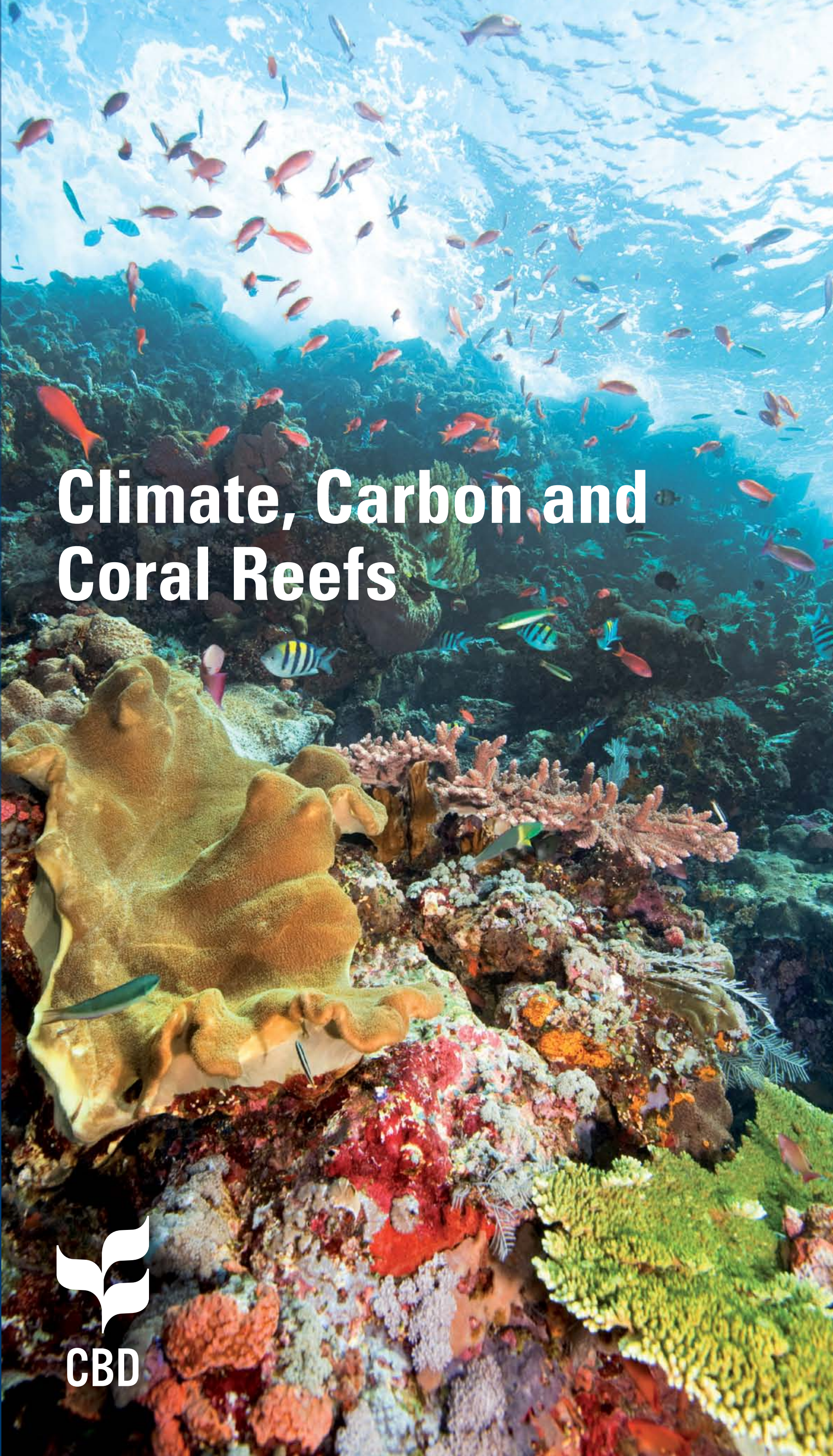

Climate, Carbon and Coral Reefs

CBD

World Meteorological Organization
Weather • Climate • Water

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Climate, Carbon and Coral Reefs

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NOTE

Foreword

Climate change is one of the most pressing issues facing the world today. Scientific research has unequivocally established that greenhouse gas emissions are leading to increasing changes in the Earth's climate. In its Fourth Assessment Report, the Intergovernmental Panel on Climate Change, a body co-sponsored by the World Meteorological Organization and recipient of the 2007 Nobel Peace Prize, stated authoritatively that the rate at which the climate is changing may be considerably greater than suggested by all earlier estimates. Increasing temperatures, sea level rise and drought, as well as changes in precipitation patterns and in the frequency and intensity of extreme events, are the source of additional uncertainties and stress on the world's ecosystems.

Climate change has serious impacts on biodiversity, while changes in biological systems can in turn affect the climate. Climate change is an important factor contributing to the loss of biological diversity, in particular since numerous species and ecosystems are unable to migrate fast enough to keep pace with the rapid changes in temperature and rainfall affecting their habitat. The Millennium Ecosystem Assessment, prepared by approximately 1 360 experts from 95 countries and published in 2005 by the World Resources Institute, made it clear that climate change is the second root cause of the unprecedented loss in biodiversity that is unfolding on our planet. After examining over 5 000 African plant species, one study determined that the proportion of suitable habitats expected to shrink in size or shift as result of climate change is between 80 and 90 per cent, or even considerably more.

Tropical coral reefs cover an area of over 284 000 km^2, providing habitat for thousands of species and yielding more than US$ 30 billion annually in global goods and services, such as coastline protection, tourism and food. Corals reefs are now threatened by the increasing concentrations of carbon dioxide in the atmosphere, while warmer sea temperatures are disturbing the delicate symbiosis between coral organisms and algae. For example, 16 per cent of all tropical coral reefs were killed off by thermal stress during a single extreme El Niño–Southern Oscillation event in 1997–1998. As a result of escalating atmospheric levels of carbon dioxide, more of this gas is being dissolved in the world's oceans. This has already reduced ocean pH and the trend is projected to continue. Moreover, the altered ocean chemistry is expected to have major corrosive effects on marine ecosystems and to alter the calcification rates of corals, phytoplankton and other species.

Observations and extrapolations from the past, as well as all projections into the future, clearly indicate the gravity of the situation, so it will be increasingly important for all those engaged in the physical aspects of climate change to work even more closely with the research communities seeking to mitigate the current tendency towards coral reef degradation. In this respect, the National Meteorological Services are being called upon with greater frequency to provide support to research in real-time oceanography and marine biology. This brochure illustrates some of the linkages among climate, carbon dioxide and coral reefs, while describing the necessary steps to appropriately assess the threats at the local and regional scales, as well as to devise suitable monitoring, conservation and mitigation strategies.

We wish to thank Mark Jury, Scott Heron, Claire Spillman, Kenneth Anthony, Peter Dexter and Mannava Sivakumar for preparing this informative brochure, which we hope will be especially useful to all those concerned with the vital conservation and protection of coral reefs.

Michel Jarraud
Secretary-General
World Meteorological
Organization (WMO)

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Executive Secretary
Convention on Biological
Diversity (CBD)

Summary

Oceans cover 70 per cent of the Earth's surface area, forming the largest habitat on the planet. Coastal and shallow-water areas contain some of the world's most diverse and productive ecosystems, including mangroves, coral reefs and seagrass beds. Coral reefs, referred to as the "tropical rainforests of the ocean", are estimated to provide benefits worth approximately US$ 30 billion in goods and services on an annual basis, including income from and resources for tourism, fishing, building materials and coastal protection.[1] Although reefs cover only 0.2 per cent of the world's ocean, they contain about 25 per cent of marine species and are renowned for their biological diversity and high productivity.

In the past two decades, corals reefs have come under siege by a growing global threat: increasing concentrations of carbon dioxide (CO_2) in the atmosphere. High CO_2 emissions lead to "double trouble" for coral reefs. First, the trapping of heat in the atmosphere leads to ocean warming, which can cause extensive coral bleaching events and mass mortalities. The global devastation of coral reefs from record warming of the sea surface in 1997/98 was the first example of what is likely to occur in the future under a warming climate. Second, high CO_2 levels lead to ocean acidification, which reduces the ability of coral reefs to grow and maintain their structure and function. Coral reefs are some of the most species-rich habitats in the world, and they are also among the most sensitive to our current high-emission path.

This brochure summarizes the CO_2 threat to coral reefs, the science supporting projections and the solutions that are needed to prevent the loss of one of the world's natural wonders.

Introduction

Coral reefs are marine systems with one of the highest levels of biodiversity on the planet and they provide an array of valuable goods and services. They protect shores and islands from the impacts of storm waves and surges. They provide habitat for reef fish and invertebrates, sustaining the livelihood of millions of people in developing countries, and generate revenues for

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1 Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, 50:839–866.

coastal communities from both tourism and commercially valuable fisheries. Accounting for these and a myriad of other services, the value of coral reefs to humankind has been estimated, on average, as US$ 130 000 per hectare per year.[2]

Estimates of the state of coral reefs worldwide by the Global Coral Reef Monitoring Network (GCRMN) – based on the expert opinions of 372 coral reef scientists and managers from 96 countries – suggest that the world has lost 19 per cent of the original area of coral reefs, 15 per cent are seriously threatened with loss within the next 10–20 years, and an additional 20 per cent are under threat of loss in 20–40 years.[3] The latter two estimates have been made under a "business-as-usual" scenario that does not consider the looming threats posed by global climate change or the possibility that effective future management may conserve more coral reefs. Threats to coral biodiversity include: coastal development, overfishing, sediment and nutrient pollution discharge, global warming, ocean acidification from CO_2 emissions, human disturbance beyond sustainable limits and inadequate management.

Climate change

The climate system is dynamic and interactive, consisting of the atmosphere, land surface, polar ice, oceans and other bodies of water, and living things. The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to assess scientific information on climate change, as well as its environmental and socio-economic impacts, and to formulate response strategies. Climate change is defined by IPCC as any change in climate over time, whether due to natural variability or as a result of human activity. Evidence from observations of the climate system has led to the conclusion that human activities are contributing to a warming of the Earth's atmosphere. Human activities – primarily the burning of fossil fuels and changes in land cover – are modifying the concentration of atmospheric constituents and properties of the Earth's surface that serve to absorb or

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2 *Science Daily*, 2009: What are coral reef services worth? $130 000 to $1.2 million per hectare per year (http://www.sciencedaily.com/releases/2009/10/091016093913.htm#at).

3 Wilkinson, C. (ed.), 2008: *Status of Coral Reefs of the World: 2008*. Townsville, Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre.

scatter radiant energy. In particular, increases in the concentrations of greenhouse gases and aerosols are strongly implicated as contributors to climatic changes observed during the twentieth century and are expected to contribute to further changes in climate in the twenty-first century and beyond.

As the Earth's climate has shown continued signs of change and climate research has intensified over recent decades, growing evidence of anthropogenic influences on global climate change has been found. Correspondingly, IPCC has made increasingly definitive statements about human influence on the world's climate. The IPCC Fourth Assessment Report (AR4), which focused on observed climate change and the potential impacts of future climate change, was released in 2007. The amount of carbon dioxide in the atmosphere has increased by about 35 per cent in the industrial era, and this increase is known to be due to human activities, primarily the combustion of fossil fuels and removal of forests. In 2005, the concentration of carbon dioxide exceeded the natural range that has existed over 650 000 years (AR4). Evidence from observations of the climate system show an increase of 0.74°C ± 0.18°C in global average surface temperature during the twentieth century and an even greater warming trend since 1950 (0.13°C ± 0.03°C per decade).

Another manifestation of changes in the climate system is a warming in the world's oceans. Warming causes seawater to expand and thus contributes to sea level rise. This factor, referred to as thermal expansion, has contributed approximately 1.6 mm per year to global average sea level since 1990 (see Figure 7a).

Perhaps of greater concern than the change in atmospheric CO_2 and temperature are the rates at which change is occurring. Recent increases in global temperature and CO_2 concentration have occurred 70 times faster and an astounding 1 050 times faster, respectively, than mean rates of change for the past 420 000 years as calculated from ice core data.[4]

Looking ahead, IPCC projects that the global mean surface air temperature will continue to rise over the twenty-first century, driven mainly by increases in anthropogenic greenhouse gas concentrations, with the warming proportional to the associated radiative forcing. An assessment based on the

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4 Hoegh-Guldberg, O. et al., 2007: Coral reefs under rapid climate change and ocean acidification. *Science,* 318:1737–1742.

available observations and an ensemble of coupled numerical models indicates that the global mean surface air temperature warming with a doubling of atmospheric CO_2 is likely to lie in the range of 3ºC ± 1ºC.

Climate extremes encompass both extreme weather, with durations of minutes to days (the synoptic timescale), and extreme climate events, with durations of months in the case of periods of wet/stormy weather, or years in the case of drought. The frequency with which climate extremes occur is expected to change during the next century. For tropical cyclones, there is a potential increase of 10–20 per cent in the intensity of storms.

Climate change and coral reefs

Climate change and high carbon emissions can affect coral reef systems in a number of ways. Emerging threats to coral reefs are bleaching and mortality associated with global warming. Elevated ocean temperatures are recognized as the primary cause of mass coral bleaching events.[5] Coral bleaching results from the loss of symbiotic algae, known as zooxanthellae, from coral tissues during times of stress.[6] The biology of reef-building corals breaks down when summer temperatures exceed the corals' physiological thresholds for an extended period of time (weeks to months). The results can be widespread bleaching, in which corals lose their ability to grow and reproduce, and in severe cases, die (Figure 1). The consequence can be loss of reef structure and habitats for thousands of associated species of fish and invertebrates. The intensity and scale of observed bleaching events have increased since the 1960s, and major bleaching events in 1998, 2002 and 2005 have negatively affected entire reef systems.[7]

Coral reefs are also under growing threat from ocean acidification, which is a chemical consequence of increasing carbon dioxide concentrations in the atmosphere. Ocean acidification refers to the reduction in ocean pH as CO_2 is

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[5] Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, 50:839-866.

[6] Glynn, P.W., 1993: Coral reef bleaching: ecological perspectives. *Coral Reefs*, 12:1–7

[7] Berkelmans, R. et al., 2004: A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. *Coral Reefs*, 23:74–83.

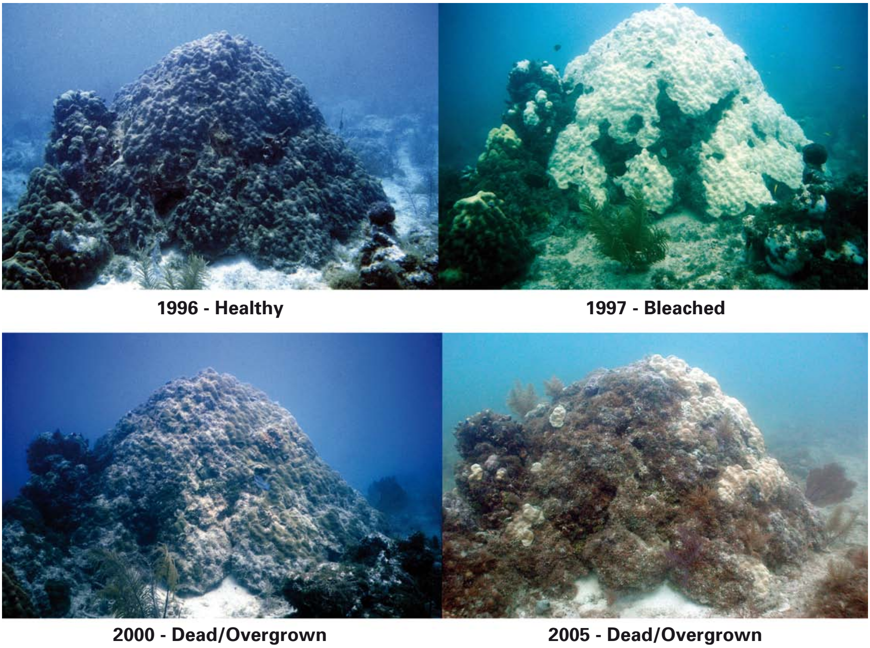

Figure 1. This 500-year-old coral head was healthy in 1996, but suffered a bleaching event in 1997 and had yet to recover to a healthy state as of 2005. (Photo: Craig Quirolo, Reef Relief/Marine Photobank)

taken up by the ocean surface. An even more critical factor, however, is that a drop in pH leads to a loss of carbonate ions, which are required for all marine calcifiers, including corals, to build their skeletons. The impacts of acidification are already visible as waters are becoming increasingly corrosive to calcifying organisms, such as corals. Calcification of corals in the Great Barrier Reef has declined by 14.2 per cent since 1990.[8] Projections indicate that if current trends in greenhouse gas emissions continue, a significant proportion of the planet's remaining reefs may be lost to coral bleaching over

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8 De'ath, G. et al., 2009: Declining coral calcification on the Great Barrier Reef. *Science*, 323:116–119.

the next century.[9] The expanding body of experimental studies suggests that ocean acidification is likely to shift coral reefs from growing to dissolving structures by the end of the century. More frequent severe storms, which are likely in the future, will exacerbate the impacts of acidification, as more brittle corals will have greater sensitivity to storm damage. Furthermore, sea level rise, in combination with increasing storm intensity and ocean acidification, will increase the risk of storm surge damage for many tropical coastal communities.

Climate change and ocean acidification can have far-reaching implications for the health and functioning of coral reef ecosystems. Global impacts of increasing CO_2 will occur in combination with regional or local-scale disturbances, such as deteriorating water quality and destructive fishing practices. These can act together to significantly degrade the resilience of coral reefs to the point that reefs are unable to recover from even minor disturbances. Such interactions or potential feedbacks between global CO_2 effects and local/regional disturbances affecting reef resources (Figure 2) heighten the urgency of abating carbon emissions.

Role of meteorological services in addressing climate and coral reef issues

Marine meteorological services have traditionally delivered warnings of gales, storms, sea waves and tropical cyclones mainly in support of shipping activities. With growing recognition of the impacts of global change on the coastal ecology, however, meteorological services are increasingly called upon to provide support to real-time oceanography and marine biology.

Using the Predictive Ocean Atmosphere Model for Australia (POAMA), the Australian Bureau of Meteorology currently provides real-time and post-processed operational information and seasonal forecasts of ocean conditions, particularly around Australia. The Ocean Services section provides high-resolution five-day ocean forecasts (BLUElink), seasonal forecasts of ocean conditions, tidal predictions, tsunami services, ocean surface wave predictions and a range of ocean temperature products.[10] In particular,

9 Wilkinson, C. (ed.), 2008: *Status of Coral Reefs of the World: 2008*. Townsville, Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre.

10 http://www.bom.gov.au/oceanography/.

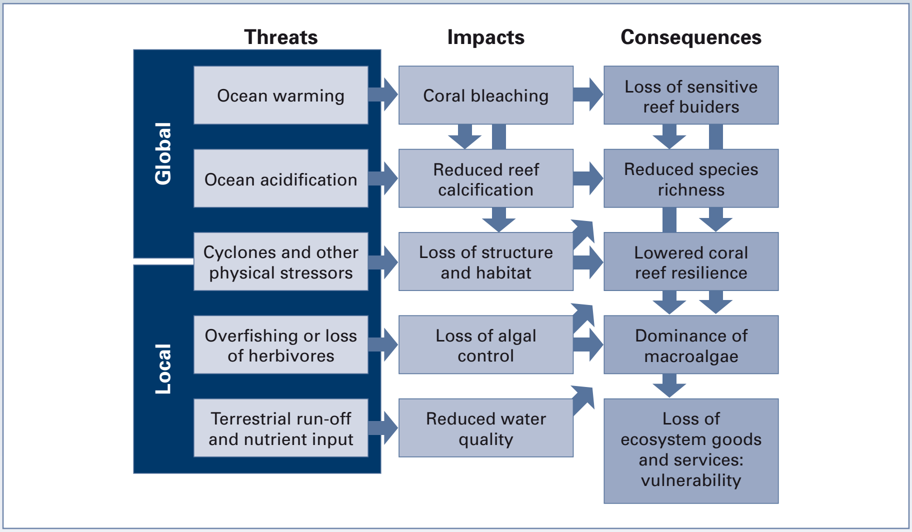

Figure 2. Links between global threats of carbon emission (here mainly climate change, ocean acidification and tropical storms) and local or regional disturbances from overfishing and declining water quality and their combined flow-on effects on reef resilience and ecosystem goods and services. (Anthony, K.R.N. and P.A. Marshall, 2009: Coral reefs and climate change. In: *A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009* (E.S. Poloczanska, A.J. Hobday and A.J. Richardson, eds). Southport, National Climate Change Adaptation Research Facility).

seasonal forecasts of sea surface temperatures from the POAMA coupled ocean–atmosphere prediction system are provided for the Great Barrier Reef.[11] These forecasts form an important component of the early warning system in the Coral Bleaching Response Plan of the Great Barrier Reef Marine Park Authority and other reef management plans. Advance warning of anomalous warm conditions, and hence bleaching risk, allows for a proactive management approach and is an invaluable tool for reef management under a changing climate.

The United States National Oceanic and Atmospheric Administration (NOAA), which includes the National Weather Service (NWS) and the National Environmental Satellite, Data, and Information Service (NESDIS), provides

[11] Spillman, C.M. and O. Alves, 2009: Dynamical seasonal prediction of summer sea surface temperatures in the Great Barrier Reef. *Coral Reefs*, 28:197–206.

significant infrastructure and support to the science and management of coral reefs. The NOAA Coral Reef Watch (CRW) programme provides global, near real-time monitoring for coral bleaching risk due to thermal stress, using satellite-derived sea surface temperature (SST).[12] With this information, reef managers can undertake local strategies to maximize the potential for reefs to survive and recover from bleaching events. More recently, CRW has provided near real-time regional risk assessments for outbreaks of coral disease, also determined using satellite SST. In addition, a global seasonal outlook for thermal stress is produced using model forecasts of SST, and will soon utilize model output from the NWS National Centers for Environmental Prediction. In situ oceanographic monitoring for coral reef science and management is provided at reef locations across the Pacific and Caribbean/Atlantic regions, and also through conservation efforts in 14 marine sanctuaries, which cover more than 380 000 km^2. The combined resources of the NOAA Coral Reef Conservation programme provide a multidisciplinary approach to the science and management of coral reef ecosystems and their users.

Sea temperature trends

The tropical upper ocean, where coral reefs grow, has warmed more than 0.01°C per year over the past 50 years and this warming rate is increasing.

Most of the tropical zone has experienced a warming rate in the upper 100 m of more than 0.01°C per year over the past 50 years, which is equal to a rate of 1°C per century (Figure 3). Elevated ocean temperatures are associated with increased risk of coral bleaching and disease outbreaks, leading to a reduction in diversity and ecosystem function. In the equatorial Pacific and Indian oceans, waters below 100 m have cooled, thus increasing stratification (warm above cool), which reduces the potential for mixing. As warm surface waters have a low solubility of CO_2 and receive a lower nutrient supply from deeper layers, primary production declines. Changes in carbonate ion availability will be compounded by the lack of mixing between upper warm and lower cool layers. Most IPCC model projections indicate a warming of 2°C in the twenty-first century (Figure 2c). In addition, air temperature trends exceed those for the ocean due to "thermal inertia", so the flux of heat from sea to air is declining. Warming of ocean temperatures also affects the frequency and intensity of tropical cyclones.

[12] http://coralreefwatch.noaa.gov/.

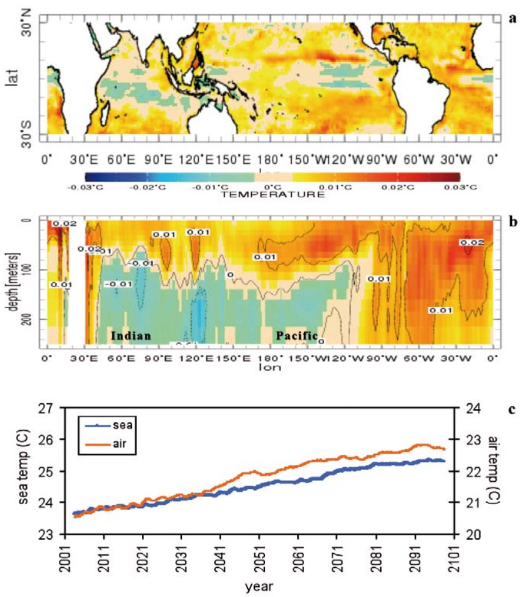

Figure 3. Temperature trends in 1958–2007 (ºC/year) from reanalysis data: (a) 1–100 m depth average; (b) east–west section averaged 30º N–30º S; (c) time projection from IPCC AR4 Geophysical Fluid Dynamics Laboratory (GFDL) model simulation, where air is averaged over 1–700 m height, sea is 1–100 m depth, and both are smoothed with a 5-year running mean. Data are drawn from the International Research Institute for Climate and Society (IRI) database (http://iridl.ldeo.columbia.edu).

Frequency of Coral Bleaching

Coral bleaching has occurred to some extent in all major coral reef systems of the world and may be increasing in frequency and severity.

Reef regions around the world experience varying thermal environments (Figure 4). Corals are, however, acclimated to the temperature range present at their specific location. While the western Indian Ocean and Caribbean are slightly cooler than other ocean basins, which means that reefs there do not experience warmer temperatures to the same extent, reefs are "conditioned" to the cooler temperatures and tend to bleach at lower temperatures (above 30ºC). Conversely, western Pacific reefs generally have a higher bleaching threshold (around 30.5ºC). Peak warming events took place in the western Indian Ocean and north-western Pacific in 1997/98, in the north of Australia and central Pacific during 2003/04, and in the Caribbean in 2005. Reports indicate that about half of the reefs affected by bleaching have recovered.[13] Models presented in IPCC AR4 predict significant increases in the frequency of sea temperatures above the 30.5°C threshold after 2040 as atmospheric CO_2 concentration rises.

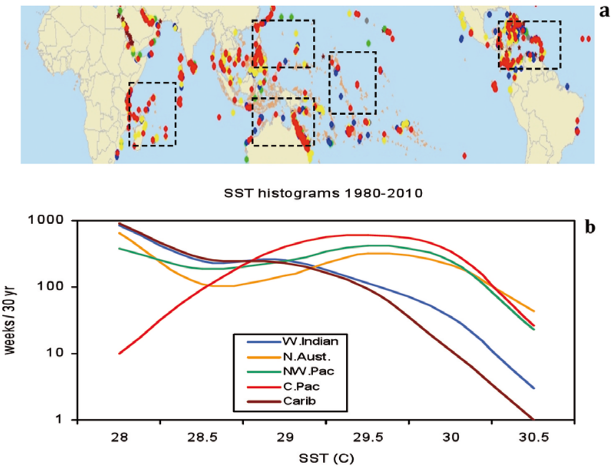

Figure 4. (a) Coral bleaching intensity (green = none; blue = low; yellow = medium; red = high. Drawn from http://reefgis.reefbase.org/, with an overlay of regional boxes for sea surface temperature analysis. (b) Frequency distribution of sea surface temperature for the five reef regions (http://iridl.ldeo.columbia.edu).

Ocean salinity trends

Variations in ocean salinity, with levels becoming both fresher and saltier, may have a significant impact on coral reefs due to their low tolerance for changes in this parameter.

Changes in precipitation, evaporation and river runoff affect the salinity of the upper ocean. Salinity trends over the past 50 years vary significantly across global reef regions (Figure 5). Ocean waters have become more fresh in South and South-East Asia, the northern Pacific and the Caribbean, where

[13] Wilkinson, C., 2008: *Status of Coral Reefs of the World: 2008*. Townsville, Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre.

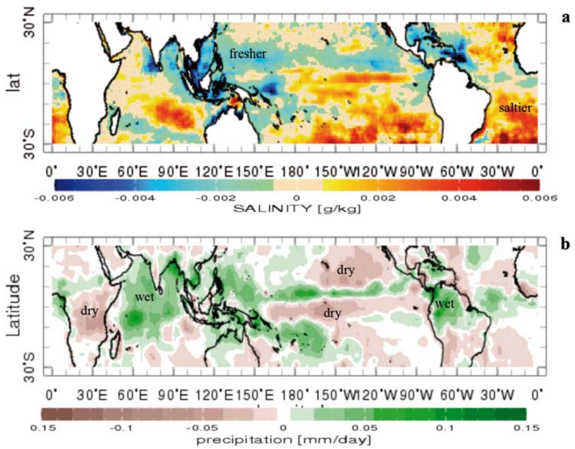

Figure 5. (a) Salinity trends in 1958–2007 (g/kg/yr), 1–100 m depth averaged; (b) rainfall trends in 1979–2009 from Global Precipitation Climatology Project (GPCP) satellite-gauge analysis (http://iridl.ldeo.columbia.edu).

rainfall during the satellite era (1979–2009) has increased. Conversely, the ocean has become saltier in the southern hemisphere, which is likely related to decreased rainfall over Africa and the subtropical Pacific. Changes in the frequency and severity of tropical cyclones may also affect rainfall, and thus salinity, in certain regions. Coral reefs have a narrow salinity tolerance range, so large fluctuations in salinity may have adverse impacts on reef health. Interconnections between salinity and hydrology also suggest that increased rainfall in South-East Asia and the Amazon region generates river plumes that extend offshore into reef environments. Associated sediment loading and harmful nutrients have negative impacts on reef ecosystem health.

Global trends in circulation

Changes in winds and currents can alter the water environment (including salinity, temperature, mixing and upwelling) to which corals have acclimated, increasing their vulnerability to disturbance events.

Easterly trade winds have generally increased during the past 50 years across the Atlantic, southern Indian and northern Pacific oceans (Figure 6). The acceleration of trade winds in the southern hemisphere (mainly since 1980) corresponds with increased evaporation and salinity (seen in Figure 5), which may result in adverse impacts on reef health in those regions.

Ocean currents have shown the most pronounced trends over the past 50 years along the Equator, exhibiting increased eastward currents across the Indian and Pacific oceans, while the Atlantic has experienced increased westward currents. The westward North Equatorial Current of the Pacific (10° N) has increased, consistent with the observed change in wind. Changes in currents can affect coral reefs through a reduction (or increase) in mixing between surface and deep waters (with follow-on effects of changes in nutrient levels), modified advection of waters (which can influence connectivity between reef systems, particularly in the open ocean) and potential changes in lagoonal flushing rates.

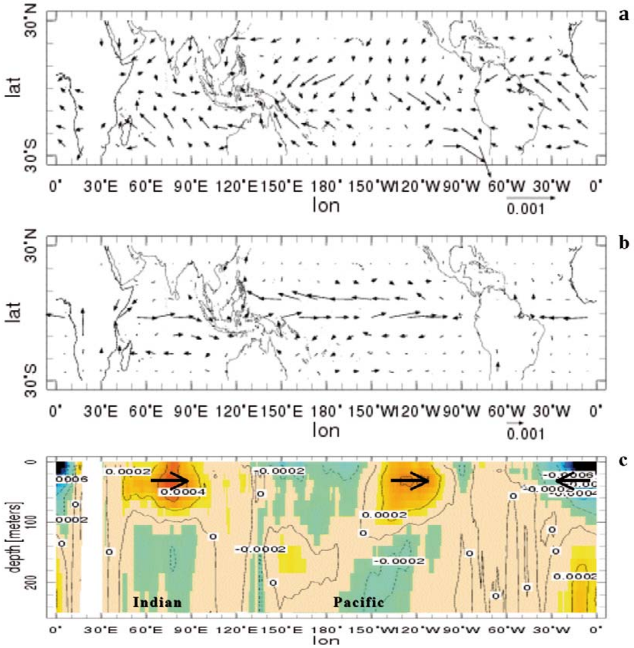

Figure 6. (a) Trends in wind stress in 1958–2007 (N/m²/yr), related to the square of wind speed (from the European Centre for Medium-Range Weather Forecasts). Trends in currents in 1958–2007 (m/s/yr): (b) 1–200 m depth averaged map; (c) east–west section averaged 30° N–30° S (http://iridl.ldeo.columbia.edu).

Sea level rise

Global mean sea level has risen at an increasing rate through the past 200 years. While coral growth can generally keep up with the rate of rise, the impacts on human communities can be significant.

Global sea level has risen at a rate of more than 1 mm per year (Figure 7a). This mean upward trend is well known, but there are regional and temporal differences. Regional differences arise not only from changes in land height, but from local differences in ocean heat content and the pattern of winds and currents. Over the past 50 years, sea levels have risen faster across the subtropical belt, particularly the northern Pacific and Caribbean (Figure 7b).

Sea level rise over coral reefs provides corals with greater space to grow upward. While corals are growing, however, and have not yet fully occupied this new space, there is the potential for increased wave action, which can

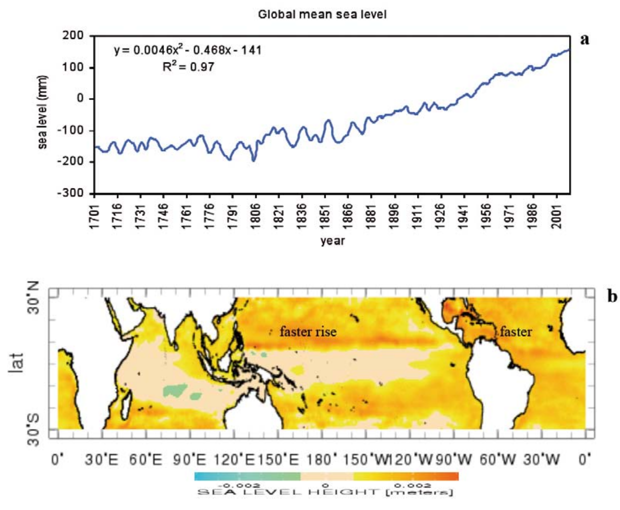

Figure 7. (a) Changes in mean sea level derived from tide gauges located between 30° N and 30 °S with polynomial fit (analysed from the Climate Explorer Website: http://climexp.knmi.nl); (b) regional variation in rate of sea level rise between 1958 and 2007 (departure from the mean global rate of rise, analysed from the IRI database via the Website http://iridl.ldeo.columbia.edu).

damage corals. Of greater potential importance for corals is increased sedimentation due to erosion from land areas that are newly exposed to seawater. The greatest impact is likely to be on human communities living adjacent to coral reefs, however, through loss of land, including that used for agriculture, due to saltwater intrusion, and increased flooding and exposure to waves.

Tropical cyclone impacts

Tropical cyclones can benefit coral reefs by alleviating thermal stress. More severe storms, however, have relocated large coral colonies and reduced coral gardens to rubble.

Tropical cyclones (TCs) develop over tropical waters in late summer and bring with them high winds, heavy rainfall and a deeper mixed layer. The formation and intensification of TCs are related to various environmental factors, including sea surface temperature, vertical wind shear and cyclonic spin.[14]

The common perception is that TCs are only destructive, but they can also provide ecological benefits to coral reef systems.[15] As the upper ocean warms during summer, corals may experience thermal stress and bleaching. TCs can mitigate thermal stress through three mechanisms. First, heat energy from surface waters is transferred into the atmosphere through evaporation. The amount of heat transferred is related to the intensity and extent of the TC. Second, surface water temperatures are cooled via increased mixing of deeper waters (upwelling), the magnitude of which depends on wind speeds and water temperature variations with depth. Third, the ocean surface is shaded by clouds of the TC, which allows further cooling of the water and reduces light stress. One example of TC mitigation of thermal stress occurred when Hurricane *Katrina* passed over the Florida Keys as a less-severe Category 1 storm on 26 August 2005. The resultant cooling halted what had been a temperature trend towards coral bleaching. Later, as the storm intensified, it became more destructive.

Waves and currents have a significant influence on the location and diversity of coral assemblages. Some coral species are better suited than others

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14 Heron, S. et al., 2008: Hurricanes and their effects on coral reefs. In: *Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005*. C. Wilkinson and D. Souter (eds). Townsville, Global Coral Reef Monitoring Network.

15 Manzello, D.P. et al, 2007: Hurricanes benefit bleached corals. *Proceedings of the National Academy of Sciences*, 104:12035-12039.

to high-wave environments. In general, "massives" (such as *Porites* spp.) are less affected by wave action than "branching" corals (such as *Acropora* spp.). Slow-growing massives often form a higher fraction of the coral population in swell-exposed areas, while faster-growing, more delicate corals generally thrive in wave-sheltered, low-swell locations. Waves generated during TCs can exceed normal conditions on all parts of the reef, however, overturning colonies and breaking coral branches, causing extensive reef damage.[16] A build-up of rubble and excess sediment can also occur, reducing the availability of suitable substrate. In March 2005, Cyclone *Fay* passed over Scott Reef, Australia, driving *Porites* colonies greater than three metres in diameter onto the reef flat (Figure 8a). Large fields of diverse coral reefs were reduced to a landscape of rubble that was soon overgrown with algae, which in turn limits the capacity of corals to recover.

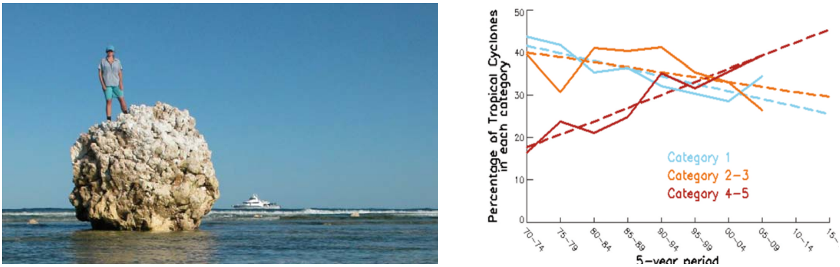

Figure 8. (a) A *Porites* colony in Western Australia that was thrown onto the reef flat as Cyclone *Fay* passed in March 2005 (Australian Institute of Marine Science); (b) global tropical cyclone frequency by category (adapted from Webster et al., 2005).

The capacity of coral reefs to survive TCs in the future will be somewhat dependent upon the combined impact of all threats that corals currently face in a changing climate, including ocean acidification and increased bleaching and disease risk. Climate change may affect the frequency and intensity of TC events. Data since 1970 have shown that the proportion of more severe TCs has increased, while weaker TCs have declined (Figure 8b).[17]

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16 Massel, S.R. and T.J. Done, 1993: Effects of cyclone waves on massive coral assemblages on the Great Barrier Reef: meteorology, hydrodynamics and demography. *Coral Reefs*, 12:153-166.

17 Webster, P.J. et al., 2005: Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, 309:1844-1846.

There are links between TC potential and climate drivers such as El Niño/La Niña, the Madden–Julian Oscillation and the Atlantic Multidecadal Oscillation. These teleconnections are difficult to simulate in current climate models, however. Nonetheless, their projections indicate a reduction in the number of TCs globally.[18] Fewer TCs contribute to a build-up of equatorial heat, which brings an increased intensity of individual events. Predicted changes in intensity are within the uncertainty estimates of the models themselves, however. But one thing is clear: the impact on coastlines of storm surges related to TCs will increase due to rising sea level.

Ocean acidification

One quarter of atmospheric carbon emissions have been taken up by the ocean. This change in ocean chemistry reduces coral growth rate and structure, and can ultimately lead to dissolving coral reefs.

The surface ocean plays a critical role in the global carbon cycle and has absorbed approximately one quarter of the carbon dioxide emitted to the atmosphere from the burning of fossil fuels, deforestation and other human activities during the twentieth century. As more and more anthropogenic CO_2 has been emitted into the atmosphere, the ocean has absorbed greater amounts at increasingly rapid rates. In the absence of this buffering by the ocean, atmospheric CO_2 levels would be significantly higher than at present and the effects of global climate change more marked.

The absorption of atmospheric CO_2 has, however, resulted in changes to the chemical balance of the oceans (which are naturally slightly alkaline), causing them to become more acidic. The change in the commonly referenced pH value since pre-industrial times (the early 1700s) has been a reduction from 8.18 to 8.07. This corresponds to a nearly 30 per cent increase in the concentration of “acidic” hydrogen ions in the ocean, however.[19] With CO_2 concentrations predicted to rise approximately 1 per cent per year in the twenty-first century, ocean pH is expected to decrease too rapidly for evolutionary adaptation of reef systems to keep pace. Acidification limits

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[18] World Meteorological Organization, 2006: Statement on Tropical Cyclones and Climate Change, WMO International Workshop on Tropical Cyclones, IWTC-6, San Jose, Costa Rica.

[19] Orr, J.C. et al., 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437(7059):681–686.

the carbonate minerals in seawater that form the building blocks for coral growth, leading to biological degradation, reduced reef resilience to stress and weakened reef structures.

Ocean pH is associated with many factors, including chlorophyll content, which is a measure of phytoplankton concentration (Figure 9a). Upwelling of cool, low pH waters from deeper layers brings nutrients to the surface, and this stimulates phytoplankton growth. This process lowers pH in the euphotic layer occupied by corals. A relatively low pH value of around 7.9 is evident across west coast upwelling zones and in the cool water tongues that extend westward near the Equator. In the mid-ocean anti-cyclonic gyres, downwelling limits chlorophyll due to low nutrient supply, and it also maintains the ocean pH at around 8.1.

Studies at individual reef sites have been conducted, and a pH proxy record has been reconstructed for the South-West Pacific Ocean that exhibits multi-decadal fluctuations in phase with a low-frequency Pacific Oscillation.[20] Some scientists believe that the downward trend in ocean pH since 1950 is partially due to this oscillation (Figure 9b). The majority opinion, however, is that ocean pH relates to CO_2 absorption, and will decline 0.2 units by 2100 (Figure 9c). As ocean pH is negatively affected by sea temperature, the physical effects of global warming may compound the chemical effects of CO_2 absorption in the world's oceans.

Direct human impacts

Various human activities, such as fishing, land use and tourism, have an impact on coral reefs. Some of these effects are accidental, while others can only be considered intentional.

Approximately 15 per cent of the world's population lives within 100 km of coral reef ecosystems.[21] Anthropogenic pollution is a serious threat to the health of coral reefs (Figure 10). In less-developed regions, river runoff

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[20] Pelejero, C. et al., 2005: Preindustrial to modern interdecadal variability in coral reef pH. *Science*, 309:2204-2207.

[21] Pomerance, R., 1999: Coral Bleaching, Coral Mortality, and Global Climate Change. Report presented by the Deputy Assistant Secretary of State for the Environment and Development to the United States Coral Reef Task Force, 5 March 1999, Maui, Hawaii (http://www.state.gov/www/global/global_issues/coral_reefs/990305_coralreef_rpt.html).

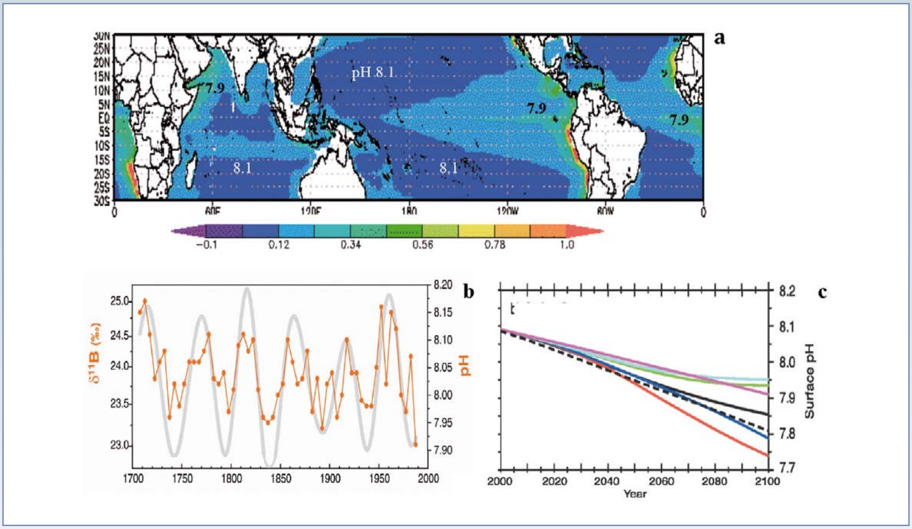

Figure 9. (a) Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mean chlorophyll (mg/m^3) with regional pH values overlaid (1998–2008) (Doney, S.C., 2006: The dangers of ocean acidification. *Scientific American*, 294(3):58–65); (b) multidecadal variations in ocean pH in the South-West Pacific Ocean, determined by variation in isotopic boron (Pelejero, C. et al., 2005: Preindustrial to modern interdecadal variability in coral reef pH. *Science*, 309:2204–2207); (c) global ocean pH change predicted by IPCC AR4 with different emission scenarios. The A1B scenario of gradual CO_2 doubling and then levelling off in 2100 is indicated in black.

(Figure 10b) into the ocean induced by tropical monsoons is often heavily polluted. The dissolved organic content is higher (as observed by satellite, Figure 10c) particularly around India, Malaysia, northern Australia and the Caribbean. The heavily populated continental margins are subject to higher loadings, while the central oceans (such as the Pacific) see little input due to distance from the coast. In developed regions, poor land-use practices (such as fertilizer use and coastal development) can similarly affect coral reefs. Increased organic matter levels have negative impacts on reef health, which are associated with smothering of corals or substrate due to sediment, increased nutrient inputs that promote algal growth, and reduced light conditions.

Measures of exploitation include fish catch in the tropics, which rose from 5 megatonnes per year to 17 megatonnes per year between 1970 and 2008, according to United Nations Food and Agriculture Organization records

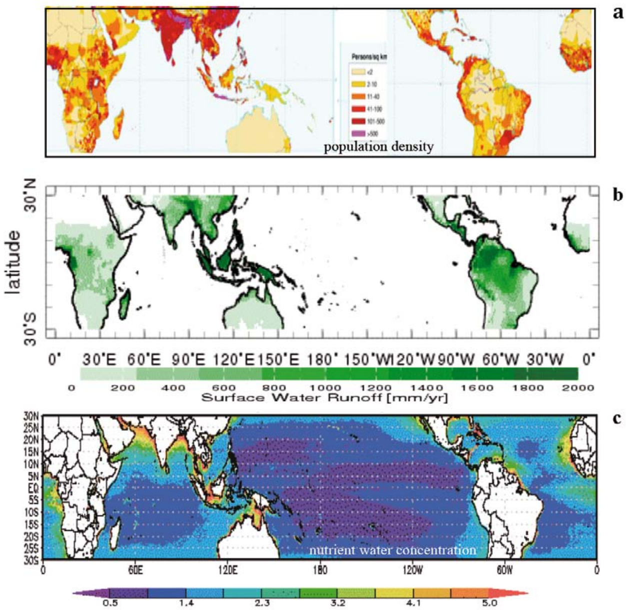

Figure 10. (a) Population density in 2005 (from http://worldpopulation.department-k.com); (b) surface water runoff in 2005, analysed from hydrological model data assimilation; (c) mean organic matter concentration, mg/m^3, 1998–2008 (using algorithm developed for the SeaWifs ocean colour satellite, analysed from the NASA Website: http://gdata2.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month).

(Figure 11). Coral reefs directly yield about 12 per cent of this total and 25 per cent of the fish caught by developing nations.[22] Fishery studies report declining populations at higher trophic levels[23] indicative of overfishing. The Caribbean has seen a significant decline in the catch since the mid-1980s. Removal of herbivores from coral reef ecosystems can reduce the resilience of reefs, because the herbivores consume algae that compete with coral recruits for space. Furthermore, destructive fishing practices (such as the use of cyanide and dynamite) also have a major impact on corals.

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22 Bennett, J., 2003: The Economic Value of Biodiversity: National Workshop. Canberra, Australian Department of the Environment, Water, Heritage and the Arts. http://www.environment.gov.au/biodiversity/publications/scoping-paper/.

23 Paddack, M.J. et al., 2009: Recent region-wide declines in Caribbean reef fish abundance. *Current Biology*, 19:590–595.

Other assessments of exploitation at the local level include a United Nations Educational, Scientific and Cultural Organization (UNESCO) study, which revealed that tourist scuba diving on one coral reef in southern Mozambique exceeded 10 000 dives per year. Such levels of use are unsustainable because of inevitable accidental damage to reefs (http://www.unesco.org/csi/act/maputaland/maputa04tourism.htm).

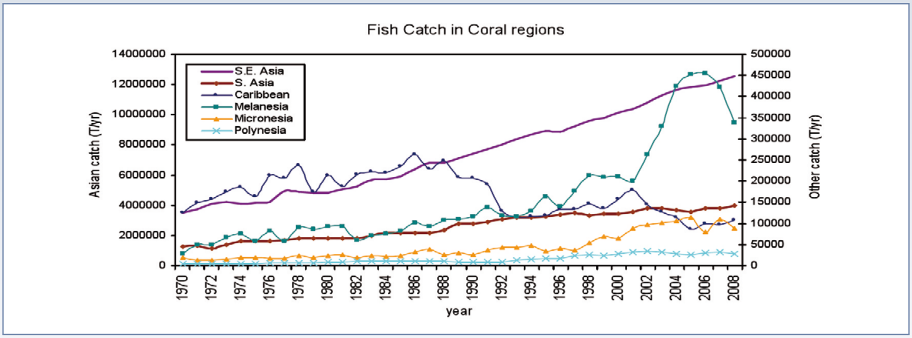

Figure 11. Fish catch in coral regions, 1970–2009 (analysed from the United Nations Food and Agriculture Organization Website: http://www.fao.org/fishery/statistics/global-capture-production/query/en).

The way forward

Immediate action by policymakers to reduce carbon emissions and atmospheric CO_2 concentrations is essential to correct the current trajectory of coral reef degradation. Improved scientific knowledge is imperative and should be used to inform an effective response.

Tropical coral reefs cover an area of over 284 000 km², with most growing above a depth of 100 m. These diverse and productive ecosystems provide a habitat for thousands of species and yield more than US$ 30 billion annually in global goods and services, such as coastline protection, tourism and food. As the world's oceans become less saturated with carbonate ions, corals will build weaker skeletons, grow more slowly and lose competitive advantage over other marine organisms. More brittle coral skeletons are easily damaged by storms, and bioerosion may contribute to less structural complexity of the reef system, reducing habitat quality and diversity. Globally, coral reefs are threatened during this century by a suite of anthropogenic and natural disturbances, including human population growth, coral bleaching from warm events, overfishing, coastal development, land-based pollution, nutrient runoff and coral disease. About 20 per cent of the original area of coral reefs has been lost, with a further 25 per cent threatened in the next century. The effects of global warming and ocean acidification compound the pervasive impacts of marine pollution and other local disturbances on reef ecosystems.

These threats to coral reefs require the immediate attention of the global community. Although oceanographers, marine biologists and resource managers will lead these efforts, inputs from National Meteorological Services are important to correctly assess the threats at local and regional scales, and to devise monitoring, conservation and adaptation strategies. The way forward could be guided by the following considerations:

- Meteorologists need to be aware of and well informed about the potential impacts of weather and climatic events on coastal and coral reef ecology. Formal communication pathways then need to be set up with marine scientists to determine how best to provide relevant data and forecasts on an appropriate timescale. Cumulative water pollution dispersion maps are an example of this type of cooperative effort.

- Concise summary reports and annual briefings on the global carbon threats, together with ongoing regional and local disturbances to the world's coral reefs, should be presented to policymakers and governments in a way that promotes environmental stewardship.

- Appropriate action at global (emission abatement) and local (disturbance mitigation) scales should consider the ecological and socio-economic consequences of reef ecosystem losses at varying scales.

- Further research and investment are required to enhance capabilities in coupled ocean–atmosphere modelling, coastal and hydrological modelling, and numerical weather prediction. This would lead to improved abilities to assess and predict the impacts on coral reef systems of ongoing and/or extreme events associated with climate change. These include, but are not limited to, impacts of climate change on climate drivers such as the El Niño–Southern Oscillation, Madden–Julian Oscillation and Pacific Oscillation, and subsequently on teleconnections with reef regions, increased river runoff, coastal circulation changes, fluctuating sediment loads, tropical cyclone generation and wave regime changes.

The World Meteorological Organization, in cooperation with other United Nations agencies, governments and the private sector, organized the World Climate Conference-3 (WCC-3) in Geneva from 31 August to 4 September 2009. The Global Framework for Climate Services (GFCS), an international effort to guide the development of climate services, was established by WCC-3. This framework links science-based climate predictions and information with climate risk management and adaptation to climate variability and change throughout the world. These climate services can effectively serve the needs of marine science and policymakers.

Information provided by WMO has played a vital role during the negotiation and implementation of various conventions and protocols aimed at protecting the environment, including the Convention on Biological Diversity (CBD). The WMO Marine Meteorology and Oceanography Programme (MMOP) coordinates and facilitates the regulation and sustained provision of global and regional observational data, products and services to address the continued and expanding requirements of the maritime user community for met–ocean services and information. In addition to the long-standing priority given to the safety of life and property at sea, MMOP has an increasing focus on integrated coastal management and societal impacts, including disaster risk reduction in the area of ocean-related hazards. The programme is implemented through the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) (http://www.jcomm.info). The long partnership between WMO and the Intergovernmental Oceanographic Commission of UNESCO (IOC) (http://ioc.unesco.org) was taken to a new level with the formal establishment of JCOMM in 1999. The creation of this Joint Technical Commission resulted from a general recognition that worldwide improvement in coordination and efficiency may be achieved by combining the expertise and technological capabilities of the meteorological and oceanographic communities. One of the initial priorities for JCOMM is the development and implementation of an operational ocean observing system for climate, on the basis of designs and requirements expressed by the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS). This observing system is now providing the data that are used to develop and implement a broad range of ocean products and services, including those needed to monitor and protect coral reefs.

The Convention on Biological Diversity has focused significant attention on the preservation and protection of the Earth's valuable coral reef ecosystems. In decision VII/5, the Conference of the Parties adopted an elaborated programme of work on marine and coastal biodiversity and included under programme element 2, which deals with marine and coastal living resources, a list of suggested activities to address coral bleaching and physical degradation and destruction of coral reefs. A Specific Work Plan on Coral Bleaching and Elements of a Work Plan on Physical Degradation and Destruction of Coral Reefs, Including Cold Water Corals, were adopted as Appendices 1 and 2, respectively. The Specific Work Plan on Coral Bleaching recognizes the urgent need to implement action to manage coral reefs for resistance and resilience to, and recovery from, episodes of raised sea temperatures and/or coral bleaching, particularly in relation to management actions and strategies to support reef resilience, rehabilitation and recovery. It also calls for information gathering, capacity-building, policy development and implementation, and financing.

The Convention on Biological Diversity is currently implementing its work plan on coral bleaching and is developing ties with relevant organizations, such as the International Coral Reef Initiative (ICRI) and its partners, the Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities (GPA-Marine) and IOC. It has also become a co-sponsor of the Global Coral Reef Monitoring Network (GCRMN). There are, however, other CBD measures, such as the programme of work on protected areas and invasive alien species, that have significant implications for the protection of coral reefs in the face of climate change. With support from the relevant CBD activities and WMO efforts, the long-term health and resiliency of coral reefs could be further secured through the following actions:

- Development of targeted multidisciplinary, cross-institutional research programmes to investigate the tolerance of coral reefs to increases in temperature and the frequency and extent of coral bleaching and related mortality events, as well as related impacts on ecological, social and economic systems;

- Implementation of baseline assessments and long-term monitoring to measure the biological and meteorological variables relevant to coral bleaching, mortality and recovery, as well as the socio-economic parameters associated with coral reef services;

- Building capacity to mitigate the impacts of coral bleaching and related mortality on coral reef ecosystems and the human communities;

- Development of stakeholder partnerships, community participation programmes and public education campaigns and information products that address the causes and consequences of coral bleaching;

- Initiation of and support for efforts to educate and inform the public, policymakers and other stakeholders of the ecological and socio-economic values of coral reef ecosystems and the importance of an ecosystem approach towards their conservation and sustainable management;

- Mobilization of international programmes and mechanisms for financial and technical development assistance for the protection of coral reef ecosystems.

Coral reefs are facing unprecedented impacts due to climate change, through a combination of threats including damage from increasingly severe tropical cyclones, more frequent temperature-induced coral bleaching events and diminished structural integrity due to ocean acidification. An immediate global response to reduce anthropogenic drivers of climate change is imperative to ensure the survival of these invaluable and diverse ecosystems.

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