
Global Climate Change and Coral Reefs: Implications for People and Reefs

Report of the UN EP-IOC-ASPEI-UCN Global Task Team
on the Implications of Climate Change on Coral Reefs

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Global Climate Change and Coral Reefs: Implications for People and Reefs

**Report of the UNEP-IOC-ASPEI-IUCN Global Task Team
on the Implications of Climate Change on Coral Reefs**

**By Clive R. Wilkinson & Robert W. Buddemeier
1994**

**with contributions from the members of the
UNEP-IOC-ASPEI-IUCN Global Task Team on Coral Reefs**

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Preface

This publication represents the deliberations of a Global Task Team of experts with experience in coral reef science and management throughout the world. The work of the Task Team was initially supported and funded by the United Nations Environment Programme (UNEP); the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the Association of South Pacific Environmental Institutions (ASPEI) who convened the first meeting of the Task Team in Guam, 27-28 June, 1992. At their subsequent meeting in Miami, 2-4 June, 1993 the expert members and representatives of the co-sponsoring agencies invited IUCN - The World Conservation Union to co-sponsor and support the work of the Task Team.

The initial stimulus for convening of a Global Task Team of experts to examine the potential impacts of climatic changes and sea level rise on the world's coral reefs came from the experiences of various UNEP and IOC sponsored Regional Task Teams established to examine the implications of climate change and sea level rise on the countries participating in the Regional Seas Programme. Several of these Task Teams had experienced difficulties in making appropriate impact assessments, in the absence of good evaluations of the potential response of reef systems to the anticipated changes.

The members of the Task Team and Secretariat are listed in Annex 1. At its first meeting in Guam the Task Team, under the chairmanship of Dr Clive Wilkinson of the Australian Institute of Marine Science (AIMS) was charged with preparing an authoritative assessment of the potential impacts of climatic change and sea level rise on coral reefs. The meeting agreed a workplan and timetable and Drs Buddemeier and Wilkinson agreed to undertake collation and editing of inputs from the Task Team members. A draft report was subsequently prepared by the co-authors and circulated to all members prior to the second meeting in Miami. At this meeting the contents of the draft were reviewed and amended and agreements on the final form and the process of finalizing the report were reached.

This meeting agreed that the conclusions of the report should be presented as an executive summary for policy makers to the World Coast Conference held in the Hague in November 1993. This summary, produced as the booklet "Reefs at Risk", was prepared and published by IUCN on behalf of the co-sponsoring agencies, and represents the non-technical summary of this report.

Preparation of this report would not have been possible without the support of the Kansas Geological Survey and the Australian Institute of Marine Science which provided invaluable infrastructural support and services to the co-authors of this report. In addition the University of Guam and the Rosentiel School of Marine and Atmospheric Sciences provided valuable facilities and logistical support for meetings of the Team. Preparation of the text was completed at the Australian Institute of Marine Science with formatting by Liz Hewlett and Christine Cansfield-Smith, and figure preparation by Steven Clarke of AIMS, and Mark Shoneweis of the Kansas Geological Service, University of Kansas. Daphne Fautin (University of Kansas), and Joanna Ellision and Janice Lough (AIMS) provided valuable technical and editorial revision. This support is gratefully acknowledged as is the support of the co-sponsoring agencies to the work of the Global Task Team.

Executive Summary

The Task

The major theme of this Report is an assessment of the potential and expected effects of global climate change on coral reef ecosystems and the peoples associated with them. This was the task of the UNEP-IOC-ASPEI-IUCN Global Task Team on the Implications of Climate Change on Coral Reefs, which was formed and supported by a cooperative effort of the participating agencies.

The Task Team approached this task with two fundamental objectives:

- a. to prepare a global overview on the potential impacts of climate change and sea level rise on coral reefs and the implications of such impacts for ecologically sustainable use of coral reefs. The overview will be based on the best available knowledge and insight into the problems relevant to its subject;
- b. to identify selected case study sites using the best available knowledge on coral reefs for specific sites.

The ultimate objective of the Task Team is to assist governments in the identification and implementation of suitable policy options to mitigate the negative consequences of the impacts on coral reefs and the associated socio-economic structures.

The Process

The Task Team met on two occasions to prepare this Report. In Guam (June 1992), the Task Team determined the major themes and structure of the report, and then in Miami (June 1993), they reviewed a substantial draft prepared by the compiling authors and suggested additional sections and material. The Report was completed as a collaborative effort by the authors, with additional editorial help, and then published by the IUCN in Switzerland.

The Report

After a general Introduction (Chapter 1), the Report covers how coral reef ecosystems interact with their environment, emphasizing potential impacts of global climate change (Chapter 2). Then follows discussions of how humans currently use coral reefs and the consequences of that use (Chapter 3), and what is climate and climate change (Chapter 4).

The predicted effects of climate change on human use of reefs and consequences of inaction (Chapter 5) are followed by the management and policy requirements to implement sustainable use and preservation of reefs (Chapter 6). A final section (Chapter 7) presents the Report's conclusions, and these are summarized below.

The Findings

Coral reefs are being seriously and increasingly stressed by exploitation and anthropogenic environmental changes, such as sedimentation, nutrient loading and pollution, physical destruction, and overfishing. These effects are distinct from, and unrelated to, climate change.

The coral reef ecosystem has evolved through massive climate changes in the past and could be expected to survive further climate change (although some of the changes will disadvantage those humans dependent on reefs as they are now). The current scenarios for climate change by the IPCC (Intergovernmental Panel on Climate Change) are less extreme than past changes experienced by reefs during geological time. But, the combination of the current changing climate and the additional, and steadily increasing stresses from growing populations, and economic and coastal development, may prove to be a lethal synergy.

Some reef communities have proved to be resilient to chronic or acute stress, but the persistence of some acute human stresses has resulted in system collapses. For example, corals have been replaced by more competitive, and less desirable, communities such as algal-dominated ecosystems, when damaged by a combination of acute and chronic stress. Climate change threatens to augment the acute stress (typically as more and greater storms or more high-temperature episodes) and some chronic stresses (such as changing oceanic acidity due to atmospheric CO₂ uptake) and add these to the chronic stresses already imposed by nutrient loading, over-exploitation etc.

Human dependence on reefs for food, materials, and income (tourism or exports) is high and growing. The threat posed by rising sea levels is a special case for the inhabitants of low coral reef islands and coastal plains, since human use and habitation of reef islands and structures may become impossible, even though the surrounding reefs are unaffected and remain healthy. If some reefs are also damaged through climate change, then destruction of islands and shorelines will be more rapid and devastating. The world's coral reefs constitute a great economic resource, but they are also of great biological, cultural, and aesthetic value and all of these values are increasingly at risk.

Our major finding is that human pressures pose a far greater immediate threat to coral reefs than climate change, which may only threaten reefs in the distant future. The essential first step to preserve reef ecosystems and protect the human communities that depend on them, is to eliminate or mitigate the present anthropogenic threats to reefs so that they may retain their natural ability to accommodate to global environmental change. At a fundamental level, this involves confronting the underlying problems of ever-expanding human populations, unsustainable exploitation and the increasing discharge of contaminants (including the greenhouse gases that drive climate change) into the environment. More immediate attention, however, should be focussed on obtaining an increased understanding of reef ecosystems and improving their protection and management.

There are examples of effective management and sustainable use of coral reefs in both traditional and modern societies. Although there are still uncertainties, the Task Team agrees

that the application of human knowledge and skills is adequate to assess the threats facing coral reefs and protect them at scales ranging from local to global. We hope that the evidence, arguments, findings and conclusions in this report will play a significant role in convincing the international community to direct its attention and efforts towards this urgent challenge, and to mitigate the losses that now appear unavoidable.

The Conclusions

Coral Reefs - General Status and Issues

- * Coral reefs are valuable economic resources for many people, providing food, habitation and income, and reefs have the highest biodiversity in the sea, therefore their conservation and sustainable management are an urgent priority.
- * Many of the world's coral reefs are severely degraded or destroyed by human damage to the environment, such as sewage and other pollution and sedimentation, and by direct over-exploitation and physical destruction; these impacts will increase with population growth and rapid economic development.
- * Climate change by itself is unlikely to eliminate coral reefs, but climate change will create hardships for people dependent upon these reefs, because of changes to reef structure, function, distribution and diversity.
- * Reef communities are not well adapted to the combination of chronic and acute human (anthropogenic) stress and climate change, and their short-term survival is threatened by these stresses acting together (synergy), even though reef communities have persisted in the natural environment over evolutionary time scales.
- * The critical time-frame for assessing and mitigating the climate change threats and implementing effective management and protection of reefs is the next few decades, while there are still reefs relatively undamaged and before expected climate change is too far advanced.

Climate Change - Specific Threats to Reefs

- * Rising sea level will not threaten most coral reef ecosystems, and may be advantageous to some, but, predicted sea level rise will devastate the habitability of low islands and coastal plains that are protected by coral reefs, necessitating urgent assistance to these threatened human societies.
- * Rising temperatures will not endanger reef survival, but frequent episodes of temperature extremes will increase bleaching and mortality, thereby disrupting the health and functioning of reefs at local and regional levels, and increasing vulnerability to other stresses.

- * Increased atmospheric CO₂ concentrations will result in more dissolved CO₂ and higher acidity in surface waters, which may lower calcium carbonate deposition rates and will fertilize algae and enhance their competition with corals, further reinforcing the effects of overfishing and nutrient pollution.
- * Increases in rainfall will dramatically change the flux of nutrients, contaminants, and sediments onto coastal coral reefs and make them more vulnerable to climate and anthropogenic changes on adjacent coastlines and in drainage basins up to thousands of kilometres away.

Management and Protection - Climate Change in an Altered Environment

- * Prompt and aggressive management to mitigate or reduce human stresses is the most effective way to preserve coral reefs and retain their value to human societies, because unstressed reefs will be better prepared to cope with climate change, and methods of bioremediation and repair of reefs already damaged are expensive and of questionable effectiveness.
- * Both assessment of reef and island vulnerability to climate change combined with the development of local and regional management strategies and global efforts to reduce the greenhouse gas emissions are both necessary, and urgently needed to counter the effects of climate change now and in the future.
- * Understanding of coral reefs, climate and environmental stress is adequate to assess vulnerability and manage and conserve coral reef resources, but such action must be prompt and should be undertaken as an integrated coastal zone management strategy, including all surrounding marine and terrestrial environments.
- * In order to preserve global reef biodiversity, protect representative reefs, and monitor climate change effects as distinct from localized human damage, we recommend that some remote reefs be declared as international marine protected areas, similar to the Antarctic.
- * Training, education and development programs are needed to reduce the need for societies and individuals to over-exploit reef resources, and to build the capacity to understand and manage reefs for long-term sustainability.
- * Engineering and other solutions to prevent sea level rise from damaging low islands and coasts may not succeed in the long-term; therefore contingency plans must be developed to address the problems of communities and cultures that may become displaced as a result.

1. Introduction

About two thirds of the world's population live within 60 km of a coastline. This proportion is increasing as people seek a better standard of living and move away from inland and upland areas. Coral reefs protect large parts of the tropical coastlines (Fig. 1.1) from wave damage and erosion and are particularly important for the livelihood of many millions of people, who obtain a considerable proportion of their food and earnings from the productivity of coral reefs.

There is currently considerable concern, however, about the fate of coral reefs and coastal areas and the consequences of changes in climate. The example of a newspaper cutting from Indonesia illustrates the degree of confusion existing as to the potential effects of global climate change and consequent sea level rise (Fig. 1.2). Much of what is reported in the media about climate change is either excessively exaggerated, badly misunderstood, or stressed from the political point of view. This has led to alarm by peoples in countries likely to be most affected by climate change and sea level rise. Nowhere is this concern more evident than on low lying coral reef islands in the Pacific and Indian Oceans.

Coral reef managers and scientists are also concerned about the future of coral reefs, but recognize that there are uncertainties in predicting climate change and how human populations will react to these threats. These uncertainties make it difficult to manage and plan for the sustainable development of coral reefs. Much of our uncertainty stems from the scales at which we consider coral reefs and their interactions with environment. These problems of scale are discussed in Box 1.1 and Fig. 1.3.

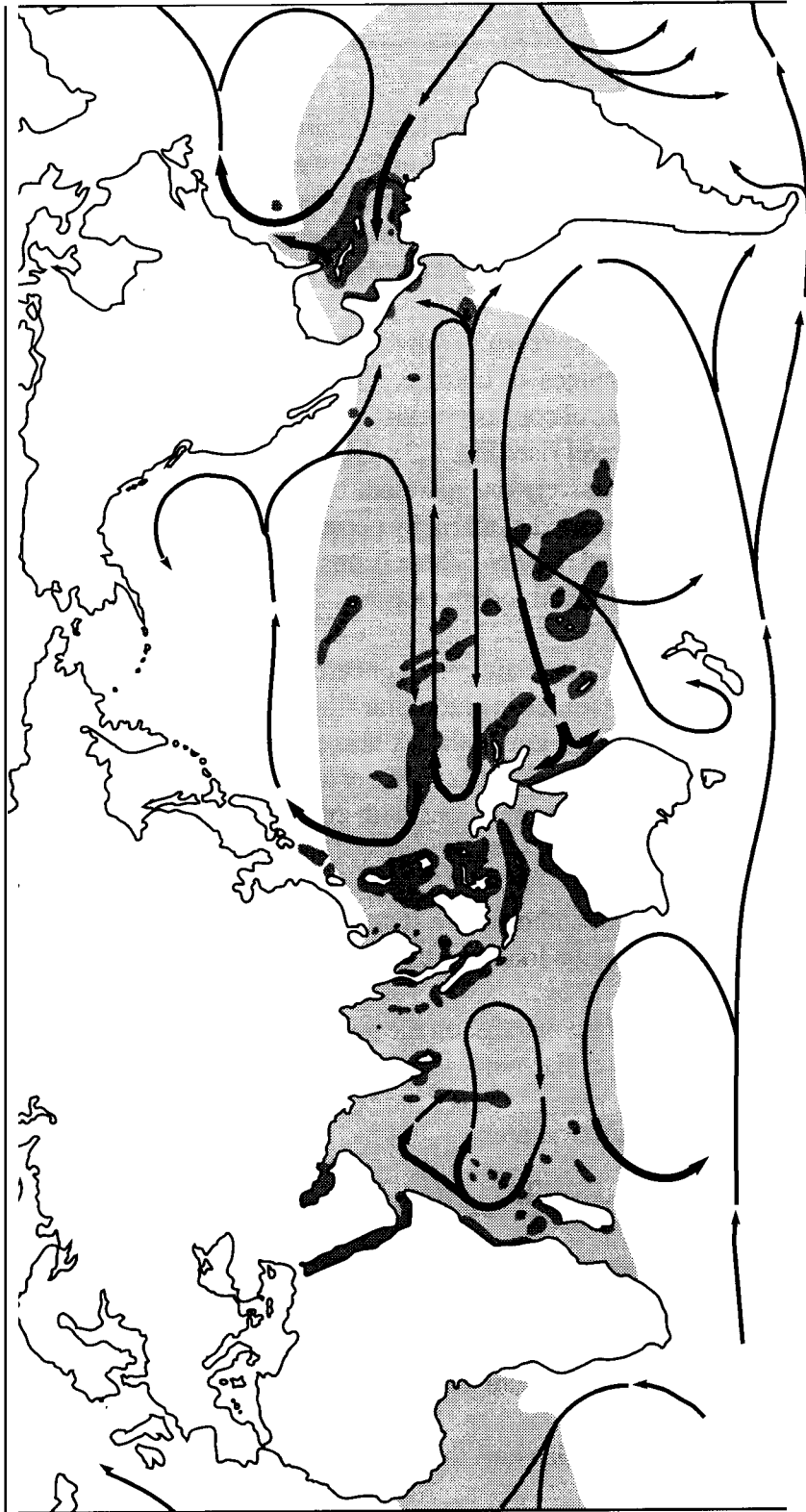
This review aims to provide an authoritative statement for planners and decision makers, who are concerned with developments likely to affect the future sustainable use of coral reefs.

We review the current state of knowledge on the potential effects of the various factors related to climate change and sea level rise on:

- . the physical structure of coral reefs;
- . the biological communities that constitute those reefs; and
- . the socio-economic impacts of such changes on people who depend on reefs for sustenance or quality of life.

To achieve this, the following structure has been adopted:

- . first, coral reef characteristics and their relationship to environmental factors are discussed;
- . second, the human uses of reefs and reef resources are described;
- . third, climate and climate change, as they relate to coral reefs, are considered; and



Main reef area Ocean currents

Figure 1.1: Global distribution of coral reefs (dark hatching), along with the major patterns of surface currents. Reefs are predominantly distributed on the eastern margins of continents where favourable currents (emphasised by thicker arrows), of clean low nutrient water, distribute larvae from the tropics into higher latitudes (from UNEP/IUCN 1988 and Veron 1986). Reef growth is generally limited by water temperature down to 18 or 20°C, (the light shaded area is the 20°C isotherm band).

Figure 1.2: Example of media misinterpretation of arguments concerning climate change from the front page of a leading English language newspaper in Indonesia.

The scientist reported a 50 centimetre rise in sea level, but the newspaper has re-interpreted this as 50 metres. A 50cm rise would cause considerable loss of land in coastal zone countries; whereas a 50m rise would eliminate large land areas in virtually all countries in the world.



finally, these are brought together to predict the effects of climate change on reefs and human uses of those reefs, and consider the implications for policy development and management of coral reefs.

Coral reefs are particularly important because they:

- provide living space and subsistence fisheries for millions of people, who have developed unique cultures based around reef resources;
- provide a livelihood for many more people in the tropics who obtain a considerable proportion of their food and earnings from the products of coral reefs or from reef-related activities, such as tourism;
- are particularly important geographic components of many countries as they support islands, protect fragile coastlines from wave and current erosion, permit the growth of mangroves and wetlands and effect the placing of the boundaries of Exclusive Economic Zones (EEZ) which in turn affects access to fisheries and seabed mineral resources;
- constitute a valuable resource for research into many of the scientific questions concerning the nature of our environment, particularly as they have the highest biodiversity of any marine ecosystem, and have barely been tapped for the rich potential of knowledge, natural products of biomedical interest, and genetic potential (see Box 1.2).

Box 1.1: Scales of Time and Space

'It's a problem of scale' is a qualifying phrase often heard in discussions of climate issues, because what is true on the long-term global average may bear little relationship to what is happening now in any particular location. But the problems of managing and understanding coral reefs are very much scale related, even without climate complications (Hatcher *et al.* 1987).

Although people living close to natural systems usually have a time perspective over human generations, government programs and political administrations usually consider the next few years, and the economic tyranny of the 'discount rate' demands that investments pay off over a few decades or less. Yet the oldest corals on a reef may live for centuries, and the cycles of natural variation in the environment and biological communities are long compared to these human perspectives.

Short time scales are also important - conditions during a few days each year will determine whether many organisms succeed in reproducing, and devastating events such as storms or human destructive activities may occur on time scales of hours today. The issues of changing climate are forcing us to confront the difficult task of understanding nature over scales of both space and time that do not seem 'natural' from our limited perspective, but are vital determinants of the nature of the world we live in and wish to preserve (Fig. 1.3).

Reefs are strongly influenced by short term events such as tidal and day/night cycles; somewhat longer events such as seasons, including monsoons and variations in the trade winds are important in structuring reefs; whereas, infrequent events such as cyclonic storms and periodic flooding events, which may re-occur at frequencies of several to many decades, have unpredictable but major effects. Global climate change falls into the long-term scale, along with such events as variations in sun spot activity and alterations in the earth's orbit.

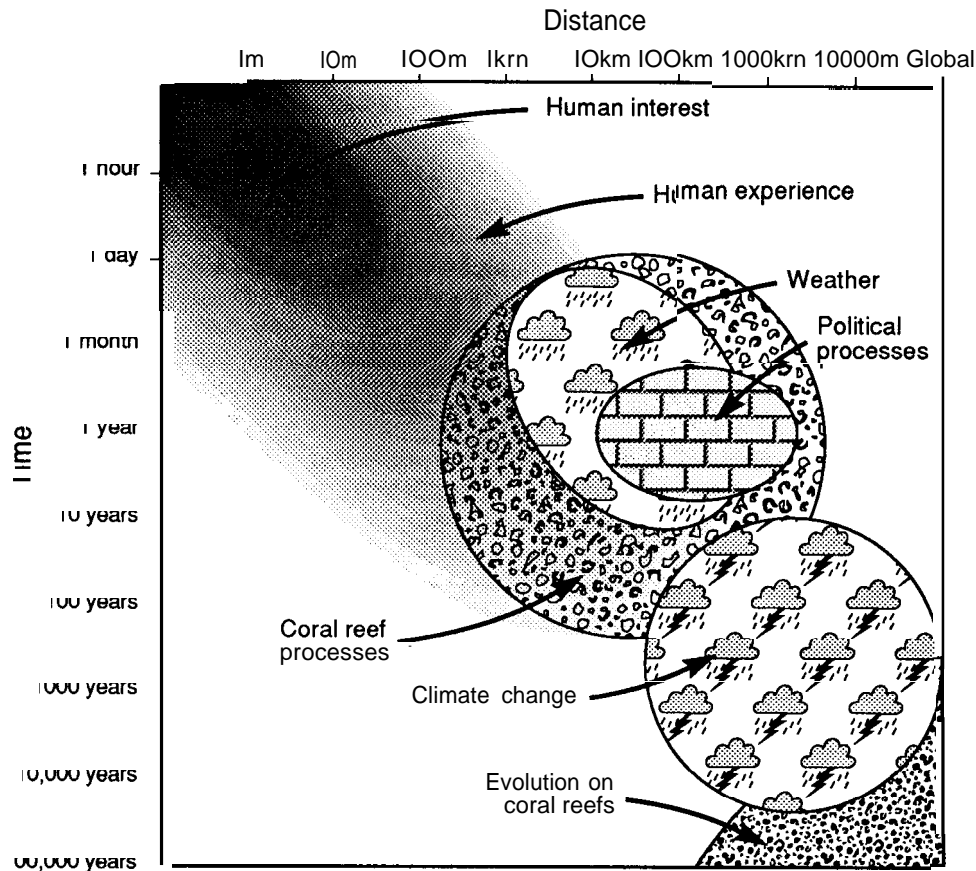
The history, current growth and future functioning of coral reefs have been, and will always be, intricately linked with climate and climate change. Variations in climate will clearly affect coral reefs in the future as they have done throughout the geological past. The major factor in both climate and coral reefs is the input of solar energy through the atmosphere to both land and sea. Any changes in the balance and flow of this energy will influence both the nature of global climate, and the growth and functioning of coral reefs. The major difference now, compared to the geological history of reefs, is that present rates of change are likely to have serious impacts on people who depend on reefs and they will interact with non-climatic local and regional stresses resulting from growing populations.

The changes that are occurring, particularly to the atmosphere but also to land and sea, are part of the increasing human (anthropogenic) impact on the global environment through, for example, the enhanced greenhouse effect and damage to the protective ozone layer of the upper atmosphere. Although these two effects are fundamentally different, both are related to the release of gases into the atmosphere as a result of human activities. Thus, we will consider the following aspects in the discussions that follow:

- . increased temperatures due to greenhouse climate change;
- . sea level rise associated with increased temperatures;
- . alterations in normal weather patterns - rainfall, cloud cover, winds;

Figure 1.3: The range of scales observed in nature, and how they vary with the environmental system considered and the perspective of the observer.

Direct human interest spans from now to decades, encompassing weather scales, with collective human experiences covering several hundred years and the whole earth. The political perspective, however, is narrow and well outside the time and space scales of climate change and reef evolution.



variations in extreme weather events such as cyclonic storms, droughts, floods;

possible alterations in ocean circulation patterns;

increased UV-B radiation due to ozone depletion; and

changes in the chemistry of seawater due to higher concentrations of CO_2 .

To date, the majority of damage to coral reefs around the world has been through direct anthropogenic stress- the pressures applied by people to coral reefs (Alcala et al. 1987; Brown 1987; Salvat 1987; Dahl and Salvat 1988; Gomez 1988; Kenchington and Hudson 1988; Kinsey 1988; Pauly and Chua 1988; Grigg and Dollar 1990). The major causes of damage are: excessive pollution from domestic, industrial and agricultural waste; poor land use practices, which increase the amounts of land derived sediments flowing onto coral reefs; and over-exploitation, particularly through damaging practices such as dynamite and muro-ami fishing, which are often used to catch fish and other animals from coral reefs that are already over-exploited.

Box 1.2: Biodiversity and its Significance

Biodiversity, the abbreviation for biological diversity, is a measure of the number of species within a particular area or volume of an ecosystem. Coral reefs have the highest biodiversity of any marine ecosystem, with enormous numbers of different species packed into small areas (Norris 1993). By contrast, there are many different species in the deep ocean, but these are sparsely distributed over vast areas. For example, within a few square kilometres on the inner Great Barrier Reef it is possible to find more than 300 coral species, all competing for space to grow (Veron in press).

The full extent of the biodiversity on a coral reef is difficult to measure, because many of the animals and plants are either very cryptic or microscopic, and few attempts have been made to assess this biodiversity. However, on the Great Barrier Reef there are more than 400 different hard and soft coral species, about 4,000 shell producing molluscs, and thousands of different sponges, worms, crustaceans and echinoderms: within this ecosystem there are at least 1,500 species of fish (Great Barrier Reef Marine Park Authority 1989). No attempt has been made to quantify the number of microscopic animals as well as the microalgae and bacteria. Coral reef biodiversity is centred around the island archipelagos of the Philippines and Indonesia and down to the Great Barrier Reef, with diversity decreasing markedly with distance away from this focus of species richness (Rosen 1981; Veron 1986). For example the number of coral species in French Polynesia, drops to about 10% of that found on the Great Barrier Reef, about 7,000 km away.

This biodiversity represents a rich resource of genetic variability, including many species that have either current or potential value as food (fish, prawns, molluscs), sources of biologically active substances of benefit to humans, or the focus of aesthetic pleasure (McNeely *et al.* 1990; Norris 1993).

The visual attraction and high biodiversity of a coral reef ecosystem is a powerful draw for tourists, particularly in the growing field of ecotourism. However, sustainable ecotourism requires extensive knowledge of the ecosystem, the component species and their interactions, so that the tourist can be provided with a meaningful educational experience, as well as enjoyment and relaxation.

The future prospects for many of the world's coral reefs are in doubt. There has been a dramatic decline in status of reefs throughout most of their range, caused by a combination of factors, most of which are not related to changes in climate. It has been predicted that more than two thirds of the world's coral reefs will be considerably degraded within 20 to 40 years unless effective management of the resources is implemented urgently (Wilkinson 1993a). This is the time frame in which the human population in tropical countries will double (World Resources Institute 1992).

This book is the compilation of opinions and predictions from a global task team of experts. Much of the material is drawn from a series of recent reviews that have addressed different aspects of climate change (Hulm 1989; Houghton *et al.* 1990, 1992; Pernetta and Hughes 1990; Pernetta and Elder 1992; Smith and Buddemeier 1992; Weber 1993), and several international meetings, including D'Elia *et al.* (1991) and Ginsburg (1993).

Most indigenous peoples, who live close to and depend on nature, have developed practices for the sustainable use of natural resources. Many Pacific island cultures developed traditional conservation and management systems to control over-exploitation (Johannes 1993). They introduced the 'limited entry' method of conserving fishery stocks on small coral reefs, long before western biologists and economists 'discovered' it for themselves (Johannes 1981). Islam states that humans are mere managers of the world and its essential elements of water, air,

the soil and plants and other animals; they are not the proprietors. Use can be made of the earth, but only when it does not disrupt or upset the interests of future generations (IUCN MEPA 1983).

It remains to be seen whether humans can act on these values and be wise managers in a world struggling with the pressures of growing populations and the desire for development.

‘The world was not left to us by our parents... it was lent to us by our children’ (African Proverb, UNICEF).

2. Coral Reefs and their Environment

2.1 Coral Reefs

Coral reefs are ecosystems of high biological diversity (biodiversity), having the greatest number of species of any marine ecosystem (Grassle et al. 1990). They occur in tropical regions at depths of less than about 100 m, and often co-exist with large human populations in the developing nations of the tropics. For these populations, reefs represent substantial resources in the form of food, trade items, building materials, or tourist attractions. Unfortunately, the condition of many of the world's coral reefs has reached a crisis point. In addition to the general trend toward reef degradation discussed in the Introduction, Wilkinson (1993a) has addressed the question of acute problems, and has estimated that as much as 10% of the global reef area has been degraded beyond recovery, with another 30% predicted to collapse within the next 10-20 years. The reefs at greatest risk are those in Southeast, East and South Asia, East Africa, and the Caribbean, where human impacts are causing reef degradation that will have serious environmental and economic repercussions in the immediate future.

Another threat to coral reefs looms on the horizon. Global Climate Change may directly impose new stresses on reefs, or it may interact synergistically with other more direct human (anthropogenic) pressures to cause added and accelerated environmental damage. These effects could accelerate the current rate of coral reef degradation in areas already stressed, and might also threaten those reefs remote from large human populations in the central Pacific and Indian Oceans and along much of the Australian Great Barrier Reef. The more remote reefs have the important potential to serve as refuges for coral reef biodiversity as reefs close to human populations become degraded, therefore the health and preservation of remote reefs is important to the ecosystem on a global scale (Buddemeier 1993).

Living coral reef communities continuously grow over previous reef structures (Fig. 2.1) composed of calcium carbonate (limestone) laid down by stony (scleractinian) corals and coralline algae such as *Halimeda* (a green alga) and *Lithothamnion* (a red alga) (Fig. 2.2). These corals and algae deposit substantial amounts of calcium carbonate in their skeletons, and this material forms the geologic structures of the coral reef (see Boxes 2.1, 2.2). This continual deposition permits a reef to 'grow' and keep up with rising sea level. Reefs also provide physical shelter for adjacent coastlines and lagoons, and provide substrate and material for populations of both humans and reef plants and animals. The reef-building corals all share an important characteristic; the symbiotic algal cells (microscopic zooxanthellae) that inhabit the animal tissue provide much of the coral's nutritional requirements through photosynthesis. This symbiotic relationship can be thought of as a microcosm of the larger reef community, where free-living as well as symbiotic algae provide organic materials that form the base of the community food chain (see Box 2.2).

Coral reefs are dynamic, integrated ecosystems with the mineral construction shared by animals and plants. With this versatility comes high diversity and complexity. With their environmental

Box 2.1: Coral Reefs - barrier, fringing, atolls and coral cays

The term 'coral reef' applies to a diversity of structures that grow in a wide range of habitats from clean oceanic waters to areas close to continents, where the influence of land runoff can be considerable. The eventual shape and form of the reefs will depend on this ambient environment and the underlying base structure. Reefs predominantly grow over previous reefs, that were killed off during massive sea level falls during ice ages. The stony corals and calcareous algae gradually build up the calcium carbonate framework until the reef reaches the sea surface, where atmospheric exposure limits further upward growth.

Barrier reefs develop along the edge of continental shelves that are sufficiently remote from sediment input from the land to encourage vigorous coral growth. Usually behind these reefs are relatively deep water ways, referred to as lagoons. Good examples are the Great Barrier Reef and the barrier reefs of Belize and New Caledonia. These barrier reefs protect the adjacent shorelines from the impact of oceanic waves.

Platform reefs grow over 'hills and mountains' formed by previous reefs or other features such as sand dunes, formed when sea level was lower. Once the reefs reach the surface, they grow outward often forming large areas of reef flats. Platform reefs are frequently found within the large lagoons formed by barrier reefs. There are good examples of platform reefs in the Bahamas, within the 'lagoon' of the Great Barrier Reef and in the Red Sea.

Atolls are formed in oceanic waters around the bases of extinct volcanoes. As the volcanic island erodes and sink, the coral reefs continue to grow upwards to the surface leaving an approximately circular structure, typically with a central lagoon, which may contain remnants of the original volcano. Atolls commonly occur in midoceanic locations and may be associated in groups of atolls (the Marshall islands, the Maldives) or in chains of high islands and atolls (Hawaii, French Polynesia).

Fringing reefs form immediately adjacent to land masses, often where there is high sediment load. These reefs form on the slopes where the land dips into deeper water and the area behind the slope usually fills in to form a reef flat. Most reefs off Caribbean islands are fringing reefs as are many reefs in Southeast Asia and East Africa.

Coral cays are islands that form on reef flats, particularly on atoll and platform reefs. These occur when sand and rubble from the reef flats accumulate into mounds through wind and wave action. When these mounds 'attract' birds and plants, a consolidation process ensues to make relatively stable structures that have attracted human occupation. There are numerous examples throughout the Pacific and Indian Oceans and the Keys of Florida are other examples. These cays are rarely more than a few metres above sea level and thus are a major point of concern for sea level rise as a result of global climate change.

setting also comes vulnerability because reefs can only exist close to the air-sea interface in warm seas, and are frequently adjacent to the sea-land interface. Changes in environmental conditions in the sea or air, or on landmasses that interact with the sea, are likely to have marked influences on the reef ecosystem (Smith and Buddemeier 1992).

2.2 Reef Interactions with the Environment

The biology, geology, biochemistry, and biogeography of coral reefs are closely related to their interactions with the environment. In order to understand how climatic issues and anthropogenic environmental change affect reefs, the following discussion summarizes the environmental factors known or believed to influence or control reef development.

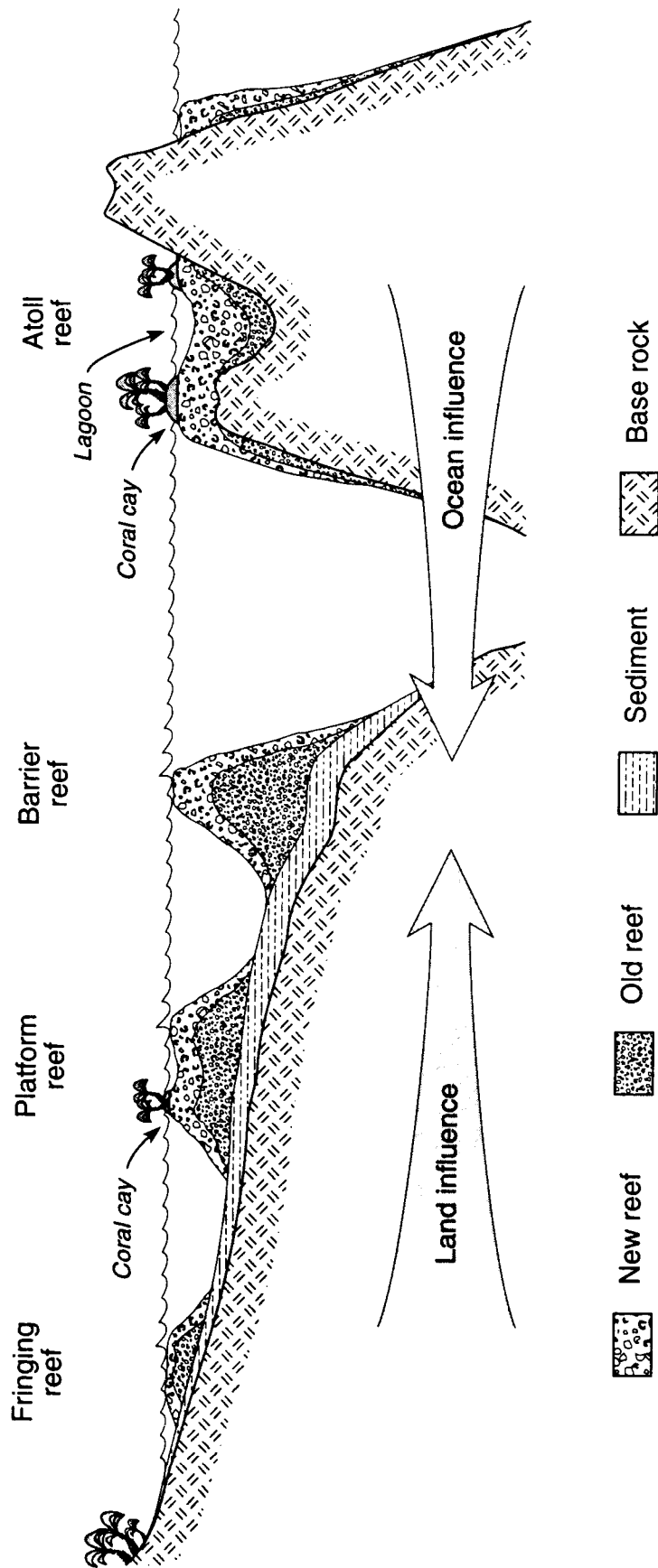


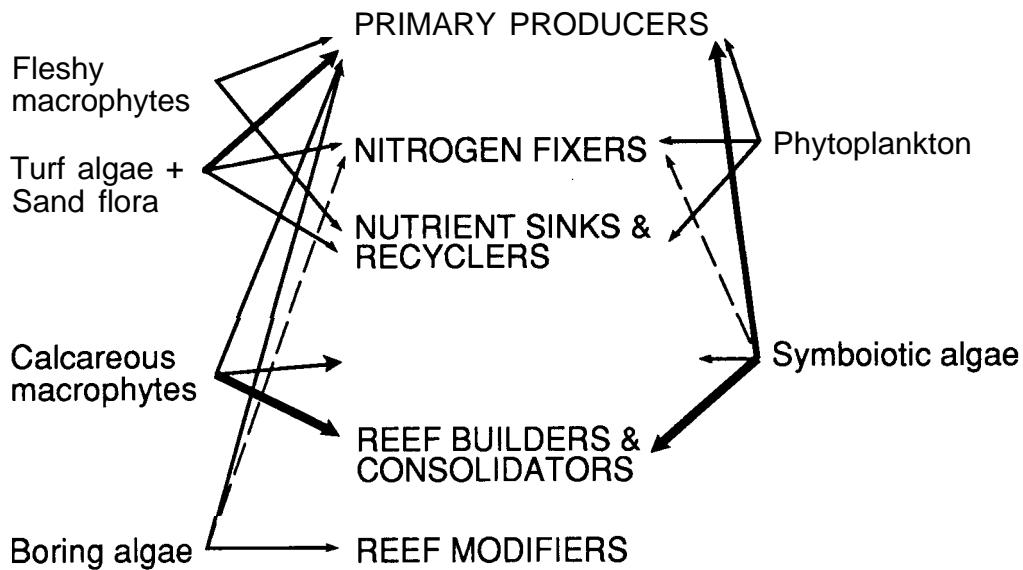
Figure 2.1: A diagrammatic representation of the different types of new coral reefs built on top of old previous reefs, over the underlying base rock, including volcanic rock and sediments. The major influences are marked as arrows indicating the direction of that influence.

Box 2.2: The Role of Algae

Algae, both macro- and micro-, may be regarded as the ‘quiet achievers’ of a coral reef ecosystem. Like all plants, algae absorb light energy in photosynthetic processes that chemically combine water and carbon dioxide to produce organic compounds. These organic compounds are directly or indirectly consumed by other reef species. In the case of the symbiotic microalgae (zooxanthellae) that live within the tissues of corals, clams and sponges, most of the photosynthetic products are transferred to the host. In many cases, this internally produced photosynthate meets all or most of the host’s energy requirements.

Free-living algae are eaten by herbivorous zooplankton, crabs, fish, or echinoderms, while substances released from the algae are consumed by heterotrophic bacteria. Algae are the primary producers of the reef community, with about 1000 known algal genera being associated with coral reefs. All of these contribute to the organic production on reefs, while about 10% of that number calcify and thereby contribute to the inorganic accumulation that supports and defines the coral-algal reef.

Figure 2.2: Classes and functions of the major types of reef algae. Line width indicates relative importance of each algal type in reef processes; dashed lines indicate a possible role (from Borowitzka and Larkum 1986).



The growth and functioning of coral reefs is best under the following general conditions:

1. water temperatures in the optimum range of about 23-30°C;
2. consistent irradiance, hence shallow, clear seas in tropical latitudes;
3. low levels of sedimentation;
4. low concentrations of inorganic and organic nutrients;

5. salinity in the range of 25 to 40 ppt; and
6. shielding from excessive levels of UV-B radiation.

Climate change will impact directly on coral reefs through variations in factors 1,2 and 6; and result in indirect changes to factors 2, 3, 4 and 5 via impacts on adjacent land masses.

Marine Environment

Coral reefs are most abundant and flourishing in shallow, well-flushed marine environments characterized by clear, warm, low-nutrient waters that are of oceanic salinity and supersaturated with calcium carbonate minerals. The following discussion reviews the key environmental factors considered to control coral reef health and distribution.

Light: Because algae (both symbiotic and coralline) require light for photosynthesis, reef communities are limited to shallow water. Light requirements and adaptation in corals are such that maximum rates of calcification and photosynthesis can be sustained down to depths of 20m in clear water (Falkowski *et al.* 1990). The depth of light penetration interacts with other environmental variables such as wave energy to control important reef characteristics so that:

- * maximum rates of reef accretion occur between 5 and 15m (Hopley and Kinsey 1988);
- * maximum productivity is sustained in roughly the same 5-15m depth range because of the ability of the coral-algal symbiosis to adapt to a range of light levels;
- * the maximum diversity of corals and other organisms occurs between 10 and 30m (Huston 1985);
- * some symbiotic corals can grow at depths in excess of 60 m,

Light penetration is reduced by turbidity, so that the depth range of reef communities can be significantly reduced where water clarity is affected by either local organic productivity or suspended sediments (Chou 1991). In addition to reduction of light levels, high sedimentation rates can have other harmful effects on corals and reefs, ranging from smothering to reduced growth rates and the inhibition of recruitment (Brown and Howard 1985; Grigg and Dollar 1990; Babcock and Davies 1991).

Water clarity also permits the penetration of solar ultraviolet (UV-B) radiation, which is known to have detrimental effects on reef organisms (Jokiel and York 1982, 1984; Siebeck 1988). Corals and most other shallow water reef animals and plants have developed mechanisms to either block out or avoid harmful UV radiation (Dunlap and Chalker 1986). Box 2.3 summarizes the ultraviolet radiation issue.

Box 2.3: UV Radiation Effects

Light is essential for the maintenance and growth of hard corals and many other species living in coral reef ecosystems, and ultimately for the primary production that supports the entire community (see Box 2.2). However, not all light is beneficial. The sun's invisible short-wavelength radiation is divided into three ultraviolet (UV) bands, according to their wavelength in nanometres: UV-C (200-280nm); UV-B (280-320nm); and UV-A (320-400nm). Solar UV-B and the shorter wavelengths of UV-A are physiologically damaging, particularly to DNA, by causing re-arrangement of the component molecules of genetic material. While UV-C is potentially most damaging (Fig. 2.3), it does not penetrate through the atmosphere. Cells that are exposed to UV usually have mechanisms to repair most of the damaged DNA, resulting in an approximate balance between damaged and repaired DNA under normal conditions (Smith and Baker 1989). However, problems arise when the levels of UV radiation are particularly high, such as in shallow tropical waters or with the recent increases in UV penetration through an atmosphere depleted in ozone. In high transparency tropical waters, biologically damaging UV radiation may be transmitted to depths of up to 20 metres, with very high levels in shallow water (Fig. 2.3).

Some shallow reef organisms have evolved UV shielding mechanisms by producing UV absorbing substances, which may be either synthesized by the symbionts (Chalker *et al* 1986) or bioaccumulated through the food chain. Thus, the symbiotic algae help to protect the host animal against the damaging effects of UV radiation, as well as providing food.

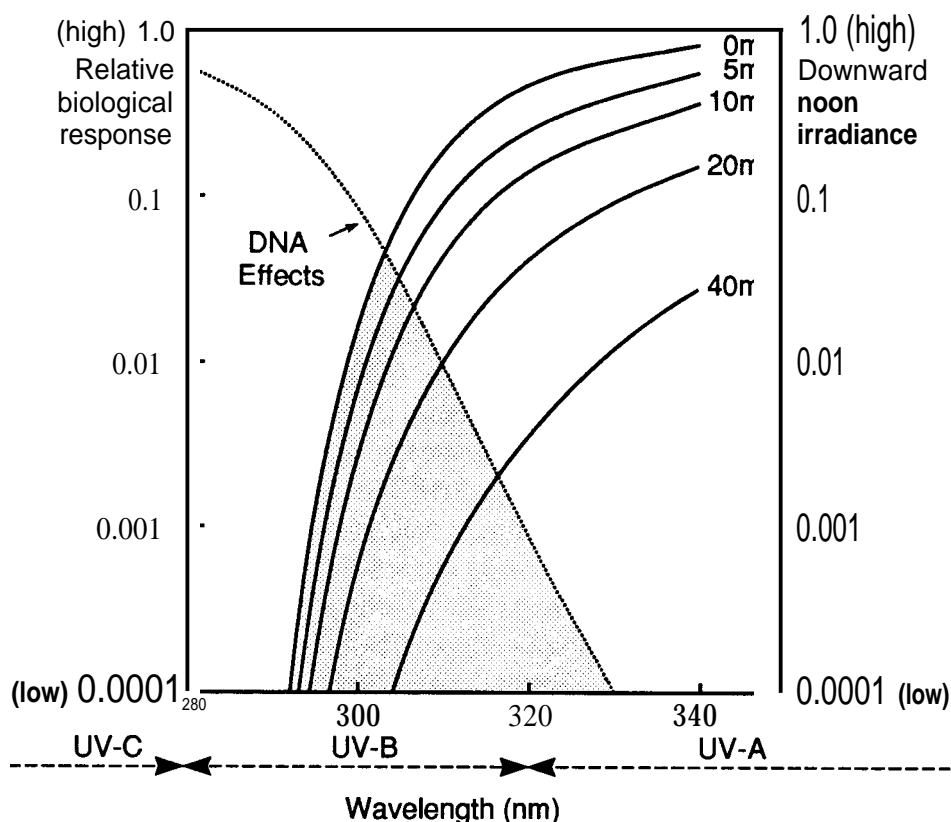
The potential hazard associated with increasing levels of UV radiation caused by depletion of the ozone layer will be to floating and suspended plankton and larvae. It is possible that the balance between damage to DNA and the natural repair mechanisms could be shifted towards irreparable damage and a consequent reduction in plankton communities and a reduction in larval survival (Jokiel and York 1982; Voytek 1989; Wood 1989).

Important unanswered questions relating to global change are: how much will UV radiation increase; whether existing protective and adaptive mechanisms can cope with any increase; and whether organisms or life stages (such as plankton) that lack UV shielding mechanisms will be adversely affected by increased UV exposure

Water Motion: Water motion, including wave action, is an important factor for determining reef zonation, reef morphology, and the depth distributions of reef corals, algae, and other key organisms (Done 1983; Huston 1985; Wilkinson and Evans 1989). Storms provide long-term occasional and episodic control of the structure of reef community development by catastrophic pruning and/or substrate renewal (Dollar 1982; Harmelin-Vivien and Laboute 1986; Massel and Done 1993), which in turn may aid coral reproduction (Highsmith 1982) and influence community succession and diversity directly at the local level (Connell 1978; Huston 1985). Storms, waves, and currents are also the driving forces for sediment and nutrient transport and for shaping the coastline by deposition and erosion. They also are important in determining local sea level. Transport of propagules (Andrews and Pickard 1990) and pathogens (Lessios 1988) by currents is a major control on the distribution of reefs, individual organisms, and related or competing communities at the large and intermediate spatial scales.

Salinity: Reef communities are at their optimum in oceanic salinities (about 35ppt), but can survive over a salinity range of about 25-42ppt, with rapid loss of organisms at higher salinities (Coles and Jokiel 1992). Salinity maintained below about 20ppt for longer than

Figure 2.3: The relationship between ultraviolet radiation effects on biological systems and its penetration into seawater. The relative biological response of DNA to different wavelengths of radiation (left axis) is compared to the downward penetration of that radiation at noon at various depths (right axis). The critical wavelengths of UV-B radiation (hatched) are those which both penetrate into the water and disrupt the molecular structure of DNA (adapted from Smith and Baker 1979, 1989)



24 hours is lethal for corals and most other reef organisms, with mortality occurring more rapidly at lower salinities. Variations in salinity are not an issue for most oceanic reefs, but may control reef development in restricted lagoons or adjacent to land masses where freshwater runoff or groundwater discharge may be intense (Smith and Buddemeier 1992). The synergistic effects of combining transient freshwater exposure with pollution or other stresses are important in determining mortality and recovery (Jokiel *et al.* 1993).

Nutrients: The relationship between inorganic nutrient levels (nitrate, phosphate) and coral reef health is somewhat paradoxical. Corals require very little external nutrient supply because they have effective internal mechanisms to recycle nutrients between the coral (animal) host and the zooxanthellae (plant) symbiont (Muscatine and Porter 1977; Hallock 1981). Other common photosynthetic reef organisms also thrive at low nutrient concentrations. Coral reef communities subjected to high nutrient levels deteriorate due to increased turbidity from plankton, increased bioerosion, poor coral recruitment, and overgrowth by filamentous algae, bryozoans, and barnacles (Birkeland 1977; Littler and Littler 1984; Tomasak and Sander 1986; Hallock 1988). The growth of reefs diminishes along a gradient from oceanic or oligotrophic (nutrient-poor) to eutrophic (nutrient-rich)

conditions near the land, upwellings or pollution (Birkeland 1988; Hallock 1988; Wilkinson and Cheshire 1988). However, this does not mean that reef communities require low nutrient conditions (Kinsey 1991). The issue is primarily one of competitive advantage; at higher nutrient levels algae and other non-calcifying benthic organisms can out-compete corals for available substrate, and in addition the corals may be concurrently attacked by increased populations of filter-feeding boring organisms (Highsmith 1980; Smith *et al.* 1981; Birkeland 1987; Hallock 1988; Grigg and Dollar 1990).

Temperature: Extensive coral reef development is limited to warm water (tropical and subtropical) environments. Many authors have suggested that the 20°C average annual isotherm or the 18°C winter isotherm coincide with the high-latitude limits to coral reef development (Fig. 1.1). Temperatures in excess of 33°C are tolerated by healthy coral communities in the northern Great Barrier Reef (Kinsey 1979) and the Arabian Gulf (Coles 1988). Within the present-day oceans, both coral species richness (Veron 1986) and rates of growth or calcification (Crossland 1988) seem to increase with average water temperatures. However, interpretation of coral temperature responses is complicated by intra- and inter-species differences and by the strong effects of local adaptation (Coles *et al.* 1976; Smith and Buddemeier 1992). Transient temperature increases of only a few degrees above the local average maximum may prove lethal to many corals (Coles and Jokiel 1977; Jokiel and Coles 1990), and even smaller increases may result in bleaching, a stress response characterized by loss of symbiotic algae (Glynn 1993; see bleaching in Chapters 4 and 5). When rapid temperature changes are considered, corals are more vulnerable to heating than to cooling and many appear to live close to their upper lethal temperature limit (Jokiel and Coles 1990). However, we do not know the absolute upper limits of coral temperature tolerance, and investigation of the rates and mechanisms of the temperature adaptation that obviously occurs is in its early stages (Buddemeier and Fautin 1993).

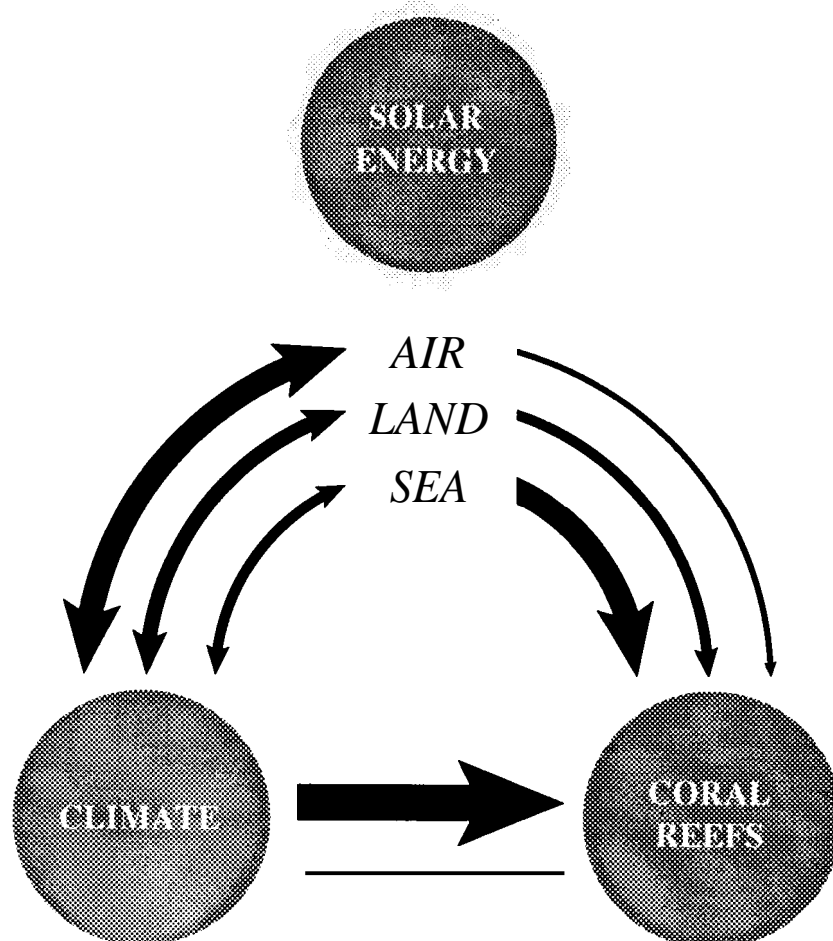
Saturation state: Calcium carbonate saturation state is a variable that appears to influence the calcification rates of at least some corals and algae (Smith and Buddemeier 1992), but little is known in relation to its overall effect on reef formation. It confounds the consideration of temperature effects on biogeography, because there is a very strong correlation between high aragonite supersaturation (see, for example, Lyakhin 1968) and high water temperatures. This is currently a matter of concern, because the effect of adding carbon dioxide to the atmosphere will be to reduce the calcium carbonate saturation state of surface ocean waters (Smith and Buddemeier 1992; see Chapters 4 and 5 and Atmospheric Environment below), which in turn may reduce the calcification of at least some organisms.

All of the effects discussed so far are controls that the marine environment exerts on the occurrence or nature of coral reefs. These reefs, however, significantly modify the marine environment in return, by constructing complex, massive, wave-resistant limestone structures nearly to sea level. They also modify the distribution of wave energy, creating protected lagoons and protecting shorelines that would otherwise be subject to the full energy of oceanic waves. These physical and biological modifications have profound implications for human societies as well as for the natural environment.

Atmospheric Environment

Although coral reefs seldom interact directly with the atmospheric environment, the atmosphere acts as an important pathway for forces that are transmitted to reefs through the water (Fig. 2.4; Smith and Buddemeier 1992). Wind strength and patterns profoundly influence the shallow marine environment at all scales from the major oceanic circulation patterns, through wave energy and the storm effects discussed above, to sea surface roughness that controls the penetration of visible and UV radiation. Cloudiness controls the amount of solar radiation (UV as well as visible) that falls on the sea surface, and both irradiance and air temperature then influence shallow water temperatures. Evaporation and precipitation influence oceanic salinity, and are determined by air-sea interactions. Because there is rapid equilibration of gases between the atmosphere and the dissolved gases of the surface ocean, changes in atmospheric composition rapidly affect the chemistry of surface waters. Rising carbon dioxide levels, which are rapidly reflected in surface ocean waters, change calcium carbonate saturation states and may therefore influence rates of calcification.

Figure 2.4: Schematic relationship of the direct transfer of solar energy through air, land and sea to coral reefs and how both climate and climate change will be indirectly involved. The width of the arrows indicates the relative importance of the transfer and impact of that energy.



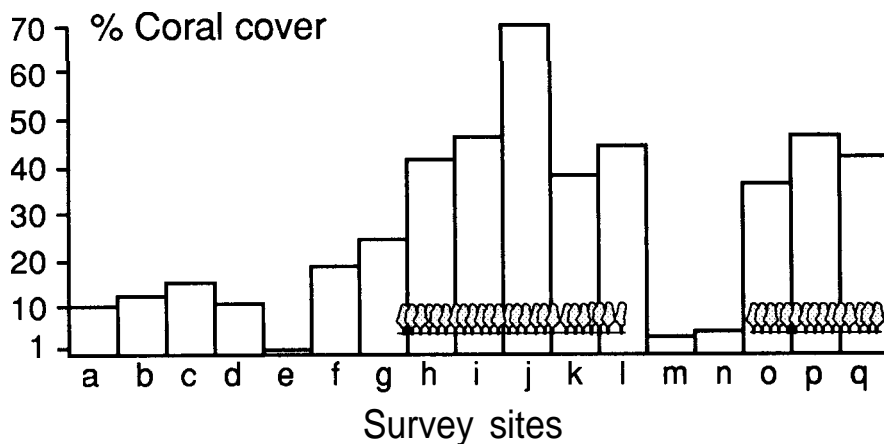
Terrestrial Environment

The land adjacent to coral reefs is a source of nutrients, and increasingly of contaminants and sediment loads from land clearing and agriculture (see Fig. 2.5). The land also focuses and delivers freshwater to nearshore reef environments; the drainage from large terrestrial areas may enter the coastal marine environment over a limited length of coastline or through a few river mouths. In this way the atmospheric and terrestrial components of the hydrologic cycle interact to have major effects on reefs close to land masses (Smith and Buddemeier 1992).

The existence of fringing and barrier reefs along coastlines is a profound influence on the structure of coasts and coastal communities (Box 2.1). In addition to the physical protection given to coastlines by reefs (see above), there may be interdependence of the reef and coastal communities. For example, coastal mangrove forest belts protect offshore reefs from sediment, pollution (Fig. 2.5; Kuhlmann 1988), and nutrient loading, and are in turn protected against physical wave damage by the reefs (Ogden and Gladfelter 1983).

One of the most significant aspects of the terrestrial environment is that it functions as a habitat for humans and a platform for their activities (Box 2.4), which are being concentrated more and more in coastal areas. Industry, agriculture, and urbanization are all human activities that may create stresses on nearby coral reef communities, but human interactions with reefs may be more direct. In many areas humans prey upon reef organisms for food, derive building materials or commercial products from the reef, or use the reef for recreation or commercial activities (e.g. tourism). Economic dependence of people on reefs may be high, adding a socio-political environmental dimension to the interactions of coral reefs with the marine, atmospheric and terrestrial environments (see Chapter 3).

Figure 2.5: Relationship between coral cover on reefs and the presence of a coastal forest belt on Ishigaki 1, Japan. Tree symbols on the figure indicate the presence of significant coastal forest belts, which are clearly associated with higher offshore coral cover, whereas reefs offshore from cleared forests have been damaged by sediment input (adapted from data in Kuhlmann 1988).



Box 2.4: Land Use Interactions

Large-scale clearing of forests for the extraction of timber and other products is occurring in many parts of the world, often without consideration for the replacement of lost vegetation. The World Resources Institute (1992) estimates that long-term deforestation rates are averaging 1 to 2% per year in many tropical countries with coral reefs, and that soil degradation continues to occur on a global scale. As a result of both deforestation and non-sustainable agricultural practices, topsoil is eroded, and rivers transport increased amounts of sediment into the coastal zone. Coral reefs in many tropical areas have suffered from sediment loads originating in deforested areas, often far inland (Hodgson and Dixon 1988).

Population growth and technological changes in agriculture have increased the nutrient loads of both surface water runoff and groundwater discharge in areas of intensive agriculture. In parts of the midwestern USA, high levels of fertilizer use have raised groundwater nitrate levels above public health limits, and the nitrate concentrations in the outflow of the Mississippi River into the Gulf of Mexico have increased by at least 5 times during the last 50 years (Turner and Rabalais 1991). This demonstrates anthropogenic alterations to the environment on a continental scale: temperate-zone farmers have significantly altered the nutrient flux into a large subtropical marine system.

2.3 Coral reef community structure and function

Environmental conditions, and changes in them, act upon the variety of organisms which constitute a coral reef ecosystem. To understand the effects of change on the ecosystem requires a closer look at the members of the community and the processes that characterize them.

Coral Reef Community Function

In a thriving coral reef community, most of the available space is occupied by photosynthetic organisms (primary producers of organic, or 'fixed' carbon), that are simultaneously calcifying (producing calcium carbonate). The high rates of gross organic and inorganic production are derived from the abundant oceanic reservoir of inorganic carbon dioxide, warm temperatures (usually above 20°C), and abundant solar radiation penetrating through clear water. The tropical waters where coral reefs grow are generally very low in nutrient nitrogen and phosphorous, which are essential for all plant growth. The metabolic processes that drive this production, in both the organism and the community are finely tuned to extract and recycle the scarce nutrient elements from the surrounding oligotrophic (low nutrient) seawater. The organic energy cycle of a coral reef is based on the productivity of two components, the primary productivity of the reef itself (benthic algae and corals) and the moving phytoplankton community from which some of the fixed energy is captured by reef organisms or drops out into the sediments.

Different parts of a coral reef system have characteristic gross primary production values. High density (near 100% cover) coral communities may produce 20gC m⁻²d⁻¹, while algal pavements and rubble or sediment communities typically produce about 5 and 1gC m⁻²d⁻¹, respectively (Kinsey 1991). Crossland et al (1991) estimated that the average net primary productivity on coral reef ecosystems is around 0.1gC m⁻²d⁻¹. Averaging these numbers over a whole reef system suggests that the annual sustainable net primary productivity must be on the order of

100gC m²yr⁻¹. This value is extremely small by agricultural standards and reflects the amount of available plant-produced carbon, not the more commonly harvested animal biomass. To compare productivity with fisheries yields, the chemist's unit of grams of carbon is converted into wet weight of biomass and corrections are applied for food chain efficiency - a rough estimate is that herbivores convert plants to meat with about 10% efficiency and a similar factor applies to the herbivore-to-carnivore step. When that is done, the yields discussed in Chapter 3 are consistent with the values presented here; a well-managed, non-destructive fishery may extract on the order of 10 tonnes km²yr⁻¹ from coral reef areas (Box 2.5).

As is the case for photosynthesis, the rate at which calcium carbonate is formed also varies in the various environments or communities found on a coral reef. The average calcium carbonate production rate is about 10kg CaCO₃m⁻²yr⁻¹ for the 100% coral/coralline algal community, about 4 for algal pavements, and 0.5 for rubble and sediment (Kinsey 1991). By making reasonable assumptions about the porosity of the carbonate and the amount of loss from the system, these calcification rates can be converted to volume of sediment produced and to reef vertical accretion rates - about 3 to 8mm per year. These rates of reef accretion will be observed only if the carbonate materials are retained on the reef, and will be less if the reef products are transported elsewhere, such as increased sedimentation on the lagoon floor (Smith 1983; Buddemeier and Smith 1988). The calcification rates obtained so far overall types of reefs in all geographic locations are sufficiently consistent that they could serve as a means of diagnosing whether reef function is normal or possibly stressed by factors like climate change.

Highly productive coral communities occupy only a fraction of the surface of an entire coral reef system. The underlying limestone structure, the sediment dominated slopes and lagoon floors and the less attractive reef flats are products of present and past coral reef communities. These parts of a reef may also be covered by productive living communities. The term 'coral reef' implies the larger system, but in discussions of the biological aspects of reefs or the reef community, the same words generally refer to the living community dominated by reef-building corals and calcifying algae. In this section, some of the key organisms and communities in the coral reef system are introduced to describe their metabolism and productivity and provide a basis for interpreting how these may change with changes in the environment - including climate change.

Symbiosis and Reef-building Corals

Reef-building corals are animals, usually colonial, which contain symbiotic algae (zooxanthellae) within their tissues (see Fig. 2.2). Energy-rich photosynthate produced by the algae is transferred to provide much of the coral's nutritional needs. The symbiosis also enables (by mechanisms not fully understood) the corals to sustain very high rates of calcification' - the source of much of the calcium carbonate that comprises the impressive geologic structure of reefs. Under suitable conditions, many coral colonies may attain an impressive size and ages of decades to centuries. They not only determine the physical characteristics of the community, but their ages and population structure defined the time scales of reef development and community turnover (Box 1.1). These time scales are often long, relative to human management and research perspectives. Although corals are the most impressive and important of the symbiotic organisms on the reef, other organisms also rely on photosynthetic symbionts for the

Box 2.5: Gross and Net Productivity and Sustainable Yield

Coral reef communities are often compared to tropical rain forests because of the spectacularly high biodiversity of organisms and apparently high productivity (Connell 1978). Although this comparison to rainforests is superficial and can be misleading, there is a genuine similarity because both ecosystems have a large standing crop of biomass, containing reservoirs of nutrients much larger than the fluxes and flows into and out of the system.

Because of internal recycling of both organic and inorganic nutrients, the apparent organic productivity of reefs is somewhat paradoxical. Reefs may have a very high gross photosynthetic rate, but this primary production is very nearly balanced by whole reef consumption i.e. respiration. Thus, the net productivity is actually quite low -- commonly 2-3% of gross productivity, which is only slightly higher than the net productivity per unit area of the surrounding ocean water (Kinsey 1991). In spite of the high standing crop of living organisms and the high gross productivity, the low amount of excess reef productivity places severe limits on the amount of organic matter that can be harvested or exported without damage to the community (Birkeland 1987).

bulk of their nutrition (soft corals and anemones, giant clams, some sponges, a few worms, and didemnid ascidians), and symbioses of many kinds contribute to the complex interconnections of biodiversity and function found on coral reefs.

Macro and Micro-algae on Reefs

The other major primary productivity component of coral reefs are the benthic macro- and micro- algae that coat many of the 'bare' surfaces (see Box 2.2). Calcareous or coralline algae not only photosynthesize, but also produce substantial amounts of calcium carbonate. Their role on many reefs is so important that it has been suggested that 'coral' reefs is a misnomer, and a more accurate term would be 'algal' reefs (Hillis-Colinvaux 1986).

The calcareous algae function in two ways: *Halimeda* are foliose algae which make major contributions to the loose sediments of many reefs; encrusting algae such as *Lithothamnion* make important structural contributions to the reef by binding and cementing reef surfaces into a durable limestone plate or block. This algal cementation is most pronounced in high energy environments, such as on the reef crest, shallow reef flats, and the seaward intertidal zone of reef islands.

The non-calcifying algae contribute the bulk of the primary productivity on most reefs. This is readily transferred up the food chain via consumption by herbivores such as fish and urchins. These 'turf' algae are an important component of the reef ecosystem, and cover all bare surfaces particularly on the shallow reef flats. When the tide rises, large populations of grazing fish systematically spread out and crop these algae.

Underneath these algae and coating the exposed sand grains, is another community of microscopic algae and bacteria. These are grazed by a large suite of organisms including molluscs, crustaceans, holothuroids (beche de mer) and echinoids (sea urchins) as well as sediment-eating fish. Many of these organisms are important food items for fishers and gleaners of reefs.

The Consumers

There is a wide range of organisms that depend on coral reef primary productivity for food. These consumers include fishes, echinoderms, molluscs, crustaceans as well as worms and microscopic components such as bacteria. These consumers are not merely a sink for organic material, but an integral part of the standing biomass that functions to recycle nutrients within the community and sustain its overall metabolism. When humans, or some other species such as pelagic fish, harvest food from the reef they too become consumers, but of a different type. Consumers who do not reside on the reef itself result in the export and loss of both biomass and nutrients (see Box 2.5). We cannot determine the direct effects of climate change on individual taxa of most organisms, over and above the effects on the community as a whole. Because the various consumers are part of an interactive food web that is only broadly understood, changes in any part of the system may be either an indicator or a cause of far-reaching effects.

Bioeroders

In parallel with the calcification build-up processes on reefs, there are a range of mechanisms for eroding and degrading the calcium carbonate (Hutchings 1986). These are important in restructuring the framework and producing sediments. Many different organisms bore into coral and algal skeletons including algae, sponges, worms and molluscs. These cause the structures to become fragile and vulnerable to fracture by the strong physical forces of waves. Another group of organisms erode calcium carbonate surfaces from the outside whilst they graze on algae. Grazing fish and sea urchins produce large quantities of sediment and, in the case of the latter, can cause massive reef destruction on polluted or disturbed reefs, particularly when the major urchin eating predators (fish) are removed (Glynn 1988a). Likewise, increased nutrient levels can favour the growth of internal bioeroding organisms, which can result in marked destruction of standing corals (Highsmith 1980; Hallock and Schlager 1986). The net result of the normal processes is, however, not destruction but reconstruction as the uppermost fragile material is broken down into fine sediments, which fill in voids and are then cemented to form coral rock (Wilkinson 1983).

Plankton

Plankton are the microscopic plants and animals that inhabit the water and whose large and medium-scale movements are controlled primarily by water motion. Plankton are important to coral reef ecosystems since they serve as food and nutrients for animals higher in the food chain, and because many important coral reef species have planktonic larvae which act as the long distance dispersal mechanism between reef areas (Box 2.6). These larvae are transient members of the plankton, but their survival is crucial to the reproduction and recruitment processes of a coral reef. Plankton communities predominantly drift in the upper few metres of the water column and hence are susceptible to changes in the amount of incident light, UV radiation, temperature and water movement (Box 2.3).

Box 2.6: Planktonic Larvae

Corals exhibit two spawning strategies for sexual propagation, both producing planktonic larval stages. Most numerous are the broadcast spawners, which release (sometimes simultaneously) millions of eggs and sperm that develop into free swimming larvae. These drift in the upper layers of the plankton for 4 to 7 days before seeking suitable reef substrata. In the other type of larval reproduction, some corals (brooders) hatch within their tissue better developed propagules which have a very short (hours) free swimming stage (Harrison and Wallace 1990). The vast majority of reef fish also have planktonic larvae. The duration of larval life varies considerably from 3 weeks to well over 3 months (Leis 1991). Many other reef organisms spend time in the plankton. One important group within this listing is the larvae of the crown-of-thorns starfish, *Acanthaster planci*, a predator of corals with episodic population explosions. Variations in conditions affecting the 3week larval life may explain these periodic outbreaks (see discussion in Chapter 5).

The prevalence of planktonic larvae among reef-dwelling organisms means that there is genetic exchange between reefs. The diversity of reef populations and the rate and nature of their recovery from disturbance depend not just on the reef itself, but on the nature and proximity of other reefs, which can serve as upstream sources of new larvae. Critical to these processes are not only the conditions controlling larval survival, but also the patterns of ocean currents, which are recognized as sensitive parts of the earth's 'climate machine' (Kerr 1993a).

Sediment Dwellers

Areas of shallow sediment (>20m water deep) often cover larger areas than either the living or dead coral habitats; however, these are often overlooked in considerations of reefs. The sediment areas have generally low productivity per square metre, but because of the large a real coverage, they are significant in terms of whole reef productivity. The bulk of their productivity is derived from a thin coating of microalgae on the sand grains (Hansen et al. 1987). These algae consist mainly of diatoms and cyanobacteria. The bulk of the sediment community gross productivity is consumed *in situ* by large populations of algal and bacterial grazing molluscs, polychaete worms, micro-crustaceans and other animals (Wilkinson 1987a; D'Elia and Wiebe 1990). These organisms in turn are preyed upon by many sediment animals as well as others, such as fish that feed over the sediment flats.

Sediment communities are also important as sites for nutrient regeneration by bacteria. Considerable amounts of organic matter fall onto or are incorporated in the sediments and demineralized into inorganic components, including forms of nitrogen and phosphorous (D'Elia and Wiebe 1990). In some coral reef areas (e.g. the Caribbean), lagoons often have extensive beds of seagrass which support large populations of commercially important animals.

3. Human Uses of Reefs and the Consequences

3.1 How People Use Coral Reefs

Coral reefs and the associated islands and coastlines traditionally provide three basic resources for human use:

a place to live;

building materials; and

local subsistence food,

More recently, reefs have become important sources of recreation and cash income derived from tourism and the export of both food and non-food products.

Inadvertently or sometimes intentionally, reefs are also serving as waste disposal sites, because large quantities of domestic, agricultural and industrial wastes are being discharged into coastal waters. Rapid deforestation is also leading to massive loads of sediment being washed onto coral reefs (Fig. 2.5).

Fisheries, either subsistence or export, are putting additional stresses on reefs by selectively removing some components from a complex ecosystem.

The inadvertent result of these human activities, although sanctioned and regulated by tradition and necessity, is chronic stress to reefs. Pollution by inorganic nutrients, organic matter, excessive sedimentation (including 'reclamation'), and over-exploitation (fishing, mining, collecting) are the major stresses to coral reefs (Grigg and Dollar 1990; Smith and Buddemeier 1992; Wilkinson 1993a). These stresses have resulted in a loss of approximately 5-10% of the world's reefs to date, with predictions that another 30% of the reefs will be effectively destroyed in the immediate future (within 10 to 20 years; Wilkinson 1993a).

The subsections that follow describe the various types of use and some of their consequences.

Reefs as Places to Live

Many people live on coral atolls and cays, on remnants of uplifted reefs or sinking volcanos, or on the flat coastal plains of reef origin that area feature of some volcanic islands (Table 3.1). Still others live on coastlines that are not constructed by corals, but where the dominant feature of the marine environment is a fringing coral reef (Table 3.1; see Box 3.1). In all, there are several tens of millions of people who harvest reef resources for subsistence and sale in local markets (Salvat 1992).

Table 3.1.

Population and geographic data for prominent countries and territories with coral reefs, grouped relative to their dependence on and integration with reefs. Those with many inhabited coral islands generally have rapid population growth rates, high population densities and low per capita incomes (GNP per Capita; US\$). Many of these are very dependent on external aid income shown as negative Balance per Capita values (the net amount of inflowing money per individual; US\$) with Nauru being the only net exporter, exporting phosphate reserves.

Country/ Territory	Atoll population 1000	Total population 1000	Growth rate %	Population density per km ²	Coastline length km	GNP per capita	Balance per capita
Atoll Islands (predominantly)							
Kiribati	72	72	2.3	104	1143	720	-215
Maldives	221	221	3.4	450	644	460	
Marshall Is	46	46	4.2	255		1000	
Tokelau	2	2	1.5	180			
Tuvalu	10	10	4.1	392	24	500	-335
Mixed Atoll and High Islands							
Comoros Archipelago		521	3.5	260	340	500	
Cook IS		17	-0.2	71	120	2600	-2120
Fed States Micronesia	16	102	4.0	144		905	
Fiji		796	1.8	44	1129	1930	-207
French Polynesia	15	196	2.7	56		13030	-2940
Palau	0.1	15	2.3	31		1020	
Samoa U.S.		47	3.6	234		4400	-1240
Samoa W.		158	0.1	54		960	-340
Seychelles	1	72		230	491	5100	
Tonga	96	0.5	129	419	1290		
Wallis & Futuna	14	1.3	55				
Small High or Uplifted Islands with Reefs							
Barbados		273		63	97	6630	
Dominica		77		77	148	2440	
Grenada		97		-190	121	2180	
Guam		133	2.2	247		8140	
Mauritius		1140	1.2	616	177	2410	
Nauru		9	2.3	443			+5924
Niue		3	-5.3	10	64		
Singapore		2905	1.3	4762	193	14210	
Trinidad & Tobago		1364	1.7	266	362	3760	
Larger Islands with Reefs							
Bahamas		274		20	3542	11750	
Dominican (Rep.)		7680	2.2	159	1288	940	
Haiti		6997	2.0	254	1771	370	
Indonesia		194950	1.9	108	54716	610	
Jamaica		2540	1.2	235	1022	1380	
Madagascar		13450	3.2	23	4828	210	

Country/ Territory	Atoll population 1000	Total population 1000	Growth rate %	Population density per km ²	Coastline length km	GNP per capita	Balance per capita
New Caledonia		180	2.0	9	2254	11000	-480
Papua New Guinea		4270	2.3	9	5152	830	-23
Philippines		67600	2.5	227	22540	730	
Puerto Rico		3815	0.9	424		6320	
Solomon Is		344	3.7	12.	5313	690	-106
Sri Lanka		17905	1.3	277	1340	500	
Vanuatu		160	2.4	13	2528	1150	-285
Continental Land with Substantial Reefs							
Australia		18010	1.4	2	25760	17050	
Belize		208	2.4	9	386	2010	
Columbia		34929	2.0	34	2414	1260	
Costa Rica		3350	2.6	66	1290	1850	
Cuba		11010	1.0	100	3735		
Ethiopia		53184	2.7	48	1094	120	
Honduras		5806	3.2	52	820	580	
India		920310	2.1	310	12700	330	
Japan		125050	0.4	332	13685	26930	
Kenya		27685	3.6	49	536	340	
Malaysia		19640	2.6	60	4675	2520	
Nicaragua		4260	3.4	36	910	460	
Oman		1519	3.8	7	2092	6120	
Panama		2660	2.1	35	2490	2130	
Saudi Arabia		15808	4.0	7	2510	7820	
Somalia		8235	3.3	13	3025	120	
Sudan		28030	2.9	12	853		
Tanzania		30400	3.7	35	1424	100	
Thailand		59825	1.5	117	3219	1570	
Venezuela		21280	2.6	24	2800	2730	
Vietnam		70990	2.2	218	3444	215	
Yemen (Rep.)		13812	3.5	26		520	

Data were obtained from World Resources Institute (1992) and World Bank (1993) with some extracted by H. Manner from Douglas and Douglas (1987), Anon (1991) and the South Pacific Commission (1992). Missing data points are listed as blanks.

Many of the islands in the Pacific and Indian Oceans consist almost entirely of coral islands (e.g. Tuvalu, Tokelau, the Maldives, the Marshall Islands, and most of Kiribati). In the Pacific, there are approximately 160,000 people who live on many coral atolls and a little more than 2 million who live on high islands that are surrounded by significant coral reefs; in the Indian Ocean, there are about 300,000 on coral islands. Populations in the Caribbean on true coral cays are much smaller because there are fewer islands. However, a large proportion of the 30 million people who live on the Caribbean islands have close contact with coral reefs (World Resources Institute 1992). In addition, there is another group of larger countries where reefs are an important component of the coastline and where many people use the resources provided by the reefs e.g. the Philippines, Indonesia, Jamaica, Kenya (Table 3.1). Here total populations are in the hundreds of millions.

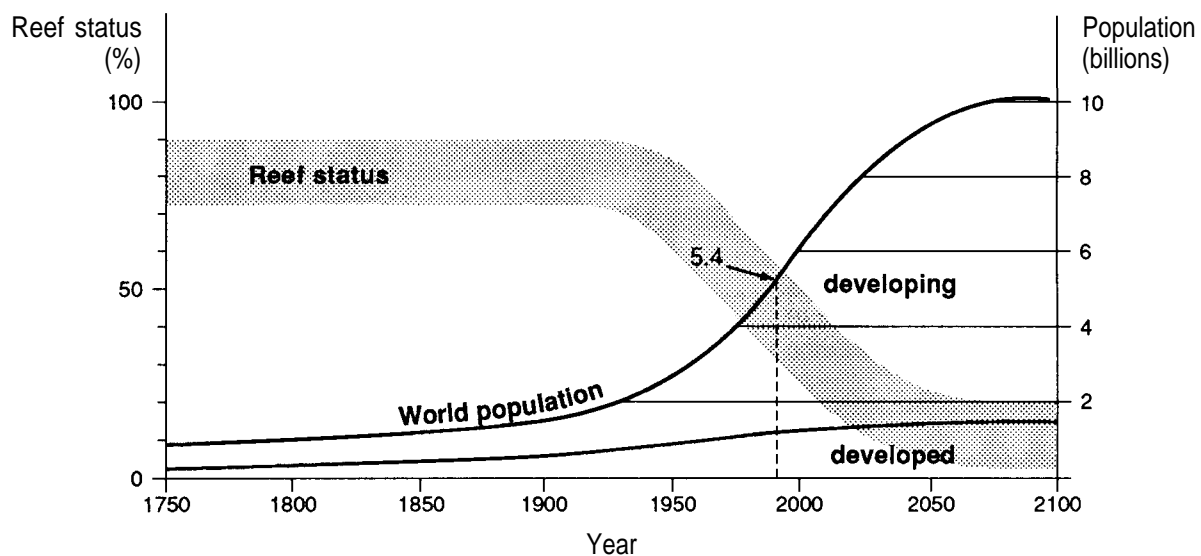
Box 3.1: Population and Coral Reefs

The world's population is approximately 5,400 million people and is expected to increase to at least 8,500 million by 2025 (World Resources Institute 1992). Most of this 3 billion increase will occur in developing tropical countries of Africa, Asia and Central and South America, where the coastal and reef resources are already stressed and over exploited.

Human (anthropogenic) stresses to coral reefs are directly related to population and its rate of growth - the higher the population and its rate of growth, the greater the damage to coral reefs (Fig. 3.1). In developing countries, a population growth rate of 1% per year is usually beyond current resources (FSM 1992), whereas most island nations far exceed this. For example, in the Maldives (Indian Ocean), population growth is 3.5%, which means a population doubling time of 20 years and in the Federated States of Micronesia, population growth is 4.2%

Figure 3.1:

The predicted relationship between the world's population and the global status of coral reefs, with the chronic stresses from expanding populations **in both developed and developing countries leading to a degradation of coral reefs (from Wilkinson 1993s).**



The Marshall Islands (Central Pacific) has one of the most rapid population growth rates in the world - 4.25%. with a doubling time of 16.5 years (the population will grow from 43,380 in 1988, to 189,440 by 2025; (FSM 1992). The population is unevenly distributed over the 24 inhabited atolls, averaging 240 per km² (total area is 181.5 km² on 33 atolls), whereas the urban areas of Majuro Atoll and Ebeye Islet have densities of 11,000 per km² and 23,000 per km². These densities are amongst the highest in the world, and cause considerable social, economic and health problems as well as severely impacting on nearby reefs with sewage pollution, waste disposal and over-exploitation of food resources. Development projects are being planned to serve an even larger population. These include tuna and local fisheries processing, and the development of infrastructure for tourism, sewage treatment, electricity production and oil storage. These will all have negative environmental impacts, which must be balanced by social and economic benefits (FSM 1992).

Migration is one way to reduce the impacts of growing populations on local resources, but internal migration only displaces impacts from outer islands to urban centres. Emigration to other countries is a practical option primarily in cases where prior historical and political affiliations exist (such as between Tokelau and New Zealand). In the long-term, emigration maybe limited by resource and political considerations, requiring other approaches to defining and maintaining sustainable human populations.

The predominant threat to coral reefs lies in the use of them by these large populations, which are also increasing rapidly. Some of the fastest growing populations in the world occur in tropical and sub-tropical countries with coral reefs (Table 3.2). Approximately 60% of 1.8 billion people who live in tropical countries of Africa, Asia (excluding China), the Pacific, and the Caribbean live within 60km of the coastline where there are coral reefs (Table 3.1 and Fig. 1.1). Population control is often difficult to implement e.g. in Asia, population growth in the Philippines continues at 2.48% with continuing disagreement between the church and State on the morality of population control, whereas in Malaysia, the government has a positive population growth strategy with current rates at 2.31%.

Large numbers of people in many developing countries are partially or nearly completely dependent on the reefs for their livelihood (Box 3.2). The degree of dependence is related to the amount of alternative food and building resources that are available. For example, people on coral reef islands like the Maldives or Tuvalu have few other resources and are dependent on the reefs for the bulk of their food and potential income. Mainland or high island nations, like Fiji or Mauritius, have alternative resources and their degree of dependence on reefs decreases in line with the amount of other exploitable resources. Continued population growth, however, and many practices associated with economic development are placing increasing pressure on reefs. In the economically developed countries such as Japan, Australia and the USA, population growth rates are approaching replacement levels and very few people are directly dependent on the reefs for either food or primary income. In some cases, however, there has been significant damage to reefs through poor land management practices.

Table 3.2.

Selected population growth rates and doubling times. Those coral reef countries with the highest and lowest rates are presented to illustrate the range (World Resources Institute 1992).

Region/Country	Annual Growth Rate (%)	Doubling Time (yr)
East Africa from Kenya to Mozambique	3.80 2.65	18 26
Caribbean from Nicaragua to Barbados	3.36 0.62	21 112
Pacific from Marshall Is. to Australia	4.25 1.22	16 57
Asia from Philippines to Malaysia	2.48 2.31	28 30
Vietnam and Japan	2.28 0.44	31 158

Box 3.2: Economics of Pacific Island States

Most Pacific island states are classified as economically developing nations (except for Nauru; Table 3.1). All of these countries have net negative trade balances, because they export low value, natural resources and import more costly manufactured goods (electronics, machinery and transport equipment), petroleum fuels, chemicals, and building materials. Trade is small in global terms; an exception is pelagic fisheries (particularly tuna), because these Pacific island nations have large Exclusive Economic Zones. Most countries are dependent on one to two exports, with other opportunities being hindered by poor infrastructure (e.g. inadequate transport and storage facilities), a lack of capital, long distances from markets, and other factors. These factors, along with the high population growth rates (Table 3.2; Box 3.1), mean that these countries will have a negative external trade balance for many years, thereby placing even greater pressure on natural resources and the development of infrastructure. Rapid growth rates in resource-poor developing countries lead to even greater resource exploitation, well above the country's carrying capacity to support human life without apparent degradation and a lowering of the standard of living. Tourism is seen as a viable growth industry for many of these developing islands, despite some potential adverse social and environmental impacts.

In these transitional Pacific economies, about 80% of the population relies on subsistence fishing and agriculture, with this percentage increasing at greater distances from growing urban centers. Heightened social-economic aspirations, however, have stimulated internal migration from outer islands and villages. External migration to access work, education, etc., has resulted in more health and environmental problems in the receiving centers (Box 3.1). More than 5,000 people from the Federated States of Micronesia and the Marshall Islands have migrated to Guam and the USA. Many Polynesians from Tokelau, Niue, Cook Islands, Tonga and Samoa live in New Zealand and make important economic contributions both to New Zealand and their homelands, particularly by sending money back to their home countries.

Box 3.3: Importance of Fishing

Fishing and gleaning off coral reefs provide important sources of animal protein for peoples who live near coral reefs. Peoples from widespread Pacific Island communities (Fiji, the Solomons and Micronesia) derive between 80 and 98% of their animal protein intake from the reefs; a similar figure was found for peoples from Cayos Miskitos reefs on the Caribbean coast of Nicaragua (Bayliss-Smith, in Pernetta and Hill 1982). Frequently more time and calories were spent on getting this food than were gained in terms of caloric energy (usually between 6 and 200%). Therefore seafood is prized nutritionally and constitutes a significant factor in the sociological structure of island communities. Seafood is also important for coastal and island peoples. For example, people in the Philippines derive up to 500% of their animal protein from marine fishes (34 kg per person per year) with coral reef fish being about 200% of this (Alcala *et al.* 1987; World Resources Institute 1992).

Box 3.4: Innovative Fishing Practices

Not all fishing practices are as labour intensive as line and spear fishing and casting of nets. Many island cultures have developed intricate fish traps, made either of stone or wooden poles, to harvest fish as they move over coral reefs. In Yap, Micronesia, some traps (called ach) are so intricate that they selectively filter out different sizes of fish (Falanruw 1992). In the entrance channels into lagoons of some French Polynesian reefs, fish traps have been constructed across the current flow to trap fish migrating in and out of the lagoons. The fish are held in the traps and harvested in bulk for shipment on the weekly steamer for the markets in Papeete, Tahiti. Successful trap development has always relied on a well developed knowledge of fish behaviour and movements and lagoon currents. However, the use of these traps, when combined with a market economy however, can result in over-exploitation of the fish stocks, because labour input is small and the financial returns are potentially large.

Reefs as Sources of Food

Before 20th century development and rapid population growth, traditional cultures living on coral reefs were dependent on their reefs for a major part of their subsistence. These cultures developed many methods for ensuring that the fish stocks were not depleted (Johannes *et al.* 1991). Although cultures have changed with the availability of imported food in many of these countries, large numbers of people living adjacent to coral reefs continue to derive much and sometimes almost all of their animal food protein from coral reefs, or from fisheries that depend on the coral reef productivity (Box 3.3).

The world harvest of finfish and shellfish in 1990 was estimated at 95 million tonnes or about 20kg per person (World Resources Institute 1992). Coral reefs provide approximately 10 to 12% of that catch, particularly snapper, grouper, emperor, jacks, grunts, goatfish and siganids (Munro and Williams 1985; Salvat 1992). The standing stocks of fishes on reefs maybe 5 to 15 times the stocks, per unit area on the North Atlantic fishing grounds, but the maximum sustainable annual harvest for coral reef fisheries is probably 10 to 20 metric tonnes km² (see Box 2.4 and associated discussion).

Sustainable fisheries yields on coral reefs are intrinsically limited by the relatively low net primary productivity of the reef ecosystem (discussed in Chapter 2). Although the standing crop of biomass on reefs is impressive and invites exploitation, the long-term sustainable harvest is limited because reef communities are controlled by low nutrient input (Birkeland 1987). There are only a few ways to increase this value, and because of the relatively long time constants of reef community turnover, over fishing maybe difficult to notice until depletion and ecosystem change is relatively advanced.

Fishing techniques vary considerably among countries and cultures, and even within individual fishing communities. Traditional fishing methods are relatively labour intensive (Box 3.4), and combined with cultural traditions that had a conservation ethic and relatively stable populations, these acted to protect reefs from overuse in the past (Johannes *et al.* 1991; Box 6.1). Expanding populations, the availability of advanced technology, and a loss of cultural traditions have all served to place much greater pressures on reefs. The predominant methods continue to be line fishing, various uses of nets, the development of fishing traps and gleaning at low tide. In many regions, fishermen resort to spearfishing, either free-diving or more recently using compressed air equipment. These extensions of traditional methods have increased fishing efficiency, while the use of powered boats has extended the range of reefs accessible to fishermen. The virtual absence of pearl shell in many lagoons, like in Tokelau, is directly attributed to the use of diving goggles, which were unknown in traditional culture (Toloa and Gillett 1989). In addition to regular fishermen, many people in the developing world fish in addition to their regular employment (White 1987). This is undertaken in the evenings, at night and over weekends. Women and children also play a major role in obtaining food for the family through gleaning reef flats at low tide for fish, crustaceans, molluscs etc. (White 1987; McManus *et al.* 1992). In some areas, many of the items amongst the catch are sold to tourists.

In many countries, destructive practices are widely used, even though governments have outlawed them and imposed harsh penalties (Salvat 1987). Dynamite, muro-ami and poison

(bleach, cyanide and vegetable extracts) fishing practices are still widely used throughout coral reef areas in the developing world, particularly in Asia (Alcala and Gomez 1987; Gomez *et al.* 1987; White 1987; Toloa and Gillett 1989; McManus *et al.* 1992). The small-scale muro-ami procedure with several fishermen driving fish into the nets by bashing the coral has been expanded in southeast Asia. Operators using several boats 'employ' hundreds of children who combine to drive fish out of the coral structures into large positioned nets with dramatic destructive effects on remote reefs (Carpenter and Alcala 1977; Hodgson 1991). Dynamite fishing is still so common in parts of the Philippines that blasts, once heard at 5 minute intervals, can still be heard at hourly intervals in many reef areas, even though such practices are illegal (McManus *et al.* 1992).

Fish stocks in many areas have declined so markedly that it has been argued that fishermen consider that they have been 'forced' to resort to destructive mechanisms to feed their families and make a living (Munro 1987). In some areas these methods have now been practiced for several generations and are considered to be part of the traditional culture.

Despite a lack of solid quantitative and historical data, it is clear that fish stocks on many coral reefs are declining markedly (Appledorn and Lindenman 1985; Russ 1985; Goodyear 1988a,b; Pauly 1989). The trends include decreased landings for many fish categories, greatly increased fishing effort (including a shift to destructive methods such as dynamite fishing), reduced average and maximum sizes, and shifts in the species composition. The coral reefs on the north coast of Jamaica are a good example. Munro (1983) reported that as early as 1959, the fish stocks were composed of only juvenile fish, with no adult fish of edible species present. This situation has further declined with continued pressure on the fish populations. A similar situation occurs in many other Caribbean sites near centres of human population e.g. Barbados. Excessive fishing pressure has also been identified throughout the Philippines, leading to marked declines in fish stocks (Alcala *et al.* 1987; McManus *et al.* 1992).

The removal of fish and other algal grazers such as molluscs and echinoids enhances the growth of macro-algae, thereby resulting in increased competition for substrate. Northern Jamaica is the best documented case of this (Hughes 1989; Liddell and Olhurst 1993). The coral reefs have effectively collapsed following Hurricane Allen in 1980 and the death of the long-spined sea urchin, *Diadema antillarum*, in 1983. These events resulted in a dramatic increase in the growth of macro-algae that smothered juvenile corals settling after the hurricane. Macro-algal growth was previously suppressed by grazing fish and echinoids but over-fishing and the death of echinoids removed predation on the algae, resulting in explosive growth. Coral cover has dropped from 50-70% to less than 5%, with no apparent signs of recovery (Fig. 3.2; Liddell and Ohlhorst 1993).

Reefs and Construction

People living adjacent to coral reefs often use them as a source of building materials. On reef islands devoid of terrigenous rocks, the only rock for building comes from limestone or corals, especially massive species. In the Maldives, there has been marked reef depletion in both living and dead coral blocks because of their use in building (Kenchington 1990). The rate of extraction increased more than 10 fold following increased demand from the developing tourist

industry. Coral reefs often serve as the only available or the cheapest source of calcium carbonate for use in making cement. This has resulted in large scale destruction in reefs in India, Sri Lanka (UNEP/IUCN 1988) and Indonesia, even though limestone deposits are available on land. In Indonesia, several reef islands adjacent to Jakarta have been mined until they disappeared (Brown 1986). Sand continues to be extracted from the reef flat of Mauritius at a rate that does not appear to be sustainable -600,000 tonnes per annum. In Fiji, more than 6 million tonnes of sand were removed per year from one bay on Viti Levu (UNEP/IUCN 1988). There are many other examples of coral rock and sand extraction around the world and most have been accompanied by environmental damage that was not predicted before or during the extraction process. Limited removal of coral for lime production is not particularly harmful and forms part of traditional culture (Box 3.5).

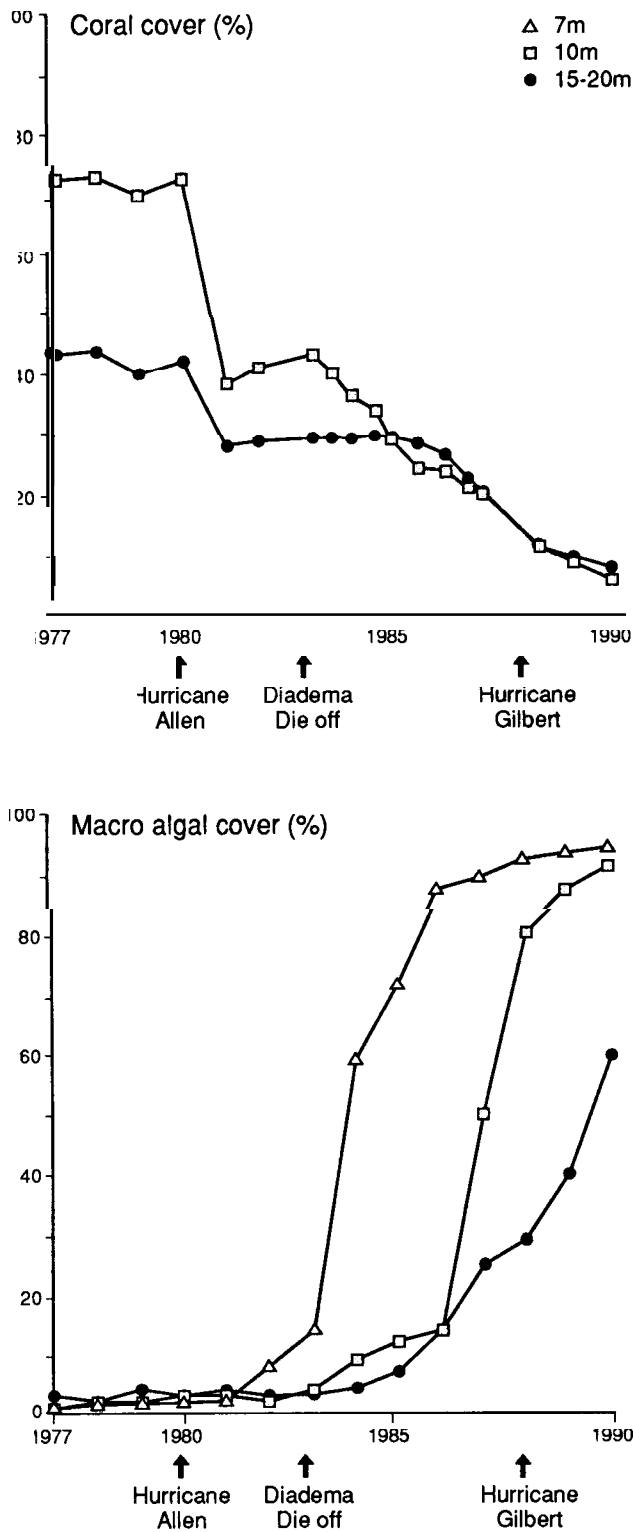
Reefs are often regarded as getting in the way, and in many areas dredging, excavation, and blasting are used to open boat channels, and create or improve harbours. Reef-derived materials are also used during land fill operations (Box 3.6) to further alter the reef environment by constructing features such as runways on the attractively flat and level surfaces of coral reefs, and to connect atoll islands with causeways that alter cross-reef water transport and lagoon circulation patterns (Kenchington 1990). In Singapore, many of the reefs have been buried under fill and garbage and the process is continuing to expand the area of the city-state (Chou 1991). Such activities often have effects reaching well beyond the reefs directly destroyed because pollutants and sediment generated by the processes are widely distributed.

Reefs as a Source of Export Income

Export fisheries are also contributing to some of the degradation that is occurring on coral reefs in many developing countries, particularly in southeast Asia. Here the Japanese, Taiwanese, Hong Kong and Singapore markets for seafood are continually expanding and much of the export product of the region is sent to these markets for prices far in excess of that obtainable in local markets. This economic incentive is leading to overharvesting of reef resources and to the increasing use of destructive practices. This overharvesting is also exacerbated by the increases in domestic standards of living, which result in the local populations having more disposable income to purchase seafood - the favoured form of food protein. Therefore, short-range exports to rapidly growing urban markets within the developing countries is an increasing pressure that may be more important than the population growth of the peoples directly involved in subsistence fishing.

Long-distance export of reef fish or food products from isolated Pacific Island reefs has not been widely developed, due to the multi-species nature of reef fisheries, the wide range of size classes, low market acceptability of tropical species in developed markets, and transportation problems and costs. Fish exports from the island of Pohnpei in Micronesia amount to only 140 tonnes per annum, and this is a twenty fold increase in 3 years (FSM 1992). Where extensive fishing for the international market has occurred, as in the case of Taiwanese harvesting of giant clams (*Tridacna*) throughout the Pacific, the results have been disastrous, with population crashes and local extinctions (Gomez and Alcala 1988; Govan *et al.* 1988).

Figure 3.2: The degradation of coral reefs on the north coast of Jamaica. Two unrelated events, a hurricane in 1980 and the death of the algal grazing sea urchin (*Diadema artilkarum*) in 1983 resulted in a collapse in live coral cover (upper) and a population explosion of large algae (lower) because the populations of grazing fishes have been over-exploited (figures provided by T. P. Hughes).



Box 3.5: Betel Nut, Sugar and Bride Price

Traditional cultures have developed a wide range of different uses for coral reef species. Many indigenous peoples in the Indo-Pacific region chew betel nut (*Areca catechu*) for its narcotic effect. The nut, when chewed with the leaf of the betel (*Piper betel*) and finely crushed lime (*calcium oxide*), results in red-orange saliva and characteristic stained teeth. Staghorn coral (*Acropora* spp.) and similar species provide the source of this lime. The coral is sun dried, heated over an open fire to breakdown the CaCO_3 to CaO , and then finely ground. This is a minor use for coral; however, in Mauritius large quantities of lime from *Porites* coral were once used to clarify sugar cane juice. Approximately 25,000 tons of coral were harvested annually, mostly from the reefs off Port Louis and Mahebourg.

Reef species have also been used as money. In the Solomon Islands, *Nassarius* shells were ground and finely polished to make necklaces for traditional bride price, exchanges, reconciliation, and other payments. This tradition of shell money is still practiced today, although often accompanied by portable cassette players, transistor radios, and cash. In Papua New Guinea, money belts and strings of *Cypraea monetawere* traded far inland and the same species was also traded from the Maldives into north India and Arabia. The kina shell (*Pinctada* sp.) is an important body decoration throughout Papua New Guinea and the word KINA has been adopted as the major currency unit (1 kina = \$1.1 US), whilst the toea (approx. 1 cent) is named after the conus arm bracelets traditionally used as a Motu bride price.

In addition to export fishing discussed above, there are some truly international forms of trade in reef products that create additional threats to reefs. Many of the curios (shells, coral, etc.) that are exported or sold within the country to tourists come from reefs. Probably the major exporter of such material is the Philippines, although this export is largely prohibited both within the country and by importing countries (Alcala and Gomez 1987). Many of the tridacnid clam species have become extinct in the Philippines (Gomez and Alcala 1988), mostly as a result of having been sold to tourists as ashtrays. This trade continues with overharvesting threatening the remaining species (Villanoy *et al* 1988).

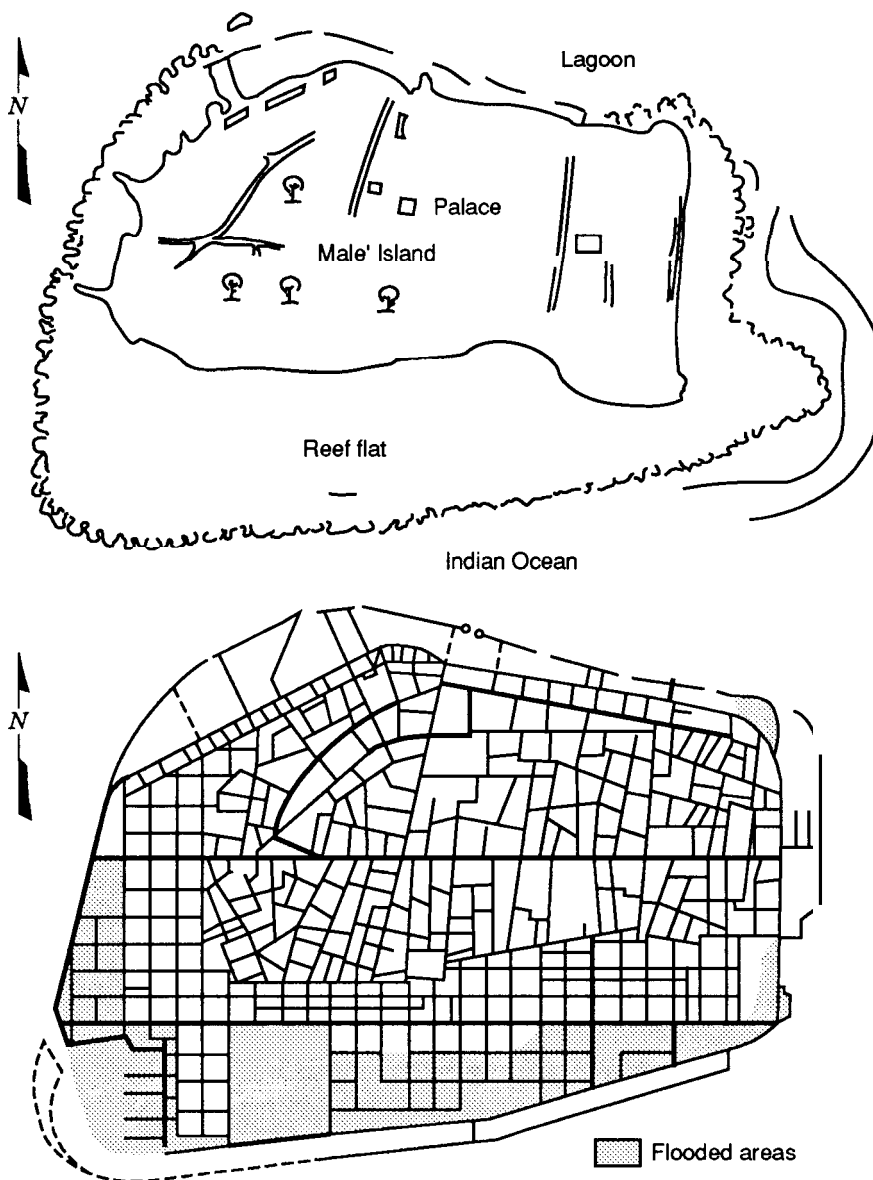
The adoption of the CITES agreement (Convention on International Trade in Endangered Species) by the United Nations has been instrumental in diminishing such trade, but this has often been to the detriment of people who previously derived their livelihoods from these exports.

Another developing lucrative industry is the collecting of aquarium fish and live corals for markets in Europe and North America. Unfortunately, a widely applied technique uses cyanide to force fish out from the coral and stun them for easy capture. Such fishing usually results in a poor success rate during capture, with an additional loss of up to 50% en route to the market because of residual cyanide effects and poor transport conditions (Wood 1985; Gomez *et al* 1987; White 1987). Poisoning also results in extensive damage to corals and other reef invertebrates that are incidentally killed during the process. Traditional reef users in Tokelau recognised this problem and banned the use of toxins from *beche de mer* because of damage to adjacent corals (Toloa and Gillett 1989). Although some juvenile reef fish can be harvested in substantial numbers without damage to the population, this is not true for long-lived invertebrates. Anemones and hard and soft corals are increasingly popular collection items; they live decades to centuries in nature with correspondingly low reproduction and recruitment rates, but are subject to high mortality on transportation and can rarely be maintained in captivity longer than a few years, even by master aquarists.

Box 3.6: Land 'Reclamation' in the Maldives

The conflict between needs for land and building materials and the value of reefs as physical protection is well illustrated by the case of Male , capital city of the Maldives (Pernetta and Sestini 1989). The original island occupied less than half the total reef area (Fig. 3.3). Population growth has created pressure for more space, and during the 1980s new land was created by pumping sand onto the reef flat on the oceanside of the island. This led to building development overvirtuallythe entire area of the original reef system. In 1987, large waves originating from a storm center in the Southern Indian Ocean resulted in extensive flooding of the city and loss of part of the reclaimed area (Fig. 3.3). The loss of the reef flat had reduced the capacity of the reefs to absorb wave energy, and waves broke over the edge of the artificial land and into the city. Protection of the island is now provided by an extensive artificial breakwater constructed at a cost of US\$1 0,000 per linear metre of reef front. This figure provides a 'shadow' value for the protective function of the reef (Pernetta 1992).

Figure 3.3: Maps of Malé, capital of the Maldives showing maps made by early visitors, with a large area of reef flat (upper) and conversion of almost 100% of the reef flat into 'dry' land by 'reclamation' (lower) with the flooding that resulted from waves impacting directly on the reclaimed land in 1987 (maps adapted from Pernetta 1992).



Reefs as Tourist Attractions

Coral reefs are magnets for tourists, as they present the popular depiction of paradise - white sand beaches and coconut palms abutting crystal clear, warm waters containing the attractive abundance of biodiversity that is a coral reef. Ideally, tourism should be the most environmentally benign way to generate income from coral reefs, as the greatest attractant for a tourist is a pristine reef with abundant fish populations. This is true only under carefully controlled conditions of resort development and operation. Uncontrolled collecting, sport fishing, and accidental damage (by waders, swimmers, and boat anchors) all have deleterious effects on tourist reefs. Also the tourist demand for seafood can result in over-exploitation of fish and invertebrates. The building and operation of the tourist facilities, however, can be far more damaging, particularly if untreated sewage and other wastes contaminate the adjacent waters. There is a need for careful control, siting, and design of resorts to avoid problems such as increased beach erosion e.g. not placing them directly on beaches and exacerbating erosion (Sudara and Nateekarnchanalap 1988).

Ecotourism is a developing trend on coral reefs with the tourist being given an educational experience, thereby enhancing the conservation ethic in both the tourist and the trainer. This development has potential to result in quality employment for people associated with coral reefs. The tourist operators depend on conservation of the resources and may act as efficient managers of the reefs for purposes of self interest, if for no other reason.

Reefs as Disposal Sites

Both by design and by unintended consequences of other actions, coastal waters and the coral reefs have become the dumping sites for wastes and byproducts of many human activities. Organic and inorganic pollution are direct results of human activity on land. In many developing countries, sewage and animal wastes are not treated, but discharged directly into the sea or into rivers which flow into the sea. Agricultural runoff, containing nitrogen and phosphorous fertilizers, and organic matter, can change the marine environment of coral reefs from oligotrophic (nutrient-poor) to mesotrophic or even eutrophic (excess nutrient) conditions. These conditions result in increased turbidity (from enhanced phytoplankton growth) and combined with excess sediments (normally co- occurring), they reduce the available light energy and therefore the depth of coral growth.

Increased nutrient loading has been implicated in outbreaks of grazing echinoids such as *Diadema* and *Echinometra*, and has been proposed as a causative agent for outbreaks of coral predators such as the crown-of-thorns starfish (*Acanthasterplanci*) and the mollusc, *Drupella*. One hypothesis is that inorganic pollution increases the survival of starfish larvae resulting in enhanced outbreaks (Birkeland 1982).

At low or moderate concentrations, nutrients area chronic stress that appear to cause little overt harm to an undamaged reef. But, if the nutrient pollution is chronic, it can seriously interfere with a reef's ability to recover from episodic acute stresses (Kinsey 1988). Coral reefs are most successful and productive in clean water with low levels of organic and inorganic nutrients,

because the principal calcifying organisms (corals and calcareous algae) are superior competitors. If the nutrient balance is upset, the competitive edge shifts towards macro-algae and filter feeding animals such as sponges, other anthozoans, molluscs and ascidians (Smith *et al.* 1981; discussion in Chapter 2). Nutrients also enhance the activity of bioeroding organisms such as sponges, boring molluscs, polychaetes, and boring algae (Highsmith 1980; Hallock 1988). The net result of pollution is that corals are overgrown or outcompeted by non- calcifying organisms, coral skeletons are weakened by bioerosion, and the solid base substrate needed for successful coral growth is lost by bioerosion and/or masked by algal overgrowth. Polluted reefs typically show net erosion, with the calcification rate being less than losses due to erosion and dissolution.

Another major stress to coral reefs is sediment input to the "coastal zone. These effects result in major changes in both community function and structure (Loya 1976). Increased sediments in the water can harm coral reefs in three distinct ways:

- . increased turbidity reduces the light available to photosynthetic calcifying organisms;
- . corals must expend considerable energy to remove fine sediments, either by means of mucus sheet release or by ciliary action; and
- . excessive sediment can result in physical burial and death of corals and other organisms.

Activities such as mining, coastal construction, deforestation, and land clearance for agriculture and development have resulted in high rates of erosion and increased sediment loading of coastal waters (Rogers 1990). Many reefs are suffering from severe sediment damage, particularly along the east coast of Africa and in India and Sri Lanka as a result of agricultural practices, in southeast Asia due to forestry activities, and in the Caribbean. Sugar cane farming is a common activity adjacent to coral reefs. Along the Queensland coast, adjacent to the Great Barrier Reef, annual cane field erosion is between 70 and 500 tonnes per hectare, whereas losses from undisturbed lands are around 4 tonnes per hectare. The losses can be reduced to 5 to 15 tonnes if zero tillage practices are adopted (Prove and Hicks 1991). Another practice with similar effects is so called land 'reclamation' e.g. Singapore is actively burying coral reefs to increase the land area available for development (Chou 1991).

There are a number of anthropogenic stresses that may affect coral reefs at a local level even though they are minor at the global scale. Chronic exposure to oil has had deleterious effects on coral reefs in areas such as the Gulf of Eilat and parts of the Arabian Gulf, but most such effects have been localized and oil pollution has commonly been regarded as having little lasting effects on coral reefs. Indeed, the massive oil spills that occurred during the Gulf War in 1991 resulted in remarkably small impacts on the coral reefs of the region (Roberts *et al.* 1993). However, Jackson (1989) has documented long-term reef community alterations resulting from a single large oil spill in Panama because the oil has persisted in the adjacent region and sediments. Heavy metals (and other complex pollutants such as pesticides and PCBS) have also been implicated in coral reef stress, but there are few conclusive data and no reported incidence of reef collapse due to such pollution.

Currently, anthropogenic stress is the major destructive factor causing long-term damage to coral reefs. This is unlikely to be reduced in the foreseeable future because development and large populations in the tropics are still growing. A major unknown is the degree to which climate change will interact with anthropogenic effects to increase destruction of reefs already stressed, or to act independently to endanger those reefs not presently threatened by human activity. Climate change may affect coral reefs through variations in such factors as water temperature, increased concentrations of dissolved carbon dioxide, altered current and/or storm patterns, and increased runoff (with effects due to freshwater, sediment transport, and pollutant transport). In addition, climate change may result in shifts in human populations, putting previously unstressed coral reefs under the influence of human activity. Conversely, those reef areas which become uninhabitable will be released from considerable human pressure.

3.2 Projected Changes in Use of Reefs

Developing Countries

Pressures on coral reefs in developing areas are expected to increase at a rate equal to, or greater than, the rate of population increase. The pressures on reefs will not, however, be uniform across all countries (Boxes 3.1, 3.2). Pressures will be greatest at the middle of the development spectrum:

- . in those transitional developing countries where traditional values have been lost and not replaced by economic development and a greater degree of environmental awareness, the direct pressures on coral reef resources from subsistence demands and export markets will increase alarmingly. Increased disposable income will result in a greater demand for seafood, as it is a favoured form of protein and the greater income will support the purchase of equipment, such as outboard motors, to increase the efficiency of extracting seafood from depleted reefs; however
- . in countries with strong or rapidly expanding economies, the subsistence pressures on coral reefs may decrease with the development of a more educated and informed population and strong environmental laws (but possibly at the expense of increased secondary effects resulting from construction, urbanization, industrialization, and tourism); and
- . in developing countries where customary law and traditional resource management practices remain in force or can be enhanced, the resources may be protected from over-exploitation (Salvat 1992).

While most developing countries have passed legislation for the protection of natural resources and the outlawing of destructive practices, mechanisms for policing the implementation of these laws are beyond their current economies and a large majority of the marine protected areas exist only on paper (IUCN/CNPPA - World Bank 1993).

The interactions between these expanding uses and stresses combined with the impacts that global climate change will have on coral reefs are the subject of Chapter 5. The present and immediate future human stresses will interact with and reinforce the consequences of climate change and may seriously damage the natural capacity of many reef systems to adapt to the challenge of changing environments. In areas not already threatened, it will be important to understand how changing climates will alter reef ecosystems and threaten their sustainable future use by people. Both perceptions and effects of the climate-derived change will depend on the degree of current and future human stresses applied to reefs. Where human pressures are high and increasing, climate change effects may be immeasurable and masked by the larger anthropogenic changes, whereas on reefs where human pressures are low and current extractive processes are sustainable, the effects of climate change may potentially be more significant. In the intermediate case of moderate pressures, the combination of human and climate stresses may turn out to be more than additive - an increased or synergistic effect.

The prognosis for the survival of coral reefs in developing countries with expanding economies and large, growing populations is poor, unless the threats are recognized and effective resource management implemented (Wilkinson 1993 b). The time frame for these impacts is one or two generations (20 to 40 years) during which time the human populations will more than double. The extent and effects of these threats will vary considerably between countries, between different reef types, and with the size and nature of the population and the history of interactions of those peoples with the reef. These threats are immediate, and in most locations they are more urgent and more dangerous than the potential consequences of short-term climate change, which may not be detectable within the above time-frame. The current and projected situation in regions where coral reefs are prominent is discussed later in this report.

Economically Developed Countries

Developed countries with high per capita income, low population growth rates, and low subsistence demands on reefs, should in principle be able to effect conservation and management programs that will maintain reefs at sustainable levels of use. In such countries, stresses on reefs are generated primarily by recreation and tourism, and indirectly as a result of commercial fishing, construction and contamination by urban, agricultural, and industrial wastes. In general, most developed countries have established laws or policies to prevent or reduce environmental degradation.

However, current evidence does not necessarily support the hypothesis that reefs adjacent to countries with greater economic wealth are well managed and suffer low levels of exploitation stress. This jeopardizes the corollary hypothesis that successful economic development will relieve reefs from the stress now occurring in developing countries. There is no consistent model demonstrating that reef management is proportional to the economic status of the country or that reefs in wealthy countries have greater chances for ecological survival in the future. Comparisons of the reefs and their management in Singapore, Japan and Florida (USA), against those of Australia and Hawaii (USA) show markedly different scenarios. These observations and prospects for future protection and management are discussed in more detail in Chapter 6.

4. Climate, Variability and Climate Change

4.1 Natural Environmental Variability and Reef Stress

Earlier chapters of this book discussed how environmental factors such as light, temperature, sea level and water movement relate to and control the biological structure and function of reef communities. This section focuses on the relationship between variations in the environment and stress in reef communities, and how such variability relates to climate and climate change.

Coral reefs can be regarded as both robust and fragile ecosystems. They have proven to be robust and persistent over geologic time scales (see Box 4.1), and they typically recover from severe but episodic damage or stress of short duration (e.g. cyclonic storms). However, their community structure and function has been recognized as fragile with respect to many of the chronic human-induced (anthropogenic) stresses imposed upon them (discussed in Chapters 2 and 3). This has raised questions concerning their vulnerability to environmental variations, natural or otherwise, over short and intermediate time scales (decades to centuries).

Coral reefs show considerable temporal change at all time scales in response to environmental variability (Grassle 1973). Daily and tidal variations are reasonably consistent and predictable. Seasonal variations are less easily generalized. Data from long-term monitoring of a coral reef flat in the Philippines (Yap *et al.* in press) suggest that reef metabolism fluctuates within relatively narrow bounds over an annual cycle, although production and respiration show correlations with changes in temperature, light, and salinity. Thus, reefs in areas of low seasonal variability in these parameters will show relatively small seasonal fluctuations, while high latitude or other seasonal (e.g., monsoonal) settings will show more variation (Crossland 1988).

Interannual variations are of particular interest, especially those associated with natural disturbances such as storms, El Nino-Southern Oscillation events (Box 4.2), temperature fluctuations (Glynn 1991), episodic low sea level events (Loya 1976), extreme population fluctuations of certain animals (especially echinoderms: Done 1987; Lessios 1988), excessive sedimentation, and high rainfall that may lead to salinity stress. Indeed disturbance is a contributing and regulating factor for the high species diversity of coral reef ecosystems (Connell 1978). Thus, coral reefs are dynamic systems that are continually changing in both space and time as a result of natural disturbances ranging from minor to catastrophic.

One of the major factors that determines the structure and community composition of a coral reef is the frequency and extent of physical damage, such as that caused by storms (Massel and Done 1993). Coral reefs in many equatorial regions rarely suffer cyclonic storms; their major physical influences are the long-range oceanic effects of more distant high-energy events, and localized storm action of generally low intensity. Coral reefs outside of the equatorial zone may experience episodic, cyclonic storms (called hurricanes in the Atlantic, typhoons in the North Pacific, and tropical cyclones in the South Pacific). Such storms originate in areas of warm water and tend to travel in curved paths to the northwest or southwest under the influence of the

Box 4.1: Corals in the Geologic Record

Scleractinian corals, and the reefs they help to form, occur as fossil deposits that demonstrate a long record of evolutionary history. Fig. 4.1 shows the history of the families of scleractinian corals, reaching back over 200 million years. This impressive record of survival is contrasted with the relatively recent history of the family Hominidae to which humans belong. Our own species, *Homo sapiens*, maybe as little as 100,000 years old.

Although this view depicts corals as hardy survivors that have existed over a range of climatic conditions (compare Fig. 4.1 with Figs. 4.3, 4.4), the path of survival has not been smooth or uneventful. The light lines in Fig. 4.1 depict the families now considered extinct, and if genus and species level extinctions could be shown, the losses over time would be even more impressive.

There have also been long time periods when the reef-forming organisms have survived, but when there has been little, if any, reef building by corals. During the early Jurassic (about 200 million years ago) and early Tertiary (about 50 million years ago) few reefs of any sort were reformed, while in the middle and late Cretaceous (70 -110 million years ago) corals were in eclipse and reef-building was dominated by rudists (large molluscs that are now extinct; Stanley 1992). Geologic history tells us that the genetic survival of the individual organisms that make up coral reef communities is an important condition but not an essential one for the persistence of coral reef ecosystems.

earth's rotation. Some areas, such as Guam, are frequently battered by cyclonic storms, while reefs in Micronesia, French Polynesia, Thailand, or the southern Caribbean experience serious storms with a frequency of less than one in fifty years. Frequent, high impact cyclonic storms influence the formation of coral reefs with high diversity but low profile. Such reefs are dominated by encrusting, massive, or rugged digitate corals, while reefs that are rarely impacted by major storms develop complex and fragile coral communities that show a high degree of vertical elevation and structural variability. Changes in the distribution, frequency, or magnitude of cyclonic storms may have major local and regional effects on the structure and growth rates of coral reefs (Lough in press).

Healthy reefs generally recover from most natural disturbances, and return to a community structure and metabolism within the 'normal' range for reef ecosystems. Where the substrate and environmental conditions remain suitable for coral reef development, recovery from major short-term stress events is often functionally complete within 10-20 years. Minor natural stresses usually have minimal effects on healthy reefs, and are instrumental in maintaining the levels and patterns of species diversity (Huston 1985). As discussed above, however, the existence of chronic stresses, whether of climatic or anthropogenic origin, may seriously compromise the normal recovery process. Chapter 3 presented examples from Jamaica where reef recovery from storm damage is believed to have been prevented by chronic stresses imposed by human activities. Growing awareness of such problems, as well as concerns about the effects of climate change, have focused increasing attention on the need to detect and understand environmental stresses on reef ecosystems (see Boxes 4.3 & 6.2).

Present-day reefs are recent in origin, having developed only within the last 8,000 years. These reefs are similar to reefs that have repeatedly developed throughout the climate and sea-level fluctuations of the Pleistocene (1.6 million to 10,000 thousand years ago; Jackson 1992). Reef organisms and reef communities have survived relatively intact throughout this evolutionary time, but individual reefs cannot be expected to persist indefinitely in their present form.

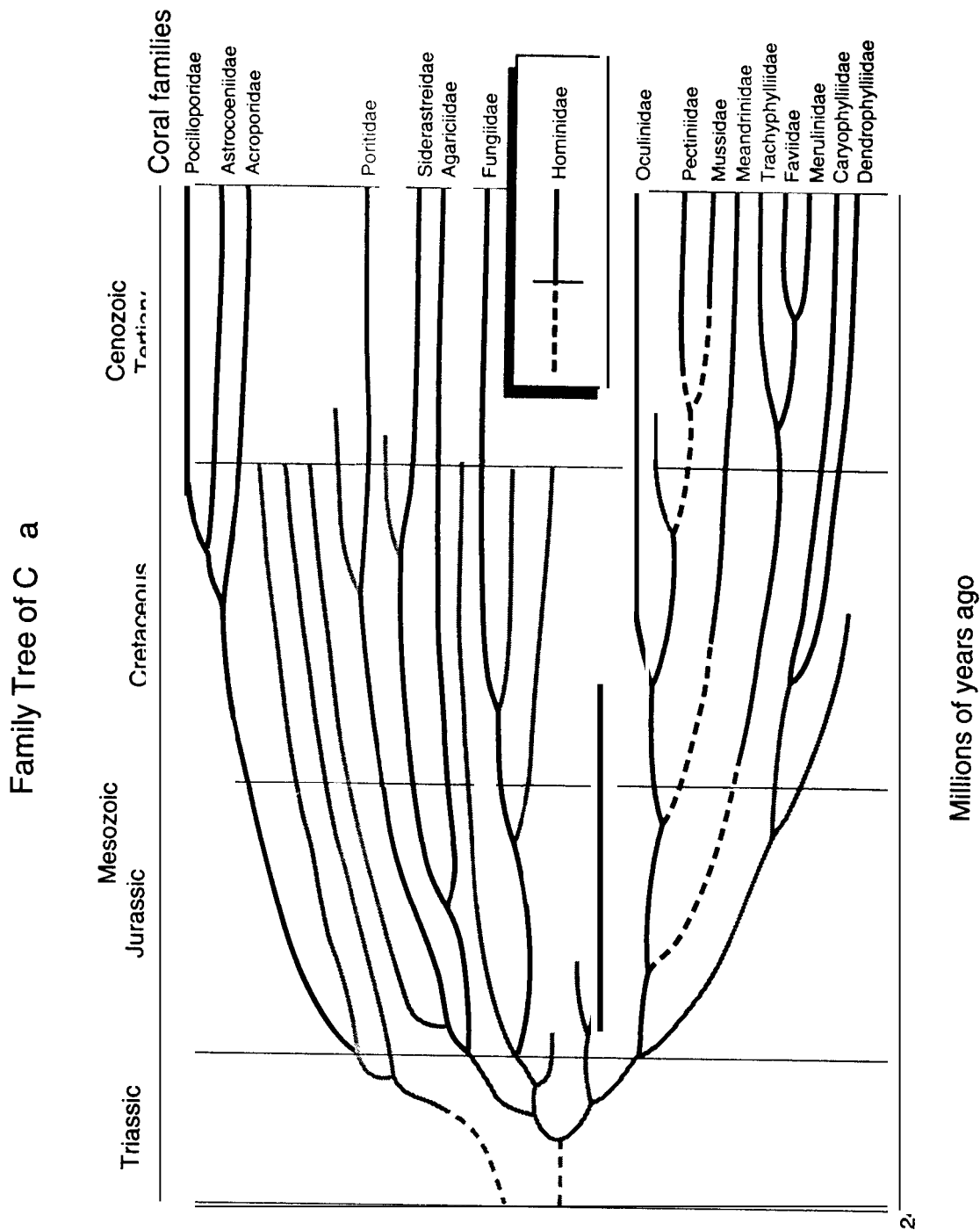


Figure 4.1: A geologic perspective on the evolutionary history of corals, with the history of the human family (Hominidae) shown for comparison (adapted from Veron 1986). Solid lines represent a continuous lineage, whereas half-tone and dashed lines represent extinct and presumptive linkages.

Box 4.2: ENSO and Environmental Variation

The El Niño Southern Oscillation (ENSO) phenomenon has been associated with such dramatic events as droughts in Indonesia, northern Australia, Brazil and central Africa, and higher rainfall and floods in western North America, Japan and possibly Europe. ENSO is a repetitive pattern of large-scale variations in atmospheric pressure and oceanic temperature across the tropical Pacific Ocean. 'Normally' there is a pool of warm water around Papua New Guinea in the Western Pacific, which induces trade winds to blow from the east into Indonesia and the surface currents to flow up the coast of South America and then across the Pacific. During the so-called El Niño phase of the oscillation, the warm pool of surface water in the west migrates eastward, changing the strength and direction of surface currents so that the upwelling in the vicinity of South America is reduced. The reduced upwelling causes a collapse of the Peruvian anchovy fishery, which has provided one of the longest records of the El-Niño phenomenon. Related effects on temperatures, storms, and precipitation across the entire Pacific basin have been recognized as part of the ENSO pattern. A counter ENSO pattern is often referred to as La Niña or the anti-El Niño.

The ENSO phenomenon is tropical, and therefore significant to coral reef environments (see Box 4.3), but its effects also extend well into temperate latitudes. Although repetitive, the ENSO phenomenon is variable in both time and intensity. Glynn (1988b) estimated that detectable El Niños occur with an average frequency of about 4 years; strong events have a return period averaging about 12 years; and the very strong events like the 1982-83 El Niño are unprecedented in recorded history, suggesting a return frequency of centuries. Speculation has arisen that this severe El Niño may have been an effect of global climate change. The combination of ENSO having a hemispheric distribution with frequencies in the years-to-centuries range, cause the phenomenon to straddle the uncertain borderline between climate variability and the range of variation within climate. Although the nature of ENSO seem certain to alter as a result of climate change, present climate models do not accurately reproduce the ENSO phenomenon, so it is not currently included in most efforts to diagnose or predict climate change. Additional clues to the past frequency and distribution may be provided by geochemical and growth records of the environment preserved in the skeletal growth bands of long-lived coral such as *Porites* (Isdale 1984; Cole et al. 1993; Dunbar and Cole 1993).

However, any changes in present-day reefs and the causes of those changes are important to the human societies that live and depend on the reefs. In order to manage and conserve coral reefs, it is essential to understand the natural temporal and spatial variability of reefs as a context for attempting to predict or mitigate the effects of either local or global environmental change.

4.2 What is Climate?

The climate of a particular region is described, measured, modeled, or predicted in terms of the prevailing conditions of temperature, rainfall, humidity, wind, and other physical variables-in effect the average expectation of weather. Weather is what we call the state of these conditions on a much shorter time scale (see Box 1.1). There may be large day-to-day and year-to-year fluctuations in the weather at any location, as well as large variations experienced by adjacent regions over similar time scales. Climate, the long-term average, is commonly discussed as if it were stable, even though there may be substantial variability in the short-term weather patterns and high inter-annual variability of the physical parameters that combine to define the climate. However, climate is not intrinsically stable; it has changed dramatically in the past, and it is expected to change in the future, particularly as a result of human modification of the composition of the atmosphere.

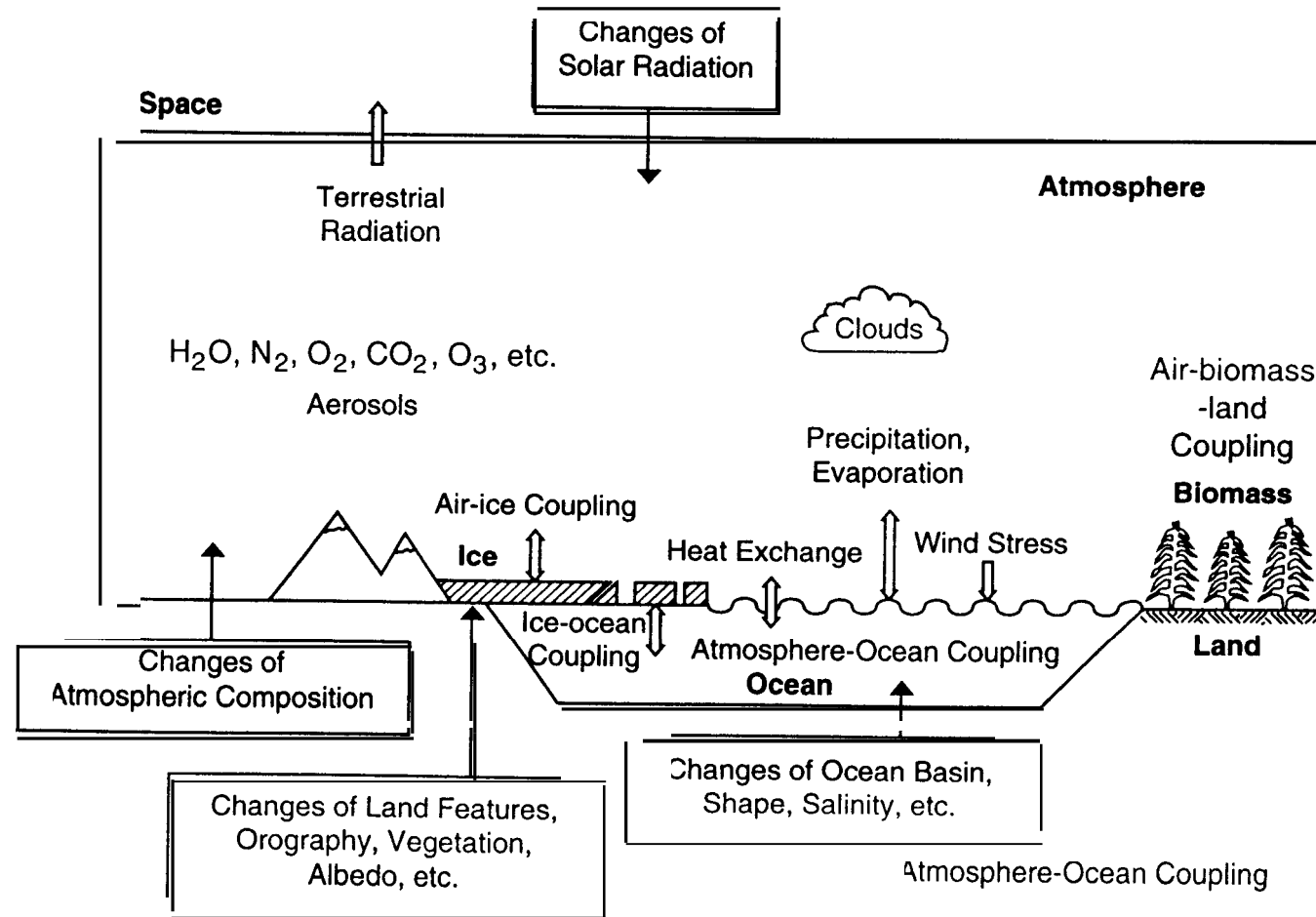
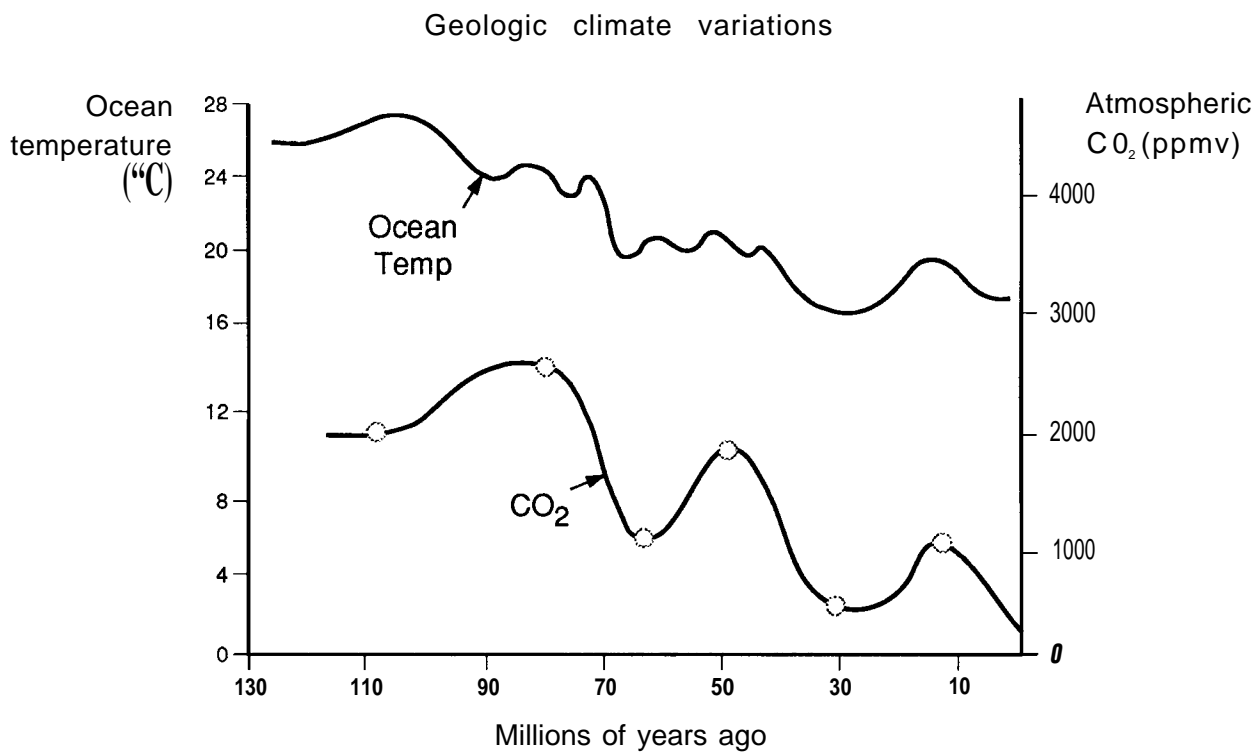


Figure 4.2: A schematic illustration of the components that influence the operation of the earth's 'climate machine'. Many of the processes are coupled (atmosphere-ocean; atmosphere-ice) or multiply connected (air-plant biomass- land). The solid arrows are processes that force the climate machine, whereas open arrows are processes that govern or change as a result of the forcing (adapted from Gates 1979)

Figure 4.3: Estimates of atmospheric CO₂ concentrations (ppmv - parts per million by volume) and low-latitude surface ocean temperatures over the past 100 million years (adapted from McCracken *et al* 1990).



Box 4.3: Coral Reef Stress and Bleaching

A focal point of concern about coral reef stress has been the phenomenon of coral bleaching, or loss of the pigmented symbiotic algae (zooxanthellae). This is a well known and generalized response to a variety of stresses, which may be followed by either recovery or death, depending on the intensity and persistence of the stress (D'Elia *et al.* 1991; Brown and Ogden 1993; Glynn 1993). Extensive bleaching associated with the 1982-83 El Nino event and some subsequent bleaching events were attributed to water temperatures significantly above the normal average high temperature range. This has led to the hypotheses that coral reefs may be particularly sensitive and vulnerable to global warming (Williams and Bunkley-Williams 1990; Glynn 1993). There is considerable uncertainty about: whether major bleaching episodes are a recent phenomenon; the relative importance of temperature and of other possibly synergistic factors such as light; and whether the process of sub-lethal bleaching is simply pathological or may be an adaptive mechanism (Buddemeier and Fautin 1993). There is no doubt, however, that bleaching can be a symptom of stress, or that temperatures above the range of the coral's normal exposure are stressful (see Chapter 5).

For example, tropical areas experience one or two monsoon periods per year, with intervening periods of calm and dry weather. Communities of plants and animals, both natural and domestic, are adapted to these conditions and may be used to describe a particular bioclimatic zone that relates ecosystems to the physical variables of climate. In some years, the monsoons may fail and result in periods of drought. If the biological communities recover, the stresses are considered to be natural climate variability, but if the rainfall (or other) patterns change so much that there is a shift in the biological community, this provides a practical biological definition of climate change.

While humans describe and measure climate in terms of physical variables, they experience it and depend on it largely because of its biological manifestations. Unfortunately, there is not a simple way to translate between the two approaches. There are three important considerations to consider when attempting to relate climate variables to biological responses.

- * The first consideration is the intrinsic scale of climate patterns -by definition they are an average over large geographic areas and time periods of decades or longer, which are not the primary scale of human observation or biological response (see Box 1.1; Fig. 1.3).
- * The second consideration is that climate is an average of physical weather variations, whereas biological communities may respond more to the variations than to the average. The predictable daily and seasonal variations are important, but the frequency and intensity of events such as droughts, floods, or tropical storms maybe more critical. Thus, the range of variation in a given climate parameter may be more important in determining the distribution and structure of a coral reef than the average of that parameter.
- * Thirdly, because humans are terrestrial animals, the usual definitions of climate refer primarily to atmospheric and terrestrial conditions. These certainly impact on coastal and shallow marine environments, but the 'climate' of marine environments is also strongly influenced by oceanic factors.

The scales and uncertainties of climate make it difficult and frustrating to relate the effects of climate change to local situations over short time scales. This is because the connections between local variability or extreme events that control biological communities and the average climate conditions derived from computer models are statistical, uncertain, and not reliably predictable. The time scale of climate definition coincides with the life-times of many important coral reef organisms (tens to hundreds of years), but it is inconveniently long for experimental biology (months to years) and very short compared to geological time scales (thousands to millions of years). Neither the time nor the space scale of the current climate change debate is well matched with our observations of what has happened to reefs in the recent or more distant past (see discussion of scale in Chapter 1).

4.3 Natural Climate Variability

Climate and weather processes are driven by solar energy input to the atmosphere and the earth's surface. This energy determines temperatures, and combines with the effects of the earth's rotation to setup currents of air and ocean water. These circulation patterns control the hydrologic cycle and have a profound influence on the distribution of organisms and ecosystems. There are many sources of variability in this complex system (illustrated in Fig. 4.2). Variations in solar energy input are important, and many scientists consider variations in the earth's orbit to have been the trigger for fluctuating glacial and interglacial episodes of the past two million years.

The chemical composition of the atmosphere is important in climate, since many gases influence the retention of heat within the earth's atmosphere. These 'radiatively active' gases (carbon dioxide, methane, water vapour, and many others) are called greenhouse gases, since

they transmit incoming sunlight, but trap heat (infrared radiation) that would otherwise be radiated away from the earth. The greenhouse effect is a natural process that has permitted life on Earth to evolve and persist, but the natural balance has been modified by human activities, and it is this artificial enhancement of the greenhouse effect that is the focus of current climate change discussions. The warming effect of radiatively active gases may be counteracted by airborne particles (from volcanoes, fires, or human activities) or by extensive snow and ice cover, which reflect incoming sunlight away from the earth.

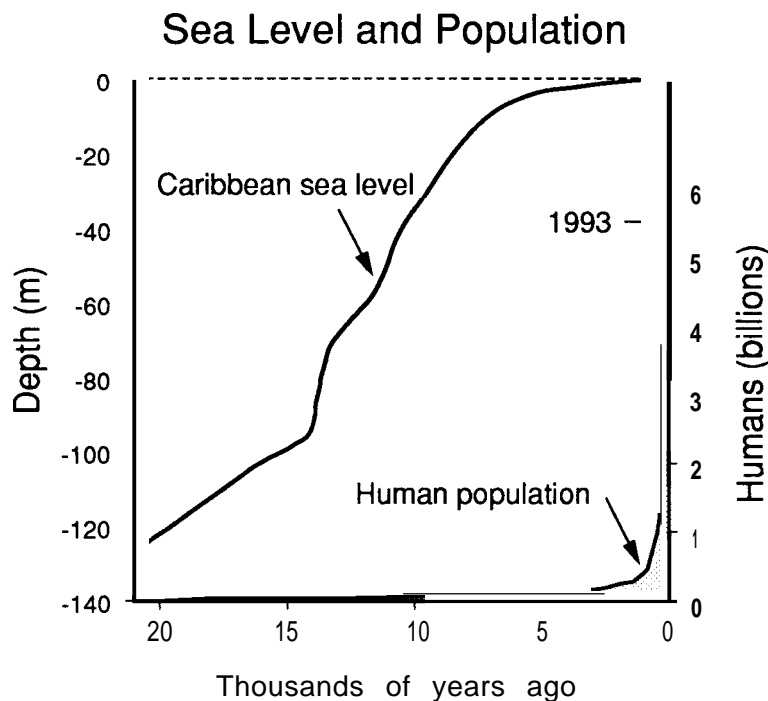
The oscillations of climate and atmospheric composition are well documented over scales of tens to hundreds of thousands of years, and known in much less detail over hundreds of millions of years. Plots aimed at reconstructing long-term variation in climate give the impression of smooth and gradual change, as is shown in Fig. 4.3. However, this impression stems from low chronologic precision and incomplete stratigraphic records (Buddemeier and Hopley 1988). Long-term averages are used, not because they represent short-term reality, but because they are all that can be justified on the basis of limited or imprecise data.

Our present understanding of climate variations in the latter part of the Quaternary period of glacial-interglacial cycles (the last 2 million years) is based on more complete records, permitting more detailed depiction of climate history in the past 150 thousand years as shown in Fig. 4.4. Temperature and atmospheric gas data are from ice core studies (top three curves); sea level curves are from sediment isotope records and shoreline observations (bottom curve). As the quantity and quality of data improve, so does the impression of rapid fluctuations in past climate. This is a particularly important issue in assessing the probable effects of human-induced climate change, since one of the frequently-asked questions is whether future rates of climate change or conditions will be unlike those natural variations that organisms have survived through evolutionary history.

Humans have a poor perspective of major climate change, since our entire civilization has developed during a single interlude of unusual climate stability. The major indicators of human civilization, such as the development of cities and written languages, have only appeared within the last 6,000 years; after the major period of Holocene sea-level rise had ceased. Rapid growth in human populations is a far more recent phenomenon, occurring during the 20th century. The relationship between human history and sea level stability is illustrated in Fig. 4.5.

There is increasing evidence for both rapid natural change, and stability punctuated by unusual events as more data become available. In modern climate, the ENSO phenomenon (see Box 4.2) is now recognized as a source of such variation. When we consider longer time scales and frequencies, there have been relatively abrupt variations even during past periods when climate was generally stable. Gordon et al. (1992) reported that formation of North Atlantic Deep Water is an important control on global ocean circulation, and is sensitively coupled to the hydrologic cycle. There is evidence of oscillations on time scales ranging from decades to centuries over the whole range of climate during the Holocene (the last 10,000 years). Because individual corals can live for decades to centuries and reef communities may persist and develop over thousands of years, our view of the effects of climate change must consider that reefs and their component organisms have evolved and survived through climatic variations that were probably as great as anything to be expected in the coming century.

Figure 4.5: Recent (Holocene) sea-level rise in the Caribbean, compared to world-wide growth of human populations (adapted from Fairbanks 1989; Digerfeldt and Hendry 1987). The development of written languages, cities, and extensive agriculture occurred largely within the past 6,000 years -- a period of unusual climactic and sea level stability.



4.4 Global Change: Causes and Characteristics

There is great concern about the consequences of rapid climate change caused by human activities. The most obvious and most likely change is enhanced greenhouse warming, caused by human production of greenhouse gases at rates faster than the oceans and biosphere can absorb them. Atmospheric concentrations of carbon dioxide, methane, and other greenhouse gases such as chlorofluorocarbons (CFCs) are increasing with population growth and development (Fig. 4.6 demonstrates these trends). Virtually all models of the earth's climate agree that global warming is the most probable result of these atmospheric changes (Houghton et al. 1990, 1992; Wigley and Raper 1992).

In addition, there are other effects caused by human alteration of the global environment that are not usually considered 'climatic,' but that will combine with climate change to affect the health, function, and distribution of the earth's ecosystems. One such effect is caused by increasing levels of carbon dioxide changing the chemistry of the world's atmosphere and surface ocean; it will result in increased acidity and reduced carbonate mineral saturation states in the water. This may have important effects on aquatic plants and calcifying organisms (Smith and Buddemeier 1992). Another global issue is the increasing amount of ultraviolet radiation (UV-B) at the earth's surface because of depletion of the stratospheric ozone layer (see Box 2.3). Large-scale nutrient loading or contamination of coastal zones and regional seas is also an issue, as are other human influences.

Figure 4.4: The history of atmospheric CO₂, CH₄, Antarctic temperature, and sea level in recent times (the late Quaternary; adapted from Raynaud et al. 1993 and Chappell 1983; ppbv - parts per billion by volume).

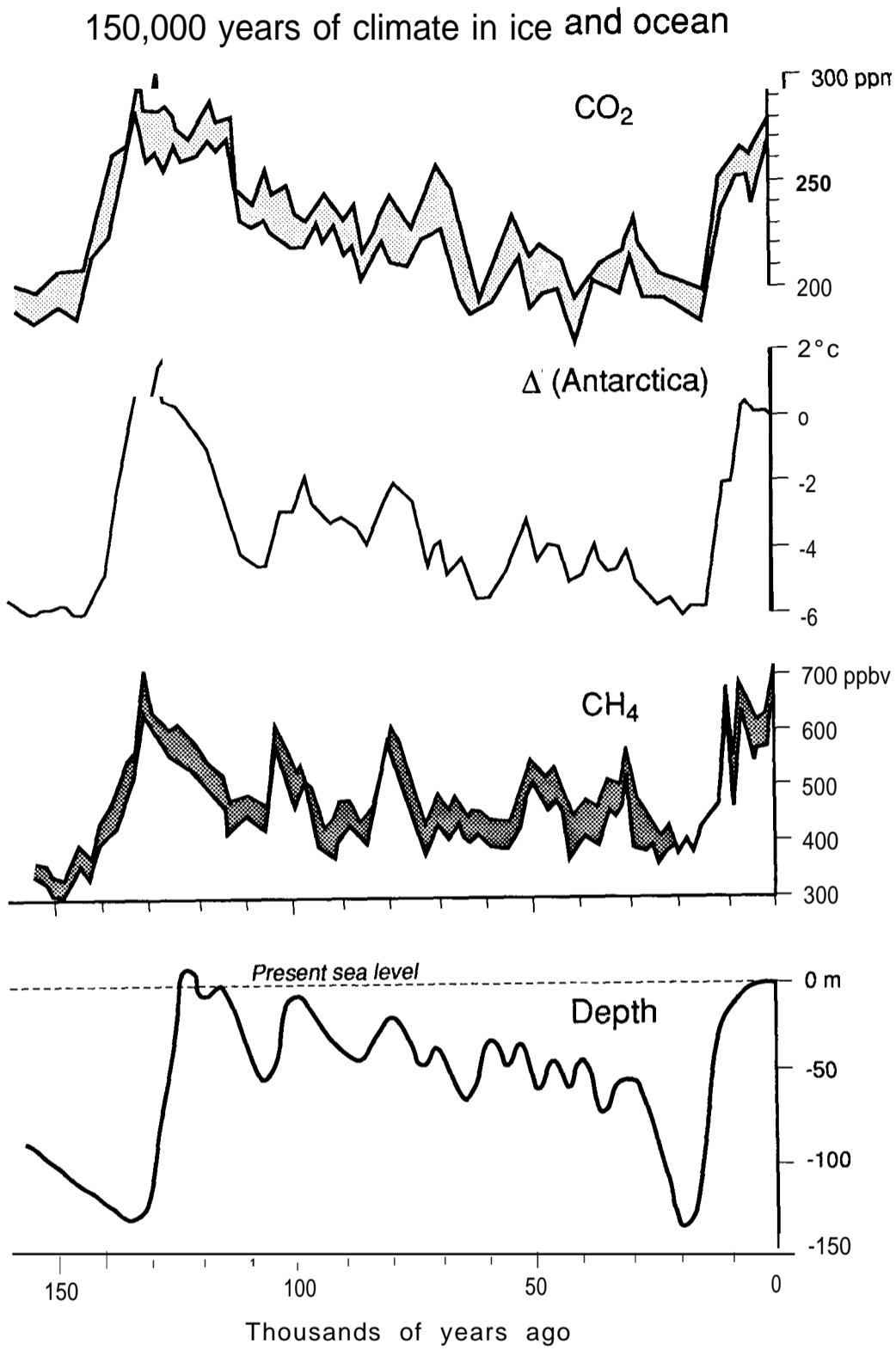
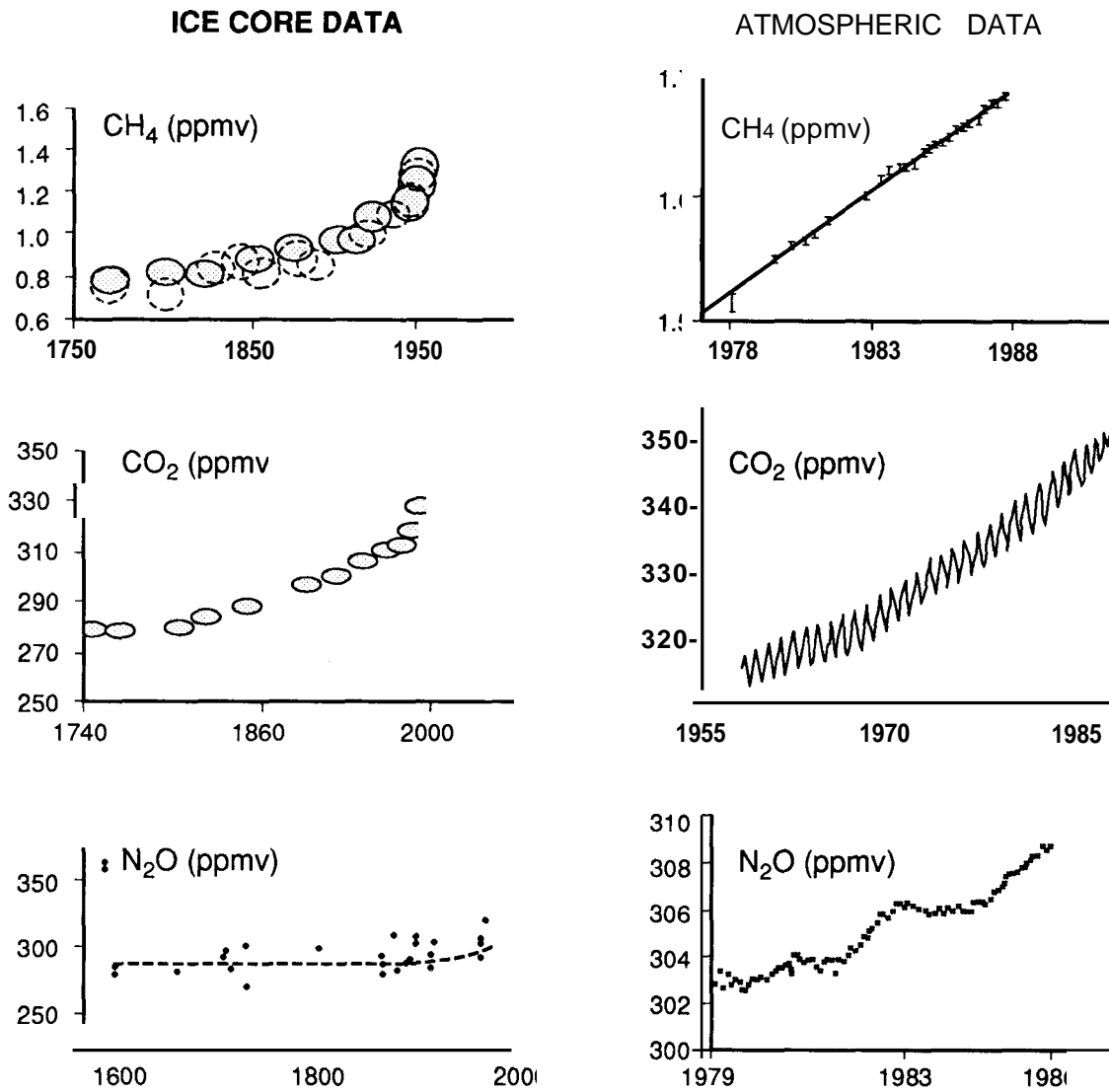


Figure 4.6: Conclusive evidence of changes in atmospheric concentrations of greenhouse gases over a variety of time scales and locations. The ice core data were obtained from Greenland and the atmospheric data from the Mauna Loa Observatory in Hawaii using more recent instrument records (adapted from Keeling 1984; Neftel et al. 1985; Stauffer et al. 1985; Pearman et al. 1986; Blake and Rowland 1988; Khalil and Rasmussen 1987; Smith and Tirpak 1989).



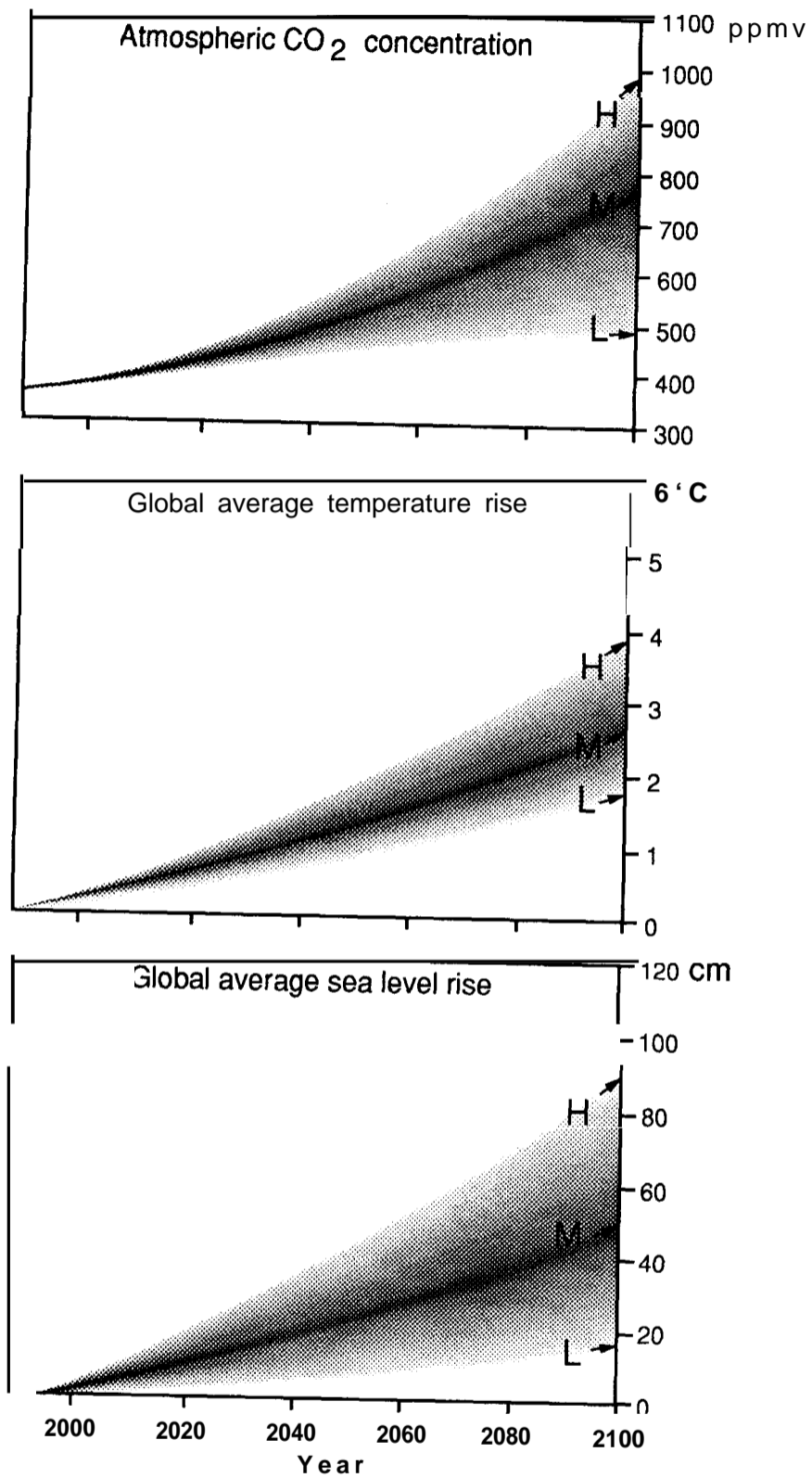
Because climate and other global or regional factors may interact strongly, it is not realistic to assess effects, protection, or management issues based on only one subset of the environmental stresses on an ecosystem. For this reason, we treat both climate and other issues as problems related to 'global change,' and focus considerable attention on the interaction between global and locally-generated stresses.

4.5 Global Change: Predictions and Scenarios

Development of global change scenarios (most scientists prefer not to use the word 'predictions' because there are large uncertainties) has depended on two approaches: the use of computer simulations of global atmospheric dynamics based on physical data; and comparison with past warm periods in the earth's history. McCracken *et al.* (1990) presented a combination of model-based predictions and paleoclimate records which are also the focus of PAGES (Past Global Changes), a part of the IGBP (International Geosphere-Biosphere Programmed), whereas considerable present-day effort is devoted to computer models. The Intergovernmental Panel on Climate Change (IPCC) has published reports (Houghton *et al.* 1990, 1992) on the probable nature of global climate change. These reports review climate predictions and the methods for developing them. The results clearly indicate that increasing concentrations of greenhouse gases in the atmosphere will change the energy balance of the planet and result in significant climate changes. Computer climate modeling is a rapidly developing field, and although there is broad consensus on the general aspects of climate change, the detailed and local predictions are uncertain and subject to revision. The IPCC updates scenarios and predictions every 2 years, based on modified gas and particle emission data, to yield revised predictions for temperature and sea level (Houghton *et al.* 1990, 1992; summarized by Wigley and Raper 1992). The following points summarize the best current consensus about future climate based on these studies.

1. Pre-industrial atmospheric CO₂ levels will double by the middle of the next century. A greenhouse warming equivalent to that doubling may occur earlier because of the effects of other greenhouse gases. (Fig. 4.7 top shows scenarios for CO₂ concentrations; Houghton *et al.* 1992).
2. Global mean temperature will increase at a rate slightly less than 0.3 degrees Celsius per decade; this is considered the most probable value, but the actual warming rate is expected to be within the range 0.16-0.37°C per decade. This will result in a global mean temperature increase of 0.5-1°C by 2030, and about 2.5°C (probable range, 1.6-3.8°C) by 2100. These are global averages; when considering coral reefs, it is important to note that warming will be greater in higher latitudes and greater over land than over the ocean. Changes in tropical sea-surface temperatures are very important to coral reefs, but are very difficult to predict with any confidence (see Boxes 4.3 and 4.4). Initial warming may also be less in the northern than in the southern hemisphere, because of the cooling effects of anthropogenic aerosols (Wigley and Raper 1992; IPCC92 results summarized in Fig. 4.7 middle).
3. Global mean or 'eustatic' sea level will probably rise at a rate of about 5cm/decade (most probable range, 1-9cm/decade); increases by 2100 are expected to be in the range of 15-90cm, with 48cm the most probable value. This value compares with recently observed rates of 1-2cm/decade, and with maximum sustained rates of sea level rise after the last ice age (Holocene transgression) in excess of 20cm/decade (Fig. 4.5). Future sea level behaviour, based on the IPCC92 estimates, is presented in Fig. 4.7 bottom (Wigley and Raper 1992).

Figure 4.7: Predictions based on IPCC92 climate change scenarios for 21st century of: atmospheric CO₂ concentration (top); global average temperature change (middle); sea level rise (bottom). M = most probable, H = high estimate, L = low estimate (adapted from Wigley and Raper 1992).



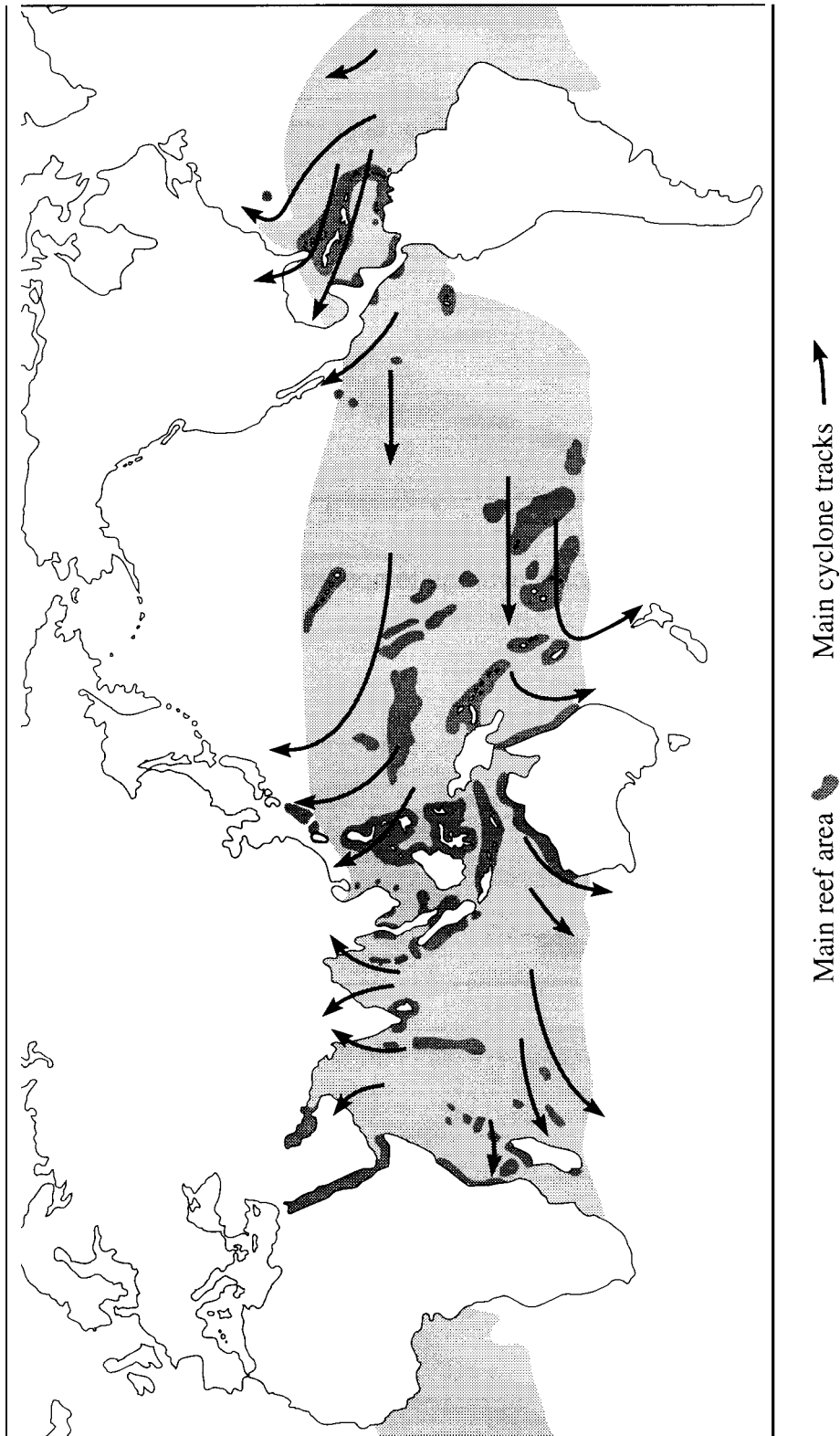


Figure 4.8: Predominant tracks of cyclonic storms in the three oceans which arise from warm equatorial waters and generally curve westwards and polewards. A disputed predication is that global climate changes will result in more frequent storms of greater magnitude that will impact on higher latitudes, eg. the arrows that will move towards the poles.

4. Changes in the frequency and magnitude of extreme events are probable. Two possible changes are important for coral reefs: a shift in rainfall patterns so that more of the total rainfall will occur during heavy storms; and a possible increase in the geographic range, frequency, and/or intensity of major tropical storms (Fig. 4.8).
5. There will also be increases in ultraviolet radiation exposure due to stratospheric ozone depletion, with increases being greater in higher latitudes than in the tropics (but absolute exposure values will be increased in the tropics).
6. Increasing atmospheric CO₂ levels will change the pH and carbonate saturation states of the world's oceans, in parallel with global climate change (Smith and Buddemeier 1992). Human-induced changes in water quality are also affecting substantial regions of the world's coastal oceans.

These predicted changes are probable, but neither the fact nor the magnitude of the greenhouse effect has been rigorously confirmed (Ebert and Karmali 1992), even though there is strong evidence for warming, sea level rise, and ozone depletion. Because climate shows significant natural variability in the absence of human disturbance, the predicted 'signal' of greenhouse climate change is not yet greater than the 'noise' of natural variability. It will not be possible to demonstrate the existence of greenhouse warming with scientific rigour and absolute certainty for a number of years, although actions need to be taken now to forestall or mitigate its effects (Wigley and Barnett 1990).

Present atmospheric models do not accurately detect or examine instabilities in climate, especially with regard to ocean behaviour and interactions. Oceanic and atmospheric circulation patterns may have multiple metastable states, such that relatively modest shifts in global or regional climate might trigger rapid transitions to different circulation patterns or states (Broecker 1987). These transitions could result in dramatic local and regional 'climate changes', possibly accompanied by small changes in the global average. These are now believed to account for some of the abrupt regional climate variations that have occurred within the past few hundreds to thousands of years (Gordon *et al.* 1992; Kerr 1993 b). Weaver (1993) discussed major oceanic changes that could result from sustained carbon dioxide build-up. Major changes in current patterns or upwelling could dramatically affect the distributions of temperature, productivity, and larval movement in the shallow oceanic regions around coral reefs, as indicated by Fig. 1.1.

Although many climatic factors cannot be predicted reliably, encouraging progress is being made in a number of areas. Understanding and modeling of ocean dynamics has improved to the point where predictions of major variations such as ENSO are now possible, and promising models of large-scale ocean circulation patterns and their controls are being developed (Kerr 1991, 1993 b). Even more important from the coral reef perspective is the use of these models to generate plausible regional scenarios (Meehl and Washington 1993), although the west Pacific 'warm pool' is resisting predictive models.

Box 4.4: Sea Surface Temperature - Critical but Elusive

Efforts to predictor identify the effects of climate change on specific ecosystems or regions are complicated, because climatic changes are still only predictable in terms of large-scale averages. Change will not be uniform in space or time, and reliable regional predictions are not yet available. Few predictions are of greater interest than sea-surface temperature, particularly for the survival of coral reefs (see Box 4.3). Unfortunately, the predictive ability of current climate change models is least detailed and trustworthy in tropical areas. There is considerable disagreement among models and many models show poor calibrations against present conditions. Some models predict that tropical sea-surface temperature (SST) will increase by 1 - 3°C after a doubling in atmospheric carbon dioxide concentration. There is widespread debate, however, about possible feedback mechanisms that could limit tropical SSTs to a maximum level of 30-31°C (Heymsfield and Miloshevich 1991; Ramanathan and Collins 1991). For the past, as well as for the future, it is difficult to distinguish reliably between temperatures like those we experience now and those a few degrees warmer. Conflicting lines of evidence suggest that tropical oceans during the Cretaceous warm period (Fig. 4.3) may have been similar to present temperatures, or as much as 5° warmer (Crowley 1991). It is important to gather more and better information about this subject, whether from models, or sediments, or both (See Box 6.2).

Improvements in regional climate prediction and impact analysis are being pursued (Giorgi and Mearns 1991). Encouraging progress is being made, and progressively more reliable and plausible regional scenarios are being developed. An example is provided by the work done for the Mediterranean (Wigley 1992; Palutikov *et al.* 1992). Similar work of more relevance to coral reef environments is in progress at the CSIRO Division of Atmospheric Research in Australia (Pittock 1992), where attention is focused on the potential effects of enhanced greenhouse warming on the distributions of tropical cyclones (Ryan *et al.* 1992) and precipitation, floods and droughts (Whetton *et al.* 1993). Because our understanding of climate change and its effects is changing more rapidly than the climate itself, it is critically important for managers and policy-makers to maintain continuous access to the latest developments in predictive models and impact assessments.

5. Effects of Climate Change on Reefs and Human Use

5.1 Background

Because coral reefs are the most biologically diverse of marine ecosystems, it is very important to concentrate on coral reefs in international efforts to preserve global biological diversity. However, an even more pressing issue from the human perspective is how the impacts of climate change on coral reefs will affect the humans that use reefs and reef resources, such as lagoonal fisheries and atoll islands. The future effects of climate change, and the interactions of these effects with all of the other human stresses imposed on coral reef ecosystems, are of interest at all scales ranging from local to global. This section discusses the impacts of climate change on reefs and the ways that humans use them.

The previous Chapter (4: Climate, Variability and Climate Change) argued that global climate change is not an immediate threat to the existence of reefs worldwide. This conclusion is an average position, which includes some reefs being adversely affected and possibly destroyed, whereas other reefs may be advantaged and experience more vigorous growth (Smith and Buddemeier 1992). Global climate change at the predicted rates will have definite effects, however, on the people who live on and use coral reefs. These effects will usually be negative for the human societies, even if the changes to the biological communities of reefs are positive. Effects on human use of reefs will depend on the location and nature of the coral reef. People who live on oceanic atolls will experience different effects than those living adjacent to fringing reefs off large land masses, and reefs near the equator will experience different effects to reefs in high latitudes, thereby influencing how the peoples will be affected.

Previous Chapters stressed that for most reefs and most human users, local anthropogenic stresses are a greater immediate (10 to 40 years) threat to reefs than climate change. One area where climate change clearly poses a major threat that outweighs the short-term hazards of anthropogenic change is the habitability of reef islands. Coral reefs will probably 'appreciate' more water flowing over them; however, human communities will not. Sea level rise and warmer temperatures will increase the potential area and range of habitats available for coral colonization, whereas the reverse is likely to be the case for human populations on low-lying islands and coasts.

Reefs as a global phenomenon and specific reefs of interest to human societies will exhibit critical differences in their responses to climate change:

- firstly, reef communities are disturbance-adapted so that occasional damage or even local devastation may be necessary and beneficial in the long term;

secondly, reef communities are living, growing systems that continually change and develop. Some reefs eventually become senescent and may even contribute to their own demise (Neumann and Macintyre 1985);

thirdly, reefs and reef islands are geologically transient features that are initiated, developed, and destroyed as the environment changes (previously without any human interference). On coral reefs, as in other ecosystems, local change is likely to be disruptive to human activities, but it may be neither avoidable nor intrinsically bad from a larger biological perspective (see discussion of scales in Chapter 1 and of the relationship of civilization to climatic stability in Chapter 4).

Indefinite preservation of coral reefs in their existing condition is, therefore, neither a reasonable expectation, nor feasible objective. There are three legitimate questions to consider in relation to environmental change and management:

what possible (or expected) changes may be detrimental both to reefs and to human use of them?

which of these undesirable changes may be avoided, and how?

how may we mitigate the effects of those changes that we cannot control or avoid?

The following discussion is intended to equip scientists, managers and policy makers with the information to develop appropriate answers to these questions for their local situations.

5.2 Effects of Changes in Environmental Factors - General

Probable coral reef responses to predicted climate changes are discussed in this section. Only general statements can be made at the global scale, as there are a wide variety of reef environments and many uncertainties associated with climate change predictions. Subsequent sections focus this information on classes of environments and more specific issues that can guide local assessments. These assessments are essential, because changes in climatic factors may be beneficial to some reefs and destructive to others, and current and future human uses of the resource vary with location. Reliable predictions about local climate effects cannot be made without considering the specific reef, land, ocean, and societal characteristics, as well as the nature of other stresses on reefs in parallel with the best available regional climate change scenarios (see discussion in Chapter 4).

The responses of reefs to climate and environmental change was the subject of a recent review by Smith and Buddemeier (1992). They categorized the major factors into climate-related forces and those associated primarily with anthropogenic effects or local environmental variability. The listing in Table 5.1 is not in order of importance or hazard, but rather in terms of scale and general predictability. Climate-induced changes and effects can be observed, measured, or predicted for some environmental factors. These individual factors are discussed below; while more subtle and interactive contributors to environmental quality are grouped together for discussion.

Table 5.1.
Dominant Sources of Near-Term Coral Reef Stresses

Climate Stresses	Other Impacts
Sea level rise**	Ultraviolet light**
CO ₂ changes**	Nutrients(*?)
Temperature change* (Freshwater)	Current/storm change
Resource use	Visible light
Sedimentation	(Freshwater)
Toxics	Turbidity

**global-trends monotonic

*trends in global mean-monotonic, local behaviour variable

Effects of Sea Level Rise

Present projections for sea level rise (probably about 0.5m over the next century; Fig. 4.7) present few reasons for concern for the overall health of coral reefs. Accretion rates for various reef systems, summarized from available data, show that reefs should be able to keep up with the expected sea level rise (shaded area in Fig. 5. 1; Buddemeier and Smith 1988). The accretion rates marked with 'a' in Fig. 5.1 were determined by alkalinity depletion measurements on living reefs, while the others are based on geologic and sediment records of past reef behaviour. Not only are the expected rates of sea level rise within the range of growth rates of healthy reefs, but reef productivity, calcification and diversity are highest within the first 5-15m depth (see Chapter 2). Therefore sea level rise would have to outpace the growth of a shallow reef by more than 10m to put a reef in danger of 'drowning.' For most modern reefs where growth or shallow productivity is currently limited by sea level or water circulation patterns, a modest rise in the sea should be beneficial. The only reefs that would be directly threatened by sea level rise are those that are stressed by other factors or occur in marginal regions (e.g. currently submerging, or in deep water at high latitudes, or otherwise at very low light levels).

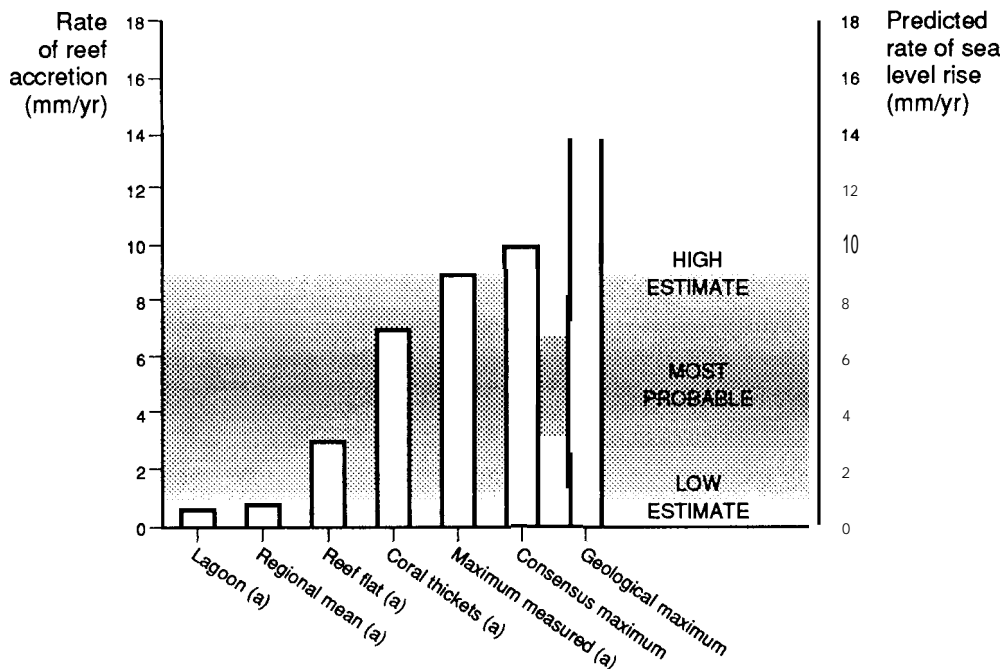
Of greater concern to humans are the secondary effects of changes in the relationship between reefs and sea level. Low islands on reefs have a critical relationship with sea level, and the areas 'behind' reefs are usually sheltered by the wave-resistant structures. The elevation and structure of many Indo-Pacific islands are the result of several thousand years of constant sea level, which followed a drop from slightly higher sea levels several thousand years ago. The responses of reefs to rising sea level are therefore unlikely to preserve the present physical relationship between reef elevation and sea level, so that even rapidly accreting reefs may become less effective wave barriers.

Additional submergence means that more water and energy will be transported across the reef to change patterns of sediment deposition and erosion, and to impact on back-reef and shoreline structures (Fig. 5.2). These changes caused directly by sea level rise are of major concern to human societies. There may also be secondary effects through changes in sedimentation, increases in terrestrial nutrient runoff, and alteration of coastal ecosystems such as mangroves.

The newly submerged reef flat communities will accelerate and produce calcium carbonate several times faster than current reef flats that are intermittently exposed; this increase may generate sufficient carbonate sediment to keep up with rising sea level (compare reef flat accretion rates with others in Fig. 5.1). The additional sediment, however, is more likely to result in outward growth and possibly some upward accretion of subtidal and intertidal island margins or shorelines. This will not elevate coasts or the centre of islands containing soils or buildings, nor will it directly replace parts of existing shorelines that are eroded by new patterns of waves and currents. The balance between sea level rise and the rate of accretion of sediments is only marginally important for coral reef existence, but is vitally important to humans who inhabit or use reef islands or reef-derived coasts. Most cays and atoll islands consist entirely of reef carbonate sands and rubble, and are little more than 2 to 5 metres above the normal high tide. A rise in sea level of tens of centimetres during the next century (about 50cm by 2100; Wigley and Raper 1992) appears small to people who live far from the ocean, but it will put these islands and their peoples at risk (Table 3.1), particularly when coupled with other effects of climate change. The human populations on many of the low-lying islands in the Pacific and Indian Oceans are larger than can be sustained by the resources of the islands and adjacent seas (Rapaport 1990; Box 3.2). These peoples are now dependent on aid from foreign countries for most of their basic needs (Table 3.1). Over the next few generations, low lying coasts and islands will be increasingly affected by rising sea level, depriving the inhabitants of habitable land - the most basic resource, and one that cannot be imported (see Box 5.1).

There is also a change in perspective with increasing populations. Whereas people once viewed the seasonal movement of beach sand as a natural phenomenon, residents who are forced to build on the shoreline regard this as erosion that must be controlled (Hameed 1993).

Figure 5.1: Measurements of potential rates of reef accretion (bars; left axis) compared with predicted rates of sea level rise to 2100 (shaded area; right axis) covering the range from high to low estimates. The growth rates of most parts of coral reefs exceed the most probable rate of sea level rise.



Box 5.1: The Threats of Sea Level Rise

When elevated high tides start to flow over the surface of islands, habitation will clearly be impossible. However, sea level rise will make low islands uninhabitable long before that through the following three mechanisms (illustrated schematically in Fig. 5.2).

Higher sea levels will erode sediments: Rising sea level will increase the mean depth of waves and the energy they transmit across the reef and against the shore. This will cause changes in coastal sediment erosion and deposition. Even if sea level rise results in increased reef growth and in greater sediment deposition at the island margins, there is no feasible way to move this onto the islands to increase the elevation of the island and raise agricultural soils. Walls and structures may provide short-term protection, but in the longer term, walls will suffer the same fate as the shores on which they are built (see Box 3.6).

Storm-related damage and inundation: In tropical cyclonic storms, islands are severely affected by large waves propagated over the reef flats. The effects are amplified by low atmospheric pressures that result in cyclonic 'storm surges'; localized rises in sea level of 4 to 6 m. If both of these effects occur during the normal high tide, islands may be completely inundated. Such inundation is more likely to occur in the future because rising sea level will interact with the probable increase in the range, frequency, and intensity of major storms as a result of global warming (discussed in Chapter 4). Although not necessarily attributable to global climate change, the experiences of the Tuomotu islands of French Polynesia provide an example. These islands have been hit by cyclones every 10 to 25 years in the past (Services Meteorologiques 1982), but during the El Niño year of 1982, 5 cyclones hit the group elevating sea level by 3 to 4m and flooding houses and crops on some islands (Dupon 1986).

Seawater will increase the salinity of ground water and soil: On many islands, the underground freshwater is essential to agriculture and is used as a reserve water supply when catchment tanks run dry (Dupon 1986). On heavily populated islands, groundwater becomes an important component of the water supply. But this island groundwater exists in a delicate balance; rain soaks through the sand to a freshwater lens that floats on top of the underlying seawater. Rising sea levels will diminish fresh groundwater supplies and affect soils and agriculture in three ways: by reducing the aquifer volume available to be occupied by fresh water and by pushing the water table closer to the surface, thus increasing evapotranspiration; by increasing salt contamination due to storm wave inundation (above); and by increasing erosion at the island margins, which will reduce the area available for rain catchment and shrink the lateral dimensions for the freshwater lens (Box 5.2; Buddemeier and Oberdorfer 1990).

effects on reef islands: additional loss of freshwater reserves; and a reduction in food productivity due to water stress in crop plants (see Box 5.2; Fig. 5.2) Near larger land masses, the evapotranspiration effects may be less important than the expected changes in rainfall distribution, which may result in a greater frequency of floods and/or droughts (see Chapter 4 discussion).

Ocean and Weather-related Patterns

Winds, rain, storms, currents, and wave energy will all change as climate is altered. Where changes occur, they may be gradual, or they may result in abrupt transitions to new circulation patterns (Broecker 1987). Two predictions and some general probabilities should be considered.

Effects of Increasing Temperature

It is assumed that the average temperature of surface ocean water in low latitudes will rise as a result of global warming (Glynn 1993), although this has not been shown conclusively (see Box 4.4). It is extremely unlikely, however, that most locations will pass any absolute temperature limit on coral or reef community survival in the near future; most reefs presently grow at temperatures well below the extremes tolerated by reefs in the warmest locations. The major problem with temperature increase will be an increased frequency and intensity of high-temperature excursions that produce bleaching and possibly mortality (see Box 4.3). Some areas that are already close to or above the upper end of the optimum temperature for coral growth may experience a reduction in reef diversity or productivity as species with lower temperature tolerances are eliminated.

The greatest temperature-related threat to peoples dependent on reefs will be the loss of the corals themselves. Even a temporary loss of live coral cover may result in reduced extractable productivity in terms of fish catches. Coral death will certainly reduce the amenity value of the reefs, thereby markedly affecting those islands reliant on income from tourists; a dead coral reef is decidedly unattractive (Kenchington 1990). The loss of corals will also result in reduced reef growth and production of sediments, further exacerbating the shoreline effects of sea level rise. Bleaching may also affect other species of commercial importance, such as giant clams (see Box 5.3).

These acute disturbances may be temporarily disruptive to human users of the reefs, but healthy reefs are expected to recover in the absence of chronic stress or too frequent repetition. Frequent climatic stresses (e.g. high temperature episodes and storms, either individually or together) may interfere with reef community recovery, and if other chronic stresses (e.g. excess nutrients) are present, the reef community may be completely replaced. The long-term prognosis will depend not only on the interaction of high temperature stress episodes with other environmental factors such as local anthropogenic stresses, but also on the nature and rate of the adaptive mechanism that has established different maximum temperature tolerances in the same coral species in different environments (Buddemeier and Fautin 1993).

A long-term effect of global warming may be the establishment or enhancement of reefs in marginal low-temperature locations. This may already be in progress in northern Japan (Veron 1992). 'Migration' of this sort would only occur over relatively long time-scales (many decades to centuries) and be primarily limited to the areas on the western boundaries of oceans where currents regularly carry coral larvae from existing reefs into higher latitudes. The nature and degree of effect that the extension of the range of reefs would have on those who use reef resources in their present locations is not known; nor is the effect on economies or cultures not previously dependent on reefs. However, this could represent an important factor in global and regional conservation of reef biodiversity.

Rising temperatures may have an additional effect on the freshwater balance of islands and coastal regions near reefs (see Box 5.1). Higher temperature will increase the evapotranspiration rate, thereby further enhancing groundwater salinity. This could have two undesirable

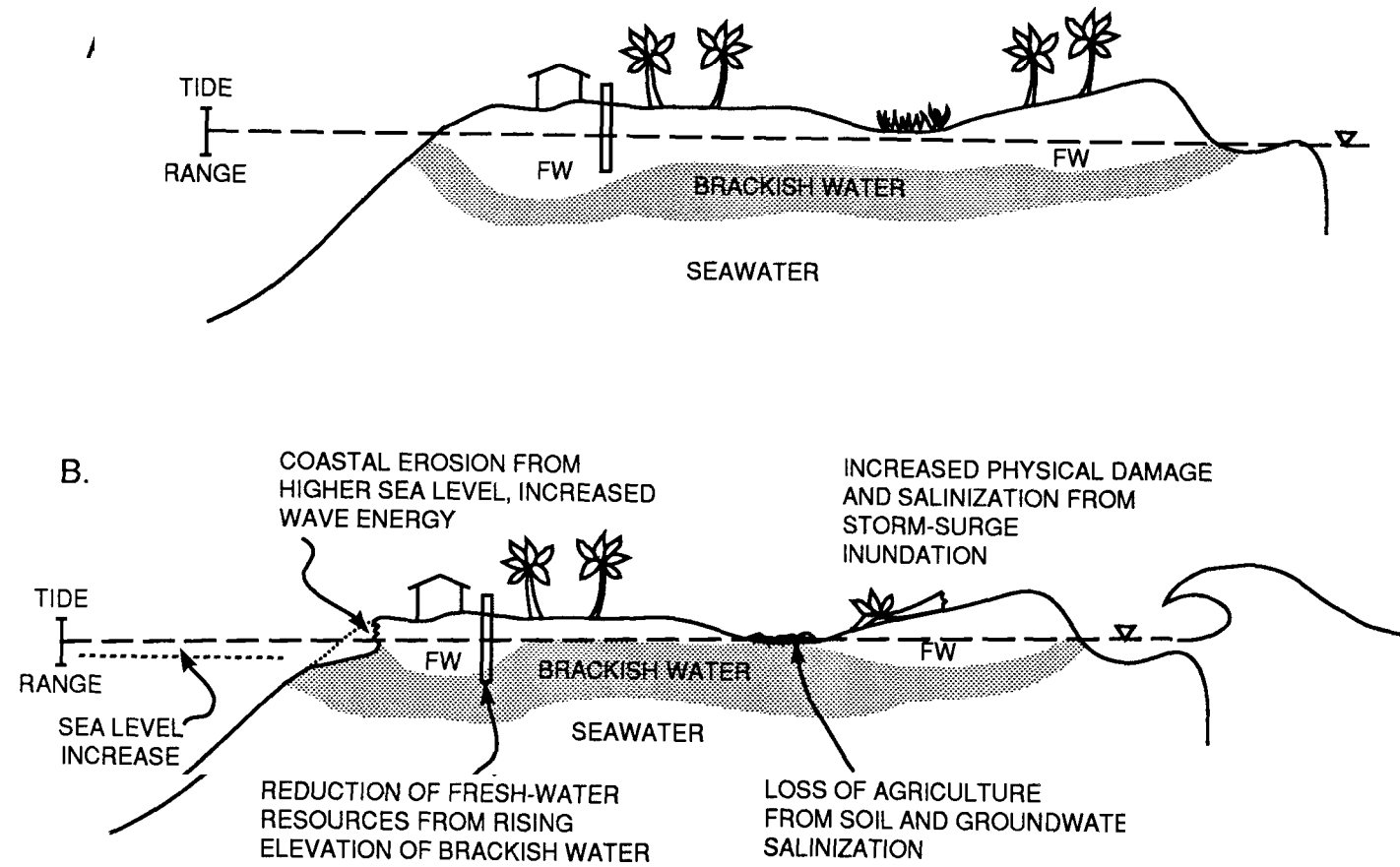


Figure 5.2: A schematic representation of the climate-change threats to reef islands and coasts, showing the current situation c reef islands (upper) and the future position with sea level rise (lower). Discussed in more detail in Box 5.1

Box 5.2: Atoll agriculture and susceptibility to sea level rise

The pattern of vegetation and agriculture on atolls closely reflects the quality and quantity of the freshwater lens. In principle, the size of the lens is proportional to the size of the island and the amount of rainfall, with the thickest and freshest part of the lens away from contact with the sea. Thus, atoll coasts are dominated by salt tolerant plants; whereas further inland, vegetation is dominated by salt-intolerant species growing above the freshwater lens. Agriculture on atolls may be divided into three categories: agroforestry, consisting mainly of salt tolerant food trees (*Cocos nucifera* and *Pandanus* sp.) in strand and coastal woodlands; woodlands and forests consisting mainly of salt-intolerant species, such as the breadfruit (*Artocarpus altilis*), towards the interior; and pit cultivation of taro (mainly *Cyrtosperma charnissonis* and *Colocasia esculenta*) in central freshwater swamps.

The pit cultivation of taro is particularly susceptible to changes in freshwater quality. Taro is grown in depressions and pits which have been excavated down to the freshwater lens, and partly filled with composting organic matter. Leaves of many species, including *Guettarda speciosa*, *Tournefortia argentea*, *Artocarpus altilis*, *Triurnfetta procurrbens*, and *Hibiscus tiliaceus* are used to form the organic soil. In Kiribati, taro (*C. charnissonis*) is planted in 20m x 10m and 2-3m deep pits with the taro corm placed in organic 'baskets' of *Pandanus* and *Cocos nucifera* and anchored in holes 60cm below the water level (Lambert 1982). Whereas in Puluwat Atoll, the taro is planted in inorganic matter bundles, 0.5m above the water level (Manner 1989). Taro swamps are also sites of high evapotranspiration and increased loss of freshwater will increase the risk of saltwater intrusion.

A rise in sea level will have a serious impact on atoll agroforestry and the pit cultivation of taro. Erosional changes in the shoreline will disrupt populations and the combined effects of freshwater lens loss and increased storm-surge effects will stress freshwater plants and increase the vulnerability to drought (Fig. 5.2).

Box 5.3: Giant Clam Mariculture

There is a specific risk that climate change will disrupt and inhibit developing mariculture programs. Giant clams (*Tridacna* spp.) are now rare in much of the Indo-Pacific, because they have been subjected to excessive human predation. Clams are prized as high quality food and for their ornamental shells, and the introduction of diving equipment has resulted in localized extinction on many coral reefs (Gomez and Alcalá 1988; Govan et al 1988).

There has been considerable recent success in giant clam mariculture aimed at replacing natural stocks and developing a sustainable export industry. Clams are relatively easy to breed in hatcheries and grow rapidly in the high light conditions on shallow coral reef-flats (Griffiths and Streamer 1988; Mingoia 1988). The meat is an important potential export item as all parts of the tissue, especially the adductor muscle, attract a high market price (Tisdell and Menz 1988). Commercial venture hatcheries have been established in: Honiara (Solomon Islands, Lat. 9°S); Belau (Pulau, Micronesia, Lat. 7°N); Samoa (Lat. 13°S); and the northern and southern Philippines (Lat. 16°N and 9°N). The goal is to provide villagers with clam juveniles to grow for both local consumption and export.

Bleaching occurs in clams as well as in corals, with the expulsion of the symbiotic algae due to excesses in either temperature or radiation (Gomez and Belda 1988; Lucas et al 1988). Thus, clams and corals will be similarly affected by any changes in the quantity and quality of light (e.g. higher levels of UV radiation) or increases in water temperature arising from climate change. This could adversely affect clam mariculture ventures, with the bleaching causing either loss of productivity or devastation in stocks of growout clams on the reef-flats.

To avoid this, it may be necessary to locate the clams in deeper water, where light and temperatures will be less susceptible to fluctuation. This will, however, result in lower growth rates and returns to the grower. Proponents of clam mariculture should consider establishing clam farms in higher latitudes and also recognize that climate change will affect runoff from the land and increase the probability of storm damage. These factors should come up during site-specific evaluations for the establishment of mariculture operations.

Box 5.4: Sea Turtles and Global Climate Change

Species and populations of sea turtles are declining so rapidly that there are risks of extinction. The greatest threats are through human exploitation of both the eggs and adult turtles. Global climate change is likely to add more pressure and may be sufficient to drive some species to extinction.

Traditional collecting of eggs from beaches where turtles nest poses the greatest pressure. In some countries, e.g. Malaysia, the Government pays more for eggs of endangered turtles than the price in the markets. The eggs are hatched either in incubators or in patrolled beach nests. Sea level rise will add to these pressures by causing losses in nests of incubating eggs when sea water flows over nesting beaches during storm surges. Eventually many traditional sea turtle rookeries on coral islands will become marginal or impossible as rising sea waters start to erode and cover the islands.

Sea turtles that nest on elevated islands and large land masses maybe only slightly affected through the loss of some beaches, in contrast to those that nest on coral islands. When it becomes obvious that coral islands will be inundated, it may be necessary to collect eggs from island nests, incubate them and release the hatchlings on higher beaches that are protected or managed.

Rising sea surface temperatures present another threat. Most turtles nest during summer, close to their upper thermal limit. It is uncertain whether turtles will be able to adapt to warmer temperatures by nesting in the cooler months (Limpus 1993). If not, then higher temperatures will result in a larger proportion of female turtles, as the sex ratio is directly determined by temperature.

Humans also harvest turtles in unsustainable amounts (Limpus *et al* 1993). For example, on Kayangel Atoll in Micronesia, no nests can be found where nesting was once common, and local inhabitants show little interest in regulation, regarding the person who catches the last turtle as the winner. Turtle populations are decreasing rapidly throughout the western Pacific, with the exception of the Great Barrier Reef. On the GBR, turtles are still frequent, but there are concerns that adults that feed outside the area are being harvested, before they can return to nest (Limpus *et al* 1993). Variations in ocean currents or the incidence of El Nino events (see Box 4.2) as a result of global climate change may further exacerbate these pressures, either by shifting adult migration patterns into regions of high human predation or by disrupting breeding cycles (Limpus 1993).

It has been predicted that the geographic range of tropical cyclonic storms will expand polewards, and that their frequency and intensity will also increase (Fig. 4.8; Ryan *et al.* 1992). Areas now in or adjacent to zones of tropical storm activity may experience increases in storm damage, thereby dramatically affecting those people who live adjacent to coral reefs. If the frequency of more powerful storms increases substantially, then some areas may become uninhabitable or require large capital expenditure to strengthen buildings and replace damaged structures. There is increasing concern within the global insurance community that climate change may be connected with a series of mega- disasters (e.g. hurricanes and other tropical storms; floods in the mid-west of the USA; fires in California). If so, they consider that premiums for insurance may have to rise beyond affordable levels or be withdrawn altogether (Leggett 1993).

It is predicted that there will be an increase in the intensity of rainfall, with relatively more rain falling in large rainfall events. This will have little impact on oceanic reefs, but could increase low-salinity stress in enclosed lagoons or reefs adjacent to land masses. Changes in rainfall patterns may be either positive or negative, but there is a probability that both droughts and floods will increase (Whetten *et al.* 1992; Meehl and Washington 1993).

Changes in waves, either as a result of wind pattern changes or sea level rise, will result in changes in the species composition of coral communities. These are unlikely to cause adverse effects on reefs, but the change may cause concern to human users. Locally, such changes are likely to contribute to alteration of sediment deposition and erosion patterns that will threaten areas now used for living, tourist facilities, or food production. Changes in large scale current patterns could result in altering the natural transport of larvae, nutrients, and sediment, with long term effects on both local and regional development of reefs, and their global distribution. Any increase in the occurrence of clear, calm weather could enhance the frequency or extent of coral bleaching.

While all of these effects will occur to some degree, the precise nature and degree of change and the areas likely to be affected cannot be predicted except in a very general and uncertain fashion. Local assessments will have to be updated regularly as improved regional models and actual experiences provide additional information.

Other Global-change Factors

Carbon Dioxide Concentration Increases

The partial pressure of carbon dioxide in the surface ocean will increase as the atmospheric concentration increases. This will produce anew equilibration state with lower concentrations of calcium carbonate supersaturation because an increase in CO₂ will increase acidity. It is unknown whether or how much coral calcification rates are dependent on the level of supersaturation, because evidence suggests that coralline algae and possibly some corals calcify less as the saturation state decreases (Smith and Buddemeier 1992). This would result in a gradual, global decrease in reef calcification with time. This gradual effect would be nearly impossible to quantify or observe conclusively at individual sites.

The production of sediment and construction of physical wave barriers by reefs depends on the maintenance of a healthy calcification rate. Even more threatening to both the physical structure and the reef community as a food source, however, is the possible transition to a community dominated by non-calcifying algae (Done 1992). Increasing CO₂ may not only gradually reduce calcification, but may also have the secondary effect of fertilizing marine algae and seagrasses (Wetzel and Grace 1983; Hackney and Sze 1988). This would enhance their ability to compete with corals for substrate, and would reinforce the effects of elevated nutrient levels that are often implicated in the change to a non-calcifying algal community. Although net organic productivity may rise, the non-calcifying communities replacing coral- algal reefs may support fewer herbivores useful to man, because of a change in the nature of primary productivity.

Visible and Ultraviolet Radiation

The availability of visible light will be affected by changes in cloud cover, water quality, and possibly surface roughness (wind patterns). It seems unlikely, however, that any changes directly due to climate effects will be great enough to enhance or degrade reefs significantly (although reduction in light may be an important side effect of anthropogenic sediment or

nutrient loading). The increase in UV-B radiation exposure as a result of continued degradation of stratospheric ozone is of more concern. Low latitude areas already experience high levels of UV radiation, and organisms have developed mechanisms for either shielding out the radiation or avoiding it. Although UV-B increases will be relatively small on average and very patchy in time and space, there may be disruption to plankton and especially to floating larvae. UV-related stress is therefore another factor that is not separately predictable on a local basis, but which contributes to a less favorable environment for reefs (see Box 2.3).

For peoples adjacent to coral reefs, UV damage to planktonic organisms, particularly larvae, may cause the loss of harvestable productivity in the oceans (see Chapter 2). If food or other commercial species are involved, the losses to people could be devastating (see Box 5.5). Another factor relevant to both visible and UV radiation is that both stresses are considered to act synergistically with elevated temperature to induce more bleaching in coral reef organisms (see above). Unfortunately, there are no effective models to predict the extent or locations of such effects.

Other

Although factors such as sediment and nutrient loading have components related to global change and natural processes, the extent of their effect on coral reefs is so dominated by anthropogenic, rather than climatic contributions, that they should be considered on a specific local and regional basis. With reference to present and expected human activities, all of the factors discussed in this section - CO₂, light, and the climate-related components of sediment and nutrient loading - are likely to contribute to a gradual increase in 'background' stress, and a decline in environmental suitability for reef productivity and calcification in many areas. These trends accentuate reef vulnerability to other environmental stresses or to over-exploitation, rather than having direct effects on human use. This underscores the need to understand our coral reef ecosystems and to manage their use in a conservative fashion.

Box 5.5: Seaweed Mariculture

Growing of seaweed is becoming an important economic activity for many people living near coral reefs. Seaweeds provide both food and additional income from the export to Japan of species rich in agar, carrageenan and alginate. Traditional methods of culture have been developed, based on a knowledge of the growth habits and environmental requirements of different species. These methods use readily available cheap building materials, placed on reef flats which are an excellent habitat for algal mariculture as there is plenty of light and wave turbulence is low. Most commercial species, such as *Eucheuma*, are grown close to the surface where they are readily influenced by available light, surface water currents and nutrient concentrations. *Eucheuma*, however, can bleach if light levels are too high, so commercial operations may be vulnerable to UV radiation increases as well as increases in rainfall and cyclonic storms due to climate change.

It is important to monitor any such mariculture projects for the effects of climate change and ensure that they are sited in areas that will receive minimal adverse impacts.

5.3 Stress Interactions and Reef Vulnerability

Stress Interactions

Some climate-change factors (temperature and storm activity) may increase the levels of acute or episodic stress on reefs; other factors will result in moderate deterioration of the environment (UV exposure and carbon dioxide chemical effects). Still others (sea level rise and oceanographic factors) may cause changes that are not intrinsically bad for reefs. However, there may be ill effects in specific locations, and any change may be seen as detrimental for human societies accustomed to reefs as they are. Coral reef communities, however, are disturbance-adapted, and likely to recover from acute stress, provided that the substrate and environmental conditions remain favorable for reef community development.

Under conditions where changing climate contributes to changing reef environments, the survival of reef communities will depend on two factors:

whether acute stress events will become so large and so frequent that they block effective recovery; and

whether chronic stress factors interfere with the normal process of recovery from acute stress.

The coincidence of multiple acute stresses is a chance occurrence, is infrequent, and will depend on the probabilities of the individual stresses. These probabilities will change as baseline conditions and the patterns of weather and climate alter. Although our understanding of ocean and climate patterns is improving, we can only discuss such probabilities on a qualitative basis. Similarly, we have relatively few examples to use for predictions of reef responses to multiple concurrent or closely-spaced acute stresses.

Chronic stresses, either alone or in combination with acute stresses, are both conceptually and practically more manageable. Anthropogenic stresses and their effects on reefs are probably the greatest threat to reef survival. Where more than one anthropogenic or climatic stress factor is concurrent, they will combine and interact. Presumably the combined effects will be more than simply additive; multiple stresses that are individually sublethal may combine to result in increased (or synergistic) effects. The management and conservation of reefs is, therefore, extremely dependent on identifying and controlling chronic stresses, and on accurately assessing their interactions.

Reefs will be particularly vulnerable when multiple concurrent stresses reinforce each other to drive the system in the same direction. The most important example is the competition between coral reef communities and non-calcifying communities (algae, soft corals, sponges). Reef communities in favorable environmental conditions (see Chapter 2) usually maintain dominance of the substrate, even if subject to episodic, acute disturbance. Nutrient loading, however, increases the competitive ability of algae and assists bio-eroding organisms in destroying the solid base substrate of reefs and coral skeletons. If either disease or overfishing eliminates

herbivores, algae are further advantaged by such reduced predation. Any acute stress that destroys or damages the coral community will further assist in an algal takeover rather than reef ecosystem recovery. Many scientists feel that this has occurred on Jamaica's once thriving reefs (Fig. 3.2). Climatic change is likely to worsen this problem by adding additional and reinforcing chronic and acute stresses. Rising carbon dioxide levels fertilize plants and may inhibit calcification, and the probability of acute stress (storms, high temperature events) will increase in many reef areas. If human uses of reefs are to be preserved, it is therefore important to reduce to a minimum the controllable anthropogenic stresses that favour algal dominance.

Classes of Reefs and Their Vulnerability

In order to provide a basis for local assessments and planning, we present the following classification of the known or probable vulnerability of coral reefs to the uncertain effects of climate change. These are presented as qualitative risk factors; overall vulnerability will depend on the intensity of the individual risks and the number of coincident risk factors. In the following list the terms 'proximity' and 'isolation' are used. It is important to assess these oceanographically and not just geographically; for example, reefs may be quite close to a contaminant source and suffer no ill effects if the current system consistently bathes them in clean water.

Qualitative Risk Factors:

- . proximity to major (continent or high island) land masses, which act as sources of nutrients, sediments and freshwater, and as a platform for a source of terrestrial drainage from damaging human activities;
 - . proximity to large or growing human populations - anthropogenic stresses are the most immediate threat to reefs, and will combine synergistically with climate-induced stresses;
 - . proximity to terrestrial environments undergoing change or development (urbanization, deforestation, agricultural conversion). This proximity must be assessed hydrologically; continental watersheds thousands of kilometres away may deliver the effects of land use to coral reefs through river discharge;
 - . heavy local human reliance on reef or reef island resources, especially with increasing populations or a growing export economy;
 - . isolation from other reef systems that could serve as biological refuges or sources of new recruits, when the reef in question is stressed or damaged;
 - . evidence of present stress or damage to reefs or reef islands, or of degradation of the surrounding marine environment;
- marginal coral reef environments for either natural or anthropogenic reasons.

An additional consideration of reef islands and coasts as human habitats must be added to these risk factors that specifically act on the reefs. Low-lying islands and coasts are intrinsically vulnerable to sea level rise. Additional factors affecting risks to human inhabitants include: dependence on fresh groundwater (for either human use or agriculture); absolute land elevation above the spring high tide level; and proximity to the present or expected future zone of tropical storms.

Using these criteria, the reefs that are least vulnerable to climate change damage are those that are least vulnerable to the complicating effects of anthropogenic stress. Oceanic reefs which support few people, but are reasonably close to other reef systems (for the provision of new larvae), may be where the effects of climate change will be most clearly noticeable but they will also be the least vulnerable to climate change effects because they are the least affected by other stresses. We suggest that a variety of oceanic reefs should be identified and entered into an International Biosphere Reserve Program, with the added purpose of serving as controls to monitor the effects of climate change on coral reef ecosystems, without the complication of other factors (Buddemeier 1993).

5.4 Developing Local Assessments and Predictions

General Overview

Managing or planning for the effects of climate change on reefs that are important to, and affected by, human societies will require local assessments of value and vulnerability and the implementation of specific policy (discussed in Chapter 6).

The summary comments and guidelines in this Chapter provide scientists, managers, and policy-makers with information to understand a local situation. A thorough assessment of risks and development of strategies for coping with climate change requires assessment of the local situation, both with regard to the reefs and the marine environment, but also with respect to the demographic, economic, and terrestrial environmental future of the region.

Reef mining and dredging can be considered as an example of the need for local assessment. Although it is possible to estimate the sustainable sediment yield for a reef and how it changes under various scenarios, climate change effects on the human use of reef sand and limestone can not be realistically estimated at present. Virtually no current mining or dredging operations are based on considerations of sustainability, although most reefs have substantial amounts of carbonate sediments that are not critical to the functioning of the reef (see Box 3.6). If extraction practices were closely attuned to current reef equilibria, community requirements, or extractable reserves, a case could be made to consider climate change effects in detail.

Global models of climate processes are improving, as are regional climate assessments, ocean models, and analysis of existing climate data, although there is still considerable uncertainty. It is important that all new assessments be reviewed and updated at regular intervals to incorporate new information and ideas. It is also important that assessments and strategies focus on the robust conclusions and approaches that are least likely to be discredited as uncertainties are resolved.

Regional Status Summaries

The following brief descriptive summaries provide general background information on the major coral reef provinces of the world. These brief descriptions cannot do justice to the scope and complexity of these areas, and the UNEP/IUCN (1988) reference work is recommended for more detail.

Caribbean Region

The greater Caribbean consists of two semi-enclosed basins of the Caribbean Sea and the Gulf of Mexico, and includes south Florida, the Bahamas, and Bermuda. The region is relatively small, with a surface area of approximately 4 million km², and few large continental shelves, except the Yucatan Peninsula and the Miskito Bank of Nicaragua. The Caribbean averages 2200 m depth with several deep trenches. Some of the world's largest rivers influence the Caribbean - the Amazon and Orinoco rivers impact directly on the Lesser Antilles and the Mississippi River plume is carried by the Gulf Stream into the Florida Straits (Muller-Karger *et al.* 1988, 1989, 1991). While a typical, tropical climate prevails in the Caribbean Sea, the northern parts in the Gulf of Mexico, Florida, and Bermuda show strong seasonal fluctuations (Ogden 1987).

Although only 70 species of stony corals are known, the coral reefs are well developed in the Caribbean and include about 14% of the estimated total global area of 617,000 km² (Smith 1978). Bank barrier, fringing, and patch reefs are the most common developments, although barrier reefs occur off Belize and the Bahamas, and atoll-like structures are found in Belize (Glovers Reef), the Bahamas (Hogsty Reef, and Venezuela (Los Roques). Algal ridges are not prominent but present on some Caribbean reefs exposed to extreme wave intensity (Adey and Burke 1976). The Gulf Stream is a major influence and extends the normal latitudinal limit of coral reefs of around 21° to Florida (26°N) and Bermuda (32°N), although low winter temperatures are sufficient to slow coral growth and restrict coral reef development in these locations. The Gulf of Mexico is heavily influenced by terrigenous sedimentation from the large rivers, but good reef development is found off the Yucatan Peninsula of Mexico and on deep banks within the Gulf at Flower Gardens Reef.

Because of its small size, relatively high latitude, and the potential influence of ice ages on climate variability, the Caribbean has long been considered as a marginal area for coral reef development (Davis 1928). The work of Adey (1978) showed that Caribbean reefs have been rapidly building carbonate structures over the past 5000 years of sea level rise and that these rates of carbonate accumulation in the Caribbean were equivalent to the Indo-Pacific. However, there are systematic environmental differences between reefs in the Caribbean and in the oceanic Indo-Pacific. Several lines of evidence indicate that the Caribbean experiences generally and consistently higher nutrient levels than the Indo-Pacific, with implications for both the organisms (Wilkinson 1987b) and ecosystems (Birkeland 1987).

The whole coastal zone of the Caribbean supports over a hundred million people, in more than 20 countries. Under the pressure of rapidly increasing human population and demands for resources, the coastal zone is the focus of intense development in housing, industry, and

tourism. Mangroves are being cut down for lumber, agriculture, aquaculture, and urban development; seagrasses are being dredged for harbours; deforestation of hillsides and wetlands is causing sediment stress on coral reefs, due to erosion of denuded land and transport of sediment to the sea; and coastal fish stocks are being depleted. Pollution from agricultural, urban, and industrial centres adds to the cumulative impact. Governments are aware of the need for conservation and restoration, but the development of sound management strategies is crippled by an insufficient understanding of how coastal ecosystems function, how they interact, and how disturbance in one system will be manifest in adjacent systems.

These human impacts are superimposed over long-term reef changes brought about by natural factors, including storms and hurricanes (Woodley *et al.* 1981; Ogden 1992), white- and black-band disease (Gladfelter 1982; Rutzler and Santavy 1983), the Caribbean-wide mass-mortality of the long-spined black sea urchin (*Diadema antillarum*) in 1983-84 (Lessios *et al.* 1984), and coral bleaching and other suspected manifestations of global climate change (Smith and Buddemeier 1992; Brown and Ogden 1993). Clearly, the structure of a coral reef in any particular location will be the result of the long-term interplay between human-induced and natural factors. There is a growing conviction that interdisciplinary studies conducted over the full range of regional development of coral reefs will provide the best opportunity to discriminate between these two factors, so that the success of management of human impacts may be evaluated (Ogden 1987; Box 6.2).

The small size of the Caribbean puts its coral reefs at particular risk from the threat of expanding human populations and resource exploitation, but this may also hold an advantage for the development of regional treaties and research programmed to mitigate these threats over time. The Caribbean has the potential to serve as a model region for the development of regional marine resource management and research.

Pacific Ocean Region

The Pacific Ocean is by far the largest, occupying about a third of the world's surface. Within this vast ocean are a large proportion of the world's coral reefs (25%; Smith 1978), with great distances between the island groups, which are mostly concentrated in the west (e.g. Micronesia, Palau, Papua New Guinea, Solomon Islands, Vanuatu). The predominant currents also flow to the west, and these have affected the distribution of species, with more species in the west, and very few capable of migrating eastwards across the Pacific.

Most of the islands in the Pacific were uplifted out of the ocean when the Pacific plate drifted over 'hot spots' to form volcanoes or when the plate collided with other plates, forcing land upwards, such that they have virtually no continental shelves (e.g. Cook Islands, French Polynesia, Fiji, Samoa, Tonga). Amongst these volcanic islands are some that are now devoid or almost devoid of large land masses, and the small amount of land has been constructed from coral reefs to form atolls (e.g. Kiribati, Marshall Islands, Tokelau). Added to these, are some islands that have been formed when older limestone reefs were uplifted during tectonic activity (e.g. Guam, Nauru, Saipan).

Virtually all high Pacific islands have fringing coral reefs. In the atolls, reefs are the dominant feature with a barrier around the outside and patch reefs in the lagoon. Thus, reef resources are the basis for much of the food and local industry.

On the eastern side of the Pacific, there are fewer reefs and these have low coral diversity. Indeed, the few species on the Galapagos reefs were almost completely eliminated during a severe bleaching event, possibly associated with a severe El Nino event in 1982-83 (Glynn 1988a,b; Glynn and de Weerd 1991).

In contrast, there are many reefs on the western margin and these are the richest in the world in terms of species of corals, fish and other groups of organisms. The reefs include the Great Barrier Reef (GBR) with approximately 3,000 separate reefs; those around New Caledonia, including one of the longest barrier reefs in the world; reefs of the Solomons and Papua New Guinea and then stretching through Micronesia and Palau to Guam. These reefs border those of the Philippine Archipelago, near the centre of coral reef biodiversity. Most Pacific coral species are believed to have originated in southeast Asia and have been transported throughout the Pacific (Rosen 1981; Veron 1986), either as larvae or as colonies attached to floating material (Jokiel 1990). The number of coral taxa diminishes remarkably from west to east (Veron 1986), while fish distribution is much less variable. These variations result from the large distances between suitable reef sites and the fact that many fish larvae travel in the plankton for weeks to months, whereas coral larvae float for only days or weeks (Box 2.6).

Contrary to the 'Pacific' name, the El Nino-Southern Oscillation (ENSO; Box 4.2) and tropical storms are major influences in this Ocean. Tropical cyclones originate in the warm equatorial waters, and generally migrate from the east and curve into higher latitudes, under the influence of the Coriolis Effect (a 'spinoff' or by-product of the earth's rotation; Fig 4.8). This will continue regardless of climate change, however, there may be an increase in frequency and intensity and a shift of the impacts into higher latitudes. Major shifts will have great impacts outside the current range e.g. northern Japan as typhoons and the Australian sub-tropical coast, New Zealand with cyclones. A shift will also impact on higher latitude lands and reefs within the storm trough (e.g. Guam, Okinawa, the northern Philippines, the central and southern Great Barrier Reef). These areas in the tropical northern and southern monsoon troughs are already hit by more cyclonic storms than other regions e.g. the northern trough is impacted by 33% of all tropical storms in the world, with Guam receiving 5 major typhoons in 1991-92.

Any increase in storm frequency and intensity will probably have a marginal impact on coral reefs in the monsoon troughs, as the reefs are adapted to disturbance. The coral communities are frequently hit, and they usually recover to form wave-resistant, robust, multispecies communities. Increased storm frequency will probably have greater impacts on reefs at the margins of the cyclonic storm belt, e.g. Samoa is rarely affected by such storms and the reefs have developed as topographically complex coral communities. A few more tropical storms will result in larger changes in Samoa, by smashing those erect and fragile communities that have not adapted to form low-relief, multispecies, encrusting carpets of corals found on exposed coasts.

The ENSO phenomenon is a product of tropical Pacific waters (Box 4.2). The recent severe El Nino episodes of 1982-83 and the one since 1991 have coincided with more cyclonic storms hitting areas not 'normally' affected. If global climate change results in more severe El Nino events, as has been speculated, then reefs like Samoa may be adversely affected in the future. For example, rarely affected reefs of French Polynesia were hit by a battery of tropical storms during the El Nino of 1982-83 (see Chapter 5).

Throughout the Pacific islands, human pressures on coral reefs are variable. The total population is estimated at 7.7 million in 1994 (including Hawaii and Papua New Guinea) with approximately 170,000 on atolls or low islands (Table 3.1). Coral reefs show adverse effects near areas of dense human populations because of: over-exploitation of commercially valuable resources; sedimentation; and nutrient runoff from coastal development activities. These have strongly affected reefs in the western Pacific, similar to those in the Southeast and East Asian Region. Most Pacific reefs are surrounded by deep oceanic waters, which rapidly dilute outflows of human pollution, however, impacts are felt in lagoons and on reef flats adjacent to large settlements e.g. Tarawa Lagoon (Kiribati; Kimmerer and Walsh 1981), Ebeye Islet (Marshall Islands - Box 3.1). However, tropical rainfall on some high islands means that large amounts of sediment are washed directly onto the reefs; this is being exacerbated as increasing agriculture results in more land clearing on steep slopes.

Less densely populated island groups, such as Micronesia (except Ebeye, Guam and Saipan), are only affected by coastal development at spot locations, but there is evidence of widespread over-fishing of commercially valuable species such as groupers, tridacnid clams and sea turtles. Recent surveys show that this over-harvesting, either due to poaching by foreign commercial vessels (e.g. from Taiwan, Indonesia, and elsewhere), or by locals using outboard motors, extends even to uninhabited reefs and areas previously considered to be pristine. Thus, it may be necessary to limit exploitation of wild populations to subsistence harvesting, and focus on commercial production via mariculture (Box 5.3).

Climate change will be most felt in the region through the impacts of sea level rise on the habitability of the low lying islands, particularly those that constitute all or most of some countries e.g. Kiribati, Tokelau. These countries are particularly active in global forums (e.g. the United Nations Global Conference on the Sustainable Development of Small Island Developing States in Barbados, April and May 1994) bringing world attention to the plight of these low lying islands, which may be lost as sea level rises (Boxes 5.1 and 5.2).

Reefs in the Pacific constitute the greatest reserve of reef biota in the world. Most remote reefs are in good 'health', although those around population centres show signs of degradation (Wilkinson 1993a). The management of reefs of the Great Barrier Reef may be regarded as a useful model for multi-purpose management of large reef areas. These reefs are, however, not typical of the region as they have formed on a broad continental shelf and are generally remote from land influences - these factors have been most significant aspects of their management. Pressures on these reefs from the land and peoples are generally low to insignificant and public acceptance of the need for management is high.

For most of the developing countries of the Pacific, there is a strong awareness that integrated reef management is necessary. Few of these countries, however, have the economic or personnel resources to implement 'western' methods of management that are advocated by consultants. Many of the cultures on islands are in transition between traditional subsistence societies to cash economies, with increasing dependence on imported goods purchased with the assistance of foreign aid (Box 3.2). Many of the traditional management practices are being eroded such that coral reef resources are being severely depleted on populated islands and even on some outlying islands as well. It is essential to acknowledge the value of these traditional

practices before they are lost and incorporate the valuable features into current management practices (Johannes *et al.* 1991).

Southeast Asian Region

The major influences on this region are both terrestrial and oceanic: the large land masses of continental Asia and the island archipelagos; and the seas which bridge between the Pacific and Indian Oceans. The region is considered separately from the Pacific because of the large influence of human populations in the ASEAN countries adjacent to the South China Sea and to the north in Indochina, China and Japan.

Southeast Asia harbours the highest diversity of corals and associated organisms in the world's oceans (Veron 1986; Leis 1991). Thus, this area should serve as a primary focus of interest with respect to losses of coral reef biodiversity, both from direct human interference, and from the longer-term effects of global climate change. There are major concentrations of coral reefs in the area, with approximately 30% of the world's total (Smith 1978). The archipelago arc from the Philippines to western Indonesia contains some of the world's most spectacular and diverse coral reefs. This area has ideal conditions for coral reef growth, because the predominant current from the Pacific to the Indian Ocean brings in clean oceanic waters to dilute the influences of the land masses.

The land exerts three major environmental influences: freshwater runoff results in wide ranges in salinity; much sediment is brought down to the ocean; and rivers focus nutrient inputs. All these result in stress to the reefs. Thus, reef growth has been limited where freshwater inputs are severe e.g. inner part of the Gulf of Thailand, west coast of Peninsular Malaysia, much of the coast of China. Most of this region is remote from the cyclonic storm belt, except for the central and northern Philippines and all countries to the north. The land is also particularly fertile and supports large human populations.

Southeast Asian nations are currently experiencing rapid rates of human population growth. The projected population of Southeast Asia will increase from 475 million in 1993 to 726 million by the year 2025 (Table 3.1; World Resources Institute 1992). East Asia currently has 220 million people, with another 1,190 million in China. These will increase to 244 and 1,512 million in 2025 respectively (World Resources Institute 1992). Since up to 75% of people inhabit the coastal zone (excluding China), the major impacts of this population growth will be on coastal resources and on the adjacent shallow-water ecosystems (Chou and Yap 1991).

Land-sea interfaces are particularly prominent in the archipelagos of Indonesia and the Philippines, and the combined coastlines of Brunei, Indonesia, Malaysia, the Philippines, Singapore and Thailand are about 99,000 km (Chou and Yap 1991). This, together with the wealth of marine resources in adjacent waters, has induced a tight dependence by the people on the sea for subsistence.

In most countries, there has been a recent population shift; people are migrating from the inland to both the larger cities (the megacities of Bangkok, Jakarta and Manila and the coastal cities

of China) and to coasts. Much of this migration is attributed to a decrease in fertility of inland soils because of poor agricultural practices. Farmers forced off the remaining fertile areas migrate to the coast seeking a living (Brown 1993). There is an additional pressure in Indonesia where peoples from over-populated Java have been 'transmigrated' to eastern Indonesia, where reef resources are still in reasonable condition.

Traditionally, coral reefs have provided vital sources of food, notably protein-rich fish, molluscs and crustaceans as well as seaweed. In addition, reef materials are used in construction (coral and sand), and for trade (corals, shells, aquarium fish; Yap and Gomez 1985).

The degradation of shallow-water ecosystems, such as coral reefs, is the most severe marine environmental problem confronting Southeast Asian nations (Table 6.1; Gomez 1988; Yap 1992). Demands on reefs by growing populations have resulted in over-exploitation of these resources, i.e. the rate of extraction of products has far exceeded the natural ability of reefs to replenish the resources. The outcome is a patent degradation of these ecosystems with reduced abundance, or even extinction of certain species, and a weakening of the reef framework. This is aggravated in some areas where fishermen resort to destructive methods of fishing, notably blasting and the use of poisons like cyanide (Alcala and Gomez 1987; Gomez *et al.* 1987). Other causes of destruction are organic pollution, particularly untreated sewage discharged directly into reefs, and the dredging of reefs to create waterways, or for mining (e.g. tin in Thailand). It is estimated that approximately 11% of the coral reef resources of Southeast Asia have already been degraded beyond recognition, either being directly mined for sand (Brown 1986) or because of other human pressures (Wilkinson 1993 b). The coral reefs of Japan and Taiwan are also severely degraded; here it is not through subsistence pressures but through industrial pollution and direct damage from the impacts of economically wealthy tourists.

Southeast Asian coral communities have been degraded by over-exploitation of commercially valuable resources, sedimentation and nutrient runoff from coastal and inland development. These activities have strongly affected Philippines reefs, such that only about 5% of the Philippine reefs are in very good condition, with about 70% being degraded (Yap and Gomez 1985; ASEAN-Australia Marine Science Project 1992). Similarly, Sukarno *et al.* (1986) report that only about 5% of Indonesian reefs are in very good condition, with about 60% degraded. There are current fears that large areas of Japanese coral reefs will be irreversibly damaged with the loss of some endemic species (Muzik 1985; Veron 1992).

Current predictions are that approximately 48% of southeast Asian reefs will collapse in the next 10 to 20 years and the remainder in 20 to 40 years, unless practices are implemented soon for sustainable management of reef resources (Wilkinson 1993b). There has been a recognition in some of these countries that reef resources require management (Katili 1992), and Indonesia, Malaysia, the Philippines and Thailand have commenced the implementation of large area management programmes for coastal resources (Chapter 6).

In East Asia, many of the reef resources of China (with the exception of the Spratly Group) have been markedly depleted (UNEP/IUCN 1988). Although the population growth rate of China has stabilized at 1.4%, the current large population on the southern coast around Hainan has

resulted in extensive reef degradation. With the rapid economic growth in Chinese coastal cities, there will be an increase in the demand for food from the sea and even greater pressures on the remaining coastal resources of the whole region.

The Spratly Islands are a special case as they are currently claimed by 6 countries: Brunei Darussalam; China; Malaysia; the Philippines; Taiwan; Vietnam. The legal status of these islands is in considerable doubt and the disputed claims could result in conflict to resolve ownership, particularly if exploitable petroleum reserves are established through drilling that has been announced by China.

Because of the political sensitivity of the Spratly Island area, there are few reliable data, although anecdotal reports state that many areas are in good condition, particularly some of those protected by the military bases of the claimant nations. Malaysia has established a tourist facility on one island with flourishing coral and fish life. Other reefs however, have been heavily damaged by dynamite and muro-ami fishing. The presence of the military is both a potential benefit and problem - greater protection from outside exploitation will be offered by the military forces, who may themselves exploit the resources using readily available explosives.

The Spratly Island reefs are remote from any land pollution and sediment discharge. Thus, the Spratlys probably constitute the best remaining reserve of viable broodstock of larval coral, fish and other reef biota in Southeast and East Asia to repopulate coral reefs in areas that are under heavy exploitation and pollution pressures (McManus 1992). These reefs, therefore, should be considered for declaration as an area of global significance and high regional importance and awarded protection as a world park, as is the case of the Antarctic (Buddemeier 1993) or for international listing as a World Heritage Area.

Indian Ocean Region

The coral reefs in the Indian Ocean occur predominantly between both Tropics (Cancer and Capricorn) and are bounded by the wet tropical coastlines in the north (India, Sri Lanka) and northeast (Thailand, Malaysia and Indonesia), and the desert coastlines (the entrances to the Red Sea and Arabian Gulf, Yemen and Oman) or semi-desert coasts of Somalia, northern Kenya and Madagascar on the western side (40°W) and the equally arid coastline of Australia on the eastern boundary (115°W). The environmental conditions affecting this region are basically similar throughout and all areas are potentially connected by ocean currents, therefore most habitats have species in common. Likewise, the social and economic conditions are comparable in most countries, with the exception of Western Australia, so that coral reefs in the Indian Ocean face similar problems.

There are many coral reefs ranging from the fringing, platform, patch and barrier reefs on the mainland coasts to the east, north and west including the island of Madagascar, and numerous atolls and fringing reefs around the island groups (the Seychelles, Mauritius, Reunion, Comoros, Lakshadweep, Maldives, Cocos Keeling and Christmas). About 24% of the world's coral reefs are contained within the Indian Ocean region (Smith 1978).

The climate within this ocean is dominated by the monsoonal cycle, hence it varies seasonally and controls the major surface currents; a large anticlockwise subtropical gyre in the south, and a reversing current in the north. During the north-east monsoon (November to April), the north equatorial current flows west and produces the Somali current (flowing south-west). During the south-west monsoon (May to October), the drift flows eastward with a clockwise branch in the Bay of Bengal and the Arabian Sea, generating a major upwelling of nutrient-rich water off the coasts of Somalia and southern Oman.

The water movement moderates the climate, such that Indian Ocean surface temperatures vary between 25°C and 30°C, with the western parts being generally warmer by 2-3°C, because of west flowing currents. The annual upwelling off Somalia and Oman, however, brings clear, cold water to the surface, and temperatures drop to less than 18°C. Surface salinity is stable, generally between 35 and 36ppt.

These upwellings bring nutrient-rich water to the surface and raise productivity to the highest levels in the Indian Ocean. Otherwise, concentrations of nitrate and phosphate are very low (oligotrophic), except in coastal areas near river mouths.

Coral reefs in the Indian Ocean have a generic diversity similar to southeast Asia, which has the world's highest biodiversity. For example, there are about 78 coral genera compared to 79 recorded from Australia (Veron 1986) and 78 from the Philippines (Nemenzo 1981). There is an apparent geographic balance in the composition of this diversity, with some Asian corals disappearing with increasing distance westwards in the Indian Ocean, which is partly compensated by genera that are restricted to the African and Arabian coasts and some island groups. Indian Ocean reefs are dominated by species of the genera *Porites*, *Acropora*, *Goniastrea*, *Favia*, *Pocillopora*, *Stylophora*, *Millepora* and *Platygyra*. The number of species is apparently smaller in the western Indian Ocean with approximately 200 species of hard corals around the in Madagascar, the Chagos islands and the Red Sea compared to 400 species in southeast Asia (Sheppard *et al.* 1992).

The value of Indian Ocean coral reefs as providers of fish and shellfish for home consumption and local markets is probably underestimated. Commercial fish associated with reefs include many species of snapper (Lutjanidae), grouper (Serranidae), emperor (Lethnidae), jack (Carangidae), grunt (Haemulidae) and goatfish (Mullidae).

Population pressures on the coasts of the Indian Ocean are not quite so intense as on islands, but they are growing rapidly. Fringing reefs, lying immediately offshore are particularly vulnerable to pollutants and sediments washed off the land, particularly in Kenya, India and Sri Lanka. They are also accessible and suffer damage from over-exploitation and recreational use. These fringing reefs are adjacent to countries with rapid growing (Kenya at 3.6%) or large populations (India, nearly 1 billion people; World Resources Institute 1992).

Atoll and barrier reefs are less vulnerable to land pollutants, but are vulnerable to over-exploitation. This is particularly the case in the Maldives, especially in Malé where about 60 thousand people crowd onto a small coral island. This has resulted in considerable degradation of the shoreline and salt water intrusion owing to previous extensive coral sand and rock extraction (Box 3.6; Kenchington 1990; Hameed 1993).

Sedimentation from coastal and marine tin mining is the major cause of damage to reefs in western Thailand, and damage to reefs off the west coast of Malaysia is noticeable adjacent to agricultural, industrial and domestic development. In the Gulf of Kutch (India), marked deterioration of coral reefs has occurred through dredging of sand for the cement industry. High coral mortality occurred on Minicoy Atoll, in the Lakshadweep islands, following dredging of the main shipping channel. In the Comoros, siltation of reefs and lagoons is lowering fishery productivity and sedimentation from inland deforestation is causing damage in the Andaman islands. In Kenya, coral in the Malindi Marine National Park has been severely affected by a great increase in sediment from the Sabaki river, because of upriver soil erosion following deforestation and agriculture.

The tourist industry is developing rapidly, particularly due to easy access for European tourists. Coral reef islands offer favorable climates, beaches, clear waters and reefs, such that tourism is the major economic factor for the Maldives and the Seychelles and continues to expand (Pernetta 1992).

There is increasing damage to reefs by endemic populations of sea urchins (echinoids) and of crown-of-thorns starfish (*Acanthaster planci*). Recently, populations of *A. planci* have caused high coral mortality in Minicoy Atoll (Lakshadweep), in Sri Lanka, and Mauritius. Reef urchins normally feed on the algal turf that covers reef surfaces, however, large numbers of *Diadema setosum* or *Echinometra mathaei* have caused the erosion of reefs, causing the corals to collapse and die. Extensive damage has also been reported off Kenya.

Management and conservation of the reefs throughout the Indian Ocean is highly variable, The countries with growing populations often have unstable economies and often lack the infrastructure and personnel to implement effective management. Countries on the coast of Africa have the most rapidly growing populations, which is being translated into pressures on the offshore reefs. There are a number of recent initiatives in Kenya and Tanzania aimed at managing the coastal resources on that part of the African coast. In the desert countries of the northwest Indian Ocean, pressures on reef resources are generally limited to domestic sewage runoff and pollution from the oil industry, and there is minimal sedimentation because of low rainfall. Reefs of the northern Indian Ocean are severely degraded, but the countries, especially India and Sri Lanka are anxious to conserve the remaining resources. Similar situations occur in the northeast Indian Ocean, where conservation pressures are increasing in Thailand, Malaysia and Indonesia. The need for reef conservation is strongest in the island states, because reef resources often dominate the local economies, both for fisheries, coral sand mining and tourism. Mauritius, the Maldives and the Seychelles are all implementing programmed of coastal zone management with a strong emphasis on ensuring that use of reefs is sustainable (Chang-Ko 1993; Hameed 1993). Population growth, however, is acknowledged as a threat to these activities (Kenchington 1990; Hameed 1993). Pressures on the reefs managed by Australia offshore (Cocos Keeling, Christmas, Ashmore, Scott, Seringapaton, and Rowley Shoals) and onshore (Exmouth, Ningaloo, Houtman-Abrolhos) are slight and all are either under active management (e.g. Ashmore Reef National Nature Reserve, Ningaloo Marine Park) or are being considered for protection and management. The major threat to these reefs is through the developing oil industry, based off the northwest shelf of Australia and northwards to Indonesia.

Climate change is recognized as a threat to the island communities, with the Maldives and Seychelles being most vocal in alerting the global community to these threats. These islands will be severely threatened by small rises in sea level, with the likelihood of large scale beach erosion and damage (Boxes 3.6, 5.1). Climate change threats to coastal reefs are in line with other areas around the world, with some concern about possible shifts in ocean currents, such as the Leeuwin Current flowing southward off Australia's west coast. This could disrupt the flow of larvae to the Ningaloo and Houtman-Abrolhos reefs which form the southern most limit of reef growth in the Indian Ocean.

Persian Gulf and Red Sea

These two areas, although small compared to the other regions, warrant special discussion because they: contain a wide range of environmental conditions; are not buffered by larger oceans of deeper water; and are of considerable conservation, scientific, economic and recreation value. Both seas were formed by relatively recent tectonic plate movement and both have narrow entrances to the Indian Ocean.

The Arabian region is arid, with large seasonal fluctuations of air and water temperatures, and hence the greatest extremes in tropical marine climates. The biota have undergone selection for survival under highly stressed conditions. Many endemic species are capable of tolerating high water temperature and salinity, although these may be close to the physiological limits (Sheppard et al. 1992). Any additional stress imposed by global climate change or direct human activities may cause significant impacts on these biota.

The Persian Gulf is small, shallow and almost closed, sloping gently from the Arabian Peninsula to deeper waters in the west near Iran reaching 80- 100m. The Gulf was formed 2 to 5 million years ago, and emptied completely during the last ice age (Pleistocene), such that present-day biota had to migrate in from the Indian Ocean as sea level rose. Coral reefs occur only in offshore, clear waters near Kuwait and Saudi Arabia. Because the temperatures and light conditions are on the edge of the limits for normal coral growth, the reefs are less well developed than in the Red Sea.

The Red Sea is a flooded rift valley that formed with the separation of Africa and Arabia about 70 million years ago and is still volcanically active. The communication at 30°N via the Suez Canal in the north is recent and narrow, and the strait of Bab el Mandeb at 12°N in the south forms a narrow connection with the Indian Ocean. The Red Sea is straight extending about 2000 km, about 180 to 360 km wide, and generally deep, with a maximum depth of 2850 m. Coral reefs have formed on much of the relatively wide continental shelf (15-30 km wide in the north and 120 km in the south). This shelf is dissected by reefs, rocky shoals, banks and islands following the rough bottom topography.

Coral reefs fringe much of the Red Sea coastline and often extend offshore for many kilometres (UNEP/IUCN 1985) and are the most conspicuous marine feature, with high diversity (about 250 species of stony corals and 180 species of soft corals; Sheppard et al. 1992). Reefs are best developed in the northern and central sections, with occasional pinnacles resembling atolls. Red Sea reefs are related to those in the Indo-Pacific group, but there is some impoverishment in the

number of the species e.g. there are about 2,000 species of fish in the Indian Ocean, and only 800 in the Red Sea.

Tides in both the Red Sea and the Arabian Gulf are not influenced by the Indian Ocean. Gulf tides are variable, from 3 - 4m in the north to less than 1 m in the south. The ebbing tide in Kuwait exposes tidal flats more than 1 km wide during the day in winter, but at night in summer. Consequently, the intertidal zone is rarely exposed to intense solar radiation. In the Red Sea, the tide is small and oscillatory; when it is high water at one end it is low water at the other with a maximum range of about 0.9 m. Because water circulation is predominantly slow, and tides oscillate back and forth, there is little mixing of the waters.

The year is divided into cooler and hotter seasons corresponding to the direction of the dry monsoon winds; northeast in winter and southwest in summer. Rain is very sparse, because both the Arabian Gulf and the Red Sea are at the edge of the Indian Ocean monsoonal gyre, but spasmodic rain may result in considerable short-term sediment input. For example, circulation in the northern Gulf of Suez is restricted, and the occasional excessive sedimentation restricts coral reef development.

Arabian Gulf coral reefs are exposed to greater variations in temperature, but there is a prolific coverage of corals, although with a limited number of species. There are wide seasonal changes in air temperature which result in sea temperatures varying between 15°C in winter and 33°C in summer. Both species diversity and percent coverage decrease approaching the shore, suggesting that coral survival is limited where physical conditions are more extreme. Only 57 hermatypic coral species occur on offshore island reefs; only 24 of these are found on inshore reefs; and no corals are found where salinities exceed 46ppt.

The marine climate in the Red Sea is remarkably uniform throughout the year (average sea surface temperatures vary from 28°C in the south to 22°C in the north), although the air temperature can vary from 6°C in the north to 42°C at Jeddah. The variation in water temperature, however, is more important (annual differences range from 8° to 18°C in the north and only 3° to 4°C in the south). This relative uniformity is due to the heated brine pools on the bottom that maintain the water below about 250 m at a constant temperature of about 21.5°C.

Extremes in temperatures profoundly influence reef biology and limit the distribution and occurrence of many species (Coles 1988, Coles and Fadlallah 1991). Temperature adaptability varies with the taxon (Smith and Buddemeier 1992), such that the species present in the Red Sea and Arabian Gulf are tolerant of extremes. Therefore, coral bleaching here is not usually associated with warming (Fouda in press), but linked to the oceanographic regimes of monsoon winds, swell and upwelled cold water in the Gulf of Oman (Salm 1991).

The two bodies of water are the most saline seas in direct connection with the world oceans, because of high evaporation and almost no freshwater input. The Gulf is shallow and has a constricted entrance at the Strait of Hormus, therefore there are dramatic variations in salinity (between 40-70 ppt compared to about 36 outside in the ocean) because water exchange with the Indian Ocean is limited. In the Red Sea, salinity averages 36ppt near the Indian Ocean, and increases to more than 40ppt in the north (and can exceed 43 ppt).

Fisheries are of immediate importance in supplying fish for consumption and for the future reduction of dependence on imported fish. Most fisheries are small scale and artisanal, although large scale industrial fishing is increasing, particularly in Yemen. Fish production from the Red Sea is small (only 0.7% of the world total), and there are indications that the marine resources are not fully exploited.

The Gulf may be the most productive water body in the world, with phytoplankton a major contributor to primary production, However, in waters shallower than 5m, subtidal benthic communities (e.g. coral reefs, seagrass beds, and sediment areas) become greater contributors. Nutrient concentrations in the Red Sea are generally lower than Indian Ocean waters, while nutrient levels in the Arabian Gulf are higher.

Fifteen countries border the Red Sea - Egypt, Sudan, Ethiopia, Eritrea, Yemen, Saudi Arabia, Jordan and Israel; and the Arabian Gulf - Iraq; Kuwait, Saudi Arabia, Bahrain, Qatar, United Arab Emirates, Oman and Iran. These countries have an estimated population of 250 million with an average annual growth rate of 3.1 % (varying from 1.8 to 5.1%). In many of these nations, much of the population live along the shores (e.g. in Saudi Arabia, 60% live on the Red Seacoast), with the coastal region becoming a focal point of development and construction. If such growth continues, the population of urban centres is expected to double, probably every 10 years, with predictable exponential increases in environmental stress.

Pollution in the Red Sea and the Arabian Gulf can be listed under three major sources: urbanization with tourism; oil exploitation and transport; and from other industries. The magnitude of pollution may be less at present than elsewhere in the world, but because these waters are enclosed with limited water exchange, the dispersal of pollutants into the Indian Ocean is minimal.

Sewage and industrial wastes are increasing and usually discharged just below the intertidal zone with considerable inputs around the cities (e.g. Suez, Jeddah, Bahrain). Considerable amounts of garbage (especially plastics) enter the sea from urban areas and ship traffic. The import of phosphate, manganese and bauxite minerals has led to increased levels in the water leading to the death of corals (Walker and Ormond 1982).

Coastal tourism is increasing and plays a major economic role in some countries. In Egypt, tourism is the third revenue earner with many of the 3 million tourists for 1993 visiting marine national parks (e.g. Ras Mohammed). Hotels, other infrastructure and sewage pollution are depleting the quality of the amenities that attract tourists i.e. clean beaches and reefs (Sheppard *et al* 1992).

The Middle East has more than half of the world's oil reserves. Most of this oil is exported via the sea or in pipelines, with the result that there is widespread pollution from the discharge of dirty ballast water by tankers, leaky pipelines, and the ineffective and inefficient operation of equipment. Oil pollution has been shown to disrupt the reproduction of Red Sea corals and lead to their consequent failure to colonize (Rinkevich and Loya 1979). The recent massive oil spills during the war in the Arabian Gulf, however, have caused little short-term damage (Roberts *et al.* 1993). Oil exports are expanding, therefore there is an increased likelihood of spills.

There appears to be increasing evidence within the region of damage to reefs by endemic populations of sea urchins (echinoids) and of crown-of-thorns starfish (*Acanthaster planci*). In some cases the urchins appear to erode the living coral tissue or attack it directly. Extensive damage of this type, first reported from the Caribbean, has now been observed in the Red Sea off Egypt, in Bahrain and in Kuwait.

While these two semi-enclosed seas may be influenced by sea level rise, they are unsuitable for the study of these effects. Sea level varies because of the high rate of evaporation and because inflow exceeds outflow in winter. Consequently mean sea level rises in the Red Sea by 10-20 cm in winter and falls by 20-30 cm in summer. However, other potential climate change effects may be of greater consequence. Any rise in sea surface temperatures could push some of the corals over the edge and an increase in rainfall could result in increased sedimentation in these enclosed seas.

6. Policy and Management Implications of Climate Change

6.1 Introduction

It is our assessment that the predicted climate change by itself will not have serious long-term effects on the status and survival of the bulk of coral reefs around the world, even though it will have potentially severe impacts on the peoples who live on and use coral reefs. Corals and coral reefs are likely to be severely impacted only in some areas; but in other areas, climate change will probably have advantageous effects on the growth of reefs. Great impacts will be felt, however, on islands and lands adjacent to coral reefs and this is where global climate change will have the greatest probable impact on people. The major problem for governments and international agencies is to develop policy options and management strategies to counter the impending effects of climate change, sea level rise and increased UV-B radiation on corals reefs and the people who live and depend on them.

The current threat to reefs from anthropogenic pressure, however, is unambiguous and directly causing a rapid decline of coral reefs. Many of the coral reefs of the world are under considerable pressure (Gomez 1988; Grigg and Dollar 1990; UNEP/IUCN 1988) and, unless effective management strategies are implemented almost immediately, it is predicted that approximately 70% of the world's reefs will be destroyed through human pressures within 40 years (Wilkinson 1993a). Climate change is a potential synergistic stress that may increase the destructive effects of local and regional human stresses to coral reefs. In addition, climate change may become the major threat to those reefs where anthropogenic stress is low - unthreatened or remote reefs which would otherwise serve as refuges and reservoirs of biodiversity.

Many island societies are currently caught between the traditional conservation strategies that worked so well in the past and modern life styles that threaten these approaches (Box 6.1).

6.2 Policy and Management Strategies

There are two major uncertainties associated with reef management in a changing environment:

uncertainties associated with our present knowledge of the degree and impacts of local and regional climate change; and

uncertainties due to our imperfect understanding of the scale and effectiveness of economic and social adjustments needed to cope with climate change.

Box 6.1: Traditional Reef Management and Conservation

Traditional societies had many effective ways to conserve and manage reef resources. These included food avoidances and prohibitions based on social class or gender; some magical or religious taboos enforced by strict fines and punishment; marine tenure systems that limited fishing rights to specific areas; optimum and closed seasons for some species according to traditional calendars; the shape and structure of fish traps and ponds that allowed small or non-target fish to escape (Klee 1980; Falanruw 1992). The power to invoke these regulations and taboos resided with either master fishermen, or other high ranking members of the social and religious hierarchy. 'Modernization' or introduction of western laws and aspirations have undermined these local controls over resources (Johannes 1993).

Tokelau is an isolated group of three atolls in the South Pacific where the authority of the Council of Elders over marine resources has been diminished through several circumstances: the cash economy has lowered community respect for the elders; these elders are now salaried and involved in non-traditional processes like budgetary management; punishment is less severe, such as relatively painless cash payments; the educated elite can easily avoid the authority; many Tokelauans return from New Zealand with different aspirations or can escape the Council's authority by departing for New Zealand (Toloa and Gillett 1989). There has been considerable over-exploitation of Tokelau's reef resources because of better transportation and a reduction in isolation, the development of export markets for marine resources, particularly giant clams, and the use of modern fishing gear (diving goggles, gill nets and spearguns; Toloa and Gillett 1989).

Elsewhere in the Pacific, other factors have also impacted on traditional practices such as: Christianity, which has replaced traditional reverence for nature spirits and fear of supernatural sanctions; fishing for local and export markets and profit rather than for subsistence and sharing the catch with the community; the abolition of local marine tenure by colonial and national laws that ignored traditional wisdom and control of marine resources; national governments that are unresponsive to reef exploitation and permit exploitation by foreigners; and population growth along with the breakdown of traditional authority over reef resources (Falanruw 1992 ;Johannes 1978) have all lead to over-exploitation - a 'tragedy of the commons' (Salvat 1992).

Therefore, it maybe necessary to adopt the 'precautionary principle' to cover as many realistic contingencies as possible. Previous unsustainable patterns of development and use of coastal resources have threatened not only coral reefs, but also other ecosystems such as mangroves, seagrass beds and coastal wetlands. Management policies designed to reverse the present direction of ecosystem degradation and introduce sustainable use patterns should be implemented before definitive cause and effect relationships are established. An additional benefit of prompt action to solve present problems will be to give ecosystems, such as coral reefs, the necessary time to adapt to the environmental conditions of a warmer world through natural adaptive mechanisms.

The use of precautionary principles to manage coral reefs is not a leap into the dark, as the principles are supported by considerable scientific and anecdotal understanding of the effects of development on coral reefs. It is now possible to predict what will happen to most coral reefs around the world, based on experience of natural and human-induced disturbance to reefs that have been closely studied or observed. It is clear that many reefs are adapted to natural disturbance and will recover, however, reefs that are disturbed by human activities are often slow to recover e.g. the Kaneohe Reefs (Jokiel *et al.* 1993).

There are two important management strategies for dealing with present environmental degradation and the potential effects of climate change on coral reefs:

- . remove or reduce the causes of stress to minimize future impacts; and
- . understand how the impacts are likely to be manifested and develop mechanisms to cope with these to minimize the effects on reefs and on the people associated with coral reefs.

Unfortunately, it is often more convenient to seek external causes for coral reef (and other habitat) destruction rather than examine those close at hand. Thus, global climate change is often regarded as an immediate threat, whereas direct anthropogenic disturbance should be the greatest concern for the survival of most coral reefs and for the people who depend on them for a living (Smith and Buddemeier 1992; Wilkinson 1993a). The prime management concern for the future of coral reefs worldwide is to reduce the negative impacts of human use and abuse and introduce sustainable development, so that reefs will continue to provide benefits for people into the future. Anthropogenic stresses are acting within an immediate time scale, whereas climate change impacts may not be readily apparent for many years to decades,

The management strategies identified above can be considered on two scales—the international, consistent with the causes of global climate change, and the local or regional, which is where specific effects will be felt and where non-climate related anthropogenic stresses originate. Examples of action at various levels may be found, but as yet no coherent philosophy or program has emerged. The summaries that follow briefly address some of the developments and issues involved in formulating and implementing these management strategies:

Strategy 1. Remove the Causes:

Countries that will be adversely affected by climate change have already made this an issue before agencies of the United Nations. A major theme at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in June 1992, was that the effects of climate change threatened all nations, but particularly the existence of low-lying countries (Chapter 17 of Agenda 21). The Maldives, Bangladesh and other countries made impassioned statements on the basis that their lands will soon disappear beneath the waves. Many of the countries under greatest threat are economically and structurally unable to cope with the anticipated effects of climate change (see Table 3.1, Box 3.2). These countries have approached the UN General Assembly with pleas to the developed world to reduce the emission of greenhouse gases, citing their very survival as a major reason. While this management aspect lies outside the scope of this report, we endorse efforts to stabilize and ultimately reduce the level of greenhouse emissions, and to phase out ozone depleting gases as outlined in the Montreal Agreement (Arrhenius and Waltz 1990).

Island countries in the Indian, Pacific and Atlantic Oceans are making concerted efforts to alert the larger industrialized countries, major aid donors and international agencies to the potential impacts of climate change on low lying nations. This was a major theme of the United Nations Global Conference on the Sustainable Development of Small Island Developing States held in Barbados in April/May, 1994, where small island nations will have their individual messages amplified through mass action. Their pleas are necessary as international economists are discounting the potential effects of climate change, arguing that a doubling of CO₂ would have a minimal impact on the world economy and insignificant dollar-term impacts on inhabitants of low lying nations (Adams 1993).

Many countries are seriously considering the call at UNCED in 1992 to reduce the emissions of greenhouse gases. For example, the strategy of the Australian Government is to stabilize greenhouse gas emissions at 1988 levels by 2000 and further reduce these 5 years later by another 20% (Council of Australian Governments 1992). Even if all greenhouse gas emissions were stabilized to 1990 levels or possibly reduced, there is likely to be a considerable lag-time before the current patterns of climate change due to past increases in greenhouse gases are reversed. A long lag-time may induce a lack of confidence in cause and effect scenarios and weaken the emphasis on reducing the emission of greenhouse gases.

Strategy 2. Assess and Mitigate the Risks of Climate Change

The debate on climate change has often been more concerned with over-exaggerated claims of potential damage and hazards (Fig. 1.2) than with reasonable prognoses for potential effects. The public media are responsible for much of this overt speculation, but it has been fueled by some groups in the scientific and environmental communities. Continued research, plus the advent of the biennial IPCC predictions have been responsible for reducing the over-dramatic predictions of doom (Wigley and Raper 1992; IPCC 1990, 1992). As one example, predictions of the most probable rate of sea level rise over the next century have diminished at least 3-fold in the past 10 years, from approximately 15 mm/yr (Buddemeier and Smith 1988) to 5 mm/yr (Wigley and Raper 1992) because of improvements in both data and models.

The broader use of the IPCC predictions has brought the arguments on climate change into an arena of reasoned scientific debate. We have used the upper and lower ranges of the IPCC predictions, so as to adequately represent uncertainties and not underestimate the potential seriousness of the problem. Similarly, crisis statements have softened about the imminent death of coral reefs due to bleaching caused by global climate change. There is a need now for rational debate and the assembly of sound scientific data (Box 6.2).

Before effective action can be undertaken by countries to counter, or prepare for the potential impacts of climate change on coral reef resources, it will be necessary to:

- perform an inventory of the resources;
- evaluate resource vulnerability using the criteria described in Chapter 5; and
- partition the degree of risk to those reef resources between climate change and other impacts, particularly those of direct human origin (such as over-exploitation, pollution, or the effects of land use).

With this information, policy makers and politicians will be in a position to assess the cost/benefit relationship of implementing action to lessen the impact, and the societal effects or requirements of those actions.

Box 6.2: Coral Bleaching and Temperature: Caribbean Pilot Program

While global climate is changing at an accelerating pace due to man's release of greenhouse gases (Rogers and Whitman, 1991), it is not clear whether there are demonstrable regional and global temperature increases and whether these will impact on marine biota (Goreau et al 1991).

Coral reefs grow best between 25-29°C, only a few degrees below their upper lethal temperature limit (although the absolute range of growth maybe between 18 and 33°C for corals adapted to a wider range of temperatures). Bleaching events in the Caribbean have captured the attention of scientists, the public, and the US Congress with concerns that they are an indicator of global climate change (Williams and Bunkley-Williams 1990). Coral bleaching (the loss of algal cells or their pigments) often correlates with abnormally high seawater temperatures or prolonged summer peak seawater temperatures, frequently during El Niño years (Brown and Ogden 1993). Bleaching generally does not kill the coral, but it does interfere with reproduction and growth (Szmant and Gassman 1990).

Good correlations are, however, lacking on the cause and effect relationship between temperature and bleaching (Ogden and Wicklund 1988). A pilot program to obtain precise records of temperature and correlate these with biological studies has been initiated by the Caribbean Coastal Marine Productivity (CARICOMP) Program. This program will examine the relationship between satellite-derived sea surface temperatures and those measured in the water column over coral reefs at 17 sites in the greater Caribbean, from Bermuda to the South American coast.

There are three specific scientific objectives:

1. To relate satellite temperature data on a regional scale to temperature measurements on a local, coastal scale;
2. To examine how (whether) large scale temperature trends influence local-scale temperatures;
3. To define any relationship between surface temperatures and those of the water column in direct contact with coral reefs.

The pilot program will use a multi-year (1946-1987) Comprehensive Ocean- Atmosphere Data Set (COADS), which provide monthly estimates of Sea Surface Temperature on a global 2 x 2 degree grid, and combine these with weekly instrument data from NOAA polar orbiting satellites at a resolution of about 18km (Muller-Karger et al. 1991; Olson et al. 1998). Fine resolution data from temperature buoys and satellites suggest that there is a small upward trend in global surface ocean temperature (0.1 - 0.2°C from 1982 to 1989; Strong 1991).

The program will investigate four problems associated with correlating localized bleaching and historical sea surface temperature records:

historical ship and satellite data have coarse space (degrees) and time scales (weeks to months);

there are very few long-term, temperature records within coral reef environments;

measurements in the tropics have decreased accuracy because the atmosphere is humid and cloud cover is generally higher; and

there is a disparity between satellite data, which are from the skin of the ocean (the upper few micrometres or millimetres that interacts with the atmosphere), and data from temperature buoys, which drift in deep water and measure the bulk of the ocean.

Such assessments may be beyond the financial and/or technical resources of some countries, e.g. small island states. We consider it extremely important that the international community develop systems whereby countries have access to consistent, practical evaluation guidelines and the technical capabilities to carry them out. The IPCC (1992) has developed a 'Common Methodology' to assess the vulnerability of countries to sea level rise. While this approach is not directly applicable to all countries (see discussions in McLean and Mimura 1993), it is a major unifying protocol for developing countries and international agencies. Further assistance is necessary for many countries through the provision of training, and on-site assessment. The International Agencies (such as WMO, UNEP, IOC and the World Bank) and developed countries will be required to provide bi-lateral and multi-lateral support to perform risk assessments on a wider range of countries. Even in countries like the Maldives, which understand the potential problems and have been the subject of many studies, there is still a strong requirement to develop local expertise in coastal zone management and engineering (Harneed 1993).

One potentially important contribution from developed countries would be provision of aerial or satellite remote sensing and mapping of reef areas and conditions. Reef areas have been estimated as approximately 617,000 km² (Smith 1978), but no detailed or quantitative inventory is available, in general or on a country-by-country basis. Remote sensing technology is beyond the resources of most countries. This type of data and mapping, provided as technical aid by developed countries, would constitute an invaluable baseline for current assessment and management and long-term monitoring.

6.3 Placing Climate Change Risks within a Policy Framework

Our current predictions are that global climate change **acting alone** will have only low-level effects on most reef ecosystems, with major adverse impacts likely to occur only in limited areas or under unusual circumstances. Reefs will generally be able to keep up with rising sea levels, but low islands and coastlines will not. The greatest pressures from climate change will therefore be on the reef-associated lands where people live, and many of the effects on reefs will be due to climatic effects on adjacent terrestrial environments and populations.

For most potentially affected reefs, anthropogenic disturbance (pollution, sediment damage and over-exploitation) is likely to cause more substantial damage to the reefs long before the potential effects of climate change are manifest. Therefore, the priority action required of policy makers and managers is to reduce human stresses on reefs. If the methods are successful in reducing the impacts within the range of natural sustainability, the normal ability of the reefs to withstand climatic variation will be enhanced, and mechanisms for further protecting reefs against climate change can then become the priority.

At present there is little that can practically be done to provide local protection for reefs from the damage resulting solely from climate change. Reefs that experience climatic stress will either recover through a shift to dominance of more resistant species, or a change in the resistance of species (Buddemeier and Fautin 1993) or recruitment of more resistant species

from outside. It is unlikely that any current known methods could protect reefs that do not have the inherent capacity to recover. This capacity to recover, however, can be augmented and sustained by actions to remove or limit non-climate stresses based on careful local assessment (see Chapter 5).

Once assessment has identified which reefs and reef-associated people will be adversely affected by climate change, the difficult decision is to determine what to do and the amount of resources to be allocated to various strategies. In this decision-making process, two conceptual approaches are critically important: one is to maintain a broad environmental viewpoint by providing Integrated Coastal Zone Management; the other is to adopt approaches variously described as 'no-regrets, 'win-win,' or 'multiple benefit' policies. The latter approach promises real, cost-effective benefits whether or not our present climate change scenarios are correct, and even greater benefits (or protection) if they are. Examples of such approaches are investment in sewage treatment systems that improve public health and coastal water quality, or development of sustainable agriculture practices that conserve soil, water, and enhance subsistence or export productivity and protect near-shore reefs in the process.

Virtually any policy or action that affects the ocean or the coastal zone is, *defacto*, a policy that will influence the responses of reef ecosystems to climate change. At the largest scale, where national population and development policies or international treaties are considered, coral reefs or even climate change issues maybe minor considerations. We urge however, that these subjects be addressed specifically at all levels, for it is the comprehensive plans and policies that have the greatest potential to solve the problems or to make them worse if assessment and analyses are inadequate.

A limited number of types or levels of action can be applied to the problems of reefs and climate change. Most of the possibilities discussed below fall into one of the following categories:

1. Local protection and regulation - actions to prevent over-exploitation or damage in specific reef areas. This includes enactment of regulatory fishing practices, the establishment of reserves or marine protected areas (MPAs), in which multi-use activities, zoning, education and local enforcement of anti-pollution laws are important. Such measures are vital components of conservation and protection strategies, and are often the only immediately practical action that is available. However, we believe that in the long term and in most areas, these measures alone will not be adequate to cope with the combined threats of population growth, development, and climate change.
2. Engineered protection or environmental modification - the physical construction of stabilizing structures to protect facilities on land and shorelines (rather than constructions to protect marine ecosystems). Such measures are usually very expensive, but rarely completely effective, and experience suggests that interference with natural coastal dynamics probably damages (or at least alters) marine ecosystems more often than it protects them. We generally discount the potential effectiveness of local engineering schemes that are more complex than the example of installing mooring buoys to prevent anchor damage. There are, however, two caveats to this position: one is that construction for other purposes must be carefully reviewed to avoid negative effects on reefs; and the

other is that engineered solutions to anthropogenic problems may be quite useful and effective, such as the examples of runoff and erosion control and sewage treatment.

3. Environmental or bio-engineering - these are special activities designed to enhance or repair reef ecosystems. When ecosystems appear to be damaged beyond their own capacity for recovery, there is a strong call for reclamation or restoration ecology (Jordan *et al.* 1987; Ravera 1989). The direct case may involve activities like providing artificial substrate to diversify habitat and increase colonization and fisheries potential - building artificial reefs. Such activities are expensive, and should be based on both excellent scientific understanding and local knowledge. Larger scale manipulations are riskier undertakings. It may be tempting to rehabilitate the damaged reefs by replacing bleaching sensitive corals with those species or strains known to have resistance to temperature stress. Our understanding of the interactions between community structure and function is too limited to attempt replacing components in these ecosystems, and the importation of organisms from another location carries a high risk of bringing along diseases or organisms that might outcompete existing species and produce an unstable ecosystem.
4. Large-scale planning and management - integrated policies, such as Integrated Coastal Zone Management (ICZM) have the greatest promise for preserving reefs at national and international levels. ICZM can protect specific reefs from human stresses, as well avoid or mitigate the negative effects of climate change. Progress, however, towards such a goal is slow, and when it occurs, reef environments may be a minor consideration. Such activities will require a national commitment to ensure that all policy decisions do not jeopardize future sustainable use for short-term gain. This may require the support of the international community and agencies in the form of aid and support for training and infrastructure development. We therefore stress the need to develop such approaches, while emphasizing what can be achieved in the interim.

6.4 Management Options to Conserve Oceanic Reefs

Oceanic reefs are those removed from the effects associated with large land masses - atolls are the most obvious examples, but reefs surrounding high islands that are small or have low relief and barrier reefs that are at a substantial distance from high islands or continents may also fall into this category. It is on the atoll islands that the threats to reef-associated human habitation are the greatest, so here we consider both the islands and the ecosystems themselves.

Reef Islands

The reef-derived islands of low-lying states such as Tuvalu, Kiribati, the Marshall Islands, and the Maldives are particularly susceptible because a small rise in sea level, combined with other climatic effects such as storm surges or alteration of rainfall patterns, may ultimately make habitation on these low islands difficult or impossible.

Engineering solutions have been suggested to combat local shoreline erosion and reduce the chances of temporary inundation by reinforcing existing shorelines, creating or replacing land by dredge and fill operations, or constructing reinforced sea walls to protect habitation, tourist resorts and other commercial enterprises, and the agricultural lands. The cost of such construction is currently beyond the budgets of small island states such as the Maldives, Kiribati and Tuvalu where the construction of protecting walls alone would cost 34%, 19% and 14% of their respective Gross National Products (Table 6.1 in IPCC 1990). Furthermore, such efforts have been less than completely effective (see Box 3.6), and in any case would be effective only against a relatively small sea level rise, because the rock and sand under most reef islands is permeable. This would allow the water table (either fresh or salt) to rise to mean sea level, regardless of whether or not the shoreline is shielded from the ocean by retaining walls.

When the costs of employing engineering solutions to protect reef islands are compared to the feasibility and the monetary (although not necessarily the social or biological) values and available resources, it is clear that engineering protection of reef islands against the climate change that is predicted by IPCC cannot be seriously contemplated as a permanent or large-scale, long-term solution. Limited application of such approaches might be an effective component of an overall strategy to buy additional time in which to develop approaches to protect the island populations and cultures independently of the islands themselves -an issue discussed below.

Table 6.1.

Perceived priorities of environmental problems in Southeast and East Asia, listing impacts in the immediate, short-term (within 5 years) and long-term (10 years or more) future from UNEP 1990.

Problem	Immediate	Short-term	Long-term
Destruction of coral reef and mangrove ecosystems	1	1	1
Sewage pollution	2	2	3
Industrial pollution	3	3	2
Fisheries over-exploitation	4	4	6
Siltation/sedimentation	5	5	4
Oil pollution	6	6	7
Hazardous waste	7	7	7
Agricultural pollution	8	8	5
Red tides	9	9	11
Coastal erosion	10	10	10
Natural hazards	11	12	12
Rise in sea level	12	11	9

Reef Ecosystems

Oceanic reefs are intrinsically less vulnerable to climate change, because of the absence of effects transmitted from and amplified by neighboring terrestrial environments (see Chapter 5, and Smith and Buddemeier 1992). In addition, most reefs are distant from significant human populations, and this removes or reduces the most serious immediate threats.

Buddemeier (1993) has emphasized that remote oceanic reefs represent the best available resource, both for preserving coral reef biodiversity into the future, and for understanding the interactions of reef ecosystems with climatic change. He proposed that a selection of remote oceanic reefs be designated as global national or international reserves by processes similar to the Antarctic Treaty, that designated an area warranting world protection and reserved for research rather than exploitation. A similar suggestion has been proposed to protect the Spratly Islands in the South China Sea and to assist in settling international disputes over these reefs (McManus 1992).

This generally positive viewpoint on the future of oceanic reefs must be modified by several other considerations. Most important is the fact that human populations in oceanic (e.g. low island) settings lack the terrestrial resources and options found on high islands and continents; they are therefore more dependent on reef resources than other populations. Preservation and protection of the oceanic reef ecosystem, although easier in some respects, is more critical. It is also important to consider isolation from other reef systems and the local range of habitats and biodiversity, when assessing vulnerability or designing protective measures.

As discussed in previous chapters, the primary threats to oceanic reefs are over-exploitation for food and materials, both for subsistence and for export, and environmental pollution and damage in areas of high population density. The possible negative effects of poorly planned or controlled tourism must also be considered, especially in planning for future development. These have the advantage of being primarily local problems that are susceptible to solution by regulation and education at the local and national level. National policies for reef protection will have limited overlap with other ecosystems, and most atolls and oceanic islands exist in environments where natural recovery can be expected without artificial bio-remediation. However, the small size and limited resource bases of most oceanic countries, means that there are serious financial problems to find alternative resources of food and income. Similarly, there is a need for both improved physical infrastructures and trained personnel for environmental assessment, protection, and education. These are discussed below.

6.5 Management Options to Conserve Near-shore Reefs

In contrast to the oceanic reefs, reefs that are on or close to large land masses face a different set of problems. These include not only fringing reefs, but also near-shore patch and barrier reefs in both continental and high island settings.

Near-shore reefs are vulnerable to the same anthropogenic stresses as oceanic reefs, and may be even more vulnerable because the larger bodies of land support populations that are not only larger, but frequently lack the cultural traditions and reef dependence of small-island cultures. In addition to direct exploitation, near-shore reefs may experience the effects of land use at some considerable distance from the coastline. Beyond these anthropogenic threats, there is a greater potential for damage to near-shore reefs from climate change because of climatic effects on the adjacent land masses, particularly increases in sediment load from land runoff and coastal erosion, and increases in nutrient loading into coastal waterways. Therefore, methods of protecting near-shore reefs from the terrestrial component of climate change are similar to those for reducing anthropogenic disturbance i.e. reduce land runoff, and urban or industrial discharge, and either reduce land clearing or employ effective erosion control measures.

Because of the greater variety of interacting ecosystems and issues, management and protection of near-shore reefs may be more of a technical and political challenge than is the case with oceanic reefs. Comprehensive technical assessments and management strategies are ultimately essential for success in this more complex environment; the major advantage relative to the oceanic setting is that there are usually more alternatives and a broader resource base to use.

Although direct engineering constructions to protect coral reefs are probably inappropriate, onshore protection of the reefs against terrestrial insult maybe useful. It is important to point out that if rising sea level or increased storms provide incentives for shoreline protection of lands adjacent to reef environments, the result is likely to be hazardous to the reefs, as seawalls usually result in increased erosion on reef flats and any alteration in current patterns will affect sediment flows (Box 3.6).

6.6 Management Issues Involving Human Populations

A common theme throughout this report has been the importance of human environmental damage as a present threat to coral reef ecosystems and the future vulnerability of reefs to climate change. This damage derives from two components: the size and density of the human population; and the nature of their activities. In principle it is possible to adjust the size of the population or control their activities; in practice, we suggest that neither approach alone will be adequate in most areas. Population stabilization is an elusive goal; reduction (by any acceptable means) to levels that previously lived in equilibrium with the ecosystems seems extremely unlikely. Pressures for development are now increasing the environmental impact of each individual in the growing human population.

Many island nations are currently experiencing high levels of population growth that threaten to overwhelm their ability to feed and house their people (Rapaport 1990). This is being accentuated by the shift of populations to the larger centres and towns, thereby overstressing food, freshwater and sewage treatment facilities, as well as environmental carrying capacity (Boxes 3.1 & 3.2). If climate change reduces the habitability of the coastlines and outer islands, migration to the district centres in search of aid, a defensible habitat, or emigration opportunities will exacerbate these problems and the environmental degradation that accompanies them.

A clear and urgent management need in such cases - and one that clearly fits into the category of large-scale national and international policy issues - is population stabilization or even reduction. Population control will reduce resource demand, environmental impact, and the number of people at risk in any environmental catastrophe. It will also reduce the political and logistic problems associated with involuntary emigration. There are two socially acceptable options for population limitation - birthrate reduction and emigration. We will not discuss birth rate reduction in detail, since we consider its importance to be beyond rational question and since there are many descriptions and programs available for those not familiar with family planning and population limitation (Hardin 1993). However, the spectre of environmental refugees and of peoples physically deprived of a homeland is one for which the international community has not yet developed an understanding or a coping mechanism.

Migration from islands and coasts endangered by future sea level rise or other consequences of climate change should only be contemplated when absolutely necessary because migration will catalyze a wide range of social, economic, and environmental consequences. The obvious option for people with adequate land resources is to provide alternative living space, food sources and in come for the migrants. This, however, will require careful defining and planning. Large-scale migration presents problems when the migration is within a political entity and even graver problems when trans-national migration is necessary. Studies of transmigration and mass relocation programs have generally shown a poor understanding of possible consequences (Kiste 1985; O'Collins 1990). Even voluntary migration by individuals for work, education, or marriage may pose problems, either for the migrant or the host city or country. Recent labour migrations from the Federated States of Micronesia to Guam, Hawaii and the West Coast of the US, of Pacific Islanders to New Zealand, and other cases have resulted in overcrowding, inadequate housing, as well as job, wage and other forms of discrimination. Education of the migrant to function in a new environment and education of the recipient country about migrant needs are both essential components of successful migration, and should be addressed well before the unavoidable need is at hand.

When apolitical, cultural, or geographic landmass is subject to serious impacts but not totally uninhabitable because of climate change, an important issue for peoples who remain and have adequate land resources will be the availability of alternate sources of food and income, and the reduction or regulation of demand for reef resources. Possible measures include job training in light industrial work, mariculture, and land based agriculture. Where feasible, the encouragement of tourism activities may provide the most lucrative alternative uses of coral reefs consistent with the goal of maintaining the natural ecology. With all of these alternatives, it is essential that the solution does not cause more degradation than the original problem. For example, poorly planned tourism or mariculture ventures can be very destructive, especially through pollution of adjacent waters.

We noted earlier that climate change effects will be gradual in their onset, and may take several generations to develop fully. This suggests that it will be important to develop transition strategies for the protection and effective use of resources while they are available, and simultaneously prepare for their loss. There are several possible options to protect people with limited land resources from the effects of climate change on the reefs on which they live.

Depending on the location, examples of these might include: removing the populations to areas less likely to be affected; protecting particularly vulnerable sections of shorelines with bund walls; providing alternative water supplies for both drinking (domestic use) and agriculture; developing alternative and more suitable crops for agriculture and mariculture; and encouraging the construction of stronger housing and business or community structures to withstand the effects of cyclonic storms.

Where habitable land remains available, an effective alternative to shifting populations is to maintain and increase the efficiency of obtaining food from the sea. One important aspect of climate change assessment is identification of fish stocks that may increase as a result of changing currents (Alcala and Russ 1990). However, most methods of increasing the catch of local fish are eventually ineffective as they result in placing greater pressures on existing stocks. A better alternative is to develop sustainable activities, such as mariculture on reefs, that are unlikely to be affected by climate change, and that do not cause degradation of the ecosystem through pollution.

Mariculture projects should be sited in areas selected for minimal adverse impacts of climate change and carefully monitored. There are few indications of potentially adverse impacts on mariculture, with the possible exception of algal and giant clam culture (Box 5.3, 5.5), which could be adversely affected by bleaching effects in low latitudes, and the siting of growout farms in areas prone to increasing levels of cyclonic storms.

The processes described, of assessment, preparation, adaptation, to any necessary relocation will redemanding and expensive. Most developing countries, and in particular the small island nations that are most vulnerable, lack the financial and technical resources to undertake the needed actions by themselves. It will be necessary for the international community to offer technical aid in the first instance, and ultimately alternative land, employment, and money for relocation, if the islands become uninhabitable. Responsibility for this is likely to be shared on a regional basis by large neighboring islands and countries that have land and resources (i.e. Pacific Rim countries and those around the Indian Ocean). If substantial assistance or migration is eventually necessary, the effort needs to be truly international to cope with problems not previously experienced. Relocations are enormously disruptive, as has been seen in several examples. The populations of Banaba, Enewetak, Bikini and the Carteret Islands have all been subject to voluntary or coerced relocations, and the accompanying problems, hardships, and lack of acceptance have been well documented (Kiste 1985; O'Collins 1990).

6.7 Financial Considerations

Combined international efforts may be required to either shift island populations to higher land or use international funds to provide other sources of livelihood and housing for affected peoples. The victims of loss due to climate and environmental change will not be limited to coral reef environments, but it seems clear that small island states will be leading candidates for receipt of any global climate funds.

It may be possible to find both social and economic models on which to base plans and assessments. Nauru is an example of an island that has been rendered largely uninhabitable by the depletion of soils through phosphate mining (rather than through climate change). Previously, consideration was given to rehousing the people on other lands or replacing resources with others financed out of the phosphate bounty. The situation still exists although legal compensation has been paid, and Nauru may prove to be an example - good or bad - of how island nations whose resources are depleted by climate change might respond.

To be effective in conservation and protection against climate change, any means of transferring climate-change reimbursement funds from the developed to the developing world (for example, a CO₂ tax) would have to apply the money to activities that are both economically and environmentally worthwhile. For example, employment of people in rehabilitation of damaged areas such as upland forests and mangroves could prevent sediment flow onto reefs; such activities would be a prerequisite for direct rehabilitation of reefs by locally based efforts to remove rubbish and replant coral species. Such activities could only be sustained and justified if it could be demonstrated that the rejuvenated reef would provide viable income, either through more fishing or through attracting tourists, or other tangible benefits of real economic value.

6.8 The Process of Management

An important, but infrequently considered issue, is the organizational and philosophical basis of the management process. It is tempting for developing countries to look towards developed countries with high per capita incomes and no direct subsistence dependence on reefs for models of reef management and protection. However, available examples suggest that performance is highly variable, and that the management approaches of developed countries should be carefully assessed before being taken as a model. Some of the examples follow.

Japan: The reefs have suffered considerable degradation, such that it is predicted that they may irreversibly collapse with the imminent threat of extinction of many coral species endemic to the Japanese islands (Muzik 1985; Veron 1992; Wilkinson 1993b). Over-exploitation and development proceeds with no apparent consideration of the likely effects on the coral reefs, in spite of the fact that there is an exploding tourism industry based on visiting and scuba diving on coral reefs. The rapid development appears to be destroying the major features that are bringing local tourists to the southern islands. A classic self-destructive example was the plan to build an airport over the reef at Ishigalci Island to bring in tourists to view the coral reefs.

Singapore: Many of the reefs have been destroyed during the rapid economic progress of the State, particularly through extensive land fill. While there are moves to reverse some of this degradation and declare some reef areas as marine reserves, the general scenario is for these reefs to decline further (Chua and Chou 1992). The situation is exacerbated because Singaporean reefs are surrounded by the rapidly developing economies of Indonesia and Malaysia.

USA - Florida: The reefs off Florida have been reported to be in serious decline (Porter and Meier 1992). Among the threats contributing to this decline are drainage of the Everglades ecosystem, alterations to freshwater flows during water supply projects, and the long-term effects of sewage disposal (LaPointe *et al* 1990). The major driving force behind this increasing stress to the reefs comes from the continued migration of people to southern USA (the 'sun belt'). Pollution may also be playing a role as the waters of the Caribbean and the Gulf of Mexico region are largely enclosed and are supporting increasing population and industrialization. Marine parks in the Florida Keys are experiencing direct damage from over-use by tourists including continuation of extensive fishing in this restricted area. In response to concerns, a comprehensive reef management and zoning plan has been developed as part of the establishment of the Florida Keys National Marine Sanctuary. This regional approach has some characteristics in common with the Australian Great Barrier Reef Marine Park Authority (see below) and is designed to solve the problems of over-exploitation and fragmented management, but it is in its early stages and its effects cannot yet be evaluated.

USA - Hawaii: Although reefs are subject to continuing human induced stress, a major success story is the clean-up and recovery of the Kaneohe Bay reef system after it became degraded as a result of acute stress (freshwater runoff) combined with the long-term effects of sewage pollution (Smith *et al.* 1981). Diversion of sewage to a deep ocean outfall resulted in nearly complete recovery of the reefs over a period of 10-15 years, demonstrating that rehabilitation and protection are both technically and societally feasible. Recovery has also been observed at the Honolulu sewage disposal sites and the Kahe Point Generating Station on Oahu, following the diversion of discharge sites to deeper water (Coles 1984; Dollar 1992).

Australia: The Australian experience is encouraging, suggesting that management can be successful for reef conservation. The Great Barrier Reef (GBR) is the largest and most comprehensively managed marine park in the world. Reefs on the GBR are generally suffering little anthropogenic damage, although there is some evidence of over-fishing of top predator species by recreational line fishers, with some small-scale commercial fishing. There is no commercial net or trap fishing on reefs and spear fishing is relatively insignificant. There is also some possible nutrient pollution and sediment damage on inner-shelf fringing reefs. Periodic Freshwater runoff from floods carrying increased sediment loads poses a greater threat to the reefs than pollution, as the freshwater can cause lethal coral bleaching and death of other organisms (Van Woessik 1991). Overall, the major destructive forces operating on the GBR continue to be natural (Lough *in press*) rather than anthropogenic: weather (cyclonic storms and freshwater runoff) and plagues of the crown-of-thorns starfish (although it has been argued that the starfish plagues result from human damage, this is yet to be demonstrated; Moran 1986). The management of the GBR has broad public acceptance, and similar management practices have been introduced for reefs off the western Australian coast (Ningaloo and Northwest Shelf Reefs) where it is necessary to integrate reef management with controls of activities on the land. In drawing parallels with other countries, however, it should be noted that northern Australia has a very low population density relative to its total reef area, and that most of the reefs are far offshore and thus naturally protected from both human and natural terrigenous influences.

7. Climate Change and Coral Reefs - Conclusions

The major task of the UNEP-IOC-ASPEI-IUCN Global Task Team on the Implications of Climate Change on Coral Reefs was to assess the potential impacts of global climate change on coral reef ecosystems and the peoples associated with them.

The following conclusions summarize the findings in the Task Team Report. This team was required to examine the potential fate of coral reefs at time and space scales relevant to the peoples who live on or near reefs and to the decision makers who must formulate policy to mitigate, accommodate or control potential impacts of climate change from accelerated greenhouse warming.

The most important issue concerned the effects of global climate change on peoples and societies whose lives and well-being are now largely dependent on coral reef ecosystems. The critical time-frame is what is happening now and for the next few decades, up to one hundred years. Thus, it was essential to examine reefs as places where people live and derive their food and incomes, rather than as geological structures that have lasted for thousands to millions of years. It is acknowledged that coral reefs have come through massive changes in climate in the past and recovered over thousands of years, but what is important now is how reefs will change in the short-term and how this will affect peoples and cultures.

To have considered the effects of climate change in isolation from all the other factors that are impacting on coral reefs, would have been misleading and ultimately futile. The vast bulk of reefs are being directly exploited and indirectly affected by human use e.g. pollution, and there are very few reefs that can be considered to be unaffected by human activities.

The following conclusions and predictions of what will happen to coral reefs relate to current scientific and anecdotal evidence, with extrapolations to reefs and situations that have not been studied. These predictions are based on the 'business as usual' scenarios of climate change formulated by the IPCC (Intergovernmental Panel on Climate Change), on current human patterns of use of coral reefs, and rates of population growth. We acknowledge that there may be alterations in human behaviour and technological improvements in the future to lessen the impacts of climate change, but such potential changes are beyond our capacity to predict.

The following are the consensus predictions and conclusions:

Climate Change and Coral Reefs - General Status and Issues

- * Coral reefs are valuable economic resources for many peoples and often the major resource of both living space, food and income for peoples living on coral islands or near coral reefs; therefore careful management for sustainable use of these resources is an

urgent priority under both climate change and human-impact threats. Reefs are also valuable reserves of marine biodiversity.

- * Climate change by itself is unlikely to eliminate coral reefs, but the effects of climate change will create hardships for people dependent upon reefs, because of changes to reef structure, function, distribution and diversity.
- * Many of the world's coral reefs are currently being severely degraded or destroyed by human damage to the environment, such as sewage, inorganic, industrial and heavy metal pollution and sedimentation, and by direct over-exploitation of fish and other species and physical destruction; these impacts will increase with population growth and rapid economic development.
- * The critical time-frame to assess and mitigate the climate change threats is the next few decades when it will be necessary to implement effective management and protection of reefs, while there are still many relatively undamaged reefs and before any adverse impacts of climate change are too advanced.
- * Reef communities are not well adapted to the combination of chronic and acute human (anthropogenic) stress and climate change, and their short-term survival is threatened by these stresses acting together (synergy), even though reef communities have evolved, adapted and survived over evolutionary time scales.
- * Climate change may reinforce anthropogenic stresses on some reefs, however, the uncertainties in present climate change models and observations make it difficult to predict the precise location, extent, and nature of these potential synergistic effects.

Chronic human stresses and pressures pose the most serious threats to the existence of coral reefs in many parts of the world. Many reefs have been so damaged that they cease to function as coral reefs, and many more are threatened by increases in human destructive activities. These threats are immediate, whereas there are few reefs, if any, that have been destroyed or markedly damaged as a direct result of global climate change.

Reefs are normally resilient to natural disturbances like cyclonic storms, and recover to form viable coral communities, but they are fragile when exposed to prolonged, chronic stresses imposed by humans. Coral reefs are also able to cope with past impacts of global climate and eventually form new reefs. The present predictions of climate change are probably within the range of variations experienced by reef organisms over the course of their evolution.

Chronic levels of pollution, sedimentation and over-exploitation are stressing reefs beyond their natural ability to recover, with many showing obvious signs of destruction e.g. few fishes, low coral recruitment, obvious death of living corals, increased bio-erosion and dominance by other organisms like algae.

The greatest concern is that the combined effects of chronic human stress and climate change will be more than additive e.g. synergistic. Current models of climate change are global

averages, and there is the distinct possibility that the impacts will be very variable with wide fluctuations in some parameters. As climate changes, it is predicted that the swings between the effects, such as droughts, flooding rains, or cyclonic storms, will increase in both the degree and frequency. The location of these variations is unpredictable and if extremes in climate parameters coincide with human stress, the effects may be more serious and exceed the natural resilience of coral reefs.

Chronic human pressures are increasing dramatically and the impacts will become particularly obvious in the next 30 to 40 years when human populations are predicted to more than double in developing countries with coral reefs.

Specific Climate Change Threats to Reefs

- * Predicted rates of sea level rise will ultimately devastate the habitability of low coral islands and coastal plains that are protected by coral reefs. Rising sea levels will not threaten most coral reef ecosystems, and will be advantageous to some, permitting upward growth of coral reef flats. This, however, will not be translated into upward growth of low lying islands. The threats to human societies will necessitate urgent international assistance to those affected countries with lands that will be rendered uninhabitable.
- * Rising temperatures due to climate change will not endanger reef survival, but frequent episodes of temperature extremes will disrupt the health and functioning of reefs at local and regional levels, and increase vulnerability to other stresses. The major impact will be through bleaching of corals and other organisms, which will result in losses of coral cover.
- * Increased concentrations of CO₂ in the atmosphere will result in more dissolved CO₂ and higher acidity in surface waters, which may lower calcium carbonate deposition rates in corals and coralline algae, and will fertilize algae and enhance their ability to compete with corals, further reinforcing the effects of overfishing and nutrient pollution.
- * Increases or variations in rainfall and water runoff will cause a decline in the status of some reefs adjacent to landmasses by dramatically changing the flux of nutrients, contaminants, and sediments flowing onto coastal reefs. These will also increase the vulnerability of reefs to climate and anthropogenic changes from adjacent coastlines and in drainage basins up to thousands of kilometres away.
- * If global climate change results in increases in the intensity and frequency of cyclonic storms, there will be localized damage to some coral reefs, but there should not be marked impacts on the survival of coral reefs at a global scale. Shifts in current patterns may have more serious effects.
- * Endangered species and populations of some animals may be adversely influenced by climate change. For example, sea turtles will be affected: by sea level rise through disruption of nesting beaches; by temperature increases altering the sex ratio in hatching turtles; and by major current shifts altering migration routes.

- * Coral reef communities are currently adapted to high levels of UV radiation but increases in UV-B due to damage to the ozone layer may cause limited damage by disrupting recruitment and fisheries productivity through declines in available larvae.

On many reefs, growth presently occurs around the perimeter because corals and algae on the reef flat are limited by exposure during low tides. Sea level rise will provide opportunities for reef flats to grow upward and produce more sediment. However, most reef islands are only a few metres above present sea level, and there is no mechanism by which the central portions of these islands can rise in elevation to keep up with sea level and simultaneously remain habitable. It is probable that people will be forced off these islands by oceanic contamination of the soil and groundwater supplies and by increased erosion and frequency of inundation by storms.

Bleaching of corals and other zooxanthellate animals is presently believed to result in large part from elevated temperatures. Mild or moderate bleaching is commonly followed by recovery, but the long-term effects of rising temperature will depend on the frequency and intensity of high temperature episodes and how they interact with other stresses. Rising temperature will probably not prove lethal to reefs on a global scale, but maybe locally disruptive.

Climate change scenarios suggest both more total rainfall and an increase in average intensity of rainfall. In areas adjacent to land, increased rainfall may induce a greater flow of inorganic nutrients and sediment onto reefs, thereby causing localized damage. This input, however, is likely to be a minor component of the increased stresses from current and future human activities.

Cyclonic storms are a natural disturbance experienced by coral reefs from which they normally recover. If the storms are stronger and more frequent, however, the structure of the coral communities will change to one that is able to resist physical turbulence. Current predictions about increases in these storms with climate change are ambiguous and the storms are not considered to be cause for immediate concern over the future of coral reefs or the peoples who live on them. The latest models do not permit any reliable predictions of changes in major ocean currents.

Coral reef communities have evolved to resist most of the high levels of UV-B radiation in tropical areas. Reefs will be exposed to a small proportional increase in UV-B radiation because of depletion of the atmospheric ozone layers, and damage is more likely to occur in cool temperate and polar regions. The predicted increases in UV radiation are unlikely to have marked impacts on coral reef communities, although larvae floating near the surface could suffer higher rates of lethal damage, leading to decreases in the populations of adults. Some prominent species of commercial or structural importance maybe lost resulting in impacts on people who use the reef.

Increases in atmospheric CO₂ concentration will equilibrate with the oceans, shifting the equilibrium of the carbonate system towards a reduced calcium carbonate mineral saturation state. This may result in decreases in the rate of calcification of corals and coralline algae, and is likely to favour the growth of macro- and micro- algae and enhance their competitive interactions with coral.

Management and Protection of Coral Reefs in an Altered Climate

- * There are two major strategies for managing coral reefs in the face of global climate change: remove the causes of climate change, by alerting the international community to the impacts of greenhouse gas emissions; and assess the vulnerability and potential impacts on coral reefs and islands and then prepare local and regional mitigation responses.
- * Prompt and aggressive management to reduce or eliminate human stresses is the most effective way of preserving coral reefs and retaining their value to human societies, because unstressed reefs will be more able to cope with climate change.
- * Our understanding of coral reefs, climate and environmental stress is adequate to assess vulnerability and develop management strategies to conserve coral reef resources, however such action should be undertaken as an integrated coastal zone management strategy, to include surrounding marine and terrestrial environments.
- * Engineering efforts to circumvent the effects of sea level rise by building walls around coral islands and reinforcing shorelines are unlikely to succeed, because seawater will permeate under porous coral reef islands and flow over them during cyclonic storms; moreover such measures will cause unpredicted ecological impacts.
- * Sea level rise is a direct threat to peoples who live on coral islands because the upward growth of coral reef flats will not be sufficiently rapid and land-fill procedures will not be economically feasible in the long-term; therefore contingency plans for the relocation of communities and cultures should be developed before low lying islands ultimately become uninhabitable.
- * Environmental or bio-remediation strategies to repair reef damage are hazardous and expensive procedures as rehabilitation by bringing in outside species may introduce diseases or competitors.
- * It will be necessary: to develop training, education and development programs for people who use or affect coral reef environments; to reduce the need for societies and individuals to over-exploit reef resources for food, building materials, or export products; to develop innovative technologies to expand resources or find alternatives like mariculture; and to build the capacity to understand and manage reefs for long-term sustainability.
- * Some remote oceanic reefs that are representative of global coral reefs should be declared as international marine protected areas, similar to the Antarctic to protect their high biodiversity.

It is particularly important to inform decision makers in developed and newly developing countries of the consequences of global climate change for people and their cultures. These countries should be urged to reduce greenhouse gas emissions from domestic and industrial applications and accept some financial responsibility for remedial actions to low lying island

communities. Assistance will also be required to assess the potential risks of climate change on peoples and resources and plan remedial actions for those peoples and resources at greatest risk.

Reefs that are not affected by anthropogenic stresses are more likely to be able to resist the effects of global climate change or they will have greater abilities to adapt and change into ecosystems that will thrive under the new climatic conditions. Reefs that are chronically stressed, however, may decline at a more rapid rate in a changing climate. Therefore, the most important action is to manage the activities of human populations to reduce the pressures of domestic and agricultural pollution, excessive sedimentation and over-exploitation of fisheries resources.

Reefs are clearly affected by activities in adjacent habitats, such that pollution from human activities on the land, including clearing of remote forests, will adversely impact on reef sustainability. It is, therefore, essential to manage coral reefs within a wider framework of Integrated Coastal Zone Management (ICZM) and involve all users within a wider area to develop effective management plans for sustainable development. Human pressures on coral reefs are increasing and will only abate when populations stabilize and other economic alternatives are provided to reduce the dependence on limited reef resources. The most important measure to protect coral reefs will be the provision of education into alternative technology, such as mariculture, and access to family planning methods.

Scientific and management knowledge is adequate to develop strategies to manage the human use of coral reefs and ensure that the ecosystems are able to cope with alterations in the environment through climate change. Scientific research on coral reefs is essential to assess whether management strategies are effective and to establish cause and effect relationships for the different stresses on reefs.

Engineering procedures to reinforce eroding shorelines and keep out rising sea waters are unlikely to succeed and may exacerbate the problem. Rising seawater will infiltrate through the porous coral reef sediments, and storms may result in shoreline erosion under and around sea wall. Engineered solutions will be effective only for a limited period of time, and may divert resources and attention from longer-range solutions.

Many coral reef islands may be rendered uninhabitable by modest rises in sea level, necessitating emigration or evacuation of their populations. Previous cases of translocation of peoples and cultures have not always been successful and there is an urgent need to plan for the evacuation of those islands at greatest risk. International support maybe necessary for these enforced migrations, particularly from countries with land masses that could be used for resettlement.

Some remediation to improve fisheries is warranted, like installing fixed moorings or building artificial reefs to enhance fisheries. However rehabilitation to repair the damage caused by human or climate change stresses is a hazardous procedure because there are no good scientific examples of success and many of failure, e.g. with the introduction of species from outside. The combination of human pressures and pending climate change are threatening the decline and possible collapse of many coral reefs close to centres of human activity. Therefore, a

representative selection of coral reefs in the world's oceans should be protected and managed as international marine protected areas to act as reservoirs of biodiversity, and sources of larvae for other stressed reefs. These reefs should be remote from human pressures such that they can also serve sites to assess the effects of climate change on reef ecosystems. The model adopted for the Antarctic is recommended and the Spratly Reefs in the South China Sea could be the first example.

Final Statement

Coral reefs have come through episodes of severe climate change in the past and have the necessary resilience to cope with the current scenarios of climate change. The peoples who live on coral reef islands, however, are likely to be severely affected by climate change, especially sea level rise. This is likely to render many islands uninhabitable and necessitate relocation of any remaining populations. Advance planning, education, and extreme care will be required if such relocations are to be successful and not result in the loss of the cultures and environmental wisdom that have developed on these islands over many years.

Coral reefs near landmasses are under even greater pressures from human uses and the intended or unintended disposal of wastes. Reefs near large centres of human population are likely to be damaged beyond recovery, unless the activities of the human populations are managed to ensure that the productivity of coral reef resources is sustained into the future.

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