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# Sea/Air Interaction

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**Opposite page:** Cyclone Favio entering the Mozambique Channel on 20 February 2007. © Nasa/Jeff Schmaltz/Goddard Space Flight Center.

## INTRODUCTION

The atmosphere and the ocean form a coupled system, constantly exchanging mass (in the form of water, gas, spray, bubbles and particles) and energy at the interface between the seawater and air. This energy exchange occurs in the form of momentum (through wind stress) and heat. In other words, the atmosphere forces the ocean through exchange of momentum, net surface heat flux and freshwater flux. The exchanges at the sea/air interface are irregular, taking place at rates which are largely induced by the dynamics at the surface. The exchanges affect the biological, chemical and the physical properties of the ocean thus influencing its biogeochemical processes, weather and climate. Heat loss from the ocean to the atmosphere plays a vital role of regulating heat balance as well as moisture and energy budgets of the atmosphere. The mean climate of the Earth over long time scales is therefore partly shaped by the convergence/divergence of the oceanic heat exchanges, which act as sources and sinks of heat for the atmosphere (Lee and others, 2010).

An understanding of the extent to which the sea and the air influence each other is about large scale sea-air interactions. The biogeochemical interaction between the sea and the air that involve gas and chemical exchanges are important to life processes. This interaction is sustained by the mixing of the surface by wind and waves to keep a balance between the ocean and the atmosphere. About half the world's oxygen is produced by phytoplankton in the sea (Falkowski 2012), which are at the base of the marine food web. The phytoplankton, through the photosynthesis process, also extract carbon dioxide ($CO_2$), a greenhouse gas that contributes significantly to current global warming (Ciais and others, 2013). The oceans therefore act as major sinks for atmospheric $CO_2$. With the exception of the Indian Ocean, where the phytoplankton levels have remained relatively stable since the 1950s, the levels in the other oceans have generally declined by about 40 per cent (Boyce and others, 2010).

Whereas photosynthesis is one of the major biogeochemical processes which take the $CO_2$ from the atmosphere to the ocean, there are other biogeochemical processes which eventually lead to the removal of $CO_2$ from the sea. The dissolved $CO_2$ may either react with the sea water to form carbonic acid or with carbonates already in the water to form bicarbonates. Either of the two processes removes dissolved $CO_2$ from the sea water. Many marine plants and animals use the bicarbonate to form calcium carbonate skeletons (or shells). If the sea/air interaction processes remained unchanged, there would be a permanent balance between the concentrations of $CO_2$ in the atmosphere and the ocean. However, the levels of $CO_2$ in the atmosphere have been rising, so more of the gas is dissolving in the ocean and which is no longer able to absorb the increased concentration of $CO_2$ in the atmosphere without changes to the acidity levels (Singh and others, 2014).

The exchanges that involve more reactive gases such as dimethyl sulphide can alter cloud formation and hence albedo (Bigg and others, 2003). Particulate matter containing elements such as iron derived from continental land masses would tend to alter ocean primary productivity with impacts on other biogeochemical exchanges that might multiply. An iron deficit in sea water could be one of the major limiting factors for phytoplankton growth. However, wind borne dust from the deserts such as the Sahara plays a significant role in replenishing this important element in the sea (Bigg and others, 2003).

Every atmospheric gas is in equilibrium with its component that is dissolved in sea water, with dissolved oxygen and $CO_2$ being among the most important gases. Dissolved oxygen is critically important for respiration of aquatic animals, which releases energy from carbohydrates, releasing $CO_2$ and water as by-products. As for dissolved $CO_2$ this gas is very important for marine plants, which use dissolved $CO_2$ to manufacture carbohydrates through photosynthesis, releasing oxygen as a by-product (Karleskint and others, 2012). The main objective of this chapter is to review the status of the Western Indian Ocean (WIO) regional sea/air interactions and their associated environmental, economic and social implications.

## CHANGES IN ATMOSPHERIC FLUXES AND CONCENTRATION LEVELS OF OXYGEN AND CARBON DIOXIDE

### *Changes in Atmospheric fluxes*

The turbulent fluxes of heat, water and momentum through the sea surface constitute the principal coupling between the ocean and the atmosphere. The fluxes play an important role in driving both the ocean and atmospheric circulations, thereby redressing the heat imbalance. The air–sea fluxes also influence temperature and humidity in the atmosphere and, hence, the hydrological cycle (Rhein and others, 2013). Consequently, the exchange and transporting processes of these fluxes are essential components of global climate. The WIO region is strongly affected by external forcing, leading to interannual climatic variability such as the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD), as well as seasonal climatic variability such as the monsoon circulation (Manyilizu and others, 2014).

### Exchange of momentum through wind stress

The exchange of momentum between the atmosphere and the ocean, through wind stress, is the primary driver of ocean circulation, particularly the surface currents. Wind stress is a measure of momentum transferred from the atmosphere to the ocean (Collins and others, 2013). However, momentum exchange is complicated by the stratification or stability of the atmospheric boundary layer, the wave field near the surface, and a host of other processes. At the global level, there is evidence that the zonal mean wind stress at the sea-air interface has increased in strength since the early 1980s (Rhein and others, 2013).

In the WIO region, the trend of surface-wind stress pattern over the period 1966-2007 showed an enhanced convergence around 15°S due to anomalous north-westerly winds from the equator (Nidheesh and others, 2013). These wind changes resulted in a large negative wind stress curl anomaly around 10°S, dynamically consistent with the decrease in total steric sea level anomaly (SSLA) observed in the southwestern Indian Ocean region. The trend of wind stress in the western Equatorial Indian Ocean (WEIO) and Southwest Indian Ocean (SWIO) sub-regions with monthly NCEP data for the period 1982 to 1994 (May through September), showed very high values over the sub-region.

### Heat flux

Information on sea-air heat fluxes over the WIO is generally scarce due to the relative paucity of data, making it difficult for one to make conclusive judgements on the general trends. At the global scale, the accuracy of the observations are also currently insufficient to permit direct assessment of changes in heat flux (Rhein and others, 2013). However, the net flux of heat at the sea surface in the tropical oceans, including the WIO region, is characterized by net gain due to incoming shortwave solar radiation, and net loss due to evaporation and heat fluxes (Jayakrishnan and Babu, 2013).

A study carried out in the east coast of Zanzibar Island, at Chwaka Bay, over a short period in January/February 1996 indicated a net gain to the bay of 275.5 W/m$^2$ due to incoming shortwave solar radiation (Mahongo 1997). The net heat loss was due to the sum of the fluxes of evaporation (157.8 W/m$^2$), long-wave back radiation (38.1 W/m$^2$) and sensible heat (17.8 W/m$^2$), respectively (Mahongo 1999, Mahongo 2000). The net heat gain to the sea was therefore 61.8 W/m$^2$ which could be accounted for by advection flux to the offshore (Mahongo 1997). Similar quantities of evaporation and sensible heat fluxes in the offshore around the same latitude and season are slightly lower, being estimated at 92 W/m$^2$ and 11 W/m$^2$ (Ramesh Kumar and Gangadhara Rao 1989).

Over recent decades, trends have been recorded in many of the parameters that affect heat transfer at the sea-air interface. These include: definitive increase in sea surface temperature (SST) (Roxy and others, 2014), in surface air temperature (Vincent and others, 2011) and in wind speed (Mahongo and others, 2012, Shaghude and others, 2013). For instance, during the period 1901-2012, the tropical WIO, which is generally cool, has experienced an anomalous warming of 1.2 °C in summer SST, at a rate that is greater than recorded in any tropical ocean region (Roxy and others, 2014). The observed ocean warming could potentially change the monsoon circulation and precipitation patterns over the WIO region with impacts on the marine food webs that would multiply due to reductions in the productive diatoms which are the basis of the food chain. This will result in relatively less energy available to support high-level marine vertebrates such as fish and marine mammals.

## Upper Ocean Heat Content

The ocean's large mass and high heat capacity allow it to store huge amounts of energy. However, due to increasing concentrations of greenhouse gases, heat radiated from the earth's surface does not escape freely into space. Most of the excess heat is therefore stored in the upper ocean, leading to the rising of the upper ocean heat content (Levitus and others, 2009). During the last four decades (1971-2010), estimates from global ocean temperature measurements indicate that the upper ocean (0 to 700 m depth) has absorbed about 137 TW of heat (1 TW = $10^{12}$ watts), equivalent to 93 per cent of the combined heat stored by warmed air, sea, land and melted ice (Rhein and others, 2013).

In the Indian Ocean, in-situ and satellite observations, ocean-atmosphere re-analysis products and re-constructed datasets show basin-scale decadal warming trends in the upper ocean heat content for the period 1955 to 2008, which were attributed to anthropogenic forcing (Levitus and others, 2009). More recently, Chu (2011) used monthly synoptic temperature and salinity datasets for the Indian Ocean between 1990 and 2009 to study the upper ocean heat content. The results indicated that the first two Empirical Orthogonal Function (EOF) modes accounted for between 24.27 and 20.94 per cent of the variance, representing basin-scale cooling/warming (EOF-1) and Indian Ocean Dipole (EOF-2) events, respectively. The observed trends in ocean heat content may therefore lead to rising sea levels and significant stress to some marine ecosystems.

## Fresh water exchange

The ocean salinity, which is a proxy indicator of freshwater fluxes to the oceans (Bingham and others, 2012), increased from 1987 to 2002 in the upper thermocline of the WIO along 32°S (Álvarez and others, 2011), reversing the freshening trend which previously occurred from 1962-1987 (Bindoff and McDougall 2000). After the recent advent of the use of Argo floats, tracking of surface ocean salinity achieved near-global coverage in 2004. The data showed an increasing trend of ocean salinity in the WIO region between 2004 and 2013. Diagnosis and understanding of trends in ocean surface salinity is important because changes in salinity affect circulation, water column stratification as well as changes in regional sea level (Rhein and others, 2013). For instance, historical salinity measurements in the WIO show strengthening of the South Equatorial Current (SEC) in the 1950–1975 interval compared with the early 2000s due to excess of evaporation over precipitation (Zinke and others, 2005). This in turn affects biological productivity, the capacity of the ocean to store heat and carbon and, therefore, the carbon cycle.

## Changes in concentration levels of oxygen and carbon dioxide

Available records from the Indian Ocean (including the WIO region) between 1962 and 2002 indicate that oxygen concentration at a mean latitudinal section of 32°S has undergone two major changes. The first change involved a pronounced decreasing trend in concentration levels between 1962 and 1987 (Bindoff and McDougall 2000). The second phase occurred between 1987 and 2002, where the concentration levels reversed to reveal an increasing trend (McDonagh and others, 2005). Bindoff and McDougall (2000) attributed the decrease during the first phase to the slowing down of the subtropical gyre circulation in the south Indian Ocean, implying that the gyre circulation may have accelerated during the second phase.

Changes in the concentration levels of oxygen may have important implications for marine ecosystems and socio-economic livelihoods of coastal communities. In view of this, Körtzinger and others (2006) have proposed oxygen to be used as one of the climate change indicators. Furthermore, measurements of oxygen generally have relatively high precision and accuracy, making oxygen suitable for being used as a target tracer on large-scale observing programs for detection of decadal changes (Gruber and others, 2007).

In the upper thermocline, subtropical, subsurface water of the Indian Ocean along 20°S (which includes the southwestern Indian Ocean), anthropogenic $CO_2$ storage over an 8-year period (between 1995–2003/2004) is reported to have increased at an average rate of 7.1 mol/m$^2$ (Murata and others, 2010). The observed change is almost two times higher than that reported during the previous decade (between 1978 and 1995), which was 13.6 mol/m$^2$ (Sabine and others, 1999).

The world's oceans play a significant role as sinks for anthropogenic carbon, sequestrating roughly one-third of the cumulative human $CO_2$ emitted from the atmosphere over the industrial period (Khatiwala and others, 2013). Other studies note that the oceanic anthropogenic carbon inventory has increased between the period spanning from 1994 and 2010 (Christensen and others, 2013). Although the carbon sequestration concept has recently triggered global concerns, very few studies have been undertaken in the WIO region. Among the outstanding studies on carbon sequestration concept conducted in the WIO region include Sengul and others (2007), Alemayehu and others (2014) and Jones and others (2014).

## METEOROLOGICAL PHENOMENA OF THE WESTERN INDIAN OCEAN

### Monsoon winds

The WIO exhibits more pronounced seasonal wind reversals than the rest of the Indian Ocean and is an important region of air–sea interaction (Benny 2002). Two types of seasonal wind systems have been documented, namely the northeast (NE) and southeast (SE) trade winds, leading to the NE and SE monsoon seasons. Both trade wind systems are influenced by seasonal shifts in the Inter-Tropical Convergence Zone (ITCZ). The most important factor that determines the generation of the monsoon seasonal wind pattern is the geographical orientation of the Indian Ocean. It is bounded to the north by the Asian continent, which largely influences the meteorology of the region. The other factor is the presence of the East African Highlands, which play an important role in establishing the upper air flow, in particular the Somali Jet, which has a considerable impact on WIO weather patterns (Slingo and others, 2005).

The SE trade winds (April-October) originate from the semi-permanent South Indian Ocean anticyclone (Mascarene High). Conversely, the NE trades (November-March) originate from the semi-permanent high pressure system centred in the Arabian Gulf (Arabian High), also related to pressure build-up over Siberia (Siberian High). The shifting of the ITCZ northwards and then southwards gives the coast of East Africa its marked biannual rainy seasons with the long rains in March-April-May and the short rains in October-November-December. Due to the effect of the Coriolis force, the NE winds veer to the northwest in the south of the equator, whereas the SE winds veer to the west in the north of the equator. An important wind-driven feature in WIO is the upwelling phenomena off the coast of Somalia. During the SE monsoon season, an upwelling of cold water mass is established in this area, characterized by lowering of SST to about 22°C on average (Mafimbo and Reason 2010).

Over the last three decades, both the mean and maximum speeds of the monsoon winds have generally strengthened in some parts of the region such as in Tanzania (Mahongo and others, 2012). While these changes could be attributed to the global climate changes, they could also be related to natural decadal cycles of the climate system, including the 22-year Hale solar cycle (Mahongo 2014). Therefore, a longer time series dataset is needed to ascertain whether the increasing trend will persist. Dunne and others (2012) have found no evidence of changes in the wind regime in the region (at Diego Garcia) during the recent past. A global assessment by the Intergovernmental Panel on Climate Change (IPCC) also noted a low confidence in changes of surface wind speeds due to uncertainties in datasets and measures used (Hartmann and others, 2013).

### Tropical cyclones

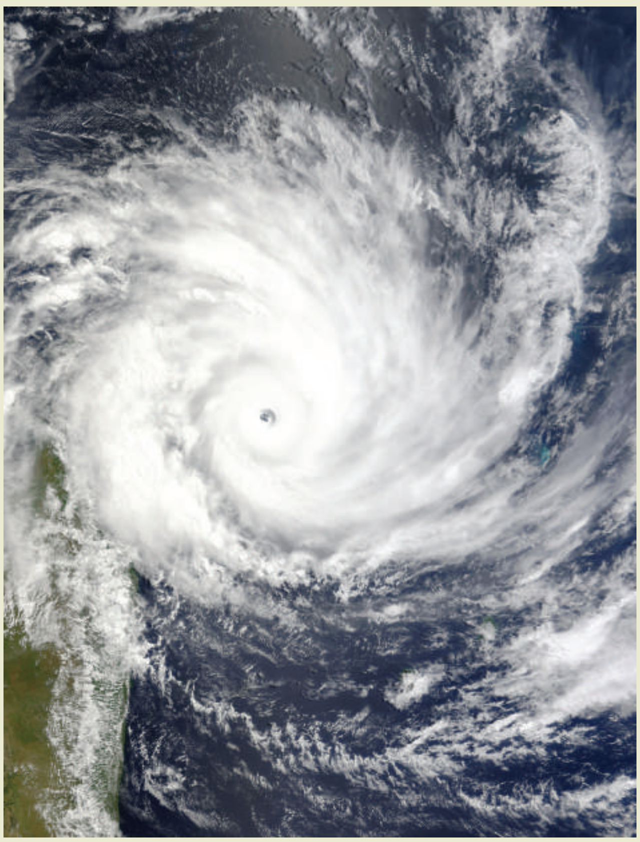
As part of planet's Warm Pool, tropical cyclones are an important feature of the meteorology of the WIO region, particularly over the southwest Indian Ocean. Cyclone activity in the WIO region is strongly influenced by anomalously warm SSTs in the tropical South Indian Ocean, which is a critical factor in their formation. Most of the cyclones originate from the east of Madagascar (50°–100°E, 5°– 15°S) and some from the Mozambique Channel during

Austral summer (Ho and others, 2006). The tropical cyclone season extends from October to May, and about 11-12 cyclones (tropical storms and hurricanes) occur annually (Bowditch 2002). In each season, about four cyclones reach hurricane intensity. The islands of Comoros, Mauritius and Madagascar lie within the region of tropical cyclone activity, while Réunion, Mayotte, Comoros, and Mozambique are also prone to direct landfall (Figure 15.1). On rare occasions, some parts of southern Tanzania and South Africa can also be affected.

Webster and others (2005) observed an increase in the annual frequency of cyclones in the South Indian Ocean within the period 1970 and 2004. The number of intense tropical cyclones also increased from 36 during 1980-1993 to 56 during 1994-2007, parallel to a simultaneous but smaller decrease in the number of tropical storms (Mavume and others, 2009). Globally however, the current datasets do not indicate any significant trends in tropical cyclone frequency over the past century (Christensen and others, 2013). It also remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust, after accounting for past changes in observing capabilities (Christensen and others, 2013). Incidentally, no significant trends were observed in the annual numbers of tropical cyclones in the South Indian Ocean between the period 1981–1982 to 2006–2007 (Kuleshov and others, 2010).

Apparently, one of the challenges in tracking changes in the frequency and intensity of cyclones is that the record of past events is heterogeneous. This is due to changes in observational capabilities and how cyclones have been measured and recorded. It is thus difficult to draw firm con-

**BOX 15.1.** TROPICAL CYCLONE GAFILO AND ITS IMPACT IN MADAGASCAR



Cyclone Gafilo approaching Madagascar on 6 March 2004. © Nasa/Jeff Schmaltz/Goddard Space Flight Center.

The Tropical Cyclone Gafilo, which struck the northeast coast of Madagascar early on the morning of 7 March 2004, was the most intense and devastating tropical cyclone ever recorded in the Southwest Indian Ocean. The cyclone was unusually large and violent, with wind speeds of about 250 km/h, and gusts of up to 330 km/h. Gafilo was the deadliest and most destructive cyclone of the 2003/2004 cyclone season.

Gafilo originated from south of Diego Garcia, and intensified into a moderate tropical storm on 3 March 2004. Gafilo became a tropical cyclone on 4 March 2004, and ultimately intensified into a very intense tropical cyclone on 6 March 2004, prior to making landfall over Madagascar early on 7 March 2004. After crossing Madagascar, Gafilo emerged into the Mozambique Channel and made landfall over Madagascar again on 9 March 2004. After a three-day loop overland, the system arrived back over the southern Indian Ocean on 13 March 2004, and transitioned into a subtropical depression on 14 March 2004.

The cyclone caused a massive destruction of property and 85 per cent of the city of Antalaha was destroyed. The cyclone claimed 237 lives, with 181 missing persons and 879 injured, and caused a property loss of about US$ 250 million in Madagascar. More than 304 000 people were displaced by the storm and more than 6 000 hectares of agricultural land were flooded, resulting in major crop losses. Total rainfall for the period 3–10 March 2004 reached values of up to 500 mm in an area from the central Mozambique Channel eastward along the northwest coastline of Madagascar.

clusions on the observed trends prior to the satellite era and in ocean basins such as the South Indian Ocean (Christensen and others, 2013). According to Christensen and others (2013), tropical cyclone numbers are unlikely to increase, but cyclone maximum intensity is likely to increase on the global average, meaning increased maximum precipitation and winds.

### Monsoon rains

Coastal rainfall in the western Indian Ocean is mostly seasonal, with the heaviest and most prolonged rains occurring during the months of March to June. Most parts of the region experience annual rainfall of between 1 000 to 2 000 mm, but local variations are common (Ngusaru 2002). Generally, the effect of rainfall and river runoff on salinity is restricted to narrow coastal fringes.

The trends in precipitation indices in the western Indian Ocean are generally weak and show less spatial coherence. Vincent and others (2011) found a significant decrease in the total annual rainfall during the period 1961-2008. Their results also indicate some increase in consecutive dry days, no change in daily intensity and consecutive wet days, and a decrease in extreme precipitation events. Weak correlations were found between precipitation indices and surface air temperature. The IPCC regional climate projections for the 21st century indicate an increase in the annual mean rainfall over East Africa (Collins and others, 2013).

### Sea Surface Temperature (SST)

The WIO region's meteorology is dominated by the seasonal reversal of the monsoon wind systems, leading to the largest annual variations in SSTs found in any of the tropical oceans. On the inter-annual timescale, the SST in the WIO region is primarily influenced by the El Niño Southern Oscillation and the Indian Ocean Dipole (IOD). Manyilizu and others (2014), using NCEP Reanalysis data stretching from 1980 to 2007, observed these two signals in the region that were prominent at periods of 5 and 2.7 years, respectively. According to the IPCC Fifth Assessment Report (AR5), the WIO region's SST trend over the period 1950–2009, computed using monthly SST data extracted from the Hadley Centre HadISST1.1 data set (Rayner and others, 2003), indicate an increase of 0.60°C (Hoegh-Guldberg and others, 2014). In the Somali Current surface waters, the same dataset indicated an increase of 0.26°Cover the period between 1982 and 2006 (Hoegh-Guldberg and others, 2014).

During 1901-2012, the tropical western Indian Ocean (50-65°E, 5°S-10°N) experienced anomalous warming of 1.2°C in austral summer SSTs, surpassing that of the Indian Ocean warm pool which increased by only about 0.7°C (Roxy and others, 2014). The increase in temperature of the generally cool WIO against the rest of the tropical warm pool region affects zonal SST gradients, and could potentially change the monsoon circulation pattern, with impacts on rainfall patterns as well as changes on the marine food webs in the region. This is due to the fact that warming causes the air over the ocean to expand and lower the atmospheric pressure consequently unsettling the wind pattern which, in turn, may lead to the changes on monsoon flow pattern.

Besides anthropogenic global warming, the natural long-term warming trend of the Indian Ocean during the period 1901-2012 was influenced by the asymmetry in the El Niño Southern Oscillation (ENSO) teleconnection, whereby El Niño events induced anomalous warming over the WIO and La Niña events failed to do the reverse (Roxy and others, 2014). The period between 1950 and 2012 was characterized by strong and frequent occurrences of positive El Niño events (Roxy and others, 2014), consistent with the period 1960-2004 (Ihara and others, 2008). The warming in the region has also been attributed to positive SST skewness associated with ENSO, as the frequency of El Niño events have increased during recent decades (Roxy and others, 2014).

## ENVIRONMENTAL, ECONOMIC AND SOCIAL IMPLICATIONS OF TRENDS IN METEOROLOGICAL PHENOMENA

Abrupt cyclogenesis is known to increase the risk of marine environmental hazards and coastline erosion particularly for island states such as Mauritius, Reunion and Madagascar (Chang-Seng and Jury 2010). The cyclones may bring severe flooding to coastal areas of Africa, as exemplified in Mozambique in February 2000 (Box 15.1). In some parts of the region, cyclones had been associated with heavy swells which created significant rises in sea levels that affected coastal infrastructure such as roads and settlements, as well as beach stability (Ragoonaden 1997). Considering the vulnerability of the coastal communities of the WIO region to tropical cyclone activity, especially the island states and low-lying areas of Mozambique, developing better monitoring and forecast tools for such sporadic weather events should be given high priority.

### Anthropogenic ocean acidification

Ocean acidification is a relatively new field of research, with most of the research conducted to-date being short-term and laboratory based. Acidification is a direct consequence of increased atmospheric $CO_2$ emissions to the atmosphere. A proportion of the emitted gas stays in the atmosphere as greenhouse gas, while some of it leaves the atmosphere to either become sequestered in trees and plants or become absorbed in the oceans. Ocean acidification alters the chemical speciation and biogeochemical cycles of many elements and compounds in sea water, creating repercussions throughout marine food chains. The chemical changes caused by the uptake of $CO_2$ cause many calcifying species to exhibit reduced calcification and growth rates, and an increase in carbon fixation rates in some photosynthetic organisms. Acidification is also known to increase erosion of carbonate rocks, degradation of coral reef habitats and alteration of the otoliths of pantropical fish species with implications for sensory function (Bignami and others, 2013).

There is a financial barrier in pursuing research on ocean acidification in developing countries, including the WIO region, due to the high costs associated with the nature of the research. Currently, a few monitoring studies on seawater pH are undertaken, but no long-term observational studies have yet been embarked on (Sumaila and others, 2014). Recently, however, some initiatives have begun to address these shortcomings through collaboration with international research institutions by studying some aspects of ocean acidification. In Tanzania for instance, the UK Ocean Acidification Research Programme is currently investigating a variety of geological records of a newly recovered borehole through marine sediments to study the response of the carbon cycle during the rapid onset of the Paleocene / Eocene thermal maximum (PETM) using new computer models (Aze and others, 2014).

In Kenya, the International Atomic Energy Agency (IAEA) is collaborating with CORDIO-East Africa through the Coordinated Research Project (CRP) to: identify and describe pathways of impact of ocean acidification, improve understanding of the vulnerability of regions and markets to ocean acidification, and quantify economic impacts of biological effects of ocean acidification to assist natural resource management and policy decisions on regional and local scales.

## ENVIRONMENTAL, ECONOMIC AND SOCIAL IMPLICATIONS OF TRENDS IN OCEAN ACIDIFICATION

Ocean acidification has only recently been recognized as a global threat, with potentially adverse environmental, economic and social implications. Being a complex phenomenon, isolating it from other factors affecting the ocean such as surface warming and coastal pollution is very challenging. Furthermore, it takes time to observe developments that impact the environment, economy and human society. The adverse effects of rising acidity include an alteration of the health of many marine species such as plankton, molluscs, and other shellfish (Table 15.1). In particular, corals can be very sensitive to increased acidity, which may lead to alteration to the reef-fish habitat.

Most of the coastal communities in the region are small-scale artisanal fishers who are highly dependent upon fishing for their livelihoods (Kimani and others, 2009). Changes to harvest could therefore be a threat to food security. Aquaculture in the region is increasing and has promising potential. A shift toward new production methods and cultured species may provide benefits to household livelihoods and small and medium enterprise development. More information is therefore needed on carbon chemistry and fisheries in the region.

Although the impacts of long-term changes in ocean acidification on marine organisms and their ecosystems are much less certain, due to the fact that the physiological attributes of marine ecosystems is highly variable, the effects among organisms will generally also be variable. Considering the generation spans of the different species, it is possible that the impact of acidification and the degree to which species adapt to their changing environment can take years or decades to observe. In the WIO region, no observational or direct experimental data or studies on trends in ocean acidification impacts have been undertaken. However, areas such as the monsoon-induced upwelling zones as well as the coastal and estuarine waters in the region are natural hotspots of special concern. These areas support lucrative fisheries, but the upwelled waters with high $CO_2$ content make them particularly sensitive to increased ocean acidification.

In view of the on-going changes in global climate and the associated alterations in ocean acidification, coastal communities in the WIO region need to have a clear understanding of the possible scale of potential impacts based on assessment of exposure, sensitivity and adaptive capacity. Case studies need to be undertaken on the environmental, economic and social impacts on ecosystems and aquatic organisms, especially for the species most vulnerable to ocean acidification. Comprehensive risk assessments should also be designed and implemented to prioritize adaptive responses.

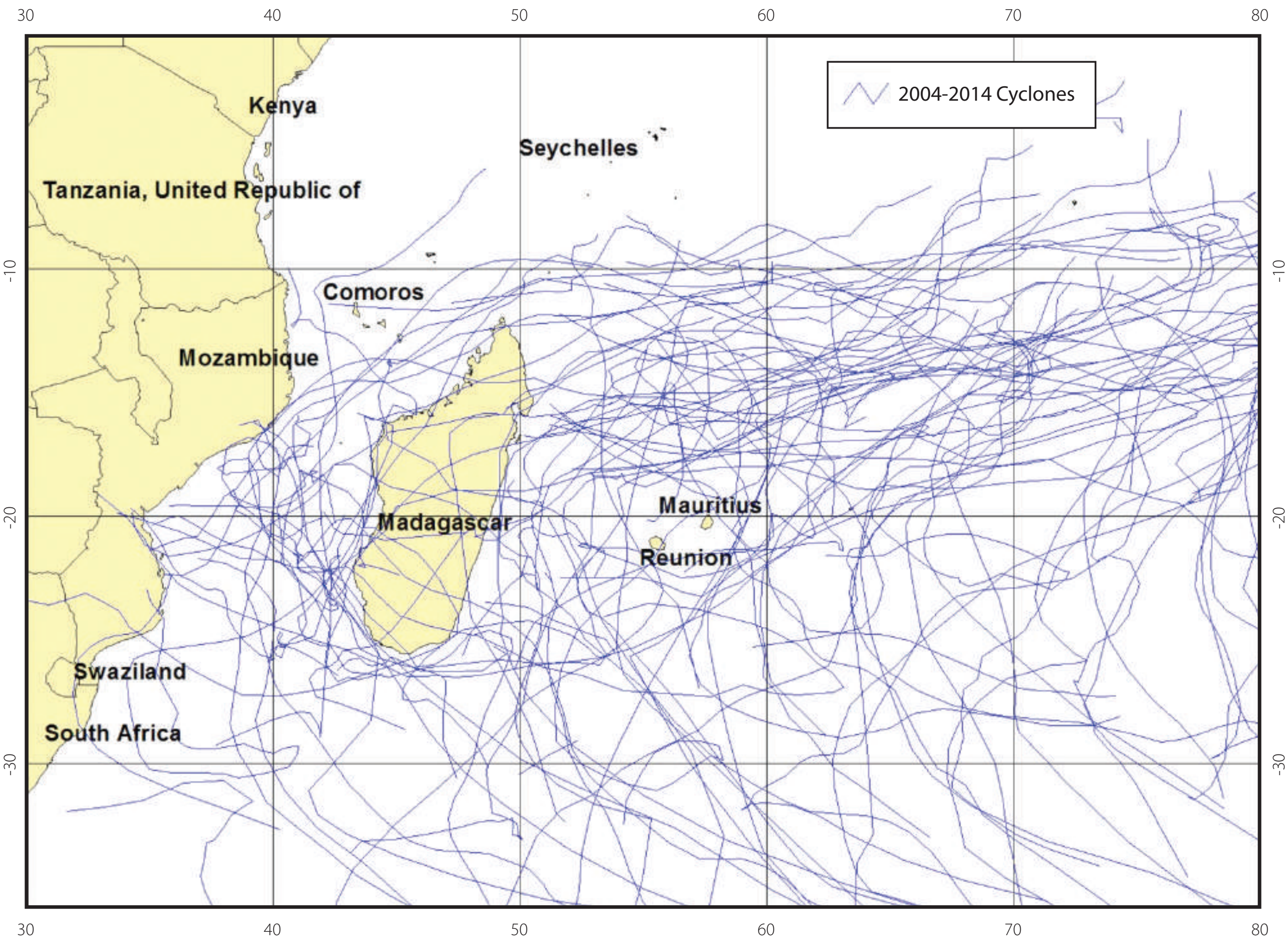



**Figure 15.1.** WIO Tropical Cyclone Trackline (2004-2014).

**Table 15.1.** Summary of the anticipated future effects of ocean acidification on different groups of marine organisms, mostly based on experimental studies from around the world. Note that none of the data is from this region. Table adopted from Sumaila and others (2014).

| Group | Main acidification impacts |
|---|---|
| Warm water corals | A relatively well-studied group. The great majority of experiments show that increasing seawater $CO_2$ decreases adult coral calcification and growth, and suppresses larval metabolism and metamorphosis. Although most warm water coral reefs will remain in saturated waters by 2100, saturation levels are predicted to decline rapidly and substantially; thus coral calcification is unlikely to keep up with natural bioerosion. Interactions with other climatic and anthropogenic pressures give cause for concern. |
| Molluscs | Significant effects on growth, immune response and larval survival of some, although with high inter-specific. Pteropods seem particularly sensitive and are a key component of high latitude food webs. Molluscs are important in aquaculture, and provide a small yet significant protein contribution to human diet. |
| Echinoderms | Juvenile life stages, egg fertilization and early development can be highly vulnerable, resulting in much reduced survival Adult echinoderms may increase growth and calcification; such responses are, however, highly species specific. |

| Group | Main acidification impacts |
|---|---|
| Crustaceans | The relative insensitivity of crustaceans to ocean acidification has been ascribed to well-developed ion transport regulation and high biogenic content of their exoskeletons. Nevertheless, spider crabs show a narrowing of their range of thermal tolerance by ~2˚C under high $CO_2$ conditions. |
| Foraminifera | Shell weight sensitive to $CO_3^{2-}$ decrease in the laboratory with field evidence for recent shell-thinning. |
| Fish | Adult marine fish are generally tolerant of high $CO_2$ conditions. Responses by juveniles and larvae include diminished olfactory ability, affecting predator detection and homing ability in coral reef fish and enhanced otolith growth in sea bass. |
| Coralline algae | Meta-analysis showed significant reductions in photosynthesis and growth due to ocean acidification treatments. Elevated temperatures (+3°C) may greatly increase negative impacts. Field data at natural $CO_2$ vents show sensitivity of epibiont coralline algae. |
| Non-calcified macro-algae; sea grasses | Both groups show capability for increased growth. At a natural $CO_2$ enrichment site, sea grass production was highest at mean pH of 7.6. |
| Coccolitho-phores | Nearly all studies have shown reduced calcification in higher $CO_2$ seawater. However, the opposite effect has also been reported, and ocean acidification impacts on coccolithophore photosynthesis and growth are equivocal, even within the same species. This variability may be due to the use of different strains and/or experimental conditions. |
| Bacteria | Most cyanobacteria (including Trichodesmium, a nitrogen-fixer) show enhanced photosynthesis and growth under increased $CO_2$ and decreased pH conditions. Heterotrophic bacteria show a range of responses with potential biogeochemical significance, including decreased nitrification and increased production of transparent exopolymer particles (affecting aggregation of other biogenic material and its sinking rate). Adaptation by bacteria to a high $CO_2$ world may be more rapid than by other groups. |

**Figure15.2.** Floods in Mozambique in January 2013. © Phil Hay/UN/World Bank.

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