# Pacific IN PERIL

## BIOLOGICAL, ECONOMIC AND SOCIAL IMPACTS OF CLIMATE CHANGE ON PACIFIC CORAL REEFS

by
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# EXECUTIVE SUMMARY

Climate change may be the single most important challenge to human societies in the 21st century. Changes to the environmental factors that govern the earth's biological systems have flow-on effects for almost every aspect of human societies. Coral reef ecosystems are especially susceptible to climate change and recent predictions have suggested that coral reefs will be seriously degraded by the changing conditions of the world's tropical oceans.

This report follows a paper published last year by one of its authors, Professor Hoegh-Guldberg. In the first two sections, it extends and updates the previous findings on coral reefs with a closer focus on Pacific reefs. It then draws upon the physical and social sciences for an answer to the following basic question:

**What do the impact of climate change on coral reefs and associated climate-change effects mean for the medium- and long-term future of the people of the Pacific?**

The answer and a consequent policy response are needed urgently. The timeline is short and everyday policy-making concerning the current election horizon or next year tends to dominate the attention of politicians. National leaders and international organisations must be persuaded to have in place development planning responses to extend the horizon and allow the necessary fundamental policy changes to occur. **The socioeconomic impacts identified in the paper are so profound that they dwarf any strategic issue currently confronting a major peacetime economy.** There is a need for urgent action on an international scale. The fate of these nations and the surrounding ocean is of worldwide concern.

Coral reef ecosystems are particularly vulnerable to changes in sea temperature, sea level and oceanic alkalinity. Increasing episodes of coral bleaching have been followed by larger scale mortality events, often totally removing reef-building corals from some locations. The last major bleaching event (1998, the largest in history) saw the removal of large areas of reef-building corals. A major decline in the condition of the corals that build coral reefs is now a distinct possibility within three to five decades. This will have major effects on marine ecosystems along the coastlines of many tropical countries. Reef-building corals are central to the health of these ecosystems. They provide much of the primary productivity and framework within which many important marine species live and the reefs they build form crucial barriers to the open ocean.

Pacific societies have been identified as being particularly vulnerable to climate change in previous studies. The impact of climate change on Pacific economies is complex and requires a truly multidisciplinary focus. The present study isolates one component of the effect of climate change, the loss of coral reefs, and assembles economic and associated data to help assess the ramifications for each of 13 Pacific nations. While the task was ambitious (and further data collection will probably refine the conclusions), the trends and conclusions within the analysis are clear. The 13 nations fall into two groups, of which four Melanesian nations are relatively resilient to change and the remaining mainly Polynesian nations generally less resistant and more vulnerable. By 2020, all 13 nations, wherever situated, are likely to face increasingly bleak conditions.

Most scientists agree that the current rate of warming of the world's oceans is a consequence of increasing concentrations of greenhouse gases in the atmosphere. The results of this study reveal that the Pacific ocean is no exception; it warmed at a mean rate of 0.79ºC over the past century.

A complex geographic pattern was associated with the distribution of warming rates. Notably, Tuvalu, Kiribati, Samoa, Vanuatu and New Caledonia had warming rates higher than 1ºC per century while Tonga, the Cook Islands (southern section) and Solomon Islands experienced minimal warming when considered over the last century. Mass coral bleaching events have increased in the Pacific and have been triggered (as they have in all other coral reef domains) by 1-2ºC thermal anomalies above the average summertime maximal sea temperatures. Recent mass bleaching events in the Pacific (eg, Cook Islands in 1994, Palau in 1998, Fiji in 2000) have seen large coral mortality events among previously rich coral reef communities. Some sites have lost all of their living coral cover, which has not returned after almost 10 years.

The available models for projecting climate change are described in detail in the report, including hindcasting to show that these models successfully describe events over the 20th century. The analysis reveals that the level of thermal stress has increased significantly. The thermal stress necessary to produce large-scale bleaching events is only apparent from the late 1960s onwards.

Projections of bleaching frequencies and intensities were prepared for the 13 Pacific nations. The projected changes [HHG2] to the frequency and intensity of mass coral bleaching events are a major cause for concern. Thermal anomalies required to produce severe mass bleaching and mortality events occur in the first few decades of the 21st century. These rapidly rise to much higher values by the middle to late part of the century. There is no evidence that reefs will be able to survive these levels of thermal stress. Indeed, all evidence is to the contrary, for example, mass mortality events in Palau and Okinawa in 1998.

To estimate significant dates for the health of coral reefs faced with unrestrained warming, a series of criteria was established. The dates at which three severe mortality events occur are critical since reefs that undergo mortality events where corals are largely removed from the reef communities are extremely unlikely to become repopulated within the three-to-four-year gap between consecutive events. These dates and the summary effect of the events occur between 2010 and 2060 (mean decade 2040) if a model (assuming no aerosol component) is applied for the 13 Pacific nations studied. The dates are slightly extended (by a decade) if an aerosol component is added. Great coherence between different general circulation models (GCMs) is also seen. **The stress required to trigger a bleaching event becomes an annual occurrence in the waters surrounding the 13 Pacific nations**

**between the dates of 2010 and 2070 (mean decade 2050)**. Put in the context of other factors such as increased human pressure, rising sea levels, more frequent cyclones and decreased alkalinity, these changes to the survivorship of reef-building corals are likely to **remove corals as dominant organisms on coral reefs in the next 20 to 50 years.** How these changes to coral reefs will impact on Pacific societies is the key question analysed in the rest of the study.

To understand the relative vulnerability of Pacific nations to the projected changes associated with climate change, a range of physical, demographic, social, economic, export and tourism indicators have been explored for each of the 13 nations, to assess their vulnerability to change and capacity to adapt. Not surprisingly, this analysis shows that the most vulnerable countries are Tuvalu and Kiribati, tiny islands in a vast surrounding ocean. Generally, the Polynesian nations tend to be small and vulnerable, with relatively limited possibilities to adapt to changed circumstances. The four Melanesian nations are larger and more adaptable to climate change than the large number of small, low-lying nations, which typically have monochromatic economies and a narrow range for adaptation. **Beyond 2020, however, every nation still functioning faces economic decline according to the scenarios developed for the report.**

Given the potential impact of climate change on Pacific societies based on even mild climate-change scenarios, planning for these futures is a top [D K4] priority. Planning must begin now to deal with the growing vulnerability of coastal dwellings and with other impacts on societies in which the majority of the populations depend on subsistence living, based on access to healthy reef systems and associated produce. International action is clearly required to secure the funding and technical assistance required to protect and, ultimately, rehabilitate the Pacific community of nations, once described as "pearls of priceless beauty and an earthly paradise".

# ABOUT THE AUTHORS

This report required a multidisciplinary team to link its diverse elements. In addition to the authors below, the report was reviewed by and received crucial input from B Hare (Greenpeace International), A Strong (National Oceanographic and Atmospheric Administration, Washington DC) and J Draunimasi (Ministry of Labour and Industrial Relations, Labour Administration and Productivity Improvement, Fijian Government). R Johnstone (CMS) also reviewed this report and contributed heavily to the discussion of coastal impacts and climate interactions.

## Ove Hoegh-Guldberg

Ove Hoegh-Guldberg is the Founding Professor of Marine Studies and Director of the University of Queensland's Centre for Marine Studies. Professor Hoegh-Guldberg specialises in the physiology and ecology of reef-building corals and began his studies at the University of California at Los Angeles (UCLA). He obtained his PhD in the laboratory of the eminent reef physiologist, Professor Leonard Muscatine. Following his studies at UCLA, Professor Hoegh-Guldberg held a postdoctoral fellowship at the University of Southern California before returning to Australia to take a post at the University of Sydney. In 1992, he took up a lectureship in marine biology at the University of Sydney. In 1999, he moved to the University of Queensland and has continued to focus on the impact of human activities on coral reefs. Professor Hoegh-Guldberg is particularly interested in coral bleaching and the potential impacts of global climate change. He was awarded a Eureka Prize for excellence in scientific research for his contributions to research in this area in 1999.

## Hans Hoegh-Guldberg

Hans Hoegh-Guldberg is a leading economist specialising in the economics of the arts, tourism and cultural sectors. He [OHG1]graduated in Economics with a first-class degree from the University of Copenhagen (1958). From 1959 until 1976, he worked as a consulting economist in three major consulting firms. During this time, he undertook major projects in tourism, Australian regional studies and economic forecasting.

Following eight years in strategic planning and new business development for a major Australian corporation, he set up his own economic consultancy, Economic Strategies Pty Ltd, in late 1984. The company has built up a leading position in arts and cultural economics in Australia – like the Pacific island economies, these areas have relatively undeveloped databases requiring a range of analytic techniques to produce valid results.

From 1992, in collaboration with his partner Isobel (an Indonesian language and cultural expert), he developed an advisory service on Indonesia for business. As part of this work, he developed scenarios, including the construction of four scenarios to 2008 following the economic collapse in that country. He maintains an active interest in Indonesia and in scenario planning. He is a Member of the Institute of Management Consultants and a Chartered Management Consultant.

## David K Stout

David Stout was New South Wales' Rhodes Scholar in 1954. He studied Economics and Philosophy at Magdalen College, Oxford, and stayed on to become an economics don at Oxford until the mid-1970s. He resigned his fellowship to head up economics at the UK's tripartite National Economic Development Council. In the 1980s, he was recruited by Unilever to head its corporate development and economics function.

Recently, he has been the Director of the Centre for Business Strategy at the London Business School. He has returned to Australia a number of times as an adviser on inflation and incomes policy. In the mid-1960s, he wrote a report, published by the UK Ministry of Overseas Development, on the New Hebrides economy and its taxation policy. Recently he has published three papers on the strategic use of scenarios.

## Herman Cesar

Herman Cesar is an environmental economist and researcher at the Institute for Environmental Studies at the Free University in Amsterdam, the Netherlands. He is also a freelance consultant for the World Bank, USAID and other organisations through his company, Cesar Environmental Economics Consulting.

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Axel Timmermann is working at the International Pacific Research Centre in Honolulu on ENSO-related topics. His background is theoretial physics (quantum field theory and relativistic hydrodynamics). In 1995 he went to the Max Planck Institute of Meteorology in Hamburg, Germany to write his PhD in meteorology. From 1998 to September 2000 he held a postdoctorate position at the Royal Dutch Meteorological Institute (KNMI) in De Blit, Netherlands. His research covers subjects such as interdecadal climate variability in the North Altantic ENSO response to greenhouse warming, nonlinear inverse modelling and ENSO and stochastic stability analysis of the ocean circulation. Axel Timmermann has contributed to several sections of the Intergovernmental Panel on Climate Change Third Assessment Report on climate change. He is involved also in bridging between the climate and climate-impact community.

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# INTRODUCTION

Tropical coastlines of the Pacific region are dominated by coral reefs and their associated ecosystems. While reef-building corals provide the basic framework, coral reefs are home to thousands of organisms that range in size from single-cell protists to whales. In addition to providing habitats for these species, coral reefs play a central role in providing a major portion of the primary productivity of these regions (Hatcher, 1988). In this manner, coral reefs are often equated to “oases” within marine nutrient deserts (Hoegh-Guldberg, 1999). As a result of their central role as the basis of major tropical coastal ecosystems, coral reefs play a critical role in the lives of millions of people worldwide. Almost half a billion people live within 100 kilometres of coral reefs (Bryant et al, 1998). Many of these either depend directly on coral reefs for their daily subsistence or derive part or whole of their income from coral reef resources (Cesar, 1996).

Industries such as tourism often form the “engine” of the economies of small coral reef nations, with up to 80 per cent of total income dependent on visitors from overseas (SPC, 2000a). Such an industry can also represent billions of dollars of annual income to larger nations. Approximately $US 90 billion flows into Caribbean economies from tourism and fishing on their coral reefs (Jameson et al, 1995). Similar amounts flow to US economies ($US1.6 billion, Birkeland, 1997) and Australian economies ($US1 billion, Done et al, 1996) from reefs off the coast of Florida and Queensland respectively. The economies of countries like the Maldives and the Seychelles are largely dependent on coral reefs through diving and other coastal tourism (Westmacott et al, 2000). Fisheries in tropical marine nations with coral reefs yield at least six million metric tons of fish catches worldwide (Munro, 1996) and provide employment for millions of fishers (Roberts et al, 1998).

The value of reefs goes beyond simple dollar values. Coral reef ecosystems play a significant role for coastal populations by providing for subsistence living. Approximately 25 per cent of the fish catch in developing countries is obtained from coral-reef associated fisheries (Bryant et al, 1998). This often unvalued component of these societies is arguably the most important for developing societies. Considering the size of coastal and national populations currently dependent on coral reefs, the full significance of their existence cannot be underestimated.

Coral reefs also play roles that extend to most aspects of tropical coastal ecosystems. By presenting a barrier to the power of waves as they arrive onshore, coral reefs play a significant role in protecting coastlines from storm damage, erosion and flooding. The barrier provided by coral reefs for tropical coastlines also makes possible a range of sheltered habitats, such as seagrass and mangrove stands, that are crucial in the functioning of marine ecosystems (Bryant et al, 1998). These would not prosper along tropical Pacific coastlines if it were not for the wave-protecting properties of carbonate reefs. Nurseries of many commercial fish species (up to 90 per cent) are found in these protected habitats. (Odum and Odum, 1955). In view of these features, it is not surprising that the rich food chains that characterise coral reef-dominated coastlines are in stark contrast to the nutrient-limited surrounding tropical ocean.

Recent studies have attempted to a put a dollar value on the “goods” and “services” provided by coral reefs. A kilometre of coral reef coastline has been estimated to provide approximately $US 1.2 million of resources over a 25-year period (Bryant et al, 1998). Given that there is likely to be over a million kilometres of coral reef worldwide, the net worth of the ecosystems is astronomical. The total goods and services provided by reef habitats have been estimated as worth about $US 375 billion per year (quoted in Bryant et al, 1998).

While coral reefs are among the most important and diverse marine ecosystems, they are also among the ecosystems most sensitive to human influence. Recent assessments of the health of coral reefs worldwide have estimated that at least 50 per cent of coral reefs will be under threat of moderate to severe damage by the middle of this century (Wilkinson and Buddemeier, 1994; Bryant et al, 1998). Overexploitation and damage from reef-related fisheries and the mining of coral rock (mining limestone), rapid and unsustainable coastal development, eutrophication and sediment impacts from river run-off are among the major concerns (Wilkinson and Buddemeier, 1994; Cesar, 1996; Sebens, 1994). Major declines in the health of coral reefs are now being reported in all parts of the world (Bryant et al, 1998).

Concern for these crucial ecosystems has led to major international initiatives (eg, International Coral Reef Initiative (ICRI), Western Indian Ocean Marine Science Association (WIOMSA), East Africa, Coral Reef

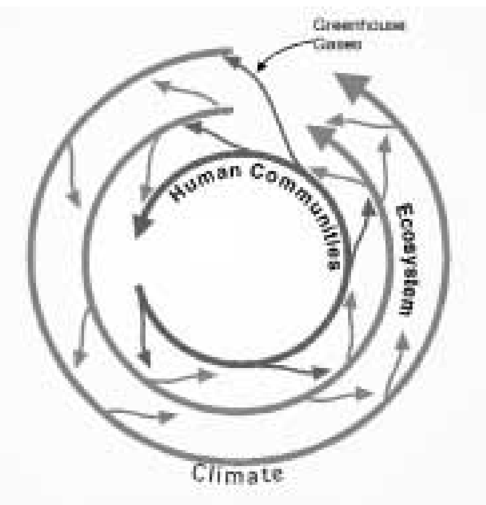



**Figure 1.** As indicated in the above diagram, human communities, the associated ecosystems, and global climatic systems are inextricably linked and interact at different scales over time and space. The development of human populations and their socioeconomic production processes lead to climate change through the direct and indirect influences of, for example, the production of anthropogenic substances and the alteration of habitats. These alterations in turn influence the function of the ecosystem and may, therefore, lead to alterations in the biogeochemical cycles such that they directly affect climate regimes. In simplistic terms, the realisation of these interactions can be responses such as increased frequency of extreme weather events, increased sea surface temperatures and the consequent bleaching of corals. More acutely, the results can be realised via direct anthropogenic threats to coral reefs and mangroves, such as toxic effects on organisms (modified after R Johnstone, Centre for Marine Studies, University of Queensland.)

Degradation in the Indian Ocean (CORDIO), Coral Reef Alliance (CRA), to name a few). World leaders have started to turn words into action with respect to the world's coral reefs (Hoegh-Guldberg, 1999). For the most economically powerful countries, the issue is of enormous importance. US President William J Clinton's Executive Order 13089 on June 11, 1998, emphasised the seriousness of the issue: "All Federal agencies whose actions may affect US coral reef ecosystems... should seek or secure implementation of measures necessary to reduce and mitigate coral reef ecosystem degradation and to restore damaged coral reefs."

Recent evidence suggests that climate change will surpass even the most insidious coastal impacts in determining the fate of coral reef ecosystems. In 1998, anomalously high water temperatures were reported on every coral reef worldwide. These thermal events ranged as high as 2oC above the summer maximal sea temperatures and led to a widespread bleaching of coral reefs (Hoegh-Guldberg, 1999; Wilkinson et al, 1999; Spencer et al, 2000). The resulting mortality was unprecedented and led to the loss of coral cover from many reefs (for some examples see Hoegh-Guldberg, 1999; L. Smith and A. Heyward, Australian Institute of Marine Sciences, pers com; Spencer et al, 2000). Analysis of temperature data over the past century reveals that the world's tropical oceans are now approximately 1oC warmer than they were at the beginning of the 1900s (Hoegh-Guldberg, 1999). Recent estimates of the rate of rise put this at an even higher rate (0.5oC per decade in the northern hemisphere tropical oceans, Strong et al, 2000a).

Projections from three of the world's major general circulation models (GCMs) reveal that current estimates of change in the sea surface temperature of the world's oceans will bring coral reefs beyond their thermal limits within the next few decades, with the elimination of living coral cover from most regions highly likely by the middle of the current century (Hoegh-Guldberg, 1999). The implication of this for subsistence living, human welfare, tourism and fishing associated with coral reefs (to name but a few) is enormous but has yet to be quantified. It is the need for an understanding and conceptual framework for these issues that creates urgency at the heart of this developing situation.

The spectre of losing coral reefs from tropical coastlines within the next 30 to 50 years has begun to focus public interest and attract enormous social, political and scientific comment. For some societies, the issue may be a regrettable loss of a favourite dive location or holiday destination. For many others, however, the loss of coral reefs strikes at the heart of the survival of entire societies and cultures. Already, small island nations in the Pacific and Indian oceans have been identified as the most vulnerable to the sea level change associated with global warming (Nicholls et al, 1999; Solomon and Forbes, 1999). These nations are low-lying with the large majority of their coastal agriculture and dwellings located within a few metres of the water level and behind the shelter of living coral reefs.

Modeling of even mild greenhouse emission scenarios projects that some Pacific nations will be partly or completely inundated by the end of 2100 (IS92a-e, see Figure 1 of Gaffin, 1997). A 38-centimetre rise from 1990 to 2080 plus storm surges will increase the current number of flood victims five-fold (to around 200 million people affected per year). When combined with other human-related impacts, it will cause the loss of up to 70 per cent of the world's coastal wetlands (assuming ca 642 and 731 ppmv carbon dioxide equivalents in two models, HadleyCM2 and HadleyCM3 respectively, Nicholls et al, 1999). These two impacts alone are being presented as important reasons for proactive policies to prepare for these possible scenarios.

The specific loss of coral reefs has not been quantified but could represent significant losses in revenue (Cesar, 1996; Constanza, 1999; Hoegh-Guldberg, 1999; Wilkinson et al, 1999). Adding to these direct losses are the social and economic aspects to the issue, many representing huge benefits to society if their worth is considered in a sustainable context. These issues, while difficult to reliably estimate or forecast, are crucial to future policy development. Policy development on the issue of climate change and its impacts on society requires input at levels that range from atmospheric and biological to economic and social. Without a clear understanding of the links between these aspects, a sound appreciation of the implications of the change being imposed on national economies is impossible. It is these aspects that require careful quantification, especially if the ambition is to proceed down the most cost-effective pathway.

The climate system, the ecosystems and the socioeconomic system are intricately linked (Figure 1). It is our socioeconomic production processes that lead to anthropogenic climate change and these climatic alterations are impacting on both the socioeconomic system (eg, increased frequency of extreme weather events) and ecosystems (sea surface temperatures leading to coral bleaching). Also, the socioeconomic system both affects ecosystems (eg, anthropogenic threats to coral reefs and mangroves) and is affected by ecosystem changes, such as coral bleaching.

This study concerns the potential impact of climate-driven changes to coastal ecosystems in the south Pacific. While the complete climate scenario (coastal inundation, changes to cyclone frequencies, loss of agricultural land, etc; IPCC, 1992) is a huge and complex issue, we have chosen to focus on the specific quantification of the loss of coral reefs to Pacific economies under the scenarios presented by Hoegh-Guldberg (1999). This is then viewed within a mid-range scenario for other changes that are likely to occur during this century under a similarly mid-range (IS92a) greenhouse influence.

In many ways, this is a conservative approach – taking one element and assessing its cost for Pacific nations over a 20- and 50-year time horizon. After carefully constructing environmental and biological impact estimates, the authors then develop scenarios that project the potential social, economic and political costs of the degradation of coral-dominated reefs off the coastlines of south Pacific nations and states. In the final section, these estimates are placed within the context of the broader range of global changes expected in the 21st century.

# CORAL REEFS IN A CHANGING WORLD

To understand the potential impact of climate change on Pacific coral reefs, it is important to understand the key components of coral reef ecosystems. This section of the study reviews how coral reef ecosystems function and then considers how environmental factors such as temperature, light and seawater alkalinity may affect the physiology and ecology of coral reef ecosystems. Only by understanding the functioning of these biological systems is it then possible to understand how climate change (through changes to sea temperature, oceanic alkalinity and sea level) is likely to affect these important systems.

In the next section, based on this type of information, climate model projections from the ECHAM4/OPHYS3 coupled general circulation model (GCM) are used to project how changes in sea surface temperature (SST) are likely to impact on reefs across the south Pacific. These projections are used together with estimates of sea level rise and alkalinity changes to set a series of crucial dates as potential points of loss of coral reef systems. The implications of these losses are then used to develop a broader understanding of the social, economic and policy implications of these changes.

## THE BIOLOGY OF CORAL REEF ECOSYSTEMS

Coral reefs often appear to be a brilliant chaotic assemblage of colour and shape. Over the past 400 million years, coral reefs have dominated the inshore waters of tropical areas of the world (Veron, 2000). Massive deposits of limestone in many parts of the world are evidence of the existence of coral reefs as early as the Ordivician (almost 500 million years ago). While these reef structures were made of different organisms, they probably shared a close semblance to modern reef systems.

By the late Devonian, the distribution of coral reefs was massive and exceeded the present-day distributions by several-fold. Meteor impacts and geological activity (volcanic eruptions) are thought to have brought reef development to an end several times during the earth's history (roughly every 60 million years). At the end of the Permian and Cretaceous periods, for example, major extinction events occurred and reefs disappeared along with up to 90 per cent of all species (Veron, 1996, 2000). After each mass extinction event, however, coral reefs have returned. While short in geological time, it is noteworthy that the re-establishment of coral reefs after these impacts took millions of years.

The diversity of life on coral reefs is quite extraordinary when compared to other reef systems. The diversity of animals and plants increases as one progresses to the equator, especially in areas such as the Indonesia archipelago, and almost every kind of organism is present – a diversity that is several times that in marine environments at other latitudes (Pianka, 1966). Coral reefs are often described as the "rainforests of the sea" as a result of this extraordinary diversity (Bryant *et al*, 1998). More than 95 per cent of all animal phyla are found in coral reefs (Thorne-Miller and Catena, 1991; Norse, 1993). The species-rich coral reef regions of the south Pacific include an estimated 800 species of reef-building corals, over 4000 fish species (five to 10 times that seen in typical temperate oceans) and many of the world's healthy populations of marine mammals (Bryant *et al*, 1998).

The high rates of primary productivity found in coral reef ecosystems were often enigmatic to early coral reef researchers. Charles Darwin puzzled over the unusual positioning of these highly productive ecosystems in waters that are very low in the nutrients necessary for primary production (Darwin, 1842), as did later workers like Odum and Odum (1955). The productivity of open ocean areas in the tropics is often as low as 0.01 $gCm^{-2}$ $d^{-1}$ (Hatcher, 1988). In contrast, coral reefs appear to beat the odds and produce rates of productivity that exceed those expected for the extremely nutrient impoverished areas of the world that they inhabit. Within coral reef ecosystems, the values for primary productivity may be many thousands of times higher (eg, algal turfs: 280 $gCm^{-2}$ $d^{-1}$; corals: 40 $gCm^{-2}$ $d^{-1}$; benthic microalgae: 363 $gCm^{-2}$ $d^{-1}$; reviewed by Hatcher, 1988).

In the waters behind actively growing coral reefs, there are often spectacular lagoons and estuarine areas that are sheltered by coral reefs. In addition to sheltering these ecosystems, coral reefs are an important source of the calcareous sediments in which grow the important ecosystems founded on mangroves and sea grasses. These ecosystems are also highly productive and are important as nursery grounds for many species, many of which are fished commercially as adults. In the Pacific, commercial fisheries can represent important export earnings. While most fisheries earnings are derived from pelagic such as tuna, the subsistence fishing in these back reef areas can also be highly significant. In addition, some back reef areas have great potential as habitats for sustainable aquaculture. Recent successes include programs to raise marine snails (*Trochus niloticus*) and giant clams (*Tridacna spp. and Hippopus hippopus*) in the Cook Islands, French Polynesia and several other Pacific islands.

## THE IMPORTANCE OF PLANT/ANIMAL SYMBIOSES IN CORAL REEFS

The puzzle as to why coral reefs are able to flourish in the nutrient-poor waters of the tropics can be traced to the recurrent theme of symbiosis (especially between plants and animals) and nutrient recycling. In circumstances where plants and other photosynthetic organisms are not ensconced in close partnerships or symbioses, primary productivity is dependent directly on the concentration of nutrients in the water column (Odum and Odum, 1955). As outlined above, the water column above coral reefs is very often devoid of the essential inorganic nutrients required for the production of organic compounds by plants and other primary producers. The clarity of the waters this includes is one of the features that serves to attract tourists to these regions: the blue waters and clear coastal waters of coral reefs are a direct consequence of the low-nutrient status of the water columns in these regions.

Animals and decomposers such as bacteria are ultimately the source of the inorganic nutrients plants need to regenerate energy and organic carbon from photosynthesis. These nutrients (in non-symbiotic situations) leak out into the water column and, in tropical regions where strong thermal stratification of the water column occurs and nutrients are continually lost from the water column, the concentration of inorganic nutrients falls to very low concentrations (Atkinson, 1992; Furnas and Mitchell, 1999). This process is countered to an extent by the efficient internal recycling of nutrients through benthic and detrital pathways (eg, Johnstone, 1989; Johnstone *et al*, 1990) but other processes are critical for overall ecosystem maintenance.

By coupling plants (primary producers) and animals (consumers) in symbioses, however, the problem of dilution is solved by close apposition of the two partners. One of the most prominent symbioses on coral reefs is that which exists between corals (animals of a phylum called Cnidarians) and tiny plant-like organisms known as dinoflagellates (plant-like protists that are often called zooxanthellae). While many other coral reef organisms form symbioses with dinoflagellates (eg, clams, sponges, flatworms), corals are the most abundant form of this symbiosis.

Corals and their symbiotic dinoflagellates are intertwined to the point where the dinoflagellates are located within the cells of the animal. Many millions of zooxanthellae occupy a single polyp (Figure 2). Zooxanthellae sit within the tissues of corals and photosynthesise, passing as much as 95 per cent of what they make in the sunlight to the animal host (Muscatine, 1990). Zooxanthellae have been shown to leak amino acids, sugars, carbohydrates and small peptides across the host-symbiont barrier, which is a rich source of nutrients and energy for the host coral (Muscatine, 1973; Trench, 1979; Swanson and Hoegh-Guldberg, 1998). The photosynthetic energy passed to the coral by the zooxanthellae is crucial to the characteristics of reef-building corals. Only corals that are symbiotic with

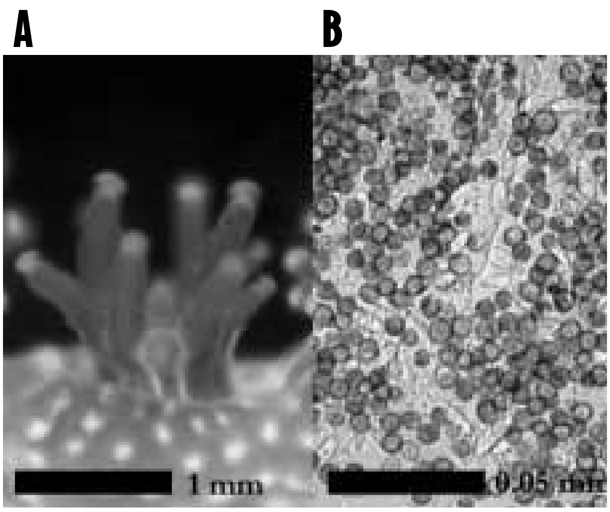



**Figure 2.** Structure of reef-building corals: a) Close-up of a polyp of the reef-building coral Seriatopora hystrix; b) Symbiotic dinoflagellates ("zooxanthellae") isolated from a reef-building coral.
Photography: O Hoegh-Guldberg

zooxanthellae are able to lay down significant amounts of calcium carbonate or limestone. Reef-building or scleractinian corals are often referred to as the frame-builders of coral reef systems and, while other organisms serve to weld the structure together (eg, calcareous red algae), corals (and their symbionts) have been the principal organisms behind coral reef ecosystems for many hundreds of millions of years (Veron, 1986, 2000).

The benefits of the primary production of corals and the associated primary producers flow down a complex food chain (Odum and Odum, 1955). Coral reefs tend to be associated with rich populations of fish, birds, turtles and marine mammals (eg, Maragos, 1994; Kepler *et al*, 1994). Traditionally, these organisms have supported small human populations. Recent increases in the human populations of tropical coastal areas have, however, put these ecosystems under threat of overexploitation which, according to some, may have started as much as 300 years ago (eg, Caribbean reefs, Jackson, 1997). A diversity of stresses is currently being applied to coral reef ecosystems.

## IMMEDIATE THREATS TO CORAL REEFS

Global assessments of the state of the world's coral reefs have been done by several organisations (eg, Wilkinson and Buddemeier, 1994; Bryant *et al*, 1998). Dramatic reversals in the health of coral reefs have been reported from every part of the world. The estimates proposed by Wilkinson and Buddemeier (1994), that 50 per cent and 70 per cent of all corals reefs are under direct threat from human activities, have recently been confirmed in a detailed assessment done by the World Resources Institute (WRI) (Bryant *et al*, 1998; http://www.wri.org/indictrs/reefrisk.htm). Bryant *et al* (1998) assessed coral reefs worldwide and estimated that 58 per cent were in grave risk of total degradation.

The most affected reefs were those in regions where human activity was highest. Caribbean, Philippine, Indonesian and East African reefs and those off the Comoros were noted as being under severe pressure. They note that (outside climate change), the reefs of the Pacific Ocean are the least threatened worldwide. Only 10 per cent of Pacific reefs are under severe threat compared to 59 per cent of South-East Asian reefs (Bryant *et al*, 1998). Bryant *et al* (1998) do note the growing pressures in the Pacific and indicate that approximately one-third of reefs are currently under moderate pressure. It should also be noted that the WRI assessment does not take into account rising sea levels and the projections that followed the devastating bleaching in 1998 (eg, Hoegh-Guldberg, 1999).

The current list of threats is long and diverse. The number of people living in close proximity to coral reefs has increased dramatically over the past century. As a result, threats have come from coastal development and land degradation (eg, Goreau, 1992; Brown, 1997a), unsustainable and destructive fishing practices (Bryant *et al*, 1998), eutrophication (increased nutrient loading) of coastal waters by fertilisation run-off (Koop *et al*, 2000), chemical and petrochemical pollution, and physical damage from mining of coral rock, tourism and reef visitation (eg, Goreau, 1992; Sebens, 1994). Mass coral bleaching is yet another major contributing factor to the decline of coral reefs (Glynn, 1993; Brown, 1997a,b; Hoegh-Guldberg *et al*, 1997; Hoegh-Guldberg, 1999). The significance of these global bleaching events has only recently been realised.

## CLIMATE CHANGE AND CORAL REEFS

Changes to the earth's temperature is one of the principal changes being forecast as a result of the increase in the greenhouse gas content of the earth's atmosphere (IPCC, 1992). Changes to the heating budget of the earth have increased the average global temperature by 0.6ºC over the past century (Jones, 1994; Vinnikov *et al*, 1990). These changes are also being seen in the ocean. Available evidence indicates that sea temperatures are also changing rapidly (Bottomley *et al*, 1990; Cane *et al*, 1997; Brown, 1997b; Winter *et al*, 1998; Hoegh-Guldberg, 1999), with estimates for the increase in sea temperatures of the tropical North Pacific being as high as 0.05ºC per year (Strong *et al*, 2000a).[N. Pacific total is 0.06ºC/year] Data from other sources, such as coral cores from the central Pacific, have confirmed the warming trend (eg, Wellington, Linsley and Hoegh-Guldberg, in preparation).

Increases in global mean surface temperature of 1-3.5ºC were estimated by IPCC Second Assessment Report using the IS92 range of scenarios. More recently the IPCC has developed a new set of scenarios which results in a project temperature increase of 1.7-4ºC by 2100. Earlier estimates of an increase in sea temperature of 1-2ºC, expected by 2100 in response to enhanced atmospheric greenhouse gas concentrations (Bijlsma *et al*, 1995), may be too low. Goreau (1990), Glynn (1991); Hoegh-Guldberg and Salvat (1995), Brown (1997b) and many others have pointed to the significance of even low rates of temperature increase in the next century for reef-building corals, concluding that global climate change is likely to increase the frequency and intensity of coral bleaching.

Similarly, climate change is likely to alter a series of other factors in the environment surrounding corals. In addition to sea temperature, the carbonate content of seawater (aragonite saturation state) and sea level have been identified as critical for coral reefs to continue to grow healthily in a changing climate (Pittock, 1999). To understand how changes to these variables are likely to affect corals and the reefs they form, the relationship of reef-building corals to environmental variables needs to be considered.

Temperature, light and water chemistry are among the key factors that affect where coral reefs flourish. Coral reefs generally occur between latitudes 25ºS and 25ºN. Their distribution mostly coincides where water temperatures range between 18ºC and 30ºC (Veron, 1986) and midday light levels do not decrease below 1500 (E $\mu^{-2}$ $s^{-1}$. Corals vary in abundance as a function of latitude (decreasing as one travels to the poles) and in relationship to such geographical features as rivers. In addition to light and temperature, the carbonate alkalinity of seawater decreases in a poleward direction, making it increasingly difficult for calcifying organisms to precipitate calcium carbonate for their skeletons (Kleypas *et al*, 1999a). Corals also exist at salinities that range from 32 parts per thousand to 40 parts per thousand, and rapid decreases in salinity cause corals to die (Hoegh-Guldberg and Smith, 1989). Sediments and water column turbidity may play similar roles in coastal areas. High sediment deposition (smothering) or reduced light quality and quantity (turbidity) have significant effects on the location of corals and coral reefs (Veron, 2000). These environmental factors combine to restrict the distribution of coral reefs to tropical and subtropical locations.

Interaction between corals and other organisms probably plays a significant role as well. Often competition with seaweeds, which appear to flourish in the higher nutrient levels of temperate waters, appears to reduce the ability of corals to grow at the highest latitudes (Miller and Hay, 1996; McCook, 2000). Interaction with predators may also be an issue. The crown-of-thorns starfish (*Acanthaster planci*), for example, can play a major role in the distribution of reef building corals (Moran, 1986). More recently, disease organisms (parasitic marine fungi and protists) are thought to play a role in determining the distribution of corals and hence the infrastructure of coral reefs (eg, Aronson *et al*, 2000; Aronson and Precht, 1999). A number of diseases have been identified since the 1970s and although, in many cases, the specific pathogens of these diseases remain undescribed, there appears to be a diversity of host pathologies that indicates a range of microorganisms are involved. The disease organisms of corals and coral reefs are thought to be either opportunistic species that capitalise on the unhealthy corals or pathogens that have been recently introduced into the marine environment.

Recent evidence suggests that diseases like white band disease are on the increase in areas such as the Caribbean and are linked to a general decline in the health of reef-building corals. Another idea is that changing land use has also led to the introduction of novel pathogens. For example, the fungus affecting gorgonians (sea fans) throughout the Caribbean Sea has been identified as Aspergillus sp., a terrestrial fungus (Smith *et al*, 1996). Aspergillus sp is thought to arrive in the marine environment from terrestrial sources as it is unable to reproduce in seawater.

The broad observation that corals growing in tropical oceans require fairly constant environments is highlighted by examples in which sudden changes in conditions lead to mass mortality of reef-building corals. Rapid decreases in salinity after cyclones or flood events, for example, can result in intertidal corals being killed (Egana and DiSalvo, 1982; Goreau, 1964). Similar observations occur where there are sudden changes in temperature or light (Yonge and Nicholls, 1931). These observations provide an important background to how corals and coral reefs will fare under the shifts being projected due to climate change. While the changes may not seem extreme at first glance (1-3.5ºC by the end of 2100 under IPCC scenarios), it is important to realise that conditions for the growth of corals have already changed. This has been proposed as the reason why extreme events like mass coral bleaching appear to have arisen for the first time during the 1980s (Hoegh-Guldberg, 1999).

## THERMAL STRESS AND CORAL BLEACHING

Coral bleaching is one of the principal responses of corals and their symbiotic dinoflagellates to sudden changes in a range of conditions (eg, salinity, temperature, light; Brown, 1997b; Hoegh-Guldberg, 1999). Normally the population densities of zooxanthellae in reef-building corals range between 0.5 and 5 x 106 cell.cm$^{-2}$ (Drew, 1972; Porter *et al*, 1984; Hoegh-Guldberg and Smith, 1989). Zooxanthellae typically show very low rates of migration or expulsion to the water column under normal conditions (Hoegh-Guldberg *et al*, 1987). Populations of zooxanthellae may be adjusted, however, as corals acclimatise to different environmental or seasonal conditions (Jones, 1995; Fagoonee *et al*, 1999; Fitt *et al*, 1999). Sudden reductions in the number of zooxanthellae will occur when conditions such as water temperature and light change around them. Normally zooxanthellae impart a brown colour to the tissues of corals. Consequently, when the zooxanthellae are expelled, corals turn from brown to white, the process termed bleaching (Figure 3).

**Figure 3.** Bleached corals photographed in French Polynesia during the 1994 Pacific bleaching event. Photography: Roger Grace/Greenpeace International

Coral bleaching may occur at local reef scales (ie, over hundreds of square metres) in response to sudden changes in salinity, temperature or light (Egana and DiSalvo, 1982; Goreau, 1964; Hoegh-Guldberg, 1999) or at geographic scales that may involve entire reef systems and geographic realms (Glynn, 1984; Goreau, 1990; Williams and Williams, 1990; Hoegh-Guldberg and Salvat, 1995; Brown, 1997b; Hoegh-Guldberg, 1999).

The latter has been referred to as mass coral bleaching. Its scale and intensity, as well as its increasing frequency, has many scientists convinced that it represents a serious challenge to the health of the world's coral reefs. This concern has been heightened by recent evidence that the specific thermal trigger required to cause coral bleaching will be exceeded on an annual basis in the next few decades.

Mass coral bleaching events have occurred in six major periods that have generally coincided with disturbances to the El Niño Southern Oscillation (ENSO) cycle (Glynn, 1993; Hoegh-Guldberg, 1999). While reduced salinity (Egana and DiSalvo, 1982; Goreau, 1964), increased or decreased light (Vaughan, 1914; Yonge and Nicholls, 1931; Hoegh-Guldberg and Smith, 1989b; Gleason and Wellington, 1993; Lesser *et al*, 1990) and chemical factors such as copper contamination (Jones, 1997a), cyanide (Jones and Steven, 1997; Jones and Hoegh-Guldberg, 1999), herbicides, pesticides and biological factors (eg, bacteria, Kushmaro and Loya, 1996) can also evoke the loss of algal pigments from symbiotic invertebrates, the primary cause of mass coral bleaching is temperature (Hoegh-Guldberg and Smith, 1989; Glynn and D'Croz, 1991; Glynn, 1993; Hoegh-Guldberg, 1999). The widespread bleaching events of 1998 have added further weight to the argument that elevated temperature is the primary variable triggering coral bleaching. The accuracy and predictive capability of the "HotSpot" program (Goreau and Hayes, 1994; Strong *et al*, 1996) has further strengthened the case for temperature being the primary variable that explains the recent spate of mass bleaching events in the 1980s and 1990s.

The advent of thermal stress in coral-dinoflagellate symbioses is very similar to the mechanism of heat stress in higher plants (Jones *et al*, 1998; Hoegh-Guldberg, 1999) and results in hypersensitivity to light of the symbiotic dinoflagellates of corals. Whereas normal light levels are essential for the survival of corals (through the powering of the photosynthetic processes of the symbiotic dinoflagellates), light intensities after heat stress are a liability. This leads to chronic photoinhibition of the symbiotic dinoflagellates and the light-dependent destruction of the symbiotic dinoflagellates. After they become non-functional, the damaged symbionts are expelled from (or begin to leave) the coral host. A complete review of the biochemical and physiological basis of coral bleaching can be found in Hoegh-Guldberg (1999).

The fate of corals following coral bleaching is of crucial importance. The severity of the thermal stress largely determines the outcome of any particular thermal event. In large and long-lived thermal anomalies, reef-building corals will die in large numbers (Brown and Suharsono, 1990; Glynn, 1990). In 1998, almost total mortality of corals was seen on part of the Great Barrier Reef in Queensland (Marshall and Baird, 2000), on Scott Reef of north Western Australia (Smith and Heywood, pers comm), in the Seychelles and Maldives (Spencer *et al*, 2000), in Okinawa (Y Loya, W Loh and K Sakai, pers comm) and in Palau (J Bruno, pers comm).

Not all corals are equally susceptible. Branching corals (eg, *Acropora)* tend to be more sensitive than more massive types of corals (eg, *Porites*). In milder events, death rates may be minimal (Harriott, 1985) and corals may make almost complete recoveries. This may take weeks to months and may result in corals that appear unaffected by the previous thermal insult (Hoegh-Guldberg and Smith, 1989). Recent evidence, however, reveals that while corals may not die, their physiologies can be severely disrupted by thermal stress (Ward *et al*, 1998; Hoegh-Guldberg *et al*, 2000).

Corals that have bleached and recovered may have reduced growth, as well as depressed calcification and repair capabilities (Goreau and Macfarlane, 1990; Glynn, 1993; Meesters and Bak, 1993). These impacts are probably a direct result of the expulsion of the photosynthetic symbionts of corals during stress and the resulting loss of metabolic energy to bleached corals. These insidious impacts on the general metabolism of corals appear also to affect coral reproduction. In this regard, there is now a well established view of the impact of thermal stress on coral reproduction. A large majority of corals that bleached at Heron Island, on southern Great Barrier Reef in 1998, did not reproduce later that year and had much reduced reproductive outputs in 1999 (Ward *et al*, 1998; Hoegh-Guldberg *et al*, 2000). These results join a growing number of studies, started with observations by Szmant and Gassman (1990), that corals which seemingly recover from bleaching may be compromised in ways that are likely to have significant impacts on the functioning and health of coral reefs. Corals that appear to have recovered may not reproduce normally.

## REDUCED OCEAN ALKALINITY AND CALCIFICATION

Increasing carbon dioxide above a solution leads to changes in the acidity and available carbonate pool. The total pool of carbonate and related ions is called the aragonite saturation state and is the resource in seawater that corals and other calcifying organisms draw on to precipitate calcium carbonate. The aragonite saturation state directly determines calcification rates of organisms like corals (Langdon *et al*, 2000). If you raise the concentration of carbon dioxide above a solution, the aragonite saturation state decreases and so do calcification rates. The projection changes to atmospheric concentrations of carbon dioxide under current greenhouse emission rates has raised additional concern as for coral reefs under climate change (Gattuso *et al*, 1998; Kleypas *et al*, 1999b).

Gattuso *et al* (1998) and Kleypas *et al* (1999b) calculated that predicted increases in the carbon dioxide concentration in the atmosphere would potentially decrease the aragonite saturation state in the tropics by 30 per cent by 2050 and that the calcification rate of corals and other organisms would decrease in concert by a similar amount. Langdon *et al* (2000) verified this conclusion and showed that reef-building corals grown under increased carbon dioxide were unable to acclimatise to the changing aragonite saturation state and that the hypothesis of Gattuso *et al* (1998) and Kleypas *et al* (1999b) was largely correct. Langdon *et al* (2000) estimated decreases of almost 40 per cent in calcification rates by corals would occur towards the later part of the current century.

Natural reef systems represent a balance between calcification and the physical and biological eroding influences that remove deposited framework (note: as opposed to carbonate sediments that form the inner foundation of reef lagoons) calcium carbonate. Almost 90 per cent of the calcium carbonate that is laid down in a coral reef structure is removed by physical and biological erosion. Rates of deposition are high (up to 20cm yr-1) compared to rates of reef growth (1cm yr-1; Done, 1999). A reduction in calcification of this size is likely to tip the balance in favour of the net disappearance of coral reef calcium carbonate. Many people have begun to speculate about the effect of a weakened reef infrastructure. Coastal erosion and loss of reef integrity are two very serious prospects for corals that are unable to calcify under a reduced aragonite saturation state. As discussed below, the implications of reduced coastal protection due to weakened or rapidly eroding coral reefs could add substantially to the potential costs associated with warming tropical seas and increased coral bleaching and mortality.

## REEFS AND RISING SEA LEVEL

Climate change is likely to result in a sea level rise of 15 to 95 centimetres over the next century (mean estimate of 50cm; Houghton *et al*, 1996). Climate model simulations are starting to provide firmer ground for understanding sea level rise and impact on human communities. Even changes under mid-range scenarios are likely to have major impacts on the frequency at which coastal areas flood during storms and the rate at which critical wetlands are lost (Nicholls *et al*, 1999). Nicholls *et al* (1999), for example, have estimated that the number of people flooded by storm surge in a typical year will be more than "five times higher due to sea-level rise by the 2080s" (up to 200 million people being at risk by 2080). Wetland losses were estimated to be as high as 20 per cent by a similar date (with 70 per cent being lost when sea level changes are combined with other stresses).

Graphic examples exist already of the impacts and types of responses that are necessary in the face of rising sea levels. Recent rapid changes in sea level (30cm) during the 1997-98 El Niño, for example, led to inundation of coastal villages in Columbia and village relocations (Correa and Gonzalez, 2000).

Many island nations in the Indian and Pacific Oceans are especially vulnerable because they are only a few metres above current sea level (Nicholls *et al*, 1999). Atoll systems may be only a few metres above sea level. Even small changes in sea level under the most conservative models for climate change over the next century are expected to cause major changes to the coastal areas of these countries. While these sorts of changes are likely to occur over longer periods during climate-driven changes to sea level, they do illustrate the vulnerability of coastal communities to changes in sea level and how barriers, like those provided by coral reefs, are likely to be even more crucial for these communities.

Coral growth and productivity also interact with changes in sea level. The requirement for light of reef-building corals and their zooxanthellae dictates that corals are limited to the upper layers of tropical oceans. Changes in sea level will mean that extant reefs at the depth limit of coral growth will experience light conditions that may not sustain coral growth and may disappear. If corals remain healthy, coral reefs will begin to grow in new areas, such as in the newly inundated coastal areas.

There is still some debate whether sea level changes represent a negative for healthy coral reefs (eg, Hopley, 1996). Hopley modelled possible coral reef productivity in response to a major (1.8m) and milder (0.5m) change in sea level and suggests that conditions under a 1.8m sea level rise may be favourable and reefs regenerate. Under a 0.5m sea-level rise scenario, however, Hopley (1996) suggests that aspects like changes to reef growth do not eventuate and aspects like sediment production may decrease and promote island recession. How sediment production on reefs may alter under climate change is complex but may be an important part of understanding how reefs will change with changing sea level (Kench, 1998).

Whether corals will keep pace with sea level change depends on future growth rates. Fast-growing coral species, such as members of the genus Acropora, add up to 20 centimetres per year (Done, 1999) to their branch tips and hence, if healthy, will keep pace with sea level change. The problem becomes considerable when the growth rates of slower growing species (eg, Porites) are considered. In this case, rates of sea level rise (0.95cm per year) begin to match upward growth rates (approximately 1cm per year, Barnes, 1973; Barnes and Lough, 1989). If growth rates are reduced by thermal and other stresses, the sea level change expected under even moderate global climate change will mean additional challenges for coral reefs in the future. It is important to point out, however, that coral calcification rates do not translate directly as reef accretion, which is about 100 times slower. In the latter case, increasing sea level may lead to faster and hence less consolidated reef accretion. This, in turn, may reduce structural strength of coral reefs and hence make them more vulnerable to storms and other erosive forces.

## ESCAPE ROUTES? BIOLOGICAL ACCLIMATION AND ADAPTATION

Biological systems are not simply inert entities – they have an inherent capacity to alter the way they respond to changes in the environment. The process by which they do this is called acclimation. The simplest demonstration of this usually occurs in any introductory physiology course, when students place animals at different temperatures for a week or so and then retest their responses to temperature (eg, Eckert *et al*, 1988). Those animals that have been sitting at a higher temperature are usually less stressed by being at that high temperature than those that have been sitting at a lower temperature which is suddenly raised to that same high temperature.

Corals and their symbiotic dinoflagellates are no different to other organisms and will acclimatise to small shifts in conditions. Corals exposed to the warmer than normal conditions often have greater survivorship when exposed to higher than normal experimental conditions (Coles and Jokiel, 1978; Meesters and Bak, 1993). Berkelmans and Willis (1999) found that corals at Orpheus Island bleached at lower temperatures than the same species in the summer, also implying acclimatisation had occurred (seasonal acclimation).

It is important to realise that there are limits to the amount of change an organism can invoke through acclimation. While corals may acclimatise to small changes throughout the year, it appears that the recent temperatures that corals have experienced in places such as Palau, Okinawa and the Indian Ocean have taken them beyond their limits of thermal tolerance. This evidence suggests that corals and their zooxanthellae are not able to acclimatise or adapt fast enough to the short, sporadic thermal events typical of recent “bleaching” years. There is no evidence (and it does not stand to physiological reason) that an exposure during one year to higher temperatures will result in greater tolerance in the following year (Hoegh-Guldberg, 1999).

Several authors have suggested that coral populations may also simply adapt to the changes in the environment that occur as a result of climate change (eg, Done, 1999). Adaptation involves the selection of more fit individuals within a population over time. Under a change in sea temperature, this might happen as follows: A bleaching event occurs and those individuals with the highest temperature tolerance survive to provide the offspring for the next generation of more thermally tolerant individuals. This continues over time until the population of corals regenerates as a more thermally fit population. The fact that corals and their zooxanthellae have different thermal optima and maxima (Hoegh-Guldberg, 1999, see also examples in this report) suggests that corals have adapted genetically to different thermal regimes as first pointed out by Coles *et al* (1976).

The observation that corals have adapted to local temperature regimes is not surprising. It is the basis of Darwinian natural selection. The observation of heat-sensitive clones (Edmunds, 1994; Brown, 1997c) among populations of corals suggests that differences in the genetic tolerance of host and zooxanthellae will provide the ground substance of change as habitats move to higher and higher thermal regimes. Corals may also change symbiotic partners as suggested by Buddemeier and Fautin (1993), allowing them to take on symbionts with higher thermal tolerances. So far, there is no evidence of the latter (Hoegh-Guldberg, 1999). Whatever the form of adaptation, it is important to appreciate that there are limits to the extent that any particular population can change and the rate at which they can do so.

The key question of whether or not coral and coral reefs will be able to adapt to climate change goes to the issue of rate. If conditions within tropical seas change slowly enough, evolution will keep pace with the changes and reefs made of corals will not disappear. If conditions change too quickly, however, conditions will exceed even the most thermally fit individuals within a given population. The recent near-total mortality events in Palau, Seychelles, Scott Reef and Okinawa suggest that (for those reefs) conditions largely exceeded the thermal tolerance of all individuals. As the thermal anomalies that are associated with these events are mild by comparison to what is forecast from current rates of sea temperature change (Hoegh-Guldberg, 1999, see also Figure 7 of this report), the rate of change is largely outstripping the rate at which corals can adapt. As stated by Hoegh-Guldberg (1999), corals are unlikely to go extinct. However, they may be rare organisms that will not function to build and maintain the coral reefs that are so important to the world’s tropical coastal populations.

## INTERACTION WITH OTHER ANTHROPOGENIC IMPACTS

How reefs change in response to increasing global warming is likely to interact with other potential stresses on coral reefs. As outlined above, coral reefs are being assaulted by a diversity of human-related impacts (eg, nutrient pollution, increased sedimentation, reef visitation and destructive fishing practices). These factors may well interact with the thermal stresses under rapidly warming tropical oceans to produce potent synergistic effects (Goreau, 1992; Wilkinson and Buddemeier, 1994; Bryant *et al*, 1998). Increased rates of coral disease may be a result of corals weakened because they are now 1ºC closer to their thermal threshold (Hoegh-Guldberg, 1999). Subtle ecosystem effects may also come into play, such as outbreaks of predators like crown-of-thorns starfish (Acanthaster planci, Moran, 1986), which may also be linked to reef disturbances relating to increased sea temperatures.

From a management perspective, coral bleaching has reopened the discussion about effective coral reef management. Reducing the pressure on reefs from overuse has never been an easy task. However, any reef management that reduces concurrent stresses to tropical coastal ecosystems is essential because healthy and unstressed reefs are more likely to recover than damaged and polluted reefs (Wilkinson *et al*, 1999; Wilkinson and Buddemeier, 1994). Yet it is not clear whether stressed reefs are more likely to witness coral bleaching and mortality than unstressed reefs. A recent comparison of bleaching inside and outside Kenya marine-protected areas showed no significant differences (McClanahan and Pet-Soede, 2000).

It is also highly likely that coral bleaching will weaken the ability of corals to resist the stresses arising from other factors. In particular, the increased incidence of disease among corals and other organisms in the Caribbean is being identified as potentially due to weakened corals from recent episodes of coral bleaching. All of these factors dictate that reefs (if they are becoming more delicate as thermal stress increases) will now need a greater level of reef and coastal zone management (Wilkinson *et al*, 1999).

## CONCLUSIONS

Coral reefs are central to the lives of hundreds of millions of people worldwide. Not only are they a source of protein and industry (tourism), they are central to the integrity of entire coastlines. Up to 58 per cent of reefs worldwide are currently threatened by human-related activities. Among these, climate change has a great potential to affect coral reefs through its influence on the physical and chemical conditions of the world's tropical oceans. Changing sea temperature and alkalinity will have major effects on the survival and ability of reef-building corals to calcify.

Coral bleaching events appear to be the first signs that coral reefs are in trouble and the majority of opinion now suggests that frequency and mortality of bleaching events is set to increase dramatically over the next few decades. Sea level is likely to be of less concern for reef-building corals when they are growing normally. If current increases in sea temperature and decreased alkalinity continue to occur, however, there is a real risk that reefs may drown as sea levels rise. This, plus the impact of larger storm surges, may lead to the removal of coral barriers within the next century.

# CLIMATE PROJECTIONS AND PACIFIC CORAL REEF ECOSYSTEMS

One of the first phases of the current study was to project how sea temperatures will change for the 14 target locations (close to 13 nations) within the Pacific. While broadly similar to the projections provided for tropical coral reefs by Hoegh-Guldberg (1999), the current study employed a series of algorithms that were adapted from the HotSpot program (Goreau and Hayes 1994; Strong et al, 1996) being run by Strong and others at the National Environmental Satellite, Data and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA) in Washington. These algorithms allow the advanced detection of mass bleaching events by tracking 1ºC change above the expected summertime maximal sea temperature (http://orbit-net.nesdis.noaa.gov/orad /coral_ bleaching_index.html). As discussed above, the link between sea surface temperature anomalies and coral bleaching is extremely tight, with almost every incidence of coral bleaching in 1997-1998 predicted in advance by the HotSpot program (Hoegh-Guldberg, 1999; Strong et al, 2000b).

## CURRENT RATES OF WARMING IN THE PACIFIC

Rates of warming of oceanic waters around 13 Pacific Island nations (1900-2000) were calculated using mean monthly sea temperature data obtained from the Lamont-Doherty Earth Observatory. Comprehensive Ocean-Atmosphere Data (COADS, up to October 1981) and IGOSS-nmc blended data (November 1981 to August 2000) sets were used for each of 14 locations to calculate the rates of change in sea temperature surrounding the 13 Pacific nations. While COADS data may include slight inaccuracies, the close coupling of this data set with the IGOSS data set post-November 1981 strengthens the confidence of the two data sets (as discussed by Hoegh-Guldberg 1999). Due to forcing of trend by the 1998 positive anomaly, data were analysed with and without the 1998 peak. The massive 1998 anomaly (up to 2ºC above the normal summer maxima) could be an extreme event and hence bias the estimation of the longer-term trends. Therefore, its effect on the trend requires a separate analysis.

The analysis of the trends in sea temperatures revealed highly significant increases over the past century at most locations (Table 1A). The overall rate of increase in sea temperature over the past century was 0.79 ± 0.29ºC (mean +95% confidence interval). Average rates were slightly lower (but not significantly so) if 1998 was included (0.73 ± 0.27ºC), which is probably due to the effect of the record cooler temperatures that followed in 1999. Rates of warming were significant in all cases except for the southern Cook Islands, Solomon Islands and Tonga, where no significant warming trend could be detected. The highest rates of warming (> 1ºC per century) occurred in Tuvalu (1.72ºC per century), Kiribati (1.51ºC per century), Samoa (1.19ºC per century), Vanuatu (1.03ºC per century) and New Caledonia (1.03ºC per century). The next greatest warming rates occurred in (in decreasing order): Palau (0.97ºC per century), Fiji and the Cook Islands (both 0.8ºC per century) and French Polynesia (0.58ºC per century). These rates match those calculated by Hoegh-Guldberg (1999), which ranged from 0.69ºC to 1.68ºC per century. As observed in that previous study, rates of warming, though very rapid in their own right, are slowest for the Pacific when compared to other coral reef sites (Hoegh-Guldberg, 1999)[1].

No very clear pattern emerges when the rates of increase in sea surface temperature are inspected as a function of geographic location (Figure 4). The highest rates of increase in the Pacific appear, however, to occur in the most western locations – possibly at the edge of the Pacific warm pool. Notably, as one goes further westward into the Pacific warm pool, rates increase. For example, rates increase in the approximated linear sequence going westward: Southern Cook Islands (0.10) < American Samoa (0.98) < Samoa (1.19) < Tuvalu (1.72ºC per century). These western locations (New Caledonia, Vanuatu) also approach the calculated rates of SST warming on the Great Barrier Reef. This matches observations made by Strong et al (1999) in a comparison that investigated heating and cooling rates in the southern and northern Pacific Oceans.

## HINDCASTING PREVIOUS PACIFIC MASS BLEACHING EVENTS

A simple inspection of SST data reveals that past bleaching events (as has been discussed previously for other sites; Hoegh-Guldberg, 1999), coincide with excursions of sea temperature above set critical thresholds that result in coral bleaching (Figure 5). Notably, recent events such as those in southern Cook Islands, Tonga and Samoa (Hoegh-Guldberg, 1994; Wilkinson, 1999), Fiji (Lovell, 2000), French Polynesia (Hoegh-Guldberg and Salvat, 1995; Hoegh-Guldberg et al, 1997) and Solomon Islands (Carlson, 1996) are associated with significant deviations from normal summer temperatures. The 1998 event in Palau, which resulted in one of the largest mass mortalities of corals, is also associated with a huge upward deflection of sea temperature (Figure 5G).

Figure 5. Seasonal sea surface temperature data (IGOSS data from Lamont Doherty Earth Observatory database) for years 1990-2000 for 13 Pacific nations. Lines indicate thermal thresholds (the interface between a normal and a bleaching year). Bleaching events that have been reported either in coral-list or in the literature are indicated by *.

The methodology used by Strong *et al* (2000b) to automate the detection of mass bleaching events with the HotSpot program at NOAA was adapted for use on past sea temperature data (1982-2000), in order to fine tune the methods to be used later for projecting how the

1. Note that rates calculated in the previous study for French Polynesia and the southern Cook Islands are slightly different in the current study from those calculated by Hoegh-Guldberg (1999) due to the slightly different methods that were used. In the previous study, COADS data was used up to December 1992 while, in the present study, COADS data was used only up to October 1981.

**Table 1: a)** Rates of warming of oceanic waters around 13 Pacific Island nations over the past century. The significance of trends is shown. Mean monthly sea temperature data were obtained from the Lamont-Doherty Earth Observatory (COADS data were used prior to November 1981 and IGOSS data from November 1981 to August 2000). Due to forcing of trend by the 1998 positive anomaly, data were analysed without (-98) and then with (+98) the 1998 peak included. "Sig" indicates significance at $p < 0.01$, no significant trends are represented by the probability values; **b)** Average rate of warming for the Pacific sites pooled and compared to rates estimated for 1900-2000 by the ECHAM4/OPHYS3 Global Circulation Model.

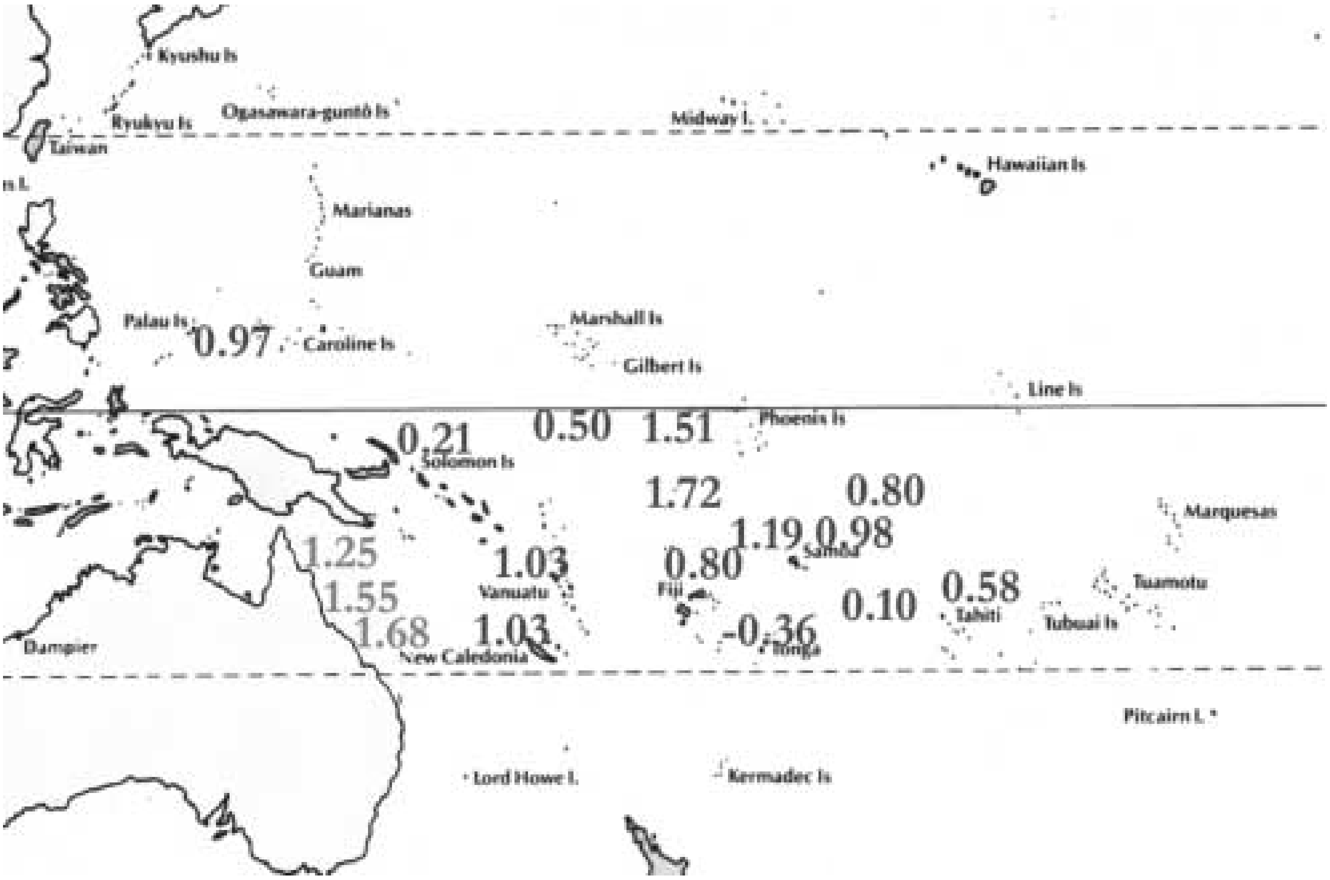
A. Rates of warming

| Location | Position | | 1900-1997 | | 1900-2000 | |
|---|---|---|---|---|---|---|
| American Samoa | 14 S | 169.5 W | 0.98 | sig | 0.68 | sig |
| Cook Islands Nth | 9.9 S | 161 W | 0.80 | sig | 0.94 | sig |
| Cook Islands Sth | 17.5 S | 163.2 W | 0.10 | 0.67 | 0.12 | 0.59 |
| Fiji | 17 S | 178.4 E | 0.80 | sig | 0.75 | sig |
| French Polynesia | 17.3 S | 149.9 W | 0.58 | sig | 0.63 | sig |
| Kiribati | 2.9 S | 171.4 W | 1.51 | sig | 1.06 | sig |
| Nauru | 2.7 S | 164.5 E | 0.50 | sig | 0.09 | 0.71 |
| New Caledonia | 20 S | 164 E | 1.03 | sig | 1.16 | sig |
| Palau | 7.3 N | 134 E | 0.97 | 0.33 | 1.06 | sig |
| Solomon Islands | 9.2 S | 160.8 E | 0.21 | 0.42 | 0.34 | 0.15 |
| Tonga | 19.2 S | 173.5 W | -0.36 | 0.29 | -0.35 | 0.27 |
| Tuvalu | 7.7 S | 177.2 E | 1.72 | sig | 1.46 | sig |
| Vanuatu | 16.1 S | 167 E | 1.03 | sig | 1.16 | sig |
| Samoa | 12.9 S | 173.5 W | 1.19 | sig | 1.10 | sig |

B. Average rates for Pacific sites pooled.

| Data source | Average rate of warming (13 locations), mean ± 95% Confidence | Difference from measured rates (A.) |
|---|---|---|
| A. COADS/IGOSS (-98) | 0.79 ± 0.29 | -------------- |
| B. COADS/IGOSS (+98) | 0.73 ± 0.27 | Not significantly different from A. |
| C. ECHAM4/OPYC3 (no aerosol effect) | 0.65 ± 0.06 | Not significantly different from A. or B. |
| C. ECHAM4/OPYC3 (with aerosol effect) | 0.33 ± 0.05 | Significantly less than A. and B. |

**Figure 4**. Map showing relative position of rates of sea temperature warming over the 1900s for 17 Pacific locations. Rates of warming calculated by Hoegh-Guldberg (1999) for data from three sites on the Great Barrier Reef are shown in light grey type.



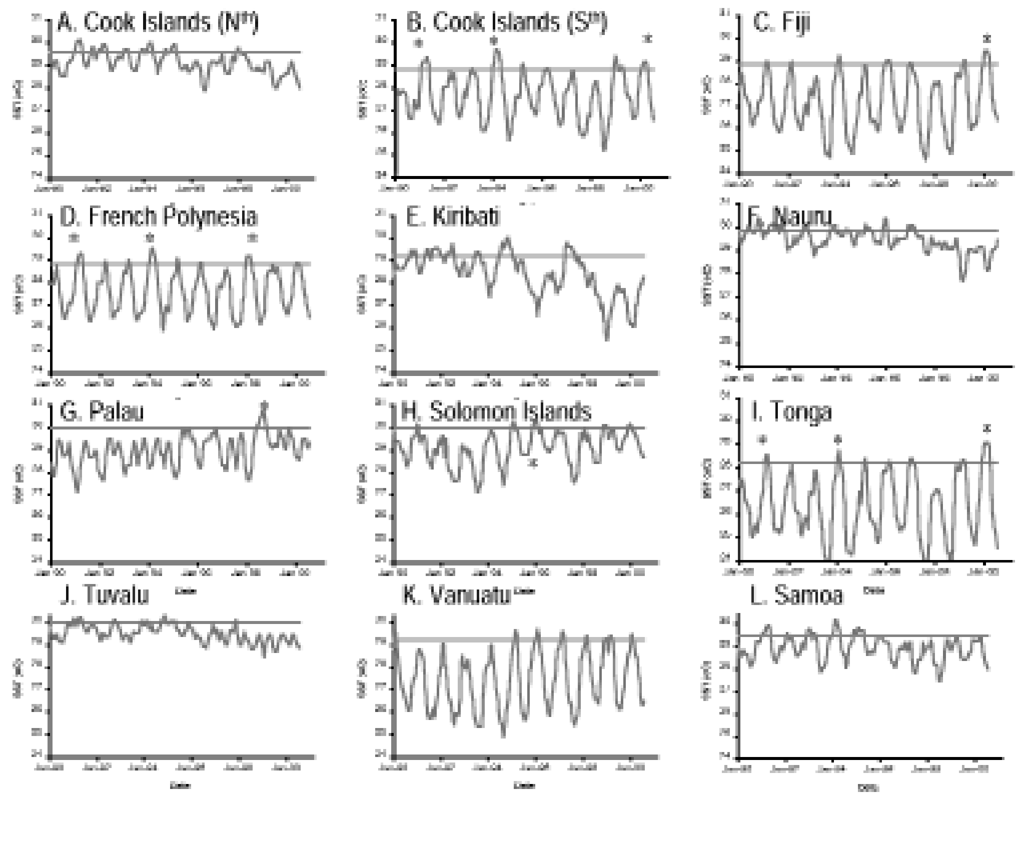




**Figure 5.** Seasonal sea surface temperature data (IGOSS data from Lamont Doherty Earth Observatory database) for years 1990-2000 for 11 Pacific nations. Lines indicate thermal thresholds (the interface between a normal and a bleaching year). Bleaching events that have been reported either in coral-list or in the literature are indicated by *.

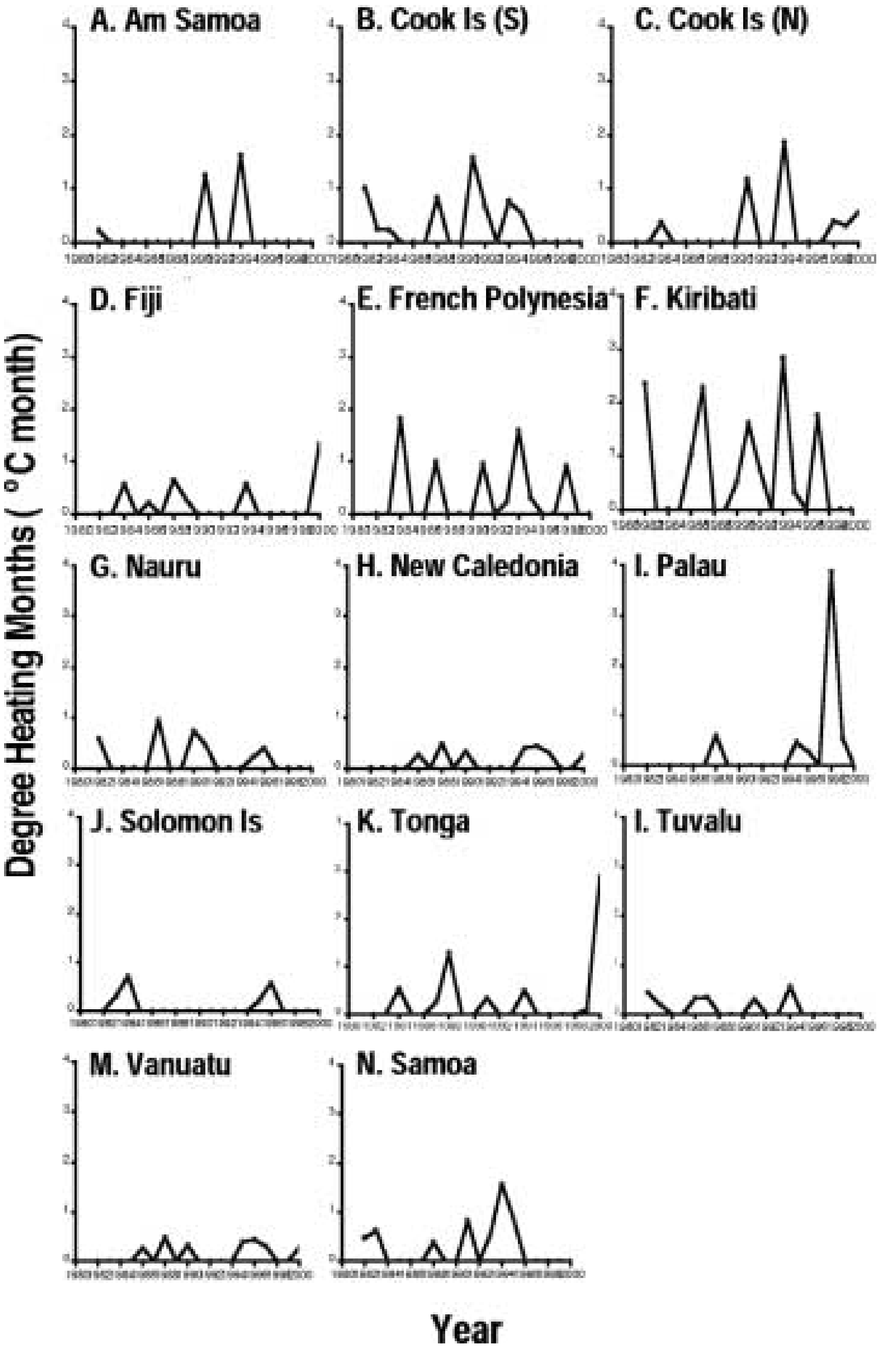



**Figure 6.** Degree Heating Months (DHM) for 13 Pacific nations (see text for explanation).

intensity and frequency of mass bleaching is likely to change over the next century. Strong *et al* (2000b) recognise the important contribution that the magnitude of a thermal anomaly and the exposure time make to intensity of a bleaching event. The NOAA satellite-derived Degree Heating Week (DHW) is an experimental product that calculates the accumulated thermal stress experienced by coral reefs. One DHW is equivalent to one week of sea surface temperature that is 1ºC above the expected summertime maximum sea (surface) temperature. Strong *et al* (2000b) and Toscano *et al* (1999) have observed that, in the past, DHWs of greater than 10 have resulted in severe bleaching and mortality among reef-building corals.

For the current study, the DHW methodology was adapted for use in the following way. Because monthly mean temperatures were the only ones available going back to 1900, Degree Heating Months (DHMs) were used instead of DHWs. In this way, as pointed out by Strong *et al* (2000b), a DHM represents 4.3 DHWs and the critical threshold for severe bleaching and mortality are DHMs that are greater than 2.3. The method was applied to sea temperature data from November 1981 to August 2000 (Figure 6) and successfully detected key bleaching events as discussed above. The same approach of Strong *et al* (1996) was used in the present study to calculate the thermal "triggers" associated with coral bleaching. Strong *et al* (1996) have found that deviations of 0.8ºC above the mean summertime maxima will usually result in a bleaching event. The thermal triggers for 14 Pacific locations were calculated from IGOSS data and are reported in Table 2.

The occurrence of thermal stress in the periods 1987-88, 1991-92, 1994 and 1998 for certain sites is accurately represented in Figure 6. Also clear from these graphs is the extent to which the intensity of events appears roughly encoded. Severe events, such as the recent Fijian and the 1998 Palauan events, are recorded as more intense than bleaching events that have been reported to be less severe, such as those in 1998 in French Polynesia and the Cook Islands (mild bleaching, personal observations). The relative intensities of events are likely to be best within data sets. In French Polynesia, the 1994 event was widely reported to be the most intense recent event (Salvat, 1991; Hoegh-Guldberg and Salvat; 1995, Drollet et al, 1994; Hoegh-Guldberg, 1999).

The event in Palau resulted in the widespread loss of corals (J Bruno, pers comm), as did similar events in Okinawa (Y Loya, W Loh and K Sakai, pers comm), Seychelles (Spencer et al, 2000) and Scott Reef off Western Australia (Smith and Heyward, in press). To verify that DHMs greater than 2.3 resulted in severe bleaching and significant mass mortality of corals, DHMs were calculated for the 1998 event in Palau, Okinawa, Seychelles (using data of Spencer et al, 2000) and Scott Reef. IGOSS data were downloaded for these locations and the DHM associated with these mortality events calculated. The DHMs associated with these severe events were 3.9, 3.0, 3.1 and 2.6 for Palau, Okinawa, Seychelles and Scott Reef respectively. By contrast, the DHMs for the southern, mid and northern sectors of the Great Barrier Reef (calculated for SST data for sectors of the Great Barrier Reef that were away from the more affected inshore sections) were 1.7, 1.4 and 0.5 respectively. Bleaching on the Great Barrier Reef was far less severe than in the four other locations (Berkelmans and Oliver, 1999).

The DHM approach used in the present study can detect past bleaching events and logically fits with our current understanding of how thermal stress culminates in coral bleaching (that is, the longer the exposure the greater the effect on the dark reactions of photosynthesis, Jones et al, 1998). This strengthens the grounds for using it to project future thermal stress on coral reefs and the intensity and frequency of coral bleaching events.

In the next section, the frequency and intensity of coral bleaching on reefs associated with Pacific nations is analysed. Most importantly, dates for critical levels of stress are determined, which drive the economic and social analysis that is the heart of the current study.

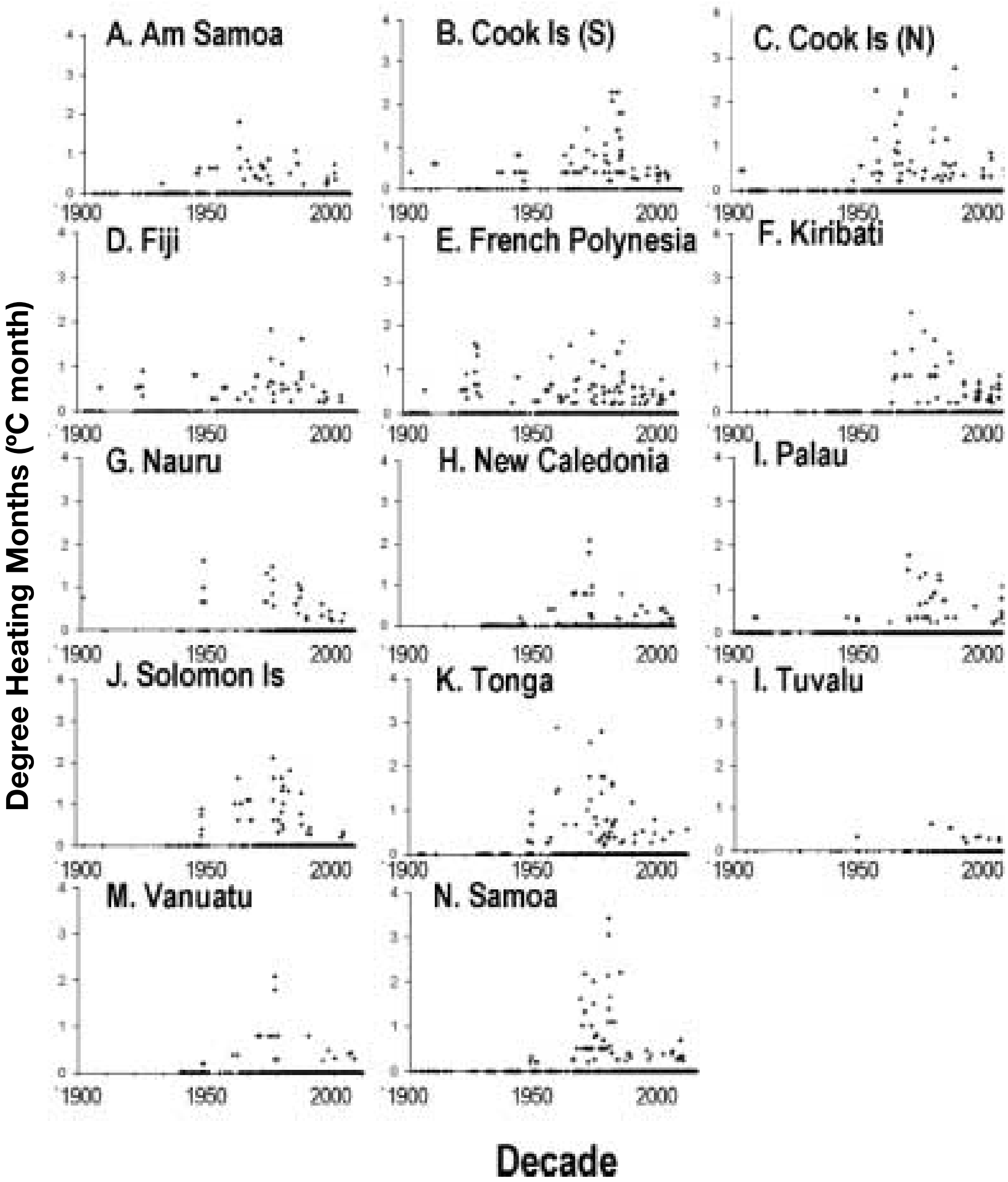



**Figure 7A.** Estimates of thermal stress associated with the warming trends detected in the Pacific Ocean. Sea surface temperature data from COADS data (prior to November 1981) and IGOSS data (November 1981 to August 2000) were compared to the mean summer maxima and positive anomalies above + 0.2°C recorded. Shown are Degree Heating Months (DHMs, two month moving point averages).

Further analysis investigated whether the last two decades of the 20th century were unusual in terms of heat stress, relative to the previous eight decades. This analysis is shown in Figure 7A. Within this data set is the interesting observation that thermal stress on reefs has been high since the late 1960s, apparently preceding known bleaching by 10 years, perhaps indicating that the first major bleaching events in 1979 were triggered by the accumulated stress of the preceding decade.

## PROJECTIONS OF CORAL BLEACHING AND MORTALITY (2000-2100)

Projections of future sea temperature were derived from the ECHAM4/OPYC3 Coupled General Circulation Model (Roeckner et al, 1996) for the period 1850 to 2100. Two runs were undertaken using the IPCC's IS92a scenarios with and without the cooling effect of aerosols taken into account. The global coupled atmosphere-ocean-ice model (Roeckner et al, 1996) was developed by the Max-Planck-Institut für Meteorologie (Bundesstrasse, Germany) and is used by the United Nations for climatology simulations. Horizontal resolution is roughly equivalent to 2.8o x 2.8o latitude-longitude. This model has been used in climate variability (Roeckner et al, 1996; Bacher et al, 1997; Christoph et al, 1998), climate prediction (Oberhuber et al, 1998) and climate change studies with a high degree of accuracy (Timmermann et al, 1999; Roeckner et al, in press). In order to reduce the drift of the unforced-coupled model, a yearly flux correction for heat and freshwater flux was employed. Simulation of the El Niño-Southern Oscillation is essential for approximating tropical climate variability and is handled well by the ECHAM4/OPYC3 model (Roeckner et al, 1996, Oberhuber et al, 1998). Changes in greenhouse gases that were used in the model were derived as follows: Observed concentrations of greenhouse gases were used up to 1990 and thereafter according to changes outlined in the IPCC scenario IS92a (IPCC, 1992). The following greenhouse gases are prescribed as a function of time: CO2, CH4, N2O and also a series of industrial gases including CFCs and HCFCs.

As noted, the model was run with and without the cooling effect of aerosols. Changes in aerosols were determined as follows: Observed concentrations of sulfate aerosols were used up to 1990 and thereafter changes according to the IPCC scenario IS92a. The tropospheric sulfur cycle was also incorporated but with only the influence of anthropogenic sources considered. Natural biogenic and volcanic sulfur emissions are neglected, and the aerosol radiative forcing generated through the anthropogenic part of the sulfur cycle only.

A simple comparison of the rates of warming over the last century, from the models, with actual rates of warming in the Pacific revealed that rates for the ECHAM4/OPYC3 greenhouse warming run without an aerosol effect (0.65 + 0.06ºC per century) did not significantly differ from those measured over the last century (0.79 + 0.29ºC per century; Table 1b). Rates for the ECHAM4/OPYC3 model run with aerosols were significantly lower than actual rates whether or not the 1998 anomaly was included (0.33 + 0.05ºC per century). It should be noted that the more recent IPCC emission scenarios (Nakicenovic et al, 2000) all anticipate substantially lower sulphur emissions than in the IS92 scenarios.

The occurrence of bleaching events was tracked using a methodology developed by Strong *et al* (1996) in which Degree Heating Months were calculated relative to thresholds derived from summer maxima during the 1990s (see Table 2). DHMs began accumulating when sea temperatures rose more than 0.2ºC above the thermal trigger temperatures. Figure 7A-N (graph a. in each case) shows the projected cumulative heat stress for the 14 Pacific locations using temperature data from the ECHAM4/OPYC3 greenhouse warming run without an aerosol effect. Notably, the cumulative heat stress per year, which has been an accurate predictor (or hindcast variable) of bleaching events in the past (Figure 6, Strong et al, 1996, 2000b), rises rapidly in the first few decades of this century. Significantly, levels as high as 15 are reached towards the end of this century. Given that corals and their zooxanthellae experience severe bleaching and mortality events at DHMs of greater than 2.3 (Strong et al, 2000b, and observations from the calculated DHMs of recent mass mortality events), the rapid rise of this index to such high levels should be of major concern.

**Table 2.** Thermal triggers used in projections of coral bleaching. Trigger temperatures for coral bleaching were calculated using the mean maximum (summer) sea temperatures for each region. Years were dropped from the analysis if large positive anomalies (greater than 1.0ºC eg, Palau in 1998) occurred.

| Location | SST trigger temperatures *(mean maximum sea temperature)* |
|---|---|
| American Samoa | 29.3 |
| Cook Islands Nth | 29.6 |
| Cook Islands Sth | 28.8 |
| Fiji | 28.9 |
| French Polynesia | 28.8 |
| Kiribati | 29.2 |
| Nauru | 29.9 |
| New Caledonia | 29.2 |
| Palau | 30.0 |
| Solomon Islands | 30.0 |
| Tonga | 28.2 |
| Tuvalu | 30.0 |
| Vanuatu | 29.2 |
| Western Samoa | 29.5 |

To provide key dates for when reefs will experience critical levels of stress, bleaching events were sorted into two categories: Mass mortality events were deemed to occur when DHMs rose above 2.3ºC months (as per 10 DHW or 2.3 DHMs and Strong et al, 2000b). Less severe events were scored when DHMs rose above 0.5ºC months. Figure 7B (b. or the lower panel in each case) outlines how the frequency of these two types of events changes over the next 100 years. As with a previous study of six coral reefs from the Caribbean and Pacific (Hoegh-Guldberg, 1999), the frequency of bleaching events generally increases steadily until a maximum is reached (10 per decade or annual events) about the middle of the current century (Figure 7A-N, dotted line in each b. panel).

Of some importance is the predicted frequency of severe bleaching events (events where DHM > 2.3). As expected, these types of events occur later in time but show the same trajectory towards a maximum later this century. If the experience of the last two decades is anything to go by, the consecutive occurrence of more than three bleaching events with DHMs of greater than 2.3 within a decade would severely reduce the cover of reef-building corals (as discussed above).

## DIFFERENCES BETWEEN MODELS

It is very important to rule out, where possible, any biases inherent within a particular GCM (model). A comparison between the output of the ECHAM4/OPHYS3 and an earlier Max Planck model (ECHAM3/LPG) and the principal model used by the Department of Atmospheric Research at CSIRO (Australia) revealed no major differences in the trends but minor shifts in the actual date at which bleaching reached a maximum (Figure 8). As noted by Hoegh-Guldberg (1999), these differences between models either delay or advance the critical dates by one to two decades. The slight differences between GCM models do not change the major conclusions of this report.

## CRITICAL DATES FOR PACIFIC NATIONS

Available oobservational evidence suggests that the waters of the southern Pacific are rapidly warming. This is occurring at an overall rate of 0.79 + 0.29ºC per century. Some regions (nations) are warming at slower rates while several nations have highly significant rates of warming that are over 1ºC per century. These nations are Tuvalu (1.72ºC per century), Kiribati (1.51ºC per century), Samoa (1.19oC per century), Vanuatu (1.03ºC per century) and New Caledonia (1.03ºC per century).

Analysis of past sea temperature data and bleaching events confirm that calculations based on Degree Heating Months are fairly accurate predictors of the frequency and intensity of past bleaching events. Using the ECHAM4/OPYC3 CGCM greenhouse warming simulation run with and without an aerosol effect revealed that heating stress is set to rapidly increase on Pacific coral reefs, rising to an order of magnitude greater than coral reefs can stand. As discussed in a previous section, the proposal that corals and their dinoflagellates will simply adapt is baseless and all available evidence (eg, increasing mortality among reef-building corals during the 1990s) suggests that corals and their symbiotic dinoflagellates are not able to evolve fast enough to keep pace with current rates of sea warming in the Pacific.

**Table 3**. Significant dates for Pacific nations as regards reef degradation from the thermal effects of global warming. The dates shown are derived from the current thermal limits of reef-building corals and climate projections using the ECHAM4/OPYC3 (Roeckner et al, 1996) model. Two runs were undertaken using the IPCC's IS92a scenarios with and without the cooling effect of aerosols being taken into account. The occurrence of bleaching events was tracked using a methodology developed by Strong *et al* (1996) in which Degree Heating Months were calculated relative to thresholds derived from summer maxima during the 1990s (see Table 2). Bleaching events were sorted into two categories: Mass mortality events were deemed to occur when DHMs rose above 2.3 (the point that has been observed as being strongly associated with mass mortality events over the past 20 years, Strong et al, 2000b). When three of these happen per decade, the year is recorded as being the point at which severe compromise of reef systems will occur (= loss of living coral cover). Bleaching events (mild to severe) were projected to occur when DHM rose above 0.5 - the point at which bleaching events become annual is shown. Years indicate the beginning year of the decade in which these conditions (either three major mortality events or annual bleaching) are projected to occur. NOTE: Projections for the model run with aerosols only went up to 2050 and some significant dates occurred slightly later than 2050 (indicated by > 2050).

| | MORTALITY | Beginning year of decades when reefs experience three major mortality events per year | STRESS | Year at which bleaching event become annual |
|---|---|---|---|---|
| | IS92a (no aerosols) | IS92a (with aerosols) | IS92a (no aerosols) | IS92a (with aerosols) |
| American Samoa | 2040 | > 2050 | 2030 | 2030 |
| Cook Islands Nth | 2040 | 2040 | 2070 | > 2050 |
| Cook Islands Sth | 2050 | > 2050 | 2050 | > 2050 |
| Fiji | 2030 | 2030 | 2040 | > 2050 |
| French Polynesia | 2040 | 2040 | 2050 | > 2050 |
| Kiribati | 2040 | 2030 | 2070 | > 2050 |
| Nauru | 2030 | 2030 | 2040 | > 2050 |
| New Caledonia | 2070 | > 2050 | 2070 | > 2050 |
| Palau | 2030 | 2040 | 2040 | >2050 |
| Solomon Islands | 2030 | 2040 | 2040 | 2040 |
| Tonga | 2030 | 2040 | 2040 | 2040 |
| Tuvalu | 2030 | 2030 | 2040 | > 2050 |
| Vanuatu | 2040 | 2040 | 2050 | > 2050 |
| Western Samoa | 2040 | > 2050 | 2050 | > 2050 |

***FIGURE 7B***

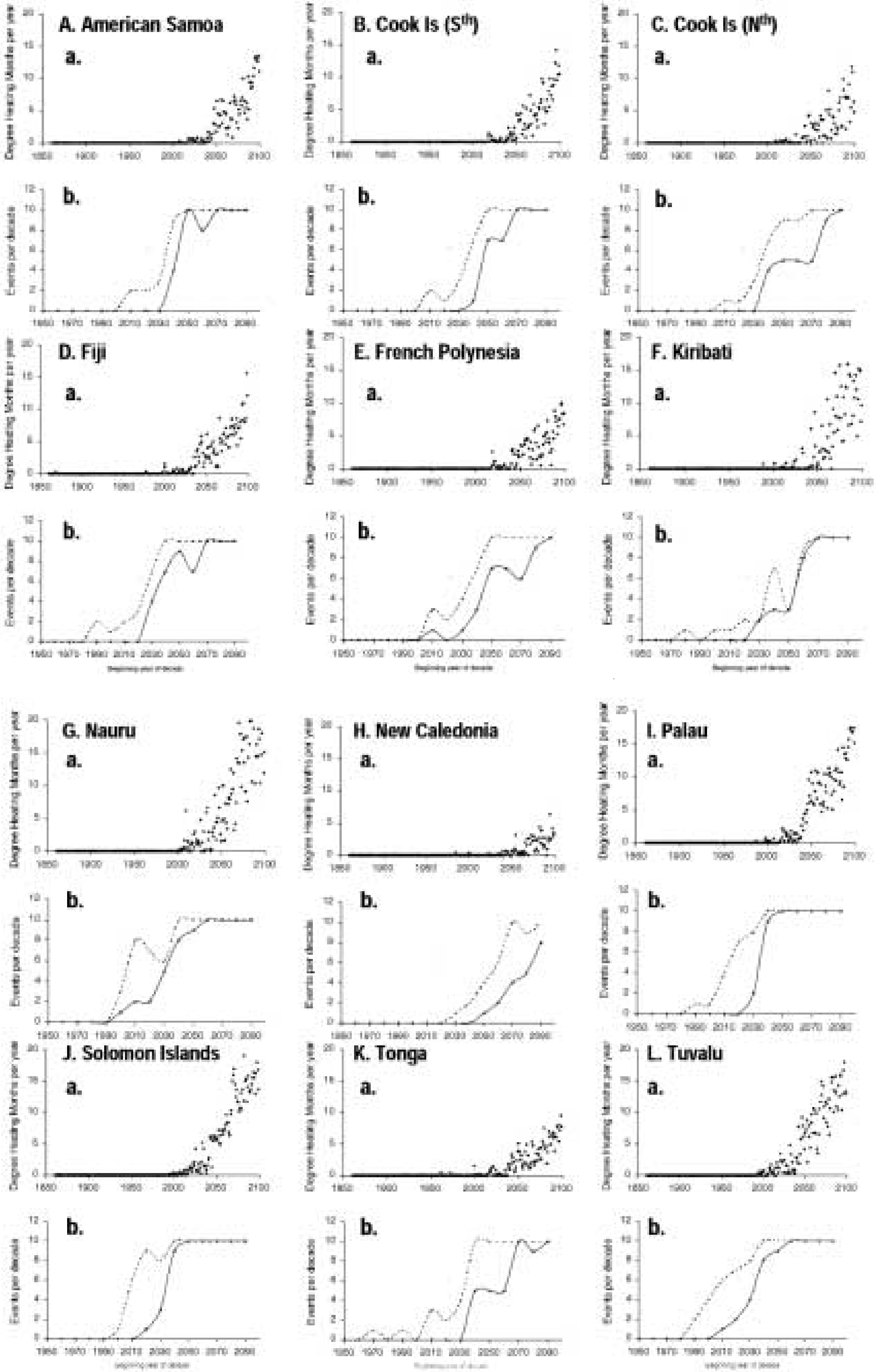

A. American Samoa
B. Cook Is (S^th)
C. Cook Is (N^th)
D. Fiji
E. French Polynesia
F. Kiribati
G. Nauru
H. New Caledonia
I. Palau
J. Solomon Islands
K. Tonga
L. Tuvalu

***FIGURE 7B CONT***

**Figure 7B.** Projected patterns of bleaching for reefs surrounding 13 Pacific nations (up to 2100). Sea temperature data from the ECHAM4/OPYC3 (Roeckner et al, 1996) model assuming minimal effect of aerosols. The occurrence of bleaching events was tracked using a methodology developed by Strong *et al* (1996) in which Degree Heating Months were calculated relative to thresholds derived from summer maxima during the 1990s from actual sea temperature data (see Table 3 and complete explanation in the text). (a) Indicates how the intensity of bleaching events is likely to change. (b) Frequency of bleaching events over the next century. Bleaching events were sorted into two categories: Bleaching events (mild to severe) were projected to occur when DHM rose above 0.5 – the point at which bleaching events become annual is shown. Severe events leading to mass mortality events (solid lines in b in each case) were deemed to occur when DHMs rose above 2.3 (the point that has been observed as being strongly associated with mass mortality events over the past 20 years, Strong et al, 2000b). Years indicate the beginning year of the decade in which these conditions (either three major mortality events or annual bleaching) are projected to occur. The area between the lines indicates a period in which reefs would be under severe stress (assuming that evolutionary change cannot occur rapidly enough).

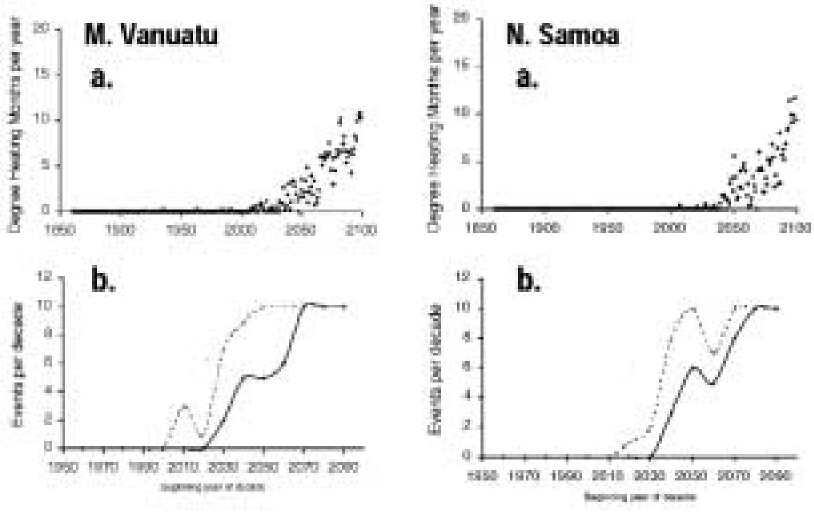



***FIGURE 8***

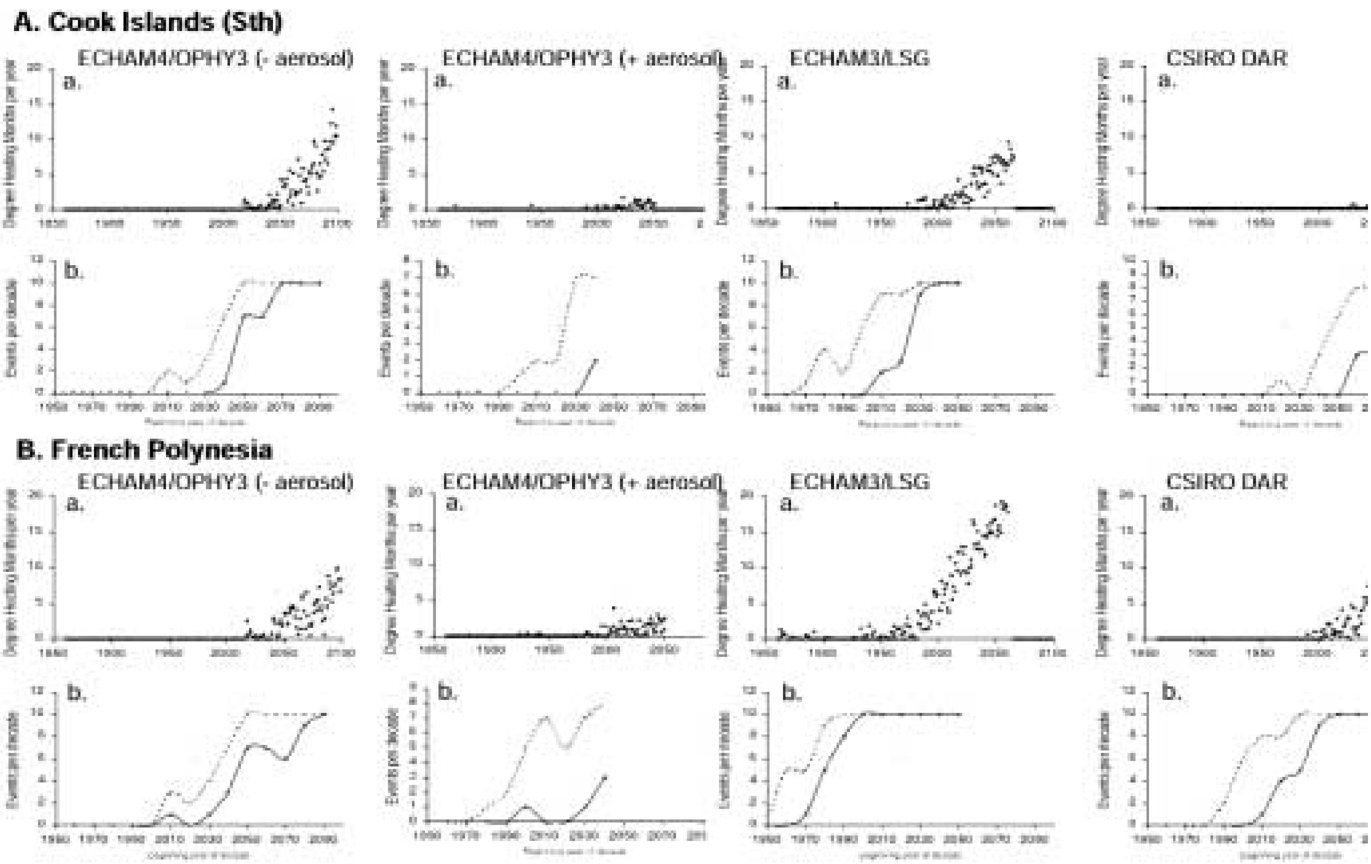



**Figure 8.** Comparison between four general circulation models for sea temperature warming at two locations in the south Pacific. Note the close similarity of the models despite different mathematical constructs.

A further analysis was pursued to generate dates which enable construction of social and economic scenarios for the south Pacific nations in question. As thermal events with DHMs in excess of 2.3 are likely to remove approximately 30 per cent of reef-building corals, the point at which Pacific reefs experience three of these events per decade can be argued as the point at which coral reefs will loose their living coral cover. Given the central importance of corals to the growth and maintenance of coral reefs, this point can be used as the projected date at which coral reefs in these countries become non-functional. Table 3 lists the simulated dates at which coral reefs off 13 Pacific nations reach the point where they are no longer likely to supply current benefits in terms of livelihood and industrial income. Table 3 also shows the beginning year of the decade in which coral bleaching (mild to severe) is likely to become annual. These dates are similar to those reported by Hoegh-Guldberg (1999) for data based on two other GCM data sets. As reported in this earlier study, the dates at which bleaching events become annual occurs slightly later in the Pacific when compared to the Caribbean and South-East Asian coral reefs. Uncertainties in the climate modelling preojections have to be taken into account such as model deficiencies and natural climate variability. These uncertainties might lead to different regional warming trends, explaining also why different CCGCMs simulate a different tropical temperature response to global warming. Hence the local differences discussed above should not be taken too literally but rather in terms of a first estimate. More research has to be done to specify regional climate change with higher accuracy.

In the next section, the data required to build the social and economic scenarios are collected and analysed. In the following section, the scenarios constructed from the atmospheric and marine science aspects of this project are combined with economic models of the various Pacific nations, to investigate the economic and social impacts of climate change on south Pacific reef systems and the societies that depend on them.

## CONCLUSIONS

Coral bleaching is triggered by exposure to elevated sea temperatures. It is due to thermal stress, which causes the zooxanthellae of corals to fail, resulting in expulsion from reef-building corals. Using sea temperature data for the past century, all sites examined in the Pacific have been warming at almost a degree per century (0.79 + 0.29ºC per 100 yr). This is bringing reefs close to their thermal threshold.

The study projects how coral bleaching will change over the next 50 to 100 years. The frequency and intensity of coral bleaching events at 14 sites across 13 Pacific nations were projected using a General Circulation Models (GCM) and information on bleaching triggers for corals growing in the Pacific and elsewhere. The technique, based on a method developed by NOAA (National Oceanographic and Atmospheric Administration, Washington DC) successfully hindcast the timing and approximate intensity of bleaching events known to have occurred in the Pacific region over the past 20 years.

The projected changes are cause for major concern. Most regions will experience annual bleaching events in the next 20 to 70 years. Severe mortality events are also going to increase – most sites will experience events on the scale of Palau, Okinawa and the Seychelles (DHM > 2.3) within the next 30 to 50 years. Some of these events will be four to five times more intense than recent mass mortality events (DHM > 10). Based on the almost total mortality of corals when DHMs are approximately 3, thermal events of this nature will cause a catastrophic decline in living coral cover in the Pacific and worldwide.

# SOCIAL, ECONOMIC AND POLITICAL OVERVIEW

## GENERAL NOTE

This section is mainly based on data compiled by the United States Central Intelligence Agency, the Pacific Community and the United Nations Economic and Social Commission for Asia and the Pacific (CIA, 2000; SPC, 2000a; ESCAP, 2000), supplemented by analysis of current economic prospects and other descriptive material. As the SPC is the first to acknowledge through its statistical development work, the statistics are not always as reliable as they should be. In Figure 9, consisting of nine sections illustrating particular indicators for each country, a light dotted pattern rather than solid colouring indicates estimates based on relationships found elsewhere. Table 4 contains the data. Tables 5 to 8 show additional indicators relevant for future assessment. Table 9 attempts to construct an index of vulnerability for these countries.

To the authors' knowledge, no-one has previously assembled physical, demographic, social, macro-economic, and foreign trade and tourism data in the form presented in this section, nor tried to develop vulnerability indicators or assess the likely degree or ability to change of this large a group of Pacific countries, from such a set of data. Within the scope of the commissioned study, we have gone as far as possible towards producing a reliable database. Given the time and funding constraints, the authors of this study have had to estimate some data rather than undertake additional data acquisition. The authors believe that, while there is obviously scope for improvement and for the provision of greater detail, the conclusions are unlikely to change as a result.

The assessment of vulnerability has different aims to a major project currently being undertaken by the South Pacific Applied Geoscience Commission (SOPAC). Its physical database, as could be expected from a funded three-year project, is much more comprehensive than the indicators developed in a short time for the current report. The SOPAC Environmental Vulnerability Index (EVI) will undoubtedly become a valuable tool not just at national level but for individual locations. Concentrating on physical factors, however, it does not replace the comprehensive socioecological orientation of our index (capable of future improvement as data are refined). Furthermore, it has not yet been finalised. A preliminary version of the index shows ratings for Vanuatu, Samoa, Tuvalu and Fiji, not surprisingly finding Tuvalu to be the most vulnerable and the others vulnerable to about the same degree (Kaly and Pratt, 2000). The index contains various sub-indices including intrinsic resilience, which is related to our concept of "ability to adapt", developed at the conclusion of this section.

The terms "nation" and "country" are used for convenience, although three areas are dependencies (American Samoa, French Polynesia, New Caledonia). Cook Islands is self-governing in free association with New Zealand. Apart from Palau at the northwestern extreme, the 13 countries form a contiguous area of the south-western Pacific roughly between the equator and the Tropic of Capricorn, and between longitudes 160oW and 140oE. The New Zealand dependencies of Tokelau (1500 inhabitants) and Niue (2100), and the French territory of Wallis and Futuna (15,300), were not included in the analysis.

For convenience, the text below refers to the individual numbered charts within Figure 9. The end of the section summarises the main characteristics of each nation, including further observations on political and other factors that may have an impact in the future.

## PHYSICAL DATA

**Physical data are essential initial inputs into establishing the vulnerability of individual Pacific countries with respect to climate change. Generally, many islands, long coastlines, large sea areas relative to land mass are indicators of vulnerability. Not all indicators point in exactly the same direction, but all should be reviewed.**

**LAND AND SEA AREAS:** Apart from the common location of small land areas in a large ocean and the occurrence of coral reefs in all of them, the 13 nations exhibit a wide range of characteristics in respect of geography and land use.

The four largest land areas belong to Solomon Islands, New Caledonia, Fiji and Vanuatu, all Melanesian nations located to the west (28,450km$^2$, 19,060km$^2$, 18,270km$^2$ and 14,760km$^2$, respectively). Together they account for 90 per cent of the total area of the 13 nations (89,500km$^2$). French Polynesia (4,167km$^2$) and Samoa (2860km$^2$) are next in line but much smaller. The seven other countries have tiny land areas, ranging from 748km$^2$ (Tonga) and 717km$^2$ (Kiribati) to less than 30km$^2$ in Nauru and Tuvalu Figure 9A (Chart 1).

Vast sea areas surround each country (exclusive economic zones, EEZ).[2] These vary from five million square kilometres for French Polynesia and more than three and a half million square kilometres for Kiribati to 120,000 square kilometres for Samoa Figure 9A (Chart 2). The ratio of EEZ to land area varies from almost 35,000 for Tuvalu, with its widespread small islands, to less than 50 for Samoa, Solomon Islands and Vanuatu Figure 9A (Chart 3). It averages 206 for all 13 nations.

Comparing these ratios with Australia, which is responsible for the third largest ocean territory in the world, puts the island nations into dramatic perspective. Australia's EEZ of 16.1 million square kilometres is a little over twice as large as the Australian land area of 7,686,850 square kilometres. This compares to the average Pacific nation, which has an average EEZ of 200 times its land mass. However, Australia's EEZ is more than three times as large as French Polynesia's EEZ.

The Solomon Islands nation has the longest coastline (5300km shown by Figure 9A Chart 4), followed by Vanuatu, French Polynesia and New Caledonia in the 2250- to 2500- kilometre range, Palau

2 The University of the South Pacific (main campus in Suva, Fiji), has an informative web site on physical, demographic and economic features (www.usp.ac.fj). It includes a map of EEZs in all 13 nations, plus Northern Marianas, Guam, Federated States of Micronesia and Marshall Islands.

## Table 4: Indicative estimates for 13 Pacific nations, physical, demographic, social, economic, trade and tourism indicators

| Chart | Indicator | Sources | American Samoa | Cook Islands | Fiji | French Polynesia | Kiribati | Nauru | New Caledonia | Palau | Samoa | Solomon Islands | Tonga | Tuvalu | Vanuatu | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A: Physical indicators** | | | | | | | | | | | | | | | |
| 1 | Land area (sq km) | CIA | 199 | 240 | 18,270 | 4,167 | 717 | 21 | 19,060 | 458 | 2,860 | 28,450 | 748 | 26 | 14,760 | 89,976 |
| 2 | Sea area (EEZ) (000 sq km) | SPC | 390 | 1,830 | 1,290 | 5,030 | 3,550 | 320 | 1,740 | 629 | 120 | 1,340 | 700 | 900 | 680 | 18,519 |
| 3 | Ratio of EEZ to land area | CIA, SPC | 1,960 | 7,625 | 71 | 1,207 | 4,951 | 15,238 | 91 | 1,373 | 42 | 47 | 936 | 34,615 | 46 | 206 |
| 4 | Coastline (km) | CIA | 116 | 120 | 1,129 | 2,525 | 1,143 | 30 | 2,254 | 1,519 | 403 | 5,313 | 419 | 24 | 2,528 | 17,523 |
| 5 | Area of coral reefs (sq km) | ICLARM | 296 | 618 | 4,048 | 1,951 | 259 | 4 | 24,000 | 1940 | 231 | 1,216 | 118 | 260 | 2,018 | 36,959 |
| 6 | Number of coral reefs | ICLARM | 85 | 16 | 204 | 114 | 36 | 1 | 19 | 101 | 28 | 77 | 90 | 10 | 90 | 871 |
| 7 | Reef area relative to land area | ICLARM, CIA | 149% | 258% | 22% | 47% | 36% | 19% | 126% | 424% | 8% | 4% | 16% | 1000% | 14% | 39% |
| 8 | Warming rates 1900-97 (Degrees Celsius)* | COADS, IGOSS | 0.98 | 0.45 | 0.80 | 0.58 | 1.51 | 0.50 | 1.03 | 0.98 | 1.19 | 0.21 - | 0.36 | 1.72 | 1.03 | |
| 9 | Arable land, permanent crops and pastures | CIA | 15% | 22% | 24% | 12% | 51% | 0% | 12% | 10% | 43% | 3% | 73% | 0% | 14% | 14% |
| 10 | Forests and woodlands | CIA | 70% | 0% | 65% | 31% | 3% | 0% | 39% | 60% | 47% | 88% | 11% | 0% | 75% | 65% |
| | **B: Demographic data** | | | | | | | | | | | | | | | |
| 11 | Population in July 2000 (000) | CIA | 65.4 | 20.4 | 832.5 | 249.1 | 92.0 | 11.8 | 201.8 | 18.8 | 179.5 | 466.2 | 102.3 | 10.8 | 189.6 | 2,440.3 |
| 12 | Annual population trends 1991-98 | SPC | 3.7% | -0.7% | 0.5% | 1.8% | 2.1% | 2.6% | 2.5% | 2.6% | 1.0% | 2.7% | 0.4% | 3.3% | 2.9% | 1.5% |
| 13 | Population projections 1998-2010 | SPC | 3.1% | 0.4% | 1.0% | 1.3% | 1.7% | 2.2% | 2.1% | 2.0% | 1.7% | 3.2% | 0.3% | 1.4% | 2.9% | 1.7% |
| 14 | Population density (persons per sq km) | CIA | 329 | 85 | 46 | 60 | 128 | 564 | 11 | 41 | 63 | 16 | 137 | 417 | 13 | 27 |
| 15 | Population under 15 years of age | ESCAP | 39.0% | 36.1% | 34.1% | 34.0% | 37.0% | 38.3% | 29.3% | 28.2% | 35.8% | 43.6% | 39.0% | 34.7% | 43.2% | 36.8% |
| 16 | Rural population | ESCAP | 52% | 65% | 54% | 43% | 63% | 100% | 40% | 31% | 79% | 87% | 64% | 52% | 80% | 63% |
| | **C: Social indicators** | | | | | | | | | | | | | | | |
| 17 | Infant mortality (per 1,000 live births) | CIA | 10.6 | 24.7 | 14.5 | 9.3 | 55.4 | 10.9 | 8.6 | 17.2 | 32.8 | 25.3 | 14.5 | 23.3 | 62.5 | 23.3 |
| 18 | Life expectancy at birth (years) | CIA | 75.1 | 71.1 | 67.9 | 74.8 | 59.8 | 60.8 | 72.8 | 68.6 | 69.2 | 71.3 | 67.9 | 66.3 | 60.6 | 67.0 |
| 19 | Index of communications equipment usage** | CIA | 2.47 | 2.39 | 0.87 | 1.75 | 0.31 | 1.39 | 2.64 | 1.34 | 1.11 | 0.19 | 0.81 | 0.43 | 0.33 | 1.00 |
| | **D: Economic indicators** | | | | | | | | | | | | | | | |
| 20 | GDP at purchasing power parity ($million) | CIA | 150 | 112 | 5,900 | 2,600 | 74 | 100 | 3,000 | 160 | 485 | 1,210 | 238 | 8 | 245 | 14,122 |
| 21 | GDP (PPP) per head | CIA | $ 2,600 | $ 5,600 | $ 7,300 | $ 10,800 | $ 860 | $ 10,000 | $ 15,000 | $ 8,800 | $ 2,100 | $ 2,650 | $ 2,200 | $ 800 | $ 1,300 | $ 6,000 |
| 22 | Fisheries and agriculture share of GDP | CIA, IMF | 4% | 18% | 17% | 4% | 14% | 5% | 4% | 5% | 40% | 50% | 30% | 34% | 24% | 15% |
| 23 | Fisheries and agriculture share of employment | SPC | 2% | 9% | 44% | 10% | 24% | 4% | 12% | 9% | 73% | 82% | 49% | 68% | 77% | 51% |
| 24 | Ratio of GDP to employment share | CIA, ESCAP | 2.21 | 2.00 | 0.38 | 0.40 | 0.58 | 1.33 | 0.33 | 0.51 | 0.55 | 0.61 | 0.61 | 0.50 | 0.31 | 0.30 |
| 25 | Electricity consumed per head (kWh) | CIA | 1,865 | 708 | 632 | 1,393 | 80 | 2,462 | 7,221 | 5,754 | 333 | 64 | 335 | 297 | 164 | 906 |
| 26 | Ratio of budget expenditure to budget revenue | ADB, CIA | 1.05 | 1.83 | 1.23 | 0.90 | 2.04 | 2.77 | 0.85 | 1.13 | 1.13 | 1.26 | 1.68 | 1.67 | 1.28 | 1.07 |
| 27 | Economic aid per head of population | CIA | $ 426 | $ 695 | $ 52 | $ 1,975 | $ 189 | $ 202 | $ 3,932 | $ 9,139 | $ 236 | $ 116 | $ 417 | $ 782 | $ 254 | 740 |
| | **E: Foreign trade and tourism** | | | | | | | | | | | | | | | |
| 28 | Merchandise exports per head of population | CIA | $ 5,289 | $ 226 | $ 485 | $ 913 | $ 72 | $ 2,564 | $ 1,946 | $ 823 | $ 113 | $ 323 | $ 81 | $ 18 | $ 185 | 665 |
| 29 | Merchandise imports relative to exports | CIA | 150% | 2024% | 156% | 406% | 617% | 83% | 242% | 506% | 476% | 113% | 863% | 2667% | 225% | 225% |
| 30 | Foreign visitors in 1995 (000) | SPC | 39,749 | 47,899 | ###### | 178,222 | 2,653 | 1,000 | 88,133 | 53,229 | 67,954 | 11,208 | 24,219 | 922 | 43,721 | ###### |
| 31 | Visitors per head of population | CIA, SPC | 0.69 | 2.54 | 0.41 | 0.78 | 0.03 | 0.09 | 0.47 | 3.12 | 0.37 | 0.03 | 0.26 | 0.09 | 0.25 | 0.25 |
| 32 | Estimated growth trends, visitors | SPC | -0.9% | 1.1% | 5.4% | 7.2% | 1.9% | 0.0% | 4.1% | 12.5% | 12.2% | -2.5% | 2.4% | 0.3% | 2.3% | 5.3% |
| 33 | Estimated spending per visitor, 1995 | SPC, ESCAP | $ 389 | $ 1,020 | $ 890 | $ 1,512 | $ 333 | $ 350 | $ 1,442 | $ 1,000 | $ 309 | $ 1,167 | $ 379 | $ 350 | $ 1,318 | $ 1,063 |
| 34 | Estimated total tourism spending, 1995 ($million) | SPC, ESCAP | 15.5 | 48.9 | 283.4 | 269.4 | 0.9 | 0.4 | 127.1 | 53.2 | 21.0 | 13.1 | 9.2 | 0.3 | 57.6 | 899.9 |
| 35 | Estimated tourism spending per head of population | SPC, ESCAP | $ 236 | $ 2,395 | $ 340 | $ 1,081 | $ 10 | $ 30 | $ 630 | $ 2,836 | $ 117 | $ 28 | $ 90 | $ 30 | $ 304 | $ 369 |
| 36 | Estimated tourism spending relative to GDP | SPC, ESCAP | 19% | 44% | 15% | 7% | 2% | 0% | 3% | 43% | 12% | 4% | 5% | 3% | 21% | 8% |

* Average for North and South Cook Islands (0.8 and 0.1 degrees, respectively)

** Main telephone lines, radios and television sets per 1,000 persons, each related to the average for all 13 nations, and then averaged to yield one index.

## Table 5: Other selected physical characteristics

| Nation | Number of islands | Remarks | Environmental issues | Climate | Tourism season |
|---|---|---|---|---|---|
| American Samoa | 7 | Five volcanic islands and two coral atolls (Rose Island, Swains Island). | Limited natural fresh water resources;substantial funds spent in past few years to improve water catchments and pipelines | Typhoons common from December to March; devastating hurricanes occur; wet season; 5,000 mm in Pago Pago. | June-September |
| Cook Islands | 15 | Southern group young volcanic; northern group older coral atolls. Rarotonga 28% of total land area. | NA | Climate 'pleasantly even'. Wet season December-March. Typhoons November-March but major events only once in 20 years. | All year |
| Fiji | 300 | Viti Levu 57%, Vanua Levu 30% of land area. Taveuni and Kadavu also substantial. Many outer islands relatively untouched (attractive reefs, lagoons, natural vegetation). | Deforestation, soil erosion. | Cyclonic storms can occur from November to January. Dry season ('Fiji winter') May-October, less rain and cyclone risk. | All year, best during 'Fiji winter' |
| French Polynesia | 118 | Five archipelagoes (Society, Tuamotu, Marquesas, Austral, Gambier) across 2,000 km. Mix of volcanic high islands and coral atolls. Six islands > 100 sq km. | NA | Wet season November-April;occasional brief, violent cyclonic storms in January. Dry season May-October; little rain, slightly cooler. Trade winds June-August can cause unstable weather. | All or most of the year |
| Kiribati | 33 | Gilbert, Line and Phoenix groups. Low-lying atolls except Banaba (highest point 87 m). Banaba scarred by phosphate mining (ceased 1979). Christmas Island largest atoll in world. | Heavy pollution in lagoon of south Tarawa atoll due to heavy migration mixed with traditional practices such as lagoon latrines and open-pit dumping; ground water at risk. Low level of some islands make them very sensitive to sea-level rise. | Wet and hot wet season (November-February). 3,000 mm in north (drier in south); typhoons can occur any time, but usually November to March. Rest of year moderated by trade winds. | March-October |
| Nauru | 1 | Nauru (highest point 61 m) surrounded by narrow coral reef. | Limited natural fresh water resources, roof storage tanks collect rainwater, but mostly depends on aging desalination plant; phosphate mining has left 90% of Nauru a wasteland, threatens limited remaining land resources | Very humid monsoon season November-February. Periodic tropical droughts and water shortages common during dry season (easterly trade winds). | March-October |

**Table 5 continued**

| | | | | | |
|---|---|---|---|---|---|
| New Caledonia | 15 | Grande Terre accounts for nearly all the area. Outlying areas: Loyalty Islands, Île des Pins, the tiny Îles Belep and a few scattered reefs and volcanic islets. | Erosion caused by mining exploitation and forest fires | Cyclones, most frequent from November to March | All year, but November-March is cyclone (and mosquito) season |
| Palau | 225 | High islands (Babeldaob, Koror, Peleliu, Angaur), low coral atolls (Kayangel, Ngeruangel), and the 200+ limestone Rock Islands. Nearly all islands in the group sit inside a single barrier reef. The nation also includes six small South-West Islands, which extend some 600km to the southwest. | Inadequate facilities for disposal of solid waste; threats to the marine ecosystem from sand and coral dredging, illegal fishing practices, and overfishing. | Wet season May to November; hot and humid. Typhoons June to December, but relatively infrequent. | All year; non-rainy months are February-March, stormiest period June-August. |
| Samoa | 9 | The two major islands, Upolu and Savai'i, constitute most of the land area. Two much smaller inhabited islands, Manono and Apolima, in the Apolimo Strait separating Upolu and Savai'i. A few tiny uninhabited islands and atolls make up the remainder of the country. | Soil erosion; active volcanism. | The wet season (or summer) is between November and April, the dry season (or winter) between May and October. Samoa lies in the cyclone belt and is periodically buffeted and bruised by cyclones, especially in the months between November and April. | Any time, but May-October best. |
| Solomon Islands | 992 | The third-largest archipelago in the total Pacific region, the Solomons are made up of mountainous islands covered in tropical rainforests, entirely clear-felled islands and many low-lying coral atols. About a third of the islands are occupied. | Deforestation; soil erosion; much of the surrounding coral reefs are dead or dying. Geologically active region with frequent earth tremors; volcanic activity | Rainfall varies enormously, peaking in the monsoon season (January and April). Cyclones occur then though they are rarely destructive. In the afternoons and for the bulk of the year, the islands are fanned by south-easterly trade winds. | July-December. |
| Tonga | 171 | Four main island groups (Tongatapu, He'apai, Vava'u and the Niuas). Fewer than 40 islands are inhabited, but most of the land has been converted to plantations or towns. Large areas of rainforest and bushland remain on the Niuas, 'Eua and many of the volcanic islands. | Deforestation as more and more land is being cleared for agriculture and settlement; some damage to coral reefs from starfish and indiscriminate coral and shell collectors; overhunting threatens native sea turtle populations. Earthquakes and volcanic activity on Fonuafo'ou. | More comfortable than the Samoas or the Solomons, winter (July to September) temperatures at 17°C to 22°C; lower when rainstorms and strong southerlies occur. Temperatures rise to 25°C to 33°C between December and April. Highest rainfall late in the season. Typhoons most likely January-March (big cyclones roughly every 20 years, medium ones every three to four years). | May-October. Hurricane seasonNovember-April can be hot, humid and wet. |

## Table 5 concluded

| | | | | | |
|---|---|---|---|---|---|
| Tuvalu | 9 | Tuvalu consists of a densely populated, scattered group of nine coral atolls with poor soil. Five of the islands are low-lying coral atolls (highest point on these just 4.6m above sea level). Remaining four islands are pinnacles of land rising solidly from the sea bed. | With no streams or rivers and groundwater is not potable, most water needs must be met by catchment systems with storage facilities (the Japanese Government has built one desalination plant and plans to build one other); beachhead erosion due to use of sand for building materials; excessive clearance of forest undergrowth for use as fuel; damage to coral reefs from the spread of the Crown of Thorns starfish. Tuvalu is very concerned about global increases in greenhouse gas emissions and their effect on rising sea levels, which threaten the country's underground water table. Low level of islands make them very sensitive to sea-level rise. | Wet season October-March (3,500 mm). Cyclone activity used to be rare; four severe hits this century - but all since 1972, and in 1997 there were three cyclones. So fragile is the Tuvaluan landmass that cyclones Gavin and Hina eroded an estimated 7% of the total surface area in 1997. | May-September |
| Vanuatu | 80 | The 80 or so habitable islands of Vanuatu straddle the Pacific Ring of Fire, giving residents a roller coaster ride of volcanic activity and tremors as well as occasional tsunamis. On some islands the land erupts out of the seabed to rise nearly 2000m above sea level, on others coral atolls and rocky islets lie only a few metres above it. | A majority of the population does not have access to a potable and reliable supply of water; deforestation; volcanism causes minor earthquakes. | Wet season November-April (more than 4,000 mm of rain annually in some places). During the dry, Vanuatu enjoys sunny days and mild, spring-like weather. The cyclone season is December-March, with possibilities for wild weather a few months on either side of that. The winds are generally more unruly during the wet season than the dry, and cyclones can hit any island. The most recent natural disaster, a severe earthquake in November 1999 followed by a tsunami, caused extensive damage to the northern island of Pentecote and left thousands homeless. | The southern winter is the best time, from April to October. However, many tour groups from Australia visit during the Christmas/January holiday season. |

Source: Mainly CIA (2000) and Lonely Planet (2000). Environmental concerns entirely due to CIA (2000).

(1500 km) and Kiribati and Fiji (around 1100 km). Nauru and Tuvalu have coastlines of 30 kilometres or less. The length of Australia's coastline is 25,760 kilometres.

An important factor is that a long coastline tends to be associated with a large number of islands, which again provides one of a considerable number of measures of vulnerability to climate change. Number of islands, listed in Table 9 in this section, is another. A possible measure not included in this analysis is ratio of land to coastline, which may be important in reflecting potential carrying capacity.

**NUMBER AND CHARACTERISTICS OF ISLANDS:** A related physical characteristic is the number of islands in each nation and their inter-relationships. Other factors being equal, problems of governance, transport and general cohesion are likely to be greater in countries with other islands distant from the administrative centre.

The number of islands varies between one and almost 1000 (Table 5). As a geographical dimension, this indicator differs from sea area or exclusive economic zone, which ranks French Polynesia ahead of Kiribati, Cook Islands, New Caledonia, Fiji and Solomon Islands. Kiribati and Cook Islands have relatively few islands, while Solomon Islands tops the scale with almost 1000, Fiji has about 300 and French Polynesia 118. The geographically tightest island nations are Samoa and American Samoa.

**ENVIRONMENTAL CONCERNS:** The information in Table 5 is taken from one source (CIA, 2000) to preserve consistency. The list is unlikely to be complete, quite apart from the relative absence of climate change effects in the source.

In summary, erosion is mentioned in five cases (Fiji, New Caledonia, Samoa, Solomon Islands, Tuvalu), fresh water shortages in four cases (American Samoa, Nauru, Tuvalu, Vanuatu) and deforestation in four cases (Fiji, Solomon Islands, Tonga and Vanuatu). Coral reef damage is mentioned in Solomon Islands, Tonga and Tuvalu. Not surprisingly, a main problem in Kiribati is

***TABLE 6: CLASSIFICATION OF REEFS (BY NUMBER OF REEFS)***

| Type of reef | American Samoa | Cook Islands | Fiji | French Polynesia | Kiribati | Nauru | New Caledonia | Palau | Samoa | Solomon Islands | Tonga | Tuvalu | Vanuatu | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Atoll | 5 | 7 | 16 | 74 | 24 | | 5 | 5 | | 7 | 2 | 7 | 1 | 153 |
| Atoll/Barrier | | | 1 | 1 | | | | | | | 1 | | | 3 |
| Atoll/Fringing | | | | 1 | | | | | | 1 | | 1 | 1 | 4 |
| Atoll/Platform | | | | | 1 | | | | | | | | | 1 |
| Atoll/Bank/Barrier/Fringing | | | | 1 | | | 1 | | | | | | | 2 |
| Barrier | 2 | | 33 | 6 | | | 3 | 20 | 1 | 7 | 5 | | 1 | 60 |
| Barrier/Fringing | | | 7 | 2 | | | | 8 | 2 | 5 | 1 | | 1 | 26 |
| Barrier/Fringing/Patch Reef | | | 2 | | | | | | | | | | | 2 |
| Fringing | 69 | 6 | 82 | 15 | 8 | | 4 | 55 | 17 | 44 | 21 | 2 | 68 | 391 |
| Fringing/Non-reef coral community | | | | | | 1 | | | | | | 1 | | 2 |
| Fringing/Patch Reef | | | 1 | | | | | | | | | 3 | | 4 |
| Fringing/Platform | | | 1 | | | | | | | | | 1 | | 2 |
| Bank | 1 | | | | | | | 1 | | | | | | 2 |
| Platform | | | 9 | 1 | | | | | | | | | 4 | 14 |
| Patch Reef | | 1 | 8 | | | | 1 | | | 7 | 4 | | | 21 |
| Pseudo-atoll | | 1 | 8 | 2 | | | | | | | | | | 11 |
| Raised Reef | | | | | | | | | | 1 | | | | 1 |
| Shoal | | | | | | | | 3 | | | | | | 3 |
| Non-reef coral community | | | | 3 | | | | | | | | | 9 | 12 |
| Various structure types present | | | 2 | 1 | | | | 1 | | 1 | | | | 5 |
| Various structures present | | | | | | | | 3 | | | | | | 3 |
| NA | 8 | 1 | 36 | 5 | 3 | | 5 | 5 | 8 | 4 | 56 | | 5 | 136 |
| Grand Total | 85 | 16 | 206 | 114 | 36 | 1 | 19 | 101 | 28 | 77 | 90 | 15 | 90 | 878 |
| **Summary** | | | | | | | | | | | | | | |
| Atoll | 5 | 7 | 16 | 74 | 24 | | 5 | 5 | | 7 | 2 | 7 | 1 | 153 |
| Atoll/other | | | 1 | 3 | 1 | | 1 | | | 1 | 1 | 1 | 1 | 10 |
| Pseudo-atoll | | 1 | 8 | 2 | | | | | | | | | | 11 |
| Subtotal atoll | 5 | 8 | 25 | 79 | 25 | | 6 | 5 | | 8 | 3 | 8 | 2 | 174 |
| Barrier | 2 | | 33 | 6 | | | 3 | 20 | 1 | 7 | 5 | | 1 | 60 |
| Barrier/other (non-atoll) | | | 9 | 2 | | | | 8 | 2 | 5 | 1 | | 1 | 28 |
| Fringing | 69 | 6 | 82 | 15 | 8 | | 4 | 55 | 17 | 44 | 21 | 2 | 68 | 391 |
| Fringing/other (non-atoll non-barrier) | | | 2 | | | 1 | | | | | | 5 | | 8 |
| All other specified | 1 | 1 | 17 | 4 | | | 1 | 4 | | 8 | 4 | | 13 | 53 |
| Total identified | 77 | 15 | 168 | 108 | 33 | 1 | 14 | 92 | 20 | 72 | 34 | 15 | 85 | 734 |
| Unspecified combined structures | | | 2 | 1 | | | | 4 | | 1 | | | | 8 |
| Not specified | 8 | 1 | 36 | 5 | 3 | | 5 | 5 | 8 | 4 | 56 | | 5 | 136 |
| Grand total | 85 | 16 | 206 | 114 | 36 | 1 | 19 | 101 | 28 | 77 | 90 | 15 | 90 | 878 |
| Subtotal atoll/total identified | 6% | 53% | 15% | 73% | 76% | | 43% | 5% | | 11% | 9% | 53% | 2% | 24% |

Source: ICLARM (1999)

the low level of the islands and Tuvalu expresses concern about sea level rises.

A natural hazard included with the environmental concerns, volcanism, is a concern in Samoa, Solomon Islands, Tonga and Vanuatu, situated on the section of the "Ring of Fire" between the Pacific and Indo-Australian Tectonic Plates.

Pacific nations are party to many international conventions related to environmental matters. The number of independent countries out of the total of 10 that have ratified or signed a particular convention gives an impression of how the main concerns rate in these nations. American Samoa, French Polynesia and New Caledonia are covered by the United States and France respectively (CIA, 2000). The most important agreements in the Pacific context are the following:

- Convention on Biological Diversity, 1992: Ratified by nine independent Pacific countries and France; signed but not yet ratified by Tuvalu and the United States.
- United Nations Framework Convention on Climate Change, 1992: Ratified by all 10 independent Pacific nations, France and the United States.
- Kyoto Protocol to the UN Framework Convention on Climate Change, 1998 (not yet in force). Ratified by Fiji, Palau and Tuvalu, signed by Cook Islands, Samoa and Solomon Islands, France and the United States. Worldwide 21 nations are party to the Kyoto Protocol, while 69 have signed but not yet ratified (as at the beginning of 2000).
- Montreal Protocol on Substances that Deplete the Ozone Layer, 1987: Ratified by all Pacific nations except Cook Islands, Nauru and Palau, and by France and the United States.
- UN Convention to Combat Desertification, 1994: Ratified by all 10 independent Pacific nations and France; signed by the United States.
- UN Convention on the Law of the Sea, 1982 (entered into force in 1994): Ratified by all except Kiribati and the United States.

With all these conventions in place there are international obligations, which imply financial and internationally legally binding commitments. The need to harmonise international, regional and national policies related to environment and other facets of development is vital to the attainment of sustainable development goals.

**WEATHER PATTERNS:** Cyclones or typhoons are recorded as a feature in practically all the nations (Table 5). The usual season is between November or December and March or April except in Palau (June to December). Descriptions range from relatively mild or infrequent to devastating. The description for Tuvalu specifically mentions that the frequency of cyclones has increased dramatically since 1972. Three hit in 1997, two of them with devastating effects.

**DATA RELATED TO CORAL REEFS:** The total reef area of the 13 nations amounts to 37,000 square kilometres, of which by far the largest area (24,000km$^2$) is around New Caledonia (Chart 5). Far down the list follows Fiji with just over 4000 square kilometres, Vanuatu, French Polynesia and Palau, with about 2000 square kilometres each, and Solomon Islands (1200km2). The average size of reef varies widely, so the distribution by number of reefs differs markedly from the area distribution (Chart 6). Of 878 reefs listed by ICLARM (1999), 206 were in Fiji, 114 in French Polynesia, 101 in Palau, 90 in Vanuatu, 90 in Tonga, 85 in American Samoa and 77 in Solomon Islands.

Given that different reef structures provide more or less protection for the adjacent coastal areas, it is useful to categorise them (Table 6). Of the 878 reefs, structures were specified for 734, of which 174 were wholly or partly atolls (24 per cent).[3] According to this database, Kiribati and French Polynesia have the highest proportion of atolls (76 per cent and 73 per cent respectively). Cook Islands and Tuvalu are next with 53 per cent each, followed by New Caledonia with 43 per cent. The last percentage is difficult to relate to the other observations because a single reef classified "atoll/bank/barrier/fringing" covers 24,000 square kilometres. Indeed, given its structural similarity to Australia's Great Barrier Reef, a detailed count would possibly result in thousands of reefs around New Caledonia. Table 6 therefore understates the true picture.[4]

As far as these statistics go, however, atolls appear to be prevalent in the countries mentioned in the above paragraph and significantly less so in the other seven (among these, Fiji has the highest proportion of 15 per cent).

Fringing reefs having no association with other structural types, as defined in the source, accounted for 391 of the classified reefs. Barrier reefs numbered 80. Evidence quoted below suggests that atolls, because of their low altitude, may be most under threat but the associated land areas are by no means the only areas affected.

Relating the total reef area surrounding these island nations to land areas yields yet another set of relationships (Chart 7). Tuvalu now stands out with its total reef area 10 times larger than its tiny land area. Further down the list follows Cook Islands with its reef area more than two and a half times its land base, and American Samoa with its reefs covering 50 per cent more than its land area. On the other hand, the huge reef area surrounding New Caledonia is "only" about one-quarter larger than the land area of the territory. In the other countries, reef areas cover between four per cent and about half the size of the respective land areas.

The above statistics may be compared to Australia, surrounded by 3294 reefs, of which 3184 are off the Queensland coast, another 39 in the Coral Sea, and 71 north and west of the continent (ICLARM,

3. Available data on area of individual reefs (situated in American Samoa, Fiji, French Polynesia, New Caledonia and Tonga) suggest that some individual observations of 'atolls' either on their own or in combination with other structures may include more than one atoll. The average area appears larger than would be expected for individual structures. The ICLARM database, while very useful and the best available information source, is still being developed.
4. The few individual reefs listed under New Caledonia may have been already counted in the database.

1999). The total reef area is not defined in the database; assuming an average of 10 square kilometres per reef, the area yields a total of about 33,000 square kilometres, almost equivalent to the total for the 13 nations.

The warming rate record from 1900 to 1997 based on COADS and IGOSS data has been included in Chart 8. The experience of climate change has been generally shared by the 13 nations included in the analysis.

**IMPACT OF CLIMATE CHANGE ON COASTAL AREAS:** Impact of climate change on coastal areas: There is no comprehensive information on this but general evidence suggests that the impact of a 40-centimetre sea level rise by the 2080s will have relatively great impact on nations of the Caribbean, and Indian and Pacific Oceans, as well as high effects in absolute terms elsewhere in the world (Nicholls et al, 1999). Case studies for the Pacific show that not only low-lying atolls but also high islands such as Upoke (Samoa) and Viti Levu (Fiji) have most of their economic and industrial infrastructures located on the coastal plains. While more resilient, they will also be significantly affected by sea-level rise (Solomon and Forbes, 1999).

**LAND USE:** Tonga, Kiribati and Samoa have the highest ratio of arable land, permanent crops and pastures (73 per cent, 51 per cent and 43 per cent respectively). At the other extreme, no such land use is recorded for Nauru and Tuvalu, and only three per cent of the total for Solomon Islands (Chart 9). The latter country has the highest area of forests and woodlands (88 per cent), followed by Vanuatu, American Samoa and Fiji, with between 75 per cent and 65 per cent each. There are no recorded forests and woodlands in the Cook Islands (although a central jungle exists on Rarotonga), Nauru or Tuvalu, and little in Kiribati (Chart 10).

Land uses other than those specified in Charts 9 and 10 account for 100 per cent in Nauru and Tuvalu, 78 per cent in the Cook Islands, and 57 per cent, 49 per cent and 46 per cent, respectively, in French Polynesia, New Caledonia and Kiribati. Examples of other land uses include urban areas as well as the unutilised areas of former phosphate mining sites (Nauru) and atolls with no defined arable lands.

## DEMOGRAPHY

The total estimated population of the 13 nations in July 2000 was about 2.44 million. Of these, 34 per cent lived in Fiji, 19 per cent in Solomon Islands, 10 per cent in French Polynesia, eight per cent in New Caledonia, eight per cent in Vanuatu and seven per cent in Samoa. This leaves 13 per cent for the remaining seven areas, home to between 11,000 and 102,000 persons each (Chart 11).

**Demographic data include population, population density, age distributions, rural population and other indicators of how different population characteristics either affect a country's vulnerability to environmental change or its capacity to adapt to such change.**

The estimated annual population growth between 1991 and 1998 was 1.5 per cent (Chart 13).[5] American Samoa (3.7 per cent), Tuvalu (3.3 per cent), Vanuatu (2.9 per cent), Solomon Islands (2.7 per cent) and Nauru, Palau and New Caledonia (2.6 per cent) showed above-average growth for the area, as did Kiribati and French Polynesia with 2.1 per cent and 1.8 per cent growth respectively. Fiji was mainly responsible for dragging down the average with an estimated growth rate of 0.5 per cent per annum.

Projected population trends for 1998-2010 (Chart 12) are largely in line with the past 10 to 15 years. Apart from Tuvalu (dropping to 1.4 per cent per annum), the strongest growing populations remain those of American Samoa, Solomon Islands and Vanuatu. Average growth for all 13 nations increases to 1.7 per cent per annum, with Cook Islands (0.4 per cent), Tonga (0.3 per cent) and Fiji (1.0 per cent) remaining significantly below average.

The overall measure of population density (Chart 14) naturally hides differences within a country.[6] Population density varies widely around the overall average of 27 per square kilometre for the total area. The minuscule nations of Nauru and Tuvalu top the scale with figures of 564 per square kilometre and 417 per square kilometre respectively. The highest population concentration in a larger area is in American Samoa (329), despite widespread forests and woodlands, followed by Tonga (137) and Kiribati (128). New Caledonia, Vanuatu and Solomon Islands are the least densely populated areas, ranging between 11 and 16 per square kilometres.

Of the total population in the 13 nations, an estimated 36.8 per cent are aged under 15 years (898,000 persons), 59.2 per cent are in what may be crudely termed the "working-age" groups of 15-64 years (1.444 million), and only four per cent are aged 65 or over (98,000). This may be compared with Australia, which in 1999 had a similar proportion of 37 per cent aged under 15 but a much larger aged component (12 per cent were 65 years of age or more). This leaves 51 per cent in the "working-age" groups according to the Australian Bureau of Statistics.

The highest incidence of young people is in Solomon Islands (43.6 per cent) and Vanuatu (43.2 per cent). Chart 15 shows that the proportion aged under 15 was significantly below the south Pacific average in Tuvalu, Fiji and French Polynesia and, especially, in Palau and New Caledonia. There was no correlation between the estimated age distributions and population growth rates.

At the other end of the age distribution, none of the 13 nations had more than about six per cent aged 65 years or more (Palau topped the scale at 6.4 per cent followed by Tonga and Tuvalu). Most had about four per cent in the senior age ranges, with Vanuatu showing the smallest proportion with three per cent.

The "working-age" groups were most strongly represented in New Caledonia and Palau (both 65.4 per cent), followed by French Polynesia and Fiji with about 62 per cent each. Even the nations with the smallest proportions in the 15- to 64-year age range showed

5 The population statistics compiled by SPC (2000a) needed adjustment in 1996-98 for the Cook Islands, Fiji and Tonga. The population estimates in CIA (2000) were helpful in making the adjustments for Fiji and Tonga, as were the time series for these countries between 1991 and 1995. However, Cook Islands suffered serious emigration between 1996 and 1999 (ADB 2000).

6 This study presents general indicators only. Distributions of population density within a country will provide important additional insights.

higher ratios than Australia's 51 per cent: Solomon Islands 53.4 per cent, Vanuatu 53.8 per cent and Tonga 55 per cent.

Most of the populations in these island nations are classified rural according to ESCAP (an estimated 62.7 per cent in total). This overall classification includes both agricultural and fishing activities, given that both are, to a large extent, subsistence activities of villagers generally living in the coastal areas. Disregarding Nauru, which is without a formal capital city and, therefore, assumed to have a wholly rural population, the proportion was highest in Samoa, Solomon Islands and Vanuatu (close to or above 80 per cent). It was below 40 per cent in Palau only (Chart 16).[7]

## SOCIAL INDICATORS

**INFANT MORTALITY** per 1000 live births averaged an estimated 23.3 (CIA, 2000). The comparable estimate showed infant mortality in Australia as 5.0 per 1000 live births (the Australian Bureau of Statistics recorded the same rate for 1998, the lowest ever). Among the 13 nations, New Caledonia and French Polynesia recorded the lowest infant mortality rates of about nine per 1000 live births (Chart 17), followed by Nauru and American Samoa with about 11 per 1000. Fiji and Tonga also had below-average infant mortality rates for south Pacific nations (14.5 per 1000 each). At the other extreme, Vanuatu has an infant mortality rate of 62.5 per 1000 live births and Kiribati of 55.4.

**Social indicators are also important indicators of whether a country is capable of coping with change or is vulnerable in this respect. Low infant mortality and high life expectancy usually indicate developed economies with sufficient resources to deal with change.**

**LIFE EXPECTANCY:** Infant mortality is correlated with another social indicator, life expectancy at birth (Chart 18). The exception is Nauru, which has a low infant mortality rate but, at 60.8 years, also a low life expectancy at birth. The only lower observations are Vanuatu (60.6) and Kiribati (59.8). Excluding Nauru, a percentage-point fall of 10 in infant mortality is associated with a 2.4-year increase in life expectancy at birth (the life expectancy of Nauruans from the correlation would be 72 years rather than 61). Conversely, a five-year gain in life expectancy is associated with a 21 percentage-point decline in infant mortality (R2 = .734; relative standard error (RSE) = 19%).

American Samoans and French Polynesians enjoy the highest life expectancy at birth, at about 75 years. The average for all 13 nations (weighted by population) was 67.0 years, compared with 79.8 years recorded for Australia by the same source (CIA). The other nations with above-average life expectancies for the south Pacific were Cook and Solomon Islands, Samoa, Tonga, Palau and Fiji. Not all these nations had below-average infant mortality rates; the regression is by no means perfect, as indicated by the 19 per cent RSE.

**OWNERSHIP OF COMMUNICATIONS EQUIPMENT** (main telephone lines, radios and television) is known for all 13 nations. As social indicators, they show some correlation with each other and with the infant mortality and life expectancy data. Telephone ownership in all 13 countries averaged 83 per 1000 persons in 1994-95, with 520 radios and 67 television sets per 1000 persons in 1997.[8]

It is apparent that a variety of factors influence these social indicators. Rather than looking for fine differences, we related the three data sets to the average for all 13 nations (Chart 19).[9] The resulting average ratio was highest in New Caledonia, American Samoa and the Cook Islands, followed by French Polynesia, Nauru and Palau. Apart from Nauru, these areas remain dependencies of, or have strong ties with, a western country (France, USA, New Zealand), as well as being relatively well off economically. The lowest index values were in Solomon Islands, Kiribati, Vanuatu and Tuvalu; Tonga and Fiji were slightly below the average.

**EDUCATION:** One socioeconomic indicator missing for most of these countries is education. Since 1990, the United Nations has published a Human Development Index (HDI), composed of life expectancy at birth, adult literacy rates, the combined primary, secondary and tertiary education ratio and GDP (PPP). This composite index is available for four of the 13 nations. In 2000, Fiji was ranked 66th among 174 countries with an index of .769, Samoa 95th at .711, Vanuatu 118th at .623 and Solomon Islands 121st at .614 (Australia was fourth at .929). These indices generally confirm the findings of relative socioeconomic conditions revealed by the analysis of 13 nations. It is noteworthy that Fiji was ranked significantly higher by its HDI than by its GDP alone (so was Australia), while the converse was true for Vanuatu. The GDP ranks were Fiji 89, Samoa 92, Vanuatu 106 and Solomon Islands 126. Australia ranked 13th (UN, 2000).

Available information on education shows that children in Pacific nations generally finish primary school. Secondary school enrolments covered 85 per cent of the age group in the Cook Islands in or around 1994, 57 per cent in Fiji, 32 per cent in Kiribati, 14 per cent in Solomon Islands, 99 per cent in Tonga, 60 per cent in Tuvalu, 17 per cent in Vanuatu and 70 per cent in Samoa (ADB, 1996). These ratios are partly associated with economic development. As far as other areas are concerned, they are all assumed to have high rates of secondary enrolments (70 per cent or more). In total, these Pacific nations have a significantly higher rate of educational attainment than East and South-East Asia (ADB, 1996).

**SAFE WATER ACCESS:** Statistics for members of the Asian Development Bank, recorded by this usually impeccable data source, show the proportion of the population

7 This statement assumes that the 43 per cent estimate shown for French Polynesia in Chart 12 is correct. The estimate was based on a positive but imperfect correlation between the ratio of agriculture and fisheries to total employment, and the ratio of rural to total population in the nine nations for which both sets of data were known (R2 = .769; RSE = 20.7%).

8 Australia, according to the same source (CIA 2000), had 92 million telephone lines in use in 1995, and 25.5 million radios and 10.15 million television sets in 1997. Including business lines, there are about five telephone lines per person in Australia, and about 1400 radios and 550 television sets per 1000 persons.

9 For instance, American Samoans had 178 telephones, 939 radios and 231 television sets per 1000 persons, yielding ratios of 2.13, 1.81 and 3.46, respectively, to the overall averages. The average ratio for American Samoa is therefore 2.47.

having access to safe water is high in the Cook Islands (an estimated 91 to 100 per cent), Tonga (100 per cent), Vanuatu (92 to 99 per cent), Fiji (88 to 97 per cent) and Tuvalu (90 per cent). It was lower in Samoa (50 to 75 per cent) and Kiribati (44 per cent), although ahead of East and South-East Asia (ADB, 1996).

**TRADITIONAL SOCIETY AND LAND TENURE:** Most of the 13 nations are strongly influenced by Polynesian and Melanesian cultural tradition, which has an important impact on their politics and economic performance. In Fiji, for instance, after coups in 1997 and 2000, the Great Council of Chiefs assumed greater powers for appointment of the President and interim Prime Ministers. No change to legislation dealing with native land can take place without two-thirds of both Houses of Parliament, and two-thirds of the Great Council of Chiefs' approval. At the same time, relatively good economic management in the country is hampered by unresolved land tenure problems as well as structural problems in key industries like sugar. The general cultural cohesion of these nations suggests that they may be flexible in their choice of domicile, including New Zealand and Australia which are both home to many Polynesian emigrants, who still retain strong links to

***TABLE 7: BRIEF SUMMARY OF POLITICAL AND RELATED CHARACTERISTICS***

| Nation | Political and related characteristics |
|---|---|
| American Samoa | Unincorporated US territory since 1900. Local parliament. Military US responsibility. Strong US assistance especially to alleviate cyclone damage. 'Americanisation' since 1960s has not obliterated traditional culture. Strong links remain with Western Samoa. |
| Cook Islands | Responsibility transferred from UK to New Zealand in 1900. Self-government in free association with New Zealand in 1965, NZ responsible for external and military affairs. Right to move to full independence in unilateral action. Emigration of skilled workers to NZ is a problem. |
| Fiji | Independent after British rule, 1970. Large Indian population, descendants of contract laborers brought by British in 19th Century. Democracy interrupted by two coups in 1987. Following constitutional change in 1997 first Indo-Fijian government elected in 1999; removed by coup in 2000. |
| French Polynesia | Annexed by France in 19th Century. Overseas French territory since 1946. Territorial Assembly and government in favour of continued relation with France; groundswell of independence calls. Resumption of Moruroa tests 1995 caused riots in main city of Papeete. |
| Kiribati | Granted self-rule by UK in 1971; full independence 1979 when US relinquished claims to Line and Phoenix groups in treaty of friendship. Democratic constitution. |
| Nauru | Independence in 1968 after successful negotiation of fair royalty agreement. In 1970, Australia, New Zealand and Britain handed over their joint control of the phosphate operations to the Nauru Phosphate Corporation. Phosphate deposit expected to be exhausted in 2000. |
| New Caledonia | Referendum on independence was held in 1998 but did not pass (put off until 2013 or later). Matignon Accords 1998 granted substantial legal autonomy to the islands; formerly under French law. Unrest of 1980s replaced by moderate approach by independence supporters. |
| Palau | Independence 1994 from US-administered UN Trusteeship. Constitutional government in free association with the US. Defense is the responsibility of the US. Under the Compact of Free Association between Palau and the US, the US military is granted access to the islands for 50 years. |
| Samoa | First independent Polynesian nation in 20th Century (1962). Dropped 'Western' from its name in 1997. Constitutional monarchy under native chief. |
| Solomon Islands | Parliamentary democracy. Self-government was achieved in 1976 and independence two years later. Ethnic unrest since 1998 crippling the country. |
| Tonga | Independence in 1970. It remains the only hereditary constitutional monarchy in the Pacific. Among the few Pacific peoples never to be colonised. Tongans have maintained their customs and traditions. |
| Tuvalu | In 1974, ethnic differences within the British colony of Gilbert and Ellice Islands caused the Polynesians of the Ellice Islands to vote for separation from the Micronesians of the Gilbert Islands. Independence was granted in 1978. Parliamentary democracy. |
| Vanuatu | The British and French who settled the New Hebrides in the 19th century, agreed in 1906 to an Anglo-French Condominium, which administered the islands until independence in 1980. |

Source: Mainly CIA (2000)

their homelands through remittances and family ties.

**POLITICAL FACTORS:** Compared with most other regions of the world, the Pacific nations are remarkable for their general adherence to democracy, which is tied quite effectively into the texture of traditional societal patterns. Table 7 gives a brief description of the political system in each country. There is really no cause to differentiate between these countries on political grounds. While an adverse future will put strain on any system, the relative political stability is a positive factor in future scenario assessment.

The same cannot really be said for the public administration in these countries. Some of them have very high public service employment, especially among the smaller nations such as Tuvalu and Nauru.

## ECONOMIC INDICATORS

**GROSS DOMESTIC PRODUCT:** Several years ago, the World Bank began to measure Gross domestic product (GDP) in terms of purchasing power parity (PPP), as the proper basis for comparing living conditions across nations. The PPP conversion factor is defined as the number of units of a country's currency required to buy the same amount of goods and services as one dollar would buy in the United States. Exchange rates were traditionally used in international comparisons to convert economic indicators into a common currency such as US dollars. In theory, they adjust through the actions of the market so that the local currency prices of a group of identical goods and services represent equivalent value in every nation. In practice, however, there can be lengthy time lags in the market's adjustment process, which can be further delayed by government actions such as currency controls, interest rate policies and trade barriers (WRI, 2000).

**Gross domestic product (GDP) and GDP per head are important economic indicators. These and other economic indicators are usually associated with ability to cope with change and relatively low vulnerability to change, although they cannot be assessed in isolation without reference to other data.**

Furthermore, many goods are not traded internationally and are therefore relatively insulated from currency movements. This is particularly important for developing third world countries, where prices at the subsistence level tend to be lower than for goods traded through modern distribution systems. Compared with conventional GDP data, PPP estimates tend to lower GDPs for industrialised countries and raise them for developing countries.

Total GDP at purchasing power parity in the 13 nations would be currently approaching $15 billion. The total for the years as shown, roughly centred at 1998, was $14.1 billion. Chart 20 shows the latest available year for each nation. Fiji accounted for almost $6 billion (1999), New Caledonia for $3 billion (1998) and French Polynesia for $2.6 billion (1997). The only other billion-dollar economy in PPP terms was Solomon Islands with $1.2 billion (1999). In comparison, Australia's GDP (PPP) totalled $416 billion in 1999 (CIA, 2000).

New Caledonia enjoyed the highest GDP (PPP) per head (Chart 21 shows $15,000), followed by French Polynesia ($10,800), Nauru ($10,000) and Palau

**Annual change in real GDP per capita, 1983-93**

| | |
|---|---|
| Cook Islands | 4.8% |
| Fiji | 1.0% |
| Kiribati | -1.3% |
| Samoa | 0.6% |
| Solomon Islands | 0.2% |
| Tonga | 2.2% |
| Tuvalu | 6.0% |
| Vanuatu | 0.1% |

Source: ADB 1996, World Bank data

($8800). With the overall average for the 13 nations currently approaching $6000, Fiji also fared better ($7300) and an updated estimate for Cook Islands would probably see this territory at around the average.

The other nations have significantly lower GDPs per head. American Samoa and Solomon Islands are around $2600, Tonga at $2200, Samoa at $2100, Vanuatu at $1300 and Kiribati and Tuvalu below $1000.

Australia's estimated GDP per head at purchasing power parity in 1999 was $22,200.

**ECONOMIC GROWTH:** A review of nine Pacific economies in the mid-1990s found that they had generally performed disappointingly since the early 1980s (ABD, 1996). World Bank statistics showed annual growth rates in real GDP per head averaging 0.5 per cent for Fiji, Kiribati, Samoa, Solomon Islands, Tonga and Vanuatu (see insert for individual rates). The only economies performing better in terms of this measure of economic growth were Cook Islands (4.8 per cent) and Tuvalu (six per cent, from a very small base).

Total real GDP has continued along a patchy path in the 1990s. GDP increased in 10 nations (including Micronesia and the Marshall Islands) by an estimated 3.1 per cent in 1996 before declining by 3.4 per cent in 1997 and barely holding its own in 1998 (ADB, 2000). With a strong improvement in Fiji and recoveries or better growth rates in Cook Islands, Samoa, Solomon Islands and Tonga, lower growth in the small economies of Kiribati and Tuvalu, and recession in Vanuatu, the overall growth rate in 1999 may have been in the order of three to four per cent. In 2000, GDP is forecast to grow by four per cent in Cook Islands.

The high rate of growth of very small economies such as Kiribati and Tuvalu should be kept in perspective. One source mentioned that an increase in public service salaries in Kiribati caused a jump in GDP. With a high aid component and a small economic base, it is possible to demonstrate growth rates that are not based on realistic long-term prospects. In Kiribati's case, roughly half the total national income (GNP) is not due to domestic production but to fishing licence fees, net investment income and seamen's remittances. Significantly, in Kiribati the "GNP rate is decelerating because of declining fish stocks associated with changing climatic conditions" (ADB, 2000).

Another small economy, Nauru, presents one of the most problematic economic cases. Further to its history of substantial growth after gaining a proper share of its phosphate resources in the 1960s, these resources are running out and no other substantial economic base exists. The current economic assessment of the country's fiscal management is harsh: fiscal planning and discipline is considered poor (ADB, 2000). The diminished asset base of the Nauru Phosphate Royalties Trust (NPRT) has not yet been given a reliable value as a basis to assess sustainable consumption levels. Following an attempt to downsize the public service to which almost all the workforce belongs, the Nauru Phosphate Corporation reportedly hired around 200 casual laborers and a significant number of retrenched public servants went into coastal fishing.

Whether or not total growth in any of the island economies is sustainable, growth cannot be judged without reference to the way the product is distributed. This is important in all economies but takes on a special dimension because of the geography of these nations. The issues of outer islands and remote communities are important across almost all Pacific nations. The Asian Development Bank made the following points in its assessment of 10 Pacific economies under its jurisdiction (ADB, 1996):

* Outer island communities are generally small, isolated and resource-poor.
* Development of cash-economy opportunities is extremely limited.
* They are disadvantaged in regional policy-making because there is a need to make sufficient allocations for urban centres to ensure their efficiency for the nation as a whole.
* In many remote communities, the strongest area of comparative advantage is in subsistence production. There is a need to build on this using more effective extension services and improved market access.
* Education is important to improve opportunities for remote communities.

**FISHERIES AND AGRICULTURE** account for about 15 per cent of the total island economies but the proportion varies markedly among the 13 nations. It amounts to half the total GDP in Solomon Islands, 40 per cent in Samoa, 30 per cent in Tonga and 24 per cent in Vanuatu (Chart 22). There is some relationship between dependency on fisheries and agriculture and GDP per head as we move from the most affluent nations to those with about-average income (four per cent for New Caledonia and French Polynesia; five per cent for Palau; 17 per cent for Fiji and 18 per cent for Cook Islands). Among the nations with less than average GDP per head, Tonga and Vanuatu fit into the correlation with 30 per cent and 24 per cent respectively. Kiribati (and American Samoa according to the estimate on Chart 22) showed significantly less than the "expected" share of GDP from fisheries and agriculture, and Samoa and Solomon Islands showed more. Tuvalu also derived a relatively high share of its GDP from fisheries and agriculture (34 per cent) if the estimate from regression analysis of the share between employment and GDP per head is correct.

**The share of fisheries and agriculture, and similar indicators, are factors in the assessment of vulnerability. A low share may imply low vulnerability to change associated with climate. In no case, however, should the assessment be made on the basis of a single indicator. They don't all pull the same way.**

The share of fisheries and agriculture in total employment shows generally larger shares than in GDP (Chart 23). This is partly due to the low value-added in these industries and partly to the subsistence nature of these industries. The ratio was highest in Solomon Islands (82 per cent) followed by Vanuatu (77 per cent), Samoa (73 per cent), Tuvalu (68 per cent) and Tonga (49 per cent). All five nations had less than average GDP per head for the 13 nations.

Chart 24 compares the share of fisheries and agriculture in GDP with their share in total employment. The shares are much lower for GDP than for employment, once again indicating the subsistence character of these industries. The exceptions are American Samoa (which is an estimate and, also, has a very low share for fisheries and agriculture in total GDP and is a special case because of the economic importance of the tuna industry), Cook Islands and

***TABLE 8: FISHERIES STATISTICS, 1994 (TONS)***

| | Reef & slope | Pelagic | Estuarine | Crusta-ceans | Beche-de-Mer | Mother of pearl | Total | Reef & slope |
|---|---|---|---|---|---|---|---|---|
| American Samoa | 8 | 43 | | 0.3 | | | 52 | 16% |
| Cook Islands | 1 | 24 | | | | 99 | 124 | 1% |
| Fiji* | 2,317 | 1,020 | 606 | 501 | 402 | 110 | 4,956 | 47% |
| French Polynesia | 1,492 | 1,173 | | 2 | | 224 | 2,891 | 52% |
| Kiribati* | 1,746 | 690 | | 13 | | | 2,449 | 71% |
| Nauru | 71 | 499 | | | | | 570 | 12% |
| New Caledonia** | 573 | NA | NA | NA | NA | NA | 1,032 | 56% |
| Palau | 492 | | | 14 | | 229 | 736 | 67% |
| Samoa* | 172 | 15 | | 21 | | | 208 | 83% |
| Solomon Islands | 87 | NA | | 2 | 622 | 439 | 1,150 | <8% |
| Tonga | 1,254 | 150 | | 25 | | | 1,429 | 88% |
| Tuvalu | 77 | NA | NA | NA | NA | NA | 120 | 64% |
| Vanuatu | NA | NA | NA | NA | NA | NA | 467 | NA |
| Proportion or reef and slope excluding Vanuatu | | | | | | | | 53% |

* Fiji total given: 6,506 t; Kiribati total given: 3,420 t; Nauru total given: 279 t; Samoa total given: 219 t.
** New Caledonia: reef and slope 55.5% of total value.

Nauru (a special case). The picture is of a dual economy with a relatively affluent services sector and a large subsistence sector. Even in the economies of New Caledonia, French Polynesia and Palau, the relatively small fisheries and agricultural communities fall into the latter category, judging from Chart 24.

It is possible to gain some understanding of the importance of the reef structures for fisheries (Table 8). The data are imperfect and subject to improvement but do allow some differentiation to be made between reef, pelagic and other types of fishing activities. Statistics for the total area, apart from Vanuatu, suggest that reef and slope fisheries account for just over half the total tonnage, with their relative importance highest in Tonga, Samoa, Kiribati, Palau and Tuvalu. The quantity of reef fishing was highest in Fiji, followed by Kiribati, French Polynesia and Tonga. Fiji had the most diversified fisheries sector with significant pelagic and estuarine fishing and a flourishing trade in trochus, mother-of-pearl, bêche-de-mer and giant clams.[10]

The subsistence farming and fishing activities provide quite an efficient means of surviving for many Pacific communities. Coupled with traditional societal systems, including common ownership of land, this prevents any one member of the community from suffering absolute poverty. Indeed, it has been possible for these nations to maintain relatively high standards of living, with poverty, starvation and severe malnutrition generally non-existent, life expectancy rates high compared with Asia and primary education coverage fairly complete. This situation is, however, increasingly under threat with emerging pockets of poverty and environments extremely vulnerable to natural disasters such as cyclones and droughts. According to the ADB, "While such hazards confront many nations, for a Pacific nation one cyclone may wipe out a significant portion of its GDP" (ADB, 1996).

Notably, poverty has become a greater threat to Pacific communities in the past few years. A joint report by the regional development banks, the World Bank and the International Monetary Fund notes: "The countries in the Pacific, despite their relative higher per capita income [compared with Asia], are vulnerable and have limited capacities to deal with external shocks." (MDBs/IMF, 2000).

**CONSUMPTION OF ELECTRICITY** per head of population is a function of various factors, including industry development and general standard of living. It averaged just over 900kWh in 1998 for the 13 nations (one-tenth of the Australian average of 9220kWh in 1998). New Caledonia again tops the scale, followed by Palau, both far above Nauru, French Polynesia and American Samoa (Chart 25). The last country, however, consumes more electricity than might be expected from its GDP per head. Fiji and the Cook Islands consume some two-thirds of the 13-nation average, Samoa, Tonga and Tuvalu roughly one-third, and Vanuatu, Kiribati and Solomon Islands much less.

**GOVERNMENT REVENUE AND EXPENDITURE:** Budget expenditures are about seven per cent higher than budget revenues, according to the most recent statistics, but inconsistencies in the data invite caution. The Asian Development Bank covering the period to 1995 calculates expenditures and revenues relative to GDP for Cook Islands, Fiji, Kiribati, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu (ADB, 1998). The first four countries include foreign aid in their revenues; this has been deducted as much as possible.

The category axis crosses the value axis at '1' on Chart 26, so that all bars pointing to the right indicate budget deficits (in the absence of foreign aid). The governments of all the countries would appear to have serious budgetary problems in the absence of substantial economic aid.

**ECONOMIC AID** is a major source of development financing of these economies. Spending includes mainly public sector investments on building and infrastructure (private investment remains generally low) and technical assistance. Aid per head of population varies widely, with Palau topping Chart 27 with over $9000 (part of a 15-year United States program providing up to $700 million in return for military facilities). The two French dependencies follow. At the other end of the spectrum, Fiji and Samoa rely relatively least on foreign grants. Total aid to the 13 countries was in the order of $1.65 billion around 1996 (reference year varies), equivalent to about $740 per head of population.

**A high level of economic aid from other countries is usually an indicator of vulnerability because such economic aid can be withdrawn. This is more likely to happen if an area is independent, whereas aid given to a dependent area by a metropolitan country is more likely to stay.**

Given the time differences, the total is not dissimilar to the total overseas development aid (ODA) from Australia ($1.43 billion in 1997-98) and New Zealand ($123 million in overseas development aid in 1995). Of course, Pacific nations receive aid from many other sources, and Australia and New Zealand donate to other countries. Nevertheless, the comparison is relevant. In 1997, Samoa and Solomon Islands received 33 per cent of their total aid from Australia, Fiji 32 per cent, Kiribati and Vanuatu 31 per cent, Tonga 28 per cent, Tuvalu eight per cent and other Pacific countries three per cent. Of the remaining countries, New Zealand would provide the main support for the Cook Islands, France for New Caledonia and French Polynesia, and the United States for Palau and American Samoa (AusAID, 1998, which is also the source of the data following).

Japan was the largest donor of overseas development aid to Pacific countries in 1997, excluding French ODA to French territories and United States ODA to former US trust territories. Of the total ODA of about $US 370 million (converted from $A 499 million at 1997 exchange rates), Japan donated 29.6 per cent, Australia 22.8 per cent, New Zealand 17.5 per cent, Europe (individual countries and the EU) 14.7 per cent, and the United States and Canada 3.5 per cent. The remaining 11.9 per cent came from the Asian Development Bank, United Nations, World Bank and from other multilateral aid.

*10* Coral harvesting is another aspect. There are currently an estimated 5000 people engaged in this activity in Fiji alone, according to one of the reviewers of this report. To reduce coral harvesting it would be necessary to divert these people into more sustainable activities such as fish and prawn farming, pearls and seaweed.

Apart from overseas development assistance and contributions to dependent territories, remittances from migrants settling mainly in New Zealand and Australia help to meet the overseas trade deficits, especially in Cook Islands, Samoa and Tonga.

## TRADE AND TOURISM

**MERCHANDISE EXPORTS AND IMPORTS:** The 13 nations have a generally narrow export base, as can be seen from the summary table below. The right-hand column shows the latest available annual total value, which in all countries with significant exports relates to 1996-98. Specific commodities are of major importance in individual countries: Canned tuna in American Samoa (largely dependent on foreign fishing vessels), sugar in Fiji, cultured pearls in French Polynesia, nickel in New Caledonia, phosphates in Nauru. Three countries have significant timber exports: Fiji, Solomon Islands and Vanuatu. Clothing is a significant export item for Cook Islands and Fiji.

**Indicators of merchandise exports and imports help to build up a picture of ability to cope with change and vulnerability to change. A diversified export base is more likely to help in these respects than reliance on few products. Another danger signal is high imports compared with exports.**

Apart from these special cases, the islands rely largely on exports of traditional products: fish and shell products from the sea, copra and other agricultural products from the land. Relative to the populations, the nations that rely most heavily on these products tend to have low exports: Tuvalu at $18 per head, Kiribati at $72, Tonga at $81 and Samoa at $113. The Cook Islands, more diversified than most of the others, exported $226 per head of population, and Palau, despite its apparent narrow base, exported $823. Of the countries with greater specialisation, American Samoa, with a population of only 60,000 in 1996, exported more than $5000 per head (Chart 28). Nauru and New Caledonia, with their mining specialties, also showed high exports per head, with French Polynesia in fourth place. The two other countries with diversified export bases, Solomon Islands and Vanuatu, had lower exports per head of population.

Australia in 1999 exported an estimated $85 billion of widely diversified merchandise, equivalent to slightly more than $5000 per head of population.

Other than Nauru and Solomon Islands, none of these countries would have anything like a positive balance of trade.[11] The imbalance is relatively greatest in Tuvalu and the Cook Islands, where merchandise imports were 27 and 20 times higher than exports respectively (Chart 29). The ratio of imports to exports was around nine in Tonga, six in Kiribati and five in Palau and Samoa. Invisible imports in the form of remittances from Tongans and Samoans who have migrated to other countries are important for these two nations in remitting money back to their families. The merchandise import/export ratio varied between one and a half and four in the remaining nations; ratios that denote seriously distorted merchandise trade balances.

As well as overseas development assistance, the trade balance gap is filled in some cases by other non-merchandise ("invisible") exports, including income derived from overseas visitors. The total balance on current account includes payments and receipts for foreign travel, insurance, remittances to and from persons living abroad, and other invisible imports and exports. Statistics to the mid-1990s (ADB, 1998) show that Kiribati enjoyed an apparently healthy and consistent positive balance on current account and that even Tuvalu achieved balance. In Fiji, the picture varied from approximate balance to $50 million deficits. Tonga was moving into a negative position by 1995 as was Samoa. Solomon Islands had a slightly negative balance and Vanuatu a serious one, varying between $12 million and $20 million, equivalent to up to 10 per cent of its GDP. There was no information for the Cook Islands.

Other foreign trade issues include the difficulty of developing a broader export base, further frustrated by the erosion of trade concessions given specially to these nations through SPARTECA (the South Pacific Regional Trade and Economic Cooperation Agreement). As the Pacific nations' closest trading partners (Japan, Australia,

Brief summary of merchandise export specialisation of 13 Pacific nations

| Country | Description | $ million |
|---|---|---|
| American Samoa | Canned tuna 93% | 313 |
| Cook Islands | Copra, papayas, fresh and canned citrus fruit, coffee, fish, pearls and pearl shells, clothing | 4 |
| Fiji | Sugar 32%, clothing, gold, processed fish, timber | 393 |
| French Polynesia | Cultured pearls 50%, coconut products, mother-of-pearl, vanilla, shark meat | 212 |
| Kiribati | Copra 62%, seaweed, fish | 6 |
| Nauru | Phosphates | 25 |
| New Caledonia | Ferro-nickels, nickel ore, fish | 381 |
| Palau | Trochus, tuna, copra, handicrafts | 14 |
| Samoa | Coconut oil and cream, copra, fish, beer | 20 |
| Solomon Islands | Timber, fish, palm oil, cocoa, copra | 142 |
| Tonga | Squash, fish, vanilla beans | 8 |
| Tuvalu | Copra | 0.2 |
| Vanuatu | Copra, beef, cocoa, timber, coffee | 34 |

Source: CIA, 2000

11. The ratios are slightly distorted because exports are counted free-on-board (fob) and imports including cost, insurance and freight (cif).

North America, New Zealand) move towards an increasingly freer foreign trade regime, the advantages formerly enjoyed by Pacific nations tend to disappear.

There may be some opportunities to replace imports. It may be difficult to develop a manufacturing base beyond existing ventures into canned tuna, some clothing and footwear, and other relatively modest efforts. Development of local supply of food, furniture and artefacts for the tourism industry may have some prospects; a study in 1986-87 in Fiji, Tonga, Vanuatu and Samoa found the import content of food and beverage purchases by hotels to be about 53 per cent. Lack of reliable and sufficient supplies of quality food was a problem (ADB, 1996).

**VISITORS:** An estimated 854,000 persons visited the 13 island nations in 1995 (Chart 30). Most went to Fiji (37.2 per cent), followed by French Polynesia (20.8 per cent), New Caledonia (10.3 per cent), Samoa (8.0 per cent), Palau (6.2 per cent), Cook Islands (5.6 per cent), Vanuatu (5.2 per cent) and American Samoa (4.7 per cent).

**High reliance on reef-based tourism is a clear indicator of vulnerability to change caused by deterioration of reef quality. The tourist industry may have a greater or lesser ability to cope with such change, dependent on the relative role of reef versus other tourism, and similar indicators.**

Per head of population, however, by far the highest numbers go to Palau (more than three times the local population in 1995) and the Cook Islands (two times more). French Polynesia and American Samoa also enjoyed high numbers relative to their populations (0.8 and 0.7 visitors per head respectively). Further down the list followed New Caledonia, Fiji and Samoa. Visitation rates were much less in Kiribati, Solomon Islands and (estimated) Tuvalu (Chart 31).

Thanks to the Secretariat of the Pacific Community (SPC), it is possible to obtain a reasonable estimate of the growth in number of visitors to the 13 nations. The estimate for 1991 was 700,000 and, for 1998, just over one million. Regression analysis shows an annual trend of 5.3 per cent ($R2 = .972$, RSE = 6.8%). The highest growth (Chart 32) was in Palau and Samoa, while Solomon Islands and American Samoa appear to have gone backwards. Good growth rates included French Polynesia (7.2 per cent), Fiji (5.4 per cent) and New Caledonia (4.1 per cent).

Between 1988 and 1993, tourism growth to the 10 Pacific member nations of the Asian Development Bank increased by 6.4 per cent per annum, compared with an increase of 4.5 per cent worldwide (ADB, 1996).

Data from ESCAP include total spending by visitors, used in conjunction with the SPC statistics for Chart 33. Spending per visitor appears to be highest in the two French dependencies followed by Vanuatu, Solomon Islands and Cook Islands. We have assumed that the average is also relatively high in Palau, which has no data. The overall average for the 13 nations was an estimated $1053 per person per year.

This leads to Chart 34, showing estimated total tourism spending in the 13 nations. Of a total estimated $900 million spent in 1995, Fiji accounted for $283 million, French Polynesia for $269 million, New Caledonia for $127 million, Vanuatu for $58 million, Palau for $53 million and Cook Islands for $49 million. Per head of population, however, Palau comes out way ahead at more than $2800 (Chart 36), followed by Cook Islands ($2400), French Polynesia (about $1100) and New Caledonia ($630).

Estimated tourism spending may be compared with conventional gross domestic product estimates to gain some idea of the role of tourism in an economy. However we are comparing two different concepts. GDP is composed of the net contribution of all industries in an economy. The GDP concept is net of payments of goods and services to other industries needed to derive the tourism product. GDP also generates imports as many hotel goods are brought in from abroad. Nevertheless, the ratios on Chart 36 make sense as a first approximation of the role of tourism in the total economy. Tourism is relatively most important, according to this estimation procedure, in the Cook Island and Palau economies, followed by Vanuatu, American Samoa, Fiji and Samoa. In the French dependencies, the economy is sufficiently diversified for tourism to play a relatively lesser role despite the high absolute spending totals shown in Chart 34.

Two further observations on tourism in a competitive environment are appropriate:

* In a world of changing competitive strengths, including the attractiveness of particular features (such as reefs), particular tourism facilities will gain a different ranking if the attractiveness of reefs deteriorates. This may cause, say, an international chain of tourism facilities to relocate from a given site to other alternatives.
* On the other hand, the tourism industry has proven its resilience in the past and may choose to differentiate its services to shift the main focus from, say, clean and unpolluted reefs to other attractions.

The willingness to pay for particular tourism services may be an important factor in this process of relating competitive choice to changing demand. Willingness to pay has been presented as an indicator of perceived reef health. The higher the willingness to pay above required profit levels the higher is the tolerable decrease before a significant impact is realised. As reefs become less attractive to tourists, this may imply a "vicious cycle": Demand decreases as the attraction deteriorates, thus eroding the profitability of the tourist operation; this leads to quality cuts in services provided, which again affects the demand patterns, and so on. In the world of multinational companies, a site may be abandoned if its attractiveness deteriorates relative to alternative locations.

## VULNERABILITY OF PACIFIC ISLAND NATIONS

It is appropriate to preface this attempt at providing vulnerability measures with a general statement on environmental concerns made a few years ago, before the climate issue became generally prominent (ADB, 1996).

Around the mid-1990s, there was a realisation that the physical environment of Pacific nations was fragile. The most immediate issues, according to ADB (1996), related to environmental degradation associated with urbanisation and damage caused by exploitation of natural resources, particularly forestry. A report sponsored by the South Pacific Regional Environmental Program (SPREP) found that all participating nations were concerned about:

* Waste management in urban entities;
* Pollution of reefs, lagoons and other coastal areas;
* The need to preserve biodiversity.

Other identified key issues included:

* Deforestation through extensive commercial logging;
* Neglect of traditional agro-forestry procedures;
* Overfishing of inshore areas;
* Overpopulation of some small islands.

Table 9 presents a "vulnerability index" based on the following assessments (within the scope of the study there was no opportunity for refinement through multivariate analysis as in the three-year SOPAC project):

* Physical exposure, from extreme = 5 to low = 1
* Outer islands (vulnerable in sociopolitical terms as well as physically). Many or all = 5; few = 1; Nauru as a special case rated 3)
* Population density/pressure, from very high = 5 to low = 1
* Foreign aid per head, from very high = 5 to low = 2 and none = 1
* Subsistence activities in fisheries and agriculture. Most = 4 and Some not = 2

With a diversity of factors acting in different ways on each Pacific nation, and realising the limitation of simple ranking approaches and weighing each measure equally in the total score, Table 9 nevertheless presents a plausible picture of how the 13 nations are ranked in terms of vulnerability. With a maximum score of five, it clearly shows the most vulnerable country to be Tuvalu, followed closely by Kiribati and, not far behind, Cook Islands and Palau. Tonga, French Polynesia, Nauru and New Caledonia are next, with the lowest vulnerability scores recorded for larger nations: Vanuatu, Solomon Islands, Fiji and American Samoa, in that order.

The most important finding, however, is that even the most robust economy is vulnerable to a significant extent. Compared with the lowest score of 2.83 (and a minimum score of one), Australia in the same framework might perhaps rate between one and one and a half. To the extent that the score makes sense in the Australian context, it might rate 2 (low/moderate) on physical exposure due to the size of the Great Barrier Reef, 1 on outer islands, perhaps 2 on population pressure due to the size of the capital cities, 1 on foreign aid as a net donor, and 1 on subsistence activities (there are no major activities of this nature except a small outback indigenous population). This implies a total

**Table 9: Summary indicators of exposure to climate change**

| Nation | Indicative GDP trend* | Physical exposure | Population growth | Outer islands | Population pressure | Foreign aid Per head, Total | Subsistence activities | Reef tourism | Political stability | Vulnerability index |
|---|---|---|---|---|---|---|---|---|---|---|
| **American Samoa** | 2.5% | Moderate | 3.1% | Few | High overall (329/sq km); Pago Pago polluted | $22m, $426, Moderate | Some fisheries are not | Important part of total tourism | Neutral | **2.83** |
| **Cook Islands** | 3.0% | Extreme | 0.3% | All 15 | Low/moderate (overall 85/sq km); 65% rural population | $13m, $695, High | Some fisheries are not | Dominant tourism activity | Neutral | **3.83** |
| **Fiji** | 3.0% | Moderate | 1.0% | Many | Low/moderate (overall 46/sq km); 54% rural population | $40m, $52, Low | Most fisheries and agriculture | Important part of total tourism | Neutral | **3.17** |
| **French Polynesia** | 4.0% | Moderate | 1.3% | Many | Low/moderate (overall 60/sq km); 43% rural population | $450m, $1,975, Very high | Most fisheries and agriculture | Important part of total tourism | Neutral | **3.67** |
| **Kiribati** | 3.0% | Extreme | 1.7% | All 33 | High (128/sq km); south Tarawa atoll badly polluted | $16m, $189, Moderate | Most fisheries and agriculture | Not much tourism but reef dominates | Neutral | **4.00** |
| **Nauru** | 0.0% | Moderate | 2.2% | None | Very high; devastated island (564/sq km) | $2m, $202, Moderate | Most, and more being forced into | Not much tourism but reef dominates | Neutral | **3.50** |
| **New Caledonia** | 3.5% | High | 2.1% | Some | Low (13/sq km); 40% rural population | $770m, $3,932, Very high | Most fisheries and agriculture | Important part of total tourism | Neutral | **3.50** |
| **Palau** | 5.0% | Moderate | 2.0% | Many | Low/moderate, overall 41/sq km | $156m, $9,139, Very high | Most fisheries and agriculture | Dominant tourism activity | Neutral | **3.83** |
| **Samoa** | 3.5% | Moderate | 1.7% | Few | Low/moderate, overall 63/sq km; 79% rural population | $43m, $236, Moderate | Most fisheries and agriculture | Important part of total tourism | Neutral | **2.83** |
| **Solomon Islands** | 3.5% | Moderate | 3.2% | Many | Low/moderate, 63/sq km; 87% rural population | $46m, $116, Low | Most fisheries and agriculture | Important part of total tourism | Neutral | **3.17** |
| **Tonga** | 2.0% | High | 0.3% | Many | Moderate/high, overall 137/sq km; 64% rural | $39m, $417, Moderate | Most fisheries and agriculture | Important part of total tourism | Neutral | **3.67** |
| **Tuvalu** | 3.0% | Extreme | 1.4% | All nine | Very high (417/sq km) | $8m, $782, High | Most fisheries and agriculture | Not much tourism but reef dominates | Neutral | **4.33** |
| **Vanuatu** | 2.0% | Moderate | 2.9% | Many | Low (13/sq km); 80% rural population | $46m, $254, Moderate | Most fisheries and agriculture | Important part of total tourism | Neutral | **3.17** |

Overall risk assessment: extreme = 5; no risk = 0.
Reference indicator of approximate future trend in the absence of climate change and reef damage.

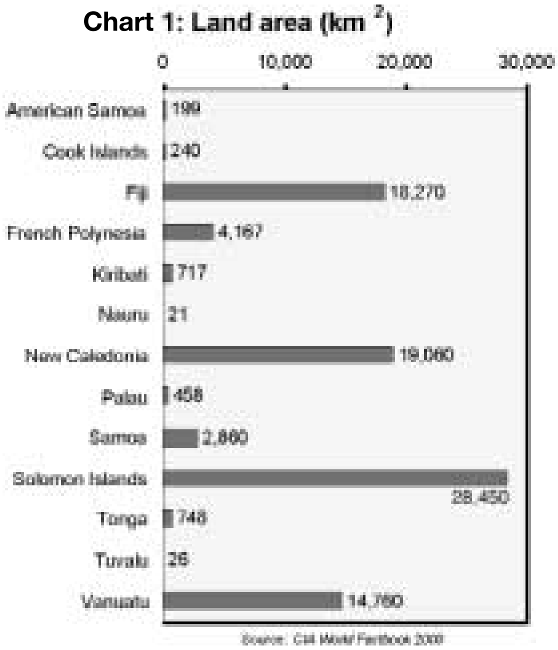
vulnerability index of 1.4 for Australia, even in a slightly harsh assessment for that country.

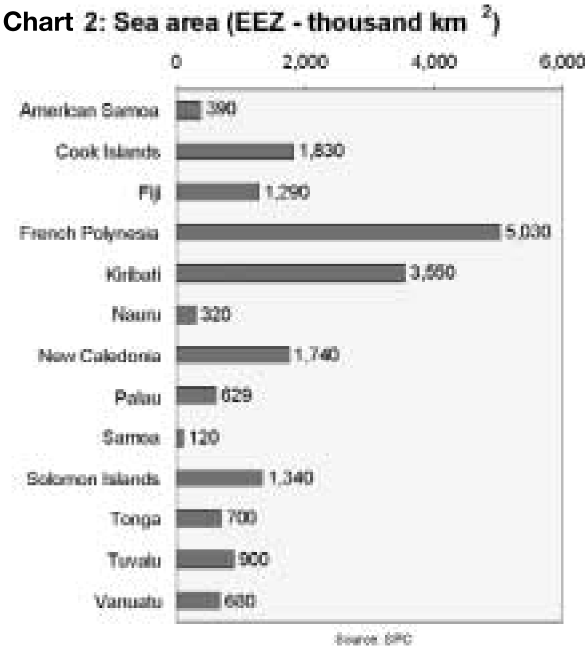
Another dimension to consider is ability or competence to adapt to adverse circumstances. This must necessarily be a value judgment, based on a variety of factors such as support from another country, size and stability of economy and GDP per head, utilisation of natural resources, traditional strength and cohesion, geographic cohesion, competence in governance, diversity in exports, environmental issues including availability of potable water, and, as a negative factor in view of the perceived threats, the importance of tourism generally and reef tourism specifically, coupled with the ability of the tourist industry to renew itself in a new situation. Our assessment is that there is a general inverse correlation with the vulnerability index, with two main exceptions: Cook Islands may have greater resilience than suggested by Table 9 and Nauru may be in a worse position despite its current high income per head of population.

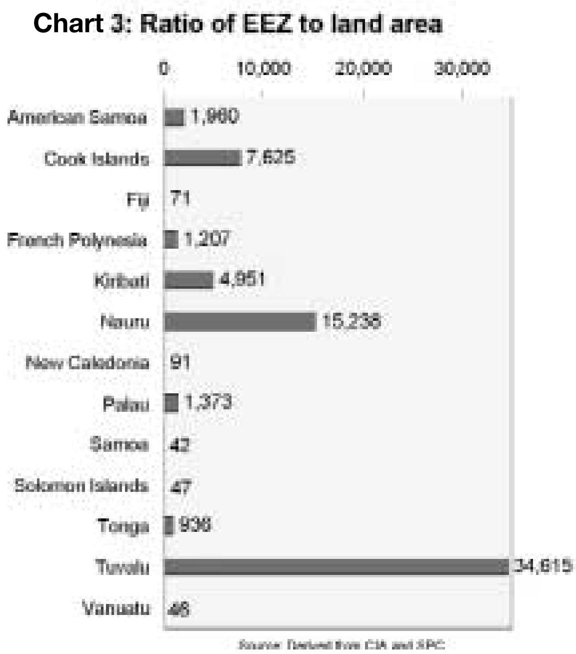
**Figure 9** on the following pages presents 36 individual charts described in the preceding text. The charts are divided into the following groups:

- Physical indicators (Figures 9a-9c: Charts 1-10)
- Demographic indicators (Figures 9c-9d: Charts 11-16)
- Social indicators (Figure 9e: Charts 17-19)
- Economic indicators (Figures 9e-9g: Charts 20-27)
- Trade and tourism (Figures 9g-9i: Charts 28-36).

### *FIGURE 9A: PHYSICAL INDICATORS*



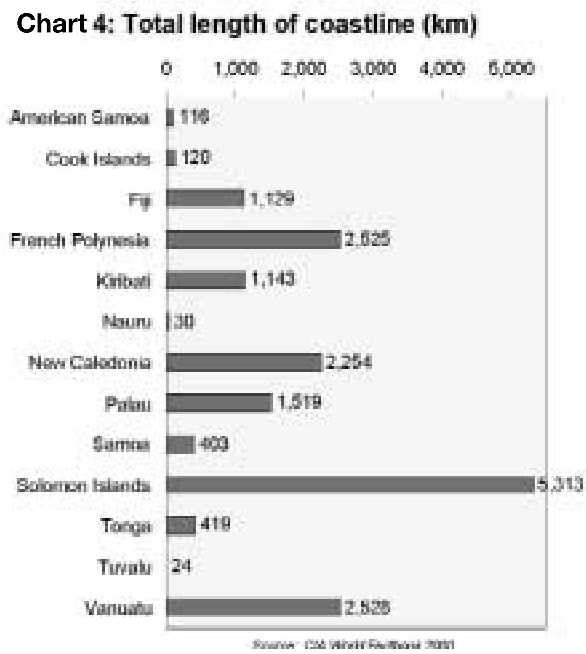



***Figure 9b: Physical indicators***

**Chart 5: Area of coral reefs (km $^2$)**

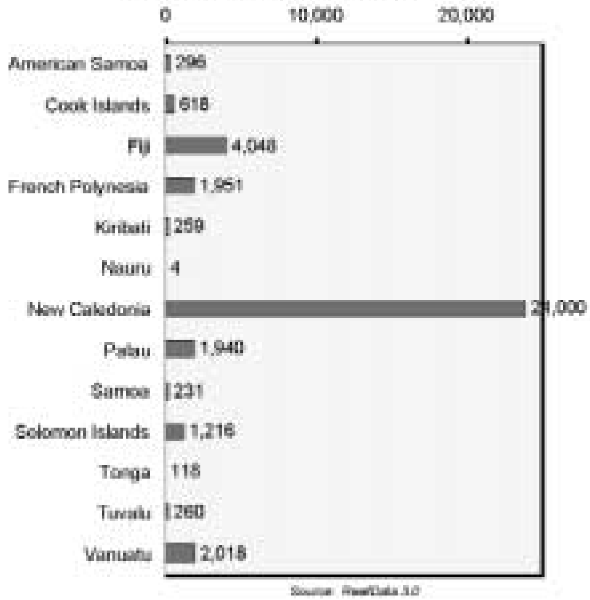



**Chart 6: Number of coral reefs**

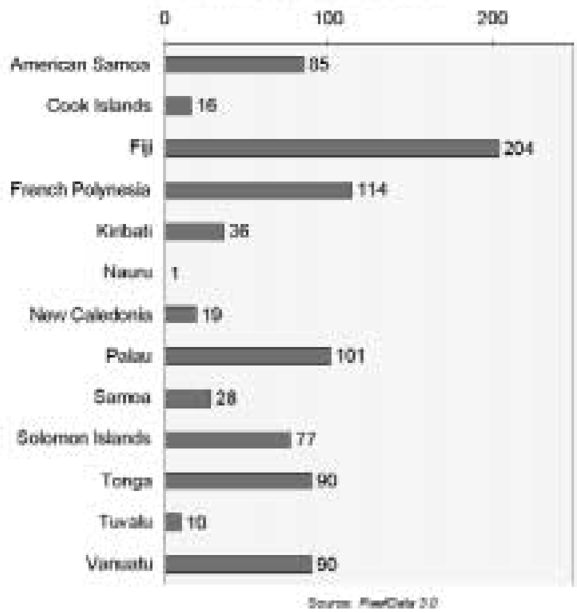



**Chart 7: Reef area relative to land area**

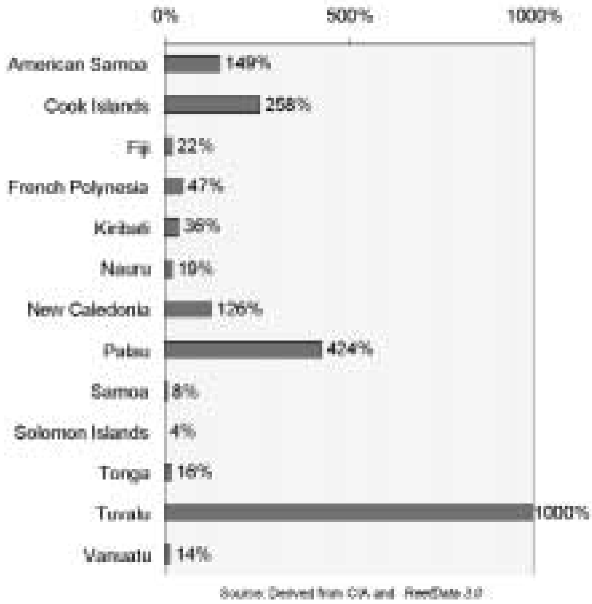



**Chart 8. Warming rates 1900-97 ( $^{\circ}$C)**

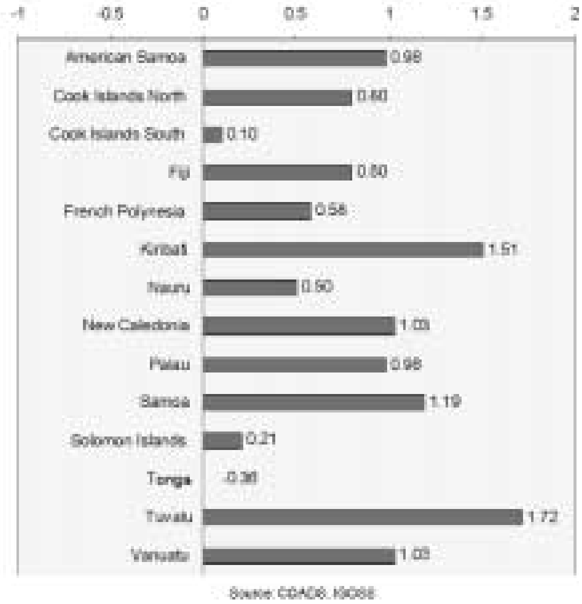


***FIGURE 9C: PHYSICAL AND DEMOGRAPHIC INDICATORS***

**Chart 9: Arable land, crops and pastures**

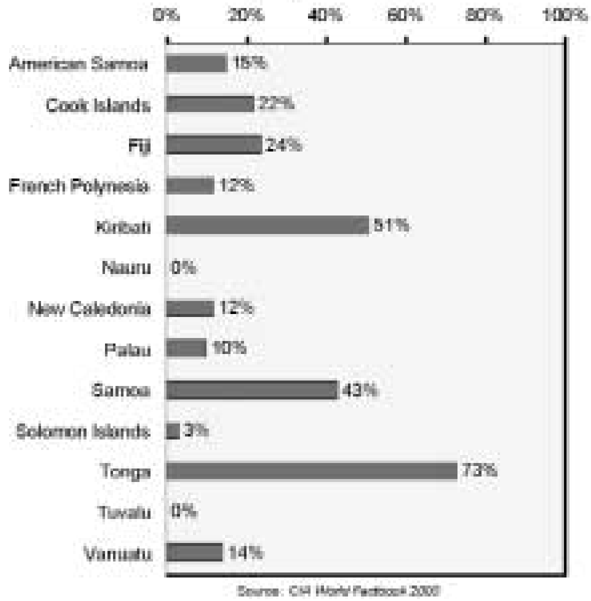



**Chart 10: Forests and woodlands**

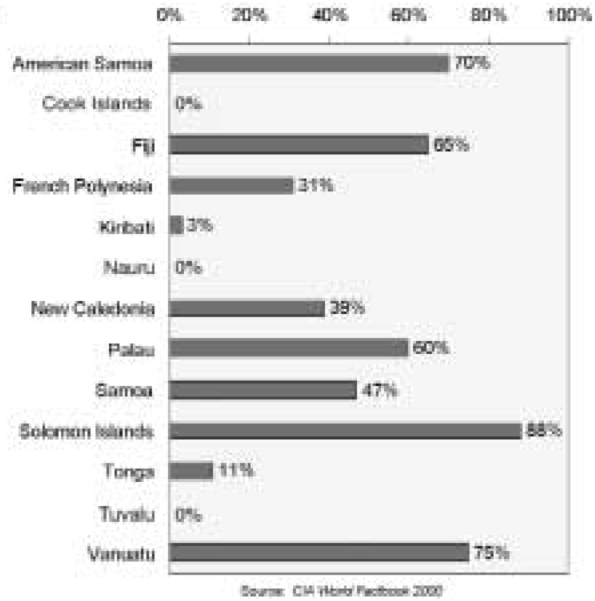



**Chart 11: Population in July 2000 (thousand persons)**

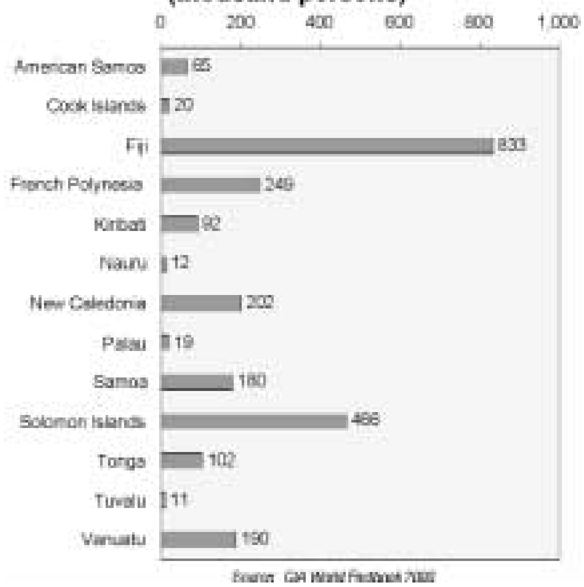



**Chart 12: Annual population trends 1991-98**

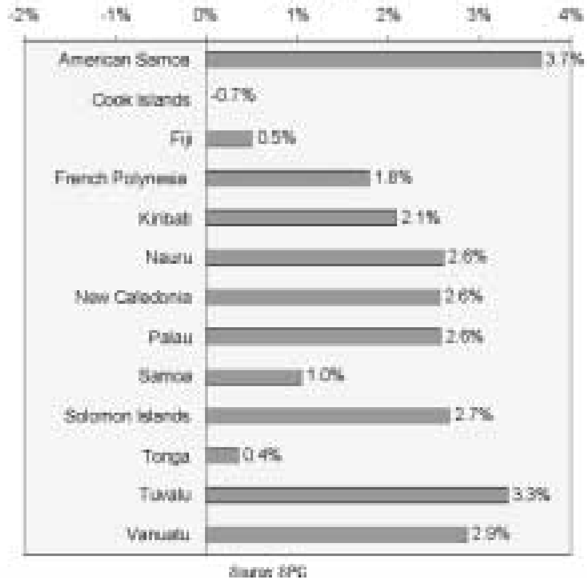


***FIGURE 9D: DEMOGRAPHIC INDICATORS***

**Chart 13: Projected population trends 1998-2010**

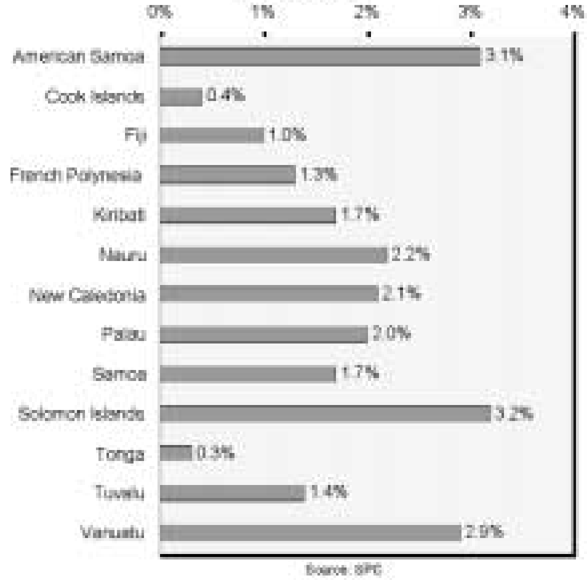



**Chart 14: Population density (persons per km $^2$)**

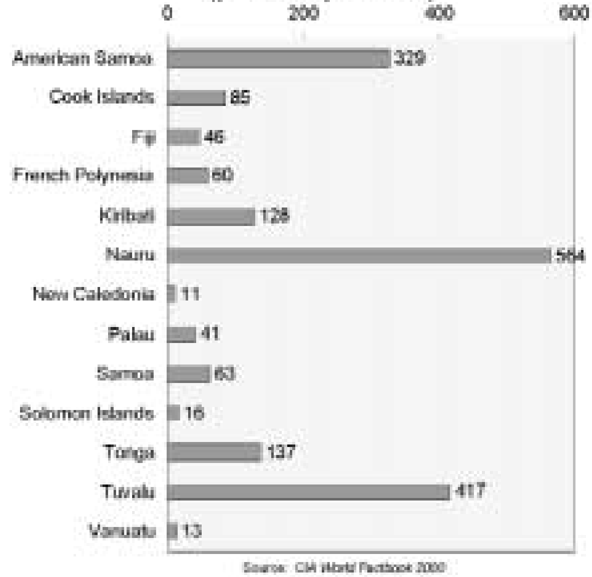



**Chart 15: Population under 15 years of age**

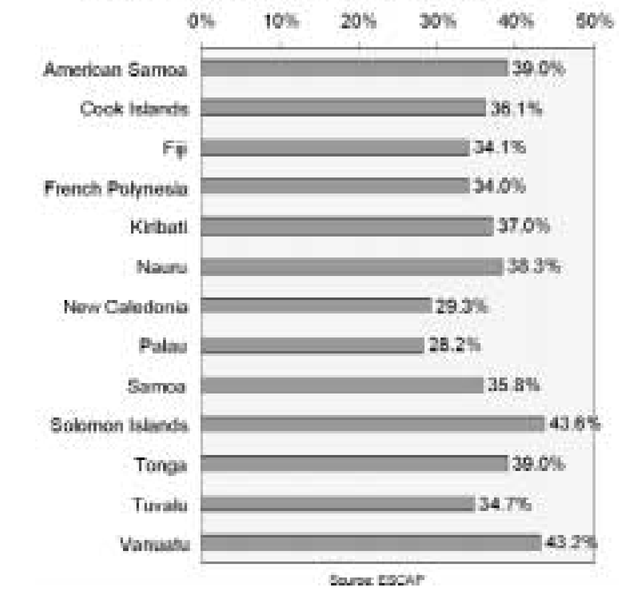



**Chart 16: Rural population**

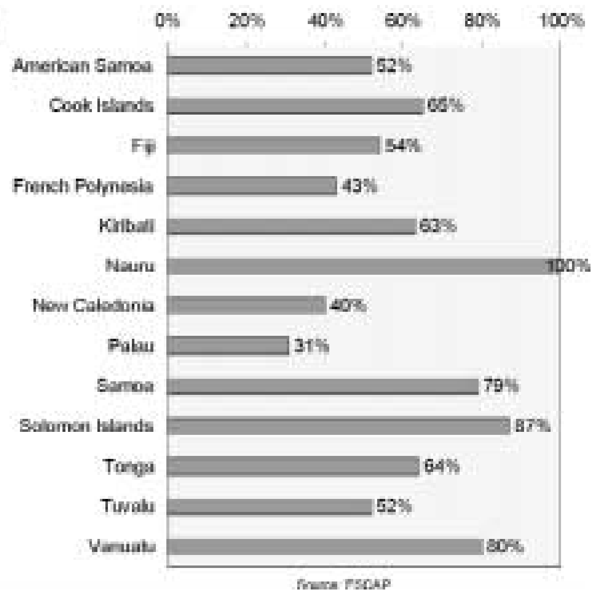
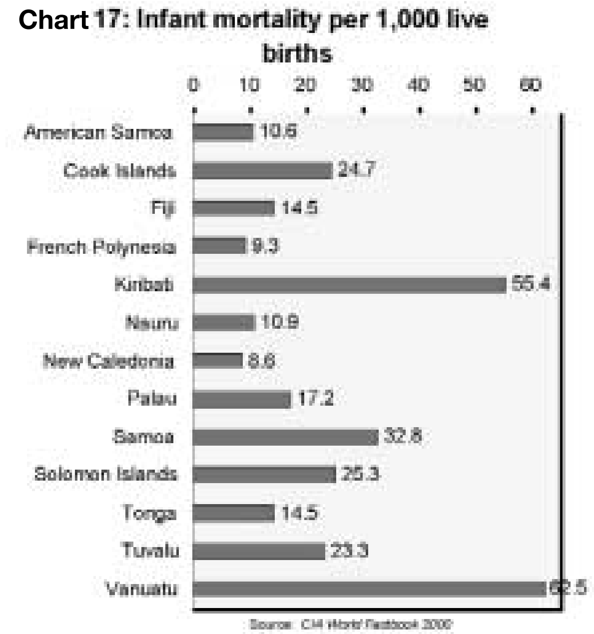
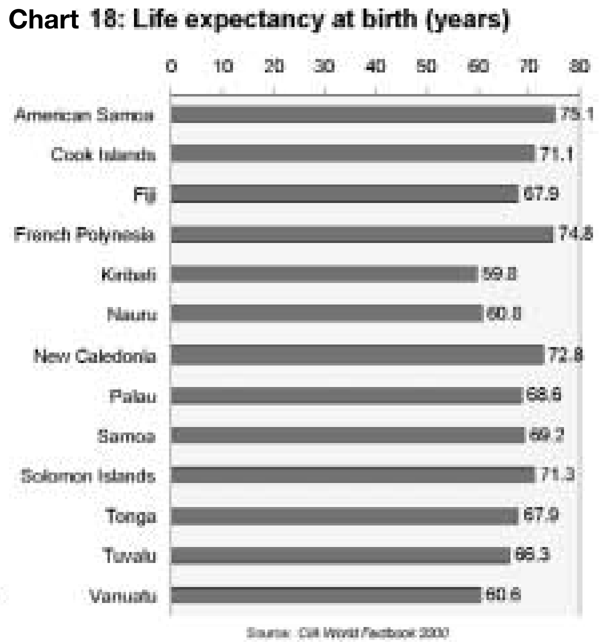
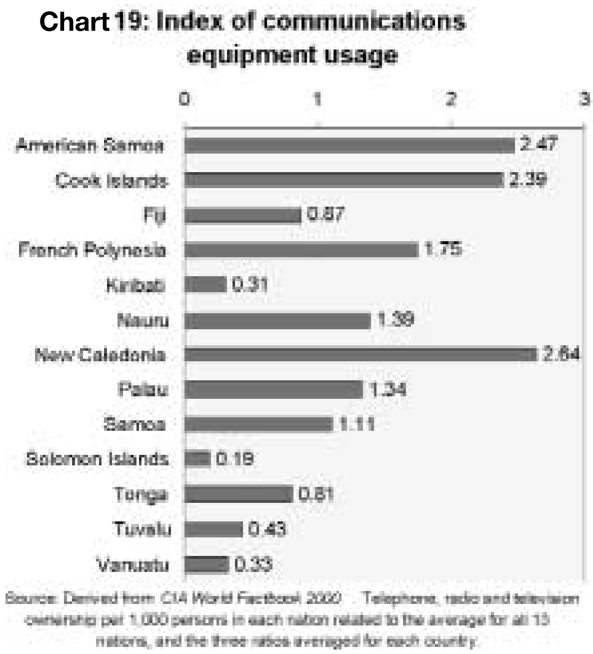


***FIGURE 9E: SOCIAL AND ECONOMIC INDICATORS***



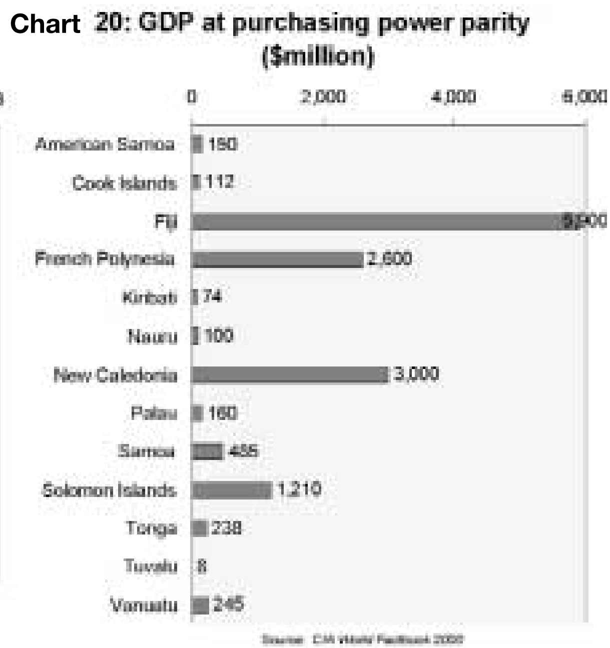
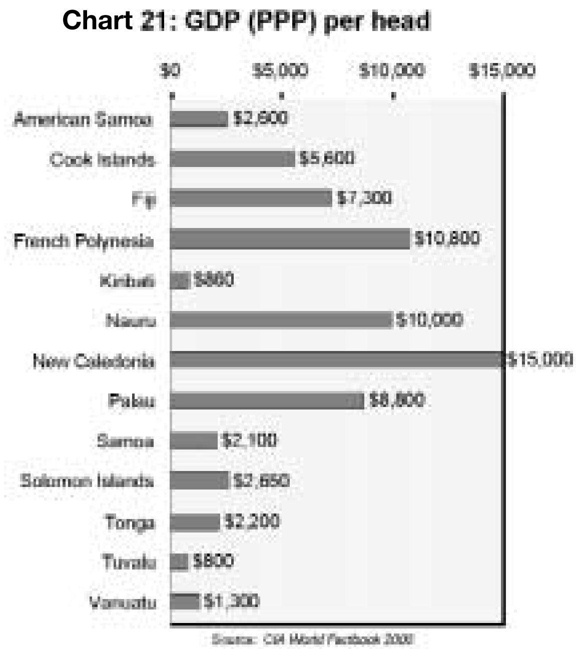
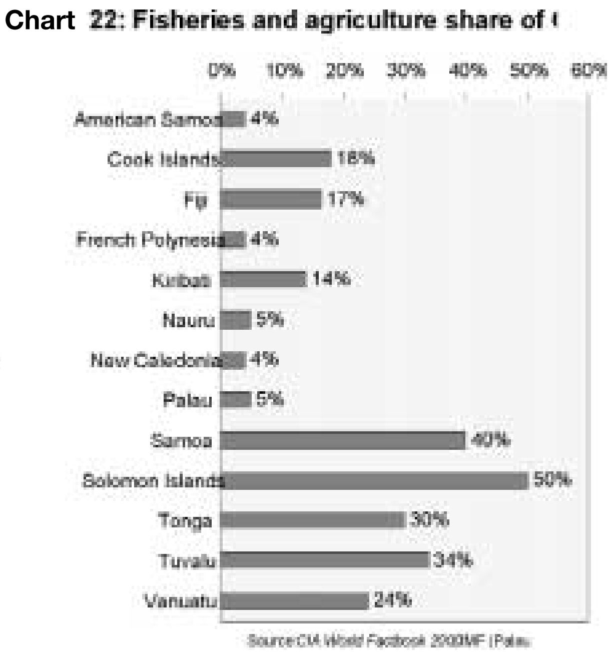
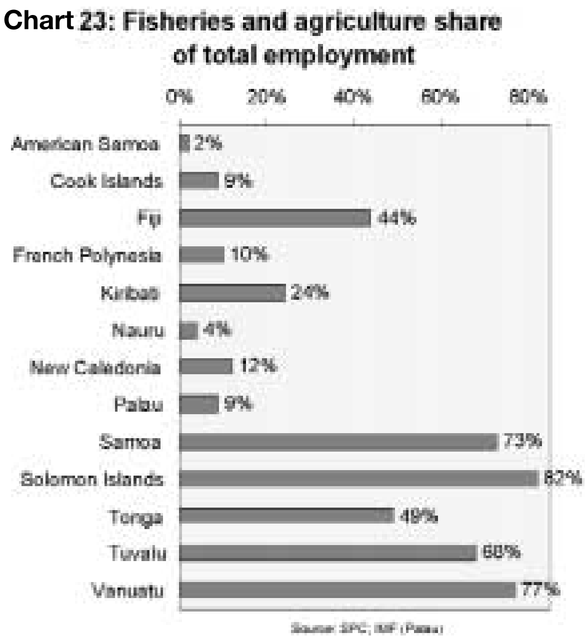



***Figure 9f: Economic Indicators***



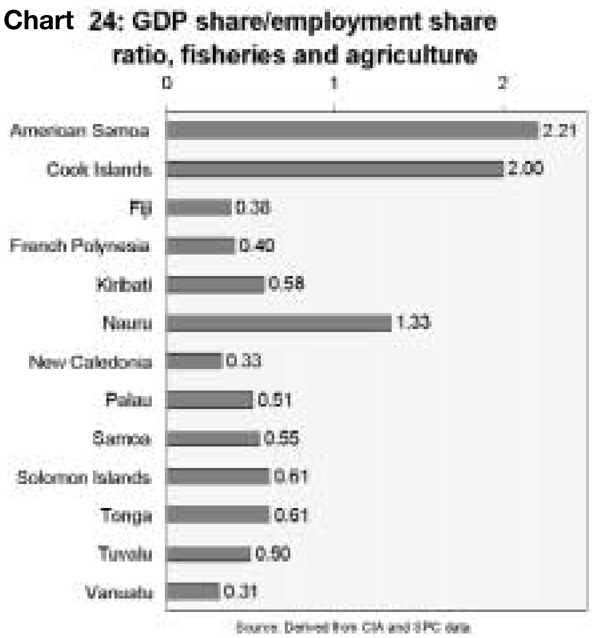
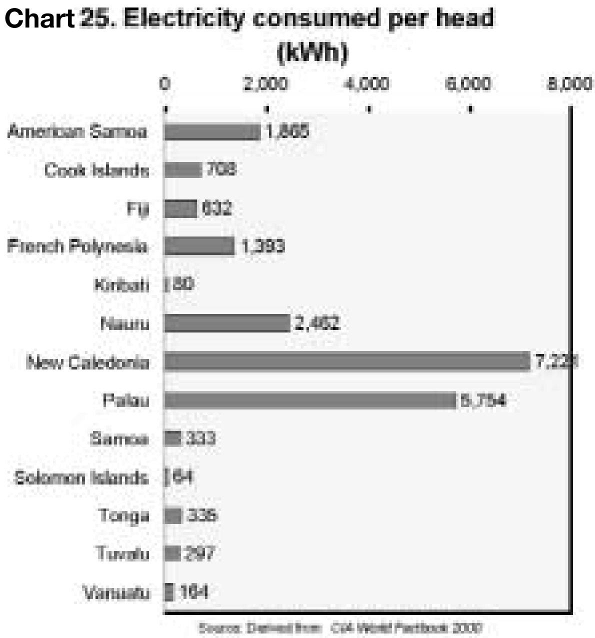
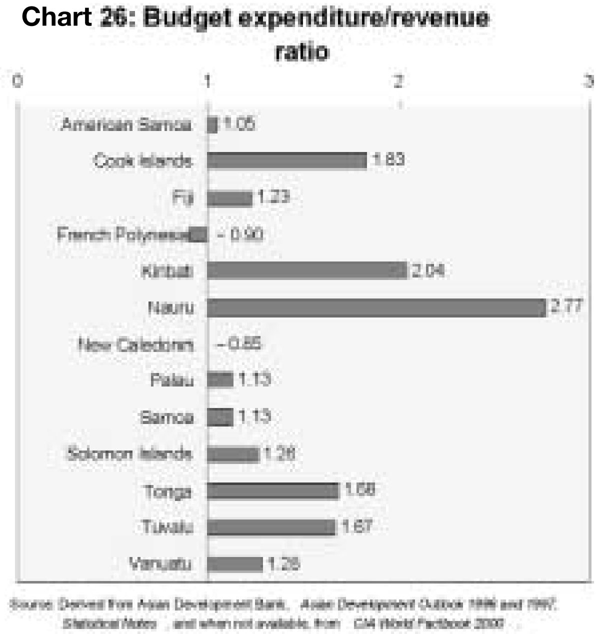
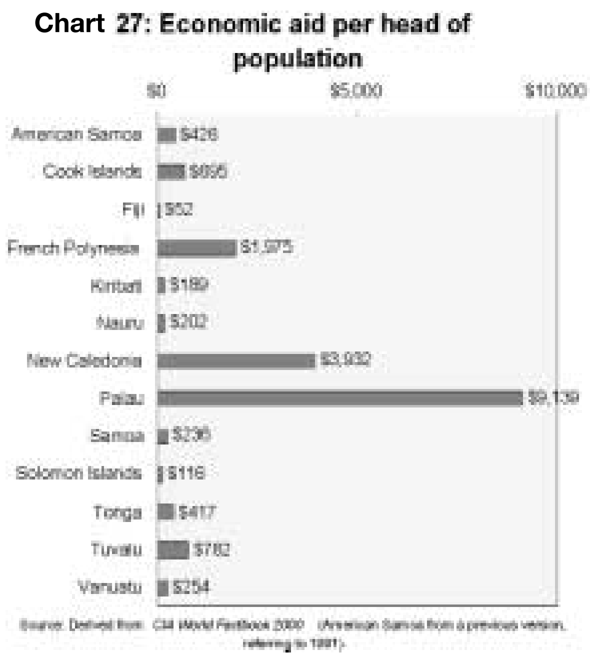



***FIGURE 9G: ECONOMIC AND TRADE INDICATORS***



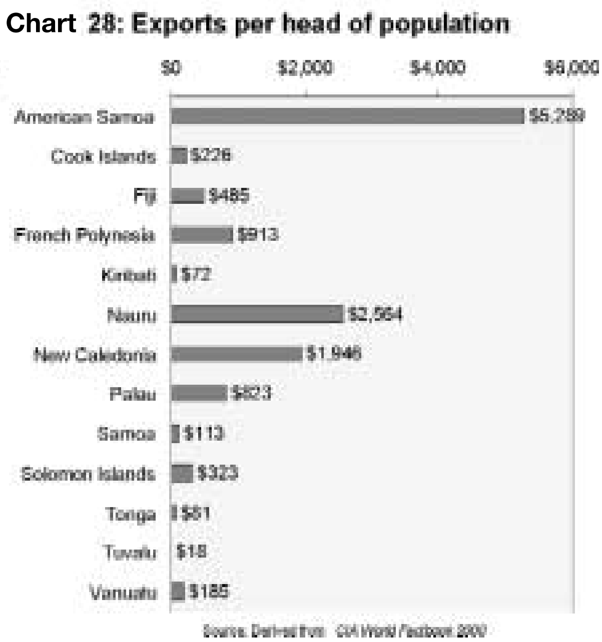
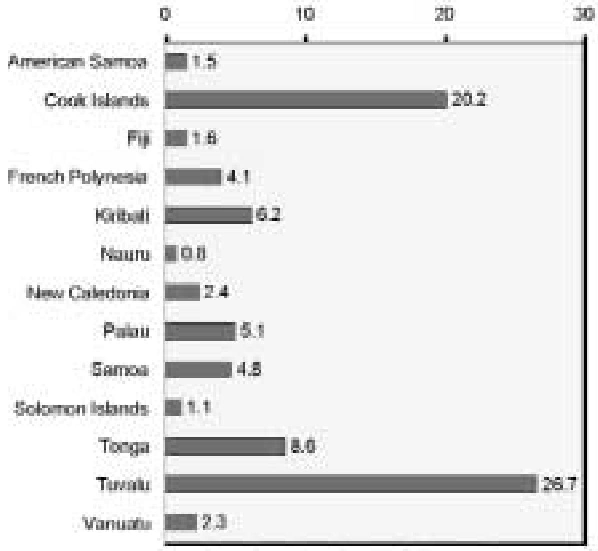



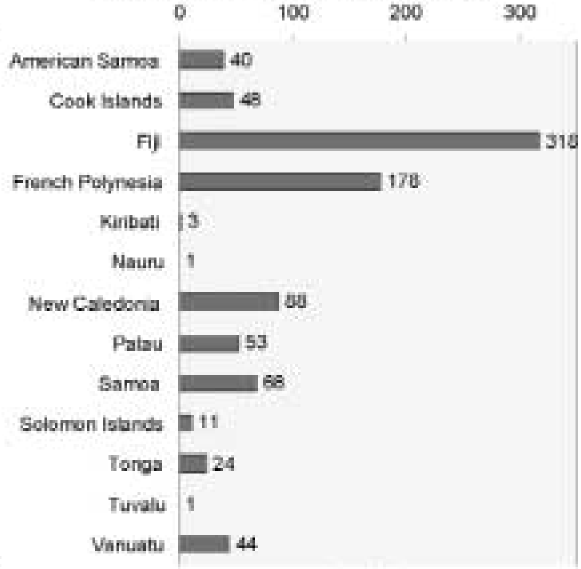
***Figure 9h: Trade and Tourism Indicators***

**Chart 29: Merchandise imports relative to merchandise exports**



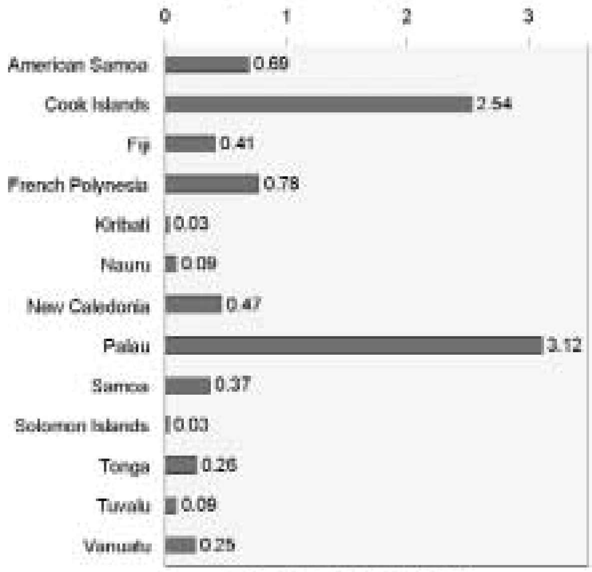

Source: Derived from CIA World Factbook 2000

**Chart 30: Foreign visitors in 1995 (000)**



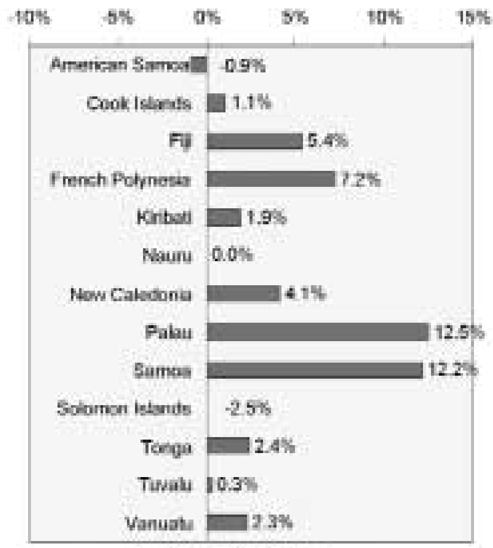

Source: SPC

**Chart 31: Visitors per head of population**




Source: Derived from SPC and CIA data

**Chart 32: Estimated growth trend, visitors**




Source: Derived from SPC data

***FIGURE 9I: TRADE AND TOURISM INDICATORS CONCLUDED***

**Chart 33: Estimated spending per visitor, 1995**

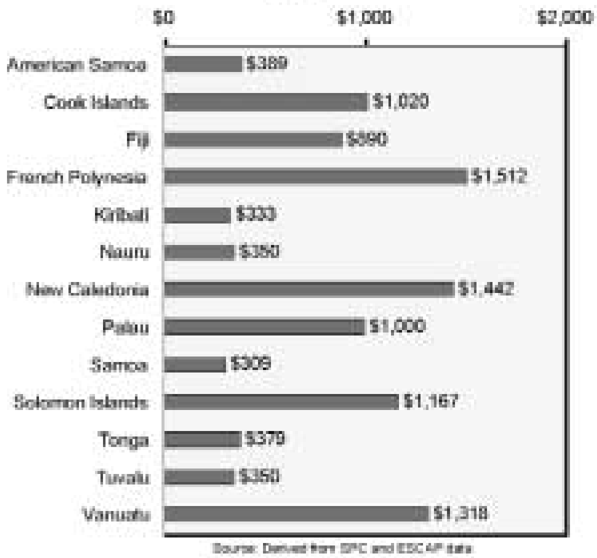



**Chart 34: Estimated total tourism spending, 1995 ($million)**

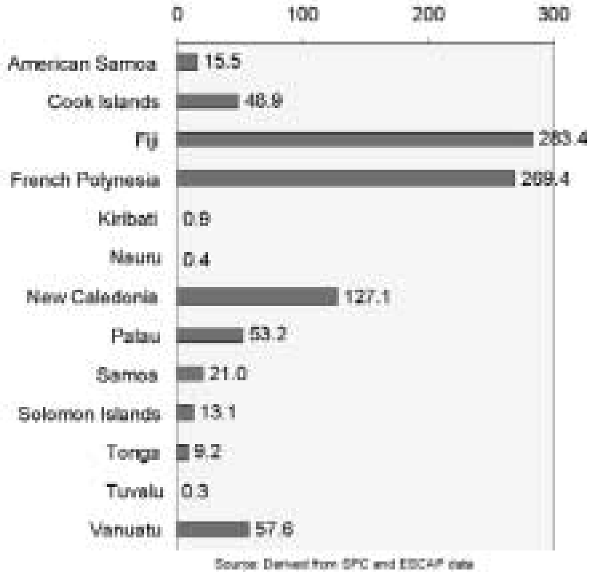



**Chart 35: Estimated tourism spending per head of population, 1995**

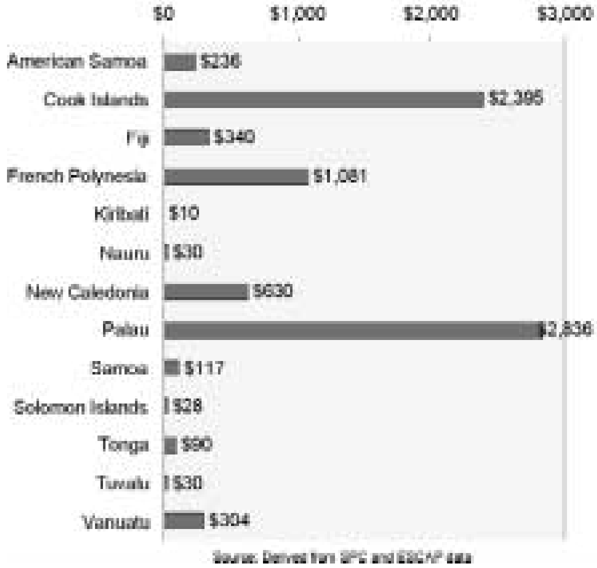
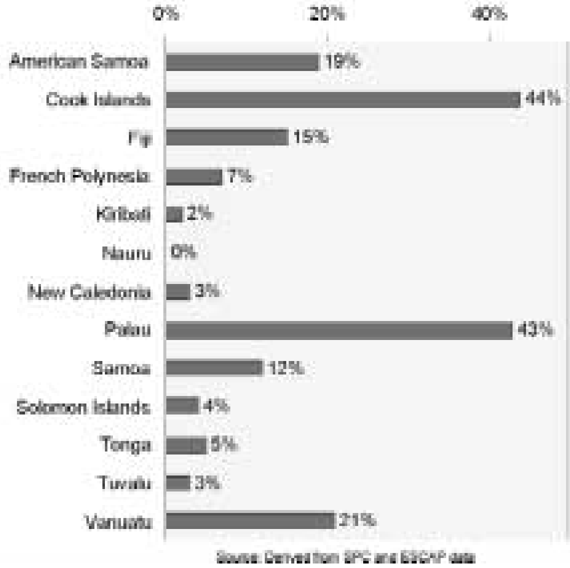



**Chart 36: Estimated tourism spending relative to GDP, 1995**



# IMPACTS OF CLIMATE CHANGE ON PACIFIC COASTAL ECONOMIES

## INTRODUCTION

Although differences between the Pacific islands are enormous, the majority of constituent populations have low incomes and their dependence on fisheries for income and animal protein intake is high. Frequent episodes of coral bleaching and subsequent coral mortality due to climate change are likely to have serious socioeconomic impacts on Pacifc islands.

In areas where overfishing and overexploitation of marine resources are already threats, coral bleaching could worsen these problems. Also, some fish that are available may become toxic as levels of ciguatera poisoning are likely to increase due to coral mortality and subsequent algal growth (Hales et al, 1999). In other areas, diving and other coastal tourism are the main income-generating activities. In Palau, for example, a large portion of GNP stems directly and indirectly from tourism revenues.

Furthermore, the land area around the Indo-Pacific Ocean is prone to seasonal cyclones and coral reefs form natural barriers to protect coastlines from erosion. Examples from other regions highlight the threat. In Sri Lanka, in the Indian Ocean, severe coastline erosion has already occurred in areas where the reef substrate has been heavily mined. Countermeasures to prevent further erosion have already cost the Sri Lankan government around $US 30 million (Berg et al, 1998). In time, coral mortality may lead to bio-erosion that could similarly deteriorate the reef substrate of Pacific reefs.

Current knowledge of the biophysical and ecological processes and consequences of coral bleaching is such that we are unable to fully refine some key issues into an accurate and high-resolution understanding of the impact of climate-induced changes in coral reefs on human societies and welfare. It continues to be very difficult to translate increases in sea surface temperature to long-term socioeconomic impacts. Within this caveat, however, we will present such estimates for tourism, fisheries and other socioeconomic services of coral reefs and develop two edges of a "window" into the future.

## UNCERTAINTY AND THE FUTURE

The uncertainty surrounding many of the relationships between coral bleaching and mortality, on the one hand, and ecosystem services, on the other, is enormous. Besides, the recovery rate of reef areas after widespread mortality is difficult to predict and depends crucially on the frequency of bleaching episodes and other concomitant influences (see discussion in section 1). Therefore, it is very difficult to draw any definite conclusions from current studies of coral reefs in the Indo-Pacific Ocean.

Nevertheless, it is vital that we build the best possible window of likelihoods to more effectively address the issues that future developments will deliver. In line with this and to structure thinking about possible future outcomes, the following two reef-based scenarios are worked out for the year 2020:

* Scenario 1 (A BLEAK PROSPECT): major reef damage with consequential damage to fisheries and other reef services;
* Scenario 2 (LESS DRASTIC CHANGE): mild reef damage and milder impacts on fishery and tourism.

Within these, we will focus on the socioeconomic impacts and potential government and business responses. Due to the different factors that affect islands within the south Pacific, we have defined two broad groups of islands, which fall approximately into the regional groupings of Melanesia and Polynesia/Micronesia.

Note: These scenarios imply that government response will play a key role in a positive outcome. This may be true at some level of human welfare maintenance but if, for example, 90 per cent of reefs are erased in an island state, it may not be conceivable that any government interjection will alter the local outcome (other than reducing the population or relocating communities and resources). These scenarios can be compared to the two scenarios postulated in Wilkinson *et al* (1999). They describe a pessimistic scenario in line with Scenario 1 and an optimistic scenario roughly corresponding to Scenario 2 of this study.

In the next section, the atmospheric, biological and economic variables are placed within the context of potential impacts of climate change. In this case, three broad categories of impact are considered: Damage to fisheries, impacts on tourism and increased coastal erosion.

## DAMAGE TO FISHERIES

The long-term impacts of mass coral bleaching and associated mortality on fishery yields are very uncertain. A recent study in Kenya by the Coral Reef Conservation Project (CRCP) has assessed the short-term impact of coral bleaching on abundance and composition of the reef fish community structure, together with biomass and composition of individual fish catches (McClalahan and Pet-Soede, 2000). Data were collected inside and outside marine-protected areas. The pre-bleaching study was completed in late 1997, some four months before bleaching started in Kenya. The study was repeated 10 months after the coral bleaching, in early 1999.

Underwater visual census (UVC) data show no clear changes in fish community structure that can be solely attributed to the bleaching and mortality (see Table 1). An exception is the increase in abundance of acanthurids (surgeonfish). McClalahan and Pet-Soede (op cit) suggest that this increase may be related to coral mortality, as acanthurids are grazers feeding on dead coral surface. The data do show significant effects of management (marine park versus exploited reefs) on fish abundance (see also McClalahan and Arthur in press). Overall catches have decreased significantly over the period 1995 to 1999, possibly as a result of overall environmental degradation. This could imply that the effect of the recent bleaching and coral mortality will become more evident only once the reefs have further eroded (McClalahan and Pet-Soede, op cit).

Note that these are short-term effects based on one episode of coral bleaching. The long-term negative effects of the 1998 coral bleaching event on fisheries were postulated by Wilkinson *et al* (1999) in their pessimistic scenario by assuming that the bleaching and mortality leads to a loss of 25 per cent of reef-related fisheries from year five until year 20, with a gradual increase in the loss over the first five years. In view of this perspective, a recent study by the World Bank (2000) on general economic losses resulting from climate change assumes that, for reefs that die due to coral bleaching, 50 per cent of the subsistence and artisanal fisheries value would be lost. This last estimate underlies our postulation for reef fisheries in Scenario 1. Scenario 2 lies within the expected range described in the literature.

The linkage between reef fisheries and pelagic fisheries is poorly understood. Moberg and Folke (1999) describe such "biotic services between ecosystems" in qualitative terms. Spurgeon (1992) discusses this biological support as an indirect use value of coral reefs and suggests using a "percentage dependence technique" to value linkage. However, no estimates are given. We have, therefore, postulated this dependence conservatively in these scenarios.

## IMPACTS ON TOURISM

Impacts of coral bleaching on tourism have been described in three recent studies following the 1998 coral bleaching event. Cesar *et al* (2000) estimate losses to the Maldives' economy from severe coral bleaching and subsequent mortality, where live coral cover was reduced from over 50 per cent to less than five per cent. Surprisingly, this has not led to a major decrease in tourist arrivals. It was estimated that tourism growth was one per cent lower due to coral mortality.

The main reason for this small decline is the successful shift to other types of tourism, especially "honeymooners" - defining a short-term solution pursued by tourist operators. Besides, with double-digit annual growth in the numbers of certified divers and relative proximity to the European market, the Maldives is guaranteed a fresh supply of relatively inexperienced divers who are mainly interested in charismatic marine megafauna, readily available in the Maldives due to low reef fishery pressure.

This percentage for the Maldives is rather low compared to results found for East Africa. A study by Westmacott *et al* (2000), based on tourist questionnaires, reported a drop of 19 per cent in dive tourists to Zanzibar in the event of severe coral bleaching. This corresponds to an estimated decrease of around 10 per cent of total tourists there (Westmacott et al, 2000). The difference between the Maldives and Zanzibar appears to be that the marketing possibilities in the Maldives allow substitution of different sub-groups of the tourism market. Also, the net outlay to travel to Zanzibar for the perceived quality of facilities (Zanzibar being more questionable to the European tourist) is greater than it is for the Maldives.

A third study by Cesar (2000) estimated even higher losses due to coral bleaching and other forms of reef degradation in a study of 17,000 resort tourists and backpackers in El Nido (Palawan, the Philippines). The resorts once catered to the exclusive high end of the dive market and the surrounding marine environment was advertised as a pristine diving area. Over the last years, it has lost this image due to the degradation of its reefs. The 1998 coral bleaching (El Niño) and the 1998 typhoon (also linked to El Niño) were the two main causes for this change. In the mid-1980s, most resort guests were divers. Currently, the percentage of real divers is estimated at roughly 10 per cent. The resorts have shifted their clientele. Currently, more than half the tourists visiting the luxury resort of Miniloc are Korean and Japanese honeymooners. The low occupancy rates suggest that the "lost" divers are a true loss to the resorts. Cesar (2000) estimates the true loss at roughly 4000 guests or 19 per cent with an annual loss of $US 3 million in net revenue including a multiplier effect.

Characteristic of the three studies discussed above is the partial substitution of one niche market (high-end dive tourism) for another. This potential is not present in most islands in the Pacific due to the long distance from the main tourism market. Without any substitution possibilities, tourism in El Nido would have gone down by 50 per cent. This number forms the basis for the postulated tourism decline in Scenario 1. As in the previous impact category, values are consistent within the range of the literature quoted.

***TABLE 10. SUMMARY OF THE EFFECTS OF MANAGEMENT, CATCH TREND, UNDERWATER VISUAL CENSUS TRANSECTS (UVC) AND BLEACHING ON THE VARIOUS FISH CATEGORIES MEASURED.***

+ = positive effect; - = negative effect; 0 = no effect; nd = no data.

| Fish Group | Management | Catch Trend | Trend in UVC | Bleaching Effect |
|---|---|---|---|---|
| Total Fish | + | - | - | 0 |
| Acanthuridae | + | nd | + | + |
| Balistidae | + | nd | 0 | 0 |
| Chaetodontidae | + | nd | 0 | 0 |
| Diodontidae | + | nd | -/0 | 0 |
| Labridae | + | nd | -/0 | 0 |
| Lutjanidae | + | - | 0 | 0 |
| Mullidae | 0 | - | -/0 | 0 |
| Pomacanthidae | + | nd | -/0 | -/0 |
| Pomacentridae | + | nd | 0 | 0 |
| Siganidae | + | - | +/0 | 0 |
| Scaridae | + | 0 | 0 | 0 |
| Others | + | - | 0 | 0 |

Source: McClalahan & Pet-Soede, 2000

## INCREASED COASTAL EROSION

Coral bleaching and subsequent mortality can decrease the coastal protection function of coral reefs. This is due to a gradual disintegration of the reef structure through bio-eroders. A study by Cambers (1992) assumes a loss of 0.2 metres of coastline based on data in the Caribbean. Berg *et al* (1998) uses a loss of coastline of 0.4 metres per year for an economic valuation of the costs of coral mining, where erosion data were based on CCD (1996). Clark (1995) describes losses in Bali due to coastal erosion stemming from coral mining activities in previous decades. Likewise, on Tarawa Atoll in Kiribati, coastal defences costing $US 90,000 had to be built to prevent coastal erosion following coral mining (Howarth, 1982, as quoted in Spurgeon, 1992). Other examples of the impact of coastal inundation are described above in the discussion of the data of Gaffin (1997) and Nicholls *et al* (1999).

The problem with calculating the costs of coastal erosion is the multitude of potential flow-on costs related to alteration of the physical and biological environments, the processes that integrate them and the consequent direct and indirect influences these might have on human welfare and maintenance. As an example of how widely such cost estimates can vary, protective revetments and underwater wave breakers in Sri Lanka were proposed to prevent further degradation of the coast, with an estimated cost of between $US 246,000 and $US 836,000 per kilometre of protected coastline (Berg et al, 1998).

One other problem with estimating the damage derived from coastal erosion due to climate-induced bleaching is that sea level rise and, possibly, increased frequencies of extreme weather events outweigh the physical impact of erosion due to bleaching. The recent World Bank (2000) study on the economic impacts of climate change on Pacific Islands does not attempt to calculate separate impacts from coral bleaching. Instead it combines all elements of climate change for the calculation of the losses. Here, as we focus solely on coral bleaching, we are unable to do this. However, we can still use the World Bank cost figures, expressing the costs per metre of land lost.

# SCENARIOS: ECONOMIC, SOCIAL AND POLITICAL CHANGE?

## BASIS FOR SCENARIO DEVELOPMENT

**CURRENT APPROACH TO SCENARIO PLANNING:** The future has become unpredictable over the past 40 years, if it ever were anything else. The "predictable" 1960s, in retrospect, look like an anomaly. This has created a need for new approaches to assessing the future to provide better planning tools for the present. Scenario analysis has evolved as a strategic planning method as the world environment has become increasingly complex, interdependent and unpredictable.

Scenario planning aims at creating an ambience by imagining future situations rather than presenting them in hard analytic terms. The preceding parts of this report are sober and scientific, based on quantitative analysis. Scenarios are not scientific in this sense. Scenario planning is the science (or art) of creating future insights to guide present action. Science and economics can analyse the known facts but, in principle, cannot deal with the unpredictable.

Scenarios are imagined futures, not forecasts. They do not come singly, as a forecast would, but in sets of alternatives or as different versions of the same driving forces. One of the hardest things to do is to think usefully about the longer-term future. Faced with the certainty that the only certainty is the future will be different from any simple extrapolation from the present, we tend to shorten our horizons so that we can feel more comfortable with assuming present trends (Stout, 1998a,b).

Previous studies support the assertion that the future is unpredictable, although these studies have often provided insights that proved to be crucial in the fullness of time. The so-called Club of Rome report is a good example (Meadows et al, 1972). However, by developing a range of equally plausible (non-probabilistic) scenarios, decision-makers are alerted to possibilities that they would not otherwise have recognised. This is a very different strategic planning approach from the traditional "predict-and-control" routine which, despite its enormous failures in the past[12], continues to attract many managers (Van der Heijden, 1996).

Scenarios may be global or specific in scope. The current study focuses on Pacific communities within a global perspective that widespread damage to coral reefs is occurring as a result of rising oceanic temperature levels. In a more general sense, specific scenarios must present internally consistent futures that are compatible with globally developed assumptions.

*12* According to Ged Davis, head of scenario planning for Shell International (the company that pioneered the modern scenario planning approach), the biggest problem in business is misjudging the future. McKinsey studied 100 companies in 1993 and found they destroyed $300 billion of shareholders' funds by simply assuming that oil prices would continue to rise after the oil shocks. "I don't think anybody can predict the future. What [scenario] work does is help you prepare better for the future than those people who don't do any work at this time." (Porter 1998)

Scenarios are stories about the future that attempt to bring all relevant influences into play in an internally consistent manner, based on a narrative supported by statistics as required. The range of influences is sometimes given the acronym STEEP (socio-cultural, technological, economic, ecological/environmental and political).

The range of possible futures helps formulate policies to offset adverse impacts, the continued need for international aid and assessments of individual nations' capacity to adapt to changed circumstances. This capacity to adapt will differ among nations and for each will depend on the severity of the change brought about in a particular scenario.

An important principle in scenario building is to develop sensitivity to signals that help illuminate the future, warn against risks and identify turning points that can send the world down very different alternative paths. For instance, reference to atmospheric accumulation of $CO^2$ in the Club of Rome report could have provided a beacon into the future by helping to formulate the appropriate what-if questions about the extent of global warming and its impact. There is a wide array of possible signals in today's world, ranging from the impact of increased inequality of incomes (nationally as well as internationally) to the impact of environmental damage. The latter naturally includes the deterioration of coral reefs under alternative assumptions about climate change, providing the focus for the development of scenarios for south Pacific nations.

The length of the scenario horizon is another matter for consideration. It is impossible to perceive world prospects in any detail after, say, 20 years, although the impact of climate change will have longer-term effects. The Swedish Environment Institute has published a global study of the 21st century as a whole (Gallopin et al, 1997, followed by Raskin et al, 1998 defining the policy responses) but the development of three scenarios, including one world receding into barbarism and another one gone "green", by necessity becomes very broad-brush as the time horizon lengthens. The role of the pessimistic case, plausible as it is as a long-term perspective, is to alert today's policy-makers to the possibility that significant ecological, economic, political and social signals exist today to warn us that events could quite possibly go horribly wrong some time during the new century.

The study makes two points about the "green" scenario. First, it may sound utopian but may nevertheless be more likely to occur than the continuation of current trends envisaged in the reference scenario. Secondly, it may not happen until after the world has entered the new Dark Age envisaged in the downside scenario. If such century-long perspectives are at all plausible they become highly relevant for current international decision-making.

One approach is to present a reference base as the main scenario and concentrate on the next 20 years or so while keeping sight of the spectre of a possible "world gone bad" in the long term as a worst-case scenario. On the upside, the development of a strong worldwide environmental movement in response to the perceived insufficiency of current policy-making could be used to escalate the pace towards a greener world through stronger policies across the broad socio-ecological spectrum.

In this approach to scenario planning, the continued evolution of the current dominant values and socioeconomic relationships of society shapes the future. The reference base may have two variants, as in the Swedish Environment Institute's study. In one variant, a minimal effort is made to correct the deepening conflict caused by factors such as global dominance of multinational corporations and consumerism on the one side, and global poverty and ecological damage on the other. The other variant is to incorporate environmental and economic agents more effectively into the scenario. This requires a focus on available policy measures, their efficiency and how they might be strengthened.

**SUSTAINABLE DEVELOPMENT:** Gro Harlem Brundtland, Prime Minister of Norway, chaired the World Commission on Environment and Development, created by the United Nations in 1983. The Commission's report (WCED, 1987) introduced the concept of sustainable development into public debate. The report defines it as follows: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

The report identifies social and ecological problems as the primary areas of concern and sees the way that society is deploying industry and technology, and distributing their benefits, as both driving and defining these problems (Tibbs, 1999). Given that global scenario writers spread themselves across a huge canvas to monitor all possible variables, this shows that the reliance on global scenarios cannot always be taken for granted.[13]

**TYPES OF POSSIBLE SCENARIO OUTPUT:** The scenarios in this paper are constructed to consider discrete points of time in the future, such as the year 2020, and an outline of the path towards this point. No attempt is made to estimate a present value of future benefit-cost flows (Cesar, 1996). This is an investment-analysis tool and in the context of the study would force us to make unjustifiable value judgments about the relative value of our world and that of our descendants. By defining the future in its own terms the scenarios become a proper instrument for policy-making, which is their true function.

**THE SPECIFIC SCENARIOS:** Of four scenarios, two deal with four relatively large island nations, predominantly Melanesian and forming a contiguous central western area (Fiji, New Caledonia, Solomon Islands and Vanuatu). The other two concern the remaining nine mainly Polynesian nations, from Tonga and Cook Islands in the south to French Polynesia in the west, Kiribati, Tuvalu and Nauru near the equator, and Palau in the far north-west. These nations are either small, spread over large areas or both (Nauruans and I-Kiribati are predominantly Micronesian rather than Polynesian).

Each of these groups is viewed using relatively pessimistic and more optimistic assumptions, both concerning the impact of climate change on reef structures, sea levels and other physical variables, and policy responses. In the first set of scenarios, continued conflict in policy-making between necessary long-term objectives and short-term vested political and business interests will retard appropriate policies from being put into place, and the assumed effect of climate change will be more severe than in the second set.

In the more optimistic set of scenarios, environmental and social policies prevail to alleviate the adverse effects of current socio-ecological forces. Policy measures could appropriately, and plausibly, include a strengthening of current environmental conventions and legislative measures to reflect the developing world opinion led by international non-governmental organisations (NGOs). This set of scenarios will be combined with relatively mild climate change effects.

The following scenarios were developed for a 20-year period. Climate-change effects are projected for longer periods and the scenarios use the vantage point of 2020 to look at the general implications of further deterioration of reef systems, sea-level increases and other effects.

***Classification of scenarios, relating to 2020***

| | |
|---|---|
| 1A: A BLEAK PROSPECT, MELANESIA | 1B: A BLEAK PROSPECT, POLYNESIA |
| 2A: LESS DRASTIC IMPACT, MELANESIA | 2B: LESS DRASTIC IMPACT, POLYNESIA |

## CLIMATE-CHANGE SCENARIO TRIGGERS

To set the scene for the following scenarios, a specific set of triggers is postulated which follows from the atmospheric, biological and economic components of this study (Sections 1-3).

**BLEAK PROSPECT SCENARIO:** The Bleak Prospect (Scenario 1) involves the extension of the atmospheric and biological studies in the first two sections of this report. It assumes that carbon dioxide has increased from present-day levels to 425 ssppmv by 2020, which is consistent with the IPPC IS92a climate change scenario.

Associated with this rise are the changes in frequency of bleaching events as outlined in Table 3 and Figure 7 – mass mortality events are set to remove reef-building corals as dominant reef organisms by 2040 (mean date of three "killer" events with DHMs of greater than 2.3, projected from Figure 7 and Table 3). Associated with this decline in reef-building corals are decreases in reef calcification of about 20 per cent (as per Langdon et al, 2000) and a rise in sea level of 20 centimetres by 2020 (assuming a mean estimate of 50cm by 2080; Houghton et al, 1996). We assume that there is no change in the frequency of El Niño Southern Oscillation but that extreme events occur on a slightly more frequent basis. The combination of sea level rise and the slight increase in cyclonic activity however is assumed to multiply through the greater impact of seas on coastlines in which the reef is now in net erosion and in which seas reach further inland. These are very similar scenarios to those developed using Hadley Centre data (Nicholls et al, 1999).

*13* Indeed, this cuts both ways. This study will have to rely on plausible world scenarios as well as making assumptions about the future change in Pacific STEEP factors that may have been the subject of other specialised studies. Therefore, some assumptions may be open to challenge in the light of new specialised evidence. Rather than being seen as invalidating scenario-based studies this should be seen as input into a constructive and healthy debate across a wide spectrum of influences.

In the Bleak Prospect scenario, the socioeconomic impacts by 2020 are postulated as follows (with further deterioration expected beyond 2020):

1) There are major direct losses in tourism income and employment. The dive industry in a number of places will collapse and overall tourism GDP and employment will decrease by between 25 per cent and 75 per cent, depending on country and resilience of local tourism industries.
2) Fish productivity drops considerably as the reef structure disintegrates, resulting in reduced catches for the fishermen, less protein in the diet, particularly for coastal communities, lower health status and possible starvation, particularly among the subsistence segments of the community. Fishermen will experience a major loss of income and reduced ability to purchase other food. Reef fishery will see its value added reduce by 25 to 50 per cent and pelagic fishery by 10 to 25 per cent.
3) A possible collapse of the protective barrier function of the reef could result in dramatic coastal erosion. Annual damage costs are postulated to be 10 to 30 per cent and significant human mortality cannot be excluded.

It is important to realise that, even in the bleak scenario, we have taken conservative values. If climate change occurs faster (which appears to be occurring, re Strong et al, 2000a) or such aspects as reef erosion and primary productivity downturns are more severe, then the impacts on the socioeconomic front are underestimated.

Less drastic impact scenario: The less drastic impact assumes that the same extent of climate change has occurred but corals and other reef organisms have adapted to the changes imposed on them. Critical to this is that reefs continue to grow and calcify and that reef erosion is compensated by moderate rates of calcification. This would require a decrease in the rate of change in atmospheric concentrations of greenhouse gases to approximately one-third of current rates.

The less drastic impact scenarios also examine conditions in 2020, with further deterioration expected beyond 2020 according to current physical models. The socioeconomic effects for the total area under review are assumed to be:

1) Direct losses in tourism income and employment are still considerable, especially in niche markets such as dive tourism. Government and tourism industry together are able to partially shift to other segments of the tourism market but the remote location of most islands makes this a challenge The loss in tourism value-added and employment is postulated to average about 15 per cent, depending on location and tourism industry resilience.
2) Fish productivity drops moderately as the reef structure disintegrates over time (though slower than the bleak prospect senario). However, appropriate measures in local fishery management are effective in mitigating the impacts. Due to ecological linkages with pelagic fisheries, there is also a small reduction in pelagic catch. Total loss in fishery GDP for reef fish is 15 per cent and for pelagic fish is five per cent. There are some social consequences associated with lower fish landings, especially among coastal subsistence communities but appropriate government responses ensure that protein intake stays above the minimum required.
3) There is moderate change in the coastal protection function due to coral mortality, as bio-erosion will be stronger than coral growth of new recruits. However, appropriate government responses mitigate coastal hazards. Total annual costs of damage from coral mortality as well as mitigation and adaptation efforts combined is postulated to be zero to five per cent of GDP.

## SCENARIOS AND ECONOMIC ESTIMATES

While the whole purpose of scenario building is to produce plausible stories of the future, it is appropriate to summarise the numerical implications in just one estimate, that of gross domestic product. This can realistically only be done as a range estimate and must remain highly tentative. It must again be very strongly emphasised that scenarios are not forecasts but a device to highlight possible future situations that require strategic planning initiatives now.

With this important qualification, we estimate that the worst-case scenario set of the two outlined in the next section implies a total GDP loss for Melanesian nations of between 15 per cent and 20 per cent or, in absolute terms, about **$1.9 to $2.5 billion in "late-1990s dollars" (Scenario 1a).** This loss is estimated in comparison with GDP growth projections as they might have developed in the absence of the climate-change triggers defined in the previous section (see left-hand column of Table 9). These economies will still grow according to these calculations but the annual growth rates will be reduced from 3.3 per cent to 2.2-2.5 per cent. Furthermore, the reduction will be concentrated in the second decade, with growth rates only deteriorating gradually.

The outlook according to this scenario is therefore that the four large Melanesian nations may be able to stave off the worst effects of economic pressure for some 10 years; however the outlook from the vantage point of 2020 is much grimmer. Of the four nations, three were defined as being moderately vulnerable and one slightly more vulnerable due to a larger tourism sector (New Caledonia). On the other hand, New Caledonia has a relatively high ability to adapt (like Fiji) and there is no basis to differentiate between growth prospects for these four nations.

The scenario for the four Melanesian nations is based on an assumption that action will be taken by themselves (even in the absence of significant foreign assistance) to alleviate the situation, notably through resource development. If this did not take place, the outlook would be significantly worse in all four nations.

The situation is more serious for the Polynesian and Micronesian nations. Contrary to the four large Melanesian nations, they do not appear to have a significant unused resource base to develop. Overall, it is estimated that GDP might be reduced by between 40 per cent and 50 per cent compared to the expected uninterrupted growth over the next 20 years in the absence of climate-change impacts (+3.8 per cent pa). The indicative rates of change over the full 20 years are between 0.3 per cent and 1.2 per cent per annum, compared with the expected 3.8 per cent in the absence of climate-change effects. **The value lost by climate change in the Polynesian and adjacent nations included in the study is estimated at between $4 billion and $5 billion.**

Any growth would be concentrated in the first decade and all nine economies are expected to shrink in absolute terms in the second decade, with the possible exception of Samoa and American Samoa.

Within the area, the vulnerability index varies from extremes in Tuvalu and Kiribati to being better than average in independent and American Samoa. The two Samoan nations are the only ones in the group with lower estimated vulnerability to climate change than the four Melanesian countries. Cook Islands, Palau, French Polynesia, Tonga and Nauru are all considered more at risk. In terms of capacity to adapt, Nauru has to be rated as low as Tuvalu and Kiribati in view of its depletion of resources and the now virtually complete exhaustion of its phosphate deposit. Cook Islands and Palau may also have relatively low abilities to adapt in view of their small size. Tonga, American Samoa and Samoa are in a better position in this respect.

## SCENARIO GROUP 1: A BLEAK PROSPECT

**SCENARIO 1A: MELANESIA:** Not until the larger island nations felt the first serious effects of the loss of their reefs in the first years of the century did they realise that one of their most precious amenities was vanishing faster than they could handle by simply leaving the adjustment of employment and overseas earnings to market forces. They could see already, as dive operators and resort entrepreneurs raced to exploit what was left before it all disappeared, the stresses on their environment and way of life magnify and accelerate.

After the "Wake-up Time!" SPARTECA-sponsored Conference in 2001, the four Melanesian nations sat down to work out what they could learn from each other, how far they needed to cooperate to develop critical mass in completely new economic enterprises, and how far they could find their own ways to replace the reef-related losses.

At their first meeting, they set out the advantages they had in common. Following the resolution of Fiji's and Solomon Islands' problems in 2000, all four had strong, democratic governments backed by efficient civil servants, competent to command the trust of their peoples. They had a good deal of land at their backs, unlike their smaller neighbours, some of which were even threatened with virtual disappearance by that other menace of global warming, rising sea levels. As things have turned out, that rise has been so severe it has significantly damaged some coastal regions in all the nations of the west Pacific. But these four nations had more to fall back on. They all had underexploited or unexploited natural resources on and under their land. They had reasonably good, or very good, transport infrastructure by land, sea and air. All of them had some experience of adding value to primary products before export. On this they could build.

In short, they had the basis on which to design joint and individual long-term recovery plans and they had the popular will to do it, once the threat was widely understood by their people. In this respect, generally high literacy rates were an advantage. New education programs were started in all four nations. Initial educational standards varied a good deal, with Vanuatu and Solomon Islands having to put the most effort into new programs. The rapid spread of email and internet connection which their governments were able to foster in the early years of the first decade, quickly brought home to their people the nearness of the threat and provided a new means to work together. All four had in place social benefit systems and tax systems with reasonably good compliance, which let them assist those coastal dwellers closest to subsistence and most severely affected by the inexorable disappearance of their coral reefs. The biggest problems were again faced by Solomon Islands and Vanuatu, which had more fishing and agriculture as subsistence activity with little marketable surplus.

New Caledonia is more advantageously placed with a limited number of outlying islands and its huge surrounding reef continuing to provide protection. However, its move to independence in 2015 may prove expensive as it is effectively cutting off, after a transitional period, the huge amount of development assistance provided by France.

The demography of the four was quite diverse. The high percentage of young people in Solomon Islands and Vanuatu was a mixed blessing. Almost half were under 15 at the beginning of the century. The scope for training in new skills and a new way of life away from subsistence fishing was greater but so was the need to create additional employment over the two decades that followed.

One route that they quickly ruled out was chasing other nations such as Micronesia and Kiribati in a competitive race to exploit deep-water fish. This called for agreements on quotas, which had some success but failed to cope with the overall fall in tuna catches. Not only were the numbers of tuna and other game fish severely limited but also their number was falling faster as a consequence of the loss of the reefs and the smaller fish that depended upon them.

Reef-based tourism had grown fast and that growth now slowed down. The relationship everywhere between tourism and the loss of coral proved to be quite complex. In newer resort areas, a lot of coral was lost while tourist numbers, including those who came to see the coral, continued to increase through the first decade of the century, such was the underlying trend growth in numbers. There was a threshold problem too. In some places, half the coral was bleached by 2010 and there was still room for an increasing number of tourists to the remaining half. The situation continued to worsen during the second decade and tourist numbers by 2020 had returned close to the levels of the turn of the century. Once all the coral has gone, as now looks likely, more severe falls in reef-based tourism will inevitably follow.

Here, another of the advantages that some of the four had over many smaller neighbours came into play – the power to raise funds and technical assistance from Japan, the United States, Australia or what had earlier been metropolitan government support. As they all now know, by the end of the second decade of the century, this exploration work has born fruit in mineral earnings and employment that were neither needed nor imagined 20 years earlier.

Vanuatu, in the old Condominium days before independence, had been supported by the rivalry of the two metropolitan governments and two large, fiercely rival trading companies. Vanuatu was able to draw on these old links to encourage new investment, helped by high educational standards and the strong tradition of effective Melanesian Cooperatives in their islands. The established symbiosis between beef and copra was extended, so that today beef is more important to Vanuatu than fish. Local value added is also being increased through the extension of the Cooperatives into sustainable timber and chipboard – very different from the indiscriminate foreign felling of irreplaceable kauri in the old days.

It has been necessary, however, to divert increasing resources towards coastal management schemes, building levy walls and other systems in defence against rising sea levels and increased cyclonic hazards, as the trend continued from the 1990s towards El Niño becomes the norm rather than the exception. This relatively unproductive activity has increased the size of the government sector and created balance-of-payments problems through greater use of foreign contractors and imported materials. Much as the new initiatives taken by the Melanesian leaders after the SPARTECA conference has added to the export base; this is placing an increasing burden as we consider the matter here in 2020. The problem is particularly serious in Solomon Islands, with its many outlying island groups, but Fiji and Vanuatu are also spending increasingly large sums on defending their coastlines.

So far, all four have been able to keep their heads above water. Size, overseas affiliations, the resources and skills to diversify away from reef-dependent kinds of tourism, cohesive societies, competent and democratic governments, improved communications and a natural resource base have all played their part in this transformation. No country in the region has the power to influence the rate of global warming and its insidious destructive effects upon their coastlines and the activities associated with their reefs. All they have been able to do is to mitigate the effects upon the people whose livelihoods depended, directly or indirectly, upon the health of the reefs.

Looking further ahead towards 2080, the picture is much more grim. The further rise in sea levels will begin to destroy the beaches and even the most passive tourists will be discouraged from visiting, as they already have been from more low-lying neighbours. Nevertheless, in the richer countries of the world, holidays continue to grow longer as wealth grows. The attraction of sun and sea remains powerful and there are very few alternative reefs left elsewhere in the world to draw tourists away. The future of tourism lies in preventing the pollution of the remaining beaches and attracting tourists in new ways, by opening up the interior as Belize and Costa Rica did in the last century, and encouraging holidaymakers to explore.

**SCENARIO 1B: POLYNESIAN AND MICRONESIAN NATIONS:** When the four Melanesian nations in the west formed their loose alliance after the 2001 "Wake-up Time!" conference, the remaining island nations felt a similar need for cooperation. The Polynesian nations of Tonga, Tuvalu, Samoa, and Cook Islands, American Samoa and French Polynesia, are all part of this group. The Micronesian neighbours Nauru and Kiribati also joined the group, as did faraway Palau, feeling a kinship with the main Polynesian group from its own ethnic origin.

There was general agreement among the group that, with a couple of exceptions, these nations were much more critically exposed to the impact of climate change than the Melanesian nations in the west. All are small in area (even the largest, French Polynesia, has less than a third of the land area of Vanuatu, the smallest of the four Melanesian nations at the 2001 conference) but all except Samoa, which is the most compact of the nations, have very large sea areas. Coastlines are long, especially in French Polynesia, Kiribati and Palau with their numerous islands, and the ratio of sea to land area is almost mindblowing in Tuvalu. Twentieth century warming rates have been significant except in Tonga and the south Cook Islands and not one nation has escaped significant warming rates during the first 20 years of the 21st century.

Taking all physical characteristics into account, including number of reefs and outlying inhabited atolls, the leaders felt that Samoa, American Samoa and, to a lesser extent, Tonga were relatively well placed. However, the situation could deteriorate rapidly in the Cook Islands, French Polynesia and Palau, and could become drastic in Kiribati and Tuvalu. They also levelled some criticism on the Government of Nauru, for failing to draw sufficient benefit from its advantageous position of having built up a huge investment base from its now depleted phosphate deposits.

Following the conference, Samoa, American Samoa and French Polynesia investigated their resource bases but found limited economic potential. Being much smaller, they are simply not as resource-rich as the four Melanesian nations.

The group did identify an advantage in the general cohesion of traditional societies, which remained a significant attraction for cultural tourism (mixed with French chic on Tahiti). Even in American Samoa, with its almost enforced Americanisation from the 1960s onwards, traditional society survived surprisingly strongly. This provided support for prevalent subsistence fishing and agricultural activities, and a bulwark against individual poverty. Nevertheless, the leaders feared that poverty would continue to rise in an increasing number of areas. The worst effects would be in the capital cities where traditional values were eroding.

Other advantages included the relative political strength and high education level in most of the nations. Samoa took an interesting initiative in the latter area with its independent National University of Samoa. Motivated both by a desire to stop students going abroad for their tertiary studies and by the developing global-warming crisis, it approached universities situated along significant reef areas in Hawaii and Queensland for assistance to develop a science department at world's-best standard, specialising in the relevant disciplines. It also extended its collaboration with the existing agricultural science campus of the

South Pacific University in Alafua. As a result of this early initiative, Samoa was going from strength to strength in the tertiary education area by 2020, to the benefit of all Pacific nations in their struggle to survive.

In the second decade of the century, Nauru finally came to grips with the situation, investing massively after the sale of a large part of its foreign investments. It began a comprehensive program to rehabilitate the island, left as a moon landscape after the removal of phosphate rock. Similar initiatives were being discussed internationally concerning the other phosphate island of Banaba, Kiribati. However, it was difficult to convince any international consortium of the success of the plan, especially as the success of the Nauruan initiative was unproved. The cost-benefit ratio was simply seen as too adverse, even in national terms, let alone in terms of corporate cash flows and profits.

As the years passed and the first decade gave way to the second, a number of crucial trends developed:

1. Both reef and pelagic fisheries deteriorated, as reefs died and the tuna catch plummeted. The impact on Kiribati in particular was drastic.
2. The rising sea level, even at only 12 centimetres during the first 20 years, coupled with increased cyclonic activity, was starting to have drastic effects on atolls, which were gradually losing their ability to resist violent wave action, and other low-lying islands in the area. For a country like Tuvalu, which consists of nothing else, and for Kiribati, this was catastrophic. It was harmful enough for the Southern Cooks, French Polynesia, Tonga and Palau.
3. Tourism followed similar trends as in the Melanesian countries. The avid reef enthusiast (looking for unharmed coral formations) gradually disappeared but the world trend in tourism ensuring continued growth during the first 10 years of the century. It was noted, however, that the vicious cycle in tourist facilities worked only too well in some places: less demand for accommodation and facilities squeezed profit margins, causing operators to lower quality, leading to further decrease in demand, and so on. Where tourism was diversified, as in Tahiti, the effects were less drastic but international chains began to look elsewhere for new development projects as the 2010s progressed.
4. Foreign countries proved reluctant to help with coastal defence infrastructures, especially in the small and remote northern countries. Eight, 13 and 16 million dollars for Tuvalu, Cook Islands and Kiribati respectively, representing levels of economic aid unchanged for 20 years, are “a drop in the ocean”, as the Prime Minister of Tuvalu remarked bitterly at his country’s 40th anniversary celebration in 2018.
5. Increasingly short of funds with international aid tending to go elsewhere, governments continued a trend first noted in the 1990s to lay off their employees. With the government the major employer in some of the smaller nations, and important in the employment scene everywhere, unemployment rose rapidly and emigration to Australia, New Zealand and other countries on the Pacific Rim rose dramatically. Populations started to fall, as had already been witnessed in the Cook Islands in the late 1990s.
6. Damage to coastal communities associated with growing numbers of increasingly severe cyclones, and an increase in sea levels averaging 12 centimetres by 2020, could not be sufficiently halted in small nations and outlying islands of larger ones. This was due to a lack of international assistance and inability to fund these constructions locally.
7. Even in Tonga and French Polynesia, the much increased need for defence of small low-lying islands, and the coastal areas of many high islands as well, put an increasing strain on resources and the balance of payments. In the absence of increased international assistance, this necessitated expenditure cutback and tighter fiscal and monetary policies generally.
8. As living conditions deteriorated in the subsistence sectors of these countries, health problems due to falling agricultural and fisheries yields, poor sanitation and poor hygiene began to take their toll, with increasing rates of malaria, gastrointestinal illness and parasitic infections. The improving trends in life expectancy and infant mortality were reversed in many of the smaller countries in the 2010s.
9. The deterioration put the natural cohesiveness of Polynesian society sorely to the test. Fortunately, most cities were small enough to prevent the degree of alienation that has been observed in big cities in South-East Asia and elsewhere. Nevertheless, a groundswell of rebellion and dissatisfaction with traditional customs as well as with elected governments developed as the two decades drew to a close. Calls for “strong” leaders were on the increase throughout.

Nowhere was the damage greater than in Tuvalu, closely followed by Kiribati. With few resources other than fisheries and subsistence farming, their economic base virtually disappeared. The income from fishing licences to foreign enterprises to use the exclusive economic zone, which had been a mainstay of these economies, fell dramatically as tuna numbers fell. Cook Islands also suffered a very large cut in its economic base from both fisheries and reef tourism. Although the reefs in the southern Cooks had been protected by a relatively slow trend in warming rates, this situation was not continuing and bleaching events became increasingly common.

Palau, like other small countries consisting of extensive island groups, was also becoming badly affected. Furthermore, the United States contribution in return for use of military facilities was being cut back in the 2010s. French Polynesia was having similar problems with military employment being reduced drastically from the early 2000s; its tourist industry, however, proved relatively resilient by providing alternatives such as inland resorts, enjoying the beautiful natural scenery and the French cooking and ambience. Nevertheless, clean reefs have always been part of the public perception of a tropical paradise, with Tahiti always having been regarded as the prime example of such a world.

Samoa, due to its relatively compact configuration, and American Samoa due to continued backing by its parent country, fared best of all Polynesian nations over the first 20 years of the century. This did not leave them unscathed by any means. It just meant that as the Polynesian leaders looked ahead from 2020 towards a grimmer world of dead reefs, the sea likely to rise by another 25 centimetres over the next 60 years, El Niño becoming the norm with attending violent cyclones, and yet other synergistic effects of the impact of factors associated with global warming coming closer into view, the two Samoas were in an incomparably better situation than the small and scattered low-lying island nations to the north and south-west.

## SCENARIO GROUP 2: LESS DRASTIC IMPACT

**SCENARIO 2A:** Melanesian nations: The worst fears of 2000 have not yet been realised. All are thankful for that. There are still some reefs left to visit. The strong underlying trend growth rate in the demand to see coral has meant that, while the numbers of tourists have not grown as fast as had once been hoped, they have at least not fallen. The slower loss of coral has left these nations with more time to adjust but it has also weakened the pressure on their governments to initiate and manage change.

The capacity to adjust is much greater in these four countries than in the others in the region, particularly those that are most isolated and have the weakest relations with foreign governments. But capacity and will are two different things. As the warning signals turned out to be weaker than at first feared, so governments, both in the developed world and in the Pacific, tended to wait and see. Coastal communities have, in general, not moved in the 20 years since 2000. Few have been trained with new skills or been tempted by alternative livelihoods. They are hanging on but the problem of global warming and associated coral loss has not gone away: it has just been slower than the worst early fears.

Trigger and response are closely related. The weaker the trigger, the slower the response. The four are much more ready for change than if they had not faced up, early in the century, to the sombre economic and social consequences of global warming, in the absence of planned adjustment. But because tourist numbers were sustained and because there was still enough healthy coral for the time being, those plans to redirect tourism and to further diversify the island economies have still to be carried out. Also, foreign aid has tended to go elsewhere as the threat in the south Pacific has had a lower global profile than might have been the case. Even within the French dependencies (both have remained so), aid has been increasingly diverted away from New Caledonia towards French Polynesia with its huge sea area and extensive island groups. However, population has grown faster than it would have done had the reefs been on course for complete destruction. By a different route than the total depreciation of the coastal assets, this growth in numbers has held down the growth of living standards.

Overall, people in the Melanesian nations are better off now than 20 years ago, with less dislocation and relocation and less income inequality than in the worst case earlier imagined. But the differences between what has emerged and the worst case is much less for these four than it is for the smaller, more vulnerable islands. And for these four, the pressure to diversify their economies has not been removed; it has merely been postponed.

**SCENARIO 2B: POLYNESIAN AND MICRONESIAN NATIONS:** What was said above about the four large Melanesian countries applies even more so to the smaller economies of the Polynesian and adjacent archipelagos. The worst affected nations are intensely vulnerable to any climate change and the milder regime is unlikely to preserve the economic health of nations such as Tuvalu, Kiribati, Palau and Cook Islands. The only saving grace is that there is a little more time but still no room for delayed responses. The trigger is more significant than in the more diversified Melanesian economies because of a greater sense of urgency, even in French Polynesia because of its desire to preserve an image of paradise in the minds of tourists worldwide. This calls for great resilience in the tourist industry, at great expense, to diversify the image, play down the coral reef image and develop new attractions as the reefs deteriorate.

The softer climate scenario gives a little more time to non-government organisations to put pressure on governments worldwide to assist in the process of rescuing as much as possible. It may also be argued that NGOs, always important in lobbying public opinion and changing industry and government attitudes, have an even greater role in this scenario if the assertion is right that weaker triggers elicit weaker responses. In any case, even the so-called mild scenario will have dire impact on small countries with low-lying islands spread across a vast ocean steadily less living up to its name, Pacific, as the impact of climate change inevitably gathers strength during the 21st century. It is only the expected pace of change that is under debate, not the long-term effects.

# CONCLUSIONS AND RECOMMENDATIONS

**The research that we have brought together in this report has convinced us that one of the most damaging and inexorable outcomes of continued global warming is the destruction of many, if not most, of the reefs in the Pacific.** This causes consequential damage to the culture and economies of the island peoples who depend, directly or indirectly, upon the health of coral. Depending on the rate of rise of sea temperatures, this destruction may vary from partial to complete and lie from 20 years to 80 years ahead. Once a reef is destroyed, we are not talking about decades but many generations before full recovery can be expected. And this is only if the cause of the stress can be removed.

There is a chain of ecological and economic dependence that carries the damage beyond the reefs themselves to the fish that colonise them; to the mangroves behind them; to the bigger fish in the deeper waters ahead of them; to the tourists from the developed world who have taken these reefs for granted for so long; and, most of all, to the islanders themselves, whose way of life and standard of life owes much to these reefs. The report has brought together what facts are known at this time about these physical and social dependencies and has tried to envisage, on the strength of those facts, what might happen over the coming 20 to 50 years. It attempts to provide a snapshot across the south Pacific of the changes that are likely to occur over a short time frame, if climate change continues to stress and deteriorate coastal resources.

**It is important to realise that, even though we searched for possible benefits or escape clauses, these could not be supported from our data and analysis. Even under mild scenarios the outlook is sombre.**

Our report has concentrated on the impacts of coral bleaching upon tourism and fishing, and the extent of dependence of the individual island nations upon these two sources of wealth. However, it must not be forgotten that there are also cumulative, collateral results of global warming that lie outside the scope of this report, that affect the societies and economies of the Pacific – the storm surges, the swamping, and the loss of beaches and farming land that the low-lying islands will inevitably suffer as sea levels rise. These will only deepen the crisis projected from our study.

Our report has shown the extent of dependence on fishing and tourism, both absolute and relative to the economies as a whole, for the Pacific nations within the study. It is possible to estimate in billions of dollars of lost revenue per year the accounting cost. But the social costs from the dislocation of coastal communities and the deprivation of the families of subsistence farmers and fishermen are not included in these accounting numbers.

This report has not tried to spell out some kind of doomsday scenario – an Armageddon for which we must all sit and wait. What governments do today will determine what kind of a future there is for reef-based economies all over the world. The point of the scenarios that we have imagined at the end of our report is to help us to think forward, beyond our present preoccupations and assumptions. Because of the acute and irreversible sensitivity of coral to even a couple of degrees' rise in sea temperature, action or the lack of it in 2000 will decide the future of Pacific island economies 20 and 80 years hence. There is still time for governments to act – but there is not much time.

We recommend action on three fronts: global; by the West Pacific region as a whole; and by the individual island economies.

**GLOBAL:** The developed world is not yet sensitive to, nor even yet widely aware of, the rate of destruction of the coral their tourists have come to take for granted. The point of such reports as this is lost if they are not key documents for the future policy framework of the Convention on Climate Change. The necessary actions that matter most lie far beyond the competence of the Pacific communities themselves. The responsibility is upon the developed and industrialised world to stop the global warming. Pacific nations must emphasise their "frontline" status in this issue.

Given the pace of globalisation and trade liberalisation, small island developing nations are at risk of becoming further marginalised. Economic development is required to achieve economic and social growth, and implement policies such as reef management, soil conservation, preventing land degradation, and a manageable level of natural resource harvest including fisheries, forestry, agriculture and marine life. Developed countries are required to contribute 0.7 per cent of their Gross National Product as official development assistance for developing countries. Over the last four years, only four countries (Denmark, Norway, Sweden and Finland) fulfilled this obligation. A change in this international attitude is urgent.

$CO^2$ accounts for more than 80 per cent of global warming pollution. Industrialised countries must reduce their $CO^2$ emissions by at least 60 per cent to move towards stabilisation of concentration of this gas in the atmosphere. Greenpeace calculates that a maximum average temperature increase of 1 degree Celsius over the next century is the upper limit the planet will be able to sustain. Anything about this safe limit would result in dangerous climate change happening so rapidly that sensitive ecosystems such as coral reefs would not be able to adapt.

**REGIONAL:** In the Pacific, the Melanesian, Polynesian and Micronesian governments need to meet, to share knowledge and ideas and to collaborate, in order to prepare strategies to reduce both the environmental degradation and its social and economic effects. Collective pressure, backed by hard local evidence, is also likely to be far more effective a shaker of developed world complacency than isolated reports that sometimes look like special pleading. A regional action plan should involve:

* participation in a program of careful and systematic monitoring of all reefs, extending the Global Coral Reef Monitoring Network;
* joining together to monitor local anthropogenic effects that add to reef stress, to assess the impacts on associated marine life and to plot the differential social and economic impacts on coastal communities. The more hard facts, the stronger the case and the stronger the individual action plans;
* a trans-Pacific accord, to which ALL the nations that fish in Pacific waters would have to be party, to prevent the overfishing of tuna and other game fish affected by the reduction of reef fish colonies and by pressures on fishermen to move to deeper waters.

  **NATIONAL:** Each country should develop its own long-term plan of action, based on its own intimate knowledge of its resources, enhanced by new surveys of its potential, where this is not yet fully known, and based also on a careful measure of the economy's degree of present dependence upon coral.
* Given the value yet vulnerability of coastal resources in these nations, monitoring and management must become national priorities. As reefs become increasingly stressed, they will become increasingly susceptible to stresses other than climate change. This will make the job of managers of these resources extremely challenging. Unified action and collected action at a Pacific level is also an urgent requirement.
* The object of the plan would be to diversify the economy, to provide wherever possible economic assistance for the people most directly affected, to build new skills and employment opportunities, to encourage inward investment and to develop new, alternative tourist attractions.
* The governments of the independent nations in the Pacific are all democratically elected and any such plan would be stillborn without popular understanding of it and commitment to it. The first national priority is therefore to make the facts known to the community through every medium of communication available.
* In support of the positive adjustments that will be needed, the high levels of literacy in general throughout these nations should be buttressed by an extended program of education, aimed at developing the new skills needed to develop new economic opportunities.

**When all is said and done, the key message of this report is inevitably addressed to the governments and citizens of the rich and industrial world. It is their carbon emissions that are the prime cause of the menace to the world's coral.** A few degrees of global warming may allow grapevines to flourish where they did not before in the gardens of the West. For the coral, just below the surface of the sea, those few degrees are a death warrant. If nothing is done to stop global warming, the only coral our children will see will be virtual coral from old underwater film.

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## NOTES