Climatic Change and the Future of Atoll States

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ABSTRACT

The combination of rising sea level and increased storminess that is expected to accompany changes in global climate due to the greenhouse effect may well have severe impacts on low-lying coral islands in tropical oceans. This paper deals principally with the atoll island states of Kiribati, Maldives, Marshall Islands, Tokelau and Tuvalu which comprise only coral-rubble islands with land rarely rising more than 3 m above present sea level. Their combined populations are about 300,000 and since colonial times, island economies have not achieved self-sufficiency. Presently they are substantially dependent on foreign aid and remittances from islanders who work overseas. The situation is worsening as natural resources decline, populations grow, aspirations for better living standards increase and the terms of trade worsen. Atoll island ecology and the ability to sustain human habitation depend in large part on fresh groundwater reserves which are related to island size. Groundwater degradation due to greenhouse-induced coastal erosion and inundation of low-lying ground will further reduce agricultural productivity and other island resources. The economic and social viability of atoll island states in the future is therefore doubtful; their people may become the first environmental refugees of the greenhouse era.

ADDITIONAL INDEX WORDS: Climate change, greenhouse effect, sea-level change, atoll islands, island economies, groundwater, coastal erosion, environmental refugees.

INTRODUCTION

No environmental issue has captured public and private imaginations throughout the world more than the 'greenhouse effect.' Indeed, perhaps no global issue has spawned such a variety of popular and academic speculations about the future. The scientific community is uncertain over actual rates of climatic change and future impacts; however, studies are drawing increasingly consistent conclusions about future trends, and pointing to the regions where the greenhouse effect (GE) will cause the most severe problems. This paper examines some of these trends in the context of atoll states in the Pacific and Indian Oceans where the GE is likely to cause substantial social, economic and political problems, and where such problems may begin to emerge early in the next century.

In the event of higher sea levels most coastal dwellers have the option of retreating inland to higher ground. Enormous economic and social dislocations can be expected in countries such as Bangladesh (Holdgate, et al. 1989), especially those with rich agricultural land and dense populations in low deltaic plains, but the most extreme situation could be faced by small oceanic states occupying low coral islands on atolls. Here high land does not exist and, if sea level continues to rise 'such states may cease to contain habitable land' (Pernetta, 1988, p. 9) and whole populations will be threatened.

This paper addresses social, economic and political factors, as well as the more usual physical ones, that will determine how atoll island countries cope with future climate and sea level changes. There is no attempt to determine precisely what these environmental changes will be in 50 or 100 years time, but rather to predict...
likely outcomes of one particular set of conditions by employing an interdisciplinary approach. In this we have attempted to bridge the growing gap between the physical and social ramifications of the greenhouse phenomenon.

There is now a large body of valuable data on coral reefs and atolls—the work of other researchers over the past decades. Yet despite the plethora of observations, measurements, radiocarbon dates and chemical analyses, there is still no good understanding of how subaerial islands on atolls form or how they might respond to future sea level changes. It is not our intention here to add to the existing data set; rather we suggest a conceptual model of atoll island evolution in response to relative sea level movements and storms that, we believe to be a fruitful direction for future research.

The paper focuses on the atoll states of Kiribati, Maldives, Marshall Islands, Tokelau and Tuvalu, which are entirely composed of low-relief coral islands (Figure 1). It does not consider, in any detail, the issues that affect atolls when they are part of larger multi-island states that include high islands, such as the Federated States of Micronesia (FSM), French Polynesia or the Cook Islands (Figure 1). The paper briefly reviews past developments and problems in the atoll states and speculates on the potential impact of climate change on future development. The socio-political repercussions of GE for Pacific atoll states have been reviewed in more detail elsewhere (Roy and Connell, 1989).

**CLIMATE CHANGE AND GREENHOUSE EFFECTS**

The build-up of industrial gases in the earth's atmosphere over the past 30 to 40 years is now well documented (Bolin et al., 1986; Pittock, 1988; Pearman, 1988b; Henderson-Sellers and Blong, 1989). The resulting climate changes are expected to raise temperatures over much of the earth's surface and lead eventually to a rise in the levels of the world's oceans (Warrick et al., 1988; Mitchell, 1989). Initially the latter will come about through expansion of surface waters in the oceans and melting of mountain glaciers (Barth and Titus, 1984; Bolin et al., 1986); not until much later will melting of the polar ice sheets significantly augment the ocean volumes (Budd, 1988; van der Veen, 1988).

Tide gauge records from around the world, analyzed by a number of researchers (Gornitz et al., 1982; Barnett, 1984; Aubrey and Emery, 1983; 1986; Emery and Aubrey, 1986; Pirazzoli, 1986; Bryant, 1988) indicate a small rise in relative sea level (1.0–1.5 mm per year) over the past few decades. However, the results are variously interpreted. Questions that remain to be resolved include (i) the extent to which the distribution of the recording stations can be divorced from regional tectonic trends and local earth movements (Bryant, et al. 1988); (ii) whether the observed sea level changes are due to the global greenhouse phenomenon or to local climatic variability (Bryant, 1987; 1988); and (iii) to what extent changes in river discharges to the oceans over the past century due to the building of dams, irrigation schemes and land clearing for agriculture have influenced the global hydrological balance (Newman and Fairbridge, 1986). At this stage, a causal connection between GE and the tide gauge data is not proven.

Lines of research currently being pursued include: (a) direct measurements of contemporary changes (e.g. atmospheric properties, mean sea levels from tide gauges, etc.) and (b) modelling to assess impacts of future climate scenarios. Because of uncertainty concerning the pattern and extent of future heating of the earth's surface (Henderson-Sellers and Blong, 1989) and the rate at which heat will be absorbed by the oceans (Pittock, 1988; Tucker, 1988), expansion of the oceans cannot be determined with any accuracy. Extreme scenarios for the next 50 years range from virtually no change in mean sea level to an elevation many metres higher (Barth and Titus, 1984; Hoffman, 1984; De Robin, 1986). A range of 20-140 cm rise in the next 50 years was adopted in Australia in order to consider possible implications of greenhouse for the future (Pearman, 1988a) but this has now been narrowed to 17-26 cm by 2030 followed by a continuing increase thereafter (Holdgate et al., 1989). The period of 50 years was chosen because it is the upper limit of most planning time-scales but, unless there...
are dramatic socio-economic changes, the GE will persist for a much longer period of time. To gauge the extent of the impact we adopt as a convenient scenario a sea level one metre higher than at present sometime in the next 50-100 years. In this scenario, rates of sea level rise for the future (averaging 10-20 mm/year) are similar to those documented during the Postglacial Marine Transgression (PMT) between 18000 to 6000 years ago when the sea rose at an average rate of 12-15 mm/year (THOM and Roy, 1985; DEVoy, 1987). Geological data from the past thus provide some basis for modelling future trends. Assumptions about the rate of sea level rise are necessarily tentative, and subject to later refinement.

The basic effect of a greenhouse-induced rise in sea level is for low-lying lands to be inundated and for coasts to erode (Roy and Thom, 1987; Short, 1988). Erosion, as opposed to inundation, is most severe on shorelines composed of unconsolidated sediment exposed to storm wave attack on high-energy coasts. Here, a gradual rise of mean sea level will progressively lift the zone of flooding, storm wave set-up and surge effects to new levels thus eroding areas hitherto considered safe (THOM and Roy, 1988). The effect of inundation of low-lying coasts can be even more widespread, causing salt intrusion into aquifers and destroying terrestrial ecosystems (Henderson-Sellers and Blong, 1989). Human responses will vary depending on the value of the coastal land under attack and the resources available to provide protective measures (Roy and Thom, 1987).

**ATOLLS AND ISLANDS**

*Geological Patterns*

Atolls are accumulations of the remains of calcareous reef-forming organisms usually arranged into a rim around a central lagoon. They are found in tropical ocean waters within 20° latitude of the equator. These reef deposits initially accumulated on the peaks of submerging mid-ocean volcanoes (Darwin, 1842; Scott and Rotondo, 1983) that have been slowly rafted across tropical oceans in migrating oceanic crustal plates. In Quaternary times the slow upward growth of the biogenic pile has been interspersed by glacio-eustatic fluctuations in sea level (Stoddart, 1973; Steers and Stoddart, 1977; Bloom, 1980; Wiens, 1962). The broad geological structure of coral atolls comprises a succession of old weathered limestones that form an irregular substrate on which the most recent (Holocene) deposits have accumulated (Figure 2a). The atoll rims and reef flats typically are higher and better developed on high-energy, windward coasts and are
composed mainly of coarse coral detritus cemented by calcareous algae (Wheatcraft and Buddemeier, 1981; Davies and Hopley, 1983). Atoll-rim detritus becomes finer towards the lagoon where the main sediment types are biogenic sands and calcareous muds (e.g. Ayers and Vacher, 1986) (Figure 2b). Storm ridges and spits of coarse rubble that build above sea level act as nuclei around which small islands (motu) grow (Figure 2c).

Radiocarbon dating studies (Davies and Marshall, 1979, 1980; Davies and Hopley, 1983; Hopley, 1982; Hopley and Kinsey, 1986; Marshall and Jacobson, 1985) show that, in most cases, upward reef growth has lagged behind rising sea level during the PMT (Davies and Montaggioni, 1985; Newman and Macintyre, 1985). It was not until one or two millennia after sea level stabilized that reef building corals reached shallow sub-tidal depths; here living corals became vulnerable to storm erosion, at least on windward coasts. Corals may initially have been more widespread in lagoons (Figure 2a) but were progressively smothered, as detrital sediments spread into the lagoons (Figure 2b). Much of the rubble that storms generate is washed landwards where, together with in situ coral and calcareous algae, it becomes cemented in the intertidal zone creating reef flats (Figure 2b). These are the foundation on which mounds of calcareous sand and coral rubble have built above sea level (Hopley, 1982; Chivas et al., 1986; Woodroffe, 1989). Precise radiometric dating of the time of formation of reef superstructures is made extremely difficult by the scarcity of in situ organic material and the rapidity with which diagenetic processes act on exposed carbonate. The same phenomenon inevitably reduces the accuracy with which relative sea level changes can be determined. Nevertheless, there is a large body of data to show that intertidal reef flats typically have radiocarbon ages less than 5000 years BP and coral islands are mostly younger than this age (Figure 3). Atoll islands are amongst the most recent of geological formations and are also the youngest in terms of human colonization.

Islands on atoll rims vary enormously in size and shape but the piles of coral/algal rubble and calcareous sand rarely rise more than 3 metres above mean sea level (Wiens, 1962). Cementation in the intertidal and even supratidal zone (Montaggioni and Pirazzoli, 1984) undoubtedly contribute to their stability. However, the occurrence of exposed and eroding outcrops of beachrock/coral conglomerate on the one hand and newly formed boulder ridges and sand spits on the other, indicate that islands are constantly changing shape (Wiens, 1962; Hopley, 1982; Flood, 1988). The diversity of coral island types has been recognized by Hopley (1982) in the Great Barrier Reef and by Wiens (1962) and Steers and Stoddart (1977) amongst Pacific atolls. Measurements by Emery and others (1954) show that most reef islands in the Marshall Islands are less than 1000 metres long and 500 metres wide. In other atoll groups, islands are narrow but reach considerable lengths and in Kiribati, islands more than 10 km long are common. Factors that influence the size, morphology and position of islands around the atoll rim are poorly understood. Storms control the size of gravel ridges and determine how frequently they are formed; tidal and wind-induced currents transport material away from islands and into lagoonal sinks; rainfall affects cementation/dissolution processes within the rubble pile; and biological processes, such as particular coral or algal growth styles, influence the generation of material that eventually forms the islands. These controls on island morphology operate within a broad framework determined by the local eustatic history and inherited Pleistocene geology of individual atolls or atoll groups. Series of beach ridges and recurved spits show that islands with these features have undergone net building or accretionary phases at some time during the late Holocene (Flood et al., 1979; Chivas et al., 1986). In contrast, features that indicate contemporary erosion include tidal channels intersecting islands and weathered coral ('makatea') surfaces around island margins and on reef flats. The ubiquitous problems of dating the transported materials that make up the islands have delayed development of meaningful models of island evolution relevant to the present discussion.

The building of atoll superstructures, especially islands, results from a combination of processes of small scale erosion and accretion, that can be observed on a day to day basis, interspersed with catastrophic changes caused by extremely violent tropical storms that occur quite rarely. Wiens (1962) and McLean (1980)
Figure 3. Radiocarbon dated material from the supra-tidal parts of atoll islands are mostly less than 4000 years old. Here data from a number of sources is shown in relation to the sea level envelope for SE Australia (Thom and Roy, 1985). Data Sources: Curry et al. (1970); Hopley (1983); Yonekura et al. (1984); Montaggioni and Pirazzoli (1984); Schofield (1977a, b); Marshall and Jacobson (1985) and Woodroffe (1989).

document a number of historical storm events in which waves passed across islands up to 8 metres above their land surfaces, hundreds of islanders died and whole habitats were destroyed—either washed away or buried in rubble.

Island Evolution

Patterns of island growth and decay related to storm activity have been documented for Ontong Java, Solomon Islands, by Bayliss-Smith (1988). In 1967 Cyclone Annie caused severe damage to vegetation, eroded coral from exposed reef fronts and formed large storm ridges or ramps of coral rubble on windward reef flats. In subsequent years products from the rubble ridges became welded to existing islands thus increasing their size, but the long-term trend was for the ridges to degrade as rubble was broken down and dispersed—the product of intermediate-intensity storms (Baines et al., 1974). Along lagoon shorelines, sandy beaches were initially cut back but then slowly recovered in the post-cyclone period, probably with the addition of the finer breakdown products from the rubble ridges. Very rare and large storms appear to be critical in suddenly generating new stores of coral rubble on reef flats which are then redistributed to maintain islands and infill lagoons. These changes are illustrated in Figure 4 and can be seen as part of a variable process of 'dynamic equilibrium' (rather than stages in an evolutionary progression) with periods of island accretion alternating with erosion (Bayliss-Smith, 1988; Stoddart et al., 1978). Individual island configurations may therefore be regarded in terms of sensitively balanced, individual sediment budgets. Figure 5 shows that island evolution depends firstly, on the 'relaxation time' or rate of decay of the land form and secondly, on the recurrence interval of major, rubble-generating storms. (Rates of coral regrowth may
Sea-Level Rise and Atoll States

Figure 4. Sequential stages in atoll island evolution following a cyclone that left a ridge of coral rubble on the windward reef flat (a). As the rubble ridge decays sediment is added to the islands and pavements of cemented conglomerate are left on the reef flat as remnants (b). The island changes shape but, with time, coastal erosion becomes dominant and sediment is washed mainly into the lagoon (c). Arrows show sediment transport pathways.

Figure 5. Stylized plots showing alternating phases of island growth and decay over a time frame of decades to centuries. The net, long-term sediment balance for atoll islands depends on the intensity and frequency of cyclones (C) that generate new supplies of sediment to the reef flat. In (a), more frequent cyclones lead to island growth; (b) shows the reverse trend.

exert an independent control on rubble production.

A state of disequilibrium may arise if environmental conditions, such as relative sea level or storminess, change with time. For example, island morphologies can be expected to differ depending upon whether an atoll is undergoing slow submergence or emergence. The theoretical effect of slow changes in relative sea level can be predicted: falling sea levels tend to promote the accumulation of sediment masses (Hopley, 1982, pp. 354–5) while rises should increase erosion. Many of the early observations of atoll islands did in fact infer a slight fall in sea level (Wiens, 1962, p. 95). While this trend has been confirmed by 14C dating in some areas (Hopley, 1982, 1983; Chappell et al., 1982), and has been predicted by earth rheology models (Nakada and Lambeck, 1989), it is disputed in other cases (Newell and Bloom, 1970; Curry et al., 1970; Montaggioni and Pirazzoli, 1984). This uncertainty is mainly due to the radiocarbon dating problems mentioned above, but also because the eustatic changes were so slow (0.1 to 0.2 mm per year) as to be masked or modified by local tectonic trends (Spencer et al., 1987).

A major control on the quasi-equilibrium state of atoll islands is storm intensity and variations in this factor will almost certainly be reflected in island morphology. In a spatial sense, McLean (1980, Figure 13) shows that cyclone frequency varies latitudinally, generally increasing away from the equator; it is therefore conceivable that atoll islands will show progressive morphological changes in the same direction—an hypothesis that remains to be tested by careful documentation of island
heights and morphologies over a wide range of latitudes. In a temporal sense, BAYLISS-SMITH (1988) suggests that storms in the mid-Holocene were more frequent and intense than at present and, at this time, reef islets slowly increased in size. He believes that the trend reversed during the late Holocene and islands then slowly reduced in size. Regional studies to document island morphology, their size and location on atoll rims and the nature of inter-island channels, reef flats etc., as were undertaken by researchers such as WIENS (1962), STEERS and STODDART (1977), need to be initiated to test the above relationships.

While the spectre of rising sea level in the future seems to follow inevitably from a greenhouse-induced warming of the atmosphere, there is growing evidence that its impact will not be the same everywhere. BRYANT (1988) has shown how past sea level changes have been influenced by local factors both climatic and oceanographic—factors whose variability may change with the GE. In this context it is noteworthy that, for atoll islands, a decrease in the frequency of large storms may cause an increase in coastal erosion. The nature of existing coastlines, whether cliffed, sandy, swampy etc., will also determine the impact of the GE. In contrast, swamp taro and Cyrtosperma taro are much more sensitive to salinity changes and grow in low areas, usually manually excavated taro pits in the central parts of islands. Salinity causes a substantial reduction in taro productivity (e.g. LEVIN, 1976; BATES and ABBOTT, 1958).

Island Ecology

Atolls are characterized by limited species diversity, especially in comparison with high islands, with only a few plant and animal types predominating (WIENS, 1962; THOMAS, 1963; STEERS and STODDART, 1977). There seems to be a direct relationship between diversity and island size, and rainfall. The main food crops are coconuts, breadfruit, taro and pandanus. In wetter conditions crops such as bananas are also cultivated. Because of the small size and the low elevation of atoll islands, virtually all plants have some tolerance to salt spray and brackish groundwater conditions. Species such as the coconut and pandanus can withstand quite high levels of salt and even occasional inundation by storm waves. In contrast, swamp taro and Cyrtosperma taro are much more sensitive to salinity changes and grow in low areas, usually manually excavated taro pits in the central parts of islands. Salinity causes a substantial reduction in taro productivity (e.g. LEVIN, 1976; BATES and ABBOTT, 1958).

Island ecology, in terms of the capacity to support human habitation, is closely tied to the existence of a permanent ground water system (WIENS, 1962). Islands above a certain size—about 1.5 ha and 200 m in diameter (CLOUD, 1952; WIENS 1962)—contain a permanent lens of fresh water surrounded by salt water (Figure 6a). The lens-like shape of the fresh water body is roughly governed by the density differences between salt and fresh water—the Ghyben-Herzberg principle. The volume of the lens is proportional to the width and surface area of the island (FETTER, 1972). Other factors influencing the character and behaviour of the freshwater lens include annual rainfall, permeability of the rock beneath the island and salt mixing due to storm- or tide-induced pressure gradients (BUDDEMEIER and HOLLODAY, 1977; VACHER, 1978; AYERS and VACHER, 1986; JACOBSON and TAYLOR, 1981).

During droughts, water table levels fall and the ground water may become brackish (LLOYD et al., 1980). Environmental stress is manifested by trees losing leaves, not fruiting and
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Figure 6. Ghyben-Herzberg freshwater lenses vary in size under present-day islands (a). They will be significantly reduced or even disappear if sea level rises and island shorelines erode (b). Because of the loss of "freeboard," storm overwash of the islands will cause salt intrusion into the groundwater to occur more frequently (c).

even dying. In Kiribati, where groundwater is the main source of drinking water on most islands, populations have been forced to migrate temporarily to areas with higher rainfall. On small islands especially, ground water reserves are particularly vulnerable to the vagaries of rainfall, storms etc. On Eauripik, an atoll in the FSM, cyclone disruption of groundwater supplies forced severe water rationing and bathing in salt water (LEVIN, 1976). However, the most severe threat to fresh water supplies is not from atmospheric factors directly, but rather from marine processes that cause coastal erosion and increase the frequency of storm overwash. Figure 7 shows in generalized form, the relationship between the dimensions of the ground water lens and island size, expressed in terms of width, and illustrates the dramatic effect of a 20 per cent reduction in island width which almost halves the volume of freshwater. Thus any decline in island area has a very dramatic influence on the availability of freshwater supplies.

While coastal erosion is invariably linked to raised sea levels, quantitative relationships between these have yet to be established for coral islands. Clearly, for a given rise in sea level, the amount of erosion will depend on the composition and height of a particular island, in its exposure to waves and currents and the
Figure 7. The maximum thickness of the Ghyben-Herzberg lens of freshwater beneath atoll islands increases in direct proportion to island width but the volume of freshwater increases semi-exponentially (Fetter, 1972). Thus changes in island width due to erosion or accretion have a disproportionately large impact on freshwater reserves.

frequency and intensity of storms. Figures 6b and 6c illustrate the types of change that might accompany a rise in sea level or increase in storminess. As erosion reduces island size, ground water lenses shrink beneath larger islands and virtually disappear under smaller ones causing all except the most hardy vegetation to perish. Sea levels rising at the rates contemplated under future greenhouse conditions, while having little effect on living coral, would outstrip the ability of islands to grow upwards and lead to a reduction in island 'freeboard' (height above mean sea level). Storm overwash would therefore become as increasingly frequent occurrence, causing damage to buildings and vegetation and salination of the ground water lens (Figure 6c). Conceivably, in the next 50 years or so, greenhouse induced coastal erosion in the order of 1-2 metres per year could reduce the dimensions of some presently inhabited islands to the point where their ground water supplies would no longer support a viable ecology or permanent habitation.

Probably the most severe situation is likely to occur on what are today the widest and most productive islands. These typically occur at bends in the reef crest where waves approach from two or more directions and series of recurved spits have formed around a central low area (Figure 8). Low areas are usually
swampy and historically have been used to grow swamp taro and *Cyrtosperma* taro; many islands of this type, such as Kuria in Kiribati and Eauripik (FSM) support relatively high population densities. The effect of a marine incursion on this type of island is illustrated in Figure 8. Not only are productive food areas in the interior of the island destroyed by saltwater flooding, but the ground water lens is greatly reduced as is the productivity of coconut and breadfruit crops. As sea-level continues to rise, however, so would the ground water table until eventually the central parts of the island become a shallow, and relatively unproductive, lagoon of brackish water.

**Atoll Island Economies and Societies**

"Coral reefs with their low sandy islets provide the most limited range of resources for human existence and the most tenuous of habitats for man in the Pacific... The soil is infertile, lacking humus, and fresh ground water is very limited... Maintaining a livelihood is a considerable task for man" (Thomas, 1963, p. 36).

Atolls vary enormously in size, both of land and lagoon areas, as do the natural resources that are available to support human populations and, most recently, in their ability to provide some form of diversified development. Atoll life was always far from that portrayed in images of the supposedly idyllic Pacific and Indian Ocean islands. Hazard, hunger and disease punctuated periods of well-being where warfare, abortion and infanticide served to reduce and control population numbers. In past times, many atolls have been depopulated and repopulated following natural disasters and migration movements of various kinds (Alkire, 1978; pp. 28-30; Connell, 1985, pp. 27-28; Connell, 1990; Osborne, 1966, p. 49; Pirazzoli, 1987). Islanders often developed cultural ties with those on other atolls so that, during periods of population-resource imbalance, their proximity to each other enabled economic exchange, personnel mobility and, on the negative side, warfare and raiding (Alkire, 1978, p. 94).

Despite the physical similarity of their environments, the atoll states discussed here are quite different in language, culture and history. They have varying degrees of political independence but all are economically dependent on the outside world (Connell, 1988; Roy and Connell, 1989). Total populations range
from more than 185,000 in the case of the Maldives to less than 2000 for Tokelau. Population densities average 200-300/km$^2$ for most atoll states but are more than 600/km$^2$ in the Maldives and an order of magnitude greater on the main islands such as Male, Majuro and South Tarawa. Typically isolated groups of people live on small islands clustered around the rims of atolls scattered over large areas of ocean; communications are tenuous. Since colonial times populations have expanded and the aspirations of the islanders for a better life style have grown. Despite some areas of increased productivity (copra and fishing), traditional agriculture has generally declined and the internal economies of the atoll states have failed to meet their people's expectations. Island countries have become increasingly dependent on imported consumer goods including foodstuffs. In the past, economic pressures were often substantially met by temporary (and often reluctant) migration overseas and the remittance of funds back home (PRIOR, 1981; MACDONALD, 1982, p. 53; CONNELL, 1986). Hopes of promoting manufacturing and tourism industries to generate foreign exchange have largely failed and, in more recent times, foreign aid, welfare funds and subsidies of various kinds have become the bases for island economies. This has led to increasingly centralized administrations and a government employment sector which only partly accommodates an increasingly well-educated workforce that is itself rapidly growing.

While out-lying islands have been depopulated, administrative and business centres are experiencing urban crowding with accompanying health and social problems (e.g. ITAIA, 1987). The need for outside aid is increasing and long-term migration overseas is now seen by many islanders as the best way to satisfy their aspirations (MARSHALL, 1979; CONNELL, 1986) though only Marshall islanders and Tokelau islanders have unconstrained rights of entry to Metropolitan states. Community dislocation and cultural decay are the inevitable consequences (SCHUTZ and TENTEN, 1979). These escalating pressures are forcing foreign nations around the Pacific rim to recognize that an offer of immigration may be an inevitable and necessary response to ailing island economies (COMMITTEE TO REVIEW THE AUSTRALIAN OVERSEAS AID PROGRAMME, 1984). For atoll states, dreams of reclaiming past self-sufficiency and control over their destiny are becoming more remote—a trend that GE seems likely to exacerbate.

### POTENTIAL IMPACTS ON ATOLL ISLANDS OF CHANGING CLIMATE

Although the climatic impacts of the GE will vary over time and from place to place in ways that are not yet possible to predict, especially at a local scale, it would seem likely that they will worsen the present difficulties of achieving development in atoll states. Rises in air and sea temperatures will influence weather patterns, change rainfall and storm frequency and intensity; sea levels may rise and coasts erode. The intertropical convergence zone is likely to shift northwards, changing the distribution of zones of upwelling and hence altering the distribution of fish stocks and thus fisheries. Slowly but inexorably there will be critical environmental changes but at unknown rates and impacts.

BAINES (1988, p. 9) states: “The consequences of changed climate, including raised air and sea temperatures, for the physiology of plants and animals and their ecological inter-relationships can only be guessed at this stage. Ecological processes, too, will change.” On atolls the relatively simple ecosystems enable some conclusions to be made with a greater degree of certainty, though nothing can be determined in quantitative terms at this stage. Specific changes that will affect atolls can be separately distinguished and examined in three principal areas. These are: firstly, the intrusion of saltwater into coastal groundwater supplies; secondly, coastal erosion and inundation of low-lying flat land; and thirdly, storm damage to coastal installations, such as port facilities. At present tourism is not a substantial source of income in four of the atoll states and disruption of coastal tourist facilities will occur only in the Maldives though it will certainly discourage future developments.

The intrusion of saltwater into groundwater lenses will have direct effects on agriculture and on the supply of potable water. The most obvious effects on agriculture will be through increased salinity in taro pits, lower crop productivity and hence a greater disinclination to continue with this labour-intensive agricultural activity. Even though coconuts, pandanus
and breadfruits are relatively salt-resistant, Ealey (1985) has shown that increased salinity in coastal areas of Thailand reduced productivity and killed off coconut palms. No crops will gain from increased salinity.

Increased salinity will reduce the potability of groundwater which, for most islanders, is currently of considerable significance. Although preference is usually given to rainwater, groundwater is a secondary source and, in drought conditions, access to it on every atoll is crucial. Significantly, freshwater is most scarce after storm surges or tsunamis have swept the sea over islands, salting soils and wells, a situation which is likely to increase under GE (Wiens, 1962). On some atolls with reasonably high rainfall such as Nanumea (Chambers, 1984), construction of better cisterns may enable groundwater usage to be minimised or ended (Holdgate et al., 1989). Costs of alternatives such as water purification and desalination are extremely high. On some of the drier atolls, including densely populated urban areas, water supply is already a critical problem. If and when groundwater becomes no longer potable, especially if combined with any long-term decline in rainfall, as is possible in some areas, human habitation will effectively be impossible.

Coastal erosion will both reduce land areas on atoll islands and, because of their minimal elevation, inundation will increase the swampliness and salinity of areas that are presently above sea-level. Especially at risk will be those areas that have previously been reclaimed from the sea, including parts of south Tarawa, and causeways such as those between Betio and Bairiki in Kiribati and in Majuro in the Marshall Islands. This loss of land will directly affect agricultural production, housing, roads, airstrips etc. In the Maldives, the international airport was closed by exceptionally large storm waves in April 1987 (Holdgate et al., 1989). There will be increased competition for scarce land in urban areas and more disputes over land tenure. Fortunately the severity of these conflicts is likely to be reduced by the custom in many communities of land tenure being organized by strips across the atoll from lagoon to ocean. The loss of land will lead to a related decline in handicraft materials (wood, pandanus, etc.) and of firewood, which is already in extremely short supply in urban areas such as Tarawa. Such changes will further threaten the already limited subsistence base and increase demand for expensive imports.

Inevitably, attempts will be made to protect coastal areas by building sea walls and other types of engineering works. The diversion of scarce resources, both human and financial, will further strain the islands’ economies and, as the problems become more widespread, may act as a heavy drain on foreign aid.

The GE is likely therefore to lead to a further decline in the few areas in which the atoll states currently demonstrate some degree of self-reliance: specifically in agriculture production. These problems will increase over time. One extremely pessimistic scenario even suggests that ‘it is conceivable that some baselines for territorial seas and Exclusive Economic Zones would have to be altered, decreasing the area of exclusive rights for marine resources and reducing potential income’ (Matos and Tiffin, 1988, p. 51; Pernetta, 1988). Long before this occurs, there will have been many more obvious negative effects. These will occur alongside continued rapid population growth, that independently increases pressure on resources. Intensification of the present structure of dependence on metropolitan states seems inevitable. Within countries it is likely to further encourage rural-urban migration in search of the ‘fast money’ of wages and salaries and away from the growing uncertainty of agricultural and fisheries incomes.

Atoll development options are naturally constrained by limited land (and sometimes lagoon) areas, and the simplicity of atoll ecosystems. These options have been artificially broadened by the introduction of new plant varieties, fertilizers, technology, and so on, from outside, but they are limited by the fact that many are expensive (and increasingly so) and far from simple to organize and maintain. More recently however, changes in aspirations and altered attitudes to traditional agriculture have resulted in a general decline of food cultivation and led to some loss of skills and knowledge (principally as modern “school” knowledge replaces inherited traditional skills). In the past, these same skills enabled survival and success in environments often threatened by natural hazards; they may be needed again to confront GE.
CONCLUSIONS—GLOBAL RESPONSES

Much of what can be currently known about the impact of GE is speculative since the order of magnitude of future physical events cannot be determined, nor is there precedent for what is likely to follow (Holdgate et al., 1989). The causes and consequences are both complex and inter-related, involving changing natural processes and a variety of human adaptations to those changes. Questions central to the greenhouse phenomenon are: will climate really change in the next 50 or 100 years?, by how much? and what will be the impacts? To expect mankind’s past (and ongoing) degradation of the world’s natural environments not to induce changes in global climate, is to be irrationally optimistic. There may be geological precedents for different world climates in the past, but there is no precedent for the speed at which present changes to the environment are taking place (see Figure 2.4 in Holdgate et al., 1989). It is therefore unrealistic to expect natural systems to compensate for, or accommodate, all these impacts without themselves changing to some extent and in ways that may make parts of the Earth less habitable for humans (LoveLock, 1988). Inevitably, the world’s climate will change; the extent of that change depends in large part on our political, social and technological behaviour in the future.

Increasingly, it is apparent that simplistic models, predicting environmental factors (temperature, rainfall, cloud cover, sea level, etc.) changing progressively and at the same rate throughout the world, are false. Even the roles of some of the factors are uncertain with new players such as the biosphere being seen as critically important by some (e.g., LoveLock, 1988). Changes will undoubtedly occur at differing rates and to different degrees from place to place. In the case of sea level change, it is probable, as Bryant (1988) points out, that local climatic and oceanographic factors will initially have a bigger local impact than the transfer of heat from the atmosphere to the oceans. Specifically, in the context of atoll islands, it is likely that degradation of present-day living conditions will come about through local factors—increased El Niño events, droughts, more storms and higher rates of coastal erosion (Love, 1987; Henderson-Sellers and Blong, 1989). Impacts will vary from place to place not only because of environmental variability, but also because of inherited geological factors that have produced differences in island morphologies and compositions.

Scientific research directions should proceed on at least two parallel fronts. Firstly, present-day climates and oceanographic processes in the tropics must be known so as to model future environmental changes likely to be experienced by atoll states. The installation of modern tide gauges, proposed by the Australian Government to the 1988 and 1989 South Pacific Forum Meeting, is an integral part of this research thrust. The second main area of research involves studies of island evolution to predict how particular islands will respond to changed environmental conditions. As suggested above, islands are the result of a precarious balance between gains and losses to piles of sediment on atoll rims—a sediment budget that is controlled by a spectrum of physical and biological processes. There are at least four inter-related topics requiring investigation:

1. Documentation of geological sediment budgets (including biogenic production, cementation, dissolution and erosion phenomena) to measure the history of island growth/decay during the mid- and late-Holocene. This must involve a large commitment to radiocarbon dating.

2. Air photo interpretation to record the regional diversity of island morphologies so as to establish patterns to correlate with other environmental variables.

3. Determination of storm regimes—frequencies, intensities and directions—from historical records and geological chronologies preserved in the islands themselves.

4. Relative sea level histories need to be compiled for individual atoll groups and related to earth-rheology models, geological indicators and climatic variables.

Uncertainty over the outcome of the greenhouse phenomenon will continue to restrict governments’ ability and willingness to respond to the problem through policy formulation. Response is least likely in the atoll states where
finance is limited, information is minimal and planning offices are small and already overstretched. Moreover, atoll states and other microstates cannot act individually or collectively to remove or reduce the causes of GE; they can only call upon international organizations to act globally. An international approach is essential but at this level, climatic change is only one element in a complex and integrated set of population, resource, economic and environmental problems. A further complication is that not all nations view GE in the same way: for high-latitude countries, global warming may be beneficial in terms of agricultural production.

The GE has now become a United Nations priority and UNEP is working towards an international convention for tackling the problem (World Commission for Environment and Development, 1987). However, there is little evidence that present socio-political systems have the capacity or willingness to control global events such as the unique greenhouse 'experiment' (Mercer and Peterson, 1988). The majority of the various management options canvassed by Goodman and Jager (1988) recognize the improbability of governments implementing the radical changes needed now to significantly modify GE. Meyer-Abich (1980) has suggested that there are three options for response: prevention, compensation and adaptation but concluded somewhat cynically that, from an economic and political point of view, prevention and compensation are much less practical than adaptation. Adaptation allows least action in the present, defers expenses into the future and does not require long-term international cooperation or agreement on long-range goals. A report on climate change by a Commonwealth group of experts tends to be more optimistic (Holdgate et al., 1989), however their action plans to control GE require such massive shifts in social paradigms as to be almost unimaginable. To what extent recent demands by third world countries, that for them to forego industrial development they should be compensated, may cause the Meyer-Abich scenario to be modified, remains to be seen but is unlikely to be significant.

Judging by the extraordinarily rapid developments in the post-war years, the nature of technological changes in the future is hard to imagine. The best-case scenario for a technological 'fix' for the GE entails massive energy conservation measures and the development of a non-polluting form of energy production, such as solar energy. A new energy technology would still take many decades, even if it was economic, before it globally replaced the present sources of energy and pollution. Behind the technology and economics there are powerful vested interests in both developed and developing countries; the export of coal and uranium is one example. Clearly, technology cannot avert, in the intermediate term, the inevitable consequences of greenhouse-induced changes in global climate.

If GE produces the kinds of results discussed here, atoll island states will eventually be overwhelmed. Conventional measures to reduce vulnerability (e.g. transferring populations, infrastructure and economic activities to higher land) are impossible. The construction of dikes and pumping stations is extremely expensive (especially when a small population is spread over a large number of islands), and it does not seem feasible to transport material (sand and gravel and even garbage from the US) to nourish the islands on the scale that would be required. Even defending the few urban areas, themselves isolated, would be an enormously costly operation, especially for impoverished and fragmented island states.

Increased emigration is seen as one response to GE, a response that builds on existing trends but is almost entirely dependent on the policies of metropolitan states. Nevertheless, as the title of a review paper discussing a concessionary Australian migration scheme implies—'Australia's Next Boat People'? (Howlett, 1985)—islanders could ultimately take migration matters into their own hands. Initially there is likely to be significant opposition to concessionary migration though, in time, when the impact of GE becomes apparent, this may decline. Concessionary migration schemes may be granted in other potential destinations such as New Zealand or even the United States. They are unlikely within the South Pacific and have not been mooted for the Maldives.

Long before the implications of the greenhouse phenomenon were recognised, appropriate development strategies for atoll states were cause for concern. Few nations have ever had such limited prospects for development, have gained so little from the technological advances
of this century yet have become so dependent on the outside world. Now it is even more crucial for there to be a focus on both scientific and development issues in atoll states. Without further substantial external assistance, there is little doubt that people who were once described as real and potential 'economic refugees' will become, in less than one hundred years, a new group of 'ecological refugees' (Pernetta, 1988) or "environmental refugees." It is extremely unlikely that actions taken within the atoll states alone will allay this gloomy forecast. Island groups such as Tuvalu and Tokelau, that were first populated less than a thousand years ago, can anticipate a future of population decline. Some of the most recently populated islands in the world may be depopulated. Some of the most recently formed islands may suffer extreme erosion, however, according to Brookfield (1989), "the probability of economic and nutritional distress, coupled with growing shortage of fresh water, is much greater than that of ultimate physical destruction" (p. 12).

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This paper is based on an earlier manuscript which dealt much more fully with the historic and contemporary economic, social and political impacts of western culture on atoll island states (Roy and Connell, 1989). The collaboration of authors from different disciplines—geoscience (PSR) and social science (JC)—had led to a degree of speculation about future events. Are we being alarmist? We think not. Environmental changes, as are already occurring on a global scale with the greenhouse experiment, could have severe repercussions for future generations. By the time we have amassed 20 or 30 years of climatic and sea-level data to be scientifically sure, it might be too late to make the necessary social changes (Pittock and Pearman, 1989). It is not alarmist to sound warnings if danger threatens.

LITERATURE CITED


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**RÉSUMÉ**


**ZUSAMMENFASSUNG**