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Ocean-sourced Carbonate Production

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Opposite page: Biogenic rocks and sediments at Ibo Island, Mozambique. © José Paula.

INTRODUCTION

Globally, atmospheric carbon dioxide (CO_2) is exchanged with the surface ocean through a gas exchange mechanism which is driven by the partial pressure differences in carbon dioxide between the air and the sea (Ciais and others, 2013). Once in the ocean, the production of carbonates is a process that is governed by a series of chemical reactions as described by Doney and others (2009). Carbon dioxide dissolves in sea water (H_2O) to form carbonic acid (H_2CO_3). This then dissociates to form bicarbonate ions (HCO_3), hydrogen ions (H^+) and carbonate ions (CO_3). These reactions are reversible and are in an equilibrium state in seawater which has a pH of around 8.1 (Doney and others, 2009). At this pH, approximately 90 per cent of the inorganic carbon is in the form of bicarbonate, 9 per cent exists as carbonate and 1 per cent is in the form of dissolved carbon dioxide (Doney and others, 2009).

Calcification is the process in which calcium (Ca) combines with carbonate ions to form the mineral calcium carbonate ($CaCO_3$) (Andersson and Gledhill 2013). Most of the calcium carbonate production in the sea is attributed to corals, calcifying algae, foraminifera, echinoderms, molluscs and bryozoans (Andersson and Gledhill 2013) and in these organisms the calcification process involves the formation of calcium carbonate deposits in shells and other skeletal parts (Doney and others, 2009, Lobban and Harrison 1994).

In the open ocean, the carbonate producers are microscopic foraminifera (microscopic animals) and coccolithophores (microscopic algae) which are carried around in the oceanic systems and once they die their calcareous skeletons sink to the bottom of the ocean and form part of the oceanic bed (Langer 2008, Shutler and others, 2013).

THE IMPORTANCE OF CARBONATE PRODUCERS TO THE MARINE AND COASTAL ENVIRONMENT

Langer (2008) indicates that benthic and planktonic foraminifera currently produce approximately 1.4 billion tonnes of of calcium carbonate per year, which ends up buried in oceanic sediments, representing approximately 25 per cent of the global ocean carbonate production. Foraminifera have also been shown to contribute to the cementation and stability of coral reefs (Langer 2008).In addition to the foraminifera, coccolithophores are widely distributed in the world's oceans and play a major role in the oceanic carbon cycles (Shutler and others, 2013).

Among coastal systems, coral reefs form one of the most diverse environments of the ocean and are estimated to host one third of all marine species (Veron and others, 2009) and they are the most visible carbonate producers. They are found in over 110 countries and contribute 900 million tonnes of global carbonate production (Langer 2008). Coral reefs in the WIO region shield the coastline from wave action and erosion and the effects of sea level rise, thus protecting lagoons and mangroves and helping to maintain habitats for a variety of commercial and non-commercial species (Veron and others, 2009, McClanahan and others, 2011).

The calcification process is an important process in the building of coral reefs and for the supply of carbonate sands to coastal lagoons (Kangwe and others, 2012). Calcium carbonate from corals and calcifying algae is the greatest source of sediment in the oceans (Milliman and Droxler 1995, Freely and others, 2004) and the contribution of carbonates to the sedimentary composition of the marine environment in the WIO region is significant (Rees and others, 2005, Kangwe and others, 2012). It has been estimated that approximately 50 per cent of all calcium carbonate that accumulates in marine sediments is stored in shallow coastal and shelf environments as well as in coral reef environments (Andersson and Gledhill 2013).

Individual corals have been documented to deposit between 0.5 – 3.0 g $CaCO_3$/cm^2/yr while estimates of larger reef areas show that calcification by corals and algae together contributes between 1.5 – 10.0 kg $CaCO_3$/m^2/yr (Andersson and Gledhill 2013). For example, the shallow-water green alga *Halimeda* sp. generates between 2.0 and 4.0 kg $CaCO_3$/m^2/ar (Andersson and Gledhill 2013).

Calcium carbonate deposits function as deterrents to predators and therefore protect the soft tissues of the organism from predation (Doney and others, 2009, Lobban

BOX 17.1. SOURCES OF SAND ON BAMBURI BEACH, KENYA

Bamburi beach, Kenya. © Jared Bosire.

In the WIO region, beach profiling in the Bamburi area, close to Mombasa, revealed that beach sediments comprise a combination of coralline, algal and siliciclastic sands. In some areas of the Bamburi beach, large-sized coral debris can be found whilst in others the debris has been broken down by wave action to contribute finer fragments of coral to the beach sands. At least 50 per cent of the beach sand is derived from a carbonate source, the contributors being corals and calcareous green algae ([2]*Halimeda* spp.) as well as molluscs and foraminifera. Beaches that are located close to creeks generally contain a greater percentage of siliciclastic sands, whose origin is terrestrial, whilst those located further from the creeks contain a greater amount of carbonates. The carbonate sands also contribute to lagoon sediments to form a substrate for seagrasses and *Halimeda* spp., which are a critical fishery habitat in the WIO region (Shaghude and others, 2013).

and Harrison 1994). Other benefits include structural support, increased surface area and the elevation of calcifying organisms above the sediment level to enable them to maintain proximity to high light levels and to keep up with the rise in sea levels (Andersson and Gledhill 2013) as is the case with corals.

In the WIO region, the sediment found on beaches is comprised of carbonates from various sources including coral fragments, calcareous green algae, shells of molluscs and spines of sea urchins (echinoderms) (Shaghude and others, 2013), as described in more details in Boxes 17.1 and 17.2.

BOX 17.2. CONTRIBUTION OF CALCAREOUS ALGAE TO THE CHWAKA BAY ECOSYSTEM, ZANZIBAR

Halimeda sp. in Cabo Delgado, North Mozambique. © José Paula.

Chwaka Bay, in Zanzibar, Tanzania, is characterized by large meadows of the green calcareous algae (*Halimeda* spp.) as well as rhodoliths (red coralline algae). The calcareous green algae are estimated to cover up to 35 per cent of the bay. The key contribution of the *Halimeda* spp. in this bay has been observed to be the production of carbonate sand. The calcium carbonate production by *Halimeda opuntia* in Chwaka Bay has been estimated to reach 17. 6 kg $CaCO_3$/m^2/yr which is higher than estimates for this species from other parts of the world.

Rhodoliths are free living nodules that are common in Chwaka Bay. They provide food, shelter and nursery grounds to fish and molluscs. In some parts of the world, rhodoliths are extracted for use as soil conditioners and fertilizers.

In Chwaka Bay, as in other parts of the WIO region, *Halimeda* spp. and other calcifying algae are found within seagrass environments. It has been thought that there is a coupling between seagrasses and calcareous macroalgae. This is because the photosynthetic process by seagrasses leads to the creation of a high pH environment which increases the saturation state of calcium carbonate ($CaCO_3$) in the surrounding water. This in turn causes high calcification rates in *Halimeda* spp. and other coralline algae (Kangwe and others, 2012). (Source: Shagude et al. 2013)

ECONOMIC CONTRIBUTION OF CARBONATE PRODUCERS TO ECONOMIES OF THE WIO COUNTRIES

In the WIO region, coral reefs are a major carbonate producer. They extend from southern Somalia to the coast of KwaZulu-Natal, South Africa. The most common form is the fringing reef. In addition, the WIO region is characterized by barrier reefs, found in Madagascar and Mayotte, atolls found in the Seychelles and patch reefs found in South Africa (ASCLME/SWIOFP 2012).

Coastal and marine ecosystems, including coral reefs, support the provision of food and income for approximately 30 million people as well as goods and services that are important to national economies (McClanahan and others, 2011). More specifically, tourism is the largest direct source of income that is directly linked to the coastal and marine environment; the region's beautiful sandy beaches, mangrove forests, lagoons and coral reefs attract over 20 million tourists from all over the world every year, injecting more than US$ 6 000 million per year into the economies of the WIO region (UNEP/Nairobi Convention Secretariat 2009). Tourism to the coastal regions of the WIO surpasses the contribution of fisheries to these economies thus making the integrity of carbonate-based habitats such as reefs and beaches a critical part of the coastal economies of the region (UNEP/Nairobi Convention Secretariat 2009).

The integrity of these habitats also contributes to the fishing economy of the coastal countries as fish and other valuable marine species such as molluscs and crustaceans find shelter within coral reef and associated seagrass habitats (UNEP/Nairobi Convention Secretariat 2009). Therefore any negative impact on these key habitats would extend to the livelihoods of coastal populations who depend on tourism, fisheries and other marine resources.

PRESSURES ON CARBONATE PRODUCERS

Ocean acidification

The most significant pressure on carbonate producers is the increase in atmospheric carbon dioxide. This is due to the combustion of fossil fuels as well as the production of cement, both key features of industrial development. Carbon dioxide has been documented to have increased from 278 ppm in about the year 1750 to 390.5 ppm in the year 2011, equivalent to about a 40 per cent rise (Ciais and others, 2013). Much of this increase has occurred in the recent past, with carbon emissions from fossil fuel combustion and cement production increasing faster during the 2000–2011 period than during the 1990–1999 period (Feely and others, 2009, Ciais and others, 2013). In the WIO region, the exploitation of oil and gas has been on the increase (ASCLME/SWIOFP 2012), and the drive towards industrialization will eventually make this region a net contributor to the increase in atmospheric carbon dioxide. Worldwide, it has been postulated that carbon dioxide levels are due to increase up to 450 ppm by 2040, if the current rate of increase persists, which is believed will cause rapid decline of coral reefs due to acidification, mass bleaching and other environmental impacts (Veron and others, 2009).

The absorption of the excess carbon by seawater causes chemical reactions that result in the reduction in the pH of seawater. The increase of carbon dioxide increases the amounts of bicarbonate and hydrogen ions resulting in the lowering of the pH which in turn lowers the concentration of carbonate ions (Feely and others, 2009, Borges and Gypens 2010, Rhein and others, 2013) thus making them less available for the formation of calcium carbonate in marine organisms. The mean pH of surface waters in the open ocean ranges from 7.8 to 8.4, thus the ocean remains mildly basic (pH >7) at present (Rhein and others, 2013). It has been estimated that the pH of the ocean surface will drop by 0.3 – 0.4 units by the end of this century (Feely and others, 2009, Rhein and others, 2013). Though the consequences of changes in pH and the saturation state of carbonate ions for marine organisms and ecosystems are just beginning to be understood, and it is expected that the calcification rates of most marine pelagic and benthic calcifying organisms will decrease (Borges and Gypens 2010, Rhein and others, 2013).

Changes in pH have been documented in cold oceans of the high latitudes where carbon dioxide is more soluble and it is projected that the impact in the tropics will begin to be seen between 2030 and 2050 (Veron and others, 2009). Further to this, Veron and others (2009) indicate that when carbon dioxide levels reach 450 ppm, calcification of coralline algae will be inhibited whilst that of corals will be reduced by half with shallow water branching corals becoming brittle and susceptible to breakage leading to habitat deterioration.

Experimental work has contributed a greater understanding of the anticipated responses to ocean acidification. Findings of laboratory experiments, which are usually short-term in nature, spanning over a period of a few hours to weeks, show that the typical response in most organisms has been the loss of the carbonate skeletons in low pH environments (Doney and others, 2009). In some organisms, reduced fertilization success and developmental rates have been documented (Doney and others, 2009). Therefore impacts on food chains are anticipated (Trilbollet and Golubic 2011). Associated organisms that feed on corals (known as bioeroders) such as boring bivalves, grazers, such as urchins and fish, are expected to show reduced grazing impacts as these organisms also have calcified parts such as shells and mouth parts which would similarly be affected by the low pH environment (Trilbollet and Golubic 2011).

Several planktonic species have demonstrated resilience to increased carbon dioxide under experimental conditions (Doney and others, 2009). From experimental work undertaken in different parts of the world, it is clear that there could be species of calcifying organisms in the WIO that could survive the pH changes that are anticipated to occur, due to genetic diversity (Veron and others, 2009).

The spatial variability of impact responses by coral reef habitats to climate warming have varied over geographical scales (Graham and others, 2008). For the WIO region it can be implied that similar variations may occur as a result of ocean acidification. In addition to this, some calcifying organisms may shift their distribution ranges to more carbonate rich environments (Doney and others, 2009).

Eutrophication and its impacts on carbonate producers

Runoff from terrestrial sources due to urban development, agriculture and deforestation form a crucial link to lowered water quality of coastal areas (Veron and others, 2009). Sewage contributes to nutrient enrichment through the enhanced amounts of phosphates, ammonium and nitrates that flow into the sea water. Bjork and others (1995) documented a 60 per cent decrease in the cover of coralline algae that were close to sewage sources in Zanzibar. Further to this, a decline in growth rates of coralline algae was also documented at high phosphate concentrations while increased ammonium and nitrate levels did not have significant effects (Bjork and others, 1995).

The effects of eutrophication can also have far reaching consequences on seagrass habitats as high nutrient levels impact negatively on seagrasses, changing habitat structure (Deegan and others, 2002). As the seagrass environment plays a critical role in supporting the calcification of associated coralline algae (Kangwe and others, 2012) the implications of the loss of seagrasses due to eutrophication would also impact the calcification process and cause a decline in the abundance of associated carbonate producers.

Impact of (rising) ocean temperature

In many parts of the Western Indian Ocean region 45 per cent of the living corals were killed through bleaching during the warm temperature events of 1998 (McClanahan and others, 2011). Since the first occurrence in the late 1970s bleaching events linked to the El Niño cycles have occurred at intervals of every 4 – 7 years and are expected to occur more frequently in the future as ocean temperatures rise (Veron and others, 2009). Small increases in sea temperature of 1 – 2 ^{o}C destabilize the relationship between corals and their symbiotic algae (zooxanthellae) on which they rely on for energy and growth (Veron and others, 2009). In corals, the symbiotic relationship between the corals and zooxanthellae is critical as the zooxanthellae enhance coral calcification by providing a favorable environment for the deposition of calcium carbonate (Pearse and Muscatine 1971). The high temperatures result in the loss of the zooxanthellae from the coral tissues leaving them bleached or white in color (Veron and others, 2009). The consequences are the physical breakdown of coral structures as well as enhanced chemical breakdown in the event of ocean acidification (Andersson and Gledhill 2013).

Studies in the WIO region documented a decline in the richness of fish species in response to the loss of coral cover due to bleaching due to the loss of the physical structure of the reef (Graham and others, 2008). Live coral has been found to be important for the settlement of fish larvae therefore bleaching events lead to diverse impacts across the food chains associated with the coral reef ecosystem (McClanahan and others, 2011).

Further to this, Graham and others (2008) noted that in areas where corals extend to a depth of 50 m such as in atoll environments, the deeper waters could provide a refuge from temperature fluctuations for broodstock of corals which enable faster recovery of corals in shallow areas of these regions. Such areas would be important for integration into monitoring and experimental studies that provide greater insights into the role of uninhabited atolls in the management of climate change impacts (Knowlton and Jackson 2008).

Bioerosion and its impacts on carbonate producers

Coral reefs are governed by constructive forces such as calcification which lead to their growth as well as destructive forces that cause degradation, which include physical, chemical and biological erosion (Trilbollet and Golubic 2011, Andersson and Gledhill 2013). The erosion of reefs internally is through organisms such as cyanobacteria, fungi, sponges and polychaetes which excavate into the carbonate structures as they search for shelter and food (Trilbollet and Golubic 2011). External bioeroders include grazers, such as echinoderms and fishes, that graze on carbonate surfaces with their teeth (Trilbollet and Golubic 2011). The process of bioerosion causes the breakdown of corals into fine sediment that is deposited on the seabed (Trilbollet and Golubic 2011). Corals are continually being eroded through these processes and bioeroders constitute a food source for fish (Stromberg 2004).

Trilbollet and Golubic (2011) have postulated that ocean acidification combined with eutrophication, increasing temperatures and high irradiance will have impacts on bioerosion rates. The lower pH caused by acidification is expected to reduce calcification rates of corals which presents an opportunity for the increase of bioerosion by internally boring organisms (Trilbollet and Golubic 2011). Under normal situations, corals are able to control the rate of intrusion by internal bioeroders however this control may breakdown under acidification scenarios. The scenario of high bioerosion and poorly developed reefs has been documented in the eastern tropical Pacific where carbon dioxide levels are naturally high and the seawater pH is low and high nutrient levels exist (Andersson and Gledhill 2013).

Climate change-related sea level rise

The variation in sea levels is due to the transfer of water between the ocean, continents, ice sheets and the re-distribution of water within the ocean due to tidal changes and changes in the oceanic and atmospheric circulation (Rhein and others, 2013). It has been estimated that globally the average sea level has risen over the 20th century, with a mean rate of 1.7 mm/a between 1900 and 2010 and of 3.2 mm/a and between 1993 and 2010 (Rhein and others, 2013). Normal reef growth has been estimated to be approximately 6 mm/a and reefs have been able to grow upwards and keep up with the rate of the rising sea level (Veron and others, 2009). However, higher rates of sea level rise will have implications on the ability of coral reefs to keep up growth, which, when combined with other stressors such as acidification and high impact weather events, degradation of the coral reef environment could be significant (Veron and others, 2009).

Extractive use of carbonate producers

The reef environments of the WIO region provide habitats for many tropical fish species that are important for commercial and artisanal fisheries. They also provide materials such as shells for sale and coral rock used in the construction industry. As a result, many coral reefs around the WIO region are under threat from over-utilization as well as from visible anthropogenic influences such as pollution, sedimentation, nitrification and the damaging effects of fishing (ASCLME/SWIOFP 2012).

CONCLUSIONS

The WIO region is still considered to be relatively pristine compared to other regions of the world, however it is increasingly being threatened with signs of degradation seen due to natural climate change variability as well as anthropogenic impacts (UNEP/Nairobi Convention Secretariat 2009). The coastal zone of the WIO region supports over 60 million people (UNEP/Nairobi Convention Secretariat 2009). This has led to pressures associated with urbanization, most significant in mainland states where urban centres such as Mombasa (Kenya), Dar es Salaam (Tanzania), Maputo (Mozambique) and Durban (South Africa) support populations of between 2 and 4 million (UNEP/Nairobi Convention Secretariat 2009).This has led to localized pollution from domestic, industrial and agricultural sources leading to the degradation of coastal waters and sediments, resulting in a loss of biological diversity, human health problems and a reduction in fish stocks and catches (UNEP/Nairobi Convention Secretariat 2009).

There is an expanding pool of knowledge about the carbonate producers in the WIO and the few studies available provide a glimpse into the critical role that these organisms play in a world of increasing carbon (Kangwe and others, 2012, Semesi 2009).

Inferences can be made from the experimental work documented by Doney and others (2009) that due to the highly diverse marine flora and fauna that characterizes the WIO region, the responses to increased acidification and eutrophication of the ocean will be varied with some species expected to be resilient to these changes.

RECOMMENDATIONS

McClanahan and others (2011) stress the importance of identifying areas where reefs have exhibited resilience to the current climate stresses and establishing management regimes in such areas to ensure that there will be a pool of genetic material that can survive the increasing climatic impacts. In their study, they identified the region from southern Kenya to northern Mozambique as critical for the focus of regional management initiatives aimed at maintaining high diversity of reef habitats by reducing fishing impacts and pollution.

Further to this, Maina and others (2013), stress the fact that human impacts such as deforestation which leads to sedimentation, overfishing, coral destruction through physical means and sewage outflows present a greater threat to carbonate producers. They argue that land use changes have a far greater impact than climate change in their study of Madagascar which faces a decline in forest cover due to increased demand for land for agriculture and mining. This has led to a high sediment load and changes in evapotranspiration, ground water discharge and sediment loading into the marine environment. For the survival of reefs in Madagascar they argue that regional land-use management is more important than mediating climate change (Maina and others, 2013).

There is a need for focused studies, that track impacts through food webs, to understand the specific responses of the carbonate producers. As described by Doney and others (2009), programmes that provide for systematic, cost-effective monitoring of surface water chemistry and long-term laboratory manipulative experiments are critical in understanding the responses of carbonate producers in a fast changing world.

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