construction materials (wood from mangroves and coastal forests, beach sand), provision of space for human settlement and urban growth and coastal defense (mangroves, beaches, dune systems).

GOVERNANCE

There are real problems in the governance of pelagic fisheries. These shared stocks constitute a vital interest for each country and there is no concerted management plan. People's vulnerability to climate change associated with the instability of these types of resources and lack of a development plan at the sub-regional level accentuates the difficulties. Studies on governance have been conducted and some recommendations are worth noting here.

Using the criteria of openness and transparency, participation, accountability, efficiency, consistency, adaptability and responsiveness, subsidiarity and proportionality, Catanzano et al. (2009) analyzed the governance attributes for countries in the region (Table 4). The main conclusions of the study indicate:

- Information on the economics is fragmented, limited, not always available and does not circulate
- Organizations involved in the process are young and not always well equipped hence an asymmetry of participation and information
- Procedures for information flows are not transparent
- Participation is well defined in the texts and laws and it has improved over the past decade. However, private organizations involved are still small, unrepresentative and lacking of knowledge in the cases handled
- General responsibilities are set within the texts and laws. The gaps exist, however, between these responsibilities and expectations and there seem to be gaps in the definition of responsibilities, tasks and objectives among countries and more gaps to overcome between institutions.

There is:

- An inconsistency between the objectives of the fisheries sector and macroeconomic objectives in most countries.
- There are inconsistent objectives and goals for the different fisheries sectors (pelagic, demersal, tuna) and the different fisheries segments (artisanal, industrial).
- An inconsistency between the objectives by fishery (by coherent management unit) and the strategies implemented (technical measures, measure of access, management of fishing capacity, development plan, etc.).
- Overall, the effectiveness of management systems in the countries has so far been limited because most stocks are fully exploited biologically.

CONCLUSIONS

The Canary Current is experiencing serious threats to all resources – fisheries, habitats, tourism areas, and the overall economy. The threats are due to overfishing, climate change, habitat degradation, and pollution. As a result, the economy and food security of the CCLME is at high risk from these threats. Science and governance need to collaborate to solve the pending crisis.

Countries **Governance criteria**	**Cape Verde**	**The Gambia**	**Guinéa**	**Guinéa Bissau**	**Morocco**	**Mauritania**	**Senegal**
Openness and transparency	=	-	--	--	+	+	-
Participation	-	-	--	--	+	+	-
Responsibility	-	-	--	--	+	+	--
Effectiveness	-	-	--	-	+	+	-
Consistency	=	-	-	-	+	=	-
Adaptability and responsiveness	-	+	-	--	=	+	=
Subsidiarity and proportionality	-	-	-	-	-	=	-
Total fisheries governance criteria	=	-	--	--	=	-	-
Background Country Governance	+	+	--	--	-	+	+
Fisheries governance evolution trend	+	=	-	=	=	=	+

Table 4. Summary of governance analysis by country.

Signs by criteria: Very low (--), Low (-), Average (=), Good (+), Very good (++)
Signs for total governance: V. unfavorable (--), unfavorable (-), favorable (+),v. favorable (++)
Signs evolution trend: Weakening (-), stable (=), improvement (+)

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4

IMPACT OF CLIMATE CHANGE IN THE GUINEA CURRENT LARGE MARINE ECOSYSTEM REGION

Stephen Maxwell Donkor and Jacques Abe

INTRODUCTION

The Guinea Current Large Marine Ecosystem (GCLME) project is funded by the Global Environment Facility (GEF) with the United Nations Industrial Development Organization (UNIDO) acting as the executing agency, UNEP and UNDP as the implementing agencies and with technical cooperation from the US National Oceanic and Atmospheric Administration (NOAA). The GCLME project is focused on the priority fisheries, pollution, and habitat degradation problems and issues identified by the 16 participating countries in western Africa from Angola in the south, to Guinea Bissau in the north - Angola, Benin, Cameroon, Congo, Democratic Republic of the Congo, Cote d'Ivoire, Gabon, Ghana, Equatorial Guinea, Guinea, Guinea-Bissau, Liberia, Nigeria, Sao Tome and Principe, Sierra Leone and Togo (Figure 1).

Figure 1. Location of the Guinea Current LME.

The major problems identified by consensus in the countries' transboundary diagnostic analysis (TDA) were unsustainable fisheries, as well as the degradation of marine and coastal ecosystems by human activities. The long-term development goals of the project are: (1) Recover and sustain depleted fisheries and (2) Reduce land and ship-based pollution by establishing a regional management framework for sustainable use of living and non-living resources in the GCLME. Priority action areas include reversing degradation of coastal areas, reversing the depletion of living resources, and aggressively developing regional capacity to manage the GCLME.

Oceans cover over 70% of the globe and the health and the wellbeing of humanity and the living environment are inextricably linked. Yet neglect, ocean acidification, climate change, polluting activities and over exploitation of marine resources have made the oceans one of the earth's most threatened ecosystems. This has put in peril not only the life forms that inhabit the planet, but the aspirations of humankind for prosperity and economic growth within the context of sustainable development (UNESCO, 2011).

Climate change is an additional stress for the vulnerable continent of Africa. Africa's climate is predicted to become more variable and extreme weather events more frequent and severe. Changing climate is expected to affect key sectors such as agriculture, water, health, disaster planning, coastal zones and ecosystem management. The regions of West and Central Africa are the most vulnerable to the impacts of climate change and perhaps the least prepared to meet the challenges. African countries contribute only about 3.8 percent of total greenhouse gas emissions, but are disproportionately affected by the impacts of climate change.

Much of west Africa's coastline is low-lying and interspersed with marshes, lagoons, and mangrove swamps that are regularly inundated at high tides and are vulnerable to storm surges, floods, droughts and sea level rise. Additionally, these areas are subject to: anthropogenic impacts from geo-engineering projects/development, canalization, sand dredging and sand extraction for construction purposes, conversion activities (rice, fish/shrimp, sugarcane, salt ponding), coastal settlements and other land-use changes. In particular, the region's wetlands and vast mangrove resources are threatened by tropical storms and flooding as well as by sedimentation and siltation.

GEOGRAPHIC SCOPE

The GCLME extends from Bissagos Island (Guinea Bissau) in the north to Cape Lopez (Gabon) and Angola in the south. Geographically the GCLME extends from approximately 12° N latitude to about 16° S latitude and variously from 20° west to about 12° east longitude. From an oceanographic point, the GCLME extends in a north-south direction from the intense upwelling area of the Guinea Current, south to the northern seasonal limit of the Benguela current. In an east-west direction it includes drainage basins of the major rivers seaward to the Guinea Current front delimiting the Guinea Current from open ocean waters (GCLME, 2006).

The coastal habitats of the GCLME include near shore waters, lagoons, mangrove swamps, estuaries, creeks, and other brackish and contiguous freshwater bodies. The total length of its coastline is 7,600 km including the coastline of the island State of Sao Tome & Principe and the insular regions of Equatorial Guinea (i.e. Bioko and Annobon islands). The region covers a total surface area of about 6.8 million km^2.

RIVER SYSTEMS

Twelve major rivers including the Congo (Congo), Niger (Nigeria), Volta (Ghana), Wouri (Cameroon), Comoe and Bandama (Cote d'Ivoire) enter the GCLME ecosystem from an extensive network of catchment basins transporting greater than 92 million tons of sediments per annum into the Gulf of Guinea (Abe et al. 2004). Among the most important rivers are the

Niger, Volta, Comoe, Sangana and the Congo. The Congo River has the second largest mean annual run-off and catchment area in the world, and freshwater run-off and sediment discharge are estimated at 30-80 tons/km^2 (GCLME, 2006).

The region's major rivers have experienced decreases in average discharge ranging from 40 to 60 percent from 1968-1972 due to a marked decline in rainfall by about 15 to 30 per cent in most areas. Over the last 50 years, high climate variability has been associated with increased desertification and food insecurity in the West African region (Niasse, 2002). The region is considered to be one of the most vulnerable to climate change and unfortunately the least prepared in terms of mitigation and adaptation to its effects. Weather patterns and changes in the strong currents and upwellings that characterize the GCLME region will bring about the greatest changes to mangrove distribution patterns.

In the following paragraphs, we attempt to summarize the expected impacts of climate change and variability on the GCLME and the socioeconomic consequences on for hundreds of millions of people who depend on the ecosystem for their livelihoods.

SEA LEVEL RISE

Sea level rise (SLR) due to climate change is a serious global threat. Dasgupta et al. (2007) in their assessment observed that sub-Saharan Africa will experience an impact from SLR. One quarter of one percent of the region's GDP would be impacted by a one meter SLR.

Within the GCLME, Guinea Bissau would experience the greatest land area impact - four percent with a two meter SLR and 10 percent with a four meter or greater SLR. Five percent of Benin's GDP and approximately 15 percent of the country's wetlands would equally be impacted, as much of the region's coastline is low-lying and interspersed with marshes, lagoons, and mangrove swamps. The potential for local impacts of SLR less than one meter would be substantial in terms of shoreline retreat and coastal erosion, increased frequency of submergence of coastal wetlands and salt-water intrusion into estuaries and coastal aquifers. The population expected to be impacted is illustrated in Figure 2.

Due to increasing rural-urban migration of more than three percent per annum, this global analysis can overlook potential local impacts.

In a comparative study, Dasgupta et al. (2007) looked at the percentage of land area, population, and GDP that could be affected by Sea Level Rise (SLR) ranging from one to five meters.

Approximately five percent of Benin's GDP would be impacted by a one meter SLR. Agricultural areas would be most impacted in Guinea Bissau. Approximately 15 percent of Benin's wetlands would be impacted by a one meter SLR.

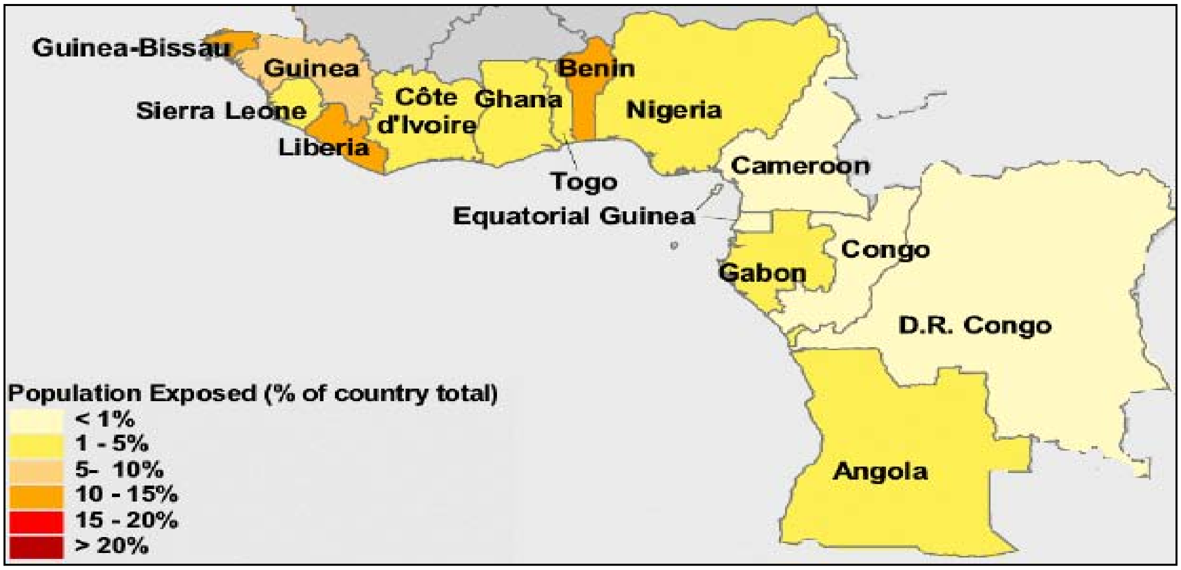

Figure 2. Impact on the populations of GCLME countries by sea level rise of 5 m (Dasgupta et al. 2007).

Global sea level is estimated to have risen by 10-25 cm over the past 100 years. The IS92a Greenhouse Gas Emissions Scenario (Archer and Pierrehumbert, 2011) estimates a global sea level rise, in addition to that recorded in the mid-1990s, of 6-25 cm by 2030, 10-65 cm by 2070 and 23-96 cm by 2100. Therefore, a sea level rise of less than one meter would inundate extensive mangrove areas in Gabon, Cameroon, Guinea, Guinea Bissau, and Nigeria. This would increase the rates of erosion of the shoreline. The coastal lagoons of Angola, Ghana and the entire lagoon complex on the west coast would also be vulnerable to sea storms, flooding and inundation. Sea level rise is also a major threat to low-lying coastal urban centers and ports, such as Lagos, Port Harcourt, Cotonou, Lome, Abidjan, and Conakry. Impacts could result in major and disastrous losses on income from coastal industries and port activities throughout the region, as well as loss of opportunities for development of tourism.

SALT WATER INTRUSION

In the GCLME region, dam construction has sometimes caused salt water intrusion into both surface and ground fresh water sources, for example in Ghana just after the construction of the Akosombo Dam. Rising sea levels have polluted the water sources for thousands of inhabitants and created an unprecedented rise in salt water-related health problems. The seasonal flood of the Volta River replenishes the floodplain and its powerful flow prevents seawater from travelling up the estuary. In the 1960s, the Volta underwent a profound change when the Akosombo Dam was constructed. Much of the river's drainage basin was flooded to create Lake Volta and the flow of water became controlled by the power generation priorities of the Volta River Authority. Over the last fifty years, mismanagement of this river system has caused a reduction in water reaching the downstream towns and villages, allowing seawater to encroach upstream and pollute the purification plants supplying fresh water.

PRODUCTIVITY

Issues related to phytoplankton in the Gulf of Guinea have been documented by several authors including most recently - Kusemiju et al. 1998, Wiafe and Frids 2000, Yakub 2002, Folack and Yongbi 2009, and CSIR 2010. Folack and Yongbi (2009) observed new appearances of

Guinadias sp., *Plantoniella* sp., *Rhizosolenia setigera*, *Thalassiothrix* sp., *Pleurosigma normanni*, *Gonyaulax spinifera*, *Ceratium fuscus* and *Ceratium lineatum* in Kribi and Limbe coastal waters.

Among zooplankton, the authors also recorded increases in numbers of species in 2006 - 2009 and new appearances of the copepods - *Oncaea* sp., *Eucalanus piletus*, *E. attenuates* and cladocera species - *Podon* sp., *Farranula carinata* and *Copilia mirabilis* in 2007-2008.

Data from the Continuous Plankton Recorder (CPR) in the Gulf of Guinea revealed increases in the sea surface temperature (SSTs) and this has serious implication for the distribution and abundance of the plankton – which constitute the prey of small pelagic fish species. A significant result of the CPR surveys is the decline in abundance of phytoplankton and zooplankton as SST increases (GCLME Productivity Demonstration Project, 2010a).

Armah (2006) recorded a total of 71 priority biodiversity areas in the GCLME region. Although several biodiversity reserves exist, many of these have not been formally designated. Museums of marine biodiversity are very few or non-existent in most of the countries. A number of Ramsar sites (wetlands of international importance) have been designated for protection or proposed. The Ramsar sites in Ghana are of high importance for maintaining the biodiversity of coastal birds, mainly migrant waders. Marine and Coastal Protected Areas, such as those in Benin, Nigeria and Cameroon, are established to limit harvesting of coastal resources and ensure their sustainable utilization. They conserve biodiversity by providing refuge for marine fauna and flora and undisturbed sites for research, monitoring, education and tourism. Strict nature reserves are required for the protection of threatened and endangered species to prevent the loss of such biodiversity. The region has not yet achieved the world target of 20 percent protected areas by 2012.

Figure 3. Stranded green algae on the beach at Half Assini on the western shore of Ghana close to Cote D'Ivoire in May 2009. Photo courtesy of Carl Fiati, EPA, Ghana.

FISH AND FISHERIES

With the advent of the GCLME project, fish trawl and productivity surveys have been conducted on the RV Nansen in 2005, 2006, 2007 and 2010 in collaboration with FAO and the Institute of Marine Research in Norway. These surveys, combined with historical information, are providing invaluable insights on the extent of fishery depletion, the carrying capacity of the ecosystem and maximum sustainable yields (MSY), as well as undesirable shifts in biological diversity. Declining catches in the artisanal sector can be related partly to a rise in sea temperature and a loss of zooplankton due to environmental causes. The region is rich in terms of diversity and abundance of fish and other marine organisms. According to FAO (2005b), during the 1950-2002 period, 22 coastal states and 47 distant water fishing nations reported about 190 species or groups of species in the commercial catches from the Western African Seas region under the influence of the Canary and Guinea currents. Important multi-national fishing fleets (EU, Japan, Korea) operate in the Western African Seas region, targeting tuna and highly valuable demersal fish species. Total production from capture fisheries in the Western African Seas region was about 3.2 million tons in 2007 including about 2.4 million tons produced by the region's coastal States (FAO, 2009).

The six member states of the Fishery Committee for the West Central Gulf of Guinea (FCWC) - Benin, Cote d'Ivoire, Ghana, Liberia, Nigeria and Togo produce about 900,000 metric tons of marine fish annually from artisanal fisheries as the backbone of fishery production in the central Gulf of Guinea region. The major fish resources in the area are round sardinella, skipjack tuna, big eye grunt, madeirian sardinella, and Bonga shad. The countries have several shared fish stocks and identified a need for cooperation and shared management of these resources.

Since 2000, capture fisheries production of the FCWC countries is in a declining trend. A Working Group of the Committee for Eastern Central Atlantic Fisheries (CECAF) agreed that stocks of small pelagic fish species along the coasts of Cape Verde, Guinea-Bissau, Guinea, Sierra Leone, Liberia, Côte d'Ivoire, Togo, Ghana, Benin, Nigeria, Cameroon, Sao Tome and Principe, Equatorial Guinea, Gabon, Congo, Democratic Republic of Congo and Angola are in decline.

The round sardinella (*S. aurita*) constituted nearly 32 percent of the catches of small pelagic species, and this is the most important species in the region. A dynamic version of the Schaefer model was used to assess the current state of the stocks. The preliminary results of the assessments indicate the overexploitation of *S. aurita* (northern and western stocks), *S. maderensis* (northern stock), and *S. maderensis* (western stock). The *Ethmalosa fimbriata* (southern stock) is underexploited while *Trachurus trecae* (southern stock) is fully exploited.

POLLUTION AND ECOSYSTEM HEALTH

A serious, noticeable impact in coastal areas is pollution arising from discharges of domestic and industrial effluents and uncontrolled disposal of solid wastes, especially in the highly industrialized and densely populated coastal cities. Fisheries, recreation, and tourism are impaired by this pollution. Sporadic mass mortalities of fish in lagoons have been reported near urban areas of Lagos, Abidjan and Accra. Visible evidence of pollution and habitat degradation includes putrefying garbage, septic and discolored waters, emission of unpleasant and offensive odors, and unsightly surroundings near urban water bodies (e.g. Ebrie lagoon). There is a paucity of reliable data on the tonnage of solid waste and volume of effluent discharge into coastal waters but the magnitude is a serious concern. Management measures have been introduced to reduce the load and control the point sources of such pollution. The root cause of coastal pollution is rapid, unplanned urbanization arising from rural-urban migration, the preference to locate industries in coastal areas with developed infrastructure, and recent political upheavals. Under the GCLME project, collaboration with the International Maritime Organization has resulted in regional oil/chemical spill contingency planning that was updated/refined through consultations and adopted by all countries during the last COP9 of the Abidjan Convention states.

The development of regionally integrated National Programmes of Action to control pollution of the Marine Environment from Land Based Sources and Activities (LBS/A) was launched with the UNEP-GPA program. Documentation of the UNEP-GPA program is available for the 16 Interim Guinea Current Commission (IGCC) countries. This has paved the path to the development of an LBS/A Protocol for the Abidjan Convention in June 2007 that was recently adopted during the 9th Conference of Parties for the Abidjan Convention.

COASTAL HABITATS

The coastal areas and resources of the GCLME play a crucial role in the socio-economy of its inhabitants. Sustainable utilization of the coastal area is predicated on the ecological, cultural and economic contributions of coastal resources to the local communities. With increasing population and rapid rural-urban drift to industrial centers in the coastal area, the dependence on coastal resources is expected to keep increasing. One such problem is the increasing number of land-based activities and processes that result in what is termed “Physical Alteration and Destruction of Habitats” (PADH) apart from those resulting from natural processes and activities (GCLME, 2006b).

There are many causes of habitat degradation in the GCLME region, however the most common involve: improper coastal/shoreline construction; uncontrolled mangrove cutting and conversion for agricultural purposes; coastal sand and gravel mining; salt extraction; port and harbor construction; oil and gas exploration and exploitation; deforestation and removal of vegetated cover; and sedimentation/siltation processes. The least common is biological alteration which includes the accidental or deliberate introduction of alien, invasive species.

The coastline is highly subject to natural erosion and sedimentation processes due to high wave energy and strong littoral transport. It is frequently intensified by human activities such as sand/gravel mining along the coast, damming of rivers, port and jetty construction, dredging, mangrove deforestation and disturbance of the hydrological cycles. Harbor and jetty construction are responsible for phenomenal erosion rates (5-25 m per year) in Nigeria, Benin, Togo, Ghana and Cote d’Ivoire due partly to alteration of long shore sediment transport and dredging activities to maintain artificial harbors. Ibe (1988) recorded coastal erosion rates for some beaches on the Nigerian coastline, their causative factors and mitigation measures while UNEP (1999) gives examples of habitat destruction arising from shoreline retreat and erosion.

On the shorelines, haphazard construction of coastal infrastructure and leisure resorts (e.g. breakwaters, piers/jetties, groynes, shipways, seawalls, hotels) is associated with various negative impacts such as accelerated sand/beach erosion, sedimentation and changing biodiversity due to changing habitat characteristics. Most of the phenomenal coastal erosion in the region is aggravated by uncontrolled sand mining and construction of coastal amenities with little or no setback limits from advancing shorelines (Fig. 4, 5 and 6). There is a need for capacity building towards improved coastal construction design and techniques. Several low-cost protective measures and techniques are in place within the region but their full effectiveness can only be achieved through better understanding of shore and ocean dynamics, government intervention through coastal land use planning, policy and legislation for improving the health, and sustainable development of the GCLME coastal area.

Figure 4. Cotonou, Hotel PLM, October, 2005 and an example of coastal retreat in Benin.

Figure 5. Coastal protection measures in Togo.

Figure 6. Interface of the sea with the Keta lagoon and protective structure built along the Keta beach in 2002-2003 to protect Togo from erosion.

The GCLME coast is home to vast forest and mangrove resources of biological and socio-economic importance. Virgin Mangrove Forest provides habitat to a variety of flora and fauna. Eight true mangrove species are found in West Africa. The five countries containing the largest amount of mangrove cover (km²) are Gabon (1,606), Cameroon (1,957), Guinea (2,039), Guinea Bissau (2,999), and Nigeria (7,386) (UNEP, 2007). Mangrove destruction and degradation result from over-exploitation/overharvesting, deforestation, and mangrove conversion activities such as rice and sugar cane cultivation, mariculture, salt ponding, sand mining, and land reclamation for various purposes. The removal of vegetation cover is a major problem leading to sedimentation along river banks, estuaries, deltas and mangroves. Excessive and destructive sedimentation rates caused by poor land use management and flooding have been reported on wetlands and river mouths of the Densu (Ghana), Niger (Nigeria); Ilha de Chical (Angola); Freetown (Sierra Leone); and coastal plains in Congo.

Figure 7. Mangrove degradation in Cabinda, Angola.

Solid and liquid waste dumping from industrialized coastal urban centers, dredged spoil disposal, and land reclamation also contribute to sedimentation/sediment mobility. Degraded mangrove sites recover rather slowly and restoration efforts are tedious and often end in poor rates of success (Figure 7). The root cause of mangrove destruction throughout the region is the absence/lack of alternative cheap energy source and perhaps poverty in rural communities which limits access to available alternatives (e.g. solar, biogas, use of briquettes). The development of alternative livelihoods for fishermen, continuing education, updating of existing legislation and enforcement procedures, and promotion of environmentally friendly fishing practices should improve ecological conditions in fragile mangrove habitats.

Mining activities result in land degradation (e.g. open pits, soil erosion, highly colored effluents from phosphate plumes, siltation and sedimentation). Mining activities have been destructive to the landscape in Togo (phosphate mines) and Guinea (bauxite and aluminum mines) among others. Oil exploration and exploitation are huge threats to the coastal and marine environment in the oil-producing countries within the region (Nigeria, Angola, Cameroon, Gabon, Equatorial Guinea, and Congo) and potential producers (Sao Tome and Principe). The value of mandatory Environmental Impact Assessment, enforcement of Environmental Management Plans including abandonment and decommissioning and periodic Environmental Audits are recommended to reduce adverse impacts and maintain good environmental quality.

PROJECTED IMPACTS OF CLIMATE CHANGE and MITIGATION ACTIONS

Climate change is widely accepted as a real threat and developing countries are already being affected. For the 16 countries bordering the GCLME, climate change is a development issue. Climate risks are highest in poor countries and the poorest countries and communities stand to suffer the earliest and the most. Climate change threatens the development gains and achievement of the Millennium Development Goals (MDGs). African countries are highly vulnerable to climate change which is expected to affect all key sectors such as agriculture, water, health, disaster planning, coastal zone and ecosystem management.

Key impacts include drought, dust and sand storms, limited water resources (water stress), agriculture/food security (reduction in soil fertility, livestock productivity and increased incidence of pest attacks), and coastal zone (flooding and extreme weather events). The risks of catastrophic events will increase with temperature. The projected environmental impacts warrant formulating actions for mitigation and adaptation. UNDP (2009b) reported that the African continent is vulnerable to climate change because of its large population living along the coast - 25 percent within 100 km of the coast and in low-lying areas. With a heavy reliance on rain-fed agriculture, a high dependence on natural resources, and poor access to modern and sustainable energy services, the countries sharing the resources of the GCLME are particularly vulnerable.

In order to mitigate these threats and address some of the concerns for the poorest countries, the World Bank in 2008 launched a Strategic Framework on Climate Change and Development and New Financing Initiatives for Mitigation and Adaptation. Also under its US $92 million program - “Supporting Integrated and Comprehensive Approaches to Climate Change Adaptation in Africa” - supported by the government of Japan, UNDP will assist 21 countries across the African continent in incorporating climate change risks and opportunities into national development processes. The key envisaged outcomes are the following:

- Countries have introduced dynamic, long-term planning mechanisms to manage inherent uncertainties of climate change;
- Countries have built leadership and developed institutional framework to manage climate change risks and opportunities in an integrated manner at the local and national levels;
- Countries are implementing climate-resilient policies and measures in priority sectors;
- Financing options to meet national adaptation costs have been expanded at the local, national, sub-regional and regional levels;
- Knowledge on adjusting national development processes to fully incorporate climate change risks and opportunities generated and shared across all levels.

THE HUMAN CONTEXT

The human context, be it political, social, cultural or economic, has both direct and indirect impacts on the environment. The population of the sixteen GCLME countries was about 240 million in 2006 and is expected to reach 542 million in 2030 (UNIDO/GCLME, 2010). Population growth rates remained positive and have increased from 2.06 percent for the period 1970-75 to 2.52 percent in 2000-2005. This is projected to decrease to 1.92 percent in 2025-2030. The population in the region as a whole is quickly transforming from rural to urban although at varying rates (adapted from WRI, 2008a – State of the Coastal and Marine Ecosystems in the GCLME region, 2010). The rapid population growth in the coastal zone has caused increased pressure on the economic and social infrastructure, with consequences for environmental health and management. Similar to conditions in the rest of the world, many of the region's poor are crowded in urban slums and exposed to socio-economic dislocations, poor sanitation, high crime rates, and serious environmental degradation.

GOVERNANCE

Restoring degraded habitats and depleted resources to enable them to regain full economic potential is a legitimate concern in Integrated Coastal Areas Management (ICAM) - a system for controlling development and other human activities in the coastal areas. This takes a long time and often incurs huge expenses. However, most restorations (e.g. mangrove restoration) are expected to yield major economic returns by reviving the major ecological and socio-economic functions of the restored habitats (UNIDO, 2001). Restoring polluted ecosystems is harder, more time consuming and expensive**.** ICAM is a comprehensive, integrated framework for policy, coordinated planning and holistic management to sustain or improve the quality of coastal environments. The approach combines resource conservation, biodiversity preservation and economic development to preserve social prosperity of coastal communities in the long term. ICAM requires the involvement of all stakeholders (public and private) and community support to sustain the functional integrity of coastal resource systems that generate goods and services for human welfare.

The GCLME Regional Coordination Unit is mandated by participating countries to be their regional hub and arrowhead in the implementation of global programs such as the GPA (with UNEP-GPA), the Globallast (with IMO), Global Mercury (with UNIDO), Early Warning Systems (with AU and IOC-UNESCO), POPs (with UNIDO), Global Ocean Observing Systems (with IOC-UNESCO), Historical Fish Data repatriation (with FAO) and Waste Water Management (with UNEP-GPA and UNESCO-IHE). The GEF-supported strategic action program provided the ecosystem-based framework for forward movement to recover and sustain GCLME goods and services.

With the clear show of political will by IGCC/GCLME member states as stated in the Abuja (2006) and Osu (2010) Declarations, the transformation of the IGCC to an independent permanent Guinea Current Commission (GCC) will provide a sustainable governance institution. The formation of the GCC will ensure an integrated ecosystem approach to managing the Guinea Current Large Marine Ecosystem and its living and non-living resources for socio-economic development. In this way, the people of the Guinea coast can meet the goals contained in the strategic action plan (Interim Guinea Current Commission, 2008).

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5

CLIMATE CHANGE AND VARIABILITY OF THE AGULHAS AND SOMALI CURRENT LARGE MARINE ECOSYSTEMS IN RELATION TO SOCIOECONOMICS and GOVERNANCE

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INTRODUCTION

In 2008, the GEF and nine countries of East Africa and the western Indian Ocean region (Comoros, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, Somalia, South Africa and Tanzania) agreed to provide financial and logistical support to a project for restoring and sustaining the goods and services of both the Somali Coastal Current LME, and the Agulhas Current LME and adjacent areas, in a single project entitled the Agulhas and Somali Current LMEs Project (ASCLME).

The Somali Coastal Current LME extends from 10°S in the south to 11°N in the north. The eastern boundary of the Somali Current LME extends northward along the coasts of Tanzania, Kenya, and Somalia, gradually tapering off as it approaches the Horn of Africa's tip.

Figure 1. Location of the Somali Coastal Current LME and the Agulhas Current LME along the coast of east Africa (from Sherman and Hempel, 2008).

Despite a series of direct observations of the Somali Coastal Current, a unified concept is still missing that could explain the observed variability of this western boundary current. Yet the two opposing views of regional circulation recognize a key role played by the monsoon (Schott and McCreary, 2001; Fieux, 2009). According to the first view (Schott and McCreary, 2001), the Somali Current is driven by the southwest monsoon during the boreal summer and extends northeastward all the way to Ras Hafun, a major cape at 10.4°N; during the boreal winter the current reverses due to the northeast monsoon and flows southwestward. The second view (Fieux, 2009) postulates the existence of two large-scale gyres that are most prominent during the summer monsoon when the southwesterly winds drive upwelling circulation off the coasts of Kenya and especially Somalia. During the boreal winter, the dominant northeasterly winds result in the spin-down of the Somali gyres. The regional circulation is further complicated by current reversals in the subsurface, intermediate, and deep layers (Reid, 2003). During the south west monsoon, wind-induced coastal upwelling brings cold, nutrient-rich water to the surface layer, creating favorable conditions for fisheries, while the sharp contrast between cold upwelled water and warm offshore waters creates sharp SST fronts easily detected from satellite imagery (Belkin, Cornillon, and Sherman 2009; Heileman and Scott 2008).

The Agulhas Current LME extends from 10°S in the north to 37°S in the south, covering a large area of southern African waters off the coasts of Mozambique and the Republic of South Africa, and encompassing the islands of Madagascar and Comoros. The Agulhas Current is a warm western boundary current flowing southwestward along the east coast of South Africa, retroflecting south of the Cape of Good Hope, then flowing eastward as the Agulhas Return Current (Lutjeharms 2007, Heileman, Lutjeharms, and Scott 2008). The source area of the Agulhas Current is characterized by a series of clockwise and counterclockwise eddies south of the Madagascar and Mozambique Channel; this area is also affected by the East Madagascar Current (Siedler et al. 2009). The Agulhas Current, Agulhas Retroflection and Agulhas Return Current are, respectively, the northern, western and southern limbs of the Southwest Indian Ocean subtropical gyre.

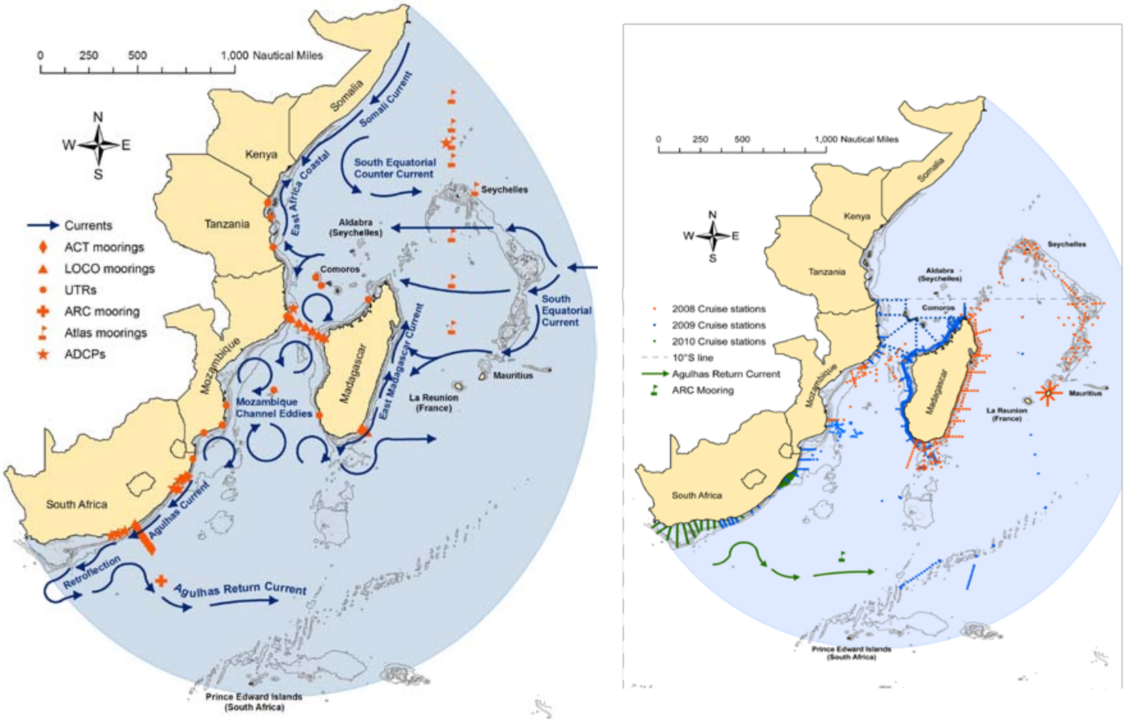

Figure 2. The ASCLME system boundary for project activities and data capture is denoted by the blue ellipse. The left hand panel denotes the known prevailing current patterns in the region (as defined or confirmed through the Project) along with deployed long-term monitoring instrumentation currently in place. In the summer, the prevailing current directions and their positions alter under the influence of monsoons, the circulation pattern of the Somali Current and the East African Current is reversed while the South Equatorial Counter Current tends to move northwards. The right-hand panel shows cruise sampling stations to date. It is notable that piracy activity in the northern region has precluded the deployment and maintenance of the northernmost ATLAS and ADCP moorings. Maintenance of the more southerly moorings is also increasingly threatened by such security issues.

The region's sectoral management and research bodies operate as a "western Indian Ocean" bloc, particularly in East Africa and the island states (Comoros, Madagascar, Mauritius, Seychelles and the French Indian Ocean Territories). This long term cooperation is proving useful for effective management of transboundary issues. To this end, the UNDP-supported, GEF-financed ASCLME Project (www.asclme.org) is coordinating regional efforts to manage the region's marine and coastal resources. This approach is enhanced by building partnerships and alliances and strengthening existing institutions, along with a comprehensive data and information collection program (Vousden et al. 2008).

Efforts to Consolidate and Build Scientific Knowledge through Development of Partnerships

The multi-national, transboundary management actions needed in the ASCLME require as much relevant information as possible at national level and garnering additional scientific information where data gaps are identified. The ASCLME Project created a novel approach to the traditional Transboundary Diagnostic Analysis (TDA)/Strategic Action Programme (SAP) approach adopted by GEF-funded International Waters projects - comprehensive Marine Ecosystem Diagnostic Analysis (MEDA) reports. These reports, compiled at a national level, give detailed insight into the state of knowledge and help harness sparse literature and other difficult to access information. The MEDA reports are vital and build support and understanding for the project. The MEDAs include comprehensive bibliographies of existing information, which will be invaluable in long term management. Ultimately, this information will be distilled into the regional TDA and be essential background information for the SAP, which will drive the implementation of management actions throughout the region. The MEDAs also provide a valuable foundation for National Action Plans/Programs and therefore provide a useful anchor for the TDA and SAP process in each country.

The ASCLME Project and its partners have undertaken several research cruises in the region. However, these efforts have been hampered by the effects of piracy on security in the northern part of the ASCLME region, and have precluded international research activities (Jones, 2011; Smith et al. 2011). A "Piracy Exclusion Zone" was put into effect, marking the area where the risk of attack was considered unacceptable. This was initially set at 10°S in 2008, but was subsequently moved to 12°S. As a result, there is a significant gap in our knowledge of the region including the extent of moored *in-situ*, long-term monitoring equipment in the exclusion zone. Given the dynamic nature of the Somali Current area, with seasonally reversing currents and an unusual tropical upwelling system, more *in situ* research is warranted. There is a large knowledge gap in the more northerly regions of the ASCLME. Plans are under development to try and address this gap through more detailed analysis of remote sensing products, repatriation of historic data, reconstruction of fisheries data, and a more recent objective to deploy autonomous gliders (self-propelled data collection platforms) within this system.

To supplement targeted research cruises and gain insight into variability caused by seasonal and other patterns, the ASCLME Project has deployed long term instrumentation and made use of existing datasets. Currently, ocean observing systems are sparse in their coverage compared with corresponding terrestrial and atmospheric systems, although programs like Argo (a global network of drifting floats that measure temperature and salinity in the upper 2,000 meters of the ocean) are helping to fill in this critical gap, along with a growing constellation of increasingly sophisticated environmental monitoring satellites.

The subsurface Long-term Ocean Climate Observations (LOCO) array has monitored current flow in the Mozambique Channel for nearly a decade (Ridderinkhof & de Ruijter, 2003; Ridderinkhof et al. 2010). In 2010, this network was extended off southwest Madagascar to monitor variability of the poorly understood East Madagascar Current. This data will form a key foundation of understanding of the broader system and provide a detailed baseline record for measuring future variability.

Further long term monitoring sites include a network of Underwater Temperature Recorders (UTRs) and current meters (ADCP – Acoustic Doppler Current Profilers) throughout the region. The Agulhas Current Time-series (act.rsmas.miami.edu/) will supply a detailed three year record of the Agulhas Current, the first such long-term data set. The ACT will likely prove vital in understanding and modeling this important oceanographic feature.

The ASCLME Project also seeks to understand the interaction between the ocean and the atmosphere. Arrays like ATLAS (Autonomous Temperature Line Acquisition System) moorings will help to correlate oceanographic parameters in the upper 500m of water column with *in situ* atmospheric measurements. In essence, an ATLAS mooring is a comprehensive atmospheric weather station above an "ocean weather station." In the Indian Ocean, this array is called RAMA (The Research Moored Array for African- Australian Monsoon Analysis and Prediction; McPhaden et al. 2009). See Figure 3 below.

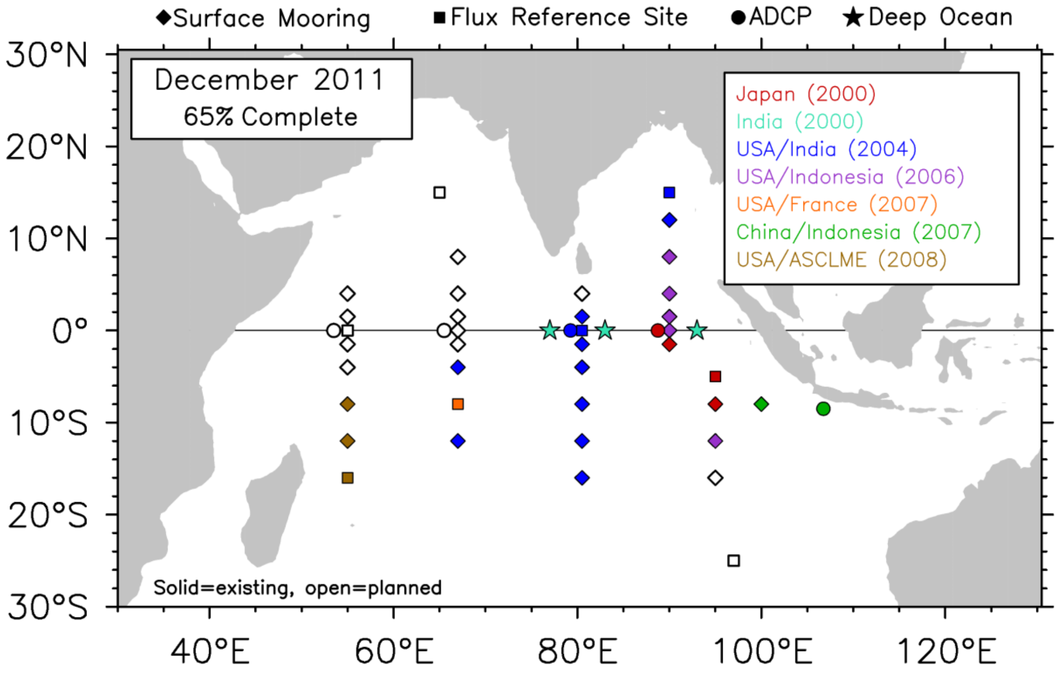

Figure 3. RAMA sites in the Indian Ocean. Note the absence of sites in the areas affected by piracy. Continued maintenance of the northerly 55ºE moorings is now threatened. Unfilled shapes denote sites with no currently deployed instrumentation. Image courtesy PMEL/NOAA http://www.pmel.noaa.gov/tao/rama/.

Such instrumentation is augmented with remote sensing (satellite) observations which require regular calibration from *in situ* measurements and are often hampered by cloud cover. The ATLAS moorings also cannot penetrate much beyond the surface of the ocean, leaving vast areas of the oceans effectively unmonitored (and usually unstudied).

The ATLAS moorings also record temperature and current data to a depth of 500 m and the LOCO moorings provide similar data down to 1000 m plus (with CTDs down to 2,600m). However, their limited coverage (3 ATLAS moorings along the 55 degree east longitude and a recently reduced coverage of 8 LOCO moorings east and west of Madagascar) leaves vast areas of these oceans effectively unmonitored on a permanent basis (and much of it unstudied).

Much of this instrumentation and data capture and analysis are being orchestrated through partnership agreements between ASCLME and a number of national, regional and overseas institutions (e.g. NOAA – US National Oceanic and Atmospheric Administration: NIOZ – the Royal Netherlands Marine Research Institute; ACEP – the African Coelacanth Ecosystem Programme; DEA – the South African Department of Environmental Affairs; DAFF - the South African Department of Agriculture, Forestry and Fisheries).

The ASCLME Project is also a partner in a number of regional and global ocean and atmosphere observing initiatives and contributes towards the objectives of GOOS (www.ioc-goos.org) in the western Indian Ocean. GOOS is designed to be a permanent system of observations, modeling and analysis to support operational ocean services worldwide. Members contribute platforms of observation, including ARGO floats, drifting buoys, installed devices on commercial and recreational vessels, research vessels, commercial ships and open-ocean moorings.

It may sometimes be challenging – if not impossible – to determine whether the ecosystem-level effects of environmental change are due to climate change *versus* environmental change caused by other human activities (e.g. fisheries, coastal development, pollution). In most cases, these impacts will likely act in concert.

Challenges to Communication and Implementation

There is often a somewhat uneasy relationship between management/governance and research/science realms. Much of this likely stems from miscommunication and misunderstanding than from truly different goals or insurmountable differences. A route must be found to surmount the “disconnect” between the two realms.

Researchers typically want to ensure their research has achieved statistically significant results at the 95% or greater level before making recommendations, while policy-makers and managers typically need answers in very short timescales. Good research takes time, and much of this research requires decadal or longer time series data for rigorous scientific consensus to emerge. Unfortunately, management of the marine environment often cannot wait until such studies are completed (where they have even begun), and requires a much more dynamic and responsive interplay between the research community and governance/management bodies.

Many policy-makers feel that scientific language is impenetrable, and conversely, researchers feel they are misunderstood by policy-makers. Clearly, there is a role for skilled scientific communicators who translate the data and information created by research for the needs of policy and management agencies. Such policy advice must convey not only factual information, but should also provide several alternative management scenarios with associated risks, which policy-makers can use to balance the various, often conflicting, needs of society as a whole.

Political changes can lead to the loss of government officials who are well acquainted with the marine environment. Assuming that all policy-makers will be familiar with these issues is unrealistic. It is likely that communication and mentorship efforts are best focused upon middle and senior management in civil service and management institutions, rather than party political structures.

The private sector has a profound impact on the marine environment and is often overlooked. Key sub-sectors engaged in utilizing the goods and services of the ASCLME are marine transport, tourism, aquaculture, mining and fisheries. Many companies within these industries see environmental issues as a marketing or social responsibility. This provides significant opportunities. Rather than forcing behavior through legislation, private sector participation can be encouraged through, for example, vessel of opportunity programs which provide monitoring data; voluntary installation of vessel monitoring systems; fisheries observers programs; and other commercially supported research/monitoring activities by offering incentives such as tax credits. Consumer perception is another powerful incentive in societies that place a premium on environmental concerns. Given that large corporations control larger budgets than many governments, these potential avenues of support should certainly be explored.

Further challenges exist in fiscal, human and infrastructural capacities within the region. Composed of developing world economies and small island states, areas of expertise can be fragmented, particularly in terms of offshore marine science. Here the ASCLME has taken a novel approach, where each country has produced a National Training Plan, which not only summarizes present capacity and training available in each of the participating countries, but proposes key national areas for priority intervention. A key starting point has been the recognition that while the ASCLME project has been able to train a significant number of individuals in the region, to be sustainable we need to work on institutional support. States also face other pressing developmental commitments, and much of the research equipment available, including research vessels, is of advanced age. Where equipment does exist, there is often a lack of expertise available, due a lack of training and staff turnover. Taking this into account, the ASCLME is compiling a Regional Training Plan. One key element of this plan is the formation of a Capacity Building and Training Alliance, made up of key training institutions throughout the region. Thus, regional training priorities can be discussed and regional priorities can be addressed. On-going and future monitoring programs will make the best use of the limited research vessels available and data from remote sensing, drifting sensors and moorings.

Environmental Variability

“Environmental Variability” consists of seasonal or other periodic cycles, distinct from climate change, and results in shifting patterns or intensities.

The continued political instability in Somalia and the related piracy activities have precluded international research activities in the northern parts of the ASCLME (Jones, 2011; Smith et al. 2011). This reduces our ability to detect change and precludes the generation of a contemporaneous detailed baseline assessment as conducted in the South.

Aside from seasonal changes and weather, the two overriding drivers of large scale environmental variability in the ASCLME region are the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). The impacts of these events can have profound effects on the region and it would be useful to be able to accurately predict them, or at least have some advanced warning of them, at the governance level.

Observed Impacts of Environmental Variability and Climate Change

Existing literature, international research, and findings from the ASCLME project illustrate the environmental variability and effects of climate change in the region. Sea level rise and warming are having specific impacts in the region. Although the global mean for sea level rise since 1992 (observed by altimetry) has been on the order of 3.4 mm per year, it has become clear that this rise is not uniform; in particular, a trend of up to 10 mm per year has become apparent around the Indian Ocean islands (Cazenave and Llovel, 2010). Although the Indian Ocean has experienced some of the strongest warming globally (up to 1ºC increase since 1950), work undertaken in the WIO region during the ASCLME project has shown that the Agulhas Current has significantly warmed by up to 1.5^{o} C since the 1980s (Rouault et al. 2009; Mathieu Rouault, University of Cape Town, pers. comm.). There is evidence that this warming is due to an intensification of the Agulhas Current system in response to an increase in trade winds in the south Indian Ocean.

Marine Life

Several living marine resources (including sardine, anchovy, west coast rock lobster and horse mackerel) seem to be shifting from the neighboring BCLME into the ASCLME region, presumably due to a response to climate change (van der Lingen et al. 2006, Cockroft et al. 2008). Sardine, *Sardinops sagax* and anchovy, *Engraulis encrasicolus* are particularly important in the diet of several seabirds, notably penguin. Shifts in west coast rock lobster distribution are affecting the breeding of bank cormorant, *Phalacrocorax neglectus* (Crawford et al. 2008). These movements have lead not only to knock-on effects on the ecosystem (notably on the African penguin, *Spheniscus demersus* (Crawford et al. 2011) and the Cape gannet, *Morus capensis*, along with other seabird and predatory species) but also on the socio-economic status of coastal communities. Canneries along the western coast of South Africa and Namibia have closed in response to the shift in stocks to the southeast.

Another concern is the effect of climate change on temperate marine flora and fauna, including endemic species, along the southern and Eastern Cape regions of South Africa. Strengthening prevailing westerlies are driving increased inshore upwelling of cold, deep water in the west, making inshore waters colder - while the Agulhas Current seems to be strengthening and warming (up to 1.5°C since 1980; Rouault et al. 2010) in the East. This may also be contributing to inshore upwelling along the landward edge of the Agulhas Current (Lutjeharms et al. 2000). The combined “pincer effect” from simultaneous warming and cooling will undoubtedly affect those species which depend on the temperate conditions which once prevailed. The effects will likely manifest as range shifts, contractions and/or extinctions. Current-driven upwelling brings water unsaturated with carbonate minerals up onto the shelf. With the possibly compounding threat of ocean acidification, it is unclear what effects such upwelling will have on calcifying organisms. It may pose a threat to southerly reefs which are considered “refuges” for corals in a warming climate. Inshore upwelling occurs both along the landward edge of the Agulhas Current (Lutjeharms et al., 2000) and along the landward edges of eddies in the Mozambique Channel when these eddies impinge on the shelf (for a recent summary of observational characteristics of such eddies see Swart et al. 2010).

It is unknown what effects warming oceans are likely to have on much of the rest of the ASCLME region. Of particular interest are the Mozambique Channel eddies, which have shown a trend in increasing Eddy Kinetic Energy (EKE) in the past, but this now seems to be decreasing again. These eddies create localized upwelling and productivity and interact with the coastal shelves, creating upwelling and drawing inshore water offshore. The eddies have been shown to be of major importance to the productivity in the area and they strongly affect distribution and behavior of top predators (Kai and Marsac 2010, M. Roberts pers. Comm.). The eddies are also related to downstream effects on the Agulhas Current, notably in the formation of Natal Pulses and, in turn, the shedding of Agulhas Rings (van Leeuwen et al. 2000). Studies of greater frigate birds, *Fregata minor*, show foraging activity is strongly correlated with eddies. The birds are dependent on these systems for food supplies and their feeding is associated with the presence of tunas. It is likely that these fish utilize the eddies due to their associated enhanced productivity (Weimerskirch et al. 2004).

The Agulhas Current as part of a global system

Increasing research in the region has begun to illustrate just how dynamic the Agulhas Current system and its upstream sources are. The research shows the current system forms a critical link in the global thermohaline circulation and climate system (e.g. Beal et al. 2011). Modeling studies and observations to date have suggested that increasing temperatures will likely lead to an increase in the transport of warm, salty Agulhas Current LME water into the South and ultimately North Atlantic. This transport can offset the disruptions to the Atlantic Meridional Overturning Circulation (AMOC) from increasing freshwater inputs from melt water. Paleooceanogeographic records further indicate the pivotal role of the Agulhas Current in the world's climate, particularly its behavior (cessation) during glaciations and inter-glacial (strengthening) periods in the Northern Hemisphere. However, it is also possible Agulhas Current leakage may cease if transport increases too much. Van Sebille et al. (2009) suggested the leakage of the ASCLME into the Atlantic would cease at 87 Sv (1 Sv = 10^6 m^3 s^{-1}). Rouault et al. (2009) note Agulhas Current transport is increasing at 3.9 Sv/decade from a current level of approximately 69.7±4.3 Sv (Bryden et al. 2005). Such measurements confirm the Agulhas Current, along with the Gulf Stream Extension, to be one of the strongest western boundary currents in the world.

Impacts of ENSO

The El Niño Southern Oscillation (ENSO) impacts the region generally during the warm phase of ENSO (El Niño), and causes drier than normal conditions in Southern Africa, and wetter than normal conditions over equatorial East Africa (normally from December to February). Conversely, the cool phase of ENSO (La Niña), causes wetter than normal conditions in Southern Africa, and drier than normal conditions over equatorial East Africa (from December to January). In the extreme, these are coupled with flood and drought conditions in respective parts of Africa. In 1997-1998 ENSO was associated with extremely wet conditions in East Africa, while the 1999-2000 event probably caused the devastating flooding in Mozambique. Although the linkages between ENSO and rainfall in the region are not totally clear, monitoring sea surface temperatures together with additional work on modeling will yield models with predictive capacities for government use. A significant link between prevailing sea surface temperatures associated with ENSO events and outbreaks of the economically important and potentially life-threatening Rift Valley Fever in East Africa illustrates the importance of such models. It is possible to provide a several-month warning before outbreaks are likely to occur, allowing time to install mechanisms to manage or mitigate the potential outbreak in both livestock and people (Anyamba et al. 2009).

Impacts of IOD

The Indian Ocean Dipole (IOD) is an irregularly oscillating ocean-atmosphere phenomenon in the Indian Ocean whereby sea surface temperatures in the western Indian Ocean become alternately warmer or cooler than the eastern part. It is normally characterized by anomalous cooling of SST in the south-eastern equatorial Indian Ocean and anomalous warming of SST in the western equatorial Indian Ocean (Vinayachandran et al. 2009). Approximately 50 percent of IOD events are associated with ENSO events, but the rest are not. IOD events cause the normal convection situated over the eastern Indian Ocean warm pool to shift to the west. This brings heavy rainfall over East Africa and severe droughts and forest fires over the Indonesian region. Convection (and the associated vertical transfer of heat) over the eastern and western Indian Ocean during the monsoon behaves like a seesaw - enhancement of one is associated with the suppression of the other. During 'positive' Dipole events, there is a tendency for increased rainfall in the tropical eastern Africa and WIO region and drought in Indonesia. Recently there have been far more positive events and far less negative dipole modes than recorded in the past. The variability of East African rainfall has a profound impact on the livelihoods of millions of people in the developing countries in the WIO region, who mainly depend on rain-fed agriculture and regional fisheries. The impact of IOD on the climate of the entire Indian Ocean and bordering countries is significant and, therefore, it is absolutely necessary that the scientific community be able to forecast its evolution well in advance. Sea surface temperatures are considered to be a key indicator for monitoring drought and heavy rain conditions in this region.

Aside from the obvious impacts of the IOD on rainfall, another effect is on the tuna fisheries of the region. IOD events are associated with reduced tuna catches in the Indian Ocean due to an apparent shift in the vertical distribution of these fishes; IOD conditions result in a deeper suitable temperature habitat range, reducing availability to the purse seine fisheries (Marsac & Le Blanc 1999, Vialard et al. 2009). This also potentially affects the economies of the region dependent on this fishery, notably the Seychelles (Res et al. 2010).

Mozambique Channel Eddies

Within the ASCLME Region, another cause of large scale variability is the presence of mesoscale dipole eddies in the Mozambique Channel. Research over the last decade has shown that no persistent north to south current exists; rather, several large eddies propagate down the channel (e.g. Swart et al. 2010). Such flow patterns have several important impacts on the channel, including fisheries, productivity, nutrient movement and presumably larval dispersal. Much of the nutrient input into the region is derived from eddy-driven upwelling. The exact triggers for the formation of an eddy in this region are not well understood. On average approximately four eddies travel down the channel per annum (Schouten et al. 2003, Swart et al. 2010). Eddies are also associated with the Agulhas Current and linkages have been observed between eddies, Natal Pulses and Agulhas Ring shedding (van Leeuwen et al. 2000). Understanding the dynamics of this system will be critically important for the management of the region's marine resources.

Impacts on Human Population

An estimated 55 million people depend on the marine and coastal resources of the ASCLME region. The coastal population is increasing at a rapid rate, partly through population growth, and partly from inland to coastal migration. This rate can exceed 10 percent per annum in some areas of East Africa.

Reconstructions of fisheries data by the *Sea Around Us* group at the University of British Columbia indicate that so-called "small scale" artisanal and subsistence fisheries produce catches that have been under-reported by as much as 500 percent. This catch may well equal, if not dwarf that of "industrialized" fisheries throughout the region. Studies in Mozambique (Jacquet and Zeller, 2007a) and Madagascar (Le Manach et al. 2012) show the artisanal and subsistence fisheries account for up to 87% and 72% of the total national catch respectively. In Tanzania, population growth has increased pressure on the fishery and unsustainable fishing methods may be threatening food security. Actual catches may be about 1.7 times larger than those reported to FAO from 1950-1970, due to chronic under-reporting and the omission of Zanzibar from official catch reports (Jacquet and Zeller, 2007b; Jacquet et al. 2010). Zeller and Pauly (2007) outlined the disparity in fishing efficiency, by catch, carbon costs, and economic and social benefits of "small scale" fisheries vs. large scale/industrialized fisheries. Such "small scale" artisanal and subsistence fisheries likely employ the bulk of people working in the fisheries sector. In addition, these fisheries normally use little, if any fossil fuels and produce little if any discards/bycatch compared with industrialized fisheries, and may be a more socio-economically and environmentally sustainable option, although in some cases (South Africa) industrialized fisheries have been shown to be a better option. The state of such small scale fisheries directly impact three Millennium Development Goals (www.un.org/millenniumgoals/), namely food security, poverty alleviation and long-term fisheries stability. In a situation where increasing numbers of people are growing ever more reliant on living marine resources for their livelihoods, the allocation of fisheries resources may be viewed as a human rights issue and a critical consideration in the development and management frameworks of countries throughout the region, and indeed throughout the developing world.

Climate change and the related problem of ocean acidification are likely to exacerbate threats to many livelihoods throughout the region, particularly those dependent on living marine resources. Many fisheries in the region are associated with coral reef ecosystems. Both warming, a known trigger of coral bleaching, and ocean acidification are likely to decrease the ability of corals to build their calcium carbonate skeletons. Weakening corals threaten to undermine the fisheries that depend on this habitat and the communities who depend on these fisheries. This may also threaten other ecosystem goods and services such as the protection of coastlines from erosion and storm surges.

Of course, the effects of climate change and environmental variability are far-reaching, and climate change will not be restricted to only the coastal zone. It is expected that ocean warming will exacerbate the frequency and perhaps intensity of severe weather events, and make environmental variability more chaotic. A dynamic and near-real time Long Term Monitoring system, tied into appropriate regional and national mechanisms, should help decision-makers to react to developing extreme conditions (Early Warning System) in time to prevent and/or mitigate catastrophic impacts on local communities. Also, detailed models may lead to fine-scale climate projections which can be used to plan adaptation and mitigation at local levels. We anticipate that developing monitoring networks will feed into such models, to keep them adjusted to real-world changes in addition to helping verify their predictive power through hind cast simulation.

Climate change will drive the resurgence and spread of tropical diseases, notably malaria (Hay et al. 2002). Approximately 90 percent of the mortality caused globally by malaria takes place in sub-Saharan Africa. In 2009, there were 781,000 deaths caused by malaria and in 2000, 985,000 people died from malaria, while well over 200 million people were affected by the disease. The negative effect on GDP in the region was 1.3 percent (www.who.int/mediacentre/factsheets/fs094/en/). This disease represents an extremely large burden on health care systems in the developing world, and accounts for 40% of health care budgets, 30-50% of hospital admissions and 60 percent of outpatient visits. Malaria, like so many pressures, disproportionally affects those living in poverty who least can afford illnesses. Besides issues like malaria, cardio-vascular and respiratory effects associated with heat waves and climate change, as well as malnutrition, cause additional deaths. The Indian Ocean and ENSO-affected hinterland sub-Saharan African regions are particularly at risk (Patz et al. 2005).

Economic Value of the ASCLME Region

The ASCLME/South West Indian Ocean Fisheries Project (SWIOFP) joint Cost Benefit Analysis has estimated that the coastal and marine resources of the ASCLME region contribute approximately US$22 billion a year to the GDP of the countries of the region. Coastal tourism contributed the largest amount to GDP at an estimated US$11 billion a year, followed by fisheries, coastal agriculture and forestry. Currently, the fisheries of the ASCLME region generate approximately US$68 million per year as resource rent (i.e. the difference between the price at which a resource can be sold and its respective extraction or production costs, including normal returns). US$59 million of this amount is generated by ASCLME countries. The fisheries of the ASCLME support about 2.7 million full and part time workers (Teh and Sumaila, 2011), generating wages of about $366 million per year. On the other hand, owners of fishing capital earn normal profits of US$60 million per year. Rebuilding and effectively managing fisheries of the ASCLME could result in annual gains of US$ 221 million while wages and the overall economic impact could increase by US$10 million and $43 million per year, respectively. In terms of distribution and equity, we find that most of the economic benefits from the coastal and marine resources of the ASCLME remain in the countries of the region.

Toward a novel management paradigm

The LME approach offers many innovative ideas towards the implementation of effective and holistic marine ecosystem management. Further challenges still exist to ensure that policy and governance structures not only embrace the approach, but ensure it receives long term support (financial, infrastructural and political). Bridging the disconnect between policy/governance/management structures and research bodies presents a challenge, and will be imperative to achieve successful interaction between data and management.

During the development and implementation of the ASCLME Project, it became clear that communication between policy/management (governance) and the technical (scientific) level was generally insufficient throughout the region. While this is a global problem, successful implementation of the LME approach demands dynamic interaction between the governance and scientific components to ensure adaptive management and required action by the countries. To this end, the ASCLME Project engaged the post of a “Policy and Governance Coordinator” to specifically focus attention and effort on building relationships with government officials. The “science-to-governance” process is not uni-directional and is equally a “governance-to-science” process. The need for this process is supported by the momentum generated by the project’s activities and partnerships at all levels, leading to a Science-to-Governance workshop/roundtable in Grahamstown in June 2011, which spurred many ideas conveyed in this paper. Based on the results and discussions arising at this roundtable meeting, ASCLME and its partners (i.e. SWIOFP, IUCN et al.) decided to place more emphasis on what is now referred to as a Science-Based Governance (SBG) approach, both at the national and regional level. National level SBG roundtables are now planned throughout 2012 to seek inputs and guidance from countries on how best to improve the communications process, as well as to guide the evolution of an effective mechanism to deliver scientific results and conclusions to the adaptive management process.

Clearly, novel mechanisms to ensure multilateral engagement and communication must be sought and implemented. In one potential tool, ASCLME and its partners are moving toward exploring and developing a dynamic management process based on a “Weight-of-Evidence” approach, which acknowledges that scientific consensus and existing datasets will not always be able to answer management/policy/governance information needs at high levels of statistical certainty, yet realizing decision-makers will still have to act – despite such informational constraints. This approach recognizes the Precautionary Principle as the starting point for identifying a need for adaptive management but steps beyond that to ensure that enough data can be collected to convince a comprehensive and multidisciplinary peer group of experts that trends are obvious despite the possible absence of 95% plus confidence limits. This weight of evidence is then further substantiated by prioritizing those issues for further study and data capture and thus gradually improving the confidence limits. In the meantime, adaptive management measures and actions are recommended though an interaction between the peers/experts and management /policy groups. With the rapidly changing status of ecosystems and their drivers (climate, water quality, resource exploitation/extraction) such proactive management is a necessity.

The Weight-of-Evidence approach (Figure 4) should encourage researchers to offer information and perhaps several alternative management scenarios with their associated risks, and with the implicit understanding that such advice may be incomplete and subject to change. Conversely, if policy-makers find their information is incomplete, they can advise the scientific and academic community and active research programs can be developed/modified to address those needs. This has clear benefits for both parties.

For managers and decision-makers at the policy level, this approach will take decision-making beyond the ‘precautionary’ approach which is often seen as being based more on supposition than strong evidence and which therefore leaves policy-makers feeling vulnerable and indecisive. It will also provide senior government leaders at the economic/finance level and management level with clearer guidance on where to prioritize activities and funding in terms of both immediate management needs and further research (this also extends to the funding agencies of course).

For scientist and research groups, this will raise the profile and importance of science generally in the policy-making and management process and encourage more support and funding to arrive at more reliable results as quickly as possible. It will also provide more precise guidance to the scientific community on which areas of research are priority and most likely, therefore, to attract funding

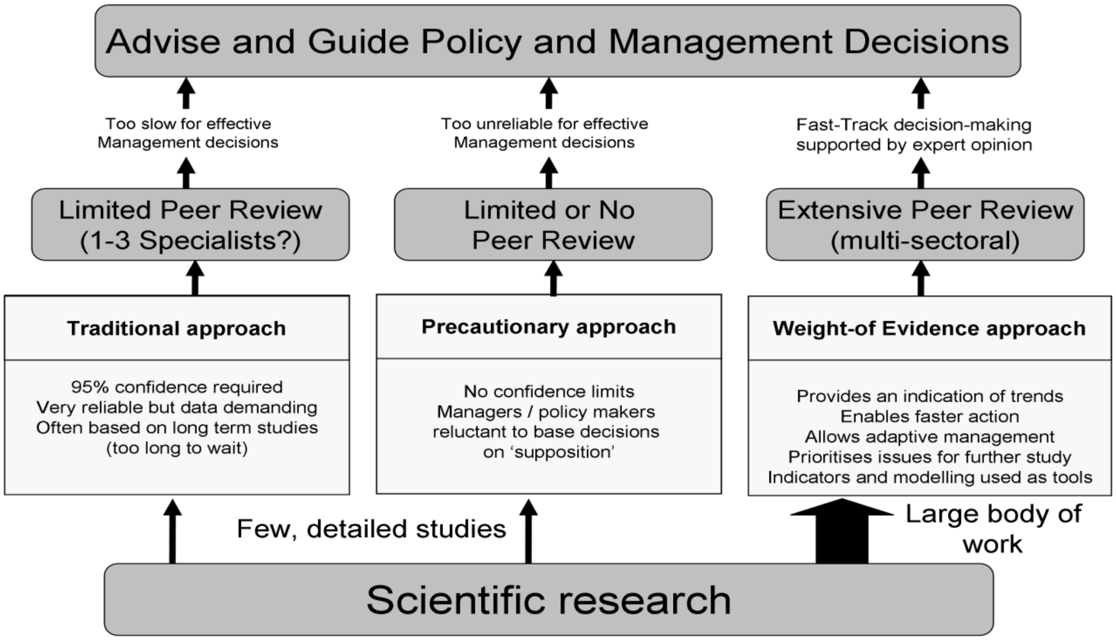

Figure 4. Diagram illustrating the proposed Weight-of-Evidence approach compared to the traditional ‘confidence limits-based’ and precautionary approaches.

Translating research information into policy advice and funneling policy/management information needs into targeted research projects has been a problem. In the past, this two-way flow of information has rarely been effectively implemented. There is a need to involve not only researchers and decision-makers but also a diverse range of stakeholders, including high-level funders, the private sector, civil society and communities. The process will require skilled practitioners who not only have the requisite understanding of sometimes complex, multidisciplinary scientific fields, but also a comprehensive understanding of the harsh realities of politics and the socio-economic balancing act that policy-makers must tackle. To some extent, the burgeoning field of “science communication” has an important role to play, but researchers, managers and policy-makers must also commit to working together to overcome these challenges.

The pressing issues of climate change and environmental variability underline the importance and critical nature of an adaptive, integrated management process to ensure the ongoing health and prosperity of the region.

CONCLUSION

There is an urgent need to complete on-going studies within the ASCLME region to establish an effective baseline for both coastal and offshore indicators in the productivity, fish and fisheries and ecosystem health and pollution modules of the LME approach. Relating these to the communities of the region through the socioeconomics module, and particularly the impacts of and vulnerability to environmental variability and climate change is important. It is imperative that this information is translated into robust mechanisms for adaptive management in the governance module. To sustain these efforts in the long term, it is necessary to create not only sound and well-supported policy and governance structure(s), but also a robust network of research and training institutions and monitoring programs which will feed reliable and timely information into resource management actions.

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6

CLIMATE CHANGE EFFECTS IN THE BAY OF BENGAL LARGE MARINE ECOSYSTEM

Elayaperumal Vivekanandan, Rudolf Hermes, and Chris O'Brien

INTRODUCTION

The effects of climate change are a reality in the Bay of Bengal and in the majority of the large marine ecosystems (LMEs) of the world. The Bay of Bengal LME (BOBLME), the northeastern basin of the Indian Ocean, is one of the largest LMEs, comprising the territorial waters and entire Exclusive Economic Zones (EEZs) of four coastal countries (Bangladesh, Maldives, Myanmar and Sri Lanka) and substantial portions of four other countries (India, Indonesia, Malaysia and Thailand), as well as a large area beyond national jurisdiction (ABNJ) – for a total of 6.2 million km^2 (Figure 1). Not only is the BOBLME one of the largest of the world's 64 LMEs, it is also the most populous with a coastal population of more than 450 million people.

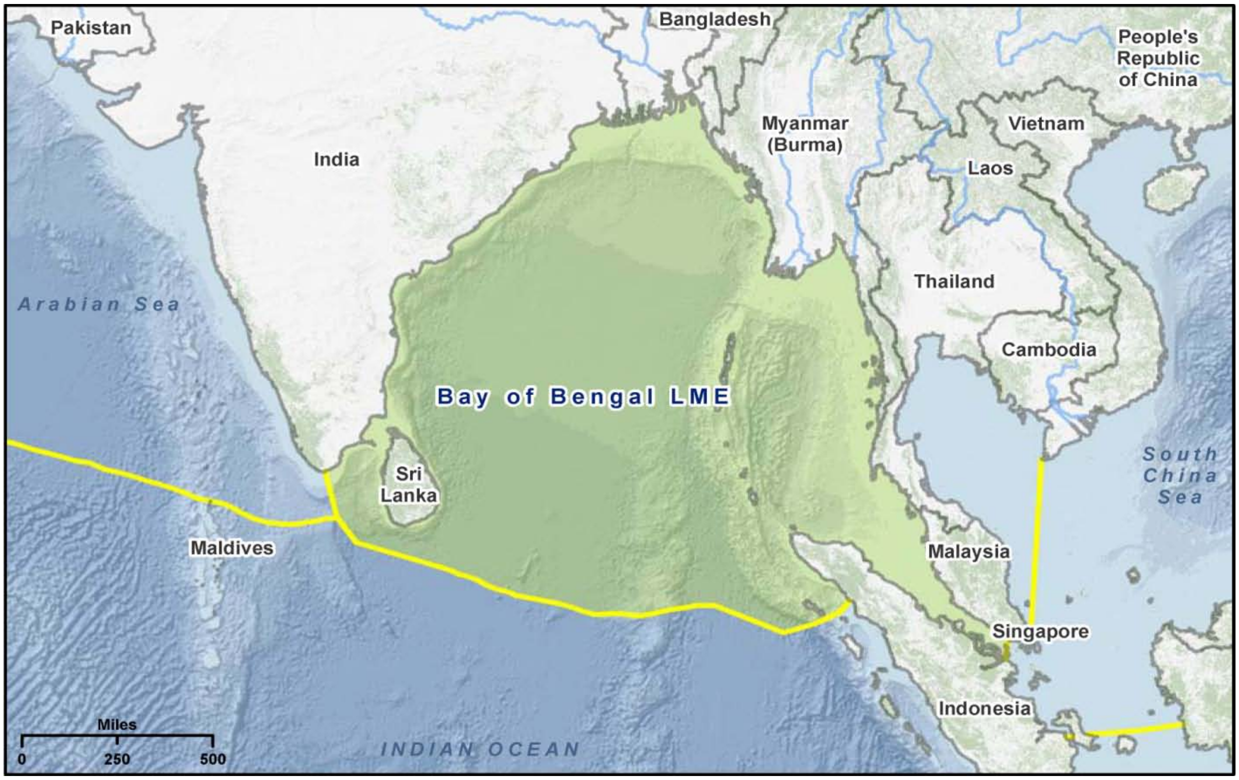

Figure 1. Location of the Bay of Bengal LME.

Climate change effects are therefore also expected to have profound impacts not only on biological systems, but also on society as a whole.

The potential outcome for fisheries may be a decrease in the production and value of coastal and inland fisheries, and a decline in the economic returns from fishing operations. The changes will affect not only the important fish trade of the region, but even more importantly, the food security in a region that is very dependent on fish for overall animal protein intake. Even disregarding climate warming, the sector is facing serious challenges. In the last ten years, production from capture fisheries is stagnant - at least for most of the Bay of Bengal due to overexploitation, depletion of coastal fish stocks and competition among stakeholders in sharing the renewable, but limited resources. Climate change exacerbates this situation. The region is recognized as being very vulnerable to climate change and sea level rise. Modeling studies show that climate change will have the greatest economic impact on the fisheries sector in Asian countries (Brander 2007), including Bangladesh, an extremely low-lying deltaic country and the Maldives, an atoll-based archipelago.

The northern Indian Ocean has been identified as one of the 17 climate change hotspots among the world oceans (Hobday et al., 2008). These areas are recognized to warm faster than 90% of the oceans. These regions are expected to provide the potential for early warning and evidence of the response by natural resources to climate change. In theory, these regions at the frontline of climate change, should also be leading in assessing impacts and evaluating adaptation options.

Ocean warming, acidification and deoxygenation

Warming affects the solubility of gases, including oxygen, and the exchange of gases between the ocean surface and the atmosphere. It could lead to less mixing between nutrient-rich deep waters and the relatively nutrient-poor surface waters of the Bay of Bengal. More stratification could make this basin far less productive than its western neighbor, the Arabian Sea.

Sea surface temperatures (SST) have increased by 0.2 – 0.3 ^{0}C along the Indian coast of the Bay for the 45 year period from 1960-2005 (Vivekanandan et al. 2009a; Fig. 2) and are predicted to increase 2-3.5^{0}C by the end of the century.

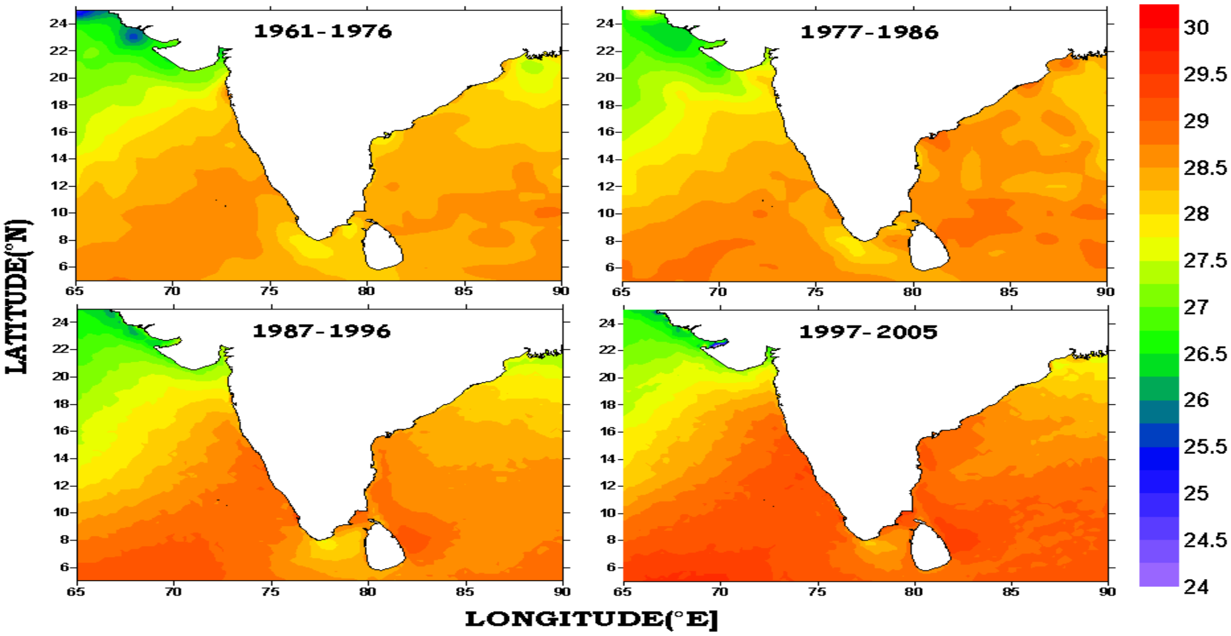

Figure 2. Rise in Sea Surface Temperature (the color code reference is given in ^{0}C at the right side of the maps (from Vivekanandan, 2011).

Sea level rise is mostly caused by thermal expansion and researchers have noted an accelerating rate of increase at 12-13 mm/decade for the northern Indian Ocean (Unnikrishnan and Shankar, 2007). The most far reaching consequences of sea level rise are threats to the coasts and coastal people through coastal erosion, inundation, and saltwater intrusion into freshwater sources and habitats, not only in Bangladesh and the Maldives, but also in Sri Lanka, Sumatra and other coastal areas of the Bay of Bengal, which may experience significantly more sea-level rise than the global mean, and this will increase the environmental stress on these coasts and islands (Han et al. 2010).

Ocean acidification has not yet been investigated in the BOBLME but ocean acidification and climate change are linked by their common driver: CO_2 (Harrould-Kolieb and Herr, 2011). Acidification is a problem concurrent with climate change and not simply a symptom of it. It is now well established through scientific studies that ocean acidification may have wide-ranging consequences for species throughout the ocean. It is not only a threat to organisms with calcium carbonate shells, but affects the physiology of many other organisms, including fish and their early life history stages (Pankhurst and Munday 2011), as well as ecosystem processes. Therefore, acidification has serious implications for society.

Ocean deoxygenation is not only caused by ocean warming and its effect on oxygen solubility, but also by increased nutrient runoff, stemming from an increase in the amount of nitrogen (fertilizer, manure, wastewater). The BOBLME has been identified as the LME with the highest potential of increased nutrient input in the coming decades (UNESCO 2008) as a consequence of the need to further enhance or intensify agriculture to feed increasing numbers of people.

These multiple stressors are likely to have serious effects, in particular on those marine ecosystems which are high in productivity and support significant fisheries.

CYCLONES in the Bay of Bengal LME

The Bay of Bengal LME is prone to cyclones during the northeast monsoon period. An analysis of the frequencies of cyclones during 1891-2010 shows that about 320 cyclones (out of which 103 were severe) affected the east coast of India. Of the cyclones that develop in the Bay of Bengal, over 58 % approach and cross the east coast of India and Bangladesh during October-December. The frequency of tropical cyclones in the North Indian Ocean is 7% of the global total, and their impact on the countries bordering the northern Bay of Bengal (North of 15^0 N latitude) is extremely disastrous. The Myanmar coast (Gulf of Martaban, Irrawaddy estuary) is also exposed to very damaging cyclones (e.g. cyclone Nargis in 2008). The problem can be fathomed from the fact that during the past two and a half centuries, 20 out of 23 major cyclone disasters (with human loss of life 10,000 or more and not considering the damages) in the world have occurred over India and Bangladesh. One of the major reasons for this is the serious storm surge problems along these coasts. A tropical cyclone of specific intensity when it strikes the northern Bay of Bengal, usually produces a higher storm surge compared to that when such a cyclone strikes elsewhere in the world. This is because of the special nature of the coastline, the shallow coastal ocean topography and the characteristics of tide. Furthermore, the high density of population adds to the severity of the problem. Government disaster management schemes and traditional coping mechanisms are in place to counter hazards, but during major disasters these coping mechanisms are found wanting.

Simulation results of Hadley Centre regional climate model for the control run (the 1990s) and for the increased greenhouse gases (GHG) run (2050s; IS92a scenario) show no significant change in the number of total tropical disturbances in the increased GHG simulation from that in the control run, but there is an increase in the number of intense events (cyclones) in the Bay of Bengal, particularly during the post-monsoon period. The frequency of cyclones having maximum wind speed, particularly in the range of 30–35 m/sec, is much higher in the increased GHG run than in the control run. This indicates that the intense cyclones may be more frequent in the increased GHG scenario than in the control scenario (SAARC-SMRC, 2000). One of the greatest impacts in the coastal regions by the tropical cyclones is due to storm surges.

SEA LEVEL RISE

Among the coastal areas, the high water marks and mean sea level are high along the northern Bay of Bengal coast. Under the present climate, it has been observed that the sea level rise (2.0 mm per year) in the northern Bay of Bengal is one of the highest. Future climate change in the coastal zones is likely to be manifested through worsening of some of the existing coastal zone problems. This region experiences seasonal erosion and some of the coastal areas regain their original profiles. Fifty percent of areas, which do not regain their original shape over the annual cycle, undergo net erosion. The large inflow of freshwater into the seas around India due to rainfall over the ocean and runoff from rivers, forces large changes in sea level especially along the coast of the Bay of Bengal. During June-October, the inflow of freshwater from the Ganges and Brahmaputra into the northern Bay of Bengal is about $7.2*10^{11}m^3$, the fourth largest discharge in the world (Shankar, 2000). Increase in sea level, in addition to causing threats to human lives, will pose problems on freshwater availability due to intrusion of seawater and salinization of groundwater. This would also result in loss of agricultural land. A one meter sea level rise is projected to displace approximately 7.1 million people in India and about 5,764 km^2 of land area will be lost, along with 4,200 km of coastal roads (Ministry of Environment and Forests, 2004).

The oceanic processes and food web in the region are strongly governed by the tropical monsoon seasons, with wind blowing from the northeast from October to February, and from the southwest from May to October. The BOBLME is exposed to strong solar heating in the lower latitudes, strong evaporation, precipitation and considerable river-runoff (from the world's largest rivers) from the Ganges-Brahmaputra-Megna estuaries in India and Bangladesh, and the Irrawaddy estuary in Myanmar.

Increased stratification may not only be a consequence of sea surface warming, but also the inflow of more freshwater from the major estuaries in the Bay of Bengal, either from increased precipitation or from the melting of Himalaya glaciers. Stratification has been identified as one of the factors limiting the productivity, as nutrients are to a large extent trapped below the euphotic zone or in the deep sea (Prasanna Kumar et al. 2002).

In fact, cyclones break up the stratification (others are eddies entering the Bay of Bengal from the equatorial zone close to Sri Lanka), and as a result increase productivity. On the downside, the cyclones cause losses of lives and coastal infrastructure.

Extended areas of low and very low oxygen have not yet been mapped in the BOBLME, but are likely to exist near coastal areas and river estuaries with high run-off of nutrients and pollutants, in particular along the eastern coast of India and adjacent to the Bangladesh coastal zone. Direct effects include reduced growth of zooplankton, low benthos biomass, and the risk of species loss and of other ecosystem services.

Fish kills have been observed in the Andaman Sea coast of Thailand. These mortalities are thought to be the result of the passing of internal waves through the Andaman Sea which lead to an episodic upwelling of oxygen-depleted deep water.

FISH and FISHERIES

All over the world, fish is the largest food source harvested from the wild. The most important characteristic of capture fisheries in the Bay of Bengal is that the resource is considered common property and the access is free and open or only weakly regulated. But, property rights to fisheries are difficult to establish, leading to intra-sectoral conflicts, among commercial and artisanal fisheries, but also between users of different types of gear. In addition, there are other anthropogenic impacts such as marine pollution from the discharge of untreated domestic and industrial effluents, and alteration and loss of critical habitats that cause considerable damage to fish populations with resulting socio-economic consequences.

Most fish species have a fairly narrow range of optimum temperatures needed for their basic metabolism and the survival of their food supply. Being poikilotherms, even a difference of 1^{o} C or 0.1 unit pH in seawater may affect their physiology, abundance, and distribution. The more mobile species should be able to adjust their ranges over time, but less mobile and sedentary species may not. Depending on the species, the habitat area it occupies may expand, shrink or be relocated. As a result, the distribution of marine fish will increase in some areas, decline in others, or shift altogether. From the recent investigations carried out by the Indian Council of Agricultural Research (ICAR) and Central Marine Fisheries Research Institute (CMFRI), the following responses to climate change by different marine fish species are discernible in the BOBLME: (i) extension of distributional boundary (Vivekanandan et al. 2009a); (ii) shift in latitudinal distribution; (iii) shift/extension of depth of occurrence (CMFRI 2008); and (iv) phenological changes (Vivekanandan and Rajagopalan 2009).

(i) Extension of the distributional boundary has been studied along the Bay of Bengal and Arabian Sea coasts of India. The oil sardine *Sardinella longiceps* and the Indian mackerel *Rastrelliger kanagurta* are tropical coastal and small pelagic fish, forming massive fisheries in India (catch during 2007: 0.7 million tons valued at about $US 150 million). Their populations are influenced by fluctuating ocean conditions, and have high population doubling time of 15 to 24 months. They are a cheap source of protein, and form a staple, sustenance and nutritional food for millions of coastal people. They were known for their restricted distribution between latitude 8^{o}N and 14^{o}N and longitude 75^{o}E and 77^{o}E (Malabar upwelling zone along the southwest coast of India) where the annual average sea surface temperature ranges from 27 to 29^{o}C. Until 1985, almost the entire catch was from the Malabar upwelling zone and the catch was either very low or there was no catch from latitudes north of 14^{o}N. In the last two decades, however, the catches from latitude 14^{o}N to 20^{o}N are increasing in the Bay of Bengal and Arabian Sea coasts, reaching 150,000 t (21% of all-India catch of oil sardine and Indian mackerel during 2007).

There was a positive correlation between the catches and sea surface temperature (SST). The surface waters of the Indian seas are warming by 0.04^{o}C per decade, and the warmer tongue ($27\text{-}28.5^{o}$C) of the surface waters expanded to latitudes north of 14^{o}N, enabling the oil sardine and Indian mackerel to extend their distributional boundary to northern latitudes. Research also found that the catches from the Malabar upwelling zone have not decreased - indicating distributional “extension” and not distributional “shift.” Assuming further extension of the warmer SST tongue in the future, it is expected that the distribution may extend further north of latitude 20^{o}N. However, if the SST in the Malabar upwelling zone increases beyond the physiological optimum for the fish, it is possible that the populations may be driven away from the southern latitudes.

(ii) The evidence for a shift in latitudinal distribution and abundance of fish emanates from the same region, but there are also signs in the Bay of Bengal coast of India. Catfish are one of the major resources along the southwest and southeast coasts of India (latitude: 8^{o}N - 14^{o}N). During 1970-2007, the catches from these coastal areas decreased from 35,000 t to 7,800 t. On the other hand, the catches from the northwest and northeast coasts (latitude: 15^{o}N - 22^{o}N) increased from 16,000 t to 42,500 t during the same period. There was a strong negative correlation between catfish catch and SST along the two southern coasts whereas the correlation between catch and SST was positive along the northern coasts. As the average seawater temperature in the southern latitudes exceeded 29^{o}C in the last decade, it appears that the catfish have shifted their distribution to the northern latitudes where the seawater temperature is between 27 and 28.5^{o}C.

The northern Indian Ocean is landlocked, and there is a natural barrier to further latitudinal shift due to the Asian continent landmass. Marine species are also inhibited by the freshwater plume of the Ganges-Brahmaputra-Megna river delta and the heavy sediment load.

(iii) Warming ocean waters cause fish species to shift to deeper depths in the water column. The Indian mackerel, *Rastrelliger kanagurta*, in addition to extension of its northern boundary, has been found to descend to deeper waters in the last two decades. This fish normally occupies surface and subsurface waters. During 1985-1989, only two percent of the mackerel catch was from bottom trawlers, and the rest of the catch was contributed by pelagic gear such as drift gillnet. During 2003-2007, about 15 percent of mackerel catch was caught by bottom trawlers along the Indian coast. The Indian trawlers operate at a depth ranging from 20 m to 80 m by employing high opening trawl nets. In the last 25 years, the specifications of trawl net such as mouth opening, head rope length, otter board and mesh size have not been modified, and hence the increase in the contribution of trawlers to the mackerel catch is not gear-related. As the subsurface waters are also warming up, it appears that the mackerel, being a tropical fish, has extended its vertical depth of occurrence to deeper waters.

(iv) There is also increasing evidence of phenological changes as a result of climate change. The process of spawning is known to be triggered by pivotal temperatures. The annually recurring life cycle events such as timing of spawning can provide particularly important indicators of climate change. Though sparsely investigated, phenological changes such as seasonal shift in spawning season are now evident in the Indian seas.

The threadfin breams *Nemipterus japonicus* and *N. mesoprion* are distributed along the entire Indian coast at depths ranging from 10 to 100 m. They are short-lived (longevity is about 3 years), fast growing, highly fecund (annual egg production around 0.2 million per adult female) and of medium size (maximum length is 35 cm). Data collected every month off Chennai (southeast coast of India) indicate that from 1981 to 2004 there were wide monthly fluctuations in the numbers of females spawning. However, a shift in the spawning season from warmer (April-September) to cooler months (October-March) was discernible. Whereas 35.3 percent of *N. japonicus* spawning occurred during warm months from 1981-1985, only five percent of spawning occurred during the same season from 2000-2004. During 1981-1985, 64.7 percent of the spawners occurred during October-March, whereas 95.0 percent of the spawners occurred during the same season in 2000 - 2004. A similar trend was observed also in *N. mesoprion*. The occurrence of spawners of the two species linearly decreased, with increasing temperature during April-September, but increased with rising temperatures during October-March. It appears that SST between 28 and 29°C may be the optimum; when the SST exceeds 29°C, the fish are adapted to shift the spawning activity to seasons when the temperature is around the preferred optimum.

Currently, it is difficult to establish how much of catch fluctuation is due to changes in fish distribution and phenology. However, these changes may have impact on the nature and value of fisheries (Perry et al. 2005). If small-sized, low value fish species with rapid turnover of generations are able to cope with a changing climate, they may replace large-sized high value species, which are already showing declining trends due to fishing and other non-climatic factors (Vivekanandan et al. 2005). Phytoplankton is the basis for the productivity of the oceans and is critically important to the flow of resources. Plankton are particularly sensitive to environmental fluctuations, and therefore those fish, which are directly dependent on plankton for food, will be strongly influenced by climate change (Briones et al. 2006). The larvae of several marine fish have wider dispersal ranges (aided by currents) than terrestrial organisms.

Major changes to ocean circulation will cause changes in dispersal pattern of larval fish, particularly the pelagics. This will change the food webs and influence fish catch. Such distributional changes would lead to novel mixes of organisms in a region, leaving species to adjust to new prey, predators, parasites, diseases and competitors (Kennedy et al. 2002), and result in considerable changes in ecosystem structure and function. With altered timing of spawning, migrations and peak abundances, there is likely to be more variability in strengths and recruitment of planktivorous species, and shifts in spawning seasons and areas. These could have detrimental effects because suitable plankton feed and particle sizes required for growth and survival of larvae may not be available.

Climate warming will also affect the inland and coastal aquaculture sectors of the Bay of Bengal LME countries. India is the world's second largest aquaculture producer and with the exception of the Maldives, aquaculture plays a major role in production of animal protein food in all BOBLME countries. Impacts of climate change will include changes in hydrology and therefore availability of water (of the needed quality and temperature), physical threats to aquaculture facilities, and prevalence or spread of known and new diseases of aquatic organisms. Indirect effects may be the availability of seed and fish meal needed for aquaculture.

HABITATS

The critical marine habitats most likely to be negatively affected by climate warming effects are the coral reefs of the Bay of Bengal LME. Lying to the west of the "coral triangle," coral reefs are found in all countries and support not only fisheries, but also the tourism industry, chiefly in the Maldives and Thailand, and to a much more limited degree in Bangladesh (St. Martin's Island off the Teknaf Peninsula in the southeastern part of the country). The largest coral reef area of India is in the western portion of the Andaman Sea, surrounding the Andaman and Nicobar Islands.

Coral reefs are the most diverse marine habitat, which support an estimated one million species globally. They are highly sensitive to climatic influences and are among the most sensitive of all ecosystems to temperature changes, exhibiting the phenomenon known as coral bleaching when stressed by higher than normal sea temperatures. Reef-building corals are highly dependent on a symbiotic relationship with microscopic algae (zooxanthellae), which live within the coral tissues. The corals are dependent on the algae for nutrition and they are responsible for the color of the corals. Bleaching (Fig. 3) results from the ejection of zooxanthellae by the coral polyps and/or by the loss of chlorophyll by the zooxanthellae themselves. Corals usually recover from bleaching, but die in extreme cases.

Figure 3. Bleached corals off Androth (Lakshadweep Islands) on April 25, 2010 (photo courtesy: Said Koya, CMFRI).

In the Bay of Bengal LME, coral reefs are found mainly in the Maldives (atoll-forming), the Gulf of Mannar, Palk Bay, the Andaman Sea and Malacca Strait, including the coasts of north Sumatra and Peninsular Malaysia. Coral reefs of the region have experienced 29 widespread bleaching events since 1989 and intense bleaching occurred in 1998, and again in 2010, when the SST was higher than the usual summer maxima. By using the relationship between past temperatures and bleaching events, and the predicted SST for another 100 years, Vivekanandan et al (2009b) projected the vulnerability of corals in the Indian Seas. The outcome of this analysis suggests that if the projected increase in seawater temperature follows the trajectory suggested by the model, reefs should soon start to decline in terms of coral cover and appearance. The number of decadal low bleaching events will remain between 0 and 3 during 2000-2009, but the number of catastrophic events will increase to 10 from 2000-2099.

Given the implication that reefs will not be able to sustain catastrophic events more than three times a decade, reef building corals are likely to disappear as dominant organisms between 2020 and 2040 and the reefs are likely to disappear between 2030 and 2060. These predictions on coral reef vulnerability are only based on the warming of seawater. Other factors such as the increasing acidity of seawater would slow down the formation of exoskeletons by the corals, and if acidification continues at its present rate, all the coral reefs will be dead within 50 years. Given their central importance in the marine ecosystem, the loss of coral reefs is likely to have severe ramifications and consequences.

Habitat loss due to climate warming and accompanying sea level rise is also expected to affect mangroves. Important mangrove areas in the Bay of Bengal are found in the Gulf of Mannar, the Sundarbans (shared between India and Bangladesh), the Andaman and Nicobar Islands, Myanmar and along the eastern coast of the Andaman Sea and on both sides of Malacca Strait. Mangrove habitats in the Bay of Bengal are under severe stress from anthropogenic factors, and this may increase as people's livelihood in fisheries is affected by climate warming.

Increased flooding and coastal erosion can also negatively affect other coastal wetlands and habitats, such as salt marshes and sea grass beds. Theoretically these have the potential to respond to sea level rise by migrating up the shore, but this depends on the availability of suitable areas for landward progression (Booth et al. 2011).

SMALL SCALE TRADITIONAL FISHERIES

The small-scale traditional fisheries will be the most vulnerable to climate change. In the east coast of India and northern Bay of Bengal, there are thousands of boats without any form of mechanization or motorization that depend entirely on wind power for propulsion. With no alternate income and with poor literacy, the fishermen who depend on the traditional type of fishing are faced by poverty. With restricted mobility, the competitive capacity of this fleet with other fishing vessels is limited. The availability of fish to this fleet is also likely to decline.

The small scale fisheries have demonstrated considerable resilience to climate variability in the past. However, any objective assessment of small-scale fisheries in the region would conclude that exposure and sensitivity to climate change threat are high, while adaptive capacity is low (FAO, 2005). Among the reasons for this conclusion are:

- the negative impacts on the sector, e.g. through habitat and ecosystem damage such as bleaching of corals, additional stress on mangroves and seagrasses;
- high dependence on fishing and related activities for livelihoods;
- many fisher folk reside in vulnerable, low-lying coastal areas which exposes their physical assets (e.g. boats, gear, homes) and puts their lives at great risk due to climate-related events such as cyclones, sea level rise and coastal erosion;
- lack of insurance and sea safety mechanisms to protect from extreme events, which are projected to become more frequent and/or intense in the future; and
- factors such as lack of consistent access to capital on reasonable terms, weak fisher folk organizations and consequently low bargaining power with governments and other sectors.

While the list of factors presented above is not exhaustive, it provides a reasonable indication of the issues confronting the small-scale fisheries sector in the Bay of Bengal. It is widely anticipated that climate change will amplify these challenges, and hence, appropriate and timely interventions are required in order to minimize the adverse effects.

Climate effects on fisheries are expected to be gradual, and both the commercial and the artisanal sectors are expected to be flexible and follow the fish or adapt to shifting fishing grounds and changed species composition. Still, economic consequences will be serious, if catches are further reduced or consist of smaller and lower value species, as is already the case due to overfishing.

Fishers and island communities will be most affected by a decline in fish resources, either from coral reef degradation or climate warming induced distribution shifts (Adam 2006). The cost of adaptation will likely be high and make fishing less profitable. Also, there is a need to promote "safety at sea" more intensively, and to incorporate disaster risk management into fisheries management plans, and fisheries management into disaster risk reduction planning.

While small-scale fisheries are not causing and at most only marginally contributing to climate change and can do little to reverse the trend of global greenhouse gas emissions and higher seawater temperatures, actions can be taken to improve the resilience of the sector to the adverse effects of climate change. According to McConney et al. (2009), such actions may include: (i) strict enforcement of existing marine pollution control protocols and abatement of contamination from land-based sources, (ii) reactivation and expansion of habitat protection and restoration programs, and (iii) control of non-sustainable practices such as overfishing, and the use of inappropriate fishing methods. Technical improvement of craft and gear for greater mobility is necessary. Government schemes for safety at sea, coast protection and rehabilitation should be a priority. The benefits of applying good governance and co-management principles in the small-scale fisheries sector are well known (FAO, 2005). Governance and co-management systems that are based, *inter alia*, on an understanding of ecosystem health and thresholds, partnerships, stakeholder inclusiveness, equity and sustainable livelihoods should also be regarded as vital elements of climate change adaptation planning for small-scale fisheries (McConney et al. 2009).

GOVERNANCE

Fisheries, including production and processing, contribute a comparatively small amount to global greenhouse gas emissions. Thus, the mitigation of climate warming will need to be accomplished elsewhere.

Climate warming mitigation options will largely have to be realized outside of the fisheries sector, as its contribution to greenhouse gas emissions, both in the producing and processing sectors, are comparatively small (Thrane 2006). A reduction of fishing effort will make a contribution to mitigation, but sustaining fisheries resources is in line with the Code of Conduct for Responsible Fisheries (CCRF) and an ecosystem approach to fisheries management.

Adaptation

The most important and critical adaptation measures will be to build capacity to increase understanding of the marine resources, and implement measures to sustainably manage fisheries. Regulatory management will be critical for climate change adaptation (Adam 2006). However, no adaptation measure can entirely eradicate the adverse impacts of climate warming and climatic variability.

Fishing and climate change are strongly interrelated pressures on fish production and must be addressed jointly. Moderately-fished stocks are likely to be more resilient to climate change impacts than heavily-fished ones. Reducing fishing mortality in the majority of fisheries, which are currently fully exploited or overexploited, is the principal means of reducing the impacts of climate change (Brander, 2007). Reduction of fishing effort (i) maximizes sustainable yields, (ii) helps adaptation of fish stocks and marine ecosystems to climate impacts, and (iii) reduces greenhouse gas emission by fishing boats (Brander, 2008). Hence, some of the most effective actions to tackle climate impacts are to deal with the familiar problems such as overfishing (Brander 2008), and adopting the Code of Conduct for Responsible Fisheries (CCRF) and an

Ecosystem Approach to Fisheries Management (FAO, 2007). In the Bay of Bengal LME, mechanisms for managing large-scale commercial fisheries such as total allowable catch (TAC) or total allowable effort (TAE) do not exist. Hence, it is a challenge to fully comply with the CCRF. The challenge becomes severe considering poor economic conditions prevalent among the coastal communities involved in traditional fishing methods, and the lack of suitable alternate income generating options for them. These factors make these small-scale fishing communities highly vulnerable to climate change, as their capacity to adapt is very limited. Efforts to reduce dependence on fishing by these vulnerable communities and integrating fisheries management into coastal policy and planning are essential (FAO 2008b).

The countries in the region are sensitized on the need to evolve adaptation measures. Activities/instruments on climate change that are in place in the countries bordering the Bay of Bengal include National Adaptation Programs of Action (NAPA), National Climate Change Fund (NCCF), and, increasingly, various insurance mechanisms.

R&D strategies	Research Initiative	Action plans	Vulnerability Assessments	Response Plans
Indian Network on Climate Change Assessment (INCCA) Himalayan Glaciers Monitoring Programme Launch of Indian satellite to monitor greenhouse gases Assessment of Forest and Tree cover as CO_2 sink Greenhouse Gas Emission Assessment 2007 Sea Level Rise Analysis Programme of National Institute of Oceanography	Establishment of Climate Change Research Centre in Indian Institute of Tropical Meteorology ICAR Network Project (i) "Impact, Adaptation and Vulnerability of Indian Agriculture to Climate Change", (ii) National Initiative on Climate Resilient Agriculture, (iii) ICAR Platform on Climate Change Sea weed Carbon sequestration study at CMFRI	National Mission on Strategic Knowledge on Climate Change National and State Action Plans on Climate Change Sectoral and Regional Analysis of Climate Change in 2030s National Carbonaceous Aerosol Programme India's National Communication to UNFCCC(NATCOM I &II) by the Ministry of Environment & Forest Establishment of Department of Climate Change by Govt. of Gujarat	Assessments in NATCOM reports Coastal vulnerability assessment under ICAR project"	Formation of Expert Group on low carbon economy National Policy of Biofuel National approach towards Sustainable Fisheries under Ministry of Forests and Environment & Ministry of Agriculture CMFRI Policy brief on climate change and Indian marine Fisheries(2010)

Table 1. Schematic of research planning process underway in India that provides direction for research associated with facilitating adaptation to climate change.

How is the Bay of Bengal Large Marine Ecosystem Project responding to the challenges of climate change?

Responses to climate change had not received much emphasis when the BOBLME project document was drafted in 2004. Still, it was recognized that the Bay of Bengal is strongly affected by monsoons, storm surges, cyclones and other natural disasters, such as the tsunami that devastated the region in December 2004, and flexibility has been built into the project so as to allow further definition of BOBLME supported activities. The project's two main directions taken for climate change response are therefore the contribution to the understanding of large-scale processes and climate change effects on the one hand, and contributions to adaptation by addressing habitat degradation, pollution and fisheries management, as well as building capacity and resilience of coastal populations.

The Bay of Bengal Large Marine Ecosystem Project is a five year, $31 million collaborative initiative involving eight coastal states: Bangladesh, India, Indonesia, Malaysia, Maldives, Myanmar, Sri Lanka and Thailand. It will run until 2014. These countries are working together to develop a coordinated program of action designed to improve the lives of the coastal populations through improved regional management of the Bay of Bengal environment and its fisheries. The major implementation partners are the Fisheries and Environment Departments of each country. The BOBLME Project is funded principally by the Global Environment Facility (GEF), Norway, Sweden, the Food and Agriculture Organization of the United Nations (FAO), and the National Oceanic and Atmospheric Administration (NOAA) of the USA. FAO is the executing agency.

Following the standard design of all GEF-funded LME projects, the BOBLME Project has two major outputs. The first is a Transboundary Diagnostic Analysis (TDA) which identifies, ranks and prioritizes water-related environmental transboundary issues such as over exploitation of fish stocks, habitat degradation, and land based pollution, and their causes, according to the severity of environmental and/or socio-economic impacts. The TDA provides the scientific basis for the development of the Strategic Action Programme (SAP) that will formulate nationally and regionally coordinated activities to address the issues and their causes. The SAP is the prerequisite for a second phase of the project that will be extended beyond 2014 and towards 2020.

The BOBLME Project follows the modular assessment approach for sustainable development, using indicators for the five interconnected modules: productivity, fish and fisheries, pollution and ecosystem health, socio-economics and governance. Among a range of project objectives, dealing with fisheries resources management and habitat conservation, is the objective to improve the understanding of large scale oceanographic and ecological processes controlling the BOBLME living resources. In line with this objective, the BOBLME Project has become an associate member of the Indian Ocean Global Ocean Observing System (IOGOOS) and has formed working groups on oceanography, climate change and ecosystem health, capacity building, adaptation to climate change, generating and exchanging oceanographic data, and ecosystem mapping and monitoring of indicators of ecosystem health. Working group members are usually made up of oceanographers from the partner countries. The BOBLME is also promoting the IOGOOS membership to their agencies and institutes.

The Sustained Indian Ocean Biogeochemical and Ecological Research (SIBER) group, in its Science Plan and Implementation Strategy, has underlined the need for deployment of biogeochemical sensors on Research Moored Buoy Array for Monsoon Analysis (RAMA) Moorings, with the Bay of Bengal identified as a priority location. The SIBER objective for deployment of biogeochemical sensors is to provide data for defining biogeochemical variability in key regions of the Indian Ocean i.e. the Bay of Bengal and for understanding the physical, biological and chemical processes that govern its functioning. These objectives are very much in line with those of the BOBLME Project and will contribute to the SIBER objectives by providing a set of sensors for the BOB-RAMA mooring that will measure CO_2, chlorophyll [fluorescence], oxygen, turbidity, and pH. The BOBLME plans for the purchase and deployment of these sensors jointly with NOAA and wants to ensure that data and information gathered as part of this activity will be freely available e.g. via the internet. Through its involvement in IOGOOS and SIBER, the BOBLME Project will not only contribute to better understanding of climate change effects in the Bay of Bengal, but also promote regional collaboration among scientists and capacity development; through participation in regional training events or oceanographic survey work.

For capacity development, BOBLME is working closely with the Asia-Pacific Fisheries Commission (APFIC) and facilitating the participation of partner countries' delegates in consultative workshops on the Ecosystems Approach to Fisheries (EAF) and the implications of climate change on fisheries and aquaculture (Sriskanthan and Funge-Smith, 2011; FAO 2011). Recognizing that current problems in weak fisheries management make the sector vulnerable to climate change, the BOBLME Project supports adaptation and increases resilience by strengthening fisheries management and providing assistance to improve fisheries assessments. By strengthening governance, the project will also contribute to the integration of climate change adaptation into decision-making and response initiatives, e.g. disaster risk management plans. This regional project is well placed to assist in coordinating responses to transboundary issues using the ecosystem approach and regional cooperation in response to climate change and its impacts on fisheries and coastal management.

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7

SUSTAINABILITY OF THE HUMBOLDT CURRENT LARGE MARINE ECOSYSTEM

Rodolfo Serra, Michael Akester, Marilú Bouchón, Mariano Gutierrez

INTRODUCTION

The Humboldt Current Large Marine Ecosystem (HCLME) is one of the largest LMEs and one of the most productive marine ecosystems in the world. It extends along the west coast of Chile and Peru (Figure 1). The HCLME is a partially wind driven, cold water, relatively low saline flow along the eastern margin of the South Pacific Ocean, starting at around 40°S with a northerly flow towards the equator. It encompasses a complex mosaic of currents, composed mainly of cold water masses with biodiversity (BD) of global importance. The relatively steady alongshore winds that blow towards the equator, drive the strong coastal upwelling from about 40°S up to 4°S, and it is this cold nutrient-rich water brought to the surface by the upwelling which drives the extraordinary productivity of this region (Tomczak and Godfrey, 2003). The HCLME provides about 18-20% of the total world's fish production (Bakun and Weeks 2008). Periodically, the upwelling that drives the system's productivity is disrupted by El Niño-Southern Oscillation (ENSO) events. When this occurs, fish abundance and distribution are significantly affected, often leading to stock crashes and cascading social and economic impacts (Arntz and Fahrbach 1996). These events cause regime shifts where anchovies and sardines alternate as the dominant species in the ecosystem. The HCLME is a global center for food security, marine biodiversity, the world's fishmeal production, and climate regulation.

Figure 1. Location of Humboldt Current LME.

Water masses and oceanic circulation

The HCLME has a complex water mass structure generated from the equatorial/subtropical Pacific and the Southern Ocean. A complete description can be found in Tomczak and Godfrey (2003), Chaigneau and Pizarro (2005a,b), Guillén (1983), Bernal et al. (1983),Thiel et al. (2007), and Schneider et al. (2003).

In synthesis, water masses off the coastal zone off Chile and Peru are colder than expected from the upwelling and the water is transported far offshore due to the ‘Ekman effect’ (or the combined influence of the South Pacific Anticyclone (SPA), the trade winds and the earth’s rotation – the Coriolis Effect). These cold waters make the lower layers of the atmosphere and coastal zones abnormally cold for the latitude. There is also a ‘thermal inversion’ effect impeding the formation of convection clouds. This in turn produces stable, low altitude clouds that when saturated produce drizzle and long lasting mist known as ‘camanchaca’ in northern Chile.

The SPA is a large-scale circulation of winds moving counterclockwise around a region of high atmospheric pressure in the Southern Hemisphere. This giant mass of cold, dry, oscillating air produces an eddy and is the origin of the Humboldt Current. The location of the eddy oscillates far south during January and from 25 to 35°S during June. The weakening or strengthening of the SPA is closely related to the ENSO phases and the latitudinal location of the wide Intertropical Convergence Zone (Fuenzalida et al. 2007, Ayon et al. 2008).

The HCLME facing climate change and anthropogenic activities

Unlike most of the world’s Large Marine Ecosystems that demonstrate rising sea surface temperatures (SST), the HCLME - along with the California Current LME- show a cooling trend as evidenced by interdecadal variations in the ocean environment that changed from a “warm period” to a “cold period” by the late 80s (Lluch-Belda et al. 1989, 1992, Schwartzlose et al. 1999). The primary productivity of the HCLME is generated from the nutrient rich, low salinity upwelling system and is classified as moderate to high at 200 - 300 $gCm^{-2}yr^{-1}$ (Chavez et al. 2008).

Regional impacts on biomass productivity during decadal, low frequency variation, represented by warm period (El Viejo) and cold period (La Vieja) (Chavez et al. 2003), and higher frequency variations such as El Niño and La Niña episodes, form part of natural climate variation (Schwartzlose et al. 1999). Anthropogenic forcing and short duration climatic events (e.g. Kelvin Waves) are superimposed on the natural cyclical climate variation so that marine species respond to climate variation in accordance to their plasticity and tolerance to changes in food quantity and quality plus the prevailing physical conditions (Bertrand et al. 2008).

Evidences of such climate variation can also be found in paleo-oceanographic studies of sediments in the HCLME area (Siffedine el al. 2008). Several studies have shown an intensification of the upwelling events and primary production since the second half of the 19th century - suggesting a major basin scale, climate change during this period (Vargas et al 2004). Furthermore, some upwelling systems such as the HCLME produce more acid waters because the CO_2 concentration increases as sinking organic matter from biological production is decomposed by bacteria (Fernand and Brewer 2008). These additions of CO_2 together with CO_2 of anthropogenic origin, cause the pH to decrease creating an acidic environment (Figure 2).

At smaller spatial scales, the anthropogenic activity in the coastal zones (urban, industrial, fishing) can affect the sustainability of some HCLME ecosystem niches. The most important economic activity in Peru and Chile is the mining industry. The effluent from the iron ore mine in Marcona Province (Ica, Peru, 14°S) supplies solutions rich in iron minerals and pollutants to the ocean. This can have strong consequences for the local environments because the HCLME is a coastal upwelling system with limited iron availability (Chavez et al. 2008) and iron is a limiting nutrient for phytoplankton growth. Iron leaching to the sea may induce massive blooms, eutrophication and a die-off of organisms when nutrients and/or oxygen become depleted (Figure 3).

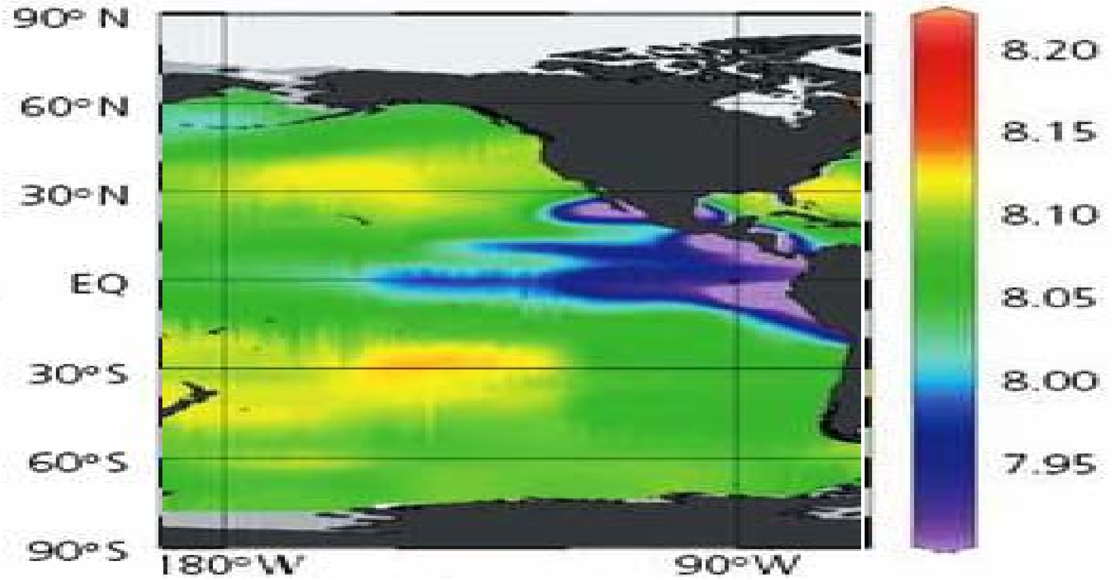

Figure 2. Chart of the Pacific Ocean according to pH. Lower values are linked to the excess CO_2 released due to respiration of organisms (e.g. micro nekton). In the case of the HCLME, there is a direct relationship between high biological productivity and relatively high acidity. Source: (www.appinsys.com/globalwarming/OceanAcidification.htm).

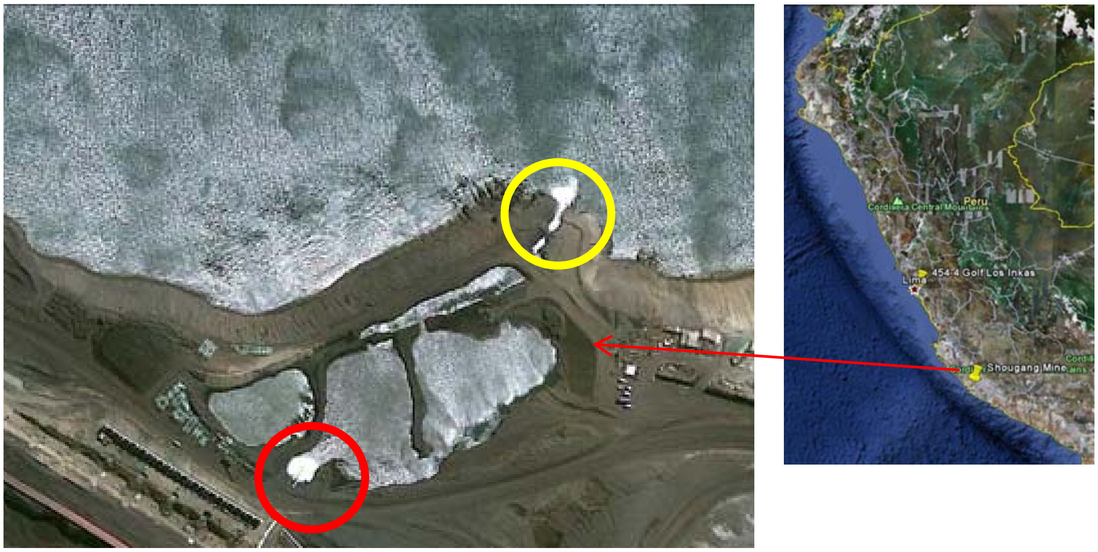

Figure 3. Water flow into a settlement lagoon (red circle) at an iron ore concentration facility on San Nicolas Bay (Marcona, Peru) and the discharge into the sea (yellow circle). The area shows a high species diversity and is close to two marine protected areas with colonies of sea lions and penguins.

CHANGING STATE OF THE HUMBOLDT

The oceanic conditions in the tropical ocean are strongly connected to the high environmental variability of the HCLME. Of the perturbations that may affect HCLME, the southern east-west climatic oscillation is the most evident source of variability. Some descriptions can be found in Shaffer et al. (1999) and Hormazábal et al. (2001). The principal variation is commonly referred as ENSO (El Niño Southern Oscillation) or the combined atmosphere/ocean coupling of physical processes. The ENSO oscillation includes La Niña (cold) and El Niño (warm) phases as well as neutral episodes.

Short and seasonal episodes of variability

One of the main features of the HCLME is the coastal upwelling (Arntz et al 2006, Thiel et al., 2007) which is the origin of a high primary, secondary and fishery productivity (Bakun and Weeks 2008) both for Chile and Peru. Nevertheless, the oceanic variability is expressed between changing limits and along different time and spatial ranges (Chavez et al. 2008, Alheit and Ñiquen 2004) from a few days to seasons, years and decades; and from small to large scales. This variability influences goods and services of the ecosystem, including fisheries and is expressed through environmental events of relative short duration such as propagation of Kelvin or Rossby waves (Dewitte et al 2008), the occurrence of other more durable events such as El Niño or La Niña, or throughout regime shifts cycles lasting decades (Thiel et al. 2007; Lluch-Belda et al. 1989 and 1992; Schwartzlose et al. 1999, Chavez et al. 2003).

To measure the changing environmental conditions of the HCLME, indicators such as Southern Oscillation Index (SOI), Oceanic Niño Index (ONI), or Pacific Decadal Oscillation (PDO) are used. SOI is based on the atmospheric pressure difference between Darwin (Australia) and Tahiti. The ENSO, although not exactly proportional to the SOI, is highly correlated with tropical sea surface temperature anomalies recorded in the El Niño Region 3 (www.cpc.ncep.noaa.gov). Fig. 4.

Interannual Variability: Kelvin and Rossby Waves

One of the main sources of variability in the HCLME comes from coastally-trapped Kelvin waves (Bertrand et al 2008) which originate in the far central Pacific (Pizarro et al. 2001, Hormazabal et al., 2001). These equatorial, large amplitude-long period waves due to variations in the wind, propagate heat eastward along the equatorial wave guide (Delcroix et al. 2000). The way they propagate depends on the wind anomalies (weakened easterlies or stronger westerlies) corresponding to two possible types: upwelling or downwelling depending on the resulting location of the thermo and oxycline when they arrive to the southeast Pacific. They continue propagating north and south as coastal trapped Kelvin waves. The longitudinal propagation of Kelvin waves can be described by variations in the vertical structure of thermal anomalies, and also analytically described by changes in the baroclinic modes (Dewitte el al. 1999) Figure 5.

There are two operational scenarios facing the propagation of Kelvin waves - the warm and the cold modes (Bertrand et al. 2008). The warm ‘downwelling’ scenario is produced when westerlies dominate the wind circulation along the surface of the tropical ocean, temperature increases and coastal upwelling decreases - at least in the northern HCLME and northern Chile. In this scenario, the thermocline is deeper and pelagic fish such as anchovy aggregate close to the coast and/or swim deeper, out of reach of top predators like marine birds. The fish also become less accessible to fishing boats.

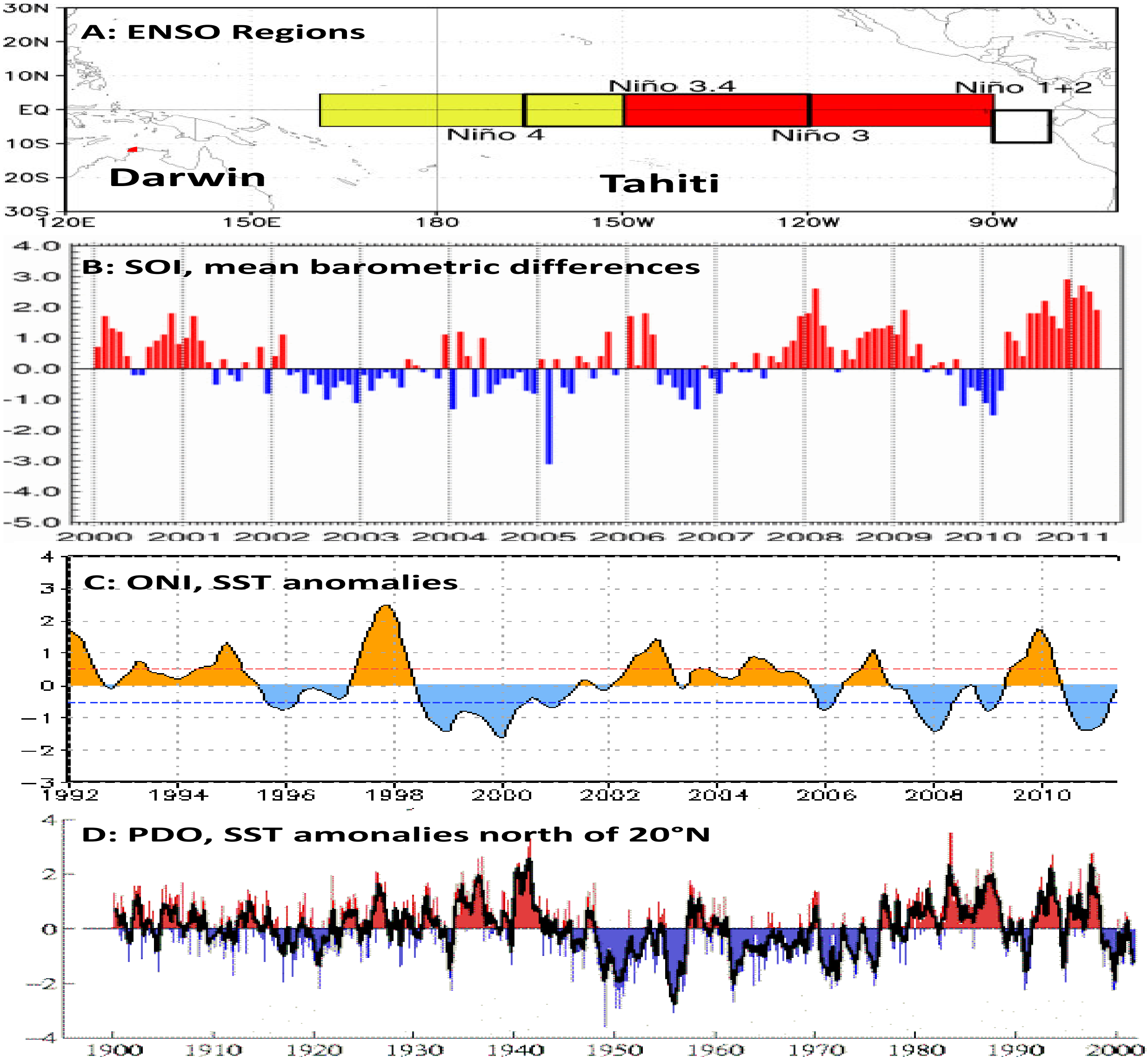

Figure 4. Some indexes used in calculating variability affecting the HCLME. A: ENSO regions and Darwin-Tahiti stations in monitoring the equatorial tropical Pacific for the phases of the ENSO cycle (El Niño, La Niña, Neutral). The tropical Pacific ocean has been divided into four Regions:Niño 1+2, Niño 3, Niño 4 and Niño 3.4. B: the SOI for 2000 to 2011, negative (blue) values are related to warm El Niño-like conditions in the tropical ocean, then positive values are a proxy of La Niña-like events. C: the ONI is based on SST departures from average in the Niño 3.4 region, and is a principal measure for monitoring, assessing, and predicting ENSO. El Niño is characterized by a positive ONI greater than or equal to +0.5°C during three consecutive months. La Niña is characterized by a negative ONI less than or equal to -0.5°C. D: PDO describe an oscillation in northern Pacific sea surface temperatures. When the PDO is in its positive phase (e.g. from 1977 to 1995), there are prevailing warm conditions in the HCLME (positive phase), then the negative phase is related to prevailing cold conditions in the southeast Pacific.

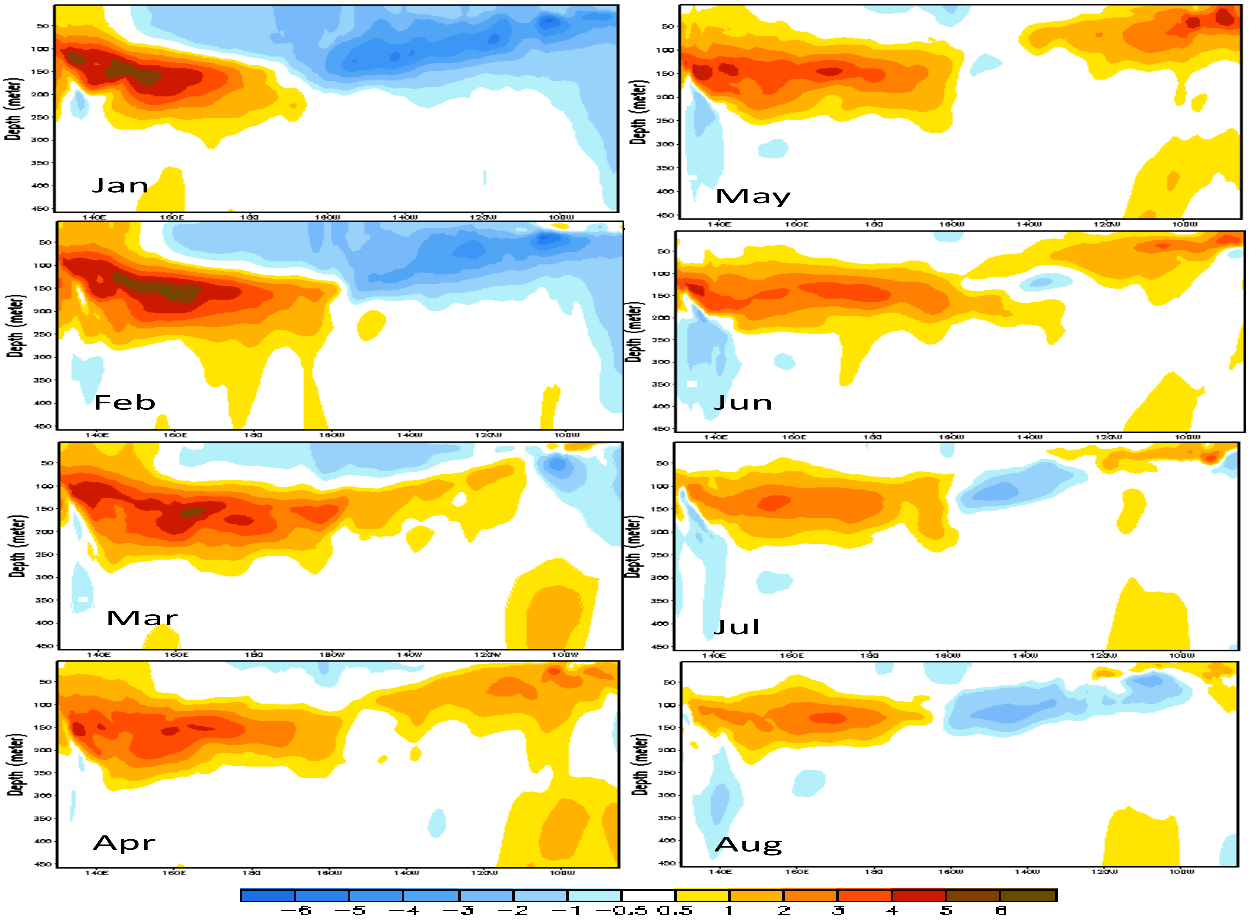

Figure 5. Thermal anomalies by months (°C) measured along the tropical ocean (X-axis) and depth (Y-axis) since January to August 2011. Red colors correspond to positive (warmer) thermal anomalies and blue colors indicate negative anomalies. Since January 2011, a set of Kelvin waves were observed developing from west to east, which are presented here as thermal progression anomalies, from left to right for each month in the figure. During April, a downwelling-type Kelvin wave reached northern Peru, dispersing and deepening anchovy and affecting the Peruvian northern fishery. During August normal conditions were restored. Images taken from NOAA-NCEP (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_update/wkxzteq.shtml).

The cold 'upwelling' scenario is produced when Kelvin waves propagate with dominating easterlies in the tropical wind circulation, the temperature decreases and coastal upwelling increases toward open ocean in the northern HCLME. In this scenario, the thermocline becomes shallower and anchovy distributes wider and closer to surface, available to predation and fishing. During this scenario, the area explored by fishing vessels, the duration of trips and catches are higher though sinuosity of trips decreases (Figure 6).

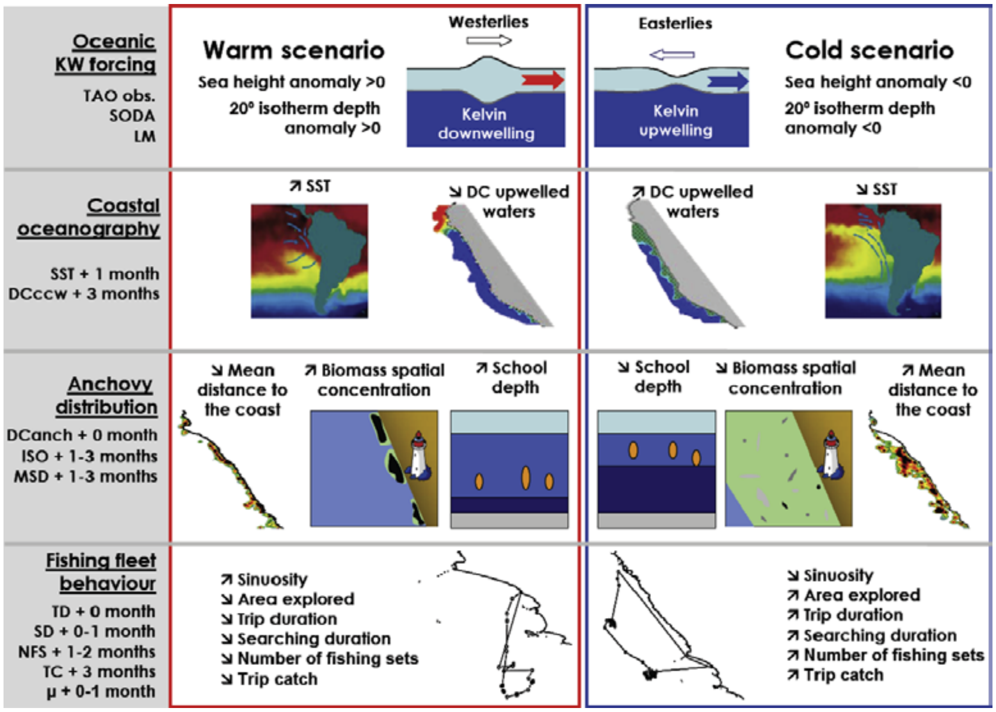

Figure 6. Bertrand et al. (2008) conceptual description about the way Kelvin waves can affect fisheries off Peru and Chile. Accordingly, two propagation scenarios are proposed. Measurements used were (i) sea surface temperature, mean distance to the coast of the cold coastal waters (DCccw); (ii) anchovy distribution: mean distance to the coast (DCanch), index of anchoveta spatial distribution (ISO), mean depth of the schools (MSD); (iii) fishing fleet behavior: mean travel duration (TD), mean searching duration (SD), mean number of fishing sets (NFS), mean trip catch (TC), synthetic index of fishing trip trajectories (I).Kelvin wave activity in the equatorial Pacific was observed through the depth of the 20°C isotherm as measured by the Tropical Atmosphere Ocean TAO/TRITON moorings (http://www.pmel.noaa.gov/tao/data_deliv/deliv.html). Used output came from the Simple Ocean Data Assimilation re-analysis of ocean climate variability (SODA).

Rossby wave formation is due to a restoring force propagating westward after Kelvin waves reach the south Pacific coasts, although part of it also propagates north and south as trapped coastal Kelvin waves (Steward 2007). In other words, as the Kelvin wave moves along the coast, it creates Rossby waves, which move west across the Pacific with a velocity dependent on the latitude (Rossby 1936). Equatorial Kelvin waves travel three times faster than the fastest equatorial Rossby waves (Dewitte et al. 2008). The way trapped Kelvin and Rossby waves generate baroclinic instabilities is possibly associated with temporal eddy activity, related to the intensification of the upwelling thermal front at inter annual scales (Chaigneau et al. 2008). Two types of eddies have been identified: anticyclonic eddies, which tend to propagate northwestward and cyclonic vortices, which migrate southwestward (Chaigneau and Pizarro 2005b).

The Niño and La Niña events

The interannual variability of the HCLME is explained by warm-cold, alternated cycles corresponding to what are now known as El Niño and La Niña events, respectively. The expression 'El Niño' was annotated for the first time by Alexander von Humboldt in 1802 (Nuñez and Petersen 2002) as cited by fishermen of the northern Peru to describe the intrusion of warm waters in late December (Christmas) when the birth of Jesus (Niño) is celebrated.

Specifically, the El Niño event is the warm phase of ENSO, or periodic warming of ocean waters in the eastern tropical Pacific. These conditions develop along the HCLME and also affect weather patterns around the world. El Niño events occur roughly every two to seven years and last from 12 to 18 months. The NOAA Climate Prediction Center's (CPC) definition for El Niño is the positive sea surface temperature departure from normal (for the 1971-2000 base period), averaged over three months, greater than or equal in magnitude to 0.5°C in the 3.4 Region. However an El Niño declared for the 3.4 Region does not necessarily have noticeable effects in the HCLME, as happened for the El Niño in 2010 along the Peruvian and north Chilean coasts.

Another way for describing an El Niño event is by a succession of Kelvin waves arriving in the HCLME area from north to south. These anomalies are caused by perturbations in the pressure fields along the equatorial Pacific as well as the weakening of trade winds. The signals are the changing sea surface level and the deepening of thermo, nutri and oxycline. Also, the upwelling is reduced or cancelled, resulting in increased environmental stress. This causes dramatic changes in the vertical distribution of low trophic level species and in turn affects top predators populations such as sea lions and seabirds.

The two decades (1980s and 1990s) featured five El Niño events (1982/83, 1986/87, 1991-1993, 1994/95, and 1997/98) alternating with three La Niña episodes (1984/85, 1988/89, 1995/96). During that period, the two strongest El Niño events during the 20th century were produced: 1982/83 and 1997/98. Nevertheless, there are decades where the alternation is relatively less pronounced (Arntz et al. 2006).

Seasonality and inter annual variability of zooplankton assemblages

Physical and biological processes are the main causes of variation in plankton biomass and composition in the HCLME (Ayon et al. 2004, Thiel et al. 2007). Those factors can occur on different time and spatial scales, including the short life cycle of zooplankton, diurnal interactions, or the length of time of inshore-offshore displacements and advection of water masses.

According to Santander and Flores (1983) and Bernal et al. (1983), anchovies and other species spawn more intensely on a seasonal basis, which suggests that favorable pelagic conditions might also be seasonal. The success of spawning is related to the moderated trade wind and upwelling intensity, which produces rich nutrients and maximum phyto and zooplankton production in the northern HCLME (Bakun and Nelson 1991) during winter months. Off Chile, the alternating periods of upwelling and relaxation support the best phytoplankton blooms (Echevin et al. 2004, Thiel et al. 2007). The same pattern is behind successful recruitment of Peruvian pelagic fish stocks (Walsh et al. 1980). It is the ''optimal environmental window" (Cury and Roy 1989) or ''optimal stability window" (Gargett 1997).

These are interannual and intraseasonal processes influenced in smaller temporal scales by the so called "vertical turbulence" (Franks 1992) which concentrate organisms otherwise dispersed horizontally, though able to maintain their depth, such as zooplankton and fish larvae (Genin et al. 2005). However, interannual and intraseasonal adverse physical–chemical processes can also be generated - leading to steep temperature gradients, low oxygen, and high ammonia concentrations. These episodes are mostly related to weak wind or to strong wind episodes. Minimum zooplankton abundance from 1970 to 1976 in the northern HCLME coincided with long periods with strong La Niña (cool) conditions, when upwelling intensity was maximal (Ayon et al. 2008) (Figure 7).

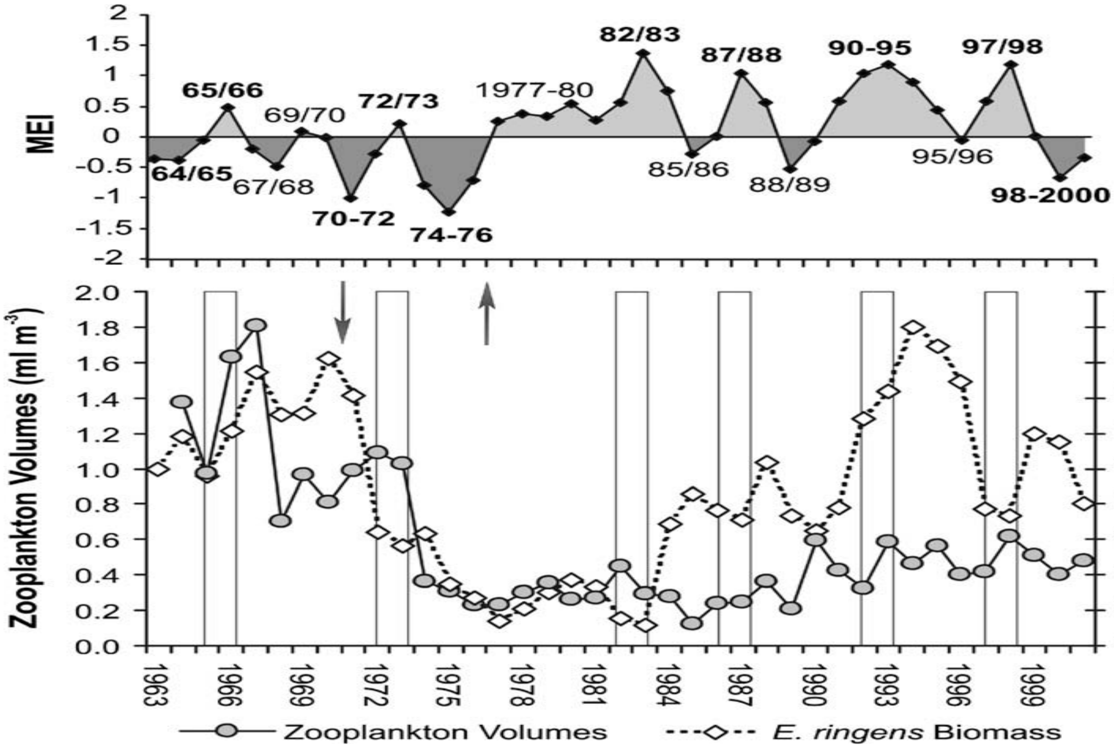

Figure 7. Mean annual tropical Pacific Multivariate ENSO Index (MEI), zooplankton volumes, and biomass of Peruvian anchoveta (*Engraulis ringens*) from 1963 to 2001. Above: the MEI time series shown is the annual average calculated from the original bimonthly MEI series (Wolter and Timlin, 1998). El Niño periods are highlighted above zero and La Niña periods are shown below zero. Source: http://www.cdc.noaa.gov. Below: average zooplankton volumes from more than 10,000 samples taken from the Peruvian coast to 300 nautical miles offshore. Values of 1979 and 1988 were interpolated with a 5-year moving average [according to Ayón et al. (2004), modified]. Strong El Niño events are shown as vertical bars. Arrows indicate global sea surface temperature regime shifts in 1970–1971 and 1976–1977 (Yasunaka and Hanawa, 2005). Source: Ayon et al. 2008.

New zooplankton research findings

The HCLME is producing enough macrozooplankton to sustain more forage fish populations per unit area than any other region in the world, although the paucity of information hampers research on this topic (Ballon et al. 2011). Nevertheless, the development of new acoustic methods for high resolution detection of the upper limit of the Minimum Oxygen Zone (MOZ) has opened new and yet unsuspected possibilities for ecological ocean research (Bertrand et al. 2010). The concept is simple – oxygen is essential for supporting life (Chin and Yeston 2011). Furthermore, a bi-frequency acoustic method has been developed for automated classification of crustacean macrozooplankton, fish, and other marine organisms. Euphausiid numbers and net sampling patterns revealed that past calculations of macrozooplankton biomass might have been underestimated by two to five times from previous estimations (Ballon et al. 2011). The total macrozooplankton biomass was calculated to be 105 g m^{-2} for a complete sampling survey in the summer of 2005, off Peru. This finding about a key trophic component of the ecosystem is consistent with the observations that forage fish consume mainly macrozooplankton (Espinoza and Bertrand 2008) and supports the hypotheses surrounding high fish production in the HCLME (Bakun and Broad 2003). Finally, these methodological developments allow scientists to revisit digitally recorded acoustic surveys for both Chile and Peru, carried out in the early

2000s - in order to extract high-resolution information on zooplankton to relate it to the physically driven primary producers and the biologically driven tertiary consumers.

DECADAL CHANGES AND REGIME SHIFTS

Beside interannual variability, there is evidence that large amplitude, low frequency variability occurs in many ecosystems of the world's oceans and is associated with "warming" and "cooling" periods (Bakun and Broad 2001). Descriptions of such interdecadal variation for the HCLME have been reported by Montecinos et al. (2003) and Montecinos and Pizarro (2005). Interdecadal variations in fish stocks - driven by the low frequency variability – are evident in large marine ecosystems including the California Current, Kuroshio Current, Benguela Current and the Humboldt Current, where alternating dominance between anchovies and sardines has been observed. The sediment records also support this phenomenon (Kawasaki 1983, Schwarztlose et al. 1999, Lluch-Belda et al. 1989 and 1992, Kawasaki et al. 1991, Serra 1991, Chavez et al. 2003, Gutierrez et al. 2007).

In this section we will focus on biomass yield as indicators of the biomass variability typically found in eastern margin of oceans, represented in the Humboldt Current ecosystem by *Engraulis ringens, Sardinops sagax, Trachurus murphyi, Scomber japonicus and Merluccius gayi*. *Strangomera bentincki*, a small and short living, endemic pelagic fish, distributed off south central Chile, is also included.

The catch biomass indicates the dominance of anchovy in the system (Figure 8). It also shows the succession of species: anchovy replaced by sardine and jack mackerel from the early 1970s to the 1990s and earlier. The recovery of the anchovy since the mid-1980s is also evident. There is also a synchronic shift in abundance of the different stocks of anchovy from north to south in the HCLME (Cubillos et al. 2007). By extension, a similar process occurs in sardine stocks.

Variations of biomass occur in both time and space as demonstrated by the spatial redistribution of maximum biomass yield for the different stocks. Figure 9 demonstrates that the major concentration of anchovy production is in northern Peru i.e. in the northern part of the HCLME; and to a lesser extent off south-central Chile, i.e. in the southern segment of the HCLME. In the latter, if the biomass yield of the common sardine is considered, the production is still much less compared with the stock in north central Peru. For sardine, the stocks in north central Peru and in southern Peru/northern Chile are a similar size, while production in central Chile is much less. However, the largest concentrations of jack mackerel are found off south central Chile. These results suggest that associated with the interdecadal change and sequential change in species dominance, the areas of main fish production might change. For example, the overall fish production in north central Peru is less when sardine is dominant versus anchovy. South Peru and northern Chile have increased fish production when sardine is dominant and south central Chile has increased fish production when jack mackerel is dominant.

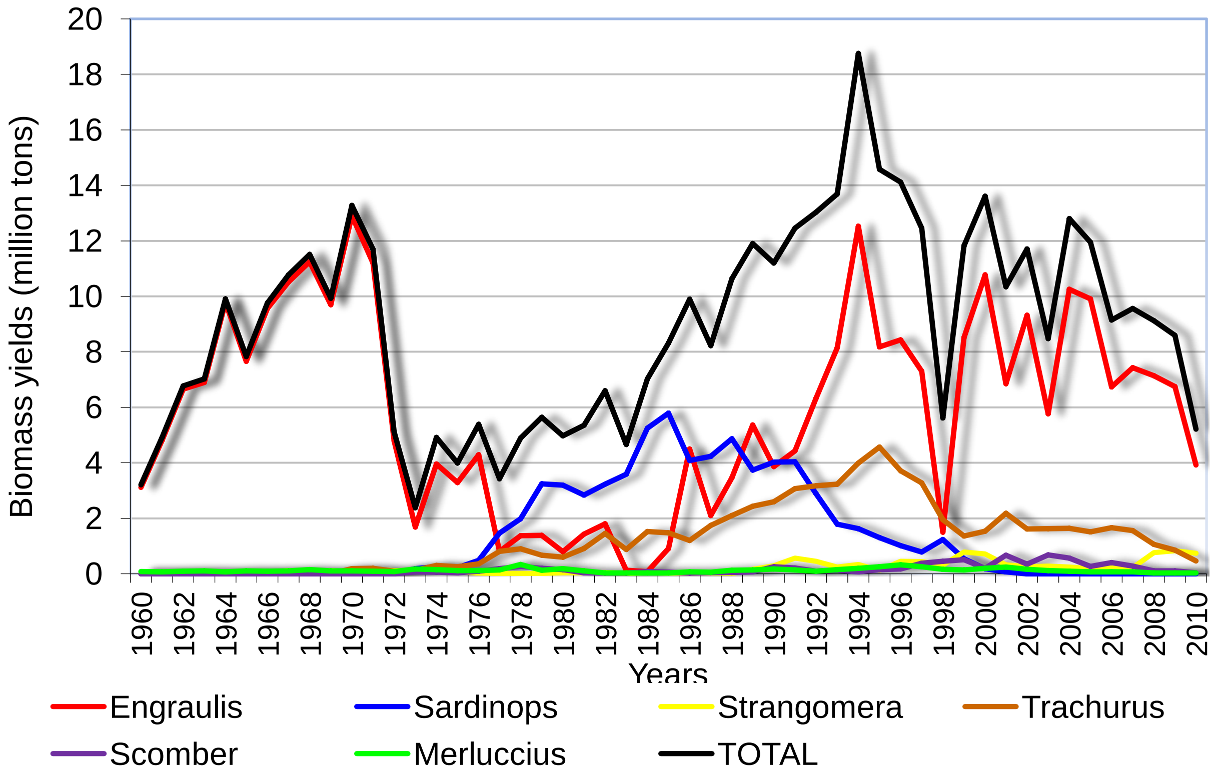

Figure 8. Biomass yield of key fish species in the HCLME during the past 50 years – in hundreds of thousands of tons (10^6) and millions of tons (10^7). The HCLME is comprised of mainly small pelagic fish species (anchovy - *Engraulis*, jack mackerel - *Trachurus*, mackerel – *Scomber*, and sardines - *Sardinops*), as well as demersal species like hake (*Merluccius*).

These variations of fish production in time and space can have strong consequences on the fishing activities and performance. The shift from anchovy to sardine had a strong impact on the Peruvian and Chilean fishing industry. The dramatic drop in anchovy abundance in the seventies created a nationalization process of the fishmeal industry in Peru. This coincided with a dramatic decrease in the fishing fleet and closure of processing plants, strongly affecting employment. The change to a sardine and jack mackerel dominated system favored the further development of the Chilean industry in north and south central Chile and included large investments in processing plants and fishing fleets. In same sense, the return to an anchovy dominated system favored the Peruvian industry and had a negative impact on Chile, leading to the closure of fishing plants and loss of employment.

Population status of guano sea birds and pinnipeds

The nutrient-rich upwelling fuels zooplankton and fish production over the HCLME, which also supports higher trophic levels, including large populations of seabirds and marine mammals. Pelagic fisheries, typically concentrated near main upwelling centers, remove an important proportion of the fish production, which affects trophic interactions in the HCLME (Thiel et al. 2007).

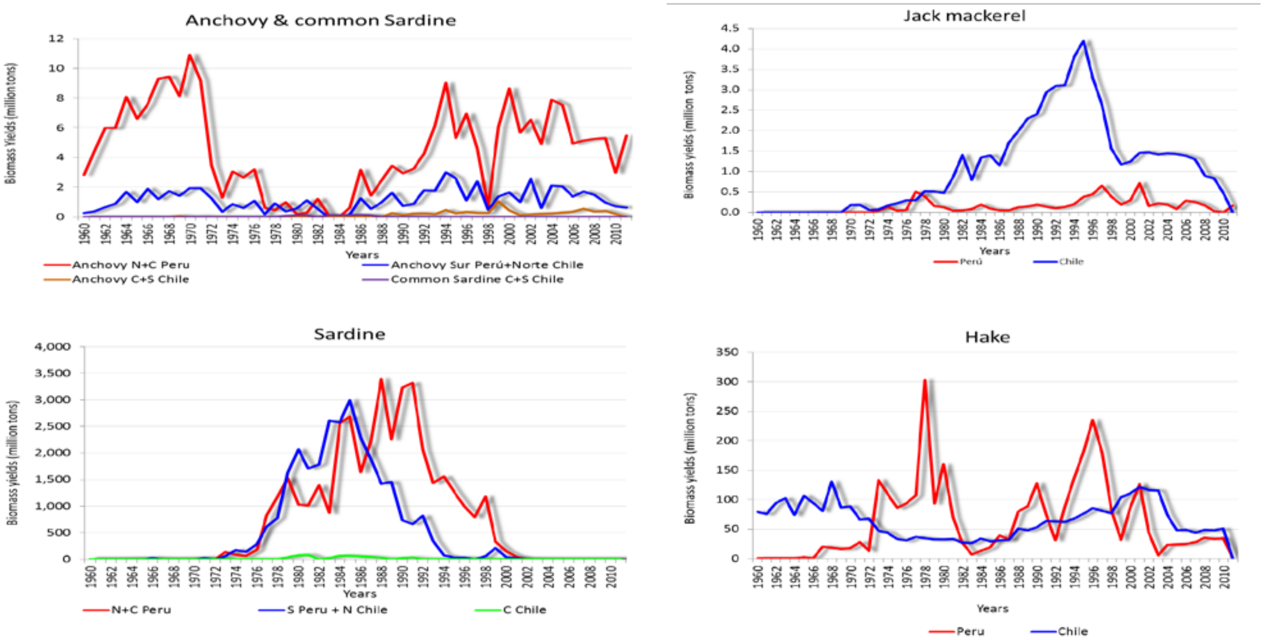

Figure 9. Yield biomass variations by different stocks. NC: north-central; SPNCH: south Peru-north Chile; CS: central south; C: central.

Furness and Monaghan (1987) determined that guano-producing birds of the HCLME have advantageous, biological features (more weight, for example) than similar species of other ecosystems due to their superior capacity for adaptation to a highly variable environment. The guano sea birds feed on a variety of coastal species, and some of them are specialized for eating anchovies. Nevertheless, the main species of guano-producing birds, the guanay (*Phalacrocorax bougainvillii*), the booby (*Sula variegata*) and the pelican (*Pelecanus thagus*) exhibit lower abundances than expected since the El Niño of 1964-1965 (Chavez et al. 2008). Despite the fact that anchovies have maintained high abundance levels since El Niño 1992, the bird populations have not followed the same trend in the northern HCLME. The combined effect of the El Niño events and the fishing activity (Goya 2000) may be hampering the recovery of guano-producing birds despite the high anchovy biomass observed in the HCLME after El Niño of 1997-98 (Taylor et al. 2008) (Figure 10).

Goya and Valverde (2006) presented complementary hypotheses for this discrepancy: (1) young birds with less strength and capacity to locate their prey represent an increase in the natural mortality rate versus an “old” population with declining reproductive capacity; (2) the El Niño events have increased in frequency since El Niño of 1957, altering the adaptive response, which would explain why there is now a lower reproductive proportion. Furthermore, sea birds take advantage of the presence of fishing vessels to feed, though often the effect became negative in the short term due to the fact the birds abandon nests to follow actively the vessels when local fish schools are depleted (S. Bertrand, pers. comm.).

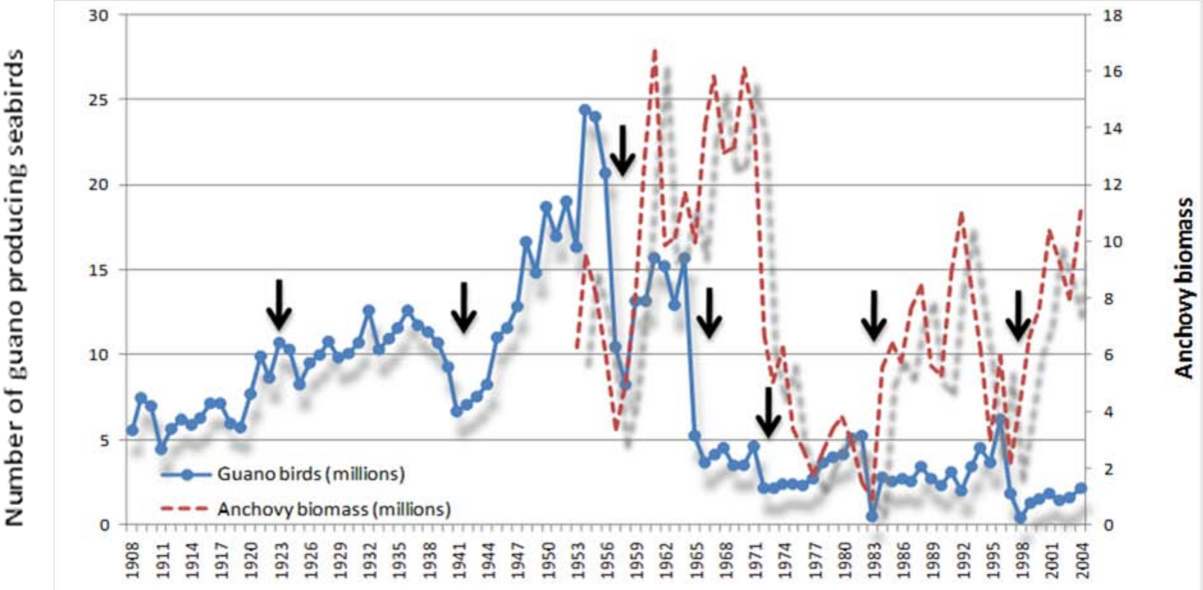

Figure 10. Abundance of birds (blue line) between 1908 and 2004 in comparison with the anchovy biomass between 1955 and 2004 (red dotted line). It can be observed that each El Niño event (the principal events are indicated by arrows) has had a negative effect on the abundance of birds. Since the 1950s, the frequency of these types of events has increased, resulting in a continuous decline in the abundance of these animals. During El Niño of 1997-1998, the number of surviving birds was very small, although they have displayed a sustained recovery. The total abundance of these populations is unknown, but they may be greater than shown, since current estimates are based on censuses restricted only to accessible areas Taylor et al. (2008).

Other hypotheses that attempt to explain the dwindling bird population are: (1) the number of small-scale fishermen has increased by 243% since 1997 (Escudero 1997) in the Moquegua-Tacna region (Estrella et al. 2006), bringing an increased human presence in nesting zones; (2) the use of illegal practices such as manipulation of explosives was acknowledged by small-scale fishermen in a survey carried out by IMARPE (2009) that illustrates how unawareness of the law led to the illegal practices; (3) the inaccessibility of the nesting zones limits the collection of scientific information on the distribution and abundance of sea birds; (4) the decreased water transparency, a consequence of higher plankton productivity since El Niño of 1997-1998, affects the birds' ability to fish; and (5) the lesser abundance of species such as dolphins and skipjack (*Sarda chilensis*) which would normally force anchovy close to surface, where birds can easily feed (Taylor et al. 2008).

Sea lions seem to have recovered their numbers after El Niño of 1997-98, at least in the northern HCLME. However, because sea lion censuses are most difficult to perform, trophic models and simulations have been used to determine the relative abundance of this species. Based on an ecotrophic model (Ecopath with Ecosim–EwE-), Taylor et al. (2008) proposed a possible "bottom-up" relationship between the anchovy and its main coastal predators (sea birds and mammals) wherein the anchovy may regulate the abundance of its predators by modifying its distribution. For instance, migrating or swimming at deeper depths for prolonged periods, as occurs during El Niño events, will limit the distribution of sea birds and mammals. Also, in the HCLME, the location of the oxycline is relatively shallow (Siffedine et al. 2008). This restricts the distribution of fish and enables predation by sea birds and mammals.

However, the sinking of the oxycline, which is characteristic of the El Niño events or periods of Kelvin wave propagation, also increases the depth of the distribution of pelagic species. If these periods last long enough, the mortality between top predators can increase dramatically (Arntz and Fahrbach 1996).

Another factor to be considered is the illegal catching and use of sea lion meat by small-scale fishermen (IMARPE 2009) as a way to protect their fishing gear from attacks by sea lions. In some locations, sea lions are also victims of poaching by fishermen. The magnitude of illegal hunting and catching of sea lions is unknown though suspected to be high (Figure 11).

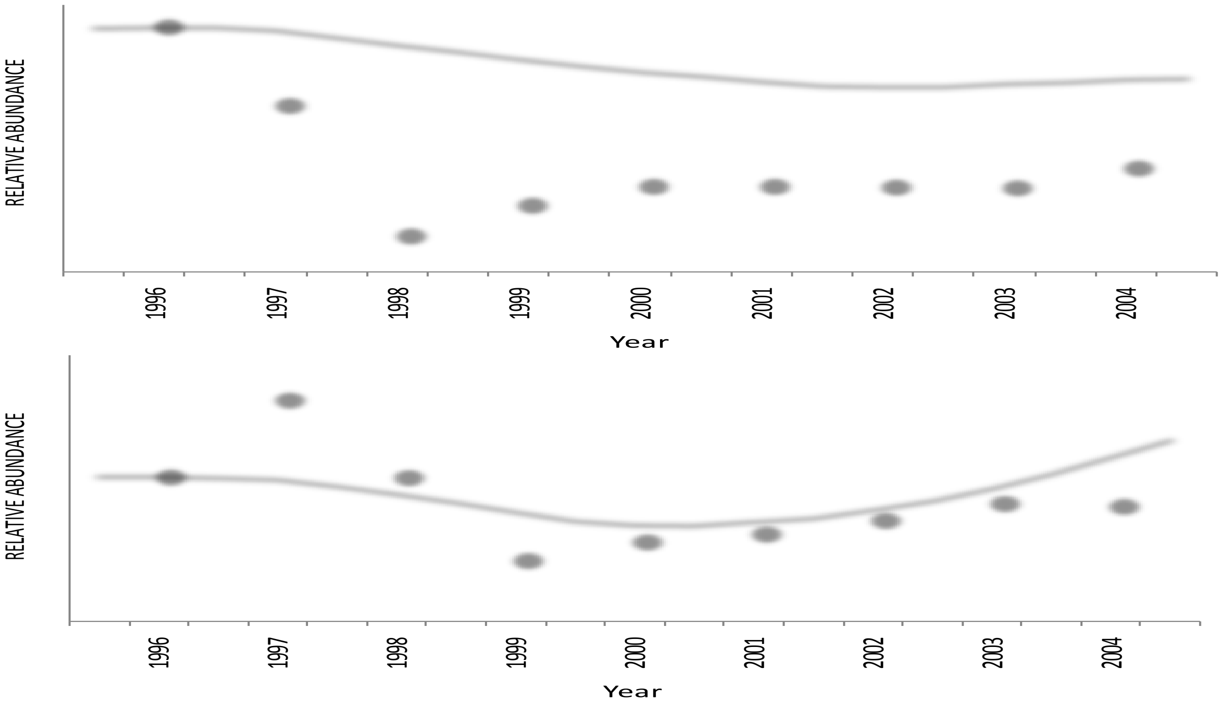

Figure 11. Time series (1996-2004) of relative abundance of birds (top) and sea lions (pinnipeds, bottom). According to the model used (continuous line) by Taylor et al (2008), the relative abundance of seabirds might be declining, while sea lions are increasing. However, the direct assessments made (circles) show that the abundance of both birds and sea lions has been on the rise since 1998. Source Taylor et al (2008).

REGIONAL COOPERATION: THE KEY TO SUCCESS

The limited understanding of the causes of variability of the HCLME (affecting the fish resources), threats to biodiversity, and the multiple uses of the ecosystem services, represent a challenge for Chile and Peru. The ecosystem they share and the complexity of the problems and issues are formidable. In addition to the importance of the fisheries, the Humboldt Current LME has globally significant biodiversity and has been designated a WWF Global 200 Ecoregion. Particularly visible and valuable are the very large colonies of seabirds and marine mammals. Sea mammals, sharks, sword fish and seabirds are top predators in the trophic chain of the HCLME. But climate variability has also an important effect on biodiversity, particularly strong El Niño events and interdecadal variation.

Barriers exist that make managing with an ecosystem approach a considerable challenge. Understanding the functioning of the HCLME requires a holistic approach. There is a need to harmonize research activities within institutions. Therefore, Peru and Chile have committed to collaborate and have asked the Global Environment Facility (GEF) to support sustainable uses in the HCLME and help form a resilient LME that can maintain biological diversity together and ecosystem services for current and future generations despite changing climatic and social pressures.

Some of these barriers are:

- The government institutions responsible for managing coastal and marine systems are fragmented and tend to be organized along political, rather than ecological, boundaries and the linkages between conservation and economic and sometimes social interests are often not appreciated.
- Deficient information and planning frameworks for consensus building and collaborative action.
- Weak institutional frameworks and capacities for ecosystem-based management for effectively incorporating scientific understanding into the decision-making process and management tools.
- Limited knowledge of management options for protecting living marine resources and their habitats.
- Incomplete coverage and representations of Marine Protected Areas (MPA) in both countries.

There is clearly a need to share expertise, to build capacity and to develop a collaborative approach to ensure the sustainability of the HCLME.

Changing habitat for pelagic fish: the LMEs synchrony

The combined pelagic fishery of Peru and Chile produces over 15% of the world’s marine capture landings (FAO 2010). Pelagic fish species play an important ecological role by transferring energy from lower to higher trophic levels. They are characterized by interannual variations in their abundance due to their dependence on environmentally-driven variables (Barange et al. 2009). Furthermore, there is evidence of multi-decadal, alternating productivity cycles among species such as anchovy and sardine (Schwartzlose et al. 1999, Lluch-Belda et al. 1989). These so called ‘regime shifts’ are possibly linked to oceanic forcing and large-scale climate trends operating at basin scale (Chavez et al. 2003, Alheit and Ñiquen 2004). An investigation led by the Global Ocean Ecosystem Dynamics (GLOBEC) highlighted the need for clarifying the existence of out-of-phase production cycles among LMEs due to their important consequences (De Oliveira 2006). If this synchrony can be confirmed, cooperative management procedures might be more efficient if local managers observe signals from other ecosystems and use specific ecological models to account for these changes.

As an example, Barange et al. (2009) investigated and produced the first comparative study on the relationships between the expansion and contraction of habitats - in the context of climate change, stock biomass, distribution area, mean density, and the synchrony and asynchrony of sardine and anchovy populations off California, Peru, South Africa and Japan. Their results indicated that when biomass of the two species increased, they increase their distribution area and density between certain limits. This was consistent with the basin model (MacCall 1990). Regarding synchrony, they found that differences in the use of space provides opportunities for diverging population paths for both species, though the ecological process explaining the observed out-of-phase fluctuations (see Figure 12) can be far more complex than a simple replacement. A different approach explains synchrony by the fact that sardine populations, in different LMEs, grow in small pockets, while anchovy grows in synchrony with other similar species. The study concluded that (1) if anchovy and sardine are equivalent species in different LMEs demonstrating synchrony/asynchrony then their habitat selection mechanisms should also be similar, and (2) whatever causes one species to decline must act positively on the second species (Figure 12).

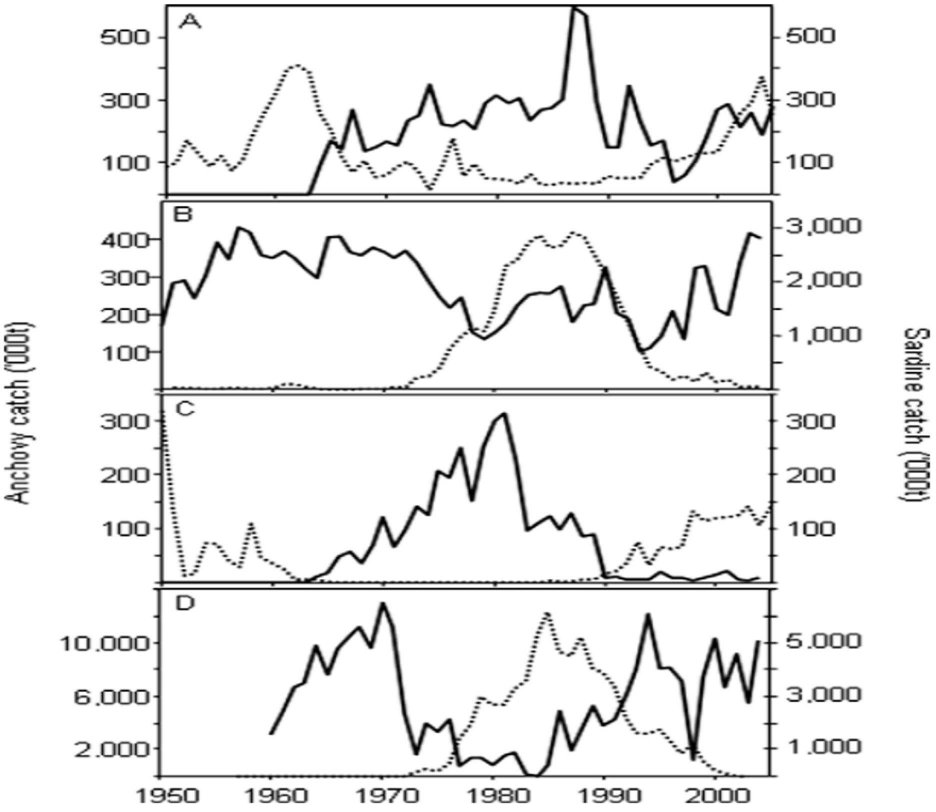

Figure 12. Landings of anchovy (solid line) and sardine (dotted line) in the Benguela Current (South Africa, A), Kuroshio Current (Japan, B), California Current (USA, C) and Humboldt Current (Peru, D). The anchovy populations appeared in synchronic phase between the Benguela Current and California Current LMEs, and out of phase with Humboldt Current and Kuroshio Current LMEs. Similarly sardine populations are in phase between Kuroshio Current and Humboldt LMEs and out of phase regarding California and Benguela LMEs (Barange et al. 2009).

TRANSBOUNDARY CONSIDERATIONS

Cooperation regarding transboundary considerations is being developed following principles established by national Peru-Chile legislation and current international laws:

- Sustainable development, as it is stated by the World Summit on Sustainable Development and the Johannesburg declaration (2001) on Sustainable Development.
- The Ecosystem-based Approach (EBA) and Code of Conduct for Responsible Fisheries as defined by FAO (1992), and the Precautionary Approach of the Rio Declaration on Development and Environment (1995).

Chile and Peru shall also promote:
- An adaptive management approach to reflect the highly variable HCLME environment.
- The use of safe, modern and clean technologies and methods.

- The approval of legal instruments to support sustainable development with special consideration of climate change challenges.
- The active participation of all stakeholders by adhering to the principles of shared responsibility, liability and commitment regarding the ecosystem services.
- Transparency in the management, monitoring, scientific and technological research, and the exchange of experiences.

TOWARDS A SUSTAINABLE FUTURE

Ecosystem Based Management (EBM) seeks to restore and sustain the health, productivity, resilience, and biological diversity of coastal and marine systems and promote the quality of life for humans who depend on them. Chile and Peru are just starting to develop the project "Towards ecosystem management of the Humboldt Current Large Marine Ecosystem" with the support of GEF and UNDP. The project will put in place a governance framework for the identification and prioritization of actions needed to preserve and maintain ecosystem services of importance for the HCLME.

The success of any management action will clearly be dependent on understanding the underlying ecosystem processes and the linkages between the Humboldt Current LME and the larger ocean-atmosphere environment. However, the sources of much of the significant variability and change in the Humboldt ecosystem lie outside the system. Regional human impact on the ecosystem includes fishing, pollution, oil production, guano, and coastal exploitation.

Unlike fixed boundary ecosystems such as the Baltic or the Black Sea, where corrective management can largely ignore external forcing, in an open ecosystem such as the HCLME, sustainable integrated management has to take the external forcing into account, and that means looking beyond the narrow confines of the various fronts. The approach to a highly variable LME like the Humboldt will be very different from one for a closed or semi-closed system. The HCLME does not function in isolation, but rather as part of the global ocean system and the synchronic, sequential changes in anchovy and sardine populations and ENSO events are clear indicators of this.

Within the next decade, it is likely that the first signs of global environmental change will become more apparent, and governments which choose to ignore this probability do so at their peril. To move forward, management requires good advice based on good science, and accordingly the regional research structures will need to be strengthened, not undermined. Access to international expertise and collaboration with other players in the Pacific is essential, particularly in terms of modeling and improving predictability.

In order to address the main transboundary problems and barriers to policy development - regional networking, capacity development and training are high priority activities. Collaboration in surveys, monitoring, and assessments are likewise seen as very important. From an LME research and management perspective, system boundaries cannot ignore regional, political and economic realities, or the interdependence of countries. However, the success of any management action will clearly be dependent on the proper understanding of the underlying ecosystem processes and the linkages between the Humboldt Current LME and other similar LMEs such as the California Current, Benguela Current and Canary Current.

Sustainable integrated management of the Humboldt Current LME requires a collective and proactive approach by Peru and Chile, not a reactive response to problems. Apart from the joint actions which the two countries are committed to, visionary thinking and innovative management on the part of the governments will be required. Management depends on good advice based on good science, and accordingly the regional research structures will need to be strengthened and demonstrate to the rest of the world how a fragile and variable large marine ecosystem can be managed sustainably.

ACKNOWLEDGEMENTS

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8

GULF of MEXICO LARGE MARINE ECOSYSTEM: RESOURCES AT RISK FROM CLIMATE CHANGE

Roberto Mendoza-Alfaro and Porfirio Alvarez-Torres

INTRODUCTION

The Gulf of Mexico Large Marine Ecosystem (GoMLME) Project is a Global Environment Facility (GEF) initiative that launched its activities in June, 2009. It aims to apply ecosystem based management (EBM) in the GoMLME (Figure 1) by removing constraints and barriers, developing tools, and promoting reforms and investments.

The Gulf LME program has been working in capacity-building activities and pilot projects in three areas: i) productivity, ii) conservation and adaptive management, and iii) cross sectoral engagement, including monitoring and evaluation frameworks. The project will help understand LME functions in the Gulf of Mexico and serve as input for LME management strategies. The LME project aims to strengthen the Gulf's living marine resources and address land-based and marine pollution – including oil pollution and nutrient loads that contribute to hypoxic zones in the region.

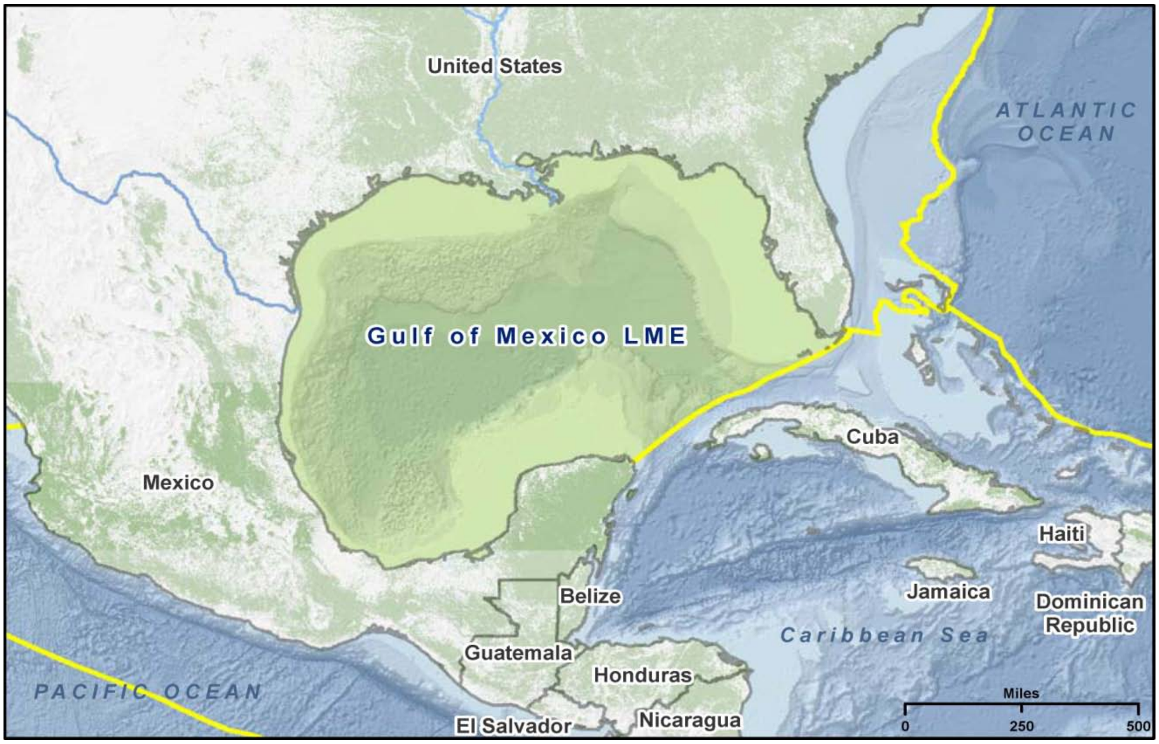


Figure 1. Location of the Gulf of Mexico LME.

Currently, there is no integrated strategy for marine policies and environmental conservation in the Gulf of Mexico. There is a need to identify and resolve problems associated with governing a transboundary water basin. All nations sharing the Gulf recognize the importance of working together to protect and manage goods and services of the GoMLME. The Gulf of Mexico LME program is fostering actions to improve environmental quality and sustainable development of resources within the Gulf, for economic growth, food security and community resilience. Based on this approach, Mexico and the US started a long-term partnership in 2009 towards the Integrated Assessment and Management of the Gulf of Mexico Large Marine Ecosystem. The principal global benefit of the project will be an enhanced understanding of LME functions and this will serve as input for LME management strategies through the Transboundary Diagnostic Assessment (TDA) and Strategic Action Program (SAP) processes. Ecosystem-based management (EBM) practices will contribute to the protection and maintenance of ecosystem functions and services (UNIDO-GEF, 2010).

World Climate Change

It is widely accepted that at least part of the earth's 0.6°C warming during the last 100 years is due to emissions of greenhouse gases caused by human activities (Allison et al. 2005). The Intergovernmental Panel on Climate Change projects that atmospheric temperatures will rise by 1.8-4.0°C globally by 2100 (IPCC 2007). A warming climate will change relevant precipitation and evaporation rates, riverine discharge, coastal habitats through increased flooding, oceanic circulations, and increase ocean acidification (Scavia et al. 2002; Roesig et al. 2005).

The productivity, distribution and seasonality of fisheries, and the quality and availability of the habitats that support them, are sensitive to these climate change effects. In addition, many fishery-dependent communities and aquaculture operations are in regions highly exposed to climate change (The World Fish Center 2009). Human-induced global climate change is now recognized as a major factor affecting the productivity of key species in world fisheries (Allison, 2010; Beamish and Peck, 2011) and is an additional pressure on fish stocks besides fishing pressure, loss of habitat, pollution, disturbances, and introduced species. It is evident that fish stocks will be more resilient to climate impacts if the stresses due to other factors, such as overfishing and pollution, are minimized (Brander, 2006).

The relationship between climate change and fisheries is a complex one, because climate change has both direct and indirect impacts on commercial fish stocks. Direct effects can alter physiology, behavior, reproductive capacity, growth, mortality and distribution, particularly during their early life history. This may lead to declines in abundance or redistribution of fish. Indirect effects alter the productivity, structure and composition of the marine ecosystems on which fish depend for food. In particular, increasing water temperatures and acidification are likely to reduce the area and quality of the coral reefs that harbor much of the coastal fisheries production. Seagrasses, which also provide nursery and feeding habitats for many species, may also be affected (Pratchett et al. 2008).

Climate Change and Fisheries in the Gulf of Mexico

Precautionary catch limits are typically used to build sustainable fisheries. These harvest policies are based on the expected productivity of the stock in a future environmental state but seldom consider how future climate change may modify productivity of the fish stock. At the single species level, climate change could significantly influence the carrying capacity, the reproductive potential, as well as the spatial distribution of the stock (Hollowed & Schirripa, 2010). At the multi-species level, changes in geographic ranges, vertical distributions, phenologies, population structures, and productivities will differ among individual species thereby altering functions of ecosystem components, including predator-prey relationships and competition, species assembly, community structure, biodiversity, energy flow, and carrying capacity (Okey and Yatsu, 2010).

Based upon long-term environmental records, there is considerable evidence of climate change during the 20th Century in the Atlantic coastal areas. Air temperatures have increased by 0.5-1.0°C and precipitation has increased by 6-8% since 1900. Water temperatures in both the coastal ocean and principal U.S. Atlantic estuaries have warmed 0.6-1.5°C since the middle of the 20th Century. The sea surface temperature (SST) is estimated to have increased 0.31°C in the Gulf of Mexico Large Marine Ecosystem between 1982 and 2006 (Fig. 2).

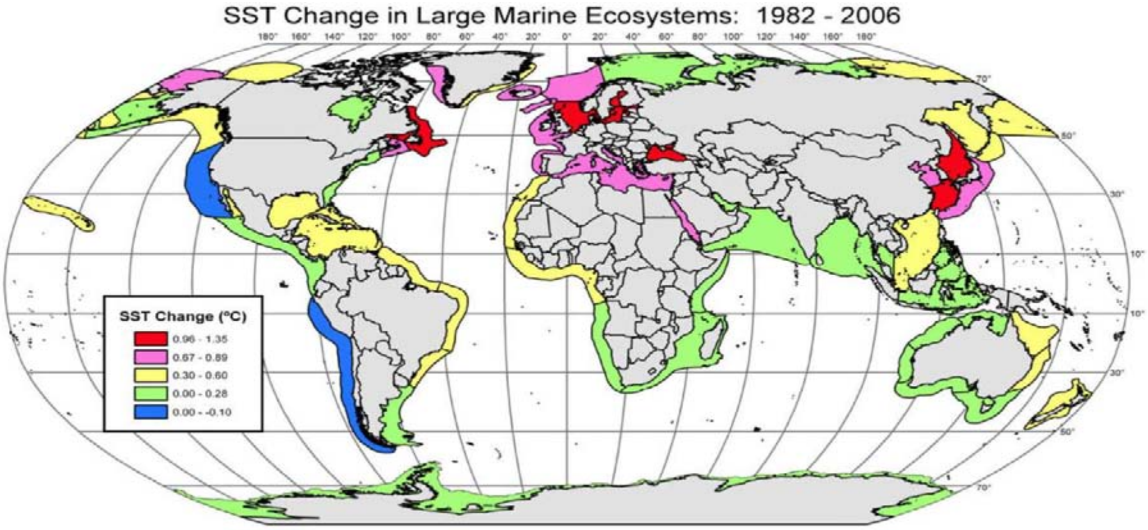


Figure 2. Net SST change (°C) in Large Marine Ecosystems, 1982–2006. Rapid warming (red and pink) is observed around the North Atlantic Subarctic Gyre, in the European Seas, and in the East Asian Seas. The Indian Ocean LMEs and Australian–Indonesian seas warmed at slow rates. The California and Humboldt Current LMEs cooled. (from Belkin, 2009).

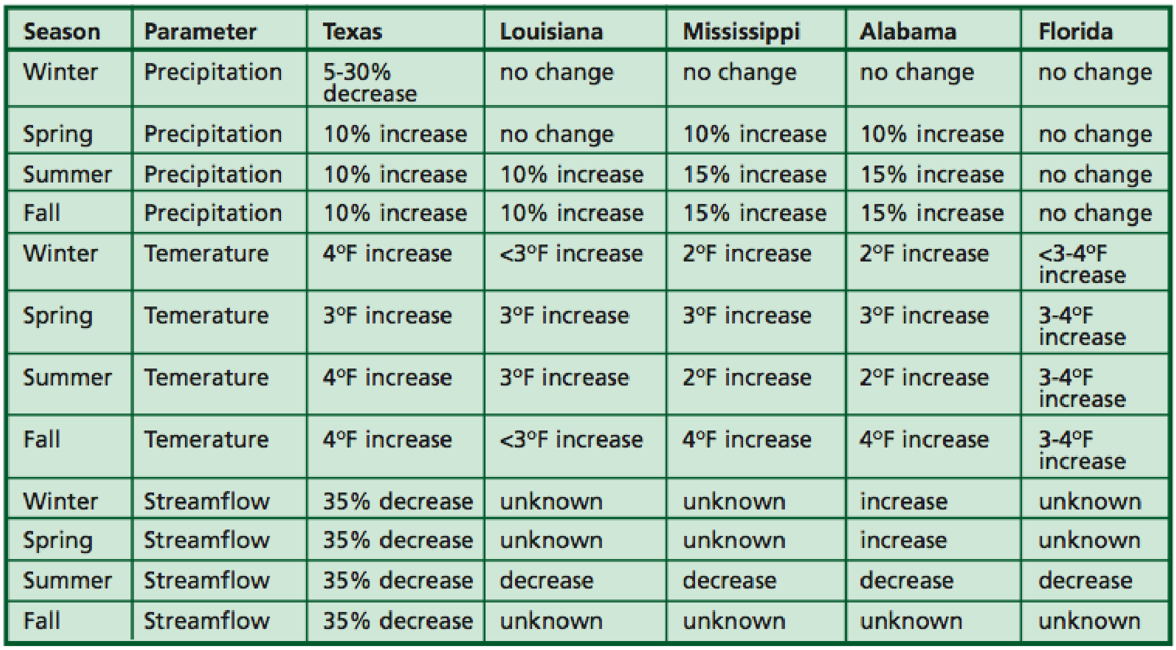
Within marine ecosystems, fish and fisheries are likely to be affected through the loss or degradation of near shore fish habitat, alteration of larval dispersion pathways, and changes in species ranges, because of physiological and behavioral responses to environmental gradients (Scavia et al. 2002; Perry et al. 2005; Hare et al. 2010).

Temperatures along the US East Coast are predicted to increase by another 2-7°C by 2099 depending on the region and carbon dioxide emission scenario. Precipitation is forecasted to increase by 6-24 percent in the same time frame, with heavy precipitation events becoming more common (Connelly et al. 2007). Commercial and recreational fisheries in the Gulf of Mexico may be affected strongly and adversely by such warming conditions and fisheries production could decrease substantially (Cheung et al. 2009).

Stream flow changes and fisheries

Changes in stream flow affect the reproductive success of many species of fish, especially anadromous fishes such as American shad, striped bass, and the Gulf sturgeon. Higher stream flows tend to support higher reproductive success of striped bass and other anadromous fishes (Martino and Houde 2004). The threatened Gulf sturgeon (*Acipenser oxyrhynchus desotoi*) is a primitive, anadromous fish that annually migrates from the Gulf of Mexico into freshwater streams.

Relationships between stream flow and the reproductive success of fishes are based on the overall magnitude and timing of flows that occur episodically during spring. Therefore, these relationships could change dramatically depending on how the amount and timing of stream flow evolves with climate change (Wood et al. 2002). Figure 3 contains a summary of seasonal precipitation, temperature, and stream flow changes, expected by 2100 due to global climate change (Swenson 2003).



Season	Parameter	Texas	Louisiana	Mississippi	Alabama	Florida
Winter	Precipitation	5-30% decrease	no change	no change	no change	no change
Spring	Precipitation	10% increase	no change	10% increase	10% increase	no change
Summer	Precipitation	10% increase	10% increase	15% increase	15% increase	no change
Fall	Precipitation	10% increase	10% increase	15% increase	15% increase	no change
Winter	Temerature	4°F increase	<3°F increase	2°F increase	2°F increase	<3-4°F increase
Spring	Temerature	3°F increase	3°F increase	3°F increase	3°F increase	3-4°F increase
Summer	Temerature	4°F increase	3°F increase	2°F increase	2°F increase	3-4°F increase
Fall	Temerature	4°F increase	<3°F increase	4°F increase	4°F increase	3-4°F increase
Winter	Streamflow	35% decrease	unknown	unknown	increase	unknown
Spring	Streamflow	35% decrease	unknown	unknown	increase	unknown
Summer	Streamflow	35% decrease	decrease	decrease	decrease	decrease
Fall	Streamflow	35% decrease	unknown	unknown	unknown	unknown

Figure 3. Summary of predicted precipitation, temperature, and stream flow changes, by season expected to occur by the year 2100. The predictions are from the Hadley Model (HadCM2) as summarized by Ning and Addollahi (1999). (Swenson 2003).

There is also a great deal of uncertainty regarding the timing of stream flow pulses in response to climate change (Wood et al. 2002). In general, the peak pulse in stream flow during spring results from the melting of the snow that accumulated throughout the winter. Increased winter temperatures will cause an earlier snow melt and cause precipitation to fall as rain instead of snow. Either of these scenarios will cause stream flow to peak earlier in the spring or even during winter. These changes may not provide the necessary environmental conditions for the reproductive success of anadromous fishes (Connelly et al. 2007).

POLLUTION AND ECOSYSTEM HEALTH

The disproportionate percentage of the population of the US and Mexico bordering the Gulf of Mexico live in coastal areas. The activities of municipalities, commerce, industry, and tourism have created environmental pressures that threaten resources in coastal and marine areas (UNIDO-GEF 2010). These pressures include urban and agricultural point and non-point sources of pollution.

Hydrocarbon pollution in marine areas is associated with the activities of the oil industry, but also with urban runoff and other sources such as vehicle exhaust, forest and grassland fires. The British Petroleum well blowout in 2010 and the collapse of the Deepwater Horizon platform heightened the need for safety precautions but also revealed the limitations of knowledge about the fate and effects of oil spills in the deep sea (UNIDO-GEF 2010). Metals are an environmental concern in the Gulf of Mexico. Mercury is the main cause for fish and shellfish consumption alerts. Metal pollution can originate from industrial waste, urban runoff, incinerators, mining and oil drilling activities.

Pesticides are an issue in the GoMLME and many of them are currently still in use, or have been recently added to Annex A of the Stockholm Convention, such as Lindane and Endosulfan. Monitoring in both countries indicates that concentrations in a significant number of sampling stations exceed the sediment quality guidelines. Emerging pollutants include human and veterinary pharmaceuticals, personal care products, brominated flame retardants, and new classes of detergents. Very little is known in the Gulf of Mexico about these pollutants and their effect on the marine environment (UNIDO-GEF 2010).

The input of raw or partially treated wastewater into the Gulf is a problem, particularly in Mexico. Urban sewage contains not only organic matter and pathogens, but also a suite of other pollutants such as hydrocarbons, metals, pesticides, and pharmaceuticals and personal care products. Waste water treatment plants are not all designed to remove these pollutants, and these compounds enter the marine environment.

The Gulf of Mexico is one of the main oil drilling areas in the world, and there are many industrial facilities associated with the oil industry both in Mexico and in the United States. The origin of many different types of hydrocarbons (biogenic, diagenic, petrogenic, pyrogenic) in the environment is difficult to recognize (UNIDO-GEF 2010). The production in the Gulf of Mexico LME is more than 400,000 metric tons per day and unfortunately the oil tankers release seven million barrels per year into the sea from washing their tanks (UNIDO-GEF 2010).

PRODUCTIVITY

The productivity in the Gulf is moderately high at (150-300 $gCm^{-2}yr^{-1}$). The productivity supports an important global reservoir of biodiversity and biomass of fish, crustaceans, mollusks, sea birds and marine mammals, though productivity has been decreasing in recent years.

The lowest surface content of Chl-a occurs in the oceanic region inside the north cyclonic gyre, at 0.5 mg/m^3 and the maximum (>3.0 mg/m^3) occurs opposite the mouth of the Rio Grande and the Panuco, Tuxpan and Cazones rivers. These maxima are associated with the cyclonic-anticyclonic circulation and the continental river discharge. Satellite images have detected low concentrations in summer (May-July) of <0.06 mg/m3 with slight increase in winter (December-February) of >0.18 mg/m^3 in the eastern and northeastern Gulf.

IMPACTS of CLIMATE CHANGE and SEA LEVEL RISE on FISH and FISHERIES

Increased hurricane intensity

The Gulf region experiences severe tropical and extra tropical storms. Evidence to date suggests that there will likely be more intense tropical cyclones with higher rainfall intensities. While the number of intense cyclones may increase, globally the total numbers globally may decrease. Intense storms and associated strong winds and precipitation can have major effects on fish populations. Likewise, prevailing environmental conditions are disrupted during storms. Severe storms are characterized by abrupt reductions in air and water temperatures, surges in freshwater flow from rivers and land, and changing wind and ocean currents (Connelly et al., 2007).

However, because hurricanes have occurred with such frequency over the evolutionary history of the region's ecosystems, these disturbances may play an important role in shaping the life-history strategy of the indigenous species (Pimm et al. 1994). In relation to this, hurricanes in the Gulf may play a potential role in stock mixing dynamics of red snapper, especially considering that Gulf red snapper can reach age 50 or more and are likely to be exposed to several hurricanes over the course of their lives (Patterson et al. 2001). High post-hurricane mortality among recently metamorphosed damselfishes (Beecher, 1973) and juveniles of other fishes (Bouchon et al., 1994) suggest that susceptibility to hurricane-induced stress may be related to life-stage. The vulnerable early life stages of anadromous fish would also be affected due to storm surge in rivers. The sudden decrease in temperature during and after a storm can cause direct mortality of fish eggs and larvae (Connelly et al. 2007). However, juveniles and adults may avoid the direct effects of hurricanes. Patterson et al. (2001) reported that hurricanes significantly affected the probability of red snapper movement. Similarly, sharks may sense pressure changes associated with storms. For example, at Terra Ceia Bay in Florida, tagged blacktip sharks swam into deeper waters just prior to Tropical Storm Gabrielle's landfall in 2001. Also, when Hurricane Charley approached in 2004, radio-tagged sharks being tracked by underwater hydrophones, moved to open water. The timing of the departure appeared to coincide with the decreasing air and water pressure. Scientists proposed that sharks respond to environmental cues (possibly sensing pressure changes in their inner ear).

Hurricanes may also negatively impact fish communities indirectly. For example, Hurricane Andrew in south Florida removed detritus and organic materials needed as a nutrient source by mangroves and lowered oxygen levels to lethal minimums for several species of fish, creating plumes of hydrogen sulfide gas (Ogden 1992).

Oysters - Oysters are typically the fisheries species most severely impacted by hurricane events in the northern Gulf. Oyster beds lie in shallow coastal areas, and can be subjected to direct physical damage and to burial by mud and other hurricane-related debris. About 90 to 95 percent of oyster mortality occurred on the major commercial reefs during Hurricane Katrina (MORE, 2007, U.S. Department of Commerce, 2007). Oyster beds and vessels along the Gulf Coast were extensively damaged, if not totally destroyed, by siltation and contamination related to Katrina.

Shrimp - Recent surveys conducted by NMFS indicate that none of the Gulf shrimp stocks were significantly impacted by the 2005 hurricane season, and most of the changes in catch- per-unit-effort recorded in 2005 were within the range of past inter-annual variation (US Dept. of Commerce 2007).

Finfish - Data collected by the NMFS Southeast Fisheries Science Center indicates that the hurricanes did not reduce the catch-per-unit-effort of finfish (in weight) (US Dept. of Commerce 2007). These surveys indicate most of the changes in catch-per-unit-effort of finfish observed in 2005 were well within the range of past inter-annual variation

Crabs and lobsters - Fishery surveys conducted by NMFS indicate the 2005 hurricanes did not significantly impact crab populations and that most of the changes in catch-per-unit-effort recorded in 2005 were within the range of past inter-annual variation (US Dept. of Commerce). Commercial landings trends of crab and lobster species appear to be driven primarily by trends in effort and other factors not associated with the storms.

The long-term effects of Katrina on fisheries are uncertain. Quantification of habitat loss is underway and estimates from satellite imagery and aerial reconnaissance reveal large losses of wetland ecosystems that support spawning areas and prey populations (Sheikh 2006).

Climate change influences fisheries through the modification of habitat characteristics, and can affect organisms to the extent that the physical, chemical and biological conditions influence their productivity, development, nourishment, reproduction and distribution (Martínez-Arroyo et al. 2011). For example, in 2005 Hurricane Wilma modified landscape (mangrove forests, sea grass beds, coastal wetlands) in areas of the Yalahau coastal lagoon, in Quintana Roo, Mexico. As a result, in 2006, French grunt and pompano biomasses decreased (WWF 2006).

Mangroves and seagrasses - Mangrove ecosystems also stabilize and protect coastlines from erosion, and reduce storm and wave impacts in coastal regions. In addition to direct threats posed by coastal development, increases in frequency or intensity of tropical storms and hurricanes in combination with sea-level rise may alter erosion and sedimentation rates in mangrove forests. Hurricanes have shaped the structure of mangrove forests in the Everglades via wind damage, storm surges and sediment deposition (Fig. 4). Immediate effects include changes to stem size frequency distributions and the abundance and density of species (Smith et al. 2009). Mangrove forests can absorb much of the energy of the average cyclone, but severe hurricanes can be devastating.


(a)
(b)

Figure 4. Ground photographs for the mangrove forest in November 2004 (a) and November 2005 (b) at the Shark River. The Mangrove forest was defoliated by the hurricanes, and several trees were blown down or leaning as a result of the hurricanes (Zhang et al. 2008).

Hurricane Andrew passed across the south-western coast of Florida in August 1992, at wind speeds greater than 240 km/h, accompanied by a 5 meter storm surge. Heavy damage was caused to about 150 km^2 of mangroves. About 60% of the trees, particularly the larger ones, were either uprooted or broken; of the upright and unbroken trees 25% were dead and 86% defoliated. Many of the surviving trees subsequently died. Initially, about 20% of large Avicennia trees died, but this rose to 50%, or even higher, over the following year (Smith et al. 1994; McCoy et al. 1996). Tall mangrove forests, distant from tidal creeks, suffered more damage than lower mangrove forests adjacent to the tidal creeks. Field observations made four months after the passage of Hurricane Wilma revealed that the hurricanes caused partial-to-complete defoliation and much damage to the woody canopy. Some of the damage may have been due to the storm surge from Hurricane Wilma that exceeded two meters along parts of the coastal zone (Fuller 2007). Surges during Wilma destroyed approximately 1,250 ha of mangroves and this set back the recovery that started following Andrew (Smith et al. 2009).The hurricanes created numerous canopy gaps, and the number of gaps per square kilometer increased from about 400-500 to 4,000 after Katrina and Wilma. The total area of gaps in the forest increased from 1-2% of the total forest area to 12% (Zhang et al. 2008).

SEA LEVEL RISE

Climatic change operates at so many different organizational levels and scales that it is difficult to predict its consequences for ecological communities (Wiens and Bachelet 2010). Global sea levels rose 10 to 20 cm over the last century (Miller and Douglas 2004) and are expected to rise about 0.5 m by 2100. This is equivalent to a two to five fold acceleration (Warrick et al. 1996). However, recent estimates predict that global sea level rise (SLR) will approach or exceed one meter by 2100. These predictions significantly alter projections from the Fourth Assessment of the Intergovernmental Panel on Climate Change (Weiss et al. 2011). State-of-the-art SLR science also suggests that the weakening of the Atlantic meridional overturning circulation during this century could result in a one meter, regional SLR along the northern Atlantic coast - earlier than the global mean arrival time (Yin et al. 2010).

The U.S. Gulf and South Atlantic coasts (with the exception of Florida) experienced rates of sea level rise that were significantly greater than those observed on the U.S. Pacific Coast. Relative sea level rise is greatest along the Louisiana coastline where the land surface of the Mississippi River Deltaic Plain is subsiding (sinking with respect to sea level) as much as 0.25 in/yr (10 mm/yr), due to a combination of natural and human-induced processes. The average rate of sea-level rise in Texas and several segments of the Atlantic shoreline is double or more the global average (Burkett 2002), while for Florida, two key planning horizons have been proposed: SLR will be 3-7 inches in 2030 and 9-24 inches by 2060 (Weiss et al. 2011). Sea level is projected to rise one foot greater than the 2010 level and two feet between 2040 and 2070 (Southeast Florida Regional Climate Change Compact Technical Ad hoc Work Group, 2011). In the case of Mexico, more than 15,000 km^2 are threatened by future SLR (Hérnandez-Santana et al. 2008) and the state of Tabasco, where important portions of the coast are subsiding, will be the most affected. Projections indicate possible inundations of different areas along the Yucatan Peninsula, and those states of Veracruz and Chiapas, as well as Cozumel Island.

Recently, Bamber et al. (2010) reported that the marine portion of the West Antarctic Ice Sheet may be inherently unstable and that, as a consequence, it may be susceptible to a rapid disintegration as a result of a relatively modest change in climatic boundary conditions. In relation to this, Mitrovica et al. (2009) have shown that if the West Antarctic Ice Sheet collapses and melts, the coastlines of North America and of nations in the southern Indian Ocean will face the greatest threats from rising sea levels (Mitrovica et al. 2009).These authors state that the rise in sea levels for most coastal sites will be significantly higher (25%) than previously expected and that the sea level change will be highly variable around the globe. Sea level rise scenarios (six meter) for the Gulf of Mexico are shown in Fig. 5.

The most serious physical impacts of sea-level rise are: (1) inundation and displacement of wetlands and lowlands; (2) coastal erosion; (3) increased coastal storm flooding; and (4) salinization (Nicholls and Mimura, 1998). Coastal wetlands (collectively comprising salt marshes, mangroves and intertidal areas) could experience substantial losses given sea-level rise (Nicholls et al., 1999). These areas are highly productive and provide a number of important functions such as flood protection, waste assimilation, nursery areas for fisheries and nature conservation.

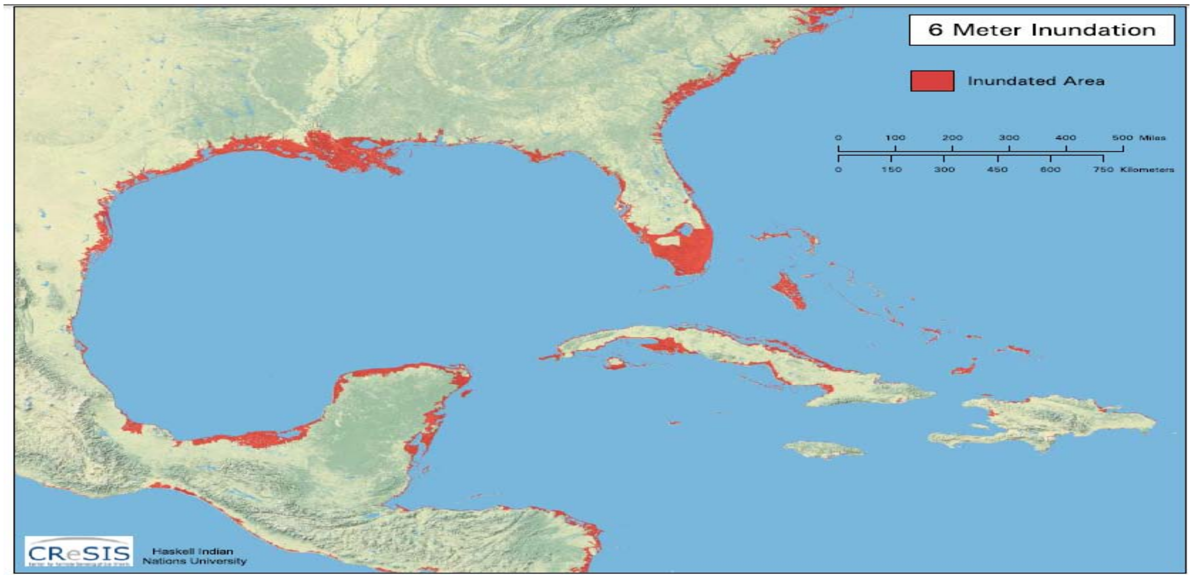
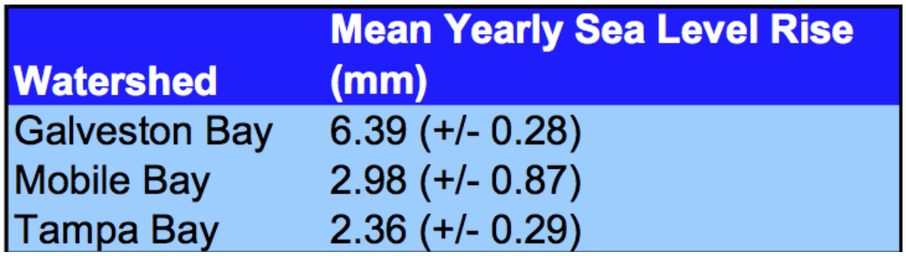


Figure 5. Sea level rise increment (6 m). Source: Center for Remote Sensing of Ice Sheets https://www.cresis.ku.edu/sites/default/files/sea-levelrise/images/southeastern_us/southeastern_us_1to6.jpg).

Mangroves - Mangroves constitute an important ecosystem in the Gulf of Mexico and south Florida. Their location, at the interface between marine and terrestrial habitats, makes them vulnerable to any change in sea level. The Gulf of Mexico has experienced dramatic wetland habitat area losses over the last two centuries. These losses not only damage species diversity, but affect water quality, flood control, and aspects of the Gulf coast economy. Coastal wetlands have proven to be susceptible to climate change, with a net loss of 33,230 acres from 1998 to 2004 in the United States (Dahl 2006). Sea level rise trends demonstrate a more drastic change in the Gulf region than either temperature or precipitation patterns. Galveston Bay has demonstrated an especially high rate of sea level rise in the last century and decreases in wetland habitat from 1955 to 2001 (Fig. 6).



Watershed	Mean Yearly Sea Level Rise (mm)
Galveston Bay	6.39 (+/- 0.28)
Mobile Bay	2.98 (+/- 0.87)
Tampa Bay	2.36 (+/- 0.29)

Figure 6. Mean yearly sea level rise in millimeters. Galveston data was collected at Pier 21 in Galveston Bay from 1908 to 2006. Mobile data is from Dauphin Island, AL, from 1966 to 2006. Tampa Bay data was collected from a site in St. Petersburg, FL, from 1947 to 2006 (Steffen et al. 2009).

Mangrove forests are arguably unique in their function as nurseries and support species important to the fishing industry worldwide. Many fish species enter estuaries as post larvae and juveniles after spending the larval stage in offshore waters where the adults spawn. Mangroves are considered unexpectedly important, serving as an intermediate nursery habitat that may increase the survivorship of young fish. Mangroves strongly influence the community structure of fish on neighboring coral reefs. In addition, the biomass of several commercially important species is more than doubled when adult habitat is connected to mangroves (Mumby et al.

2004). Sea level rise has led to significant geomorphological changes of coastal systems, salinity intrusion in estuaries, and loss of associated wetlands around the world, including the Mississippi (Day et al. 2007) and the Grijalva/Usumacinta (Ortiz-Perez et al., 2008). Near shore sessile organisms (oysters, etc.,) would be at greatest risk from sea level rise.

Fish - Rising sea levels could adversely affect fish populations by reducing the extent and quality of important habitats. For example, sea level rise will result in the loss of coastal marshes and submerged aquatic vegetation habitats (Connelly et al. 2007). Several fish inhabiting mangroves have roles as ecosystem engineers, such as the Atlantic goliath grouper (*Epinephelus itajara*) (Fig. 7), which inhabits mangrove root systems as juveniles, and caves, shipwrecks, and rocky reefs as adults; red grouper (E. morio), which excavates habitat throughout its benthic life in Karst regions of the Gulf of Mexico and western Atlantic, from the coast to the shelf-edge; and tilefish (*Lopholatilus chamaeleonticeps*), a species that lives on the continental slope and constructs elaborate, puebloesque burrows.

Figure 7. Atlantic goliath grouper – Walt Sterns. Source : (www.earthtimes.org/conservation/goliath-grouper-comeback-success-story/1482/)

Loss of nursery function (fish shelter and sustenance) of tidal flats is likely if increases in sea level continue at the projected rate. This will lead to increased levels of turbidity from the resuspension of sediment materials over tidal flats and mud banks. Loss of this habitat could lead to the displacement or population shift of recreationally and ecologically important marine fish species including tarpon (*Megalops atlanticus*), red drum (*Scianenops ocellatus*), snook (*Centropomus undecimalis*), mullet (*Mugil cephalus*), and small epibenthic forage species such as silver jenny (*Eucinostomus gula*), pinfish (*Lagodin rhomboids*), and rainwater killifish (*Lucania parva*).

Sea turtles - Even a small rise in sea level could result in a large loss of beach nesting habitat for marine sea turtles. The three most vulnerable land areas in the United States to sea level rise are Louisiana, southern Florida and the Chesapeake Bay. Since 1930, South Florida has had a relative sea-level rise of about 23 cm (Wanless et al. 1994). This is a rate of 30 cm per century. The global increase in sea level in response to global warming is projected at 60 cm for the coming century (Davis et al. 2005). Sea level rise in Florida will be especially problematic as the beaches of Florida are some of the most important sea turtle nesting habitat in the world.

CURRENTS and CIRCULATION

The Gulf of Mexico is a semi-enclosed sea that connects in the east to the Atlantic Ocean through the Straits of Florida, and in the south to the Caribbean Sea through the Yucatan Channel. Currents through the Caribbean Sea, the Gulf of Mexico and the Florida Straits constitute an important component of the subtropical gyre circulation of the North Atlantic Ocean. The Loop Current is the dominant feature of the circulation in the eastern Gulf of Mexico and the formation region of the Florida Current-Gulf Stream system. It originates at the Yucatan Channel. The Loop Current is a warm ocean current that flows northward between Cuba and the Yucatán peninsula, moves north into the Gulf of Mexico, loops east and south, just south of the Florida Keys (where it is called the Florida Current), and then just west of the westernmost Bahamas joining the Gulf Stream. The Loop current reaches peak speeds of 1.5 to 1.8 m/s on the western side of the channel near the surface. In the Loop (inside the Gulf) intense speeds reach 1.7 m/s. The Loop episodically sheds warm-core rings (called an "Eddy" or "Loop Current ring") at intervals of approximately three to 17 months. These rings have diameters of about 200-300 km, vertical extent 1000 m, swirl speeds 1.8-2 m/s; they generally translate westward at approximately 2-5 km/day and have lifetimes of months to approximately a year (Oey et al. 2005).

The shelves bordering the Gulf of Mexico cover the full range of continental shelf morphologies. At the western edge, the shelf is only a few kilometers wide. Over the Campeche bank, off the West Florida and Texas coasts, the shelf width ranges over a hundred kilometers. In addition, given the nearly closed coastline, the shelf has widely varying orientations relative to the prevailing easterly trade winds. The Campeche Bank and the West Florida shelf are influenced by the swift Yucatán or Loop Current.

Drainage into the Gulf of Mexico is extensive and includes 20 major river systems (>150 rivers) covering over 3.8 million square kilometers of the continental United States (Moody, 1967). Annual freshwater inflow to the Gulf is approximately 10.6×10^{11} m^3 per year (280 trillion gallons). Eighty-five percent of this flow comes from the United States, with 64 percent originating from the Mississippi River alone and nearly 70 percent from the Mississippi and Atchafalaya rivers (Fig. 8). Additional freshwater inputs originate in Mexico, the Yucatan Peninsula, and Cuba.

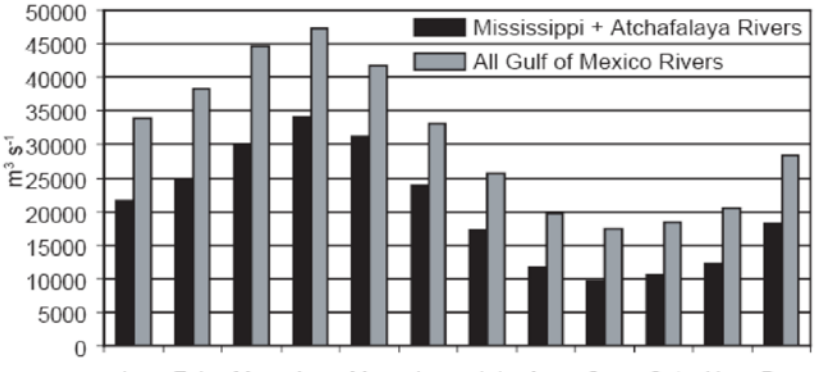


Figure 8. Riverine influence on the Gulf of Mexico (Source: Morey et al., 2005).

Patterns of wind stress create a momentum transfer generally towards the west, with the exception of the southwestern region, where the mountain chain near the coast channels the wind to the south, towards the isthmus of Tehuantepec (Fig. 9). Seasonal maps of wind stress curl are characterized by positive curls over the western and southwestern Gulf.

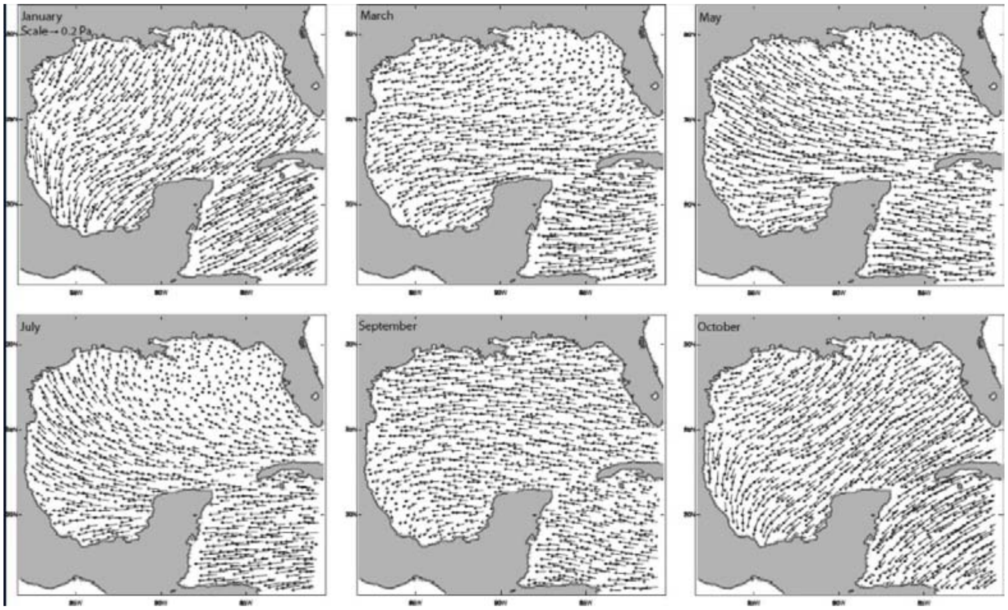


Figure 9. Surface wind monthly variability. Spring transition vs. Fall transition. (Source: Morey et al. 2005).

During the winter, atmospheric variability is produced by frontal incursions from the northwest, with basin wide effects and a consistent behavior. The less intense summer variability is produced by changes in atmospheric pressure distribution over the Gulf region and along the path of tropical storms and hurricanes. The surface circulation of the western Gulf of Mexico presents three main features: a cyclonic gyre over the Texas-Louisiana shelf, an anti-cyclonic gyre in the central region, and a cyclonic gyre in the Bay of Campeche (Gutierrez de Velasco, 1996). The deep circulation in the Gulf is also cyclonic (DeHaan and Sturges, 2005). Associated with the Loop Current are a number of smaller cyclonic and anticyclonic eddies, producing a very active eddy field in the Gulf of Mexico (Fig. 10). Speeds within these eddies can be greater than 1 m/s, and eddy pairs can form strong jets between them. The eddies extend to depths of several hundred meters and remain offshore of the continental shelf. As they spin against the continental slope, they can force exchanges of fluid across the continental shelf break (Morey et al. 2003).

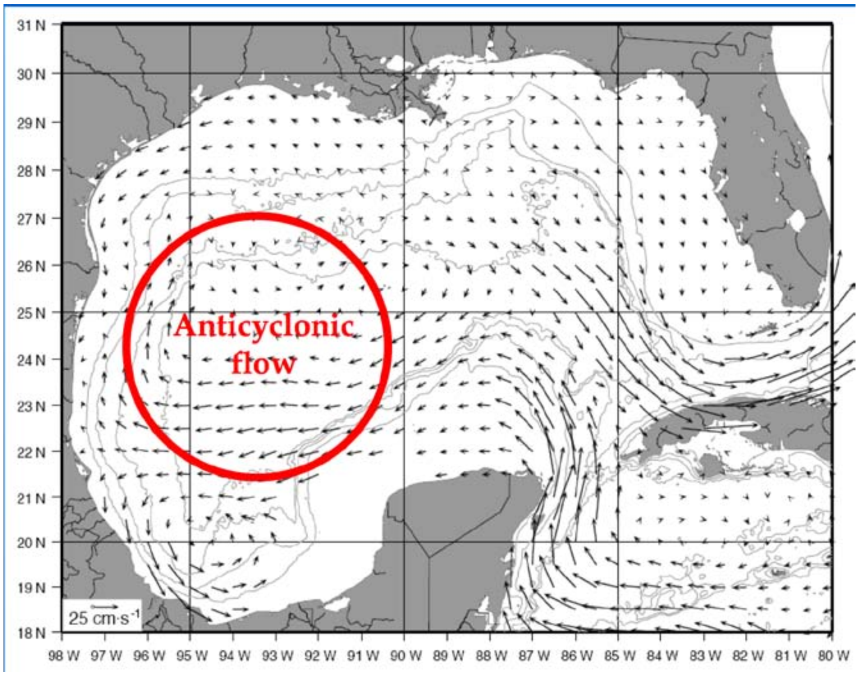


Figure 10. Flow in the upper layers of the Central and Northwest Gulf.

OCEAN CIRCULATION, LARVAL DISPERSAL AND RETENTION

There is a close link between ocean circulation and larval dispersal. Many benthic marine organisms release propagules that spend time in the water column before settlement. During this period, ocean currents transport or disperse the propagules (Shanks et al. 2003). These early, vulnerable stages are a common feature of most marine species, where larval dispersal and survival can be a key driver of population dynamics (Roughgarden et al. 1988) and population genetics (Palumbi 2004). Larval dispersal also can act as a homogenizing force (Fauvelot et al. 2003) and provide an opportunity for local adaptation (Swearer et al. 1999), depending on the circumstances. The scale over which larval transport (or retention) occurs varies substantially among species and even among locations, for a single species. For some species, larval dispersal is minimal and possibly nonexistent e.g. the damselfish, *Acanthochromis polyacanthus* (Thresher 1985), whereas at the other extreme dispersal can occur over thousands of kilometers e.g. *Anguilla rostrata* and *A. anguilla* (McCleave et al. 1987). However, the larvae of most coral reef fish species live for weeks to months, and they can be transported tens to hundreds of kilometers.

Dispersal - Gag grouper illustrate an interesting example of the importance of current intrusions and larval dispersal. Gag grouper (*Mycteroperca microlepis*, Goode and Bean, 1880) is an important reef fish with an estuary-dependent life stage (Fig. 11). Gag are long lived (up to 30 years), grow to maximum size of 145 cm, and have a protogynous life history, a type of sequential hermaphroditism where fish initially mature as females and later switch into males. As they mature, gag undergo a series of ontogenetic habitat shifts (McGovern et al., 1998).They spawn off-shore (between 60-100 nautical miles) in large aggregations from late winter to early-spring. After a larval period of about 40 days, they move into near shore sea grass beds. In autumn, gag juveniles migrate from sea grass beds to near shore patch reefs until they approach sexual maturity.

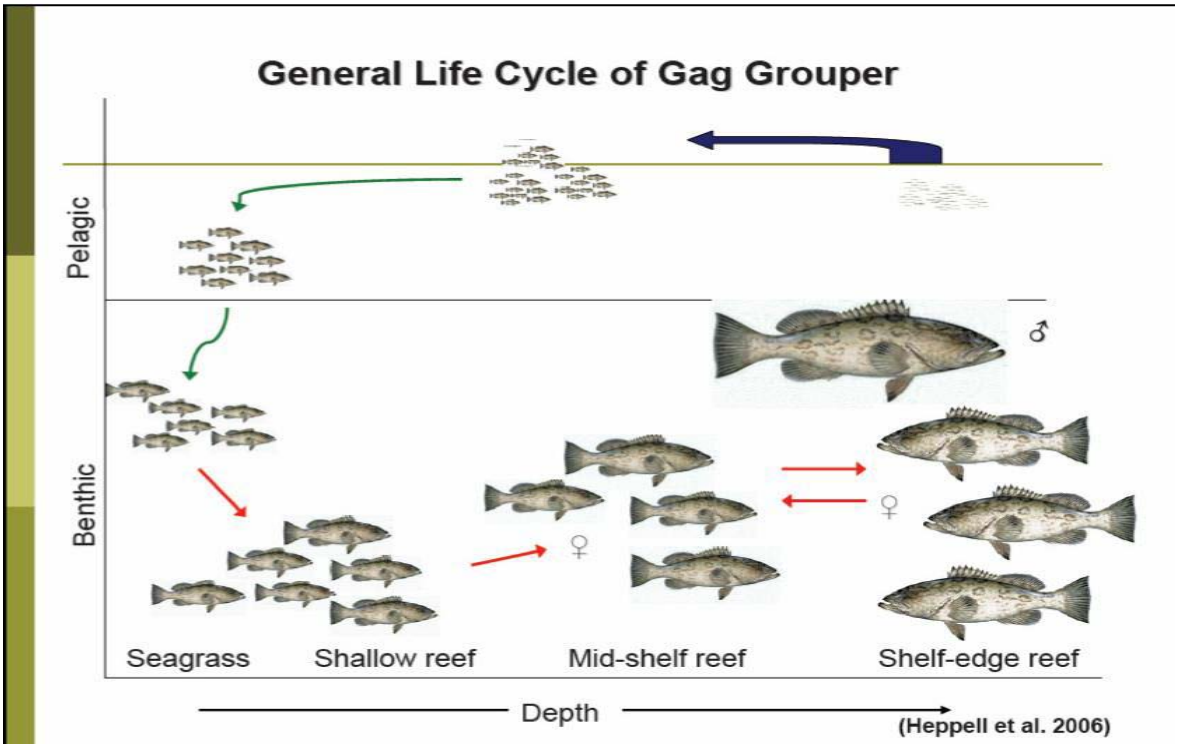


Figure 11. The general life cycle of gag, *Mycteroperca microlepis* (Heppell et al. 2006).

Jue (2010) assessed the genetic differentiation and connectivity of gag across the Gulf of Mexico. He determined that gag groupers along the Yucatan Peninsula of Mexico appear to be both a historical and contemporary source population of migrants for populations along the Florida Gulf Coast (Fig. 12). They suggested that because gag off the eastern portion of Campeche Banks (21°–23° N) spawn roughly a month earlier than the gag on the West Florida Shelf, the larvae resulting from these spawning events could be transported from Campeche Banks to the southwest Florida coast, a distance of 600 km, and in this way these larvae could account for the earlier spawning and settlement dates seen in west Florida gag south of 28° N. Furthermore, particle movement studies conducted by Toner et al. (2003) suggest that current intrusions were capable of transporting larvae from Campeche Bank to the west coast of Florida. Estimates of migration describe asymmetric gene flow from Campeche Bank to the West Florida Shelf. These migration rates, as well as supporting ecological data, match well with the hypothesis that population across the Gulf of Mexico are currently connected via larval dispersal. Periodic connectivity among populations appears to happen at a high enough frequency to effectively link these populations via larval dispersal. In addition to ecological evidence, estimates of the time of divergence suggest that on-going migration accounts for the low differentiation between populations (Jue 2010).

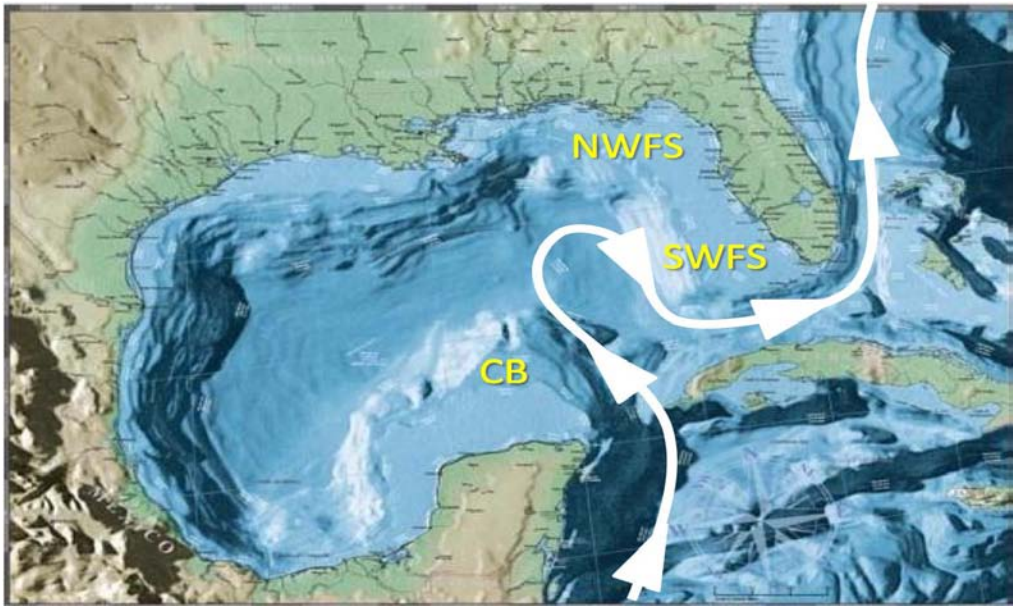


Figure 12. Map of the Gulf of Mexico showing Campeche Bank (CB) and the two regions of interest on the West Florida Shelf: the North West Florida Shelf (NWFS) and the South West Florida Shelf (SWFS). Distributions of gag are not believed to be continuous between the two regions due to a break in typical adult gag offshore habitat. Solid line and arrow indicate general location and direction of the Gulf Loop Current and Gulf Stream Current in the region. (Jue, 2010).

Retention - The Atlantic coastal waters of the Florida Keys contain a shallow reef system bordered by a major western boundary current, the Florida Current. Previous studies have shown that the outer shelf region of the upper Florida Keys is strongly influenced by the Florida Current and the transient passage of Florida Current meanders and eddies (Lee et al. 1992). When the Loop Current is present, its outer edge spawns smaller scale meanders and cyclonic eddies that are carried in an anticyclone around the Loop Current (Fratantoni et al. 1998).

Once one of these smaller eddies makes the full transit around the Loop, it may get trapped between the northern edge of the Florida Current and southwest of the Dry Tortugas (westernmost key of the Florida Keys). These quasi-stationary cyclonic “Tortugas gyres” are 50–100 km in size, and may reside for between 50 and 140 days, maintaining their position until being pushed out by the arrival of the next gyre transiting around the Loop Current. Once displaced into the Straits of Florida, the Tortugas eddies are deformed (and shrink) by the topography and the curvature of the Middle Keys as they propagate downstream between the shelf/slope topography and the Florida Current at a rate ranging from 5 to 16 km/day. Circulation velocities of the gyres range from 20 to 50 cm sec^{-1} (Lee et al. 1994) prior to being absorbed beyond the Pourtales terrace, where the shelf narrows and the Florida Current moves close to shore.

The passage of the Tortugas gyre into the Straits of Florida contributes to cross shelf flow (between the Florida Current and the shallow shelf) and is a potential source of enhanced nutrients in the Florida Keys system (Lee et al. 1994). Further, the inshore flow associated with these eddies provides a countercurrent circulation to the strong Florida Current. Their infrequent (up to two to three per year) (Fratantoni et al. 1998) but relatively slow passage (Lee and Williams, 1999), interjects considerable variability in coastal flow, which is counter to the flow conditions of the Florida Current (Fig. 13), and may serve as a retention mechanism for coastal-derived larvae that would otherwise be carried away by the strong, unidirectional Florida Current

(Lee et al. 1992, 1994; Lee and Williams, 1999).

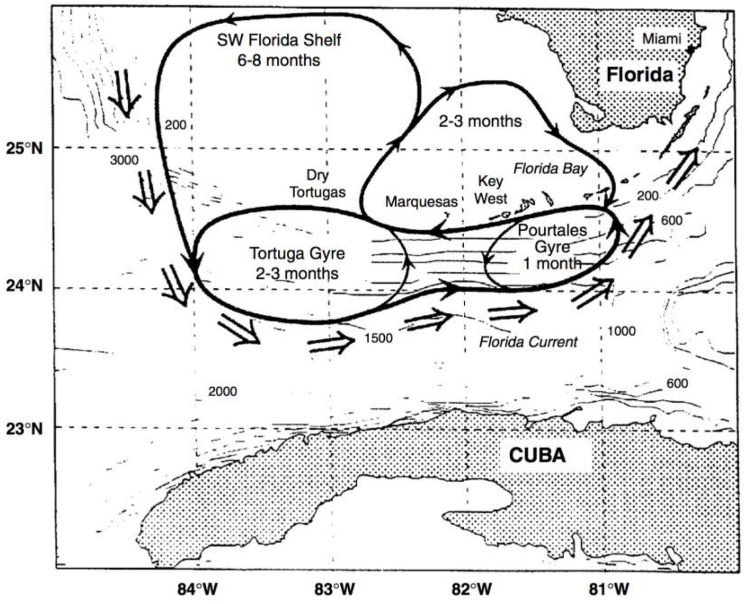


Figure 13. Hypothesized larval transport pathways of varying duration based on observations of circulation and hydrographic structure in waters south and west of the Florida Keys. (Cowen, 2002).

It should be emphasized that larvae are not the only, or always the most important, dispersive phase in animal life histories. Sperm dispersal and post-larval dispersal by drifting, rafting, dislodgement, or adult migrations can contribute to the patterns of connectivity and gene flow often attributed to larvae (Levine 2006)

The above-mentioned physical processes may undergo important variations as a result of climate change. Large ocean currents are primarily wind-driven, but teleconnections such as ENSO and the NAO can influence the variability of these currents in a number of ways. Baringer and Larsen (2001) found that the speed of the Florida Current, which is the beginning of the Gulf Stream, was negatively associated with NAO.

Shifts in Spatial Distribution

One of the most significant biological impacts of global climate change is the alteration of an organism’s body temperature, which ultimately drives almost all physiological processes (Helmuth et al. 2011). For ectotherms such as fishes, water temperature and its links to metabolism and swimming ability is a key environmental variable. For marine fish larvae, swimming speed and consequent dispersal are positively affected by temperature (Munday et al. 2009). Although only limited numbers of species will face entirely unsuitable conditions for persistence, others will experience drastic reductions and fragmentation of distributional areas, or extend their distributions, creating new natural communities with unknown properties. Indeed, some authors have argued that these reorganizations of communities will produce stronger distributional effects than will the direct effects of climate change on species distributions (Peterson et al. 2002).

Several examples of range shifts have been made evident in the Gulf of Mexico. Childs (1997) reported one ray species (the Chilean devil ray *Mobula tarapacana*) as a new record for the Gulf of Mexico. He also reported a shark and two ray species (*Carcharhinus perezi*, *Dasyatis centroura*, and *Mobula hypostoma*) as rare records for the northwestern Gulf of Mexico. Additional northward range extensions have recently been documented for fishes within the Gulf of Mexico.

The authors observed a concurrent increase (nearly 20%) in the number and occurrence of juvenile subtropical and tropical fishes collected in sea grass meadows along the northern Gulf of Mexico. For example, the 2006-2007 surveys revealed numerous additions of juveniles of tropical species that were completely absent in the 1970s, including: *Lutjanus synagris* (lane snapper), *Epinephelus morio* (red grouper), *Chaetodon ocellatus* (spotfin butterflyfish), *Mycteroperca sp* (grouper, non gag), *Centropristis philadelphica* (rock sea bass), *Fistularia tabacaria* (bluespotted cornetfish), *Ocyurus chrysurus* (yellowtail snapper), *Thalassoma bifasciatum* (bluehead wrasse), *Abudefduf saxatilis* (sergeant major), *Acanthuridae spp.* (surgeon fish) and *Sparisoma viride* (stoplight parrotfish).

Corals - There are several additional reports of biological responses to increasing temperatures in the northern Gulf of Mexico that appear to constitute the beginning of a coherent ‘climate fingerprint’ (Parmesan and Yohe 2003). A warming-associated weakening of alongshore advection (Pisias et al. 2001) could actually break down certain marine biogeographical barriers that currently prevent range expansions. Recently, two coral species of the genus Acropora have expanded their ranges poleward along the east coast of Florida and into the northern Gulf of Mexico (Precut and Aronson, 2004). First, spatially extensive thickets of the staghorn coral, *Acropora cervicornis*, were discovered off Fort Lauderdale in Broward County, Florida in 1998 (Vargas-Angel et al. 2003), where they had not been observed during the 1970s and 1980s. More recently, colonies of the elkhorn coral, *Acropora palmata*, have been observed as far north as Pompano Beach in northern Broward County (Precht and Aronson 2004). Also, elkhorn coral was seen for the first time in 2002 on reefs of the Flower Garden Banks in the northern Gulf of Mexico. The sudden appearance of Caribbean acroporid corals well north of their previously known extant range is associated with decadal-scale increases in annual sea surface temperature (SST) in the western Atlantic (Barnett et al. 2001). At the latitudinal extremes of Caribbean reef systems, an increase in SST of only 1–2°C should encourage temperature-sensitive corals such as the acroporids to expand their ranges.

Mangroves - Coastal plants may also be sensitive to changes in air and water temperatures. For example, changes in frequency of freeze events will alter ecosystems of the east and west coasts of the Gulf of Mexico because shoreline vegetation is strongly influenced by the frequency of frost from Texas to south Florida. In south Florida, episodic frost or freezing events help shape ecosystems because tropical plants (including mangrove species) and animals are highly vulnerable to such events. If climate change reduces the frequency of episodic freeze events, over time the coastal red mangrove communities should shift farther north of Tampa Bay on Florida’s Gulf of Mexico coast and Laguna Madre on the Texas coast.

In Louisiana, black mangrove is periodically damaged or killed by freezes, consequently, mangroves growing at their distributional limits do not reach the height or biomass attained by trees at tropical latitudes. In 2000, a historic drought and related factors led to extensive dieback of smooth cord grass, but left black mangrove undamaged (McKee et al. 2004).

Manatees - Distribution of the endangered West Indian manatee (*Trichechus manatus*) has changed through time as the population has declined throughout its range (Powell and Rathbun 1984, Lefebvre et al. 2001). Once common along the Gulf of Mexico coast, manatee populations are now confined largely to peninsular Florida and southeastern Georgia in the winter, with poorly defined migrations north and east during summer (Powell and Rathbun 1984, Fertl et al. 2005). Manatees occurring west of Florida and to the north of Mexico are considered to be strays originating from populations in either Florida or Mexico (Powell and Rathbun 1984). Historically, manatees were found along the entire Gulf of Mexico Coast from the Suwannee River in Florida to the Bay of Campeche, Mexico, and considered common in south Texas. The occurrence of the West Indian manatee sightings have increased during the last decade in Alabama, Mississippi, and Louisiana, northwest of the core population in Florida and the Caribbean. Manatees were reported most often in estuarine habitats, usually either near a freshwater source or natural or industrial warm-water springs/runoffs during winter months. Temperature is the overriding factor in determining the geographic extent of suitable habitat to manatees (Smith 1993). Traveling manatees use warm-water refuges along their migratory routes during both the early spring and late fall in a 'stepping-stone' strategy, which may permit them to migrate earlier in the spring as well as remain at sites later into the fall (Deutsch et al. 2003). The presence of artificial warm-water sources outside of the manatee's traditional range may attract an increasing number of manatees and could increase the incidence of cold-related mortality in this region. (Fertl et al. 2005).

Effects on species interactions - Over the short-term, range expansions may increase local biodiversity as poleward-advancing species outpace pole-ward retreating species (Hickling et al. 2006). Over longer time scales, however, poleward range expansions may have consequences similar to those now being observed with nonnative species invasions, by modifying local dynamics of competition, predation, herbivory and parasitism in ways that are not yet understood, but that could alter the functions of the ecosystem and the productivity of selected fisheries. Predation pressure in marine ecosystems generally increases from the poles to the tropics (Vermeij 1978), so warming due to climate change could cause an ecological shift to increased predation. For example, warm winter conditions of the past decade have favored predatory game fishes that have become more numerous in the Laguna Madre than elsewhere in Texas (Robinson et al. 1997). In turn, densities of small fishes, shrimps and crabs are lower in Laguna Madre sea grass beds than elsewhere in the Gulf of Mexico (Sheridan and Minello 2002).

In addition, nutrient availability, including too much nitrogen, can increase the decomposition of the below ground organic material, perhaps leading to marsh collapse. Thus, the survivability of salt marshes is not dependent on one factor, but the interaction of many factors, including those affected by global climate changes. These complex relationships between habitat sustainability and ecosystem health can be cumulative and long-term in nature (Ning et al. 2003).

Recruitment - Changes in the global or regional climate are likely to impact fish stocks and hence fisheries. It is of primary importance to know what changes in fish stock productivity can be expected in response to climate change and to design appropriate management strategies (Brunel and Boucher 2007).

Temperature - Given that temperature increases in the coming century are predicted to exceed 1°C, the major biological change resulting from higher temperatures in Gulf of Mexico coastal waters may be altered distributions of coastal organisms. The geographic ranges of heat-tolerant species such as commercial shrimp may expand northward, while the southern range boundaries of heat-intolerant organisms such as soft clams and winter flounder may retreat northward. The more mobile species should be able to adjust their ranges over time, but less mobile species may not. However, long-term variability in temperature and other physicochemical factors may affect stocks. For example, the collapse of the pink shrimp, *Farfantepenaeus duorarum*, fishery in the southern Gulf of Mexico has been related to a declining recruitment rate since the early 1970s. Recently it was reported that shrimp stock declination follows a fall in primary production, which is proportionally related to salinity decrease and inversely related to seawater temperature in a long term framework (Ramírez-Rodríguez et al. 2006 and Arreguín et al. 2008). These variations together with sea level rise are likely the result of large-scale mode (i.e., pattern) of natural climate variability, such as the North Atlantic Oscillation (NAO) (Fig. 14) (Arreguín et al. 2008).

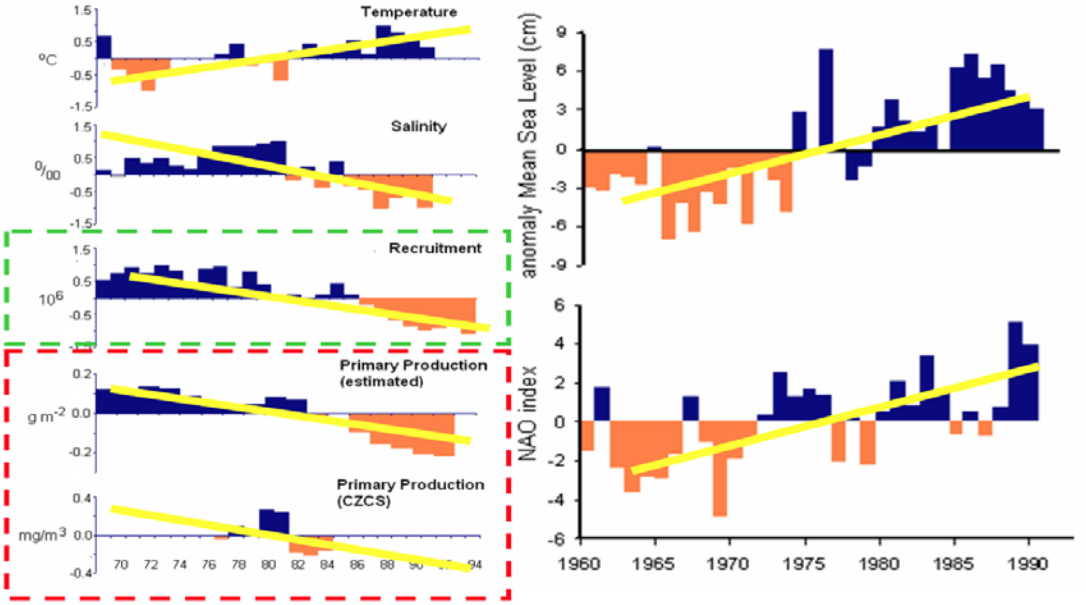


Figure 14. Recruitment and long term effects of climate change on pink shrimp (Arreguín et al. 2008).

Higher temperatures also may have positive effects. Some commercially valuable estuarine-dependent species in the lower latitudes have higher growth rates and larger annual harvests when temperatures are higher. For example, shrimp harvest is generally highest in tropical climates and declines northward, so an increase in temperatures could increase the annual yield of shrimp in temperate waters like the Gulf of Mexico, as long as temperatures did not exceed lethal levels.

RISING SEA LEVELS – nursery areas

Shelf fisheries of the southeastern United States are dependent on estuaries and there is apparent linkage between coastal wetlands and fishery productivity. Quantitative surveys document that high densities of shrimps and blue crabs directly use northern Gulf marsh surfaces. Manipulative experiments demonstrate that such marshes provide these fishery species with increased resources for growth and with protective cover to reduce predator related mortality. Thus, access to the marsh surface is an important component in controlling the link between secondary productivity and coastal wetlands (Zimmerman et al. 2000). Rising sea levels will initially increase access to marsh surfaces by fish and invertebrates, perhaps increasing their production in the short term (e.g. Gulf of Mexico shrimp harvests). However, depletion or loss of marshes will have important effects on nutrient flux, energy flows, essential habitat for a multitude of species, and biodiversity (Ray et al. 1992). Furthermore, in salt marsh and mangrove habitats, rapid sea-level rise would submerge land, waterlog soils, and cause plant death from salt stress (Forbes and Dunton 2006).

As wetland losses accumulate, then the flushing rates may decrease as open water habitat increases and the estuary deepens. A lower flushing rate could lead to more harmful algal blooms (because of longer residence time) or higher salinities (because of increased seawater mixing through the estuarine mouth (Turner 2003).

Freshwater flows

Model predictions for climate change in the northern Gulf of Mexico suggest that both temperature and river flow will increase. The results of various climate change model predictions suggest that there will be increases in precipitation on the order of 10 percent for all of the Gulf states, except Florida (Turner 2003). If runoff along the Gulf Coast increases, estuarine flushing rates would increase, leading to reduced yields in shrimp and other species favoring high salinities (Fig. 15) (Ning et al. 2003). For example, there is an annual variation in the Gulf of Mexico shrimp catch that is negatively related to annual variations in river flow (more flow, less shrimp and vice versa), implying a riverine control on estuarine salinity (Turner, 1992). The implication of the relationship between river flow and shrimp yields shown in Figure 15 is that a 30 percent rise in river discharge could result in a 15 to 20 percent reduction in shrimp yields in the northern Gulf of Mexico (Ning et al. 2003). Increasing runoff rates and outflow into the Gulf of Mexico could increase nutrient loads and alter water temperatures, exacerbating already serious eutrophication and low oxygen levels (Diaz and Rosenberg 2008). Changed fresh water inflows into the ocean will lead to changes in turbidity, salinity, stratification, and nutrient availability, all of which affect estuarine and coastal ecosystems (Justic et al. 2005), but consequences may vary locally. For example, increased river discharge of the Mississippi would increase the frequency of hypoxia events in the Gulf of Mexico, while increased river discharge into the Hudson Bay would lead to the opposite (Justic et al. 2005).

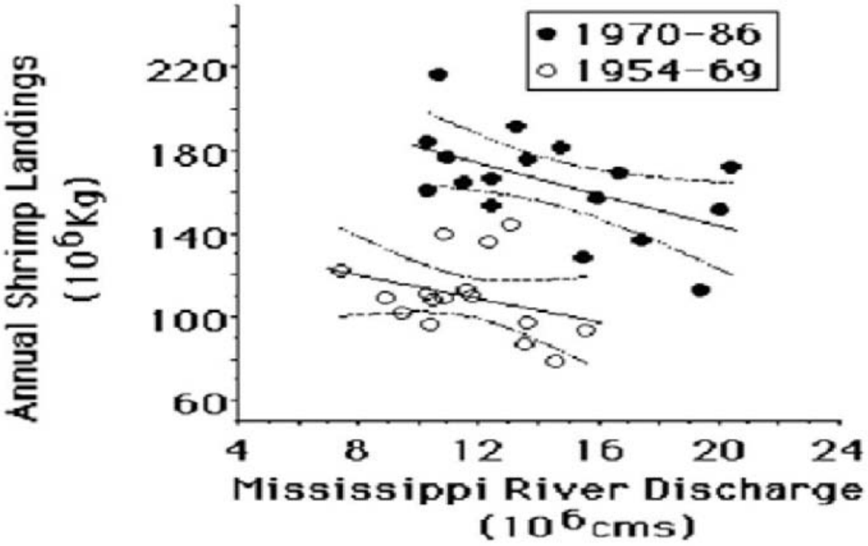


Figure 15. The relationship between the annual yields of shrimp in the Gulf of Mexico and discharge of the Mississippi river. The 95% confidence limit for the y value of each linear regression is shown. Temperature is also an important covariable. (Turner, 2003).

Major changes have occurred in Florida Bay and in the harvest and recruitment characteristics of the pink shrimp, Tortugas fishery over decades (Fourqurean and Robblee 1999). In 1987, a sea grass die off began in western Florida Bay characterized by the rapid death of turtle grass, *Thalassia testudinum* (Robblee and DiDomenico 1991). Sea grass die off was followed by extensive and persistent algal and turbidity blooms over much of the bay. Researchers think the loss of the estuarine characteristics of the bay and chronic hypersalinity (Zieman et al. 1988) led to the sea grass die-off. Shrimp harvests declined to period-of-record lows during the late 1980s, roughly coinciding with sea- grass die-off and other environmental changes in Florida Bay. This decline may in part be due to changes in freshwater inflow affecting salinity in the bay. Juvenile pink shrimp (*Farfantepenaeus duorarum*) have a broad salinity tolerance range at their optimal temperature, but the salinity tolerance range narrows with distance from the optimal temperature range, 20–30^{o}C.

Hypoxia - The effects of hypoxia are most obvious in the benthos through mortality, elimination of larger long-lived species, and a shifting of productivity to non- hypoxic periods (energy pulsing) (Diaz and Solow, 1999). Escalating cultural eutrophication in estuaries has increased the frequency, spatial scale and duration of concurrent hypoxia (dissolved oxygen, DO, ≤ 2.0 ppm), which is often associated with specific regions of estuarine bottom, where shrimp may have higher risks of exposure with negative impacts (Yip-Hoi, 2003). Using data from shelf wide assessment survey of waters west of Mobile Bay, Alabama to Sabine, Texas (9-110m) during June of 1982, Leming and Stuntz, (1984, cited by Craig et al. 2001) found that demersal shrimp and finfish catch per unit effort (CPUE, kg/h) varied independently of dissolved oxygen for levels above 2.5 mg/L but declined to near zero at lower oxygen concentrations. Renaud (1986) reported hypoxic (< 2.0 mg/L) and anoxic (0.0 mg/L) bottom waters at near shore (depth <16 m) and offshore (4-20 m depth) sites off Louisiana during a 2 week period in June 1983. Atlantic croaker were not at stations with hypoxic bottom water, and shrimp catches never exceeded 2 kg/h in the areas (Fig. 16).

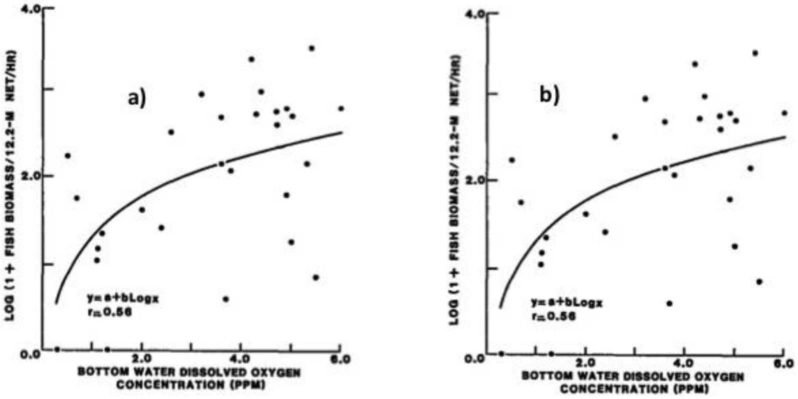


Figure 16. Offshore fish biomass of fish(a) and shrimp(b) in relation to bottom water dissolved oxygen concentration (Renaud, 1986).

Altered reproductive patterns

The relationship between recruitment and spawning stock in fisheries has been a fundamental subject of many studies (Ye, 2000) and the increased influence of climate on recruitment through changes in the spawning stock has been demonstrated (Ottersen et al. 2006). Climate change may impact the spawning stocks of different species in different ways. Reproduction is one of the most critical life-history stages that is disrupted by environmental stressors because even minor, persistent declines in gamete production (fecundity) by individuals can have long-term impacts at higher levels of biological organization, leading to population declines and community disturbance (Cushing 1979). Recently, Thomas and Rahman (2011) showed the widespread reproductive disruption in Atlantic croakers (*Micropogonias undulatus*) collected from hypoxic sites approximately 120 km apart in the extensive northern Gulf of Mexico continental shelf hypoxic zone. Gonadal growth and gamete production were impaired in croakers from hypoxic sites compared with fish from reference normoxic sites east of the Mississippi River Delta (Fig. 17). Male germ cells were detected in approximately 19 percent of croaker ovaries collected in the hypoxic region, but were absent in ovaries from normoxic sites. In addition, the sex ratio was skewed towards males at the hypoxic sites. The masculinization and other reproductive disruptions were associated with declines in neuroendocrine function, as well as ovarian and brain expression of aromatase. A similar incidence of ovarian masculinization and decline in ovarian aromatase expression were observed in croaker after chronic laboratory hypoxia exposure (Thomas et al. 2007), indicating that ovarian masculinization is a specific hypoxia response and is due to decreased aromatase activity. The production of fully mature eggs and sperm capable of fertilization was less than 20 percent of that at the reference sites, suggesting that the reproductive output of croakers was severely decreased over a large area of approximately 3,000 km^2. Chronic, decreased reproductive output due to recurring hypoxia every year has a much greater potential long-term impact on the size of croaker populations. The results suggest severe reproductive impairment can occur over large coastal regions in marine fish populations exposed to seasonal hypoxia, with potential long-term impacts on population abundance.

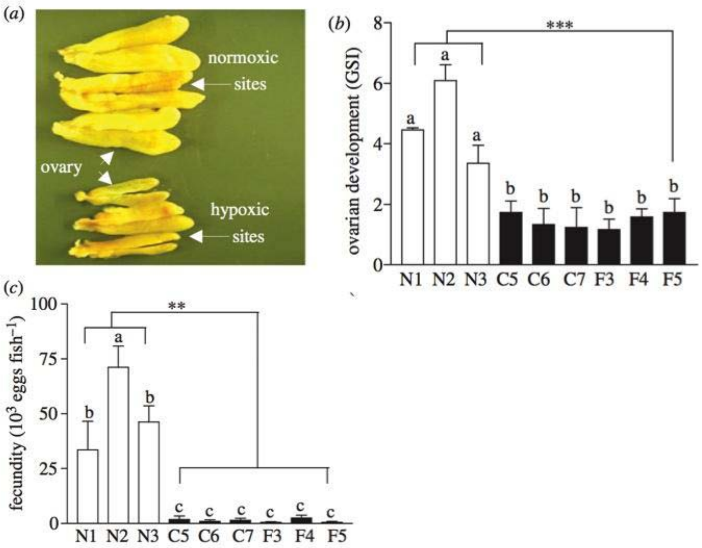


Figure 17. (a, b) Ovarian growth, (c) fecundity in female croakers collected from six hypoxic sites (C5–C7, F3–F5) and three normoxic sites (N1–N3) in the northern Gulf of Mexico during 27 September–2 October 2007. (a) Gross appearance of representative ovaries from hypoxic and normoxic sites. (b) Gonadosomatic index (GSI), an index of ovarian growth. (c) Fecundity. Asterisks denote significant differences between normoxic (reference) and hypoxic sites (nested ANOVA, $^{**}p < 0.01$, $^{***}p < 0.001$). Each value represents the mean ± s.e.m. (n= 8 – 12). Individual site differences are indicated with different letters (Fisher's PLSD, $p < 0.05$). (Thomas and Rahman 2011).

Giant bluefin tuna are the largest members of the family Scombridae, attaining body sizes of more than 650 kg (Block et al. 2005). These traits underlie their capacity to exploit environments ranging from subarctic feeding grounds to subtropical spawning areas. Top pelagic predators such as bluefin tuna are in precipitous decline globally because of overexploitation (Myers and Worm, 2003). Atlantic bluefin tuna have been considered overexploited since 1982, and recent catches continue to exceed historical levels (Sissenwine et al. 1998). The distribution, migration, aggregations and foraging of the major pelagic species or Scombridae (tuna, mackerels and sierras) respond to surface temperature and to the location of oceanic anomalies (frontal systems, convergences, vortices, thermocline, mixed layer) (Martinez-Arroyo et al. 2011). Although this species is widely distributed, the vast majority of spawning in the western Atlantic has been recorded only in the Gulf of Mexico, from mid-April to June (Stokesbury et al. 2004, Block et al. 2005). Atlantic bluefin tuna exhibited breeding behavior in the western Gulf of Mexico and the frontal zone of the Loop Current. Breeding areas used by the bluefin tuna were significantly associated with bathymetry, SST, eddy kinetic energy, surface chlorophyll concentration, and surface wind speed, with SST being the most important parameter.

Altered trophic interactions

Long-term biomass data indicate predator-prey coupling between cod and prey species such as shrimp (*Pandalus borealis*), snow crabs (*Chionocetes opillo*), and lobster (*Homarus americanus*) (Worm and Myers 2003). Overfishing in the last 30 years has caused a rapid decline in the abundance of many cod stocks and a corresponding increase in prey species abundance across the north Atlantic, offering strong evidence for top-down control of this food web. These results show that changes in predator populations can have strong effects on prey populations in oceanic food webs. Additional evidence indicates that, historically, the strength of this trophic interaction is sensitive to ocean temperature, whereby cooler temperatures probably weaken the interaction strength (Worm and Myers 2003). A similar trophic interaction is found in tropical and semitropical ecosystems. For example, warm winter conditions of the past decade have favored predatory game fishes that have become more numerous in the Laguna Madre than elsewhere in Texas (Robinson et al. 1997). In turn, densities of small fishes, shrimps and crabs are lower in Laguna Madre sea grass beds than elsewhere in the Gulf of Mexico (Sheridan and Minello 2002).

Regime shifts

‘Regime shifts’ were first identified in terrestrial communities (Noy-Meir 1975) and applied to marine ecosystems to describe concurrent fluctuations in anchovy (*Engraulis encrasicolus*, Engraulidae) and sardine (*Sardina pilchardus*, Clupeidae) populations in several regions of the world (Lluch-Belda et al. 1989). Regime shifts and trophic cascades in marine ecosystems have been documented in both coastal and offshore food webs (Scheffer et al. 2001, Jackson et al. 2001, de Young et al. 2004, Frank et al. 2005), as results of natural (for example, climate) as well as anthropogenic forcing (for example, fishing and eutrophication).

Hypoxia can enhance the effects of large-scale changes in benthic communities by reducing the abundance of large, slow-growing, deeper dwelling animals and facilitating smaller, fast-growing species that can colonize surface sediments rapidly following hypoxia (Diaz and Rosenberg 1995). Reductions in the abundance and size structure of benthic organisms have been observed in the northern GoM with hypoxia (Rabalais and Turner 2001). The loss of benthic communities and the inability of the communities to recover with repeated hypoxic events (Karlson et al. 2002) may make ecosystems more vulnerable to the development and persistence of hypoxia. In addition, with the loss of sediment buffering capacity through the loss of electron acceptors (NO_3, O_2, Fe^{2+}, Mn^{2+}), there is a change in sediment metabolism from aerobic to anaerobic pathways, changing the production rates and processing of organic matter (Dale et al. 2010). It appears that hypoxia has gotten worse in the Gulf of Mexico following the record breaking 1993 spring floods, i.e. smaller river flows now induce a larger response in hypoxia. Regime shift has occurred in coastal marine ecosystems that have been affected by large-scale hypoxia (Conley et al. 2007 cited in Dale 2010).

There is strong scientific evidence that areas in the northern Gulf of Mexico are stressed by hypoxia (review in Dale et al. 2010). In the hypoxic/anoxic zone of the Louisiana inner shelf, many taxa are lost during the peak of hypoxia. Certain typical marine invertebrates are absent from the fauna, for example, pericaridean crustaceans, bivalves, gastropods, and ophiuroids (Rabalais and Turner 2001). Hypoxia has well documented catastrophic consequences to the benthos, including animals with multiyear life spans, and creates large areas without commercial quantities of shrimp and fish.

Ocean acidification

Effects of climate change, such as ocean acidification, have already begun in the Gulf of Mexico. Aragonite saturation is threatening all hard corals on a global basis. Important fisheries habitats, such as coral reefs, will markedly decline or disappear (Ishimatsu et al. 2005, Kleypas et al. 2006). Besides, ocean acidification in the Gulf of Mexico will have direct effects on important commercial calcifying organisms – lobsters, crabs, scallops, clams.

Ocean acidification has already been shown to have detrimental effects on calcifying organisms, such as corals and phytoplankton, but relatively little is known on how this process change will affect marine vertebrates. Turley et al. (2005) suggest that if environmental CO_2 concentrations increase to a threefold pre-industrial level, then many fish and complex organisms are likely to accumulate high levels of CO_2 in body tissues and fluids. Higher internal levels of CO_2 could hinder growth, reproduction and development (Turley et al. 2005). Early results in Alaska, a highly acidic area, have shown species of crab and fish with increased levels of stress hormones and reduced metabolisms, demonstrating a response in which energy is diverted from growth and reproduction and spent on maintenance (Bates & Mathis 2009). If fish species respond to hypercapnia through reducing growth and reproduction, larvae will not only be less in number, but possibly also their physiology may be altered. Increased CO_2 in internal fluids, especially in highly energetic species like squid, can affect mobility, survival or reproduction (NOAA 2010). Furthermore, it is plausible to suggest that reduction in growth due to acidification could result in longer duration of pelagic stages, which could result in higher mortality rates. Increased CO_2 in seawater can affect the ability of fish to detect critical olfactory, or sensory, cues (NOAA, 2010). Acidification will alter speciation (ionic form) of various metals, nutrients, or toxins in a way that may affect species reproduction and survival (NOAA, 2010).

SOCIOECONOMIC CONDITIONS in the GULF of MEXICO

There are two kinds of socioeconomic problems in the Gulf of Mexico LME, those related to insufficient knowledge for informed decision-making and those derived from the economic and social system in the whole GoM LME region. Ecosystem functions produce benefits, beyond those accounted for by assigning prices to products of commercial value. However, it has not been defined how to assign market values to those benefits related to the natural capital economy. Decisions are incomplete if they do not include all the benefits and costs of the ecosystem that supports the economy (UNIDO-GEF, 2010).

Oil production in the Gulf region is a major sector of the regional economy with important benefits: jobs and infrastructure growth. At the same time, coastal landscape and marine ecosystems face major environmental impacts and commercial fishing is an important component of the GoM LME's economy. In the US during 2010, commercial fishermen landed 1.3 billion pounds of fish and shellfish worth approximately $635 million USD, whereas in Mexico 371 million pounds of catch were worth 344 million USD. Marine sport-fishing is another industry of regional importance, providing jobs and recreational activities. The Gulf of Mexico LME is traversed by major shipping lanes and port facilities contribute to important sources of employment. The volume and value of shipping has increased in the Gulf region. In Mexico, two out of five ports receive up to 80 percent of imports for the Gulf of Mexico. In the US, six of the top 10 leading shipping ports are located in the Gulf (UNIDO-GEF 2010).

Poverty is a major problem in the Gulf's coastal states with 60-80 percent of its population classified as poor. People are settling in areas prone to be affected by meteorological events (floods, etc.) in absence of remunerated employment. This explains four phenomena: a) the significant increase of migration flows towards the most dynamic economic areas, such as the US northern border; b) the increase in poverty and employment in unproductive (and illegal) activities; c) a spatial redistribution of population, increasing in cities in dynamic economic areas and decreasing in rural and deprived urban areas, and d) increasing pressure on natural resources and ecosystems (UNIDO-GEF 2010).

Habitat destruction and the depletion of fishery resources are factors that increase the vulnerability of the region to events like climate or socio-economic change and diminish resilience in human communities and ecosystems. It is therefore necessary to consider alternatives that expand opportunities for economic development that generate employment and investment in programs that sponsor a regulated use of natural resources and promote the protection of threatened ecosystems (coastal lagoons, mangroves, sea grass beds, sand dunes) (UNIDO-GEF 2010).

GOVERNANCE

Governance within nations of the Gulf is complex due to differing and sometimes overlapping authorities at federal, state and local levels. Moreover, cultural considerations of history, language, politics, religion, and socioeconomics complicate efforts to better integrate governance mechanisms among the three nations that share the Gulf (UNIDO-GEF 2010).

The three surrounding countries of the Gulf (US, Mexico and Cuba) have had a long history of cooperation and partnerships; a vast range of organizations, institutions and government agreements has been created in the past to work together on issues such as fisheries, migratory species, and research priorities. Organizations such as The Gulf of Mexico Fishery Management Council (GMFMC), The Gulf States Marine Fisheries Commission (GSMFC), the International Commission for the Conservation of Atlantic Tunas (ICCAT), the MEX-US-Gulf Bilateral Oil Spill Response Agreement and the Gulf of Mexico Program under the Environmental Protection Agency's (EPA) mandate, among others, have worked together in the past. Today, cooperation has expanded considerably and no longer focuses exclusively on topics concerning fisheries and their management issues (UNIDO-GEF 2010).

The Gulf of Mexico Alliance (GOMA), the Gulf of Mexico Large Marine Ecosystem Project (GoM LME), Tri-national Initiative for Marine Science and Conservation in the Gulf of Mexico and Western Caribbean, the Bi-national US-Mexico group under GOMA's Habitat Conservation and Restoration team and the International Workshops Series on Governance for the Gulf of Mexico (started by the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University, Corpus Christi [HRI-TAMUCC], and supported by other Mexican and Cuban institutions) are clear proof of new and innovative schemes for regional collaboration. All these certainly represent alternatives and arrangements to be considered when confronting trans-disciplinary, multi-stakeholder and multi-national problems (UNIDO-GEF 2010).

For decades, the treaties and institutions set up between the United States and Mexico to deal with transboundary and bi-national issues have served as models of cooperation around the world. Transboundary impacts (overfishing, the use of coastal resources, oil pollution discharge) require common strategies for problems that originate in one country but that will impact the whole LME due to the connectivity.

Despite the good examples of cooperation, some unresolved environmental questions could create bi-national strife in the near future. The question of national sovereignty will continue to play a large role when confronting issues that require transboundary solutions such as water availability, energy development and electricity, proper handling and disposal of hazardous waste streams and invasive marine species (UNIDO-GEF 2010).

CONCLUSIONS

The stress of human activities on land and in the ocean is changing coastal and marine ecosystems and threatening their capacity to provide important benefits to society, such as healthy and abundant seafood, clean environments for recreational activities, and protection from extreme meteorological events such as hurricanes and flooding. Fish and fisheries and habitats are important transboundary issues at risk from climate change. The increasingly frequent intense tropical cyclones occurring in the Gulf have already impacted the population dynamics of important sport fishing species such as red snapper as well as key commercial fisheries resources (oysters, shrimp, crabs, lobsters and several finfish species). Still a more serious threat is the negative impact of hurricanes on essential nursery habitats such as mangroves and seagrasses. Another point of concern is sea level rise. Projections indicate potential threats to vulnerable species such as sea turtles, nursery areas, and loss of mangroves and tidal flats with the consequential displacement of recreationally and ecologically important marine fish species. Finally, observed changes in ocean circulation will likely affect the dispersal of early life stages of ecologically important species such as groupers, thereby interrupting population's connectivity, genetic variability and chances of survival.

Ecosystem-based management (EBM) is an appropriate approach to address these problems by integrating ecological, social, and economic goals and recognizing humans as a key component of the ecosystem - to sustainably manage natural resources and biodiversity by maintaining ecosystem processes, functions and services (Clarke and Jupiter 2010).

A holistic approach is required in face of the rapid decline in biodiversity. It is paramount to maintain the defined alliances of the nations sharing the Gulf of Mexico LME and support development of collaborative processes to define problems and find solutions. This EBM approach should include systematic monitoring and assessment of key ecosystem indicators as the basis for achieving clearly stated management goals. Through interagency cooperation and coordination of management results, it will be possible to provide governance options for restoring and sustaining Gulf of Mexico goods and services and socioeconomic benefits to coastal communities in Mexico and the United States. Within the context of the joint Mexico and U.S. GoMLME program, it is important for both nations to initiate, sustain, and enforce habitat and species protection and include public education and involvement in moving the project forward.

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9

REVIEW OF CLIMATE CHANGE EFFECTS IN THE YELLOW SEA LARGE MARINE ECOSYSTEM AND ADAPTIVE ACTIONS IN ECOSYSTEM BASED MANAGEMENT

Qisheng Tang and Jianguang Fang

INTRODUCTION

The Yellow Sea is a typical large marine ecosystem with distinctive bathymetry, hydrography, productivity, and trophically dependent populations. Shallow but rich in nutrients and resources, the Yellow Sea Large Marine Ecosystem (YSLME) has productive and varied coastal, offshore, and transboundary fisheries. Over the past several decades, the resource populations in the YSLME have changed greatly. Many valuable resources are threatened by unsustainable exploitation and by the effects of climate change. Promoting sustainable development of the sea and implementing effective management strategies is an important and urgent task.

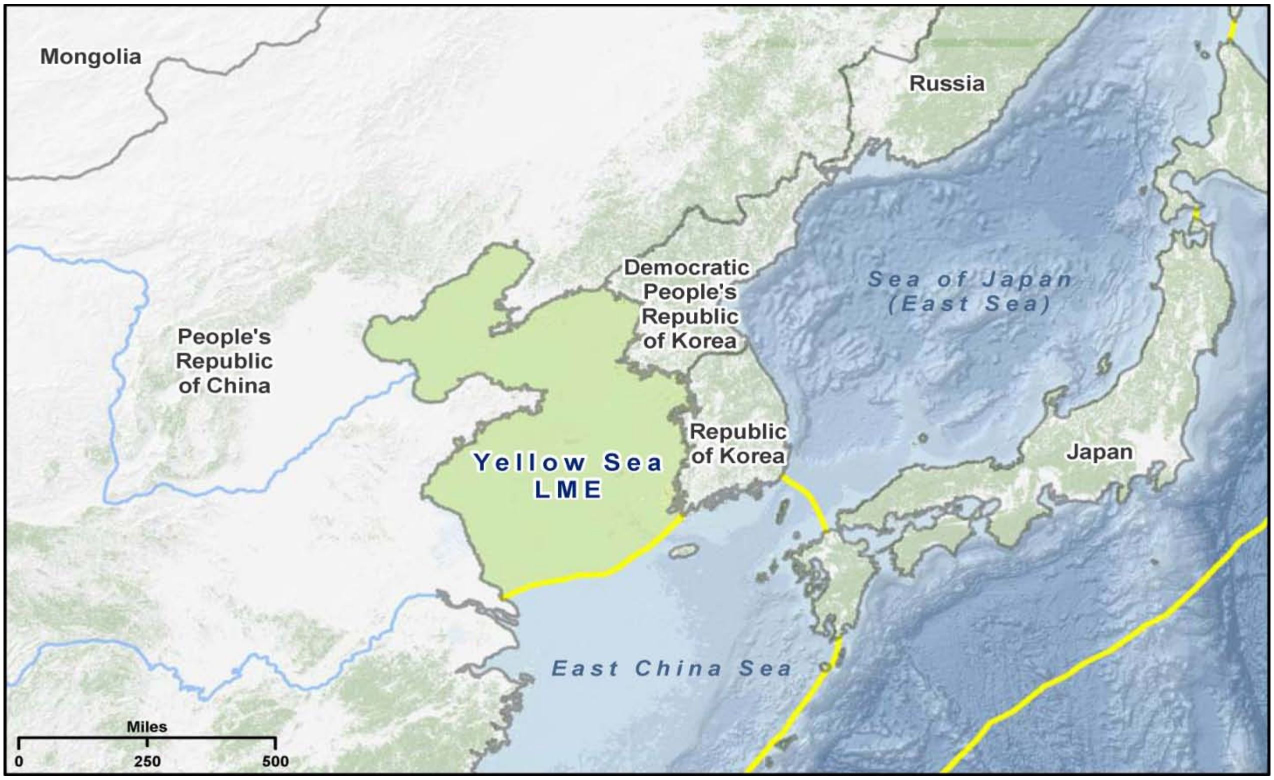

Figure 1. Location of the Yellow Sea LME.

The purpose of this chapter is to describe the YSLME, with emphasis on the changing states of productivity and biomass yields in the ecosystem and the causes for these changes. Suggestions for adaptive actions in ecosystem-based management in the YSLME are discussed in the final section.

Main Characteristic of the Yellow Sea Large Marine Ecosystem

The Yellow Sea LME is a semi-enclosed shelf sea and located between continental North China and the Korean Peninsula. It is separated from the West Pacific Ocean by the East China Sea in the south, and is linked to an arm of the Yellow Sea in the north. It covers an area of about 400,000 km^2, with a mean depth of 44 m. Most of the Sea is shallower than 80 m. The central part of the sea, traditionally called the Yellow Sea Basin, ranges in depth from 70 m to a maximum of 140 m (Figure 1).

The general circulation of the Yellow Sea LME is a basin-wide cyclonic gyre comprised of the Yellow Sea Coastal Current and the Yellow Sea Warm Current. The Yellow Sea Warm Current, a branch of the Tsushima Warm Current from the Kuroshio Region in the East China Sea, carries water of relatively high salinity (> 33 PSU) and high temperature (> 12°C) northward along 124°E and then westward, flowing into the Bohai Sea in winter. This current, together with the coastal current flowing southward, plays an important role in exchanging the waters in this semi-enclosed sea (Figure 2).

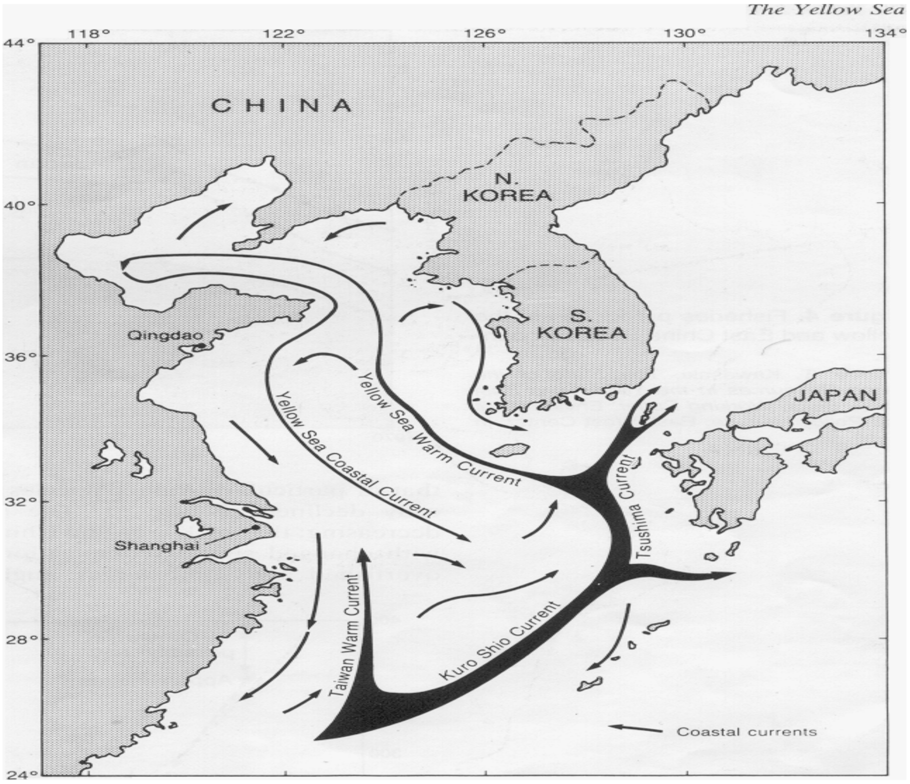

Figure 2. Schematic diagram of the winter current system in the Yellow Sea LME (from Gu et al. 1990).

Below 50 m, the Yellow Sea Cold Water Mass forms seasonally and is characterized by low temperature. Bottom temperatures are less than 7°C in the central part. The mass is believed to be the remnant of water chilled in the north and left over from the previous winter (Ho et al. 1959; Guan 1963). Stratification is strongest in summer, with a vertical temperature gradient greater than 10°C/10 m. All rivers into the Yellow Sea LME have peak runoff in summer and minimum discharge in winter, which has important effects on salinity of the coastal waters.

The Yellow Sea LME lies in the warm temperate zone, and its communities are composed of species with various ecotypes. Warm temperate species account for about 60 percent of the total biomass of resource populations; warm water species and boreal species account for about 15 percent and 25 percent, respectively. The Yellow Sea LME food web is relatively complex, with at least four trophic levels. There are two trophic pathways: pelagic and demersal. Anchovy and macruran shrimp (e.g. *Crangon affinis* and southern rough shrimp) are keystone species (Tang 1993). About 40 species, including almost all of the higher carnivores of the pelagic and demersal fish, and the cephalopods, feed on anchovy. *Crangon affinis* and southern rough shrimp, which are eaten by most demersal predators (about 26 species) are numerous and widespread in the Yellow Sea LME. These species occupy an intermediate position between major trophic levels and interlock the food chain to form the Yellow Sea food web.

Approximately 100 species are commercially harvested, including demersal fish (about 66%), pelagic fish (about 18%), cephalopods (about 7%), and crustaceans (about 9%). About 20 major species account for 92 percent of the total biomass of the resource populations, and about 80 species account for the other 8 percent. With the introduction of bottom trawl vessels in the early twentieth century, many stocks began to be intensively exploited by Chinese, Korean, and Japanese fishermen (Xia 1960). The stocks remained fairly stable during World War II (Liu 1979). However, due to a remarkable increase in fishing effort and expansion to the entire Yellow Sea LME, nearly all the major stocks were fully fished by the mid-1970s, and the resources in the ecosystem began to be over-fished in the 1980s (Tang 1989). Aquaculture is a major activity in Yellow Sea coastal waters. Mariculture species include oysters, clams, scallops, mussels, seaweed, shrimp and some fish.

CHANGING STATES of the YELLOW SEA LARGE MARINE ECOSYSTEM

Changes in Ecosystem Biodiversity

Over the past 60 years, dramatic changes in species composition, dominant species and the community structure of resource populations in the Yellow Sea LME have been observed — from small yellow croaker and hairtail in the 1950s and early 1960s to Pacific herring and chub mackerel in the 1970s to Japanese anchovy and sandlance after the 1980s. Small-sized, fast-growing, short-lived, and low-valued species increased markedly in abundance during the 1980s and assumed a prominent position in the ecosystem's resources and food web thereafter (Figure 3). As a result, larger, higher trophic level, and commercially important demersal species were replaced by smaller, lower trophic level, pelagic, less-valuable species. The most recent surveys indicate that the abundance of pelagic species such as the Japanese anchovy is declining, while the biomass of demersal species is increasing (Figure 4). The stock of small yellow croaker has shown a recovery trend since middle 1990s (Jin 2006).

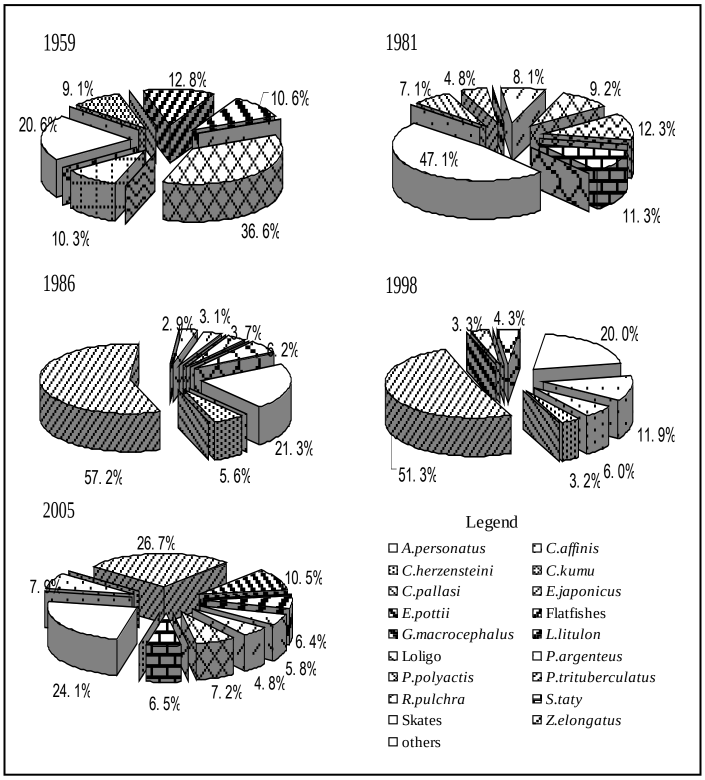

Figure 3. Changes in species composition of resource populations in the Yellow Sea LME (based on biomass yields data of spring survey).

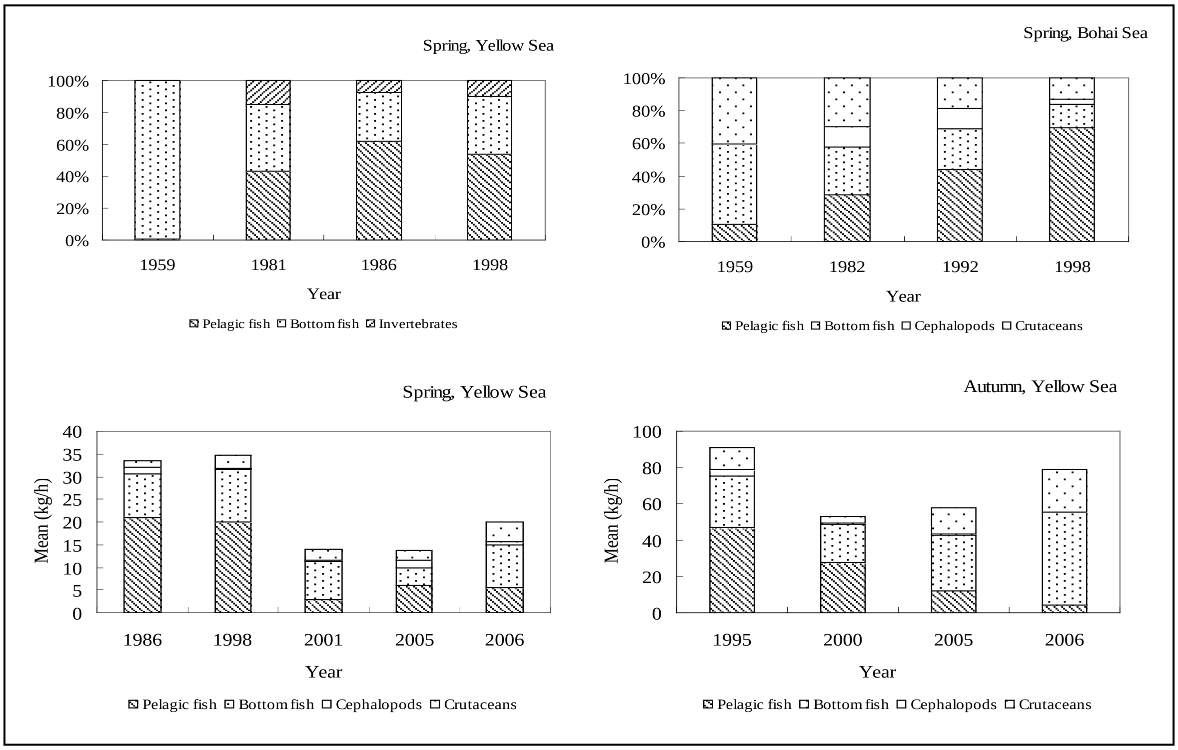

Figure 4. Changes in community structure of resource populations in the Yellow Sea LME (based on biomass yields data of survey).

Changes in Ecosystem Productivity

Annual variations of ecosystem productivity have been observed in the Yellow Sea LME. As shown in Figure 5, primary productivity in the Bohai Sea decreased noticeably from 1982 to 1998. Over the past 40 years, there was a decline in phytoplankton biomass, seemingly linked with nutrient changes (Tang 2003). Zooplankton is an important component in Yellow Sea communities. The dominant species, *Calanus sinicus*, *Euphausia pacifica*, *Sagitta crassa*, and *Themisto gracilipes*, are all important food for pelagic and demersal fish and invertebrates. The annual biomass of zooplankton in the Bohai Sea has decreased noticeably since 1959. However, zooplankton biomass increased in the sea in 1998, possibly due to the decline of the anchovy stock, which was the most abundant species before 1998. Fish stocks have decreased since the 1980s, although biomass yields were at a high level in 1998-2000 in the Yellow Sea LME. As a result, the trophic level of fish stocks declined from 4.1 in 1959-60 to 3.4 in 1998-99 in the Bohai Sea; and from 3.7 in 1985-86 to 3.4 in 2000-01 in the Yellow Sea (Zhang and Tang 2004).

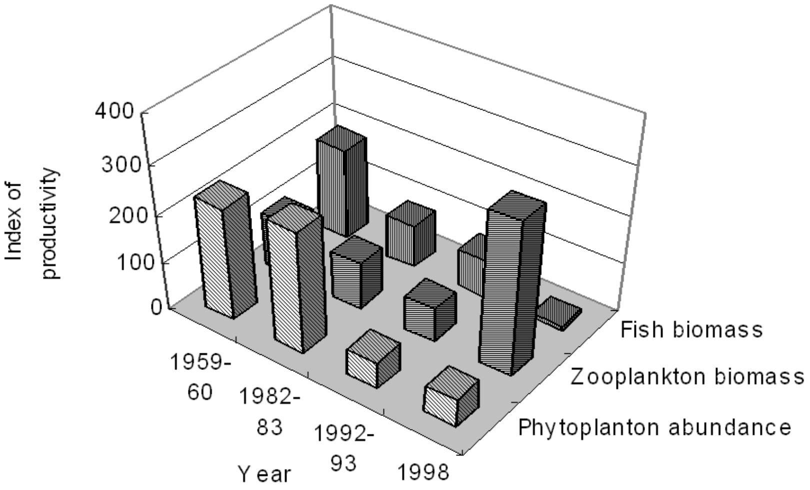

Figure 5. Decadal-scale variations of ecosystem productivity at different trophic levels in the Bohai Sea (phytoplankton abundance, ×10^4cell m^{-3}, zooplankton biomass, mg m^{-3}, fish biomass, kg $haul^{-1}$ h^{-1}; from Tang et al. 2003).

Changes in Ecosystem Health

Major pollutants entering the Yellow Sea LME are organic material, oil, heavy metals and pesticides. Pollutants from municipal, industrial and agricultural wastes and run-off, as well as atmospheric deposition, are 'fertilizing' coastal areas triggering harmful algal blooms and oxygen deficient 'dead zones'. The harmful algal blooms and low levels of dissolved oxygen in the water make it difficult for fish, benthic fauna and other marine creatures to survive and for related social and economic activities to be sustainable. Since the 1970s, the annual mean water temperature and level of dissolved nitrogen in the sea increased by 1.7°C and 2.95 μmol L^{-1}, respectively, while dissolved oxygen, phosphorus, and silicon decreased by 59.1, 0.1 and 3.93 μmol L^{-1}, respectively (Lin et al. 2005). As a result, the frequency of occurrence of harmful algal blooms has gradually increased, and the size of hypoxic areas (where DO≤2mg/l; Li et al. 2002) is on the rise in coastal areas (Figure 6). These events affect the most productive areas of the marine environment and lead to the destruction of important habitats needed to maintain ecosystem health.

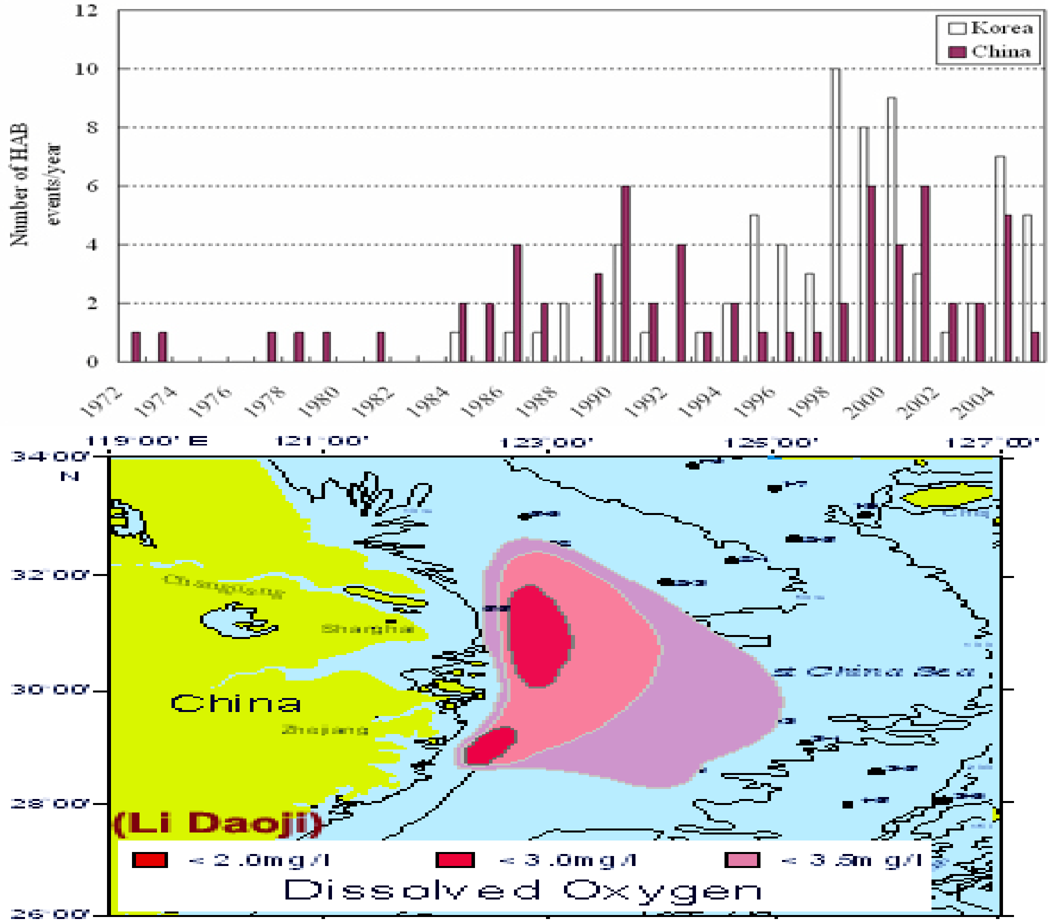

Figure 6. Increase in frequency of harmful algal blooms (top panel) and spatial extension of eutrophication in the YSLME (bottom panel).

Climate Impacts

Generally speaking, changes in the quantity and quality of the ecosystem resources of the YSLME are attributed principally to human pressures, as demonstrated by many studies (e.g., Tang 1989, 1993; Zhang and Kim 1999). However, an analysis of inter-decadal variations of ecosystem production in the Bohai Sea indicates that it is difficult to use traditional theory (e.g. top-down control, bottom-up, or wasp-waist control) to directly and clearly explain the long-term variations of production levels in the coastal ecosystem (Tang et al. 2003). We observed that under the same fishing pressure, the biomass yields of some exploited stocks in the Yellow Sea appear to be fairly stable (e.g. Spanish mackerel), or recovered (e.g. small yellow croaker). Changes in biomass yields and species shifts in dominance cannot be explained merely by fishing pressure. Climate change may have important effects on the recruitment of pelagic species and shellfish in the Yellow Sea LME. A new study identifies four SST regimes in the Yellow Sea LME over the past 141 years: a warm regime (W) before 1900, a cold regime (C) from 1901 to 1944, a warm regime with a cooling trend (WC) from 1945 to 1976, and a warm regime with a warming trend (WW) from 1977 to 2007 (Figure 7A). During the period of 1982 through 2006, sea surface temperature of the YSLME increased by 0.67°C (Belkin 2009).

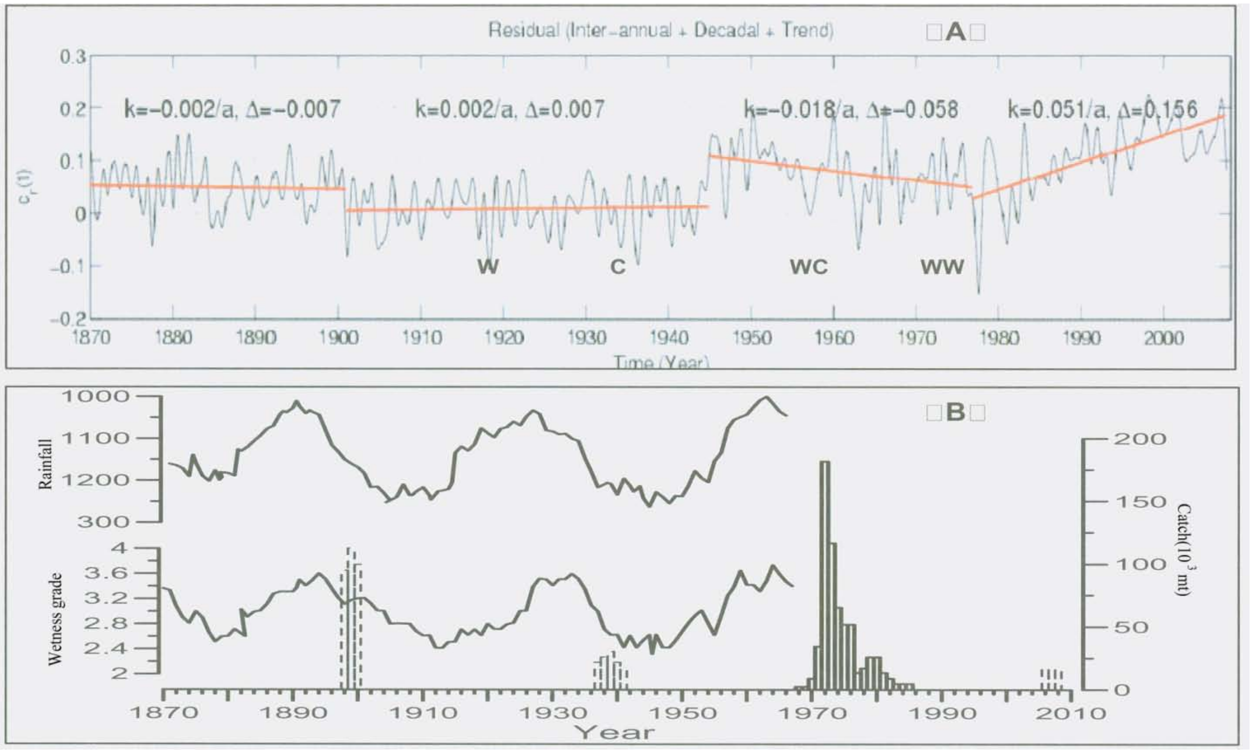

Figure 7. (A) The residual SST after removing its annual signal. W, C, WC and WW refer to the four regimes characterized by, respectively, warm, cold, warm with cooling trend, and warm with warming trend (from Huang et al. 2012). **(B)** Relationship between the fluctuations in herring abundance of the Yellow Sea and the 36-yr cycle of wetness oscillation in eastern China (adapted from Tang 1981).

SST regime shifts and fluctuations in Pacific herring abundance in the Yellow Sea LME show a strong correlation. Pacific herring in the YSLME has a long history of extreme variability and corresponding exploitation. In the last century, the commercial fishery experienced three peaks (1900, 1938 and 1972), followed by periods of little or no catch (Tang 1995). Since 2005, both herring stocks and eelgrass (where herring spawn), have increased in Sanggou Bay - a former major herring spawning ground and now a large scale mariculture area. However, the recovery is not complete (Figure 7B). At the same time, several unusual events have occurred in the coastal areas. A false killer whale visited Qingdao Bay. The last time local people saw false killer whales was more than 30 years ago. On 18 January 2008, a sperm whale landed on 'Herring Beach' in Sanggou Bay. This was the first time local people saw a species this large (body length, 19.6 m; weight, 51.1 t). We believe that there may be two types of shifts in ecosystem resources: systematic replacement and ecological replacement. Systematic replacement occurs when one dominant species declines in abundance or is depleted by overexploitation, and another competitive species uses the surplus food and vacant space to increase its abundance. Ecological replacement occurs when minor changes in the natural environment affect stock abundance, especially for pelagic species. Two types of shifts may be occurring in the ecosystem. The regime shifts in the Yellow Sea LME are likely to have important effects on ecosystem resources in other areas of the North Pacific Ocean.

ADAPTIVE ACTIONS in ECOSYSTEM BASED MANAGEMENT

Mitigation and Recovery Practice

There are many ways to recover the resources in a stressed LME, such as reducing excessive fishing mortality, controlling point sources of pollution, and gaining a better understanding of the effects of natural perturbations. After 1995, China closed fishing in the Yellow Sea and East China Sea LMEs for two to three months in the summer. This fishing ban has effectively protected juvenile fish, leading to an increase in the quantity and quality of fish catches. During 2003-2010, the nation's target for "Double Control" on the number and power of marine fishing boats was realized when nearly 30,000 Chinese fishing boats were taken out of service.

In order to recover the resources of the Yellow Sea LME, artificial enhancement has been encouraged. Since 1984, the experimental release of penaeid shrimps in the Bohai Sea, the north Yellow Sea and in the southern waters off the Shandong Peninsula has achieved remarkable ecological, social, and economic benefits. The release of scallops, abalone, and arkshell was also successful. These successes point the way forward for artificial enhancement programs in the Yellow Sea LME and suggest the recovery of ecosystem resources is possible. In 2006, the Chinese State Council promulgated the Program of Action on the Conservation of Living Aquatic Resources of China. This program has provided guidance for the conservation of living aquatic resources, and plainly called for strengthening aquatic resource protection and increasing fishery stock enhancement. Since then, stock enhancement has become a public activity in China and we hope to establish a national day for these releases. From 2006 to 2010, about 50 billion seedlings of several species were put into the Chinese coastal waters. This activity significantly increased living resources and fishermen of Shandong Province recaptured 215,000 tons of shrimp, jellyfish, crab and other released species. Therefore, artificial enhancement practices are an effective resource recovery strategy that should be expanded to the LME scale.

New multi-trophic mariculture model

Studies of the ecosystem dynamics of the Yellow Sea LME have provided new scientific knowledge, such as:

- **There is a negative relationship between ecological conversion efficiency and trophic level at the higher trophic levels (Tang et al. 2007)**: This new finding indicates that the ecological efficiency of species at the same trophic level would increase when fishing down marine food webs at lower trophic levels and ecosystem resources will be increased. Based on this finding, a new harvest strategy using ecosystem-based management should be considered, and the development of different harvest strategies according to different requirements. If we are concerned with big fish, A (harvest species at high trophic levels, may be called as top harvest strategy) will be selected; if we need more seafood, B (harvest species at low trophic levels, may be called as non-top harvest strategy) will be selected. In the case of China, B should be selected and new development of mariculture (including seaweeds, shellfish, finfish and others) will be a good choice.

- **Shellfish and seaweed mariculture increase atmospheric CO_2 absorption by coastal ecosystems (Tang et al. 2011):** As we know, China is the largest producer of cultivated shellfish and seaweeds in the world with an annual production of >10 million t (Mt). Through mariculture of shellfish and seaweeds, it is estimated that 3.79 ± 0.37 Mt C yr^{-1} are being utilized, and 1.20 ± 0.11 Mt C yr^{-1} were removed from the coastal ecosystem by harvesting from 1999 to 2008. The result illustrates that cultivated shellfish and seaweeds can indirectly and directly take up a significant volume of coastal ocean carbon. Shellfish accomplish this by removing phytoplankton and particulate organic matter through filter feeding (Figure 8), while seaweeds carbon through photosynthesis. Thus, cultivation of seaweeds and shellfish plays an important role in carbon fixation, and therefore contributes to improving the capacity of coastal ecosystems to absorb atmospheric CO_2.

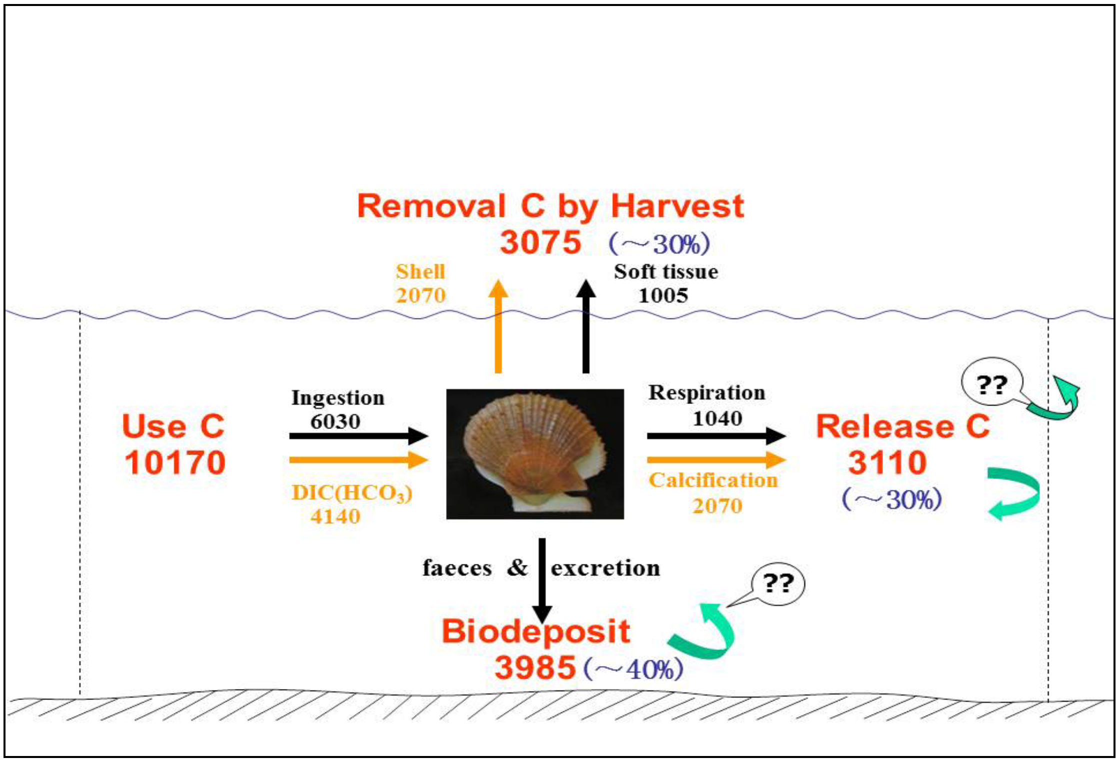

Figure 8. Carbon budget of scallop (*Chlamys farreri*) during a farming cycle (unit: mg C/ind./500 days; unpublished data, adapted from Zhang et al.)

This new scientific knowledge encouraged us to develop a new mariculture model - integrated multi-trophic aquaculture (IMTA). The new multi-trophic aquaculture model is adaptive and efficient (Figure 9). Not only does IMTA provide more production but it also indirectly or directly reduces excess atmospheric CO_2 and nutrients, and increases the social acceptability of culturing systems. The various forms of IMTA implemented in the Sanggou Bay of Shandong Peninsula are introduced as follows:

- **IMTA of long-line mariculture of abalone and kelp:** Longline mariculture of abalone (*Haliotis discus hannai*) is predicted to expand rapidly in Northern China in order to meet the increasing consumer demands. As with net cage mariculture, long line mariculture requires artificial feed (fresh and dry macroalgae usually manually fed). This will have negative effects on natural ecosystem and may eventually impact of the health of the cultured abalone if the water quality decreases sufficiently. New approaches that include the introduction of integrated mariculture of abalone and kelp（*Laminaria japonica*）are required to minimize the negative effects of the growing mariculture industry on the environment. One potential benefit of IMTA is that the cycling of nutrients is facilitated. Excretory and waste products generated by the abalone are taken up as nutrients by the kelp and converted into plant biomass to provide food for abalone in this system (Figure 10A).

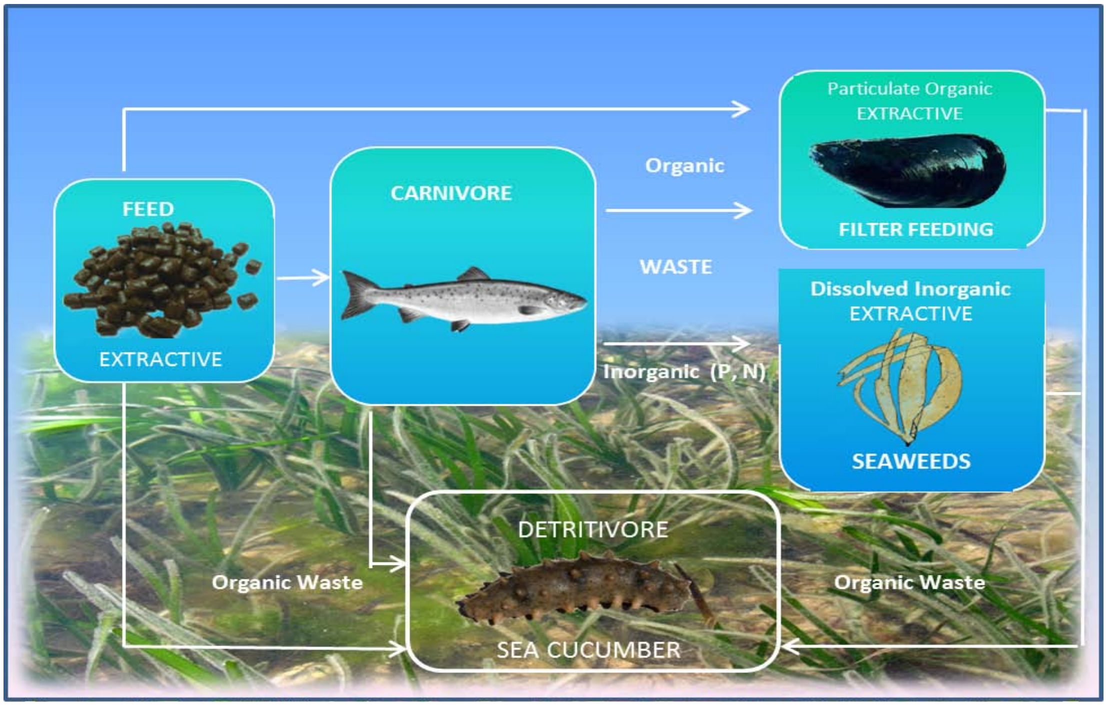

Figure 9. IMTA concept and process: The particulate waste in the water column is removed by filter feeding bivalves, while the portion that ends on the seafloor is utilized by the sea cucumbers. The dissolved inorganic nutrients (N, P & CO_2) are absorbed by the seaweed that also produces oxygen, which in turn is used by the other cultured organisms (Fang et al. 2009).

For each cultivation unit, there were four long line rafts. The length of one long line is 80 meters and the distance between two long lines is about 5 m. Therefore, the total area was about 1,600 m^2. For each long line, 30 net cages are hung at 5 m in depth. About 280 abalone (shell height: 3.5-4 cm) were cultivated at each net cage. Kelp is hung horizontally between the abalone lantern nets. There are about 70 plants of kelp cultured on each rope. The interval between two kelp culture ropes is about 2-3 m. About 33,600 individual abalone and 12,000 individual kelp were cultivated at each cultivation unit. Kelp were cultivated beginning in Nov. 2008 and harvested in June, 2009. When the kelp grow to 1 m in length, they can be removed from the culture rope, and put into the net cage for feeding the abalone. The net cage should be fed and cleaned once a week. In this way, the abalone can reach market size (8-10 cm) in two years.

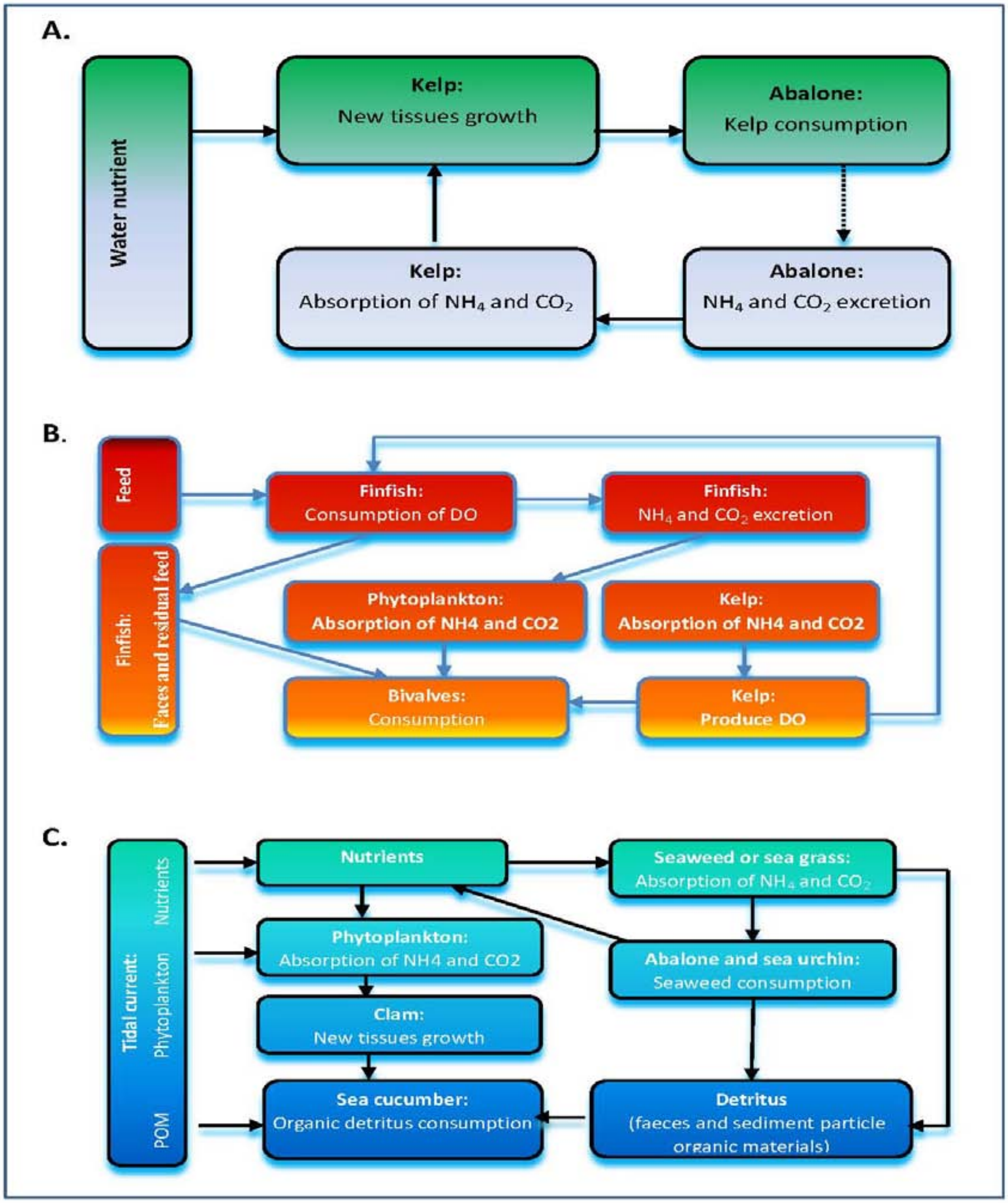

Figure 10. Diagrammatic representation of IMTA of A (long-line culture of abalone and kelp), B (long-line culture of finfish, bivalve and kelp.) and C (benthic culture of abalone, sea cucumber, clam and sea weed). (unpublished data from Fang et al. Yellow Sea Fisheries Research Institute).

Water quality is an important factor to consider in assessing the impacts of abalone farming on the environment. From our survey results, in the abalone farm area, ammonia concentration showed a significant increase in summer. Therefore, in the co-culture mode (abalone and kelp), ammonia is considered the limiting factor. Ammonia excretion rates of abalone should not exceed uptake rates by kelp in order to ensure good water quality for abalone growth. According to the ammonia excretion rate of abalone and the biomass of abalone at a mariculture unit, the total ammonia released into the water column from April to November was calculated at 2.16kgN. Based on the growth rate of kelp and its content of N (1.34% of dry weight), the theoretical biomass of kelp for one mariculture unit was calculated to be 10,080 individuals. In the demonstration area of abalone and kelp long line mariculture, 12,000 individual kelp were cultivated - enough to absorb the excreted ammonia by the abalone. The yield of abalone of such an IMTA unit is about 900 kg. Based on the market price in 2009, the production value of each IMTA unit is about 10,000 US$ per 1600 m^2 in two years.

- **IMTA of long-line culture of finfish, bivalves and kelp:** In this system, seaweeds can be used to remove and transform dissolved inorganic nutrients from the effluent of both finfish and bivalves and provide DO to the finfish and bivalves. The bivalves filter the suspended particle organic materials, from the fish feces, residual feed, and phytoplankton (Figure 10B).

Kelp and *Gracilaria lemaneiformis* were selected as the bioremediation species in December ~ May (Winter and Spring) and June ~ November (Summer and Autumn) respectively. The nitrogen balance equation can be represented as follows: N（seaweed）= N（fish excretion）+ N（feed residue）+N（fish dead). The conversion factor between dry and wet weight of these two species was about 1:10. Nitrogen content of Kelp and *Gracilaria lemaneiformis* was 2.79 percent and 3.42 percent (dry weight), yield of Kelp and *Gracilaria lemaneiformis* was 5.6 kg (wet weight)m^{-2} and 3 kg (wet weight)m^{-2}. The optimal co-cultivation proportion of fish cage and macroalgae in winter and spring was 1(kg ww): 0.94(kg dw), while in summer and autumn it was 1(kg ww): 1.53 (kg dw) (Jiang et al. 2010).

In the systems, particle size is important for filter feeders such as shellfish or other organisms that are capable of consuming organic particles. The Pacific oyster (*Crassostrea giga)*, can filter particulates smaller than 541 μm (Dupuy et al. 2000). In the present study, we studied the effects of the contribution rate of POM-control area on POM-cage area, waste feed and feces on the oyster food source. The assimilation efficiency of fish aquaculture-derived organic matter is about 54.44% (10.33 % waste feed and 44.11 % fish feces) by the ingestion activities of oyster. If, for example, 41.6 % of the total solid nutrient loads from fish cages are within the suitable size class (Elberizon et al. 1998), the oysters will be able to recover about 22.65 % of the total particle organic matter leached from fish cages. Bivalves functioning as recyclers of organic matter could contribute to environmentally clean aquaculture and could increase the profitability of fish cultivation. But, in order to achieve the maximum nutrient recovery efficiency of IMTA systems, the particles may have to be resized through various mechanical means or deposit feeders such as polychaetes and sea urchins（*Strongylocentrotus nudus*）ingest the other size fractions.

- **IMTA of benthic culture of abalone, sea cucumber, clam and sea weed:** In this system, seaweed and clam are produced from natural seedlings. Seaweed is used as food for abalone and sea urchin, while seagrasses provide the shelter for swimming animals and benthic organisms. Sea cucumbers utilize the feces of clam and abalone, and natural organic sediment as food. The ammonia-nitrogen excreted by feeding animals is absorbed by phytoplankton and seaweed. Phytoplankton is used as the food source for clams. Meanwhile, seaweed and phytoplankton provide DO to the animals (Figure 10C).

IMTA was carried out by the Chudao Island Company, located in the south cape of Sanggou Bay. The cultivation of abalone, sea cucumber, sea urchin, clam and seaweeds takes place at 5-15m depth. The main sediment type in Chudao Island is sandy-silt, while Sanggou Bay's surface sediments are mostly clay-silt. The total IMTA demonstration area is nearly 665 ha. The main enhancement species are sea cucumber (*Apostichopus japonius)*, abalone, sea urchin, arkshell (*Scapharca broughtonii*) and clam (*Ruditapes philippinurum).* In the IMTA area, the natural seagrasses and seaweed are abundant, and seagrasses cover an area of about 400 ha. In the spring (April or May) of every year, nearly 300,000 juveniles of sea cucumber and 150,000 juveniles of abalone are released into the area and the other species occur naturally. In 2009, the demonstration area produced 1.5 tons of abalone, 20 tons of sea cucumber, 180 tons of manila clam, 80 tons of arkshell, and 2.5 tons of sea urchin, with a value of more than 10,450 yuan RMB per ha.

- **Carbon budget in the IMTA system of kelp, abalone and sea cucumber:** The carbon budget for an individual abalone during the farming cycle (about 900 days from seeding to harvest), is shown in Figure 11. When a 1 kg abalone is harvested, the total ingested carbon is 2,460 g (kelp is the food source) and 1,350 kg is utilized for respiration, 110 g carbon for soft tissue and shell growth, 630g carbon for bio-deposit, and 370g carbon lost in feeding. In this system, 88 g carbon is utilized by sea cucumber, of which 8g is utilized for respiration, 2g of carbon for soft tissue growth, and 10g of carbon for bio-deposit. These results show that nearly 40% of the total ingestion of carbon is utilized to form biodeposits (including feces and feed loss), part of which sinks and is buried in the sediment. Therefore, when harvesting 1 kg of abalone (in fresh weight with the shell) in IMTA farming, 1100g carbon will be utilized from seawater (using kelp as a food source) and 112 g of carbon will be removed from the sea by harvest. This result demonstrates that the application of the IMTA model can remove the carbon from sea.

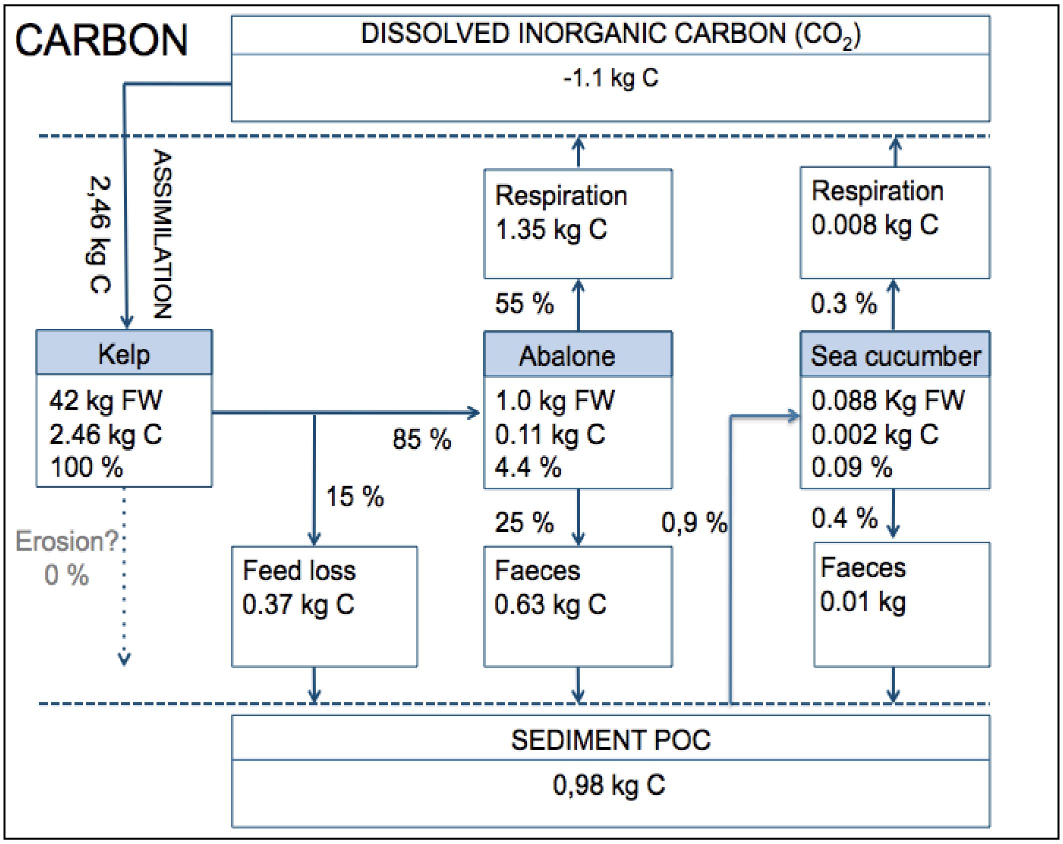

Figure 11. Carbon budget in the IMTA system of kelp, abalone and sea cucumber during a farming cycle (unpublished data from Zhang et al.).

- **Analyses of the economic and environmental benefits of IMTA:** Aquaculture provides not only material products but also many other service functions. Based on the 17 major value parameters and methods by Costanza et al. (1997), the core services of the mariculture ecosystem in the Sanggou Bay were selected and quantified through a market value approach, carbon tax approach and shadow project approach, respectively (Liu et al. 2010). Using the systemic evaluation approach, the value of the mariculture ecosystem services on four different modes including the kelp monoculture mode, scallop monoculture mode, abalone & kelp IMTA mode, kelp & abalone & sea cucumber IMTA mode in the Sanggou Bay were estimated and evaluated. The following tables present a classification of aquaculture ecosystem service and function using a “systemic evaluation approach” to evaluate the total value of different mariculture modes.

The value of food provision service and climate regulating service in different aquaculture modes are shown in Tables 1 and 2. The value of the mariculture ecosystem services provided by the IMTA mode was much higher than monoculture and IMTA mode.

Table 1. Value of food provision service in different aquaculture mode*

Aquaculture mode	Aquaculture species	Yield	Market price	Income	Cost	Value
		kg/ha/a	y/kg	CNY/ha/a	CNY/ha/a	CNY/ha/a
monoculture	kelp	27,000	6.0	162,000	67,500	94,500
monoculture	scallop	18,000	4.6	82,800	22,500	60,300
IMTA	kelp	30,000	6.0	0	72,900	0
	abalone	17,308	200	1,730,769	1,032.808	697,962
	Total			1,730,769	1,105,707	**625,062**
IMTA	kelp	30,000	6.0	0	7.2900	0
	abalone	16,615	200	1,661,538	926,815	734,723
	sea cucumber	3,600	120	216,000	21,600	204,000
	Total			1,877,538	948,415	**929,123**

* Unpublished data from Liu et al. Yellow Sea Research Institute. Currency is Chinese Yuan. kg/ha/a = kilograms per hectare per year

Table 2. Value of climate regulating service in different aquaculture mode*

Aquaculture mode	Fixed & removed C kg/ha/a	Released CO_2 kg/ha/a	Value (CNY/ha/a)				
			Benefit		Lost		Total value
			Reforested cost	Carbon tax	Reforest-ed cost	Carbon tax	Average value
Monoculture kelp	8,424．00	0	2,197.82	9,232	0	0	5,715.26
Monoculture scallop	1,741.169	22.3460	454.2711	1,908	5.830	24.49	1,166.14
IMTA kelp+abalone	23,638.85	32.0394	6,167.37	25,908	12.36	51.95	16,005.62
IMTA kelp+abalone +sea cucumber	24,054.75	31.0211	6,275.88	26,364	8.093	33.99	16,298.54

* Unpublished data from Liu et al.

Scientific Basis and Support

An essential component of effective ecosystem management is the inclusion of a scientifically based strategy, to monitor and assess the changing states and health of the ecosystem, by tracking key biological and environmental parameters (Sherman and Laughlin 1992, Sherman 1995). Under this requirement, the Strategic Action Program supported by the Global Environmental Facility (GEF) for the Yellow Sea LME is currently underway (UNDP-GEF 2009). The long-term objective of the project is to ensure environmentally sustainable management and use of the Yellow Sea LME and its watershed, by reducing stress and promoting the sustainable development of a marine ecosystem that is bordered by a densely populated, heavily urbanized, and industrialized coastal area. In order to further understand the Yellow Sea LME, the ongoing China-GLOBEC III/IMBER I and IMBER II Program, entitled “Key Processes and Sustainable Mechanisms of Ecosystem Food Production in the Coastal Ocean of China” (Tang et al. 2005) and “Sustainability of marine ecosystem production under multi-stressors and adaptive management” (Zhang 2011), have been approved for the National Key Basic Research and Development Plan of China (2006-2010, 2011-2015). The program goals are to identify key processes of food production in coastal and shelf waters based on the ecosystem approach and provide a scientific basis for ensuring food supply in the new century, by establishing a marine management system before 2015. Related to this requirement, the International Waters project supported by the GEF and the UNDP lead to the development and multi-country adoption of the Yellow Sea LME Strategic Action Programme (SAP) in 2009.

Therefore, it is necessary to promote further synergies with other research projects and establish joint programs for monitoring and assessing the Yellow Sea LME using ecosystem-based management.

Monitoring and assessing the changing states and health of the YSLME represents a scientifically based strategy for effective ecosystem recovery and sustainability. A comprehensive process-oriented study of ecosystem goods and services should be considered, for a better understanding of the interactions among the important physical, chemical and biological characteristics of the ecosystem. This will increase the predictive capability of Yellow Sea LME managers.

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10

LARGE MARINE ECOSYSTEMS AT RISK FROM ACIDIFICATION DURING CLIMATE CHANGE

James R. D. Oliver, Steve Widdicombe, Oliver Hasinger and Dan Laffoley

WHAT IS OCEAN ACIDIFICATION?

Ocean acidification is the change in ocean chemistry driven by the oceans' uptake of carbon dioxide from the atmosphere. Oceans are an important sink for carbon dioxide (CO_2) and absorb approximately 25% of all the CO_2 produced by anthropogenic activities each year (Sabine et al. 2004). The removal of CO_2 from the atmosphere and storage in the world's oceans has acted as a buffer against accelerated climate change but has led to changes in the oceans' chemical composition.

As more and more CO_2 is emitted into the atmosphere, the ocean has absorbed greater amounts at increasingly rapid rates. This is altering the system's ability to adjust to changes in CO_2 that naturally occur over millennia, significantly changing the chemistry of the seas, and leading to progressive acidification. While carbon equilibrium chemistry is well understood, coastal sea carbon chemistry is complex in space and time. This makes predicting future impacts in shallow coastal areas extremely challenging (Doney et al. 2009).

WHAT IS HAPPENING?

Carbon chemistry reactions in the oceans drive the system towards physicochemical equilibrium; the concentrations of atmospheric carbon dioxide interact with the ocean according to the following equation: $CO_{2(g)} + H_2O \leftrightarrow H_2CO_{3(aq)} \leftrightarrow H^+_{(aq)} + HCO_3^-{}_{(aq)} \leftrightarrow 2\,H^+_{(aq)} + CO_3^{2-}{}_{(aq)}$ (Doney et al. 2009).

As can be seen in Figure 1, ocean acidification causes the concentration of hydrogen ions in the oceans to increase, and therefore the pH to decrease. The uptake of atmospheric carbon dioxide is occurring at a rate exceeding the natural buffering capacity of the ocean, and the pH of the ocean surface waters has decreased by about 0.1 units since the beginning of the industrial revolution (Pearson & Palmer, 2000). If current carbon dioxide emission trends continue, the ocean will continue to undergo acidification, to an extent and at rates that have not occurred for tens of millions of years (McLeod et al. 2008).

The Earth's atmosphere has, in the past, endured episodes characterized by higher levels of CO_2. However, these high levels are thought to have built up slowly giving the oceans' carbonate buffering system time to compensate for these changes. What is different now is not the amount of CO_2 entering the atmosphere, and ultimately the oceans, but the speed at which this is happening. Recent studies show that the current uptake of CO_2 by the surface waters of the ocean – and the resulting rate of ocean acidification – is about 100 times faster than at the end of the last glacial period (20,000 years ago), the last time CO_2 significantly rose (Raven et al. 2005). Ecosystems have proved their ability to accommodate change when it is gradual, in time scales that are usually over hundreds of thousands of years. It is not known how well the marine ecosystem will adapt to changes that are occurring over decades.

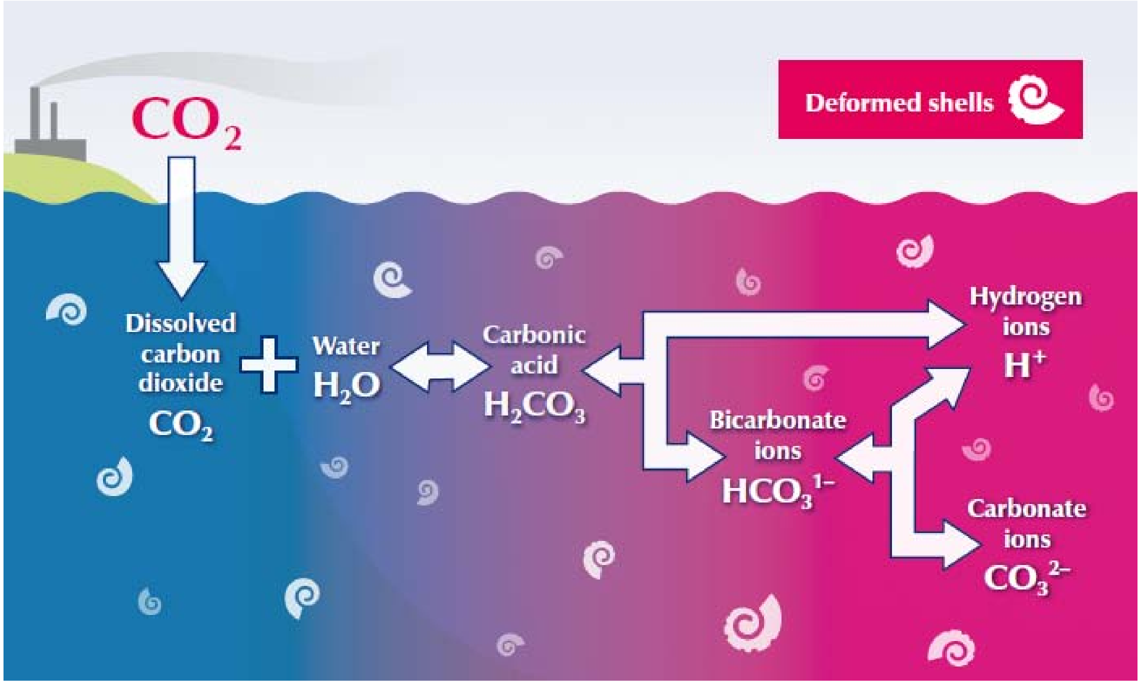

Figure 1. The burning of fossil fuels results in increased CO_2 in the atmosphere being taken up by the ocean resulting in it becoming more acidic (University of Maryland).

In addition to the changes in pH, ocean acidification also causes a decrease in concentration of carbonate ions. Carbonate ions (CO_3^{-2}) are essential to the calcification process that allows certain marine organisms to build their calcium carbonate shells and skeletons. However, increases in atmospheric CO_2 levels lead to increases in the concentration of carbonic acid and bicarbonate ions, causing a decrease in the concentration of carbonate ions (Doney et al. 2009). Even though some organisms use bicarbonate for their calcification, low concentrations of carbonate ions can have a significant effect on net calcification rates thereby slowing down the growth rates and decreasing the structural strength of calcifying organisms; such as hard tropical corals, cold water corals, mollusks, crustaceans, sea urchins, certain types of plankton, and some algae (e.g. Smith & Buddemeier 1992, Kleypas et al. 1999). This can happen in two ways. Firstly, the low pH can put greater stress on organisms as they try to maintain their acid-base balance. This occurs because it is suspected that more energy is required to pump the ions into and out of their cells and tissues to buffer acidosis.

This, in turn, means less metabolic energy may be available for calcification. In the second case, if the carbonate saturation of seawater goes below a value of 1 (i.e. it is under-saturated with respect to carbonate ions), it will become corrosive to calcium carbonate. Therefore, any calcified organisms living in under-saturated seawater will either have to increase their rate of calcification to compensate for this dissolution or they will experience a reduction in net calcification. While a number of organisms have demonstrated an ability to maintain net calcification rates when exposed to under-saturated seawater this up-regulation requires an energetic commitment which needs to be met by either increased feeding or by diverting energy from other physiological processes such as growth or reproduction.

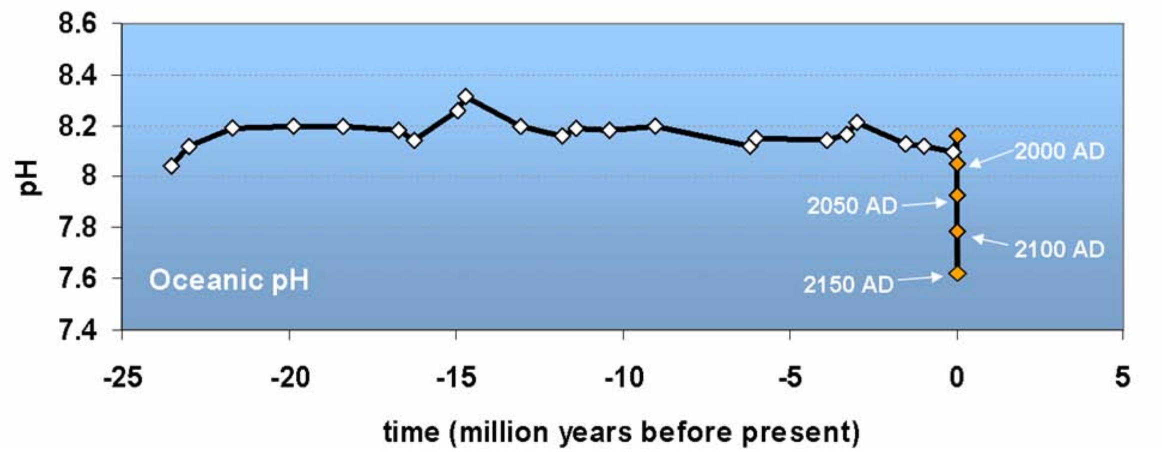

Figure 2. Past (from Pearson and Palmer, 2000) and predicted (from Turley et al. 2006) variability of marine pH. The rate and level of acidification occurring at present has not been experienced by marine organisms for about 20 million years.

Recent studies suggest that the changes in ocean chemistry due to the oceanic uptake of CO_2 from the atmosphere could also be affected by global warming-induced changes in precipitation. A combination of increases in CO_2 and a shift in weather patterns will change the chemical composition in rivers, in turn affecting the oceans by changing the amount of calcium and other elements in ocean salts. Data from this research suggests that there could be a more dynamic relationship between climate and ocean chemistry, resulting in biogeochemical reorganization on shorter time scales than previously thought (Cao et al. 2011).

In addition to terrestrial run-off, various other factors can locally influence the main chemical reactions of CO_2 with seawater thereby adding to the effects of ocean acidification. For example, acid rain, which consists of sulfuric and nitric acids originally derived from fossil fuel combustion, often falls on the coastal ocean (Doney et al. 2007). Acid rain can have a pH between 1 and 6; its impact on surface ocean chemistry may be important locally and regionally even if very small globally. Coastal waters are also affected by excess nutrient inputs, mostly nitrogen, from agriculture, fertilizers and sewage. The resulting eutrophication leads to large plankton blooms, and when these blooms collapse and sink to the sea bed, the subsequent respiration of bacteria decomposing the algae leads to a decrease in seawater oxygen, an increase in CO_2 and a decline in pH. Furthermore, warming can increase the release of methane from hydrates which is rapidly transformed into CO_2 by bacteria.

THE CONSEQUENCES OF OCEAN ACIDIFICATION

A doubling of the concentration of atmospheric carbon dioxide, which could occur in as little as 50 years, may cause major changes in the marine environment, specifically impacting calcium carbonate-producing organisms, such as corals or calcifying plankton. This could in turn have effects cascading through the food chain, causing damage to other very valuable marine ecosystems. Organisms that are at serious risk from ocean acidification include reef-building corals (including cold water corals), calcareous benthic invertebrates (including mussels and scallops) and planktonic calcifiers (Fabry et al. 2008).

The impact of ocean acidification on marine species and food webs will potentially affect major economic interests and could increasingly put food security at risk, particularly in tropical regions that are especially dependent on seafood protein. Furthermore, the impact of ocean acidification on coral reefs may compromise community security in low-lying areas that are protected from erosion and inundation by these ecosystems.

The harmful effects of ocean acidification are not isolated from other ocean stressors such as land-based sources of pollution, overfishing and over-extraction of marine resources, ocean warming and invasive species. The magnitude of the cumulative impacts on the ocean would now appear to be greater than previously understood. The impact of such stressors is often negatively synergistic meaning that the combination magnifies the negative impacts of each one occurring alone. This is already resulting in large-scale changes in the ocean at an increasing rate and in some regions has resulted in ecosystem collapse (Rogers & Laffoley, 2011).

Recent studies have sought to understand the mechanisms by which the multiple climate-related stressors of ocean acidification, temperature and hypoxia impact upon the physiology of marine organisms. By considering the relationship between temperature and organism performance, Pörtner & Farrell (2008) described how the stress associated with hypoxia (low oxygen) or hypercapnia (high CO_2) could not only reduce an organism's maximum level of physiological performance but could also reduce its tolerance to extreme temperatures. Given the importance of thermal tolerance in setting the abundance and distribution of marine organisms, it is clear that ocean acidification therefore has the potential to alter the biogeographic ranges of marine species. For example, in a modeling study by Findlay et al. (2010), it was shown that the extinction of a barnacle population from its most southerly current distribution would occur around 10 years sooner when the impacts of both ocean acidification and warming were considered, compared to estimates based on warming alone.

OCEAN ACIDIFICATION AND PRODUCTIVITY

On a global basis, ocean acidity has increased by 30% since the beginning of the industrial revolution and the rate of acidification will accelerate in the coming decades (Orr et al. 2005). As mentioned earlier, a trend towards more acidic conditions will make it harder for animals and plants to make and maintain their shells thereby threatening their health and ultimately their existence. Some organisms are especially sensitive to small changes in acidity and there is some evidence that they are already being affected (Wootton et al. 2008). The ocean provides about half of the Earth's productivity and humankind takes direct advantage of this through its fisheries and shellfisheries. Limited research has been carried out on the potential effects of ocean acidification to date; therefore, there are only a few indications about how these essential processes will be impacted.

Planktonic calcifiers, such as coccolithophores, foraminifera, and euthecosomatous pteropods, are known to be particularly vulnerable to acidification (Fabry, 2008). Planktonic calcifiers play a major role in the Earth's Carbon Cycle by absorbing CO_2 from the atmosphere and retaining it in the oceans as well as providing food for commercially important fish and cetaceans. In experiments, their shells, which protect them from small predators, seem to be readily damaged by pitting, peeling and partial dissolution when place into acidified seawater (Orr et al. 2005).

Effects on plankton communities could produce a domino effect, cascading through the entire marine food chain as all marine life is ultimately dependent on such microscopic plants and animals at the base of the food chain. The picture is not always the same, however, because an organism's response is often context-dependent. Some experiments have shown coccolithophores display different sensitivities and can grow bigger under high CO_2 conditions (Igelsias-Rodriguez, 2008; Hikami et al. 2011). It is important to note that even under conditions of extreme acidification (Kiel fjord); calcifying animals (mussels) can still flourish (Thomsen et al.

2010). However, in these situations, organisms are spending more energy fighting against the impacts of ocean acidification (i.e. maintaining homeostasis and building calcified structures) and therefore have less energy left for somatic growth and suffer reduced productivity. It is clear, therefore, that ocean acidification will cause considerable changes that will have widespread ecological implications (Fig. 3).

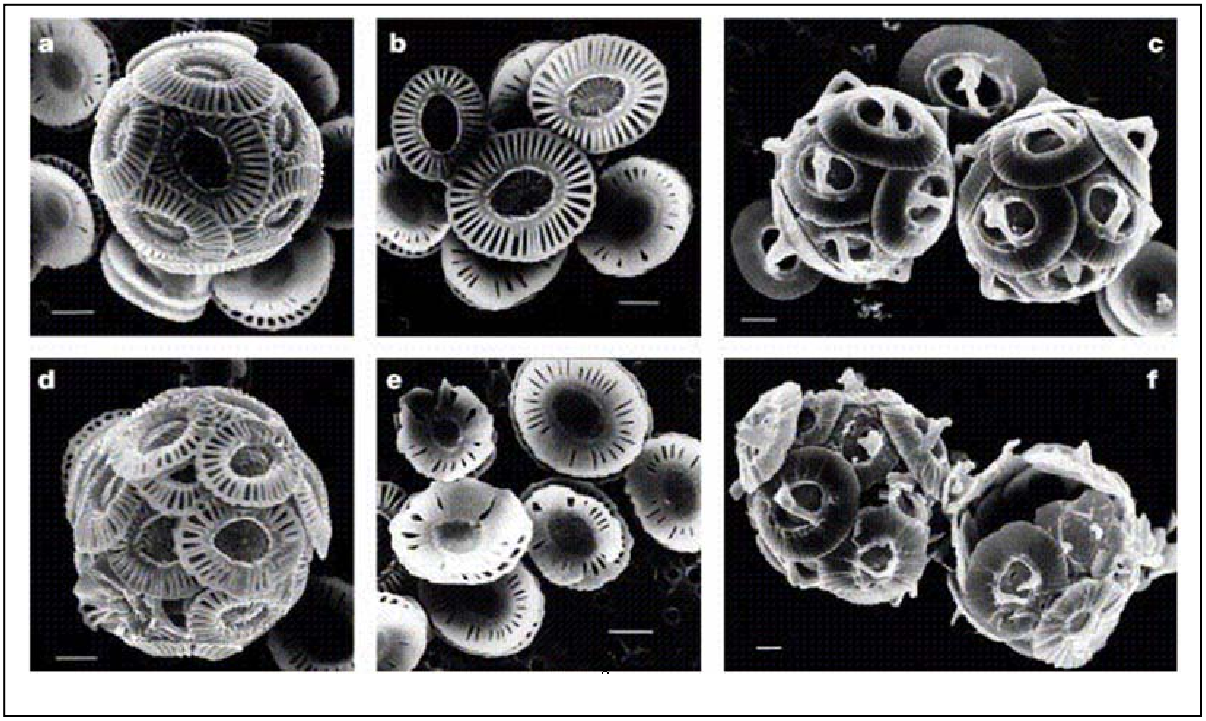

Figure 3. Effects of increased CO_2 on phytoplankton coccolithophores *Emiliania huxleyi* (a,b,d,e) and *Gephyrocapsa oceanic* (c,f): growth and structure are seriously compromised. Riebesell et al. 2000.

The impacts of ocean acidification may have much deeper consequences for ocean life, beyond those affecting the ability of species to build calcium carbonate shells; more complex impacts on ocean chemistry come into play. Biologically-important nutrients such as nitrogen, phosphates, silica and iron, which often limit plankton growth, could, as conditions become more acidic, be reduced and in turn affect primary production (Turley & Findlay, 2009). Another sector likely to experience detrimental effects is the multitude of species living hidden under the seafloor. These organisms, known as infauna, mix and irrigate the mud and sand (a process known as bioturbation) which increases the exchange of oxygen and nutrients between the seabed and the overlying water. In coastal areas this process ensures that nutrients vital to life are released back to the water to support the plankton that drive ocean productivity. Consequently any change in the abundance, distribution or activity of infaunal animals could have a considerable effect on the productivity of coastal waters.

Although infaunal organisms live within the seabed, an environment that is naturally high in CO_2, it does not mean they will necessarily be tolerant of the effects of ocean acidification (Widdicombe et al. 2011). Firstly, infaunal organisms depend upon the supply of organic material from the overlying water as a source of food. By changing the amount, the quality and the specific timing of this supply it is evident that ocean acidification impacts on the pelagic zone could have damaging effects in the benthos. Secondly, many infaunal species produce pelagic larvae that spend a significant amount of time in the overlying water column. During these vulnerable early life stages, changes in ocean chemistry could have significant impacts on their growth and survival (Dupont et al. 2008). Finally, even though they live deep within the sediment many infaunal species maintain a permanent connection to the overlying water via tubes or burrows. This means that they are more susceptible to changes in seawater chemistry than would first be expected (e.g. Wood et al. 2008).

Another area of interest has been the possible effects of ocean acidification on the biogeochemical reactions driven by microbial organisms such as bacteria and archea. One specific process of great concern is nitrification, a specific step in the marine nitrogen cycle in which nitrogen is converted from ammonium to nitrite and nitrate, which are the key nutrients for marine phytoplankton that contribute around 50 percent of global primary production. Simulating changes in pH expected over the next 20-30 years, research suggests that ocean acidification could reduce nitrification rates by 3–44 percent within the next few decades, affecting oceanic nitrous oxide production, reducing supplies of oxidized nitrogen in the upper layers of the ocean, and fundamentally altering nitrogen cycling in the sea (Beman 2010, Kitidis et al. 2011). This could have ramifications for the entire ocean food web as less nitrification would limit the nutrients available to the plants and algae that use them to fuel growth and production. The food web is complex, however, and the precise implications of the study's results are still unclear.

Even though ocean acidification is a global phenomenon (Fig. 4) there are some places that are likely to see greater changes than others. For example, high latitude Polar Regions are among the most productive on the planet; they are also where acidic conditions are predicted to increase the most over the next two to three decades. This is because cold water has a higher capacity to absorb CO_2 than warm water. Model-based predictions show that the Arctic Ocean will be first to cross this ocean acidification-related chemical threshold, when waters change from 'oversaturated' with calcium carbonate to 'under saturated'. If levels of atmospheric (and oceanic) CO_2 continue to rise at current rates, then by 2018, around 10 percent of the Arctic Ocean is projected to have crossed this threshold, rising to one-half by 2050. By 2100, it is likely that the entire Arctic Ocean will be in a state that can dissolve unprotected calcium carbonate structures (Orr et al. 2005). Moreover, some areas, such as upwelling systems and coastal fjords, already experience periods of low pH and high CO_2. These natural acidification events are predicted to increase in both severity and duration as a result of progressive ocean acidification.

OCEAN ACIDIFICATION AND ECOSYSTEM HEALTH

Ocean acidification is expected to have a detrimental effect on a number of vulnerable marine habitats. In the case of reef-building corals, calcification rates of tropical corals have been predicted to decrease by between 17 and 35% by 2100 (Kleypas et al. 1999). Reduced skeletal growth may be manifested as slower growth rates, or weaker coral skeletons that are more susceptible to storm damage. Furthermore, encrusting plants that cement the coral reefs together secrete a form of calcium carbonate (aragonite – the most soluble form of calcium carbonate) that will readily dissolve should the seas continue to become more acidic. It is predicted that if atmospheric CO_2 levels continue to rise as expected, by 2050 conditions for warm water coral reefs will be marginal and extinctions of some species can be expected (Hoegh-Guldberg et al. 2007).

The outlook for cold water corals is expected to be equally bleak. Deep, cold ocean waters are naturally under saturated with carbonate ions causing the shells of most calcifying organisms to dissolve in acidified waters unless specifically adapted. Surface waters are oversaturated with

Time series records of atmospheric CO_2 at Mauna Loa and surface pH and pCO_2 at Pacific Ocean station Aloha. Source after Feely *et al.*, *Oceanography* (2009).

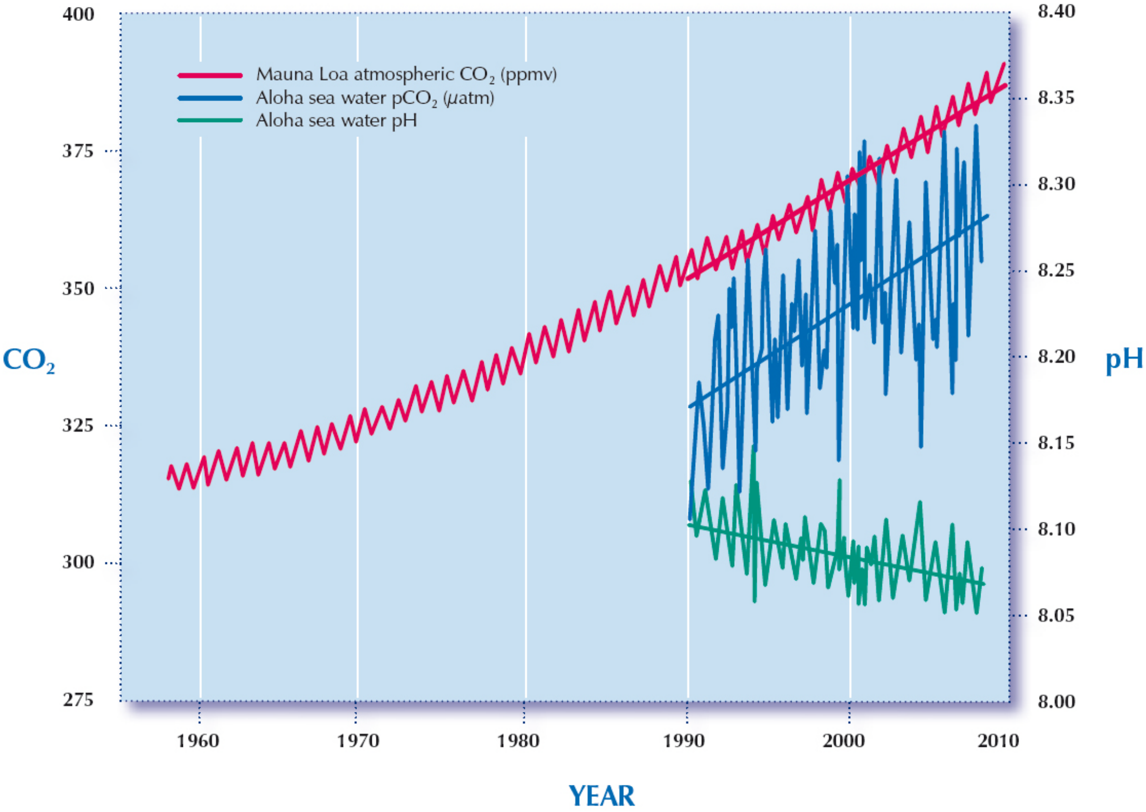

Figure 4. Time series records of atmospheric CO_2 , in parts per million volume, ppmv (red), at Mauna Loa and surface pH (green) and pCO_2 (uatm, blue) at Pacific Ocean station ALOH. Redrawn by Ian Kirkwood from the original by Feely et al. 2009.

carbonate ions and do not readily dissolve shells. The saturation horizon is the level below which calcium carbonate minerals undergo dissolution (Feely et al. 2002). Those organisms that can survive below the saturation horizon do so due to special mechanisms to protect their calcium carbonate from dissolving. As ocean acidification causes this horizon to rise vertically in the water column so more and more calcifying organisms will be exposed to under saturated water and thus vulnerable to dissolution of their shells and skeletons. Up to 70% of deep-sea corals are located in areas that are predicted to be under saturated by 2100 (Guinotte et al. 2006). This means their growth and structural strength would be severely impacted.

Seagrasses, by contrast, use CO_2 for photosynthesis rather than bicarbonate like most marine microalgae, so certain species of sea grass could benefit, leading to ecological regime shifts (Doney et al. 2009). Sea grass also benefits from the removal of calcified epiphytes in high CO_2 areas, which clears leaves for photosynthesis. However, even if sea grass itself does well, the ecosystem does not. Recent ocean-based studies revealed that the infauna and associated biodiversity in the sea grass beds was reduced in the high CO_2 areas of the vents studied (Martin et al. 2008).

OCEAN ACIDIFICATION, FISHERIES AND AQUACULTURE

Ocean acidification is not only progressively decreasing the ability of many organisms to build their shells, but will also progressively affect ecosystems' structure and function (Hall-Spencer et al. 2008 and Doney et al. 2012). Ocean acidification could trigger a chain reaction of impacts through the marine food web, beginning with larval fish and shellfish, which are particularly vulnerable. This will affect the multibillion-dollar fishing industry and threaten the food security of many of the world's poorest populations.

Corrosive waters can dissolve clam shells, eat away at corals and kill fish eggs. Scientists experimenting with pteropods from the Gulf of Alaska, tiny marine snails that swim in the open ocean, exposed these organisms to slightly acidified seawater in a laboratory. The snails' protective shells were seen to dissolve (Shirayama and Thornton, 2005). Given that these organisms constitute up to 60 percent of the food for Alaska's juvenile pink salmon, the salmon fishery could be at risk if the salmon are unable to switch to another food source, such as copepods. Similar creatures support many of the major fish species in Alaska's North Pacific, which in turn supports the billion-dollar Seattle-based industry that provides half the United States' catch of fish (Laffoley & Baxter, 2009).

In 2007, the shellfish industry along the north western coastline of the United States caught a glimpse of a phenomenon that could become more frequent as ocean acidification progresses. The combined effects of strong upwelling and acidification were seen to accelerate the movement of corrosive "acidified" water originating from the deep ocean onto the continental shelf. This type of occurrence impacts shallower marine habitats and species closer to the coast. Alongside this discovery, between 2007 and 2008, there was a 70 – 80% loss of production in the main farms supporting the $111 million/year oyster industry in the US Pacific Northwest region (NMFS statistics) as oyster larvae failed to survive. Oyster larvae are particularly susceptible to ocean acidification as their early shells are made from an easily eroded form of calcium carbonate. By 2010, however, farms were back up near peak production by closely monitoring the pH of seawater piped into farms to dodge episodes of 'bad water' (i.e. acidified seawater) and working overtime to produce larvae in 'good water' periods. These short-term actions form the first part of a three-stage approach from the industry to tackling this problem. In the medium term, work will need to focus on cultivating more resilient brood stock, while the longer-term objective must be to promote policies to reduce emissions and strengthen research and monitoring.

Mollusks alone accounted for $748 million (19 percent) of 2007 US domestic landing revenues (NMFS statistics). Fishery losses due to ocean acidification would drive job losses in affiliated industries through economic linkages that are currently difficult to quantify. It is clear, however, that secondary economic losses following decreased fishery harvests would be concentrated in specific regions, many of which have less economic resilience for enduring losses of fishing revenues.

Some hope for the aquaculture industry may lie in selective breeding and the monitoring and management of the seawater piped into farms. Recent research on selective breeding was able to demonstrate that the aquaculture populations of oyster that had been specifically bred to maximize growth rates were more resistant to ocean acidification than were the wild populations. Moreover, there is some evidence that aquaculture populations may actually show some adaptive tolerance to ocean acidification (Parker et al. 2011). Although oyster larvae are particularly sensitive to ocean acidification, recent results show that the biological responses of calcifying biota to acidification will be species-specific, meaning that the biological responses will be much more variable and complex than thought previously. In experimental aquaria under different pCO_2 levels, Eastern oyster (*C. Virginica*) showed significant decrease in growth (16%) and calcification (42%) when pre-industrial and end of 21st century pCO_2 treatments were compared, while Suminoe oyster (*Crassostrea ariakensis*) showed no change to either growth or calcification (Miller et al., 2009). Other recent research provides hints for future improvement in the monitoring and management of seawater use in the aquaculture industry. The study on the biocalcification in the Eastern oyster in relation to long-term trends in Chesapeake Bay pH (Eastern coastline of the United States) has shown that estuarine waters are more inclined to acidification as they are less buffered than marine waters and subject to additional acid sources from natural and anthropogenic origins (Walbusser et al. 2011). Moreover, Walbusser et al. demonstrated that biocalcification is not only significantly declining, with a reduction of ~0.5 pH, but that the decrease in biocalcification is mitigated with higher temperature and salinity.

Lobsters (and crustaceans in general) have a different type of shell and a different mechanism for growing their shells from mollusks and corals. Lobster shells are exoskeletons containing a large proportion of chitin along with calcium carbonate minerals, and they are shed periodically instead of added to continuously. When preparing to molt, lobsters are thought to remove a lot of the minerals from old shells and preserve them in their bodies to deposit into the new skeleton later. In spite of these differences in growth mechanisms compared to mollusks and corals, a recent review of the physiological and ecological responses of crustaceans to ocean acidification reveals a negative effect on growth rate and molting frequency in marine crustacean species, but little effect on egg production (Whiteley 2011). The sensitivity of marine crustaceans to ocean acidification is known to be dependent on the iono- and osmoregulation abilities of each species. The species most at risk are living in low-energy environments with low metabolic rates and low routine levels of activity, such as the deep sea and polar environment. They are particularly vulnerable because they have limited physiological capacities to adapt to environmental change (e.g. low buffering capacities). By contrast, crustaceans that currently inhabit fluctuating environments, such as estuaries and shallow coastal regions, are more likely to be tolerant of ocean acidification. Without more study on the long-term (months) exposure to pCO_2 levels expected by 2100 and 2300 on representatives from all marine crustacean classes, it is presently unclear whether this difference in growth mechanism will affect how lobsters respond to ocean acidification. Without more study, it is premature to say that crustaceans will be ‘safe’ from ocean acidification (Whiteley 2011).

It has been often reported that ocean acidification will put at risk marine species that synthesize calcareous exoskeletons or shells, but it is unclear how marine fishes will be affected by this process of acidification. During recent decades, negligible effects of high CO_2 exposure on juvenile and adult fish have been extensively documented. However, less is known about the sensitivity of fish during their early life stage. As larval survival is known to be the bottleneck to recruitment (Frommel et al. 2011), as well as the bottleneck to population replenishment and sustainability (Munday et al. 2010), it is crucial to better understand this concern. The latest research on the effects and consequences of ocean acidification on fish, have focused on growth, behavior and survival during the early life stage of fish. Growth rates and average survival of different commercial fish (such as the Atlantic cod, Frommel et al. 2011; Moran et al. 2010) and non-commercial fish (such as *Menidia beryllina*, Baumann et al. 2012) exposed to high CO_2 levels during their early life stage are drastically reduced. Moreover CO_2 levels expected in the world’s oceans later this century have shown detrimental behavioral effects on larvae by impairing olfactory discrimination and homing ability of marine fishes (Munday et al. 2009). When larvae were reared at high pCO_2 levels (>700ppm), their behavioral responses to olfactory cues were completely disturbed. Above this level of exposure, many individuals weren’t able to locate suitable adult habitat and to avoid predators. In some case, larvae became even attracted by the smell of predators (Munday et al. 2010). Frommel et al. reported in 2011 that exposure to CO_2 resulted in severe to lethal tissue damage increasing with CO_2 concentration in Atlantic cod larvae. In addition, impacts of relevant CO_2 concentrations on larval fish have been found to include detrimental effects on otolith size (Checkley et al. 2009). These are bony structure used by fish to sense orientation and acceleration. Asymmetry between otoliths can be harmful for individuals. According to the current knowledge, the effect of ocean acidification has clearly the potential to enhance natural mortality of commercial and non-commercial fishes and could therefore affect populations of already heavily-exploited fish stocks with potentially profound consequences for marine biodiversity.

The growth and level of photosynthesis of certain marine phytoplankton and plant species may increase with higher CO_2 levels, but this is by no means a general rule (Rost & Riebesell, 2004). For others, higher CO_2 and rising acidity may have either negative or neutral effects on their physiology (Giordano et al. 2005). Therefore, particular marine plants will be ’winners’, while others will be ‘losers’ and some may show no signs of change. Some of the experiments that have been done so far suggest that the likely new dominant phytoplankton and plant species in the future acidified ocean may be less able to support the productive, diverse food chains that humankind presently relies on to support healthy ocean ecosystems and fisheries resources.

Finally, it is important to note that warmer more acidic ocean conditions appear to be favoring smaller phytoplankton species such as dinoflagellates. However, this could increase the occurrence of harmful algal blooms (HABs), many of which are dinoflagellate-based.

OCEAN ACIDIFICATION AND SOCIOECONOMICS

If ocean acidification continues to proceed as many predict, many commercial interests, from commercial and recreational fishing to tourism, as well as ecosystem services such as the protection of shorelines by coral reefs, are likely to be harmed. More difficult to quantify are the cultural and lifestyle changes that communities will have to make to adapt to changing marine ecosystems. Ocean acidification is therefore not just a problem for corals and other marine life. It has the potential to change the way humans feed themselves, earn their livings, run their communities, and live their lives (WHOI 2010).

To gauge the likely socioeconomic impact of ocean acidification, it is important to look at the potential scenarios for species of economic importance. In the United States, for example, in 2007, from a total of approximately $4 billion in the first-sale revenues of U.S. commercial fisheries, approximately half was made up of direct sales of calcifiers (WHOI 2010). However, the remaining revenues, which come from predator-type fish species, would also be under threat as they are also dependent on calcifiers as a food source. It is expected that fisheries that depend heavily on mollusks are likely to be hit harder.

Coral reefs are hugely important sources of food and revenue for hundreds of millions of people. Through a combination of warming and acidification, many regions of the ocean will become inhospitable to coral reefs thus affecting food security, tourism, shoreline protection and biodiversity. Coral reefs provide habitat for many species of fish that are the main source of protein for local people. If corals disappear so would the fish that depend on them. Economic valuations of ecosystems need to be treated with caution but one attempt at calculating the worldwide value of shoreline protection by coral reefs was estimated at $9 billion a year (Cooley et al. 2009). For island nations, when coral reef tourism is added into the equation, the potential losses in income and employment become staggering.

Due to the complex interactions between marine species in the food web, it is not easy to predict which species could be potential winners in the changing marine environment. Some animals will tolerate higher acidity; some may even thrive on it; but there will probably be fewer species overall (Widdicombe and Spicer 2008), and the mix of species in a given locale will almost certainly change (Cooley 2010). A typical example of an observed shift, from a thriving community dominated by mussels and calcifying algae to one dominated by seagrasses, non-calcifying algae, and invertebrate species that do not make shells, will not alleviate concerns about future food security.

The potential shifts in species composition in the oceans would force humankind to change its economic and cultural systems. An example of the type of adaptation that is likely to be required is a shift from single-species to ecosystem fisheries management strategies—for example, to focus less exclusively on managing one species, such as cod, and instead consider the many factors, such as weather, human-caused pressures, and interactions with other organisms, that affect the ecosystem where the cod live. Aquaculture will also need to adapt by, for example, cultivating species that are more resistant to ocean acidification or by adjusting the pH of ocean water brought into their facilities, if economically feasible. The varying regional impacts of ocean acidification will call for different regional approaches adapted to local conditions (Cooley 2010).

OCEAN ACIDIFICATION AND GOVERNANCE

Ocean acidification is no longer a theoretical marine chemistry issue. The trend towards more acidic ocean conditions is already being measured in the open ocean, and this has been recorded with increasing accuracy in recent years through the Hawaii Ocean Time-series and the Bermuda Atlantic Time-series. As acidity and sea temperature increase, the ocean's ability to absorb atmospheric CO_2 will be reduced, thus exacerbating the rate of climate change. Since 2005, major scientific studies have started around the world and although there are many unanswered questions, there is considerable scientific consensus that ocean acidification is both real and is a major threat to our way of life. The Inter-Academy Panel on International Issues Statement on Ocean Acidification for example states that 'Even with stabilization of atmospheric CO_2 at 450ppmv (parts per million by volume), ocean acidification will have profound impacts on many marine systems. Large and rapid reductions of global CO_2 emissions are needed globally by at least 50 percent by 2050.' (Inter Academy Panel 2009)

Geo-engineering proposals focused on decreasing input of solar radiation into the atmosphere will have no impact on atmospheric CO_2 and will therefore not alleviate ocean acidification, whilst other geo-engineering solutions remain the subject of considerable doubt as to their potential contribution towards mitigating ocean acidification. There are therefore no currently-available solutions proven to remediate ocean acidification once it has occurred and the only course may be to let nature take its course. This will inevitably involve a long-term recovery process and it could take upwards of 10,000 years for the ocean to restore its carbonate equilibrium, with biological recovery taking perhaps even longer (Orr et al. 2005).

Specific measures to reduce ocean acidification in the future will necessarily involve action to reduce the rapid increase in anthropogenic atmospheric CO_2; however, due to the time lag between CO_2 emissions and their eventual partial absorption into the oceans, acidity in the oceans will continue to increase for some years to come. Early and substantial emission cuts are therefore of paramount importance if ocean acidification is to be properly addressed in the long run.

Ocean acidification may be best dealt with under the auspices of the United Nations Framework Convention on Climate Change (Harrould-Kolieb & Herr 2011). As ocean acidification is not a symptom of climate change, but rather a concurrent problem, new opportunities have to be sought which can address climate change and ocean acidification at the same time.

Remaining action, beyond the use of technologies that may potentially remove CO_2 from the atmosphere, will likely be centered on garnering information and knowledge on the likely effects of ocean acidification and adapting human activities so that additional stress on already-weakened ecosystems can be avoided. Reducing pressures on food fish stocks and developing environmentally-sustainable aquaculture using species resistant to lower pH, may provide the best chance to maintain food security (UNEP 2010).

Furthermore, identification of ocean regions that demonstrate higher resilience to ocean acidification may, through sound management and protection, create future refuges (different types of marine protected areas) that have a greater ability to resist change and to recover quickly. The severity of ocean acidification impacts is likely to depend, in part, on the interaction of acidification with other environmental stresses, such as rising ocean temperatures, over-fishing and land-based sources of pollution (Laffoley & Baxter 2010). In practical terms, the focus should therefore be on action to reduce, or where possible prevent or eliminate, at the regional or local scale, these environmental stressors, such as over-fishing, pollution and eutrophication. Alongside this, there is a need to strengthen ocean resilience by allowing the ocean space and time for recovery from human impacts, through designating and ensuring protection of an effective network of marine reserves and by implementing effective marine planning (Laffoley & Baxter, 2011). Affording adequate protection to marine areas of ecological importance, as part of a representative network, will be a key part of maintaining ecosystem resilience and offering a starting point for future ocean recovery. International coordination of integrated ocean acidification research will also be essential to support future ocean recovery.

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It is inevitable
that the 7,021,213,399 people
who inhabit the planet as of June 20, 2012
will leave their mark.

It is still possible to make individual and collective choices that will result in restoring and sustainably developing the ocean's full potential for present and future generations.

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