RESPONDING TO CLIMATE CHANGE IN MOZAMBIQUE

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THEME 8
Oceanic Climate Change Under Continued Global Warming

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EXECUTIVE SUMMARY

In the report presented here, the possible impacts of global warming on the mean climate of the Mozambique Exclusive Economic Zone are investigated. Global warming is a process by which the atmosphere of the earth is rapidly increasing in temperature due to the systematic increases in man-made greenhouse gas pollutants. Greenhouse gases such as carbon dioxide and water vapour function to absorb outgoing solar radiation before it can escape to space. Since the 1960's the amount of greenhouse gases in the planet's atmosphere has escalated to the highest levels in about four hundred thousand years, leading to accelerated global warming. The rapid warming of the earth's atmosphere is, in turn, causing other earth systems, such as landmasses and oceans, to systematically change regarding their mean climate, a process that is projected to continue throughout the present century and possibly for centuries to come.

The objectives of the study were;

1) firstly, to present the current state of scientific knowledge on the oceanographic climatology of the Mozambique Channel,

2) secondly, to present trends in climate for the Southern Hemisphere atmosphere and oceans, which influence the climate variability in the Mozambique Channel,

3) thirdly, to construct ocean climate change scenarios for the Mozambique EEZ based on readily available global and regional ocean model simulated trends, and
4) lastly, to discuss the possible impacts of large scale oceanic climate change on the present-day oceanographic climatology of the Mozambique Channel.

The climatology (the long-term average) of the general circulation, temperature and salinity, sea-level, and chlorophyll concentration are presented for the South Western Indian Ocean, in which the Mozambique EEZ is nested. This climatology was then used as a reference to compare ocean climate change scenarios against.

In order to calculate how the climatology of the South Western Indian Ocean may change with increased global warming, the trends in climate for atmospheric and ocean circulation were reviewed for the Southern Hemisphere. The published scientific information on this topic elucidates an increasing southward shift of the high-latitude westerly winds and a concomitant intensification of the Antarctic Circumpolar Current due to anthropogenic induced global warming. The impact of the Southern Ocean climate change has been shown to be channelled northward to the southern Indian, Atlantic and Pacific oceans. Based on the combined information pool of Indian Ocean mean climatology and Southern Hemisphere climate trends, it was possible to construct two ocean climate change scenarios for the Mozambique Channel region.

Presented in this report are the "warmer water" and "cooler water" ocean climate change scenarios for the Mozambique EEZ. The "warmer water" ocean climate change scenario is based on the assumptions that, a) the South Equatorial Current (SEC), the main supply source of upper layer oceanic water to the Mozambique Channel, will not change its present-day mean position and that, b) the SEC is warming in correlation with global warming trends. Under such assumptions it can be shown that increasingly warmer upper layer waters will be supplied to the Mozambique Channel via the northern East Madagascar Current leading to a "warmer water" ocean climate compared to the present-day climatology. Such a "warmer water" ocean climate change scenario will induce higher temperatures and lower salinities, sea-level rise and decreases in chlorophyll densities for the greater Mozambique Channel, including the Mozambique EEZ. It is assumed that under the "warmer water" ocean climate change scenario the mean circulation pattern will remain the same as today, with the northern East Madagascar Current still being the main supply of warm upper layer oceanic waters to the channel.

The "cooler water" ocean climate change scenario is based on the assumptions that, a) the South Equatorial Current will migrate southwards from its present-day mean position and that, b) the South Equatorial Current's warm equatorial waters will be diverted away from the northern Mozambique Channel inlet, supplying all its waters via south of Madagascar to the Agulhas Current instead. Under such assumptions it can be shown that as the warm equatorial waters are diverted away from the Mozambique Channel, Central Water underlying the upper tropical watermasses, may upwell to the ocean's surface, forming an extension of the South Indian Tropical Gyre to the north. The South Indian Tropical Gyre, characterise by "cooler" oceanic waters and higher primary production could then supply "cooler" waters to the Mozambique Channel due to the southwards advection of its waters through the northern inlet. This process in essence could induce a "cooler water" ocean climate change scenario compared to the "warmer water" ocean climate scenario, for the region. The "cooler water" ocean climate change scenario will entail a change in mean circulation, cooler sea temperatures, sea-level fall, and an increase in chlorophyll densities compared to the "warmer water" scenario.

Presently, the lack of regional coupled atmosphere-ocean climate models for the Mozambique Channel is an impediment for projecting future climate trends with high accuracy. It is thus beyond the scope of this report to give specifics on how the present-day rate of change available from published information sources may change in the future. Climate Change Science is still a developing science, however, the planetary climate changes projected by this science is to date the best estimates by which decisions can be made today for a better tomorrow under the continued threat of global warming.

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CHAPTER 1: Oceanic Climate Change study for the Mozambique Exclusive Economic Zone: Rationale and methodology.

1.1 INTRODUCTION

Global warming of the earths' atmosphere and oceans is a phenomenon that have been documented to be real (IPCC, 2007). It is projected that the impacts of earth system warming will manifest within the earth's biogeosphere within the 21st century, making information about projected changes to natural environments critical for present day policy making. In the report presented here the impacts of global warming on the mean climate of the oceanic environment of the Republic of Mozambique is investigated to establish how the oceanic domain will manifest in the future. Such futuristic visions are only possible with sophisticated technologies currently available for scientific inquiry, such as global coupled atmosphere-ocean-ice climate models, which allow earth scientists to probe into possible future climates of the earth.

Projecting future climates of earths' atmosphere and oceans under increased emissions of greenhouse gasses (e. g., carbon dioxide, CO_2), the cause of global warming, is a relatively new science. Currently mostly global scale climate model projections are available, which give indications of how the global earth system will respond to rapidly increasing atmospheric and oceanic temperatures. In most cases these global climate model projections are the only information available for policy and decision makers associated with governments of the global community.

Computational restrictions currently prevent the application of global climate models at spatial resolutions high enough to resolve regional topographical features such as regional mountain ranges, and or ocean floor ridges and mounts, all of which are important inclusions to correctly simulate on regional space and time scales. Also, circulation features with small spatial scales (< 100 m in diameter) such as oceanic vortices, and continental shelf circulation patterns are in most cases not resolved due to limited computer space and time. The consequence of such a lack of resolution is that the climate change projected by global climate models to be due to global warming will be under- and over-estimated on regional scales, potentially leading to incorrect climate change adaptation and mitigation strategies.

In order to overcome this lack of regional resolution, scientists are downscaling large global climate model results using higher resolution regional climate models. This scientific practice is, however, computationally and financially expensive and requires high densities of regional specific field data, both to inform and validate regional scale climate models. Downscaling to higher resolution regional climate models may, therefore, not be readily accessible to developing countries in the Southern Hemisphere, where oceanic field data are sparse, and where computational and human capacities and research funds to do such high-tech scientific work are rare. Yet, it is here in the developing world where this type of climate change information will be needed the most.

In the present study regional climate projections were generated by using published scientific results from global climate models. Although global climate models do not resolve regional specific change trends, they do afford regional specific boundary conditions, into which regional specific climate models can be nested. The latter allows for environmental parameterization within which future ocean climates can be scientifically conceptualized for the Mozambique oceanic environment.

It should be noted that the information presented in this report is aimed at decision makers, and is not a scientific treatise. It is recognized that communication between decision/policy makers and the scientists who create the foundation upon which these environmental decisions are based, is of critical importance, even more so when the two groupings communicate in languages that use different symbols and terminology. In order to overcome this impediment, the scientific information presented in the present report was extracted from high quality peer-reviewed scientific journals and rewritten in nomenclature that is readily accessible for decision makers who may not necessary have the scientific background to read contemporary scientific literature. The information presented in the report is complementary to Intergovernmental Panel on Climate Change's (IPCC) 4th assessment report, i. e., the information presented here builds upon the information presented by the IPCC, by giving higher resolution climate change information specific to the region of interest.

In essence, the author sought to produce a glimpse into plausible future climates of the Mozambique oceanic environment, relying on limited research funds, limited data resources and limited scientific information, to answer the key questions posed by the present study, and to derive the most plausible future oceanic climate change scenarios for the Mozambique oceanic waters.

1.2 AIM AND KEY QUESTIONS

The aim of the present literature and data analyses is to present the current state of scientific knowledge on the climatology of the oceanic environment of Mozambique and to project according to readily available global ocean climate model results how the present-day ocean climatology may change as the Earth warms up.

In order to achieve the above aim the following key questions are addressed in the analysis:

1) What are the present day characteristics of the broad oceanic climate, its variability, and scenarios of future climate change for the South Western Indian Ocean and specifically the Mozambique oceanic environment?
2) What will be the effects of enhanced anthropogenic forcing on ocean dynamics?
3) What will be the effects of enhanced anthropogenic forcing on the temperature and salinity, sea-level, and oceanic productivity climatology of the Mozambique Channel?

1.3 STUDY AREA

The study focused on the oceanic waters of Mozambique's Exclusive Economic Zone (EEZ) which covers 508 092 km^2 of the western Mozambique Channel (fig. 1.1). The Mozambique Channel is located in the south western Indian Ocean between 12°South and 26°South latitude and 33°East and 40°East longitude.

The continental shelf of the Mozambique EEZ covers about 70 000 km^2, which is the marine environment normally shallower than 200 m in depth from the ocean's surface to the bottom (fig. 1.1). The continental shelf region presents a unique marine ecosystem which supports importance fisheries. The broadest and most important continental shelves of the Mozambique EEZ are the Sofala Bank and Delagoa Bight (fig. 1.1).

Although, the focus study area is contained within the Mozambique EEZ, the oceanography of the larger south Indian Ocean has been incorporated into the study, since the oceanic influences and perturbation important for climate considerations of the Mozambique EEZ are generated within this larger ocean basin. Also, oceanographic information from the Southern Ocean and the equatorial Pacific Ocean have also been factored into the analysis, since changes in these far-a-field ocean basins impact on the climate of the Mozambican oceanic environment.

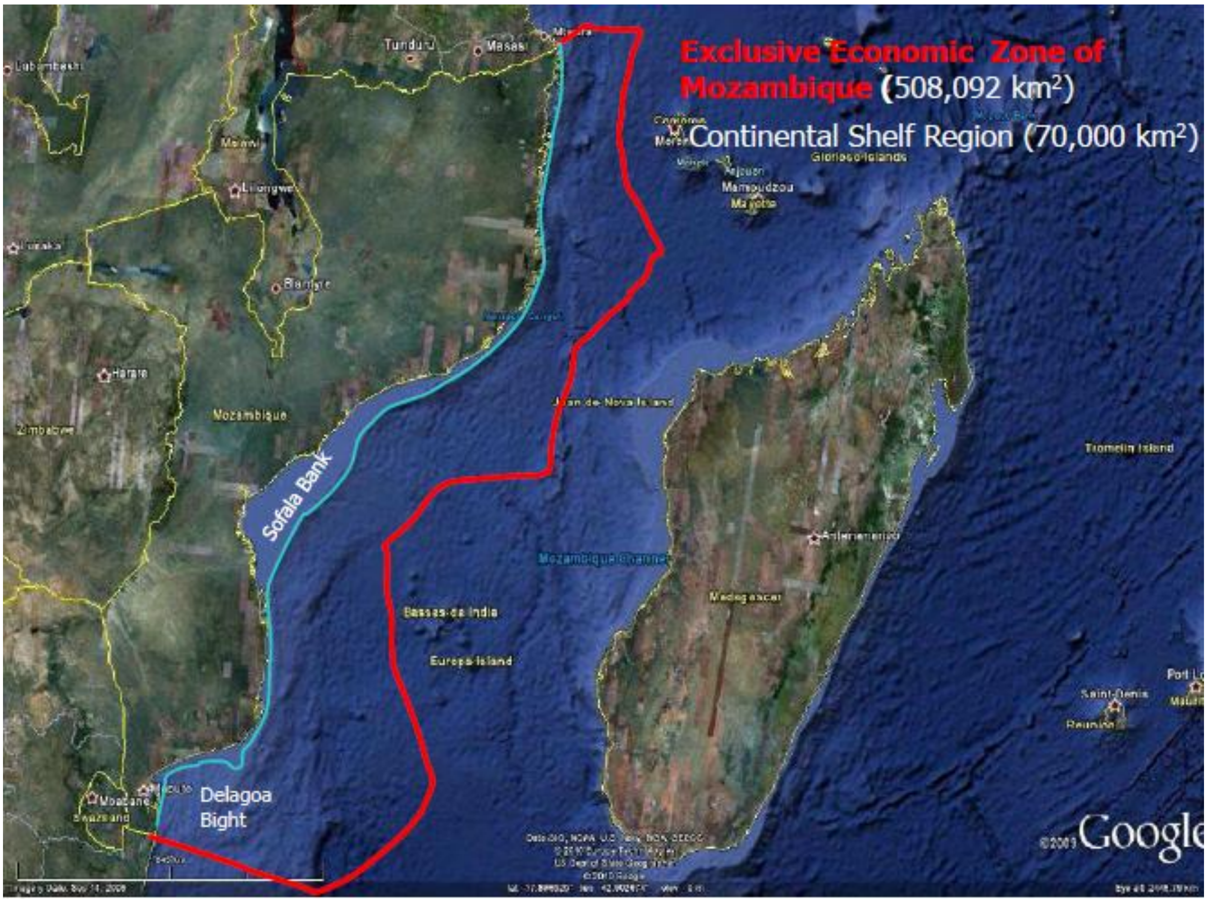

Figure 1.1. A Google Earth map of the study area which covers the Mozambique Channel and the oceanic region around Madagascar.

The region from the coast of Mozambique to the red line boundary represents the oceanic waters of Mozambique (Exclusive Economic Zone) which covers 508 092 km^2. The region between the coast and the thin blue line is the continental shelf of Mozambique covering 70 000 km^2. The two broadest continental shelf regions of the Delagoa Bight and the Sofala Bank are indicated.

1.4 METHODOLOGY

The scientific method used to create plausible future ocean climate change scenarios for the Mozambique EEZ, was as follows:

1) Firstly, the present day ocean climatology for the Mozambique Channel was established by way of a literature analysis of published peer-reviewed scientific information available on this subject. The tacit ocean climatology for the South Western Indian Ocean, which includes the Mozambique ocean environment, was used as a departure point, or a scientific foundation, on which future ocean climate change scenarios were build.
2) Secondly, the projected impacts of global warming on the Southern Hemisphere oceans were established, using published peer-reviewed atmosphere-ocean climate model results. The published scientific information on this topic elucidates an increasing southward shift of the high-latitude westerly winds and a concomitant intensification of the Antarctic Circumpolar Current due to anthropogenic induced global warming, which is systematically changing the climatology of Southern Hemisphere oceans and atmosphere. Thus, in order, to determine how the present-day ocean climatology of the South Western Indian Ocean will change due to global warming, Southern Hemisphere oceanic and atmospheric observed trends in climate and future projections were included in the pool of scientific information which was used to derive future oceanic climate change scenarios for the Mozambique ocean environment.
3) Thirdly, global climate change model projections were used to obtain regional scenarios of change over the area of interest. Global models do not provide high resolution information for near-coastal marine environments, like the Mozambique oceanic waters. They do, however, provide boundary conditions for the region, e. g. for the South West Indian Ocean, which can be used to establish higher resolution change and departures from the present day ocean climatology for the region under investigation.
4) Finally, future oceanic climate change scenarios were constructed by, a) scientific deduction, b) working strictly within the limits of the data and information gathered in steps 1, 2, and 3 above, and c) using the established physics and biogeochemistry of the medium under investigation, i. e., the ocean.

1.5 LAYOUT OF REPORT

The chapters that follow are arranged systematically so to illustrate the scientific process that was followed to arrive at futuristic scenarios of the ocean state of the Mozambican oceanic waters, as described in the methodology.

In Chapter Two, the mean climatology of oceanic parameters important to characterize the present state of the ocean environment of Mozambique is presented. In Chapter Three, contemporary scientific information is presented on the impact of global warming on the mean climate of the Southern, Pacific and Indian Oceans. This information was then used to derive qualitative future oceanic climate change scenarios from for the region of interest. In Chapter Four, the "warmer water" ocean climate change scenario for the Mozambique EEZ is presented and in Chapter Five the "cooler water" ocean climate change scenario is presented. In Chapters Six and Seven the possible impacts of the "warmer water" and "cooler water" ocean climate change scenarios are respectively discussed for the Mozambique EEZ. In Chapter Eight, oceanic climate change monitoring is discussed for the Mozambique EEZ.

CHAPTER 2: The oceanographic climatology of the Mozambique Channel

2.1 INTRODUCTION

The ocean's climate is determined by averaging oceanic parameters collected over long periods of time, usually extending over 50 years or more. These oceanic parameters may include the velocity and direction of oceanic water flow, temperature, salinity, sea-surface height, and chlorophyll (proxy for phytoplankton density).

In this chapter the contemporary oceanic climatology for the Mozambique Channel is presented as a departure point for discussing future oceanic climate change for this ocean environment. The information presented here is taken from peered-reviewed scientific journal publications that span the period of the last 30 years.

2.2 GENERAL CLIMATOLOGY

2.2.1 General circulation

2.2.1.1 Mozambique Channel and the Mozambique EEZ

The portrayal of the general circulation within the Mozambique Channel before the beginning of the 21th century is markedly different from what is now tacitly accepted to be the mean circulation of this oceanic region.

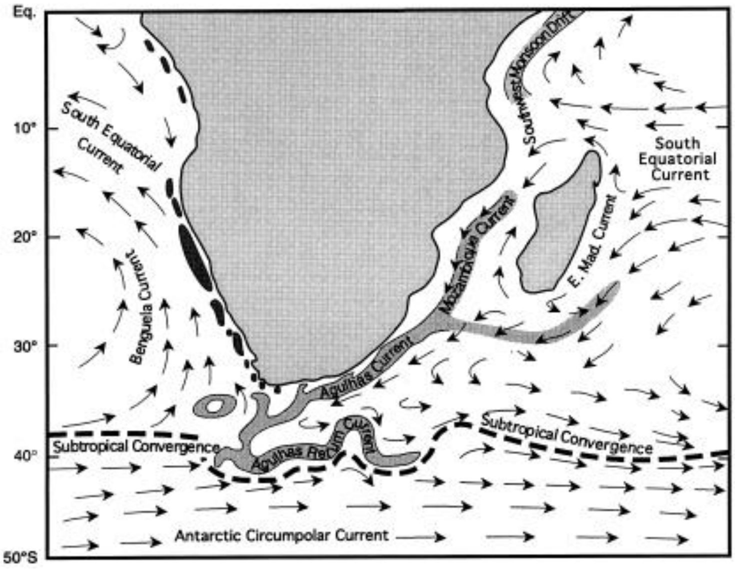

Figure 2.1. The illustration of the main general circulation features around Southern Africa (after Lutjeharms et al. 2001).

Hydrographic data collected within the Mozambique Channel first suggested the continuously southward flow of the Mozambique Current (fig. 2.1). This current supposedly transported warm saline oceanic waters southwards, close to the coast of Mozambique. The current mainly contained equatorial waters and subtropical waters, which in turn supplied the Agulhas Current along the east coast of South Africa (fig. 2.1).

This portrayal of the general circulation of the Mozambique Channel was first challenged by a numerical general circulation model, which offered a drastically different picture of the flow (fig. 2.2). Biastoch and Krauβ (1999) was the first to suggest that instead of a continuous Mozambique Current physics demanded the formation of anti-cyclonic (anti-clockwise rotating) vortices, also known as anti-cyclonic Mozambique Channel Eddies (MCEs) at the narrowest part of the channel (fig. 2.2). This numerical hypothesis was confirmed by hydrographic instrumentation that was moored to the ocean bottom along the narrows of the Mozambique Channel and also with satellite remote sensing data (de Ruijter *et al.* 2002; Ridderinkhof & de Ruijter 2003; Schouten *et al.* 2003).

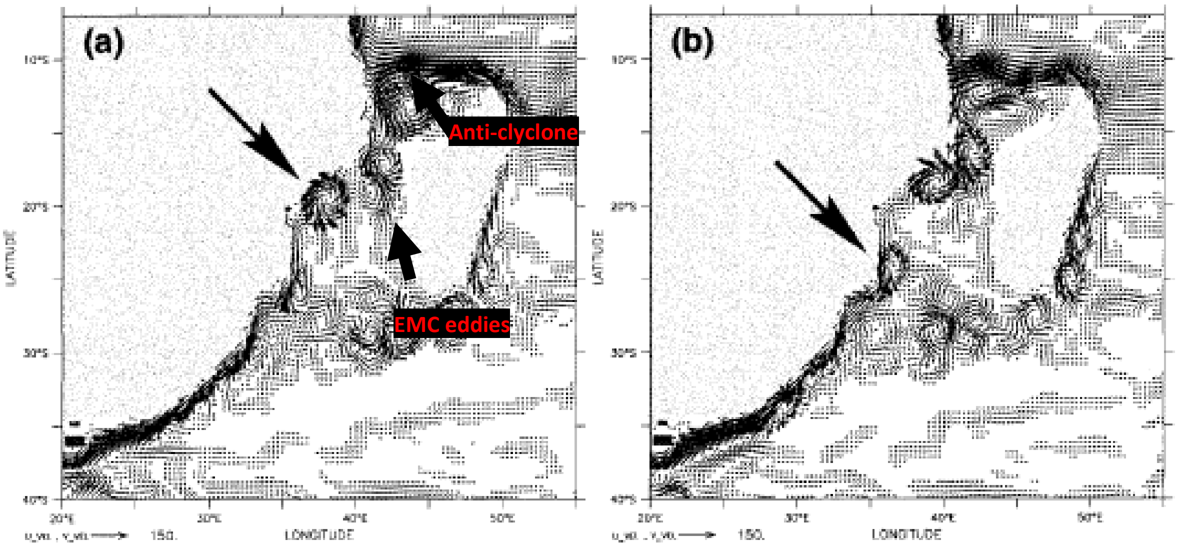

Figure 2.2. Modelled velocity vectors in 41-m depth of water for the South Western Indian Ocean (after Biastoch and Krauß, 1999).

The black arrow indicates the movement of a Mozambique Channel Eddy from north to south closed to the coast of Mozambique. The anticyclone trapped in the northern Mozambique Channel is indicated, as well as the smaller East Madagascar Current (EMC) eddies south of Madagascar.

It was shown that these MCEs are formed at the narrowest part of the Mozambique Channel, and are then advected southwards close to the Mozambique coast (de Ruijter *et al.* 2002). MCEs are formed on average four times per year with diameters of about 200 km, with a mean southwards translations speed of 4.5 $cm.s^{-1}$ (de Ruijter *et al.*, 2005). Hydrographic data show that these eddies reach from the surface of the ocean to the bottom, and carry intermediate, thermocline and warm tropical surface waters at a transport rate of 15 Sv (= 10^6 $m^3.s^{-1}$) (de Ruijter *et al.*, 2005).

The circulation along the coastline north of the narrowest part of the Mozambique Channel, from the Tanzanian-Mozambican boundary to the narrows, are characterized by a continuous coastal current, with speeds in the order of 0.5 $m.s^{-1}$ (de Ruijter *et al.*, 2005). This coastal current is the

western boundary current of an anti-cyclonic ocean gyre which is trapped between the Comores to the north, and the narrowest part of the Mozambique Channel (fig. 2.2).
A deep flow along the western boundary below 2000m was recently determined (de Ruijter *et al*., 2002; van Aken *et al*., 2004, Ridderinkhof and de Ruijter, 2003) to be an extension of the Agulhas Undercurrent (Beal and Bryden, 1997), transporting Antarctic Intermediate Water and North Atlantic Deep Water equatorwards close to the continental slope of the western Mozambique Channel.

Besides MCEs, other prominent eddies are also formed at the southern apex of Madagascar (fig. 2.2), where they are pinched off at the termination of the East Madagascar Current (EMC) retroflection. These EMC eddies are smaller in diameter than MCEs, and are propelled towards the African continent, where some of them interact with the circulation of the Delagoa Bight. The coastal region from the Delagoa Bight towards Ponto D'Ouro (at the Mozambican-South African border), is a region where the Mozambique Channel Eddies and the East Madagascar Current Eddies congregate and mix to form the source water of the Agulhas Current (fig. 2.3). This region is a region of high eddy kinetic energy (i. e., a region of high mixing and turbulence) (fig. 2.3) (Lutjeharms, 2006).

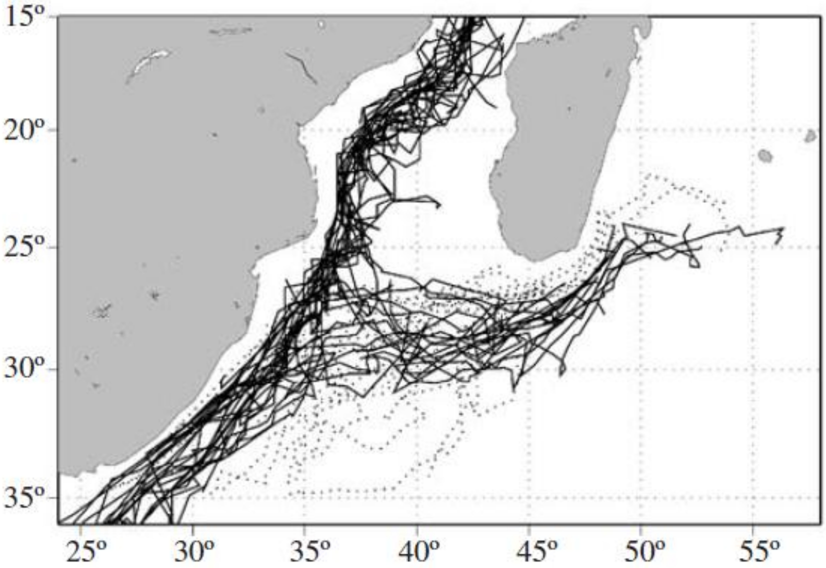

Figure 2.3. Combined tracts of eddies derived from sea-surface height satellite remote sensing data.
The image shows the regions along the coast of Mozambique and the south-eastern coast of Madagascar where eddies dominate (thin black lines). These two pathways of eddy translations meet in the region centred at about 35^oE *and* 27^oS*, where eddies interact and mix to form the source water of the Agulhas Current. (Lutjeharms, 2006).*

2.2.1.2 The Sofala Banks and Delagoa Bight

The Sofala Bank general circulation is largely influenced by off-shore circulation features, e. g., by southward passing anti-cyclonic MCEs, which interact with the water column of the Sofala Bank (Lutjeharms, 2006; Tew-kai and Marsac, 2008; Weimerskirch *et al*., 2004). The MCEs have peripheral currents in the order of 3 knots (fig. 2.4a), which have been shown to force chlorophyll-enriched waters from the Sofala Banks off-shore into deep waters, supporting a deep-sea fish-enriched ecosystem, off the continental shelf of the Sofala Banks (Weimerskirch *et al*., 2004; Tew-kai and Marsac, 2008).

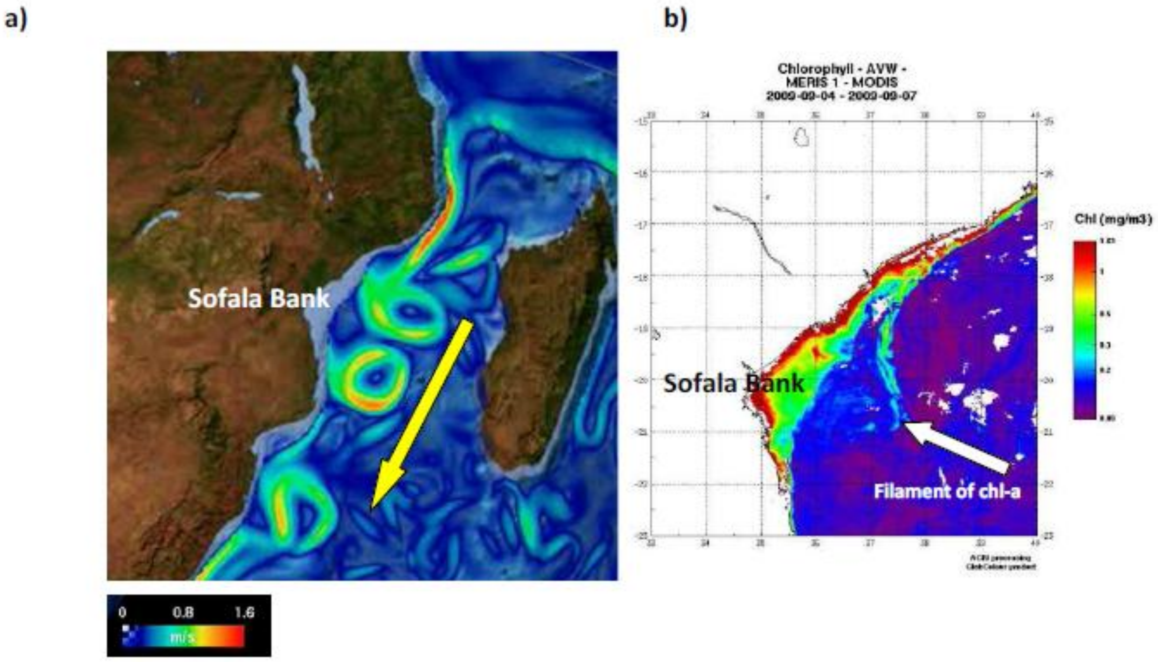

Figure 2.4. a) Numerical model output (Biastoch, IFM-GEOMAR, University of Kiel, Germany) showing the MCEs along the coast of Mozambique with peripheral currents in the order of 1.6 m.s^{-1} (3 knots). b) A satellite image of chlorophyll-a (chl-a) concentration (mg.m^{-3}) at the surface along the Sofala Bank. The white arrow indicates to a filament of chl-a waters which was forced off the continental shelf by a Mozambique Channel Eddies into deep waters.

The Delagoa Bight (25°S) south of Sofala Bank forms the second most prominent continental shelf region of Mozambique. The Delagoa Bight circulation has been described as a quasi-permanent cyclonic eddy (fig. 2.5) (Lutjeharms and Jorge da Silva, 1988). This eddy is responsible for the upwards displacement of cold, nutrient-rich water to the surface due to its cyclonic movement.

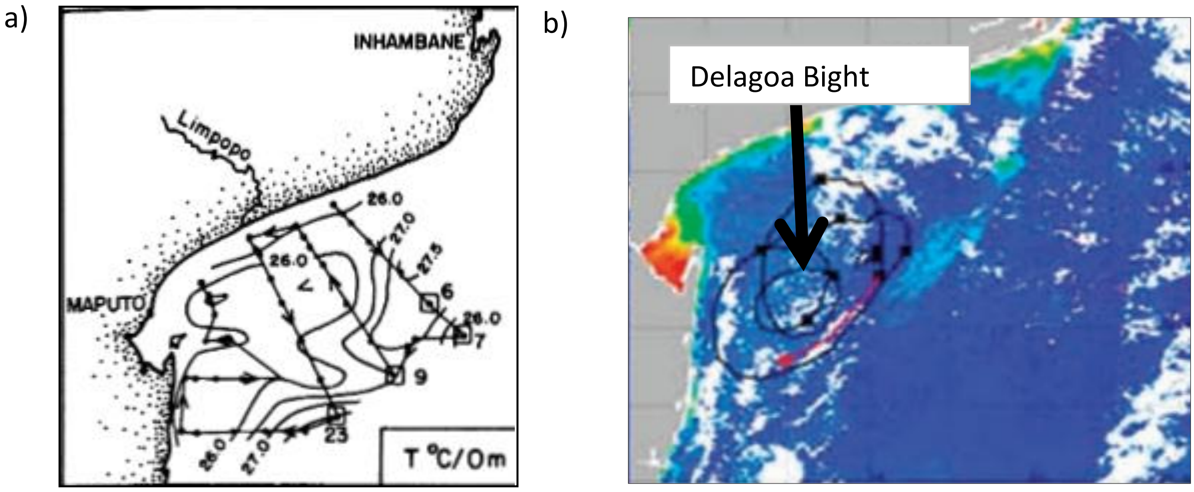

Figure 2.5. a) Temperature data collected at the surface of the Delagoa Bight showing the quasi-permanent clockwise circulation within the bight (after Lutjeharms and Jorge da Silva, 1988); b) Ocean colour image of the Delagoa Bight region overlaid with the tracks of a surface drifter showing the cyclonic water movement within the Delagoa Bight (after Lamont et al., 2010).

2.2.2 Temperature and salinity climatology

2.2.2.1 Mozambique Channel and the Mozambique EEZ

The watermasses (oceanic waters with distinct temperature and salinity properties found at distinct depths within the water column) within the Mozambique Channel are shown in figure 2.6. The temperature and salinity data were derived from relatively old hydrographic data, but homogenously covers a greater part of the channel than more modern data (Lutjeharms, 2006).

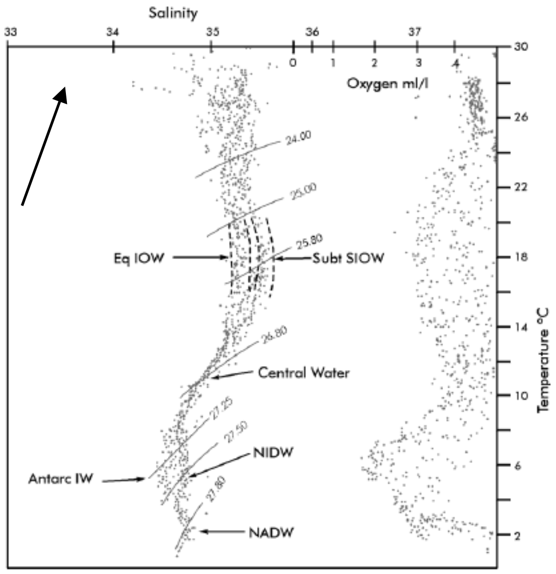

Figure 2.6. The temperature-salinity and temperature-oxygen characteristics of the water masses in the Mozambique Channel. Water masses presented in the T/S diagram are Equatorial Indian Ocean Water (Eq IOW) (also called Tropical Surface Water), Subtropical South Indian Ocean Water (Subt SIOW), Central Water, Antarctic Intermediate Water (Antarc IW), North Indian Deep Water (NIDW) and North Atlantic Deep Water (NADW). (taken from Lutjeharms, 2006).

Temperatures and salinity of watermasses found within the Mozambique Channel vary between 2°C to 30°C and between 34 to 36 salinity units, respectively (fig. 2.6). The upper part of the water column consists of warm Equatorial Surface Waters identified as relatively fresh water, due to high equatorial precipitation (Eq IOW, see fig. 2.6). Equatorial Surface Water is transported into the channel via the northern Mozambique Channel inlet, as an extension of the South Equatorial Current (Sætre and da Silva, 1984). Equatorial Indian Ocean Water (also called Tropical Surface Water) is found largely in the northern and central parts of the channel (Lutjeharms, 2006).

Subtropical South Indian Water (Subt SIOW, see fig. 2.6) occupies the upper 300m of the water column in the southern channel, while in the central channel it is partly covered by Tropical Surface Water (Sætre and da Silva, 1984). Subtropical South Indian Water is identified by a salinity maximum between 35.5 and 35.7 salinity units, with temperatures of around 16°C, at average depths of 200m (Schumann, 2005). Schumann (2005) suggests that the Subtropical Surface waters enter the Mozambique Channel mainly via the southern inlet of the channel. At the same temperature, Equatorial Indian Ocean Waters are also observable with lower salinities of between 35.1 and 35.3 (Lutjeharms, 1991).

Below the abovementioned surface waters, South Indian Ocean Central Water (CW) is found in a depth range of between 350m to about 600m (Schumann, 2005; Sætre and da Silva, 1984), with the deeper Central Water made up by contributions from Antarctic Intermediate Water (AAIW) and North Indian Deep Water (NIDW) (fig. 2.6).

Below the central waters are found intermediate and deep water masses. Antarctic and North Indian Intermediate Waters are found with temperatures as low as 5°C, and salinities that range from 34.5 to 35.0. Below these are found North Atlantic Deep Water (NADW) mainly transported into the region from the south via the Mozambique Undercurrent (Ridderinkhoff and de Ruijter, 2003).

2.2.2.2 The Sofala Bank and Delagoa Bight

The water masses of the broadest continental shelf regions of Sofala Bank and the Delagoa Bight are similar than for offshore water masses at the same depths (Lutjeharms, 2006). There are, however, exceptions when river run-off dilutes the continental shelf waters, creating distinct continental shelf water masses.

The Sofala Bank is a region of high river run-off which leads to severe dilution of the oceanic surface waters. The salinity of surface waters close to the Zambezi River mouth on the Sofala Bank may drop as low as 20 salinity units when water at the continental shelf edge is 35.4 (Lutjeharms, 2006) (fig. 2.7).

Freshwater can extend to a depth of 15 m directly off the Zambezi River mouth; and to 30 m off the Luala River mouth (fig. 2.7) (Lutjeharms, 2006). The high salinity values south of the city of Beira is due to marsh runoff (fig. 2.7) (Lutjharms, 2006).

The temperature/salinity characteristics of the Delagoa Bight during a dedicated hydrographic cruise of austral summer 1982 show temperature ranges of between 5 and 28°C and salinity values of between 34.5 and 35.6. (fig. 2.8).

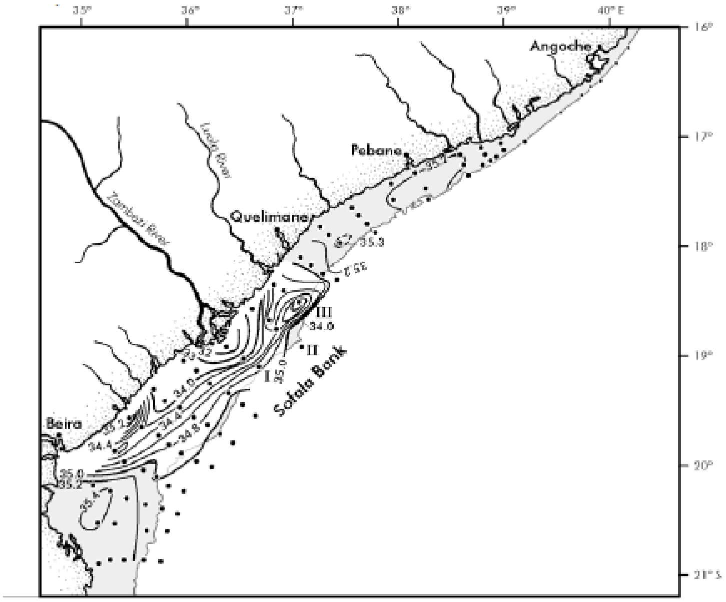

Figure 2.7. The surface salinity on the Sofala Bank based on a cruise of 1982 (Lutjeharms, 2006).

Water masses in the Delagoa Bight Eddy have temperature-salinity characteristics which suggest upwelling within the core of the eddy from depths of 900m, bringing nutrient-rich waters from below to the surface for primary production (Lutjeharms, 2006).

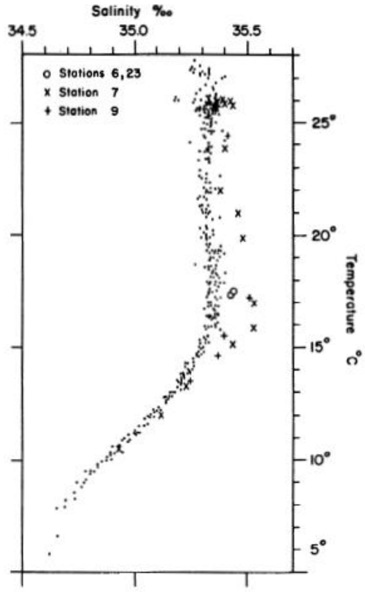

Figure 2.8. The temperature-salinity characteristics of the water masses in Delagoa Bight collected during a dedicated hydrographic cruise of austral summer 1982 (after Lutjeharms and da Silva, 1988).

2.2.3 Trends in the sea-surface height climatology

Sea-surface height climatology for the South West Indian Ocean averaged over a 48 year period, using both coastal tide gauges and sea-surface height data from satellite altimetry instruments, clearly show regions of sea-level rise and fall for the South Western Indian Ocean (fig. 2.9) (Church *et al.*, 2004). Sea-level fall is shown for the regions from the equator southwards to about the Tanzanian-Mozambican border, and from the narrowest part of the Mozambique Channel southwards to approximately the southern inlet of the channel (25^{o}S). In turn, sea-level rise is found for the east coast of South Africa, and for a small region between the Comores and the narrowest part of the Mozambique Channel (fig. 2.9). The numerical model results of Biastoch *et al*. (2009) show the same geospecific sea-level rise and fall patterns as described by Church *et al.*'s (2004) sea-level climatology of 48 years .

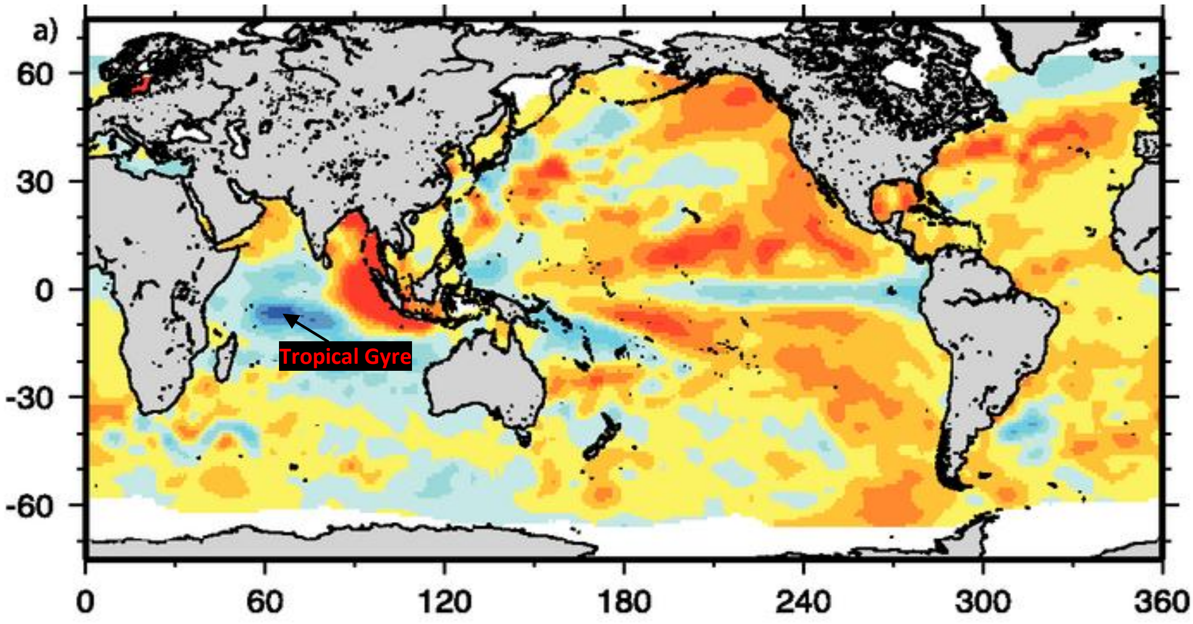

Figure 2.9. Geographic distribution of long-term linear trends in mean sea-level (mm.yr^{-1}) for 1955 to 2003 based on the past sea-level reconstruction with tide gauges and altimetry data (updated from Church et al., 2004).

Yellow to red represents sea-level rise of between 0 to 2 mm.yr^{-1} , and light blue to dark blue sea-level fall of between 0 to -2 mm.yr^{-1} (source IPCC, 2007).

A study by Han *et al*. (2010) that investigates both the observed and numerical model results of sea-level trends in the Indian Ocean further suggest spatially coherent patters of sea-surface height trends. Han *et al*. (2010) presents 6 spatial maps of sea-level trends (figure 2.10) derived from different numerical and assimilated models (details of the forcing and assumptions for these models will be discussed in the following chapter). Although, all the model results show sea-level fall for the Tanzanian coast and for the off-equatorial Indian Ocean region (South Indian Tropical Gyre) and sea-level rise for the South African east coast, the results for the Mozambican coast is less conclusive (fig. 2.10). Three experiments, i. e., HYCOM, SODA total and SODA dyn indicate a sea-level rise of between 3-18cm/century, whereas the other three experiments, i. e., POP dyn, LM MR, and LM EXP, show sea-level fall of -3 to -15cm/century (fig. 2.10). It should be noted that these model results are indicative of sea-level trends modelled for the period 1961 to 2008.

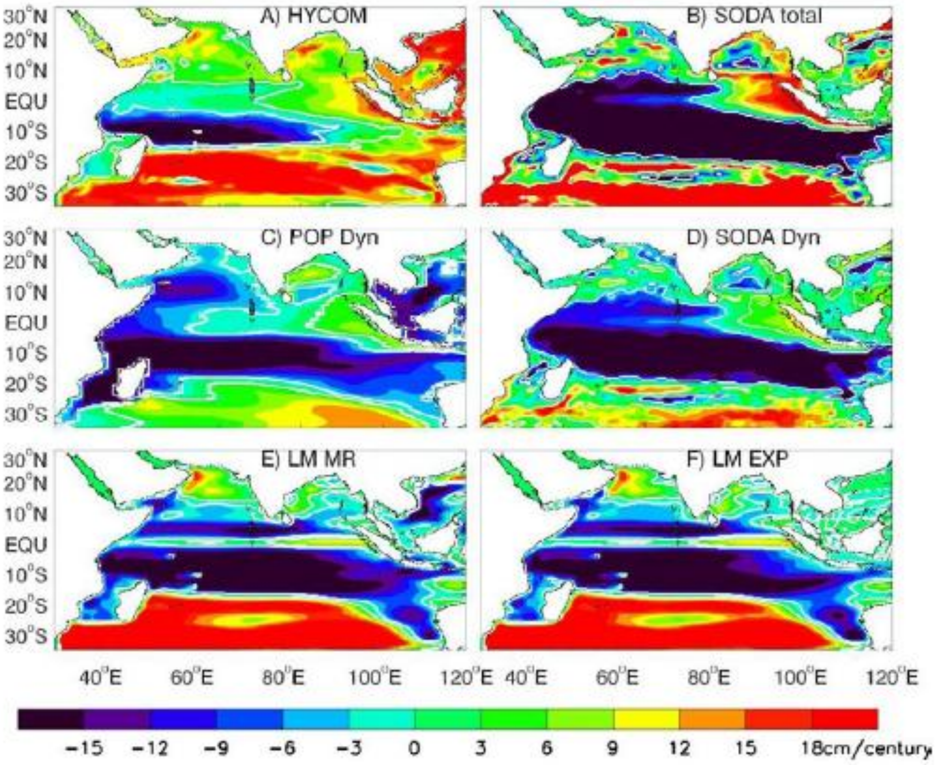

Figure 2.10. Annual mean Sea-level Anomalies (cm/century) spatial plots from six ocean model experiments for 1961 to 2008 for the Indian Ocean (after Han et al., 2010).

A) Hybrid Coordinate Ocean Model (HYCOM), B) Simple Ocean Data Assimilation Model (SODA total), C) Parallel Ocean Program Model (POP), D) Simple Ocean Data Assimilation Model (SODA dynamic), E) and F) Linear Model (LM Main Run) and (LM Experimental Run). Each of the models is discussed in some detail in chapter 3 of this report.

2.2.4 Chlorophyll climatology

2.2.4.1 Mozambique Channel and the Mozambique EEZ

An 8 year climatology of chlorophyll-a concentration obtained from the SeaWIFS (Sea-viewing Wide Field-of-view Sensor) satellite instrument is presented by Omta *et al*. (2009) for two oceanic regions, which includes most of the Mozambique Channel and the Mozambique EEZ (see fig. 2.11). Maxima in chlorophyll concentrations were obtained for austral winter and minima in austral spring and summer. The annual mean and amplitudes associated with the observed seasonal cycle are 0.3 and 0.1 mg Chl/m^3, respectively (Omta *et al*., 2009). For box I values range from 0.2 to 0.4 mg Chl/m^3, and for box II values are between 0.1 and 0.25 mg Chl/m^3 (fig. 2.11). Phytoplankton blooms with chlorophyll values ranging between 0.3 and 0.7 mg.m^{-3} appear in localized patches in winter within the Mozambique Channel, compared to the very low chlorophyll concentrations (up to 0.2 mg.m^{-3}) that characterizes most of the area in spring (Omta *et al*., 2009).

Furthermore, a statistical study concerning the coupling between sea-surface chlorophyll concentrations and the physical ocean dynamics within the Mozambique Channel show high co-variance (Tew-kai and Marsac, 2008). The latter study shows strong seasonality in the chlorophyll concentration and the partitioning of the Mozambique Channel into distinct chlorophyll regions. The northern and southern Mozambique Channel chlorophyll concentrations are shown to be driven by seasonality, whereas the central section is shown to be driven by mechanisms without seasonality. In the central Mozambique Channel mesocale dynamics driven by cyclonic and anti-cyclonic eddies enhance phytoplankton production (Tew-kai and Marsac, 2008; Weimerskirch *et al.*, 2004). Tew-kai and Marsac (2008) identify three mechanisms for dynamical enhancement of surface chlorophyll concentration for the central Mozambique Channel, 1) cyclonic upliftment of nutrient-rich deep water within the core of the cylonic eddies, 2) eddy-eddy interaction which generate strong frontal mixing favourable for phytoplankton production, and 3) offshore advection of chlorophyll-enriched waters from the Sofala Banks by passing southward propagating eddies.

2.2.4.2 The Sofala Bank and Delagoa Bight

In contrast to the greater Mozambique Channel, the regions where the continental shelf is the broadest and shallowest, i. e., the Sofala Bank and the Delagoa Bight, exhibit the highest chlorophyll concentrations within the Mozambique oceanic waters. A study by Boge (2006), who used a 8 year time series of SeaWIFS ocean colour data, reveals these areas of high chlorophyll concentrations along the coast of Mozambique (fig. 2.12).

The area between 15°S to 22°S, which covers the Sofala Bank region, and the area between 24°S and 26°S, which covers most of the Delagoa Bight, can be clearly recognized as continental shelf regions with high levels of chlorophyll compared to the adjacent open ocean (fig. 2.12). Values greater than 1 mg Chl/m^3, not surpassing 10 mg Chl/m^3, are found here on the average.

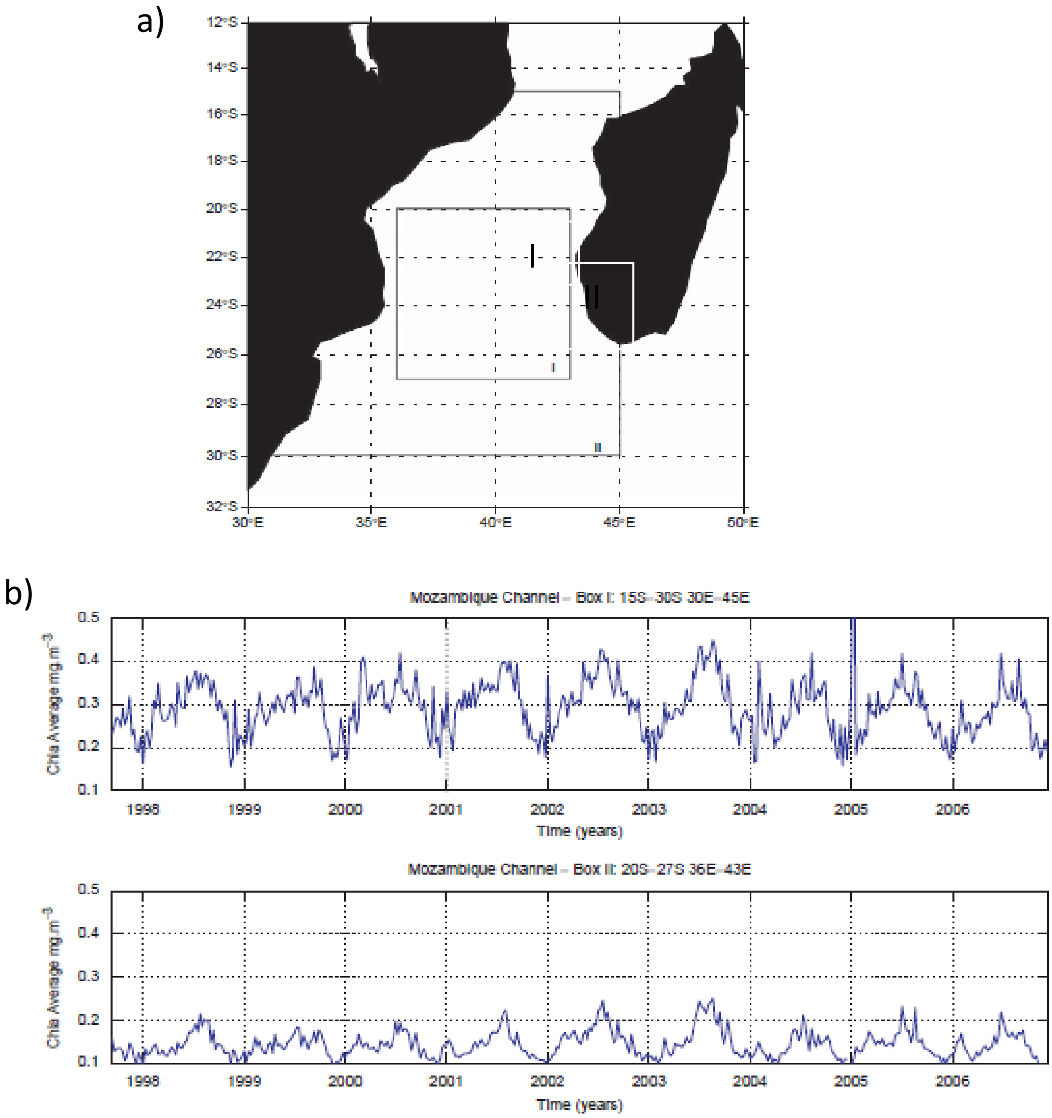

Figure 2.11. a) The two regions over which average chlorophyll concentrations were calculated. b) Seasonal variability in chlorophyll concentrations in mg.m^{-3} for box I and II for the period 1998 to 2006 (Omta et al., 2009)

According to Boge (2006) the high chlorophyll concentrations along the Sofala Bank are mainly due to high nutrient loads being injected by the various rivers running out onto the bank. Tew-kai and Marsac (2008) also suggest phytoplankton enhancement due to offshore advection of nutrient-rich continental shelf waters, which need to be replaced by deeper nutrient-rich oceanic waters from the edge of the shelf. The Delagoa Bight’s high chlorophyll concentrations are mainly derived from upwelled water from as deep as 900m, bringing deep cold nutrient-rich water continuously to the surface as the Delagoa Bight cyclonic eddy gyrates within this semi-enclosed embayment (Lutjeharms and Jorge da Silva, 1988).

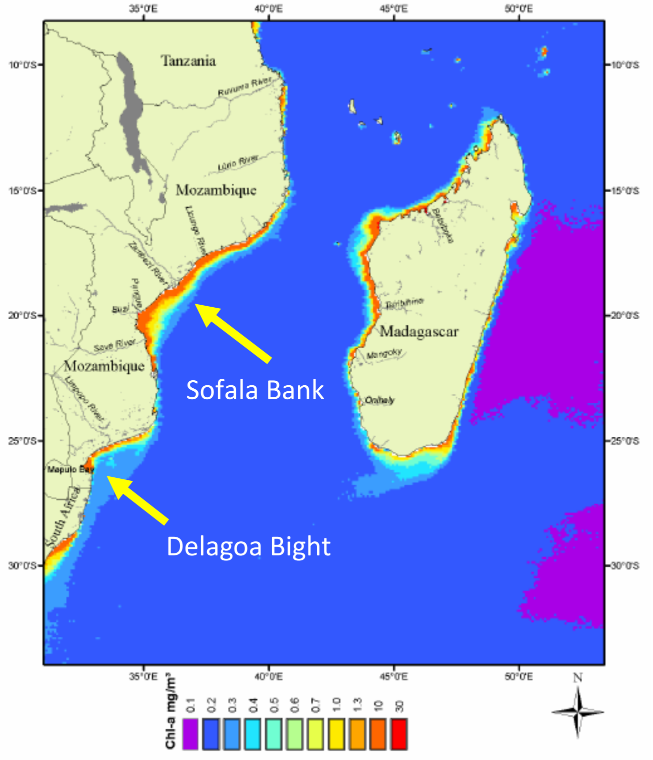

Figure 2.12. The image shows the chlorophyll concentration average based on SeaWIFS data from September 1997 to September 2005 with a 9 km resolution for the Mozambique Channel (after Boge, 2006). The two continental shelf areas with high chlorophyll concentrations are indicated for the Sofala Bank and the Delagoa Bight.

CHAPTER 3: Future Oceanic Climate Change trends for the Southern Hemisphere.

3.1 INTRODUCTION

The global ocean circulation is formed via various complex interlinking water pathways and mechanisms that connect each of the major ocean basins, i. e., the Pacific, Atlantic, Indian, and Southern Ocean basins, together as one. These inter-connections channel climatic, as well as shorter time-scale changes from one ocean region of the global ocean to the other. It is in this context that it is necessary to present the current trends and projected future change of the global ocean, in order to arrive at the oceanic changes plausible for the Mozambique oceanic waters.

Moreover, in order to create plausible oceanic climate change scenarios for the Mozambique Channel region, inter-annual climate modes, e. g., El Niño and La Niña modes, and Indian Ocean Dipole modes, that have been shown to impact on the oceanic climate of the South Western Indian Ocean, must be taken into consideration. This includes observed and projected changes to these oceanic modes under continued anthropogenic induced global warming.

The chapter concludes with a brief description of three seminal peer-reviewed scientific publications that were used extensively to construct ocean climate change scenarios for the Mozambique EEZ. These three papers present the most comprehensive scientific results on current oceanic climate trends and projections of future change for the region of interest, as they take into consideration climate influences from the greater oceanic domain bordering the Mozambique Channel, such as the Indo-Pacific tele-connections through the Indonesian Throughflow and the Tasman Outflow, the Indo-Pacific Atmospheric Bridge, the Indo-Pacific Warm Pool, as well as the Southern Ocean climatic trends.

3.2 PROJECTED CHANGES TO THE SOUTHERN HEMISPHERE OCEANS CLIMATOLOGY DUE TO ANTHROPOGENIC INDUCED GLOBAL WARMING.

The world's ocean was responsible for absorbing approximately 84% of the total increase of heat content of the Earth system for 1955–1998 (Levitus *et al*., 2005). As a result the global ocean's heat content has increased by 14.5 x 10^{22} J from 1955 to 1998 corresponding to a mean temperature increase of 0.037^{o}C (fig. 3.1) (Levitus *et al*., 2005). It is projected based on greenhouse gas emission estimates from the IPCC's 4th assessment report that the warming trend within the global ocean will continue during the 21st century.

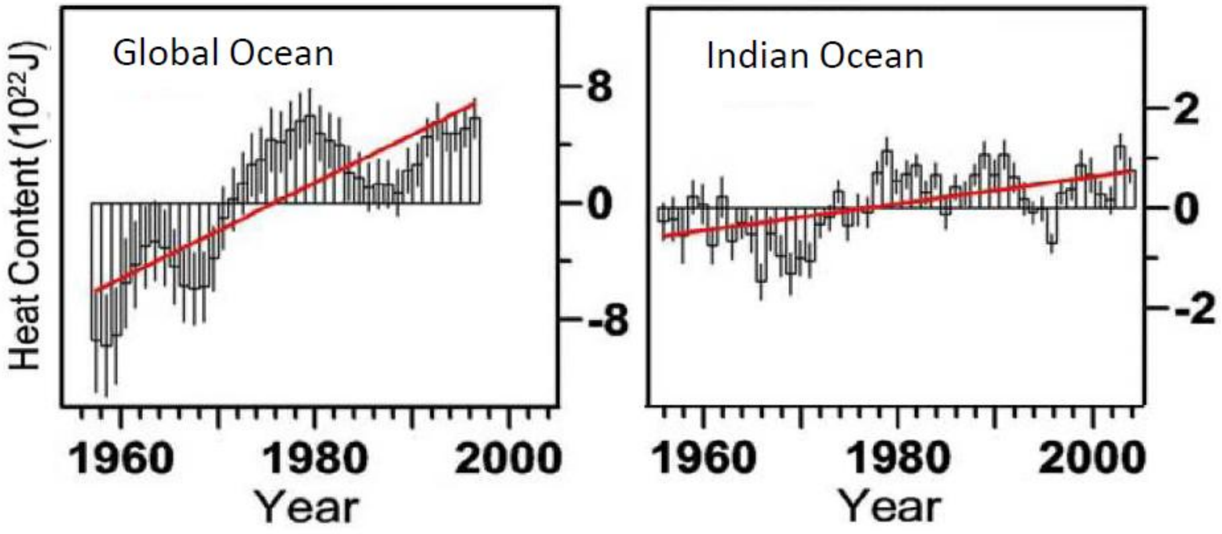

Figure 3.1. Time series of 5 year running composites for 1955 to 1998 ocean heat content for the upper 3000 m for the global and Indian Ocean. The linear trend is plotted as a red line. (after Levitus et al., 2005).

The Indian Ocean as a whole shows the same mean warming trend as for the global ocean and the other ocean basins (fig. 3.1; also see Levitus *et al*., 2005). However, the warming of the Indian Ocean is not homogeneous, but rather exhibit geographically specific distributions of warming and cooling. The climatology of Levitus *et al*. (2005) clearly show that certain geographic region in the Indian Ocean exhibit rapid cooling trends at the ocean's surface and sub-surface, for example the south Indian Ocean tropical region between the Equator and 10°S (fig. 3.2). In contrast, the warming trend for the Indian Ocean is positive centred around 43°S and 23°S (fig. 3.2) (Levitus *et al*., 2005).

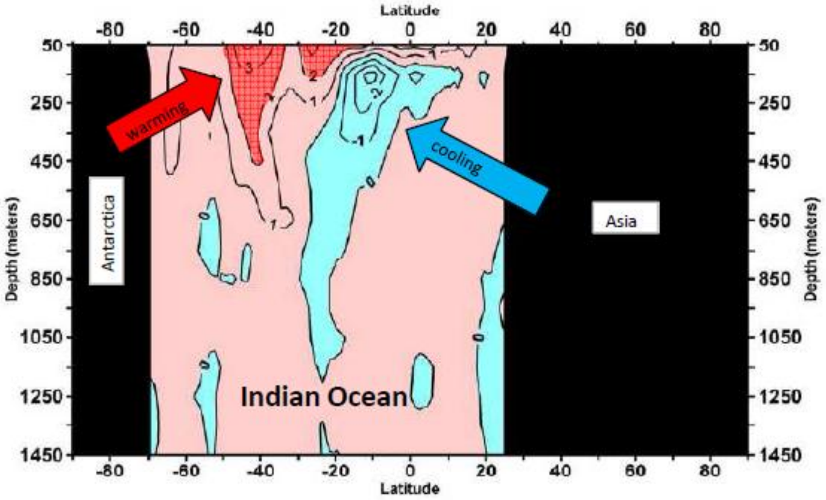

Figure 3.2. Linear trend of the zonally integrated heat content of the Indian Ocean for 100 m thick layers. Trend values are plotted at the midpoint of each 100 m layer. Contour intervals is 1 x 10^{18} J/year. (after Levitus et al., 2005).

The physical mechanisms triggering these warming and cooling trends in the Indian Ocean climatology can only be comprehended by evaluating observational oceanic and atmospheric data and numerical climate modelling results for the Southern Hemisphere (SH). The latter scientific information, which is discussed below, unambiguously links the changing Indian Ocean climatology to anthropogenic induced alterations to atmospheric climate and atmospheric processes of the Southern Hemisphere.

The main climate mode of the Southern Hemisphere is known as the Southern Annular Mode SAM an index of the pressure gradient measured between 40^{o}S and 56^{o}S. A high (positive) SAM index indicates an intensification of the high-latitude westerly winds and a lower (negative) SAM index indicates a relaxation of the westerly wind band over the Southern Ocean. SAM has been steadily increasing over the last 40 years due to anthropogenic induced global warming and ozone depletion over Antarctica (Cai, 2006; Roemmich, 2007; Toggweiler and Russel, 2008). Observational data and contemporary climate models show that the positive trend in SAM is associated with an intensification and southwards shift of the SH high-latitude westerlies (Toggweiler and Russel, 2008). The southward shift of the high-latitude westerlies has relocated itself directly above the planet's largest ocean current, the Antarctic Circumpolar Current (ACC) (Toggweiler and Russel, 2008). The intensification of the overlying westerlies has in turn intensified the ACC, due to direct momentum transfer from atmosphere to ocean (Toggweiler and Russel, 2008).

Furthermore, satellite, *in-situ* observations and climate model simulations all reveal an amalgamation of the Sub-tropical Gyres of the south Pacific, Indian and Atlantic Oceans (called the Southern Hemisphere Super Gyre) linked via inter-ocean outflows south of Australia and Africa (fig. 3.4) (Ridgway and Dunn, 2007; Speich *et al*., 2007).

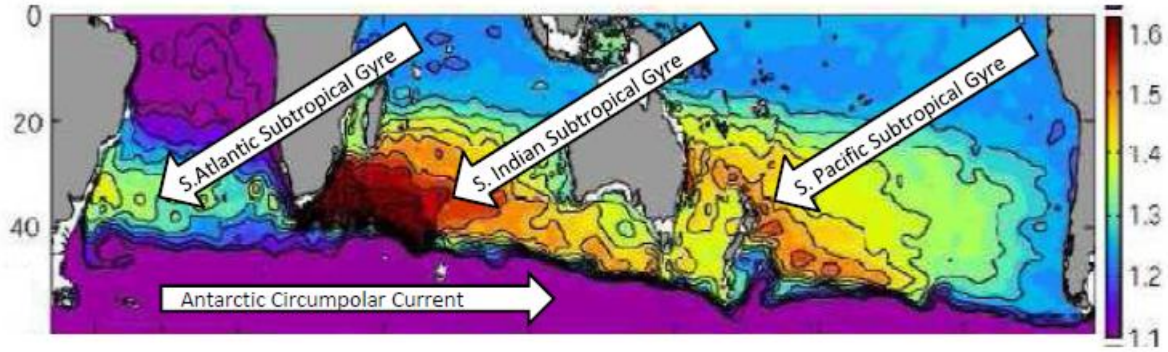

Figure 3.4. The mean steric height for the 0 to 400 m layer (contour interval 0.02 m), showing the Super Gyre connections between the Subtropical Gyres of the Atlantic, Indian and the Pacific Oceans.
The steric height is a measure of vertical expansion and contraction of the oceanic water column between the surface and a reference depth, in the above case, the 400m depth. Connections are via the Agulhas Retroflection and Tasman outflow, south of Africa and Australia, respectively. The southern boundary of the Super Gyre is in contact with the eastward flowing Antarctic Circumpolar Current of the Southern Ocean.
(after Ridgway and Dunn, 2007).

Since, the southern boundary of the Super Gyre is in contact with the eastward flowing ACC, the acceleration of the ACC due to anthropogenic induced global warming has been shown to have lead to an intensification and southwards shift of the Southern Hemisphere Sub-tropical Gyres over the last 40 years (Saenko *et al*., 2005).

The southward shift of the South Indian Sub-tropical Gyre is thus in part responsible for the warming along 43°S, as warm water transports to these region increases via a stronger Agulhas Current (Cai *et al*., 2007; Cai *et al*., 2010; Rouault *et al*., 2009). The southwards shift and intensification of the South Indian Sub-tropical Gyre is also responsible for the off-equatorial upwelling, due to intensification of the South Indian Tropical Gyre, with concurrent shoaling of the thermocline ridge north of Madagascar (Cai *et al*. 2007).

Contemporary global climate models based on present day atmospheric CO_2 levels and projected levels of increasing CO_2 levels, motivated by the IPCCs estimates of a 1% increase in CO_2 per year up to the year 2100, indicate that the above oceanic climate trend in the SH ocean circulation will continue (Saenko *et al*., 2005). The climate models elucidate the following;

1) A further intensification and southward shift of the high-latitude westerlies with an affiliated increase in the Antarctic Circumpolar Current transport,
2) A southwards migration and intensification of the Southern Hemisphere Sub-tropical gyre circulations;
3) A further intensification of the western boundary currents of the SH Sub-tropical Gyre systems – e. g., the Agulhas Current, East Australian Current and the Brazil Current, and
4) Further warming of the Southern Hemisphere oceans between 40 to 50°S, with increased off-equatorial subsurface upwelling and cooling between the Equator and 10°S.

3.3 LARGE-SCALE OCEANIC MODES IMPORTANT FOR OCEANIC CLIMATE IN THE MOZAMBIQUE CHANNEL

In order to understand the impacts of the important oceanic modes, e. g., La Niña, El Niño, and Indian Ocean Dipole, on the oceanic climate of the South West Indian Ocean it is necessary to first understand the general circulation of the Indian Ocean south of the Equator.

The most prominent circulation feature of the South Indian Ocean is the South Equatorial Current (SEC), which transport equatorial and subtropical waters from the eastern sector of the Indian Ocean into the South Western Indian Ocean (fig. 3.5). The South Equatorial Current flows from the eastern sector of the Indian Ocean basin towards the western sector between 15°S to 20°S (Schott *et al*., 2009). It is a broad and shallow current, and derives most of its water from the recirculation of water within the South Indian Subtropical Gyre (fig. 3.5). The second largest contribution is from the Pacific Ocean via the Indonesian passages known as the Indonesian Throughflow (ITF) (Speich *et al*., 2007; Ridgway and Dunn, 2007). The ITF decreases and increases in intensity with oceanic climate modes of El Niño and La Niña, respectively (Gordon, 2005). The third largest contribution is from south of Australia, which has been termed the Tasman outflow, which mainly contributes intermediate watermasses (Speich *et al*., 2007) (fig. 3.5).

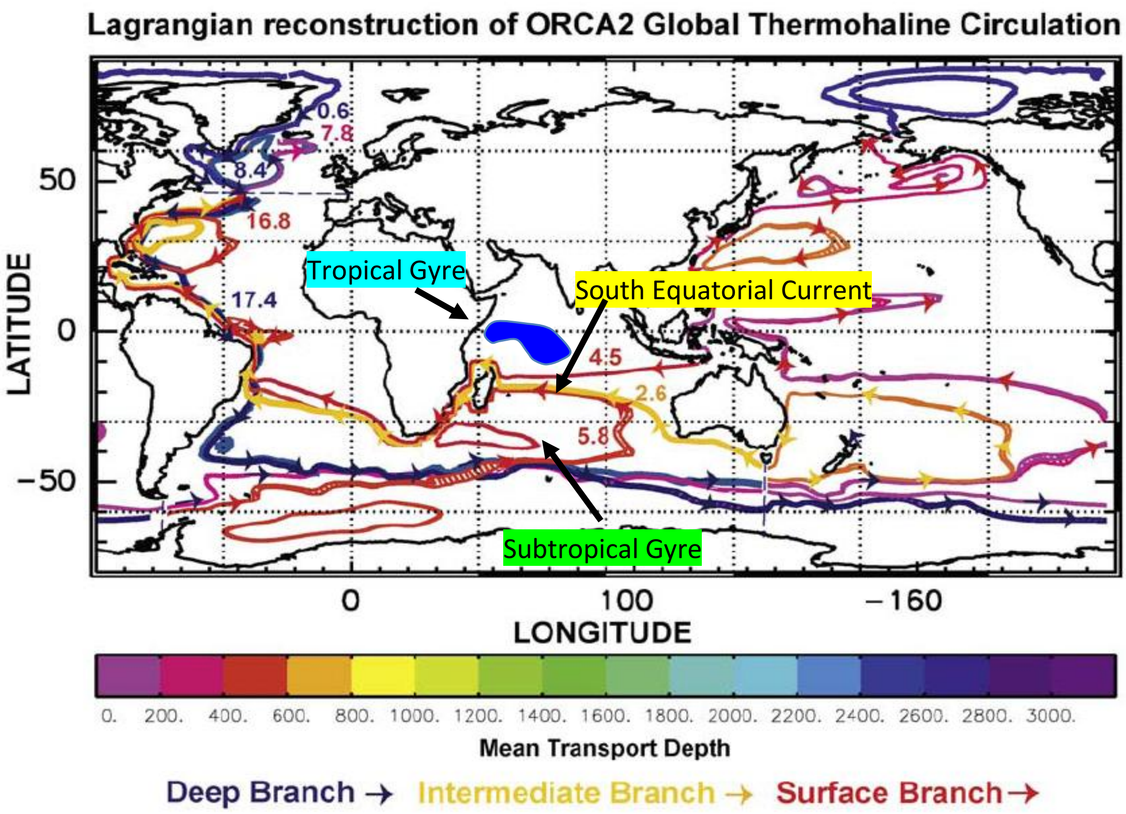

Figure 3.5. Lagrangian pathways of water parcels in a global model simulation of global oceanic water movement. (after Speich et al., 2007).
The South Equatorial Current, the South Indian Ocean Subtropical Gyre and the South Indian Ocean Tropical Gyre are indicated within the South Indian Ocean.

The SEC forms the northern peripheral current of South Indian Ocean Subtropical Gyre (fig. 3.5). The SEC flows zonally until it reaches the island of Madagascar, where it bifurcates into a northern and a southern branch (Schott *et al*., 2009). The northern branch (northern East Madagascar Current) rounds the northern tip of Madagascar, with part of it supplying upper watermasses to the Mozambique Channel. The southern branch forms the southern East Madagascar Current which terminates in a prominent retroflection south of the island, and spasmodically sheds anti-cyclonic vortices towards the African Coast (Siedler *et al*., 2009). The SEC is the main contributor of watermasses to the Mozambique Channel (Ridderinkhof *et al*., 2010).

The South Indian Ocean Tropical Gyre is found immediately north of the western SEC between 5^{o}S and 12^{o}S (fig. 3.5). It has been shown that the SEC intensity is positively correlated to the intensity of the Tropical Gyre, i. e., a stronger (weaker) SEC leads to a stronger (weaker) South Indian Tropical Gyre (Palastanga *et al*., 2006; Schott *et al*., 2009; Ridderinkhof *et al*., 2010). The interplay between the SEC and Tropical Gyre is critical for understanding the inter-annual oceanic climate variability within the western sector of the Indian Ocean (Schott *et al*., 2009) and the Mozambique Channel (Ridderinkhof *et al*., 2010). Moreover, it has been shown that the SEC is influenced by the flux variability through the Indonesian passages due to oceanic climate modes switches between El Niño and La Niña (Gordon, 2005; Schott *et al*., 2009), i. e., El Niño (La Niña) leads to decreased (increased) in the ITF, which in turn induces weaker (stronger) western SEC fluxes. Ridderinkhof *et al*. (2010) also indicated the teleconnection between Indian Ocean Dipole mode and the intensity of the SEC, which directly controls the amount of transport through the Mozambique Channel, i. e., +IOD (-IOD) creates weaker (stronger) western SEC flow. The latter studies all show that the oceanic climatic state of the Mozambique Channel is tightly coupled to large scale oceanic climate modes as far afield as the eastern Pacific Ocean.

The El Niño and La Niña modes are due to changes in the coupled atmosphere-ocean system over the tropical Pacific (Scott *et al*., 2009). Anomalous increases (decreases) in equatorial easterlies of the eastern equatorial Pacific Ocean leads to shallower (deeper) thermocline depths in this region causing La Niña (El Niño) events (Schott *et al*., 2009). These events impact on the ocean climate in all major ocean basins of the world's ocean.

In the Indian Ocean, El Niño creates negative SST anomalies over the Indonesian Island passages and the Eastern Equatorial Indian Ocean, creating atmospheric subsidence and anomalous easterlies here (Schott *et al*., 2009, and references therein). These conditions create in turn large planetary waves that propagate towards the South Western Indian Ocean. The downwelling planetary waves deepen the thermocline especially north of Madagascar leading to sea-surface warming, and thus creating a zonal sea-surface temperature and pressure gradient between east and west (Schott *et al*., 2009).

During El Niño the flux through the Indonesian passages weakens, and the western SEC is reduced due to in part the downwelling in the region of the Tropical Gyre and due to a reduced contribution of momentum from the ITF (Gordon, 2005; Ridderinkhof *et al*., 2010). In this latter scenario the SEC reaches the Island of Madagascar at about 20^{o}S, and creates the bifurcation of the SEC into a northern and southern branch (Schott *et al*., 2009). In this scenario warm tropical water is dispensed via the northern branch current around the northern tip of Madagascar into the Mozambique Channel. During La Niña modes the opposite is true.

La Niña in the Pacific Ocean induce stronger fluxes through the Indonesian Passages, creating conditions that leads to a stronger western SEC, a southwards displacement of the SEC, and the intensification and southwards displacement of the Tropical Gyre (de Ruijter *et al*., 2004; Gordon, 2005; Ridderinkhof *et al*., 2010; Palastanga *et al*., 2006). The intensification of the Tropical Gyre brings cooler water to the subsurface east, north and west of northern Madagascar leading to negative SST anomalies in this region (Schott *et al*., 2009). During La Niña the bulk of the SEC is force south of Madagascar (de Ruijter *et al*., 2004; Palastanga *et al*., 2002). Palanstanga *et al*. (2006) reported a northward (southward) extension of the SEC and a retreat (enhancement) of the Tropical Gyre, associated with the weakening (strengthening) of the western SEC.

The second most important oceanic mode is the Indian Ocean Dipole (IOD) mode. The positive Indian Ocean Dipole (+IOD) mode is typically created due to anomalous easterly winds in the Eastern Equatorial Indian Ocean (EEIO) (Schott *et al*., 2009). The latter induces shoaling of the thermocline in the eastern equatorial part of the Indian Ocean creating cool sea-surface temperature (SST) anomalies there. Concurrently, on the opposite side of the Indian Ocean basin, warming occurs around the northern tip of Madagascar. The typical +IOD thus manifest itself through a zonal gradient of tropical SST, with cooling off Sumatra and warming in the South Western Indian Ocean (Schott *et al*., 2009).

The positive IOD mode see-saws with its opposite mode, the negative Indian Ocean Dipole (-IOD) mode. During the -IOD mode, a sea-surface warming appears in the eastern equatorial Indian Ocean while a cooling of the sea-surface is observed in the South West Indian Ocean Tropical Gyre (Schott *et al*., 2009).

The surface and sub-surface expression of the –IOD and +IOD ocean climate states are comparable with the ocean climate state created by the El Niño and La Niña modes, respectively. The positive/negative IOD and the El Niño/La Niña oceanic modes are significantly correlated but do not always occur together (fig. 3.6) (Schott *et al*., 2009).

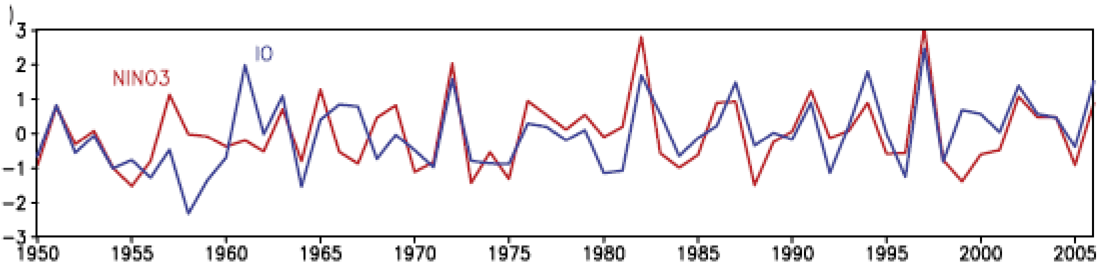

Figure 3.6. Nomalized time series of the Niño 3.4 index (red line) and the IOD index (blue line) (Schott et al., 2009).

3.4 NUMERICAL MODEL PROJECTIONS OF OCEANIC CLIMATE CHANGE TRENDS

Three peer-reviewed scientific publications that are used in building the oceanic climate change scenarios for the Mozambique EEZ are presented here in some detail. These publications are the most recent scientific investigations to explore the oceanic climate change in the Indian Ocean under continued anthropogenic induced global warming for the 21th century.

1) Warming in the Agulhas Current System since the 1980's (Rouault *et al*. 2009)

In this paper Rouault *et al*. (2009) first use satellite sea-surface temperature and sea-surface height remotely sensed data for the period 1985 to 2006 to investigate the trends in these parameters for the greater Agulhas Current System. They also use latent and sensible heat fluxes, in-situ temperature measurements, surface wind speeds for the period 1960 to 2005. The data show that the Agulhas Current has been warming at a rate of 0.7°C per decade since 1980's. The data also elucidate that the Agulhas Current has intensified since the 1980's creating increased eddy kinetic energy in the Agulhas Retroflection area, south of the continent of Africa.

The data further indicate that all the oceanic parameters under investigation increased in correlation with sea-surface temperature after the 1980's. Rouault *et al*. (2009) then show that the oceanic climate change observed in the Agulhas Current System is highly significantly related to changes in the wind field over the south Indian Ocean. And since, the transport in the Agulhas Current is a function of the integral of the wind stress curl over the south Indian Ocean, they conclude that the driving force behind the rapid ocean climate change in the Agulhas Current

System since the 1980's is forced by increase wind stress curl over the South Indian Ocean using statistical relations between observed variables.

Rouault *et al*. (2009), furthermore, use the Regional Oceanic Modelling System (ROMs) specifically set-up to numerically model the greater Agulhas Current dynamics in the South Western Indian Ocean and the South East Atlantic Ocean to detect the possible causes and consequences of the warming trend in the Agulhas Current System by way of numerical modelling. The model was forced using the 1958 to 2001 SODA (Simple Ocean Data Assimilation) ocean reanalysis data set, and the NCEP wind data reanalysis. The model was not forced by observed SST.

The numerical model results mimics the warming trend in the Agulhas Current Systems observed with satellite SST data extremely well. The model results further elucidate that the cause of the warming is derived from increasing incoming lateral heat fluxes from the source area of the Agulhas Current proper. The Agulhas Current has two main source pathways, i. e., a) the transport of equatorial and subtropical upper waters via the Mozambique Channel, and b) the transport of mainly subtropical upper waters via the southern East Madagascar Current, passing south of Madagascar. The numerical model results show that the flux through the Mozambique Channel was not the source of the warming. However, the oceanic water supply via south of Madagascar was identified as the source of the present warming trend in the Agulhas Current System.

Rouault *et al*. (2009) clearly show that the warming of the Agulhas Current is related to increases in wind stress over the south Indian Ocean, which is consistent with the polewards shift of the high-latitude westerly wind systems of the Southern Hemisphere, and the intensification and southwards displacement of the South Indian Ocean Subtropical Gyre System, due to anthropogenic induced global warming.

The important conclusions which are used from this paper for the creation of oceanic climate change scenarios are that the source of the warming of the Agulhas Current is derived from the South Equatorial Current which feeds the Agulhas Current with oceanic waters via south of Madagascar and not via the Mozambique Channel. From these conclusions it can be surmised that the South Equatorial Current must be warming up due to anthropogenic induced global warming.

2) Patterns of Indian Ocean sea-level change in a warming climate (Han *et al*., 2010)

The aim set out in this paper was to improve estimates of the geographic variability in sea-level change for the Indian Ocean since 1960, from when warming of the world's oceans has been attributed mostly to increases of human-produced greenhouse gases.

Han *et al*. (2010) use the best in-situ and satellite observations, tide-gauge data, reanalysis of assimilated model data, and then use general circulation models to investigate the causes of the observed trends for Indian Ocean sea-level change.

Observations based on available tide gauge data for the Indian Ocean Rim show that sea-level has been rising except along the Tanzanian coast (note: no tide gauge data were available for the Mozambique Channel). The observed sea-level anomalies for the Indian Ocean were well mimicked with the HYCOM numerical model. The HYCOM model show a large region of large scale sea-level fall centred in the south tropical Indian Ocean (fig. 2.10). Satellite altimetry data confirms this sea-level trend.

Han *et al*. (2010) conclude from the good model-data agreements that the HYCOM model captured some major physical processes that determine the geographic variability in Indian Ocean sea-level. It should be noted that the HYCOM model did not include the effects of melting ice. The HYCOM model, as well as the other general circulation models that were used, where forced with wind fields for 1958-2001, and spun-up using the comprehensive ocean-atmosphere dataset monthly climatology fields.

All the model results indicate that the geographic variability in the sea-level change is mainly due to changing wind fields over the Indian Ocean causing the redistribution of mass, with thermal expansion and salinity effects, increasing the basin's mean sea-level.

Han *et al*. (2010) also describes the driving forces behind the changes in wind stress across the Indian Ocean. And by using two state-of-the-art atmospheric general circulation models forced by SST trends of the Indo-Pacific Warm Pool (fig. 3.7), surface winds stress and Ekman pumping trends that correlates with the sea-level change patterns was revealed.

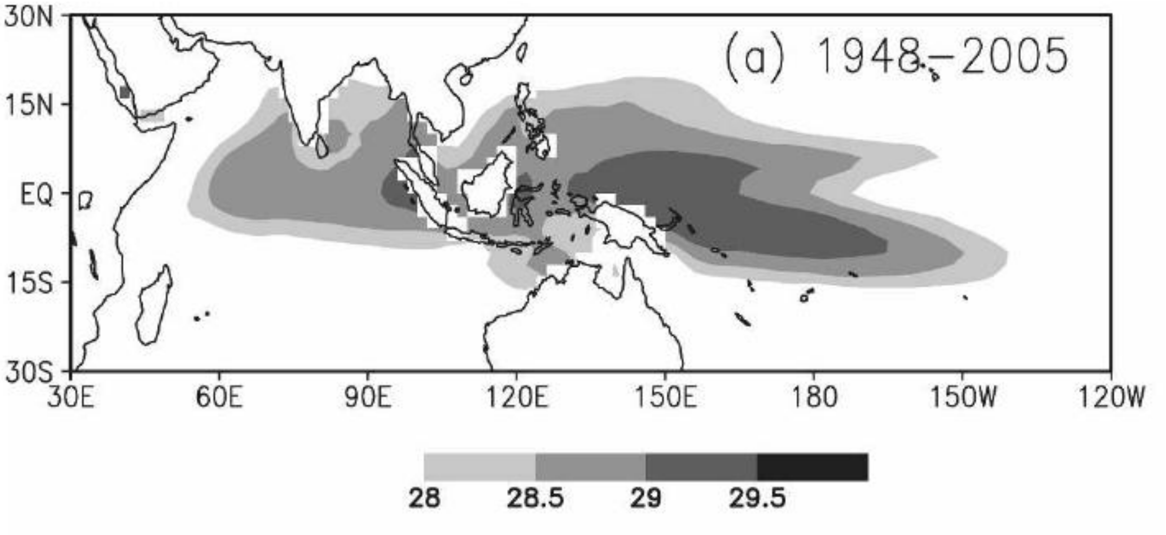

Figure 3.7. The graphic show the geographical area covered by the Indo-Pacific Warm Pool. The shaded region represents the long-term (1948-2005) annual mean sea-surface temperature for the region. The SST scale is shown below (after Wang and Mehta, 2008).

The results show that the SST increases in the Indo-Pacific Warm Pool (IPWP) during the past few decades is primarily caused by anthropogenic forcing due to global warming. The increased warming of the SST over the IPWP over the eastern Indian Ocean has lead to the combined enhancement of the tropical Hadley Atmospheric circulation cell, and the Walker Atmospheric circulation cell. This combined enhancement has in turn lead to specific patterns of wind field changes which are driving increasing upwelling of cold deep waters in the South Western Indian Tropical Gyre region, and increasing downwelling in the South Indian Ocean Subtropical Gyre, leading to increasing sea-level fall and increasing sea-level rise in the respective oceanic regions.

The supplementary material of this paper presents numerical circulation model results, as well as assimilated model results for the Indian Ocean which were be used in the construction of oceanic climate change scenarios for the Mozambique Channel. Each model is briefly described below;

1) The Hybrid Coordinate Ocean Model (HYCOM) (fig. 3.8)
This model has been configured for the Indo-Pacific ocean Basin with 0.33° x 0.33° horizontal resolution and 20 layers in the vertical. The southern and northern boundaries (Indian Ocean) are closed and sponge layers of 5° are applied that relax model temperature and salinity fields to Levitus climatology (Levitus *et al*., 2005). The HYCOM was spun-up for 30 years using COADS monthly climatology fields (Slutz *et al*., 1985) and ERA40 wind field forcing for the period of 1958 -2001. The sea-level anomalies from HYCOM include dynamical effects (mainly wind-driven mass redistribution), thermal expansion and salinity effects. The effect of continental ice retreat is not included in HYCOM.

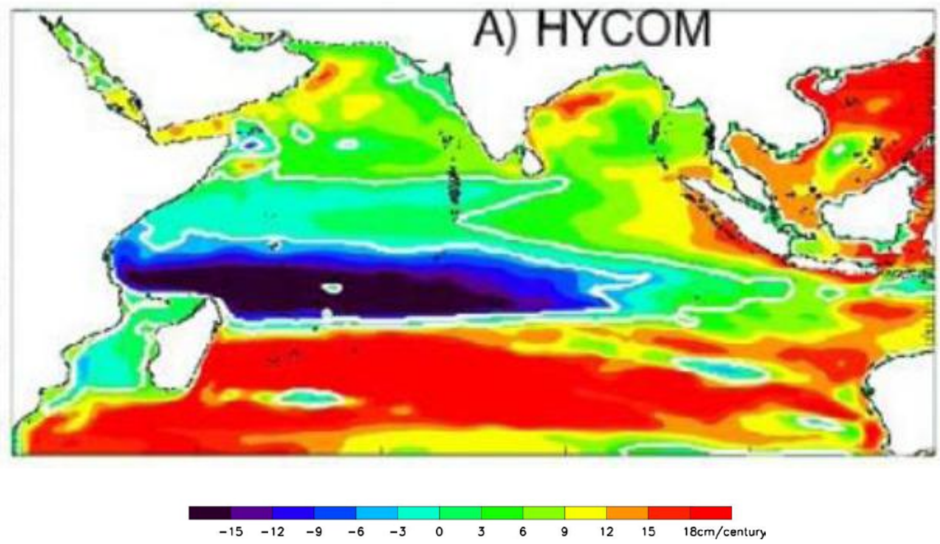

Figure 3.8. Spatial-temporal map of modelled sea-surface height anomalies (cm/century) derived from HYCOM (Han et al., 2010).

2) The Parallel Ocean Program (POP) (fig. 3.9)
The POP used by Han *et al*. (2010) is the ocean component of the National Center for Atmospheric Research (NCAR) Community Climate System Model version 4 (CCSM4). POP is forced by the interannually varying forcing dataset (CORE.2-IAF), spanning 1948-2006. Surface fluxes are computed from bulk formulae using the prognostic ocean model SST and an observed atmospheric state. The initial condition for the experiment is a state of rest, with temperature and salinity prescribed from the global climatological distribution of the 1998 World Ocean Atlas. The models sea-level change is dynamical and results mainly from wind-driven mass distributions.

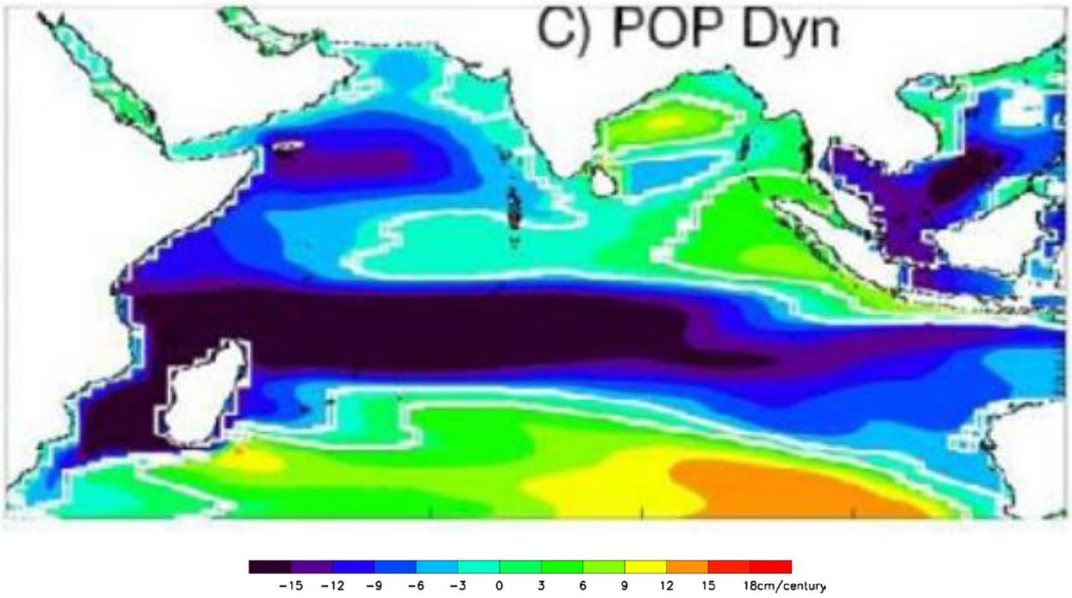

Figure 3.9. Spatial-temporal map of modelled sea-surface height anomalies (cm/century) derived from POP dyn (Han et al., 2010).

3) Linear Model (LM) (fig. 3.10)

The linear continuously stratified ocean model is set up for the Indo-Pacific basin with 0.33^{o} x 0.33^{o} horizontal resolution. The equations of motion are linearized about a state of rest with a realistic background stratification calculated from the Levitus temperature and salinity climatology. Closed boundaries are applied at the northern and southern Indian Ocean. LM was first spun-up for 30 years using the monthly climatology of COADS wind stress forcing. ERA40 wind stress forcing for the period 1958-2001 was used for the LM MR (main run) experiment. A parallel experiment (LM EXP) was also performed, in which the Pacific wind stress is fixed to the 1958-2001 mean.

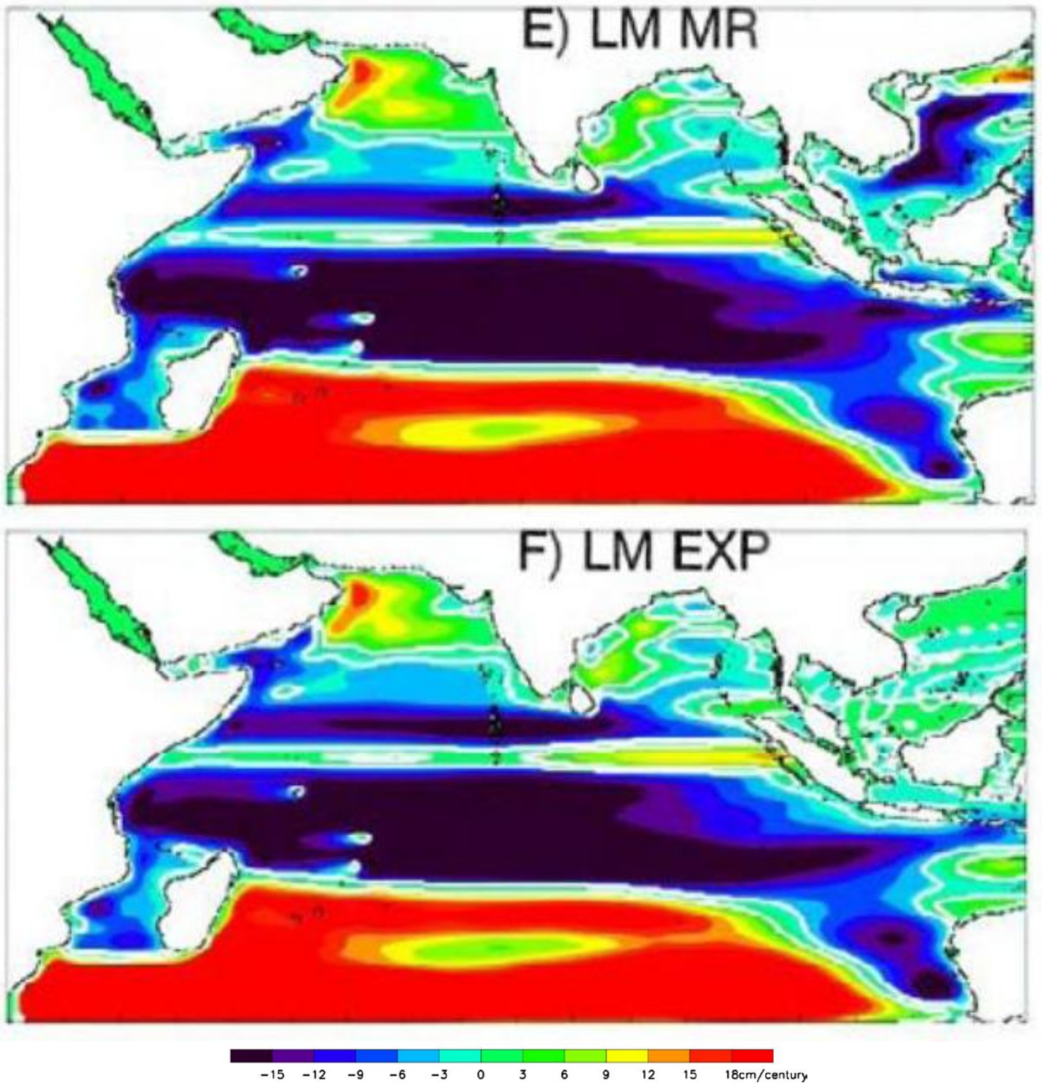

Figure 3.10. Spatial-temporal map of modelled sea-surface height anomalies (cm/century) derived from LM Main Run (MR) and LM experimental run (EXP) (Han et al., 2010).

4) Simple Ocean Data Assimilation (SODA) (fig. 3.11)

SODA is based on Parallel Ocean Program (POP) physics with an average 0.25°x0.4°x40-level resolution. Observations include virtually all available hydrographic profile data, as well as ocean station data, moored temperature and salinity time series, surface temperature and salinity observations of various types, and night-time infrared satellite SST data. The output is in monthly-averaged form, mapped onto a uniform 0.5°x0.5°x40-level grid. The reanalysis provides three types of variables, those well constrained by observations, those partly constrained by dynamical relationships to variables frequently observed, and those poorly constrained.

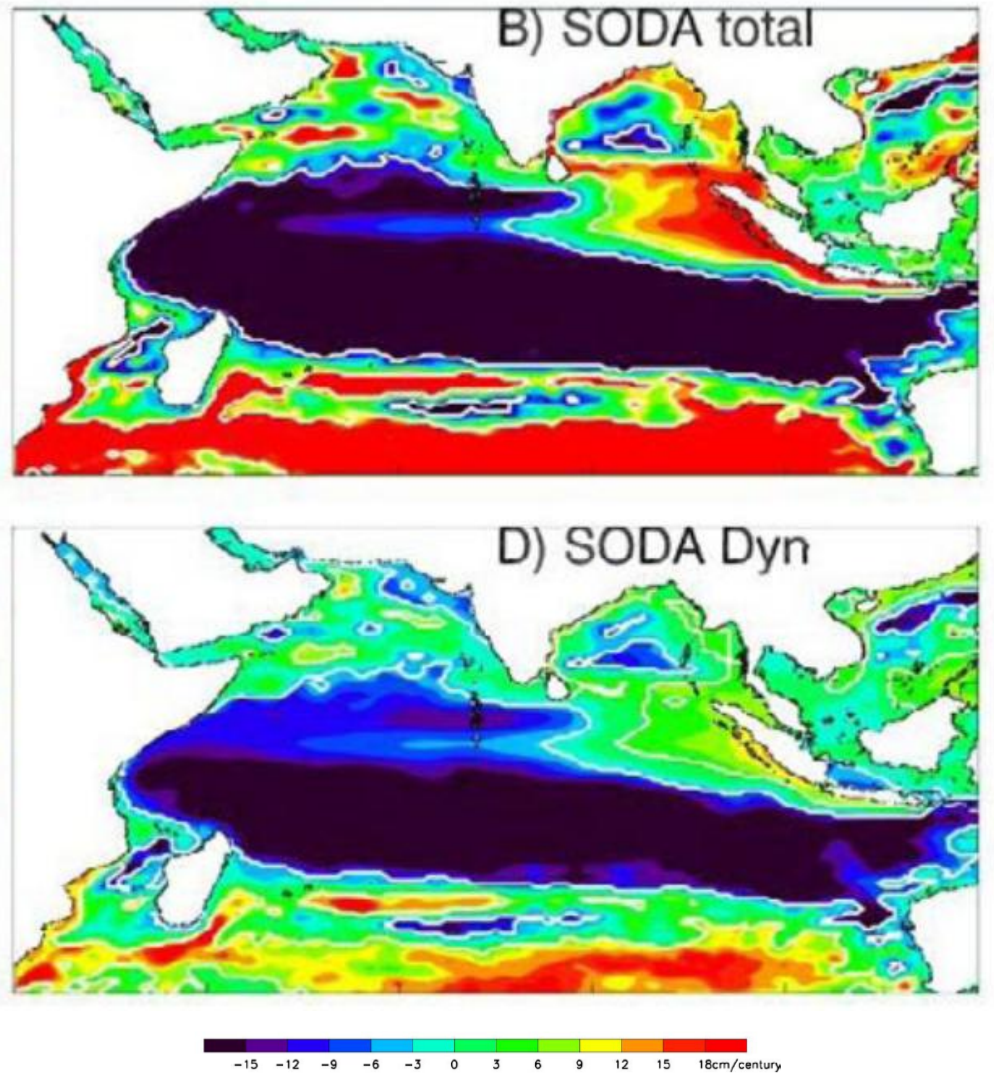

Figure 3.11. Spatial-temporal map of modelled sea-surface height anomalies (cm/century) derived from SODA total and SODA Dyn (Han et al., 2010).

All six spatial results show the dominant oceanic features highlighted by the Han *et al*.'s (2010) paper;

1) The large-scale off equatorial sea-level fall coinciding with the south Indian Ocean Tropical Gyre region stretching from the western Indian Ocean to the eastern Indian Ocean.
2) The large-scale sea-level rise associated with the south Indian Ocean Subtropical Gyre
3) Sea-level rise along the northern most Indian Ocean coast in the Bay of Bengal and the Arabian Sea.

The results for the Mozambique Channel region is however not conclusive, with 50% or the spatial results showing a sea-level rise, and the other 50% a sea-level fall for the last 60 years.

3) Anthropogenic aerosol forcing and the structure of temperature trends in the southern Indian Ocean (Cai *et al*., 2007).

Cai *et al*. (2007) use a coupled atmosphere-ocean climate model with a comprehensive aerosol scheme (sulphate, particulate organic matter, black carbon, mineral dust, sea salt, long-lived greenhouse gasses, ozone and volcanic aerosols) in its simulation for the period 1871 to 2000, with and without (control experiment) the effects of increasing anthropogenic aerosols. The Cai *et al*. (2007) paper, however, only focuses on the results for the period since 1951. The atmospheric model used in this study is a low resolution, flux adjusted (spectral R21) version of the CSIRO atmospheric general circulation model. The R21 model has 18 levels in the vertical and a horizontal resolution of approximately 5.6^{o} in longitude and 3.2^{o} in latitude. The oceanic component has the same horizontal resolution as the atmospheric model with 21 levels in the vertical.

The model results are in high correlation with the climatology of the Indian Ocean derived by Levitus *et al*. (2005), showing a deep warming trend reaching 800m centred at 43^{o}S and an off equatorial subsurface cooling. Cai *et al*. (2005) explain the observed model temperature trend as due to the polewards shift and intensification of the south Indian Ocean Subtropical Gyre, and to the export of heat from the off-equatorial Indian Ocean towards a stronger and southwards displaced Agulhas Current outflow. They conclude that the stronger warming rate in the mid-latitudes is due to the increasing export of heat from the off-equatorial regions, which in turn creates stronger cooling trends in the south Indian Ocean tropics. The horizontal distribution of the above trend relocates the south Indian Ocean Subtropical Gyre centred at 43^{o}S and the south Indian Ocean Tropical Gyre at 20^{o}S, with the South Equatorial Current by passing the southern tip of Madagascar (fig. 3.12).

The important conclusions which was used from this paper to construct future oceanic climate change scenarios were, 1) the southward displacement trend of the South Indian Ocean Tropical Gyre, the South Equatorial Current, and the South Indian Subtropical Gyre, and 2) the off-equatorial cooling and the warming of the South Indian Subtropical Gyre, induced by anthropogenic global warming.

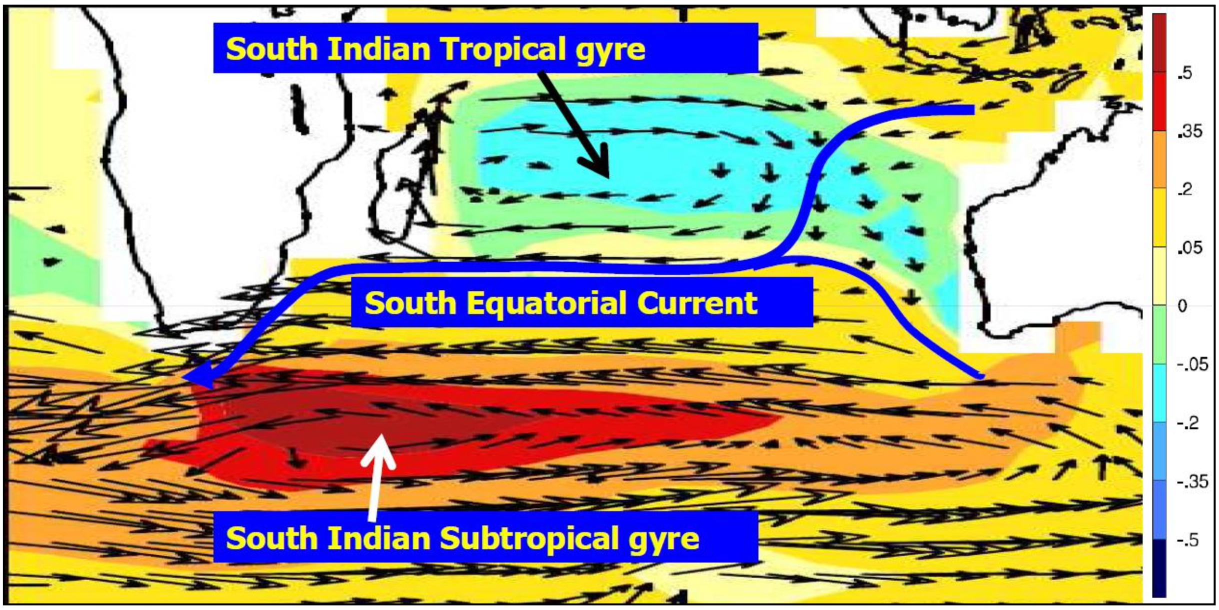

Figure 3.12. Model results from a coupled ocean-atmosphere climate model forced with increasing anthropogenic greenhouse gases showing the trends of the upper 800m oceanic heat content for the South Indian Ocean in terms of vertical averaged temperature, superimposed are averaged oceanic currents (vectors). *Units are in ^{o}C per 50 years. (adapted from Cai et al., 2007). The importance of this illustration is to indicate the southward displacement of the main circulation features of the South Indian Ocean and possible future positions of the South Indian Tropical Gyre, the South Indian Subtropical Gyre, and the South Equatorial Current under continued global warming.*

CHAPTER 4: The “warmer water” ocean climate change scenario for the Mozambique Channel

4.1 INTRODUCTION

This chapter presents the systematic approached and assumptions made to build a “warmer water” ocean climate change scenario for the Mozambique Channel.

4.2 RELATING SEA-LEVEL TO THERMAL EXPANSION/CONTRACTION OF THE UPPER LAYER WATERMASSES

The numerical and assimilated model results presented by Han *et al*. (2010) show a 50% possibility for sea-level rise in the Mozambique Channel since 1958 (fig. 2.10). The HYCOM numerical model (fig. 3.8) and the SODA assimilation model (fig. 3.11) results show the possibility for a sea-level rise of between 0 to 12 cm/century for greater Mozambique Channel over the last 60 years. Furthermore, SODA total and SODA dyn (fig. 3.11), both show that the coastal region of Mozambique may have experienced even greater sea-level rise of the order of 9 to 18 cm/century compared to the rest of channel. Since, sea-level rise is assumed to be correlated with warm oceanic waters in studies (e.g., Han *et al*., 2010), the assumption is made here that most of the sea-level rise indicated for the Mozambique Channel was due to thermal expansion of the warm upper layer water masses there.

Thermal expansion of oceanic water and freshwater contribution from melting polar ice sheet are noted to be the main and equal contributors to global sea-level rise (IPCC, 2007). There may however, be other sources of regional sea-level rise and fall. For example, Han *et al*. (2010) clearly show that the force of surface winds over the south Indian Ocean can cause both sea-level rise and fall due to the geospecific redistribution of mass related to differential wind patterns, which is in turn coupled to cooler or warmer SSTs through the dynamical ocean processes of upwelling and downwelling, respectively. Thus, a cyclonic wind stress curl will lead to upwelling of deeper colder waters to the surface of the ocean creating a negative SST anomaly and a sea-level fall (Han *et al*., 2010). The latter dynamical process is used by Han *et al*. (2010) to explain the large area of sea-level fall for the South Indian Ocean Tropical Gyre, and thus directly linking colder denser oceanic waters to the lowering of sea-levels.

The opposite is also true. For example, for the South Indian Ocean Subtropical Gyre, where the predominant anti-cyclonic wind stress curl generates downwelling, and which in turn leads to the warming of upper layer watermasses and raising sea-levels (Han *et al*., 2010).

A further assumption that needs to be made for the “warmer water” ocean climate change scenario is that the warming (expanding) upper water masses in the Mozambique Channel is imported into the Mozambique Channel due to thermal advection via the northern East Madagascar Current, an extention of the south Indian Ocean South Equatorial Current (Schott *et al*., 2009). Han *et al*.’s (2010) models indicate that the warmer (expanding) trend of the upper waters in the Mozambique Channel may continue into the 21th century. This will only plausible under the assumption that the underlying physical mechanism responsible for the modelled sea-level trends will continue to function during the 21st century. If the latter should hold true, it would be expected that the warm water imported into the Mozambique Channel will also be increasing in temperature. Thus, from the latter assumption it is reasonable to expect that the source of this imported waters must also be warming, viz. that the SEC must be warming due to anthropogenic induced global warming.

4.3 THE WARMING OF THE SEC

Rouault *et al*. (2010) show that the Agulhas Current system is warming up at a rate of 0.7°C per decade and that this increasing amounts of heat is derived from a warming SEC. Thus it can be assumed from the above findings of Rouault *et al*. (2009) that the upper watermasses found in the Mozambique Channel will also become warmer, as the SEC warms up, since the SEC is the main source of water to the Mozambique Channel.

Another piece of scientific evidence to support a warming SEC is found in the zonally integrated climatology of Levitus *et al*. (2005) (fig. 3.2). The temperature climatology indicated two regions of intense warming in the South Indian Ocean, i. e. centered at 43°S and 23°S. The warming at 23°S which reaches a depth of 250m can be assumed to portray the warming trend in the South Equatorial Current, which is on average located at around 20°S and is a shallow current in the depth range similar to the temperature climatology indicated by Levitus *et al*. (2005).
The question then arises as to the cause of the warming of the SEC.

4.4 WARMING TREND IN THE INDO-PACIFIC WARM POOL

The Indo-Pacific Warm Pool is a oceanic region characterized by persistently warm sea-surface temperature higher than 28°C which is the threshold for atmospheric deep convection (Wang and Mehta, 2008). The pool covers a large geographically area (fig. 3.7) spanning the western equatorial Pacific and eastern equatorial Indian Ocean, and includes the Indonesian Throughflow region. According to Wang and Mehta (2008) this region supplies warming upper layer watermasses to both mean and anomalous ocean currents. And since the South Equatorial Current obtains approximately 35% of its transport from the Indonesian Throughflow (Speich *et al*., 2007) it can be assumed that the IPWP supplies increasing heat to the South Equatorial Current.

In an experiment with state-of-the-art atmospheric general circulation models forced with SST trends of the Indo-Pacific Warm Pool region, Han *et al*. (2010) show that the SST warming trends in the Indo-Pacific Warm Pool during the last few decades is caused primarily by anthropogenic forcings. They further explain that it is the increasing temperature of the IPWP that is driving the currently observed increasing wind stress curl over the tropical and subtropical southern Indian Ocean which is in turn responsible for the cooling trend (sea-level fall) and warming trend (sea-level rise) over the Indian Ocean.

It is therefore reasonable to assume that the SEC will continue to warm with the expected continuation of human-induced global warming for the 21st century.

4.5 THE "WARMER WATER" OCEANIC CLIMATE CHANGE SCENARIO FOR THE MOZAMBIQUE CHANNEL

Considering the above environmental trends for the Indian Ocean is it then possible to assume that as global warming continues more warm waters will be advected into the northern inlet of the Mozambique Channel via the warming SEC, leading to an increasingly "warmer water" ocean climate compared to present-day climatology. It should be noted that the "warmer water" ocean climate change scenario is structured on the important assumption that the SEC will remain within it current mean position centred at around 20°S, allowing for the water supply via the northern East Madagascar Current to the Mozambique Channel.

CHAPTER 5: The "cooler water" ocean climate change scenario for the Mozambique Channel

5.1 INTRODUCTION

This chapter presents the systematic approached and assumptions made to build a "cooler water" ocean climate change scenario for the Mozambique Channel.

5.2 RELATING SEA-LEVEL TO THERMAL EXPANSION/CONTRACTION OF THE UPPER LAYER WATERMASSES

As for the "warmer water" ocean climate change scenario in the previous chapter, the numerical model results presented by Han *et al*. (2010) show also a 50% possibility for sea-level fall in the Mozambique Channel since 1958 (Fig. 2.10). The POP model (fig. 3.9) and the LM (fig. 3.10) show that sea-level has fallen between 0 to -15 cm/century for greater Mozambique Channel, for the last 60 years. The assumption is made here that the sea-level fall indicated for the Mozambique Channel by these models is due to thermal contraction of colder upper layer water masses. This assumption is also made by Han *et al*. (2010), who state that colder waters is denser and thus lowers sea-level.

Furthermore, the result from the POP numerical model shows the possibility of an uniform fall in sea-level for the Mozambique Channel of between -21 and -15 cm/century since 1958 (fig. 3.9). The LM MR and LM EXP results (fig. 3.10) show, however, that the region along the west of Madagascar have experience a sea-level fall of between 0 and -6 cm/century, while along the coast of Mozambique the sea-level has fallen between -9 to -15 cm/century. It can thus be assumed based on the assumption that sea-level fall is correlated to cold surface waters, that the latter results suggest the possibility of a flow of a cold water current close to the coast of Mozambique under the "cooler water" ocean climate change scenario.

It is clear from the spatial maps of Han *et al*., (2010) that the oceanic waters creating this sea-level fall close to the coast of Mozambique was derived from the South Indian Tropical Gyre (fig. 3.10). Thus is can be assume here, based on numerical model results from Han *et al*. (2010) that the cause of sea-level fall in the Mozambique Channel may be due to thermal advection of colder waters from the South Indian Tropical Gyre into the Mozambique Channel via the northern inlet. Figure 3.10 clearly show the possibility for the extension of the South Indian Tropical Gyre into the Mozambique Channel up to the southern inlet of the Mozambique Channel. The southern inlet of the Mozambique Channel, in turn, is closed by a warm zonal extension of the South Equatorial Current from the tip of Madagascar toward the Delagoa Bight (fig. 3.10).

5.3. The southward migration and intensification of the South Equatorial Current

As described in chapter two, global warming has induced the intensification and southward migration of the South Indian Ocean Subtropical Gyre (fig. 3.12) (Cai *et al*., 2007). Since the northern peripheral current of the South Indian Ocean Subtropical Gyre is the South Equatorial Current, it is assumed here that the SEC has also intensified and migrated southwards. The latter assumption is supported by the numerical model of Rouault *et al*. (2009) which clearly suggest that the supply of warm SEC waters to the Agulhas Current has increased via the south of Madagascar since the 1980's. Thus it is clear from Rouault *et al*.'s (2009) results that since the

1980's the transport of the SEC has slowly been diverted south of Madagascar, instead of north, due to anthropogenic induced global warming. The increasing diversion of warm SEC's south of Madagascar means that less warm water will flow through the northern Mozambique Channel (Rouault *et al*., 2009). The diversion of warm waters away from the Mozambique Channel may lead to the upwelling and thermal advection of colder denser waters into the Mozambique Channel and thus to an increasingly "cooler water" ocean climate change scenario relative to the "warmer water" ocean climate change scenario.

The intensification and southward migration of the SEC and the South Indian Ocean Tropical Gyre are expected to continue into the 21 century (fig. 3.12) (Cai *et al*., 2007; Rouault *et al*., 2009). The combined mechanism of a southward migration of the SEC and the increasing mass divergent trend of the Tropical Gyre support a "cooler water" ocean climate change scenario for the Mozambique Channel.

CHAPTER 6: Possible impacts of the "warmer water" scenario for the Mozambique EEZ

6.1 INTRODUCTION

This chapter presents the possible impacts of the "warmer water" ocean climate change scenario for the Mozambique EEZ. It mainly presents the possible changes, due to the "warmer water" ocean climate change scenario, to the ocean climatology that was presented in chapter 2, i.e., the general circulation, temperature and salinity climatology, sea-level climatology and chlorophyll climatology.

6.2 POSSIBLE CHANGES TO THE GENERAL CIRCULATION OF THE MOZAMBIQUE CHANNEL

The "warmer water" ocean climate change scenario is based on the main assumptions that the South Equatorial Current, the main supply source of oceanic waters to the Mozambique Channel, a) will not change its current mean position, and b) will be become warmer in correlation to increasing anthropogenic induced global warming. This will suggest that the present tacit general circulation for the Mozambique Channel will remain the same, except that warmer oceanic waters will be supplied to the Mozambique Channel via the northern East Madagascar Current.

Thus the present day general circulation will be expected to remain under the "warmer water" ocean climate change scenario. This general circulation may be compared to what is currently experience under El Niño and +IOD climate events, when the transport of the South Equatorial Current is reduced due to a decrease in ITF (Gordon, 2005; Ridderinkhof *et al*., 2010).

It is foreseen that the mean flux through the Mozambique Channel will still be largely in the form of Mozambique Channel anti-cyclonic vortices, which carry warm water from the northern Mozambique Channel to the southern inlet, close to the coast of Mozambique.

6.3 POSSIBLE CHANGES TO THE TEMPERATURE AND SALINITY OF THE MOZAMBIQUE CHANNEL

The "warmer water" oceanic climate change scenarios will entail increasing temperatures for the upper equatorial and sub-equatorial watermasses currently found in the Mozambique Channel. Presently Tropical and Subtropical Surface Waters have a temperature range of between 15 and 30^{o}C (Lutjeharms, 2006). It can be expected that under the "warmer water" oceanic climate change scenario the temperature maximum may surpass the 30^{o}C mark. The rate at which warming will take place under a "warmer water" ocean climate scenario is unknown for the Mozambique Channel, and is extremely complicated to calculate such trends without the use of a regional atmosphere-ocean coupled climate model.

An assumption on which the "warmer water" ocean climate change scenario was build is that the increasing heat content of the SEC is derived from the Indo-Pacific Warm Pool via the Indonesian passages. It is known that the IPWP is a region of net 1-2 m/year atmospheric freshwater input to the ocean (Wang and Mehta, 2008, and references therein). This net sink of atmospheric freshwater might in turn be important for lowering the salinity of the SEC, which will lead to a decrease of salinity climatology in the Mozambique Channel.

6.4 POSSIBLE CHANGES TO THE SEA-LEVEL CLIMATOLOGY OF THE MOZAMBIQUE CHANNEL

A "warmer water" oceanic climate change will imply sea-level rise due to thermal expansion of the upper watermasses. The numerical and assimilation models results of Han *et al*. (2010) give the best estimate for the rate of sea-level rise for the Mozambique Channel of between 0 to 18cm/century. The results from the HYCOM numerical model show a uniform rise of between 0 to 9cm/century for the entire Mozambique Channel from northern inlet (12^{o}S) to the southern inlet (26^{o}S) for the last 60 years. However, if the present-day general circulation is assume under the "warmer water" oceanic climate change scenario, it would be expected that a more heterogeneous distribution of sea-level rise will manifest within the Mozambique Channel, as the warm core eddies (greater thermal expansion) normally propagate southwards close to the shore of Mozambique. The SODA assimilation model portrayal (fig. 3.11) of the expected sea-level rise under the "warmer water" oceanic climate change scenario is thus more realistic, which show that the Mozambican coastal region could experience higher levels of sea-level rise of between 9 to 18 cm/century compared to 0 to 9 cm/century for the rest of the Mozambique Channel. It should be noted that the sea-level change presented by Han *et al*. (2010) are for the last 60 years, and not projections for the future. However, these rates of change are thus far the best, if the assumption is made that the physical mechanisms underlying the results of Han *et al*. (2010) is to continue for function during the 21st century.

6.5 POSSIBLE CHANGES TO THE CHLOROPHYLL CLIMATOLOGY OF THE MOZAMBIQUE CHANNEL

The present day chlorophyll climatology for the open ocean Mozambique Channel varies seasonally between 0.1 to 0.4 mg Chl.m^{-3} (Omta *et al*., 2009). It is commonly known that warmer (colder) oceanic waters contain lower (higher) chlorophyll concentration (e. g., Machu *et al*., 2005), and thus it will be expected under the "warmer water" oceanic climate change scenario that the current mean chlorophyll climatology will decrease to values below the present day chlorophyll climate.

Chlorophyll concentrations for the open ocean Mozambique EEZ can become relatively oligotrophic (low in chlorophyll concentration) and may fall to values of between 0 to 0.1 mg Chl.m^{-3}, which is the chlorophyll surface concentration for the South Equatorial Current (Machu *et al*., 2005). Whether the continental shelf region will experience lower chlorophyll concentrations or not under the "warmer water" oceanic climate change scenario is difficult to ascertain without regional specific physical-biogeochemical climate modelling. As mentioned by Lutjeharms (2006) most of the water on the continental shelf is derived from the open ocean, thus the probability for lower chl-a concentrations for the continental shelf regions are a possible future. In turn, and "warmer water" oceanic climate change scenario will offer increase coastal precipitation leading to higher nutrient loads from the main rivers onto continental shelves, and thus to higher chlorophyll concentrations.

CHAPTER 7: Possible impacts of the "cooler water" ocean climate change scenario for the Mozambique EEZ

7.1 INTRODUCTION

This chapter presents the possible impacts of the "cooler water" ocean climate change scenario for the Mozambique EEZ. The chapter mainly presents possible changes, as a consequence of the "cooler water" ocean climate change scenario to the ocean climatology that was presented in chapter 2, i.e., the general circulation, temperature and salinity climatology, sea-level climatology and chlorophyll climatology.

7.2 POSSIBLE CHANGES TO THE GENERAL CIRCULATION OF THE MOZAMBIQUE CHANNEL

The "cooler water" ocean climate change scenario is based on the main assumptions that the South Equatorial Current will, a) migrate southwards from its mean position, and b) supply all of its warming equatorial waters from the south of Madagascar into the Agulhas Current System, as global warming continues into the 21th century. Moreover, it is well documented that the southwards migration of the South Equatorial Current coincides with the intensification and southward extension of the South Indian Tropical Gyre, which upwells cooler waters to the ocean's surface creating sea-level fall north and east of Madagascar (Han *et al*., 2010; Ridderinkhof *et al*., 2010; Palastanga *et al*., 2006; de Ruijter *et al*., 2004). Three numerical model results of Han *et al*. (2010) show the possibility of the southwards extension of the South Indian Tropical Gyre into the Mozambique Channel and in so doing lower the sea-level there and thus forcing a "cooler water" ocean climate scenario for the Mozambique Channel (figs. 3.9 and 3.10).

Han *et al*. (2010) is the only scientific study that allows for some conceptual model of the possible circulation within Mozambique Channel under the "cooler water" ocean climate change scenario. The numerical model results exhibit the possibility for a cold water current extending from the Tropical Gyre, southwards close to the coast of Mozambique (fig. 3.10).

Two of the model results, which supports the "cooler water" ocean climate change scenario suggest that the southern Mozambique coast from the Delagoa Bight to the South African-Mozambican border will be under the influence of the warming waters of the South Equatorial Current, and therefore this region may experience increasing warmer waters flowing southwards close to the coast. Notwithstanding the results of Han *et al*. (2010) it will be expected that under the "cooler water" ocean climate change scenario that the mean circulation in the Mozambique Channel will be cyclonic, as this region will be largely influence by the cyclonic circulation of the tropical gyre system of the South Indian Ocean.

7.3 POSSIBLE CHANGES TO THE TEMPERATURE AND SALINITY OF THE MOZAMBIQUE CHANNEL

The "cooler water" ocean climate change scenario assumes the all the warm Tropical Surface Water and Subtropical Surface Water will be diverted south of Madagascar and away from the northern inlet of the Mozambique channel, effectively removing most of the warm upper waters from the Mozambique Channel. This will impact especially on the present-day temperature and salinity climatology for the region.

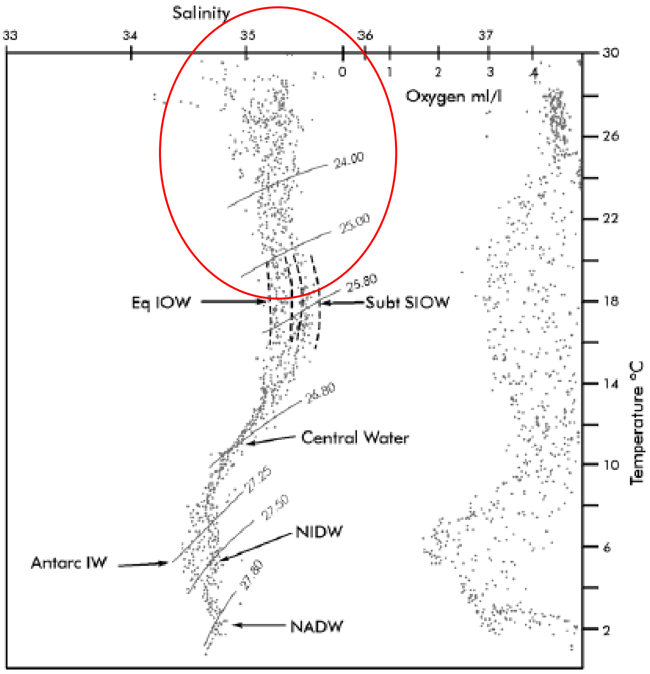

Figure 7.1. As for figure 2.6. The red oval indicates the upper warm Tropical Surface and Subtropical waters that will be displaced by the underlying Central Water mass under the "cooler water" ocean climate".

It is assumed under the "cooler water" ocean climate change scenario that both Tropical and Subtropical waters (temperature range = 15 to 30°C) will be removed from upper layers of the Mozambique Channel (fig. 7.1, red oval), which will force the underlying cooler Central Waters (temperature range = 6 to 15°C) to the surface as an extension of the South Indian Tropical Gyre. The upwelling of Central Water will also introduce less saline waters to the surface with salinities below 35.3, than the current climatological mean.

Although, the sea-surface temperatures for the northern and central Mozambique Channel could drop to values around 15°C, incoming solar radiation could considerably heat the upper surface layer to higher than 15°C.

The southern part of the Mozambique coast, from the Delagoa Bight to the South African-Mozambican border, could still experience the influence of warmer Sub-tropical Surface water (temperature range = 16 to 24°C; salinity range = 35.3 to 35.7) at the surface, introduced here by the South Equatorial Current via south of Madagascar (Han *et al*., 2010)..

7.4 POSSIBLE CHANGES TO THE SEA-LEVEL OF THE MOZAMBIQUE CHANNEL

A "cooler water" oceanic climate change will imply sea-level fall. This is aptly portrayed in three of the numerical model results of Han *et al*., (2010), which clearly show the possibility of the southward penetration of the South Indian Tropical Gyre into the Mozambique Channel (figs. 3.9

and 3.10). The South Indian Tropical Gyre is characterise by upwelling of cooler deeper waters to the surface and sea-level fall (Schott *et al*., 2009; Han *et al*., 2010). One of Han *et al*.'s (2010) model results that support the "cooler water" ocean climate indicates a uniform sea-level fall of between -9 and -15 cm/century for the Mozambique Channel for the last 60 years (fig. 3.9), while the other two indicate a heterogeneous distribution (fig. 3.10). The latter two model results show that sea-level fall could be more aggravated along the coast of Mozambique (-9 to -15 cm/century) compared to along the west coast of Madagascar (0 to -6cm/century). The latter distribution supports the conceptual idea of a cold ocean current derived from the Tropical Gyre flowing close to the Mozambican coast southwards.

The southern EEZ of Mozambique, from the Delagoa Bight to the South African-Mozambique border, could however still be vulnerable to sea-level-rise due to the supply and southwards flux of warming waters from the South Equatorial Current extension into the Agulhas Current.

7.5 POSSIBLE CHANGES TO THE CHLOROPHYLL CLIMATOLOGY OF THE MOZAMBIQUE CHANNEL

As mentioned before, it is commonly known that colder oceanic waters contain higher chlorophyll densities than warmer waters (e. g., Machu *et al*., 2005). Thus it can be assumed that under the "cooler water" ocean climate change scenario, higher than the present day climatology chlorophyll concentration will be found for the surface waters for the greater Mozambique Channel in the future under this scenario.

As has been shown, under the "cooler water" ocean climate change scenario the main supply of cold waters to the Mozambique Channel could be derived from the South Indian Tropical Gyre extending into the channel. The cooler waters of the tropical gyre are shown to be more productive than the rest of the South West Indian Ocean (Machu *et al*., 2005). Machu *et al*. (2005) calculated the concentration of chlorophyll in the Tropical Gyre to be between 3 and 9 mg Chl.m^{-3}, which is above the present day chlorophyll climatology for the Mozambique Channel. Also, the primary production of between 100 and 180 gC/m^{2}/yr in the Tropical Gyre is much higher than for the rest of the South Western Indian Ocean (Machu *et al*., 2005). Thus as the Tropical Gyre waters penetrates into the Mozambique Channel under the "cooler water" ocean climate change scenario higher primary production and thus higher chlorophyll concentration will manifest for most of the Mozambique EEZ.

An exception will be again, the southern Mozambique EEZ, from Delagoa Bight to the South African-Mozambican border, where oligotrophic waters from the South Equatorial Current extension will lead to chlorophyll poor oceanic waters there.

CHAPTER 8: Oceanic Climate Change Monitoring for the Mozambique EEZ

8.1 INTRODUCTION

In order to monitor oceanic climate trends it is necessary to engage in long-term collection of data sensitive to oceanic trends over periods of decades. These instrument recordings should be made continuously without long periods of interruption. Thus, ocean climate change monitoring instruments should be relatively inexpensive to purchase and to replace, and should be easily accessible from the mainland for maintenance repair and data collection.

It is also recommended to engage with established international ocean monitoring organizations involved with long-term ocean monitoring, e. g. CLIVAR, OdinAfrica, GEOSS, etc., so to dovetail with established ocean monitoring programmes that have had years of experience. Such alliances will allow for robust exchanges of professional expertise, know-how and new technologies. The importance of such streamlining with global ocean monitoring systems is that by using the same monitoring instruments and data analysis methods, recently start-up ocean monitoring data could be easily extrapolated or correlated backwards allowing for greater spatio-temporal coverage of parameters sensitive to oceanic climate change for the region of interest.

The streamlining of ocean monitoring system *modus operandi* and the exchange of time-series data are especially important between neighbouring countries with connecting EEZs. This is mainly due to the fact that ocean climate change is a trans-boundary climate change issue which does not respect political borders. Such cooperation between neighbouring countries will allow for a more comprehensive understanding of ocean climate trends and spatio-temporal variability across political boundaries, and will afford for better inter-institutional calibration of environmental monitoring systems, and thus to better quality controlled *in-situ* data available for scientific analysis. Oceanic climate change monitoring cooperation between neighbouring state with linking EEZs, as well as with global monitoring programmes, will in the end analysis lead to a decrease in uncertainties of ocean climate trends on regional scales, especially for Southern Hemisphere developing countries. An increase in environmental data density for a region will lead to more accurate future climate change projections affording more reliable climate change adaptation and mitigation strategies for the present and future.

8.2 EXISTING LONG-TERM OCEANIC CLIMATE CHANGE MONITORING FOR THE MOZAMBIQUE EEZ

The flux of oceanic water through the Mozambique Channel (Mozambique Throughflow) forms part of a global thermo-haline conveyor belt of inter-ocean currents that are critical in understanding the global climate system (fig. 3.4). The Mozambique Throughflow impacts immediately on the downstream dynamics of the Agulhas Current, which in turns determined the amount of warm saline Indian Ocean water to be injected into the Atlantic Ocean, which in turn conditions the Atlantic Ocean for deep convection in the Greenland Sea, which impacts the global climate system (Schott *et al*., 2009, and references therein). It is for this reason that a ocean monitoring system has been deployed in the narrowest region of the Mozambique Channel since 2000 up to the present (Ridderinkhof *et al*., 2010). The ocean monitoring systems consists of a collection of deep-ocean monitoring instrumentation which are moored to the ocean floor, stretching from the coast of Mozambique to the east coast of Madagascar (see Ridderinkhof *et al*., 2010). This data series is one of the longest hydrographic data sets published in scientific literature and have revealed many interesting oceanic features that have not been known to exist along the coast of Mozambique before.

Other long-term data sets current available for the Mozambique EEZ are satellite data collected by various remote sensing instruments specifically engineered to monitor the ocean's variability on regional scales. Some data sets start in the early 1990s. It is foreseen that satellite monitoring of the oceans will continue into the future, with satellites instruments becoming more sophisticated with the discovery of new technologies. There is currently a variety of data sets available from ocean monitoring satellite instrumentation which can be easily accessed to study the ocean climate of the EEZ of Mozambique. These include bio-physical data from MODIS (Moderate Resolution Imaging Spectroradiometer) on NASA's Aqua satellite and MERIS (Medium Resolution Imaging Spectrometer) on the European Space Agency's ENVISAT satellite. Also available is temperature data from the AMSR (Advanced Microwave Scanning Radiometer) on the Aqua-satellite which allows for Sea-surface Temperature (SST) scanning through clouds. Also merged Sea-surface Height (SSH) data obtained from Jason, TOPEX/Poseidon, Geosat Follow-On, ERS-2 and Envisat satellite altimeters which allow for tracking meso-scale (100 to 300 km diameter) circulation features close to the coastal regions.

In-situ data from surface temperature drifters and Argo floats that are presently scattered all around the global ocean (fig. 8.1) continuously measuring ocean climate change sensitive parameters, and which also flux through the Mozambique Channel, are available to study long-term trends in temperature, salinity and velocity climatology for the Mozambique Channel.

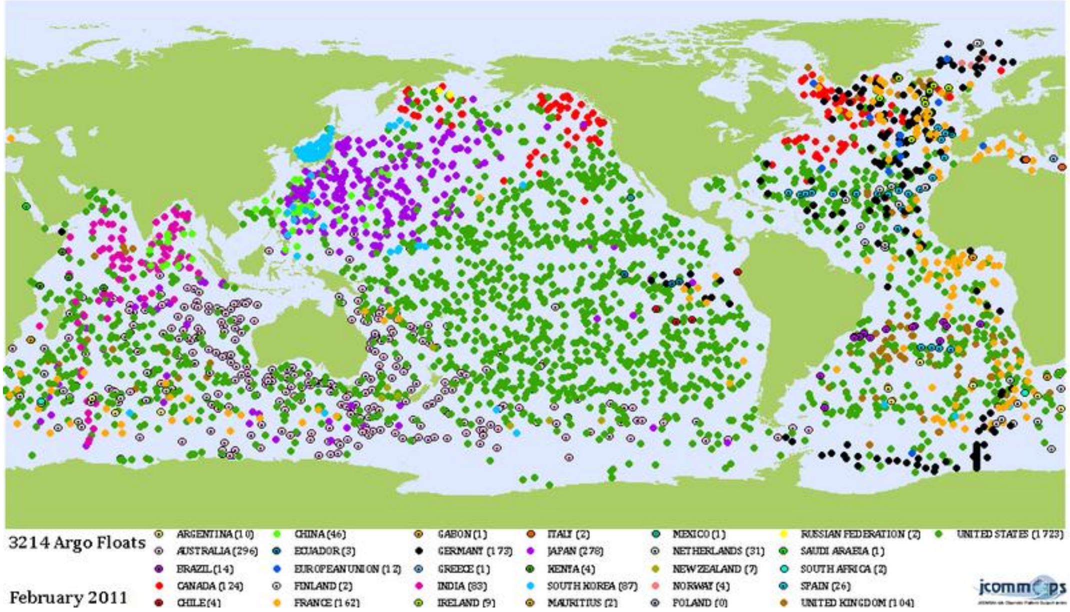

Figure 8.1. Spatial distribution of the 3214 Argo floats from different countries around the global ocean for February 2011.

The above are just a reflection of the main features of a global effort to monitor the ocean on a continual basis to evaluate the oceans response to global warming.

8.3 SUGGESTED MONITORING OF THE MOZAMBIQUE EEZ

Two published scientific papers, i. e., Church *et al*. (2004) and Han *et al*. (2010) highlight the absence of long-term tide gauge data along the Mozambique coast for the validation of sea-level trends. In order, to measure ocean climate change trends within the Mozambique EEZ, long-term sea-level rise and fall measurements from tide gauges are highly recommended. Tide gauges are relatively inexpensive and easy to maintain for period over decades. Such a tide gauge coastal monitoring system should include tide-gauge stations for the northern sector of the Mozambique EEZ, north of the narrows, the central sector which covers the Sofala Banks, and the southern sector which covers the Delagoa Bight to the Mozambique-South African border. Tide gauge stations should be located nearby port-cities, either where there is a marine research institute or the presence of the Mozambican Navy. The latter is recommended for the needed insurance of continuous operation of tide-gauge monitoring station for periods extending 20 years and more.

Another important oceanographic parameter that needs to be measured for periods extending 20 years and more, in tandem with tide-gauge measurements, is underwater sea temperatures, at lease for the continental shelf regions, to the north and south of the narrows and from the Delagoa Bight southwards. The combined monitoring of sea-level and ocean temperature for the Mozambique EEZ will be a reasonable monitoring system to evaluate oceanic climate change, i. e., a “warmer water” or a “cooler water” ocean climate, over time periods extending decades. The above two oceanographic measurements are relatively inexpensive to set-up and to maintain for long periods of time, and thus it is recommended here that these measurements could form an initial ocean climate change monitoring system for the Mozambique EEZ on which more elaborate (more expensive) monitoring systems can be built in the future.

8.4 DOWNSCALED COUPLED OCEAN-ATMOSPHERE CLIMATE MODELLING

Regional ocean models for the South West Indian Ocean and the South East Atlantic Ocean to study the inter-ocean exchange between oceans south of Africa have been engineered and these models do include the Mozambique Throughflow. They include ocean physics (e. g., Biastoch *et al*., 2009 and Rouault *et al*., 2009), as well as ocean biogeochemistry (e. g. Machu *et al*., 2005). These models are however, not climate models per se, but rely on climatology of the past to calculate ocean climate trends since the 1960’s.

As have been indicated in the present report, to project future oceanic climate change within high reliability time-scales will require regional coupled ocean-atmosphere climate models for the region of interest, which is currently not available for the Mozambique Channel. This is, however, an expensive endeavour. But the only scientific method available to make accurate projection concerning ocean climate trends for the future as anthropogenic induced global warming continues to rapidly alter our planets’ atmosphere and oceans.

Conclusion

The oceanographic and atmospheric climatology and climate trends since the 1960's presented in this report for the south Indian Ocean, in which the Mozambique EEZ is nested, allow for clear evidence that climate change for the region is inevitable due to anthropogenic induced global warming. Based on an understanding of the inherent dynamics of the South Indian Ocean, the oceanographic climatology for the last 50 years, and climate trends of the past, derived from numerical models and global atmosphere and ocean models, it was possible to construct two plausible future ocean climate change scenarios for the Mozambique Channel.

The "warmer water" ocean climate change scenario is based on the assumptions that the South Equatorial Current (SEC), the main supply source of upper layer oceanic water to the Mozambique Channel, will not change its present-day mean position and that the SEC is warming in correlation with global warming trends.

The "cooler water" ocean climate change scenario is based on the assumptions that the South Equatorial Current will migrate southwards from its present-day mean position and that the South Equatorial Current's warm equatorial waters will be diverted away from the northern Mozambique Channel inlet, supplying the Agulhas Current instead via south of Madagascar.
Based on the fact that Rouault *et al*. (2009) show that warming SEC water is being diverted away from the Mozambique Channel, it is here implied that the "cooler water" ocean climate change scenario may be more probable then the "warmer water" ocean climate change scenario.

The lack of regional climate models for the region, which should incorporate the combined environmental effects due to global warming, e. g., the Indo-Pacific Warm Pool trends, the southwards migration and intensification of the South Indian Subtropical Gyre, and the intensification of the South Indian Tropical Gyre, does not allow for more accurate projections of ocean climate change for the Mozambique Channel. Such modelling experiments, supplied with regional specific long-term ocean data, sensitive to changes on decadal time-scales, is the only method that will be able to afford accurate projection of future climates for the Mozambique Channel, allowing for higher certainty in climate change adaptation and mitigation strategies regionally.

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