

# NEW DIRECTIONS IN GENE TRANSFER BIOTECHNOLOGY OF FISH

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## ABSTRACT

Numerous laboratories have reported varying degrees of success from initial attempts at producing transgenic fish. These early efforts have produced results typically characterized by low levels of transgenicity and transgene expression, as well as high levels of mosaicism. Much research is needed before this technology becomes a routine and cost effective method for the development of new genetic fish stocks. New techniques and strategies that we are using to alleviate such problems and to increase the efficiency of gene transfer technology for fish include the following: 1) utilization of zygote and/or sperm electroporation methodology, in place of microinjection, to more efficiently introduce transgene DNA into the fish embryo; 2) co-introduction of purified fish nuclear proteins with the transgene DNA to help ensure its incorporation into the cell's nucleus; 3) development of an "integration cassette" DNA construct to target the integration site to increase the frequency of chromosomal integration, reduce the incidence of deleterious insertional effects, as well as increase the chance for transgene expression; and 4) utilization of a sensitive assay for transgenicity that does not require killing the larval fish. Once developed and tested, these experimental protocols should be readily adaptable to a wide variety of aquatic organisms. Although there are certainly environmental and ethical concerns regarding transgenic work, we think that the establishment of precise experimental protocols, with predictable results, will greatly reduce the potential for long term problems and allow this powerful technology to have a significant and beneficial impact on aquatic science.

## INTRODUCTION

Gene transfer biotechnology originally served as a valuable technique for basic molecular and cellular biology investigations. The power of this technology is evidenced by how quickly it moved from basic research into more applied areas such as biomedical, industrial and agricultural biotechnology applications. The introduction of foreign genes into developing embryos is now possible for a variety of animal and plant species (for review see Pursel, et al., 1989). This technology has already resulted in the development of improved plant and animal genetic stocks, the mass production of biological compounds (e.g., insulin), and is likely to become a valuable medical tool when applied to somatic cell gene therapy for humans suffering from genetic disorders. The U.S. Food and Drug Administration has recently released guidelines to pave the way for genetically engineered food products to reach the marketplace. Most importantly, these established guidelines are no stricter than those for any other food products.

Delivery of transgene DNA (foreign DNA) via standard microinjection into the one-celled fish zygote is a labor intensive, highly technical process. Moreover, the process is tenuous for fish because the transgene DNA cannot be directly delivered into the male pronucleus, as is done for mammalian species, but rather must simply be injected into the active cytoplasm of the newly fertilized egg. Furthermore, for many species of fish, the egg's chorion provides a formidable barrier to microinjection attempts. Once the

DNA has been injected, the investigator must then rely on chance that the transgene DNA actually gets incorporated into the newly forming nucleus so that it has an opportunity to integrate into the host genome. If integration is successful, additional problems can arise. For example, the integrated transgene might be located in a region of chromatin that will not allow it to be expressed, or, in the process of integrating, the transgene might destroy vital genetic information that will have deleterious effects on the viability of the embryo.

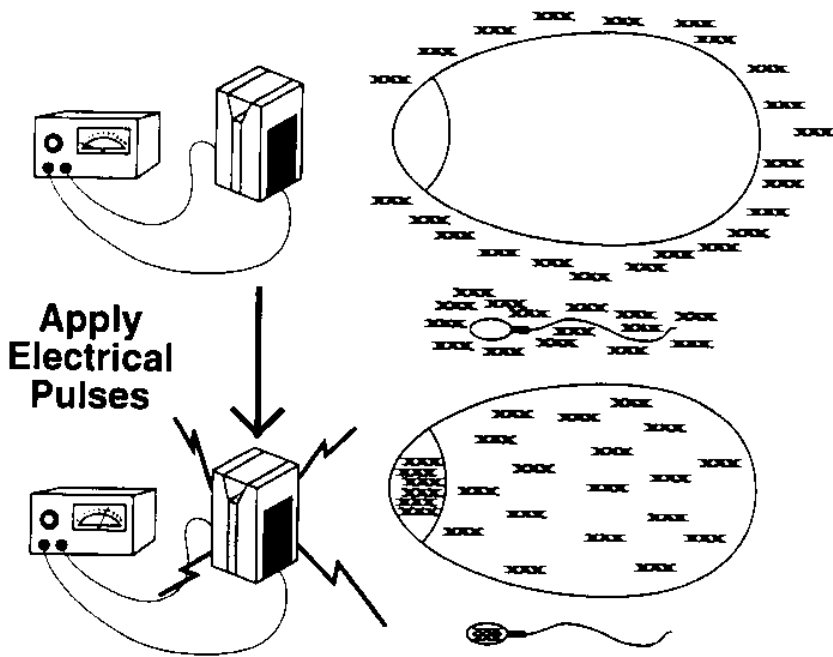
Several laboratories have reported varying degrees of success in their initial attempts at producing transgenic fish (Chourrout, et al., 1986; Dunham, et al., 1987; Chen, et al., 1989; Guyomard, et al., 1989; Rokkones, et al., 1989; Schneider, et al., 1989; Zhang, et al., 1990; Phillips, et al., 1992; Hew and Gong, 1992; Gross, et al., 1992). There is, however, much research to be done before this technology becomes routine and cost effective. Early efforts, including our own (Phillips, et al., 1992; Paleudis et al., 1992) have produced variable results that have typically been characterized by low levels of transgenicity and transgene expression, as well as a high incidence of mosaicism. Our research program fills an important niche in the application of gene transfer biotechnology to aquatic systems because it endeavors to integrate basic laboratory and applied fisheries components. In order to enhance our productivity and to make this technology routine and cost effective, we are moving away from early standard protocols and are applying new techniques and strategies.

### **ELECTROPORATION: HIGHER TRANSGENE DELIVERY RATE**

We have been able to successfully microinject both tilapia (Phillips, et al., 1992) and salmon eggs in previous experiments. However, as an alternative to microinjecting individual fish embryos, we are now employing electroporation as a means of simultaneously introducing transgene DNA into large numbers of fish embryos (preferably at the one-cell zygote stage). Electroporation, in which a brief electrical pulse makes the membrane of a cell temporarily permeable to macromolecules, is a relatively new technique for producing transgenic animals (see Figure 1). It is expected that this methodology will greatly increase the efficiency of transgene DNA introduction into the fish embryos and gametes. Buono and Linser (1991) and Liu et al. (submitted) have reported the production of transgenic zebrafish and medaka, respectively, through the use of electroporation. We have successfully worked out the electroporation parameters that allow the introduction of marker molecules into early stage tilapia embryos. Similarly, we are planning the electroporation of sperm as an alternative means of producing transgenic fish. Gagne, et al. (1991) used electroporation of bovine spermatozoa to carry transgene DNA into bovine oocytes. The spermatozoa were not transgenic, per se, but were used as vectors to carry the DNA into the oocytes at the time of fertilization and egg activation. Fish sperm is a particularly promising model since we are able to extend sperm viability with extender solutions (Scott and Baynes, 1980).

### **NUCLEAR PROTEINS: ENHANCED ACCESS OF TRANSGENE DNA TO ZYGOTE NUCLEUS**

The incorporation of a foreign gene into the fish genome is critically dependent upon the ability of that DNA to enter the cell's nucleus. This is typically accomplished in mammalian studies by microinjection of the DNA directly into a pronucleus shortly after fertilization. Because the physical characteristics of most fish eggs prevent direct delivery of DNA into the nuclear elements, an alternative method has been devised. A critical step in the formation of an embryonic cell nucleus after fertilization is the



### Cells take up DNA through temporary pores in their cell membranes

Figure 1. Gene transfer into fish by electroporation. One-cell zygotes and spermatozoa are treated with electrical pulses that cause the cell's membrane to become temporarily permeable to macromolecules such as DNA. Electroporation is quickly replacing microinjection technology as the method of choice for the simultaneous introduction of transgene DNA into a large number of fish embryos.

reassembly of the nuclear membrane. Nuclear membrane formation is an ordered process with discrete intermediate steps. One of these steps is the initial assembly of nuclear membrane around each of the chromosomal elements. The chromosomes are made up of chromatin material which mainly consists of a combination of DNA and DNA-binding nuclear proteins. The association between DNA and nuclear proteins causes the chromatin to condense. The newly forming nuclear membrane components begin to assemble around the DNA only after the chromatin is fully condensed. The nuclear membrane forms around each chromosome resulting in numerous small nuclei which subsequently fuse to form a single large nucleus containing all chromosomal elements (Alberts, et al., 1989; Newport and Forbes, 1987). It is believed that nuclear proteins play an important role in the reassembly of the cell's nucleus. Recently, Kaneda et al. (1989) reported a greater than 95% efficiency in the rapid transportation of the DNA into the nuclei of cultured cells via vesicle complexes when nuclear proteins were included. Furthermore, when plasmid DNA and nuclear proteins were co-introduced into rat liver cells, the plasmid DNA was carried into the cell nuclei and expressed at a rate 5 times greater than DNA co-introduced with non-nuclear proteins. High mobility group (HMG) nuclear proteins were used in these studies because they are known to be involved in the formation of nucleosomes, a basic element of chromatin structure. In addition, HMG proteins recognize and bind both single and double stranded DNA (Goodwin, et al., 1978; Elton, et al., 1987) and serve to protect the DNA from DNase enzymatic digestion (Hentzen and Bekhor, 1985). Using a modified method of Nicolas and Goodwin (1982), we have successfully purified fish HMG nuclear proteins (see Figure 2)

for electroporation into one-cell embryos with the transgene DNA. Co-introduction of these nuclear proteins should help to ensure that the transgene DNA is protected from degradation and increase the chance that it becomes incorporated into the nucleus (see Figure 3).

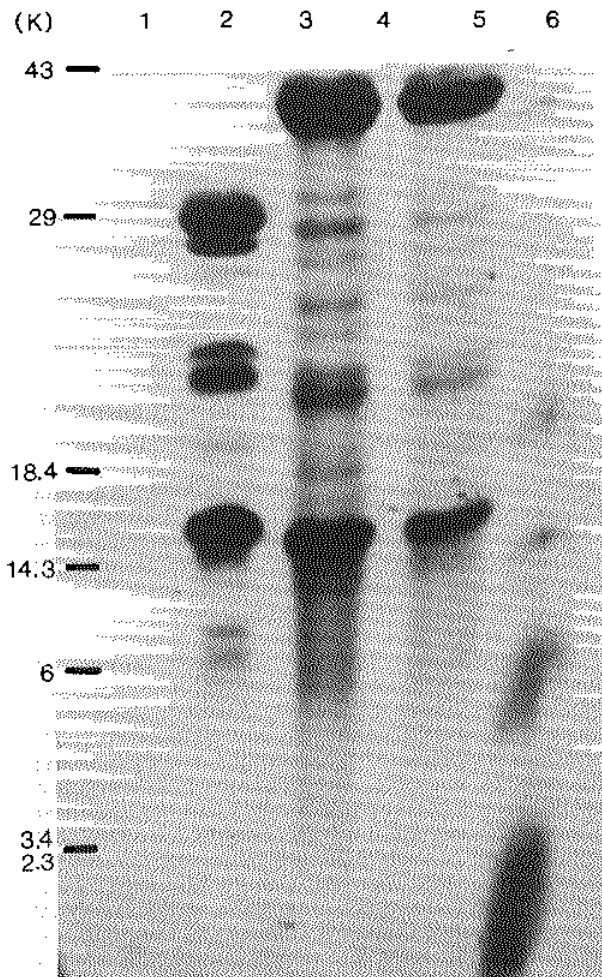


Figure 2. Purification of fish nuclear proteins. Shown here is a coomassie blue stained acrylamide gel containing high molecular weight (HMG) nuclear proteins purified from salmon (lane #3) and tilapia (lanes #4 and #5). Molecular size markers are shown in lanes #1 and #6 (lane #2 is empty). These nuclear proteins are co-introduced with foreign DNA to protect the DNA from enzymatic degradation and to help ensure that the DNA becomes incorporated into the nucleus (see Figure 3).

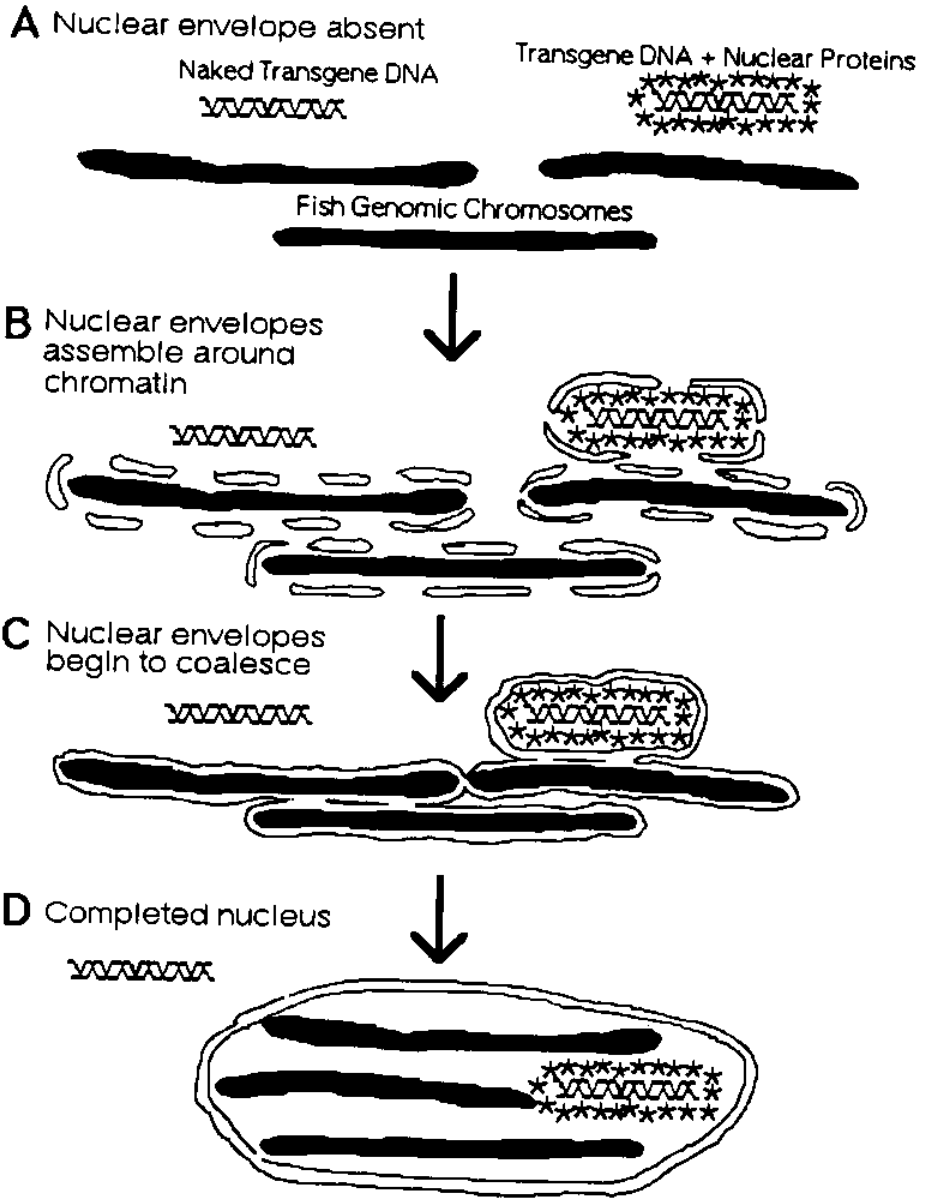


Figure 3. Illustration of the proposed action of nuclear proteins in delivering transgene DNA elements into the nucleus. Chromatin, a combination of DNA and nuclear proteins, serves as a critical factor in the reassembly of the chromosomal elements into the cell's nucleus. By ensuring that the introduced DNA has access to the nucleus, nuclear proteins can potentially enhance the chances for the stable integration of transgene DNA into the fish genome during the early embryonic period.

## **INTEGRATION CASSETTE TECHNOLOGY: STRATEGY TO ENSURE OPTIMAL TRANSGENE INTEGRATION INTO HOST GENOME**

While the timing of the introduction of transgene DNA into the embryo and its accessibility to the host nucleus are both important considerations, the actual integration process is critical for the successful production of a transgenic fish. An undesirable integration site could be lethal if the transgene inactivates important genetic information in the host's chromosomes. Similarly, the transgene might not be functional if it becomes incorporated into a heterochromatin region of the genome that prevents it from being actively expressed. We are in the process of designing a transgene DNA construct to target the chromosomal integration site in order to: 1) increase the frequency of successful chromosomal integration of the transgene, 2) reduce the incidence of deleterious insertional effects, as well as to 3) increase the chance for transgene expression. In doing so, we are taking advantage of a biological phenomenon known as "homologous recombination" that serves as the foundation for genetic recombination during normal meiosis and the integration of retroviral elements into host chromosomes. In order to accomplish this, specific DNA flanking sequences that are homologous to DNA in the fish genome will be included at each end of the transgene DNA construct. These sequences are designed to increase the frequency of integration and to ensure that integration is at a non-lethal, expressible site within the host fish genome. For this purpose, the nucleolar region of the fish genome, containing the multiple-copy ribosomal RNA (rRNA) genes, has been selected as the integration target site. DNA sequence information is readily available for rRNA genes and these genes have proven to be highly evolutionarily conserved. We have targeted the rRNA genes because there are hundreds of genomic copies of the rRNA genes to serve as targets, and insertion (disruption) into one or more of these target genes would presumably have no effect on normal cellular processes. Since cells constantly produce ribosomes for, the rRNA genes are constitutively expressed. Therefore, an integrated transgene would be located in a chromatin region (chromosomal context) that would optimize its chance for expression. For these reasons, we consider our transgene DNA constructs to be "integration cassettes." Furthermore, due to the evolutionary conservation of the rRNA genes in vertebrates, the identification of a successful integration cassette flanking sequence for tilapia would represent a DNA construct that could be directly applied to gene transfer efforts in other fish species.

## **POLYMERASE CHAIN REACTION: SENSITIVE ASSAY FOR TRANSGENICITY**

The sensitivity of the Polymerase Chain Reaction (PCR) protocol to amplify specific sequences of DNA permits the analysis of the genome of fish from small samples of tissue, blood, or gametes, while allowing the fish to remain alive. This is an important consideration when attempting to obtain viable brood stock for genetic studies. Additionally, this sensitivity allows for earlier screening of live animals which will provide faster, and more reliable, feedback regarding the effectiveness of transgene methodology. However, in order to use PCR techniques to detect a particular genetic element, the researcher must know the nucleotide sequence of that genetic element in order to make the necessary DNA primers. In the present application, detailed knowledge of the "integration cassette" construct makes PCR primer sequence identification relatively straight forward. After the initial PCR screening for transgenicity, transgene integration is verified for positive samples via standard Southern blot analysis (see Paleudis, et al., 1992). The digoxigenin non-radioactive chemiluminescent detection system is used in order to avoid the disadvantages associated with the use of radioactive DNA probes, namely safety risks, requirements for special laboratories and training of personnel, hazardous waste disposal expenses and protocols, instability of probes, and higher costs (Holtke, et al., 1992).

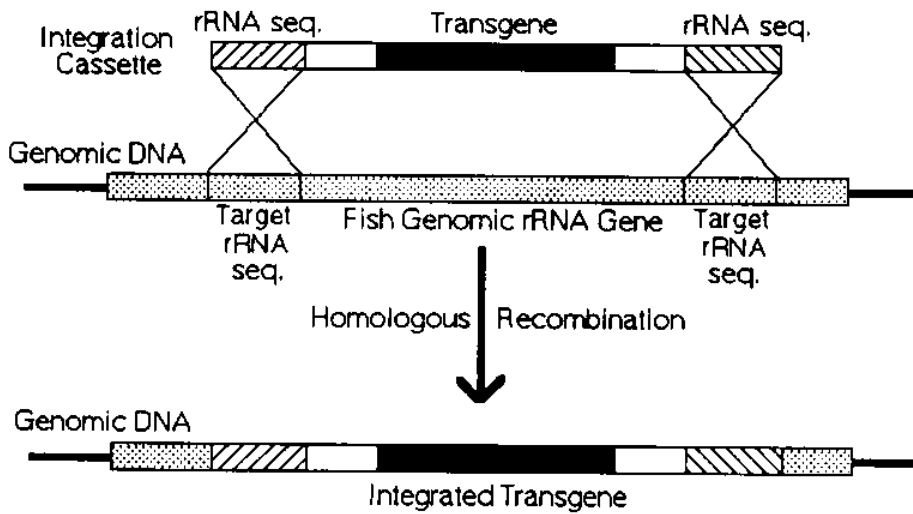


Figure 4. Integration cassette technology. Our current work with fish embryos employs a homologous recombination strategy in an attempt to increase the success rate for the production of transgenic fish while minimizing potential problems associated with random DNA integration. The transgene DNA is inserted into a DNA construct that contains flanking DNA sequences that are homologous to regions of the multiple-copy ribosomal RNA genes of the fish genome.

### SUMMARY

Once developed and tested, the experimental protocols presented here should be readily adaptable to a wide variety of aquatic organisms and scientific applications. Along with the advent of gene transfer biotechnology comes significant ethical and moral considerations (Kohler, et al., 1992). However, with the use of sound scientific methodology under the guidance of established Recombinant DNA guidelines, gene transfer technology is certain to provide many more benefits than problems. In practice, gene transfer technology is not unlike the selective breeding techniques initiated thousands of years ago by our agricultural-minded ancestors, the major difference being the accelerated pace possible with modern science. Basic research done now will lay a strong foundation for very important uses of biotechnology in response to unforeseen problems and situations that mankind will face in the future.

### ACKNOWLEDGMENTS

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# A NATIONAL MARINE SANCTUARY FOR HAWAII'S KOHALA

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## ABSTRACT

Title III of the Marine Protection, Research and Sanctuaries Act of 1972, 16 U.S.C. § 1431 *et seq.*, (the "Act") authorizes the Secretary of Commerce to designate discrete areas of the marine environment as national marine sanctuaries to protect their special conservational, recreational, ecological, historical, research, educational, or aesthetic qualities. The Act is administered by the National Oceanic and Atmospheric Administration (NOAA).

In December 1977, NOAA received a nomination for a humpback whale national marine sanctuary in the waters off Maui, Hawai'i. In January 1984, NOAA released a Draft Environmental Impact Statement/Draft Management Plan. Based on the comments received, subsequent review and consideration of the site was suspended.

In October 1990, Congress directed NOAA to determine the feasibility of establishing a humpback whale national marine sanctuary in Hawaiian waters. After significant public, State, and Federal consultation, NOAA published and transmitted its study to Congress in December 1991. In November 1992, the Hawaiian Islands Humpback Whale National Marine Sanctuary was designated.

Four critical factors will determine the success of the Nation's newest national marine sanctuary: 1) a clear understanding of the benefits and limits of sanctuary designation; 2) an understanding and appreciation of Hawaiian culture; 3) cooperation from marine and coastal user groups; and 4) coordination between NOAA and the State.

## INTRODUCTION

The Hawaiian story of creation, the *Kumulipo*, tells us of Earth's creation. Out of the realm of darkness, light, air, land, and water were created. The creatures that live on the land and in the water were formed and life on earth began. Among the largest creatures created were the *kohola*, or whales, whose guardian on land was the *ili-ahi*, or sandalwood tree. The *Kumulipo* tells us "...a procession of *kohola* are passing by, the *opule* are swimming in schools for a long distance, and the ocean is thick with them." (Beckwith, 1951; Johnson, 1981). Reflecting upon this magnificent tale, it is ironic to note that the *kohola* and its guardian, the *ili-ahi*, are both endangered species.

The *Kumulipo* indicates that the early Hawaiians were very aware of their environment, which they valued as a treasure for all; a treasure to be preserved for future generations. Preservation was a way of life. In westernized terms, the Hawaiians

practiced conservation and wise management of their resources because their lives and the lives of future generations; the survival of the Hawaiian race; depended on it.

Presently, we are witnessing a renewed interest in protecting one of the largest creatures referred to in the *Kumulipo* - the humpback whale.

## HISTORICAL EFFORTS TO PROTECT THE HUMPRACK WHALE

Efforts to expand protection for the humpback whale beyond that offered by the Marine Mammal Protection Act and the Endangered Species Act date back to the late 1970s. During that period, numerous workshops and symposia dealing specifically with issues such as harassment, behavioral indicators of stress, and activities which might constitute harassment, were held. The results of this process included a set of formal recommendations by the U.S. Marine Mammal Commission, the issuance of a "Notice of Interpretation" on *Humpback Whale Harassment in the Hawaiian Islands Area* (44 FR 113, 1979) by the National Marine Fisheries Service (NMFS), and the formal submission of a proposal to the National Oceanic and Atmospheric Administration (NOAA) in 1977 for a humpback whale sanctuary in Hawaiian waters (NOAA, 1983).

The Marine Mammal Commission recommended a wide range of management alternatives to ensure the protection of the whales, including increased Federal enforcement presence during the whale season (Figure 1). The NMFS notice identified principal calving areas in Maui County waters, defined "taking" by means of harassment under the Marine Mammal Protection and Endangered Species Acts, and the identification of specific human activities which constituted harassment and, consequently, were subject to regulation (Figure 2). This notice currently serves as the principal means for protecting the humpback whale and managing its habitat in Hawai'i. The proposal for marine sanctuary status, submitted by a private researcher, recommended three boundary alternatives, all within the waters of Maui County but excluding the area referred to as Penguin Bank off the northwest coast of Moloka'i (Figure 3). The purpose of the proposed sanctuary was to "*preserve, protect, and manage essential, specialized habitat of the Hawaiian humpback whales, and to conserve genetic resources of the Hawaiian humpback breeding stock. In addition, the proposal is submitted to allow scientific research and education in support of humpback whale stock management, and to provide an ecological baseline to compare and predict the effects of man's activities on other humpback whale calving/breeding areas.*"

Although the 1977 proposal was not successful, interest in protecting humpback whale populations and their habitats has continued. In October 1990, the 101st Congress directed NOAA to study the feasibility of designating a national marine sanctuary in the waters adjacent to Kaho'olawe Island (Public Law 101-515), giving special consideration to the effects of such a sanctuary on the population of *kohola*, or humpback whales, that inhabit the island's waters. In response to this directive, NOAA conducted a series of meetings in Hawai'i to solicit comments from Federal, state and local agencies and the public. The results were transmitted to Congress, published and distributed in December 1991 (NOAA, 1991).

In its report, NOAA concluded that the waters surrounding Kaho'olawe merit further consideration as a sanctuary because of their biological, cultural, and historic significance. In addition, NOAA suggested that other sites within the Hawaiian Archipelago may be investigated for consideration as a component of a possible multi-site national marine sanctuary. However, the feasibility of establishing a national marine sanctuary in Hawaiian waters appears to depend on four critical factors:

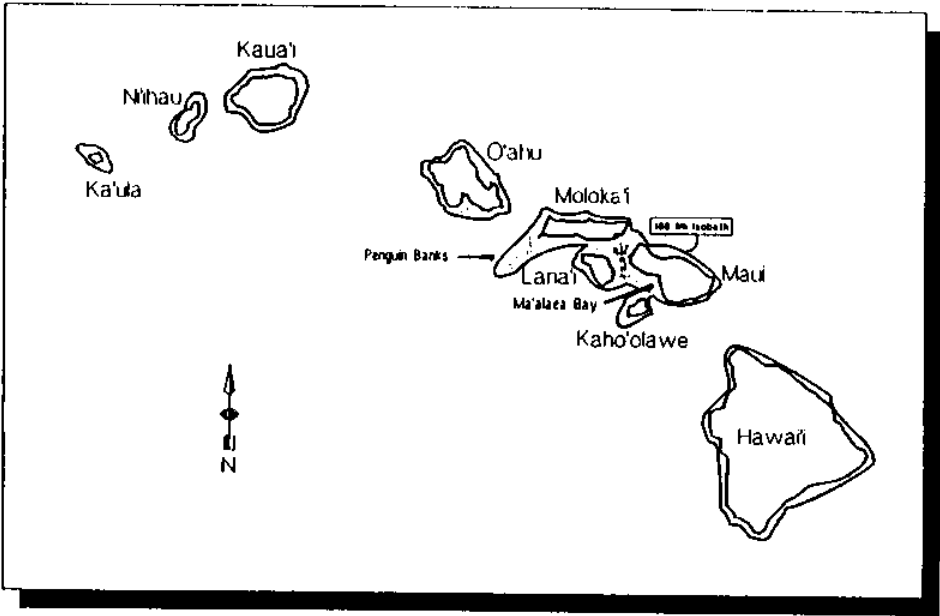


Figure 1. 1979 Marine Mammal Commission workshop recommendation

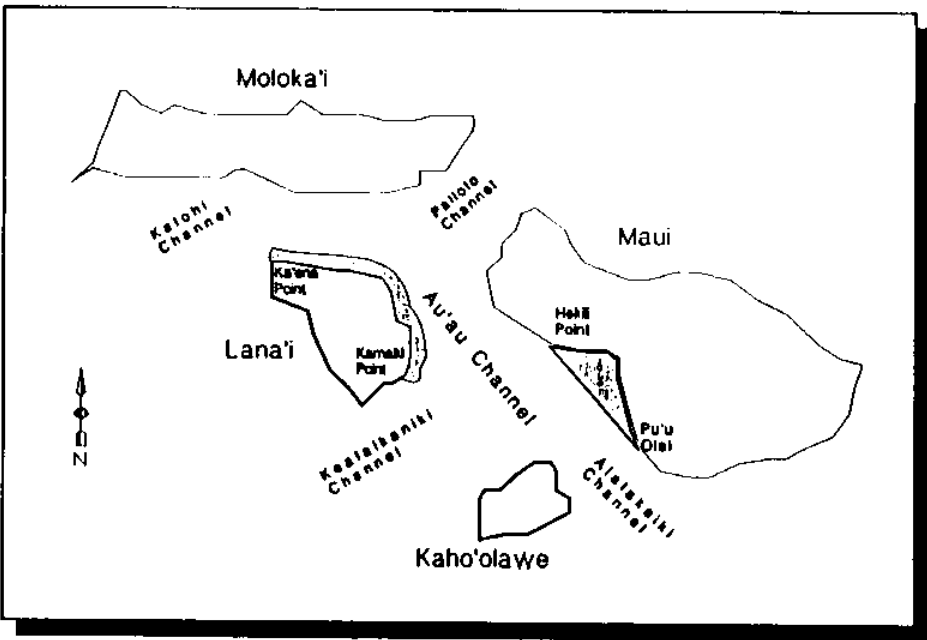


Figure 2. NMFS "Cow/Calf Zone"

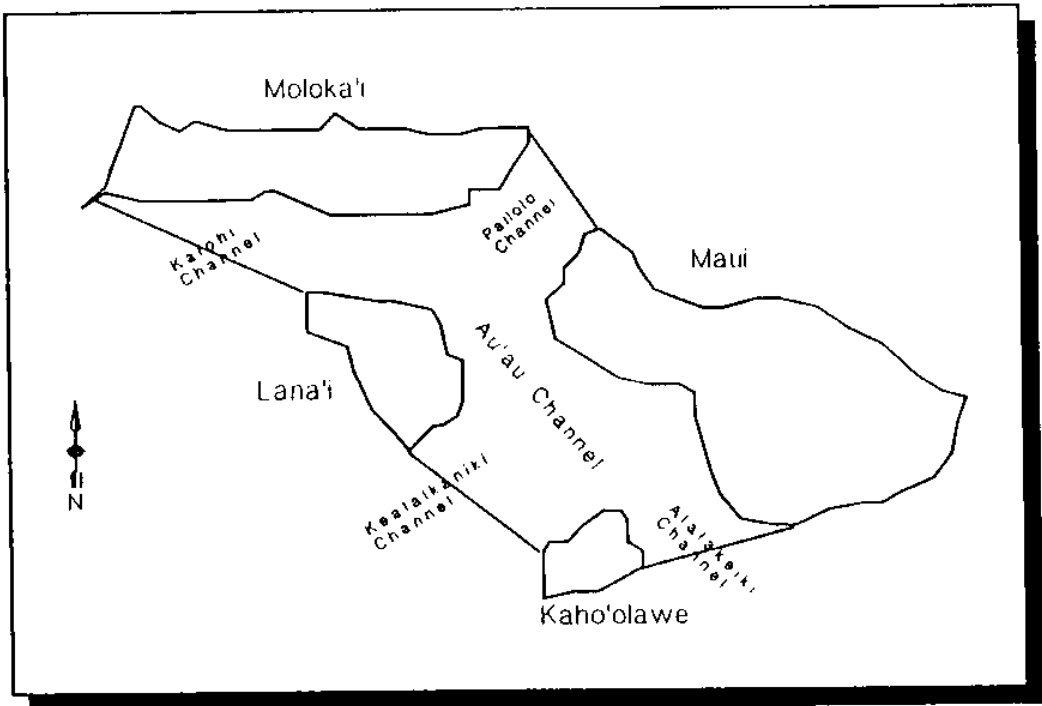


Figure 3. 1983 National Marine Sanctuary Program proposed boundaries

- 1) A clear description of the benefits and limits of the National Marine Sanctuary Program with respect to conservation and management of marine resources in Hawai'i;
- 2) An understanding and appreciation of Hawaiian culture and traditions and the incorporation of native Hawaiian interests in sanctuary planning and management;
- 3) Cooperation, from marine and coastal user groups, including recreational and commercial fishermen, other recreational users (such as divers, whale watchers, thrillcraft operators), coastal development interests, and environmental organizations; and
- 4) Coordination between NOAA and the appropriate State agencies.

### **THE NATIONAL MARINE SANCTUARY PROGRAM: WHAT CAN IT DO FOR HAWAII?**

Congress passed the Marine Protection, Research and Sanctuaries Act (MPRSA) in 1972 to preserve nationally significant ocean resources. Under the MPRSA, the Secretary of Commerce may designate ocean and coastal waters, and areas of the Great Lakes, as National Marine Sanctuaries. Aside from protecting natural resources, such as fish, mammals, seabirds, and coral reefs, historic and cultural resources, such as

shipwrecks and the marine portions of ahupua'as (traditional Hawaiian land divisions that usually extend from the uplands to the sea), could also be considered for inclusion. The MPRSA provides the only opportunity under U.S. law to designate and manage discrete, offshore areas on an ecosystem basis. Other laws allow the management of individual resources, such as marine mammals and fish.

The MPRSA is administered by the Sanctuaries and Reserves Division of the Office of Ocean and Coastal Resource Management, National Ocean Service, NOAA, Department of Commerce. The major goals of the NMSP are to provide enhanced resource protection through comprehensive and coordinated management and conservation; to support, promote and coordinate scientific research on, and monitoring of, specific marine resources; to enhance public awareness, understanding, appreciation and wise use of the marine environment; and to facilitate multiple uses, to the extent that they are compatible, with the primary objective of resource protection (NOAA, 1991).

In general, Federal, State and county resource management statutes have been unable to keep pace with the increasing urbanization of Hawai'i and the pressures that are brought to bear on its resources. Recognizing this as a statewide problem, the Hawai'i legislature created the Hawai'i Ocean Resources Management Program (Act 235, HRS Chapter 228) to develop a comprehensive, coordinated, and integrated ocean policy. The Hawai'i Ocean and Marine Resources Council, formed in response to Act 235, has developed the Hawai'i Ocean Resources Plan. The Plan identified a number of issues regarding the need for coordinated, comprehensive management of Hawai'i's ocean resources (Hawaii Ocean and Marine Resources Council, 1991), including the establishment of marine conservation areas. Like the other national marine sanctuaries (Figure 4), the MPRSA can help the state of Hawai'i manage its ocean resources through a comprehensive, coordinated management regime.

Based on its experience in developing sanctuary management plans for a diversity of ecosystems and government entities, the NMSP has the capability of helping the state to tailor a resource management plan, consistent with Act 235, that will address a marine resource of State, national, and international significance: the humpback whale and a significant part of its habitat. The lessons learned from this planning process will undoubtedly provide valuable insight to the State in further addressing its other ocean resource management issues.

## KAHO'OLAWE, THE KOHALA, AND HAWAIIAN CULTURE

To many Hawaiians, Kaho'olawe is the symbol of the revitalization of native Hawaiian culture. Part of this resurgence involves the traditional practices of subsistence fishing, canoe navigation, and the honoring of Hawaiian ocean and agricultural deities. *Aloha aina*, the belief that the land is the religion and the culture, and *ke ola kai*, the life of the ocean, are central to understanding the importance of Kaho'olawe to Hawaiians. In addition, its status as a *wahi pana* (sacred place) and *pu'uhonua* (place of refuge or sanctuary), makes it very significant to Hawai'i's culture.

In Hawaiian culture, the oral tradition of *mele*, or songs, chants and genealogical recitations that recorded significant historical events, do not refer specifically to the humpback whale, but to a generic whale called the *kohola*. As one of the most depleted species on earth, the *kohola's* scattered populations inhabiting the world's oceans today represent a small fraction of their former numbers and stand as reminders of man's recent history which has seen the humpbacks and other whale species extensively exploited by coastal and high seas whalers.

# National Marine Sanctuary Program

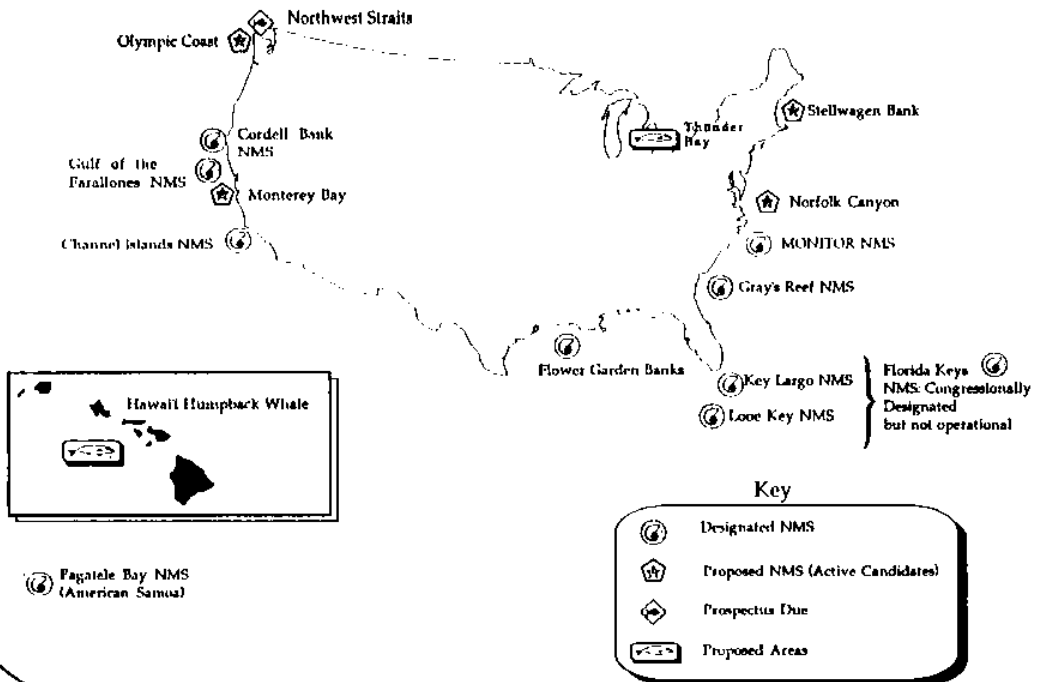


Figure 4. Status of national marine sanctuaries

Similar to the *kohola*, many feel Hawai'i has been overexploited, depleting the islands of its people, its culture, and its ocean resources. Aluli and McGregor (1991) quote a Hawaiian *kupuna* (grandparent or ancestor) to describe the importance of the ocean to Hawaiians: *Mai ke kai ke ola, mai ke kai mai ka make ... From the ocean comes life, from the ocean comes death.* As the primary source of life, Hawaiians believed depletion of the ocean's resources would lead to the end of the Hawaiian people and life itself.

Thus, like Kaho'olawe, the *kohola* is symbolic of the status of the Hawaiian culture in the twentieth century - that of an endangered culture. Creating a *pu'uhonua* for the *kohola* in Hawaiian waters will, to many, be a symbolic recognition of the importance of Hawai'i, its culture, and its resources, on a national and international scale.

## SANCTUARY DESIGNATION AND THE USERS

Each winter, the shallow, warm waters surrounding the Hawaiian Islands provide an ideal place for humpback whales to breed and tend their young. These "large-winged" mammals begin entering Hawaiian waters as early as November, where

they remain until late spring when they depart for their summer feeding grounds off the south coast of Alaska (Baker and Herman, 1981). These seasonal visitors to Hawai'i represent the largest and most widely known of the three breeding populations remaining in the North Pacific (Herman, 1979).

Although sighted over deeper waters throughout the major islands, the shallow waters found within the 100-fathom (183 meter) isobath appear to be the preferred habitat and, consequently, play host to the greatest number of wintering humpbacks (Glockner-Ferrari and Ferrari, 1985). These waters have also been traditionally shared by residents and tourists, who engage in a wide range of commercial and recreational activities such as boating, fishing, thrillcraft, and diving.

Some of these activities, particularly those directly resulting from heightened enthusiasm for research and the profitability of whale watching charters, might contribute to the harassment of the species if not regulated. Such cause and effect relationships, however, are not entirely substantiated by scientific research. If such correlations are established in the future, State and Federal authorities already possess the means to amend their regulations appropriately. What human activities affect the behavior and/or biological fitness of the seasonal whale population in Hawai'i are still issues of sufficient importance to warrant further evaluation.

In most currently designated national marine sanctuaries, the effects of the designation on the user groups have been positive. For instance, the philosophy of multi-use has had a major impact on the planning and management of all marine sanctuaries, as it has allowed the input of user groups throughout the planning process. Many user groups have been active in helping develop management plans, directing research and developing successful interpretive programs. Because of the multi-use philosophy and the opportunity for local input in the planning process, fishing, diving, boating, and a number of recreational and commercial activities are allowed in most areas.

### **THE STATE AND NOAA: A PARTNERSHIP OF NECESSITY**

The failure of the 1977 proposal was due in large part to the lack of a strong State-NOAA partnership. Although the proposal had its merits, its detractors and supporters, NOAA was left to do a lot of the day-to-day work from Washington, D.C. This made timely response to important issues impossible. The State, on the other hand, was left in an unenviable position of addressing NOAA policy questions the public had. As a result, an accurate picture of what sanctuary designation means, what it would do for the State, and its effect on the various users was not well-articulated.

In order to provide for timely response to issues of local concern, NOAA has placed a liaison in Hawai'i to work directly with the Office of State Planning. Like its counterparts in the other "study areas," the liaison is crucial to maintaining a clear line of communication between NOAA, the State and other affected public and private organizations and individuals. More importantly, it allows NOAA and the State to quickly respond to issues of national, international and local concern. If designation is to be successful, NOAA and the State must maintain this important line of communication.

## THE HAWAIIAN ISLANDS HUMPBACK WHALE NATIONAL MARINE SANCTUARY

On November 4, 1992, President Bush signed Public Law 102-587 establishing the Hawaiian Islands Humpback Whale National Marine Sanctuary to "support, promote, and coordinate scientific research on, and monitoring of, that portion of the marine environment essential to the survival of the humpback whale...." Subtitle C of the MPRSA, also known as the Hawaiian Islands National Marine Sanctuary Act, designates areas of the marine environment "seaward of the upper reaches of the wash of the waves on shore...." and includes the 100-fathom isobath "adjoining the islands of Lanai, Maui, and Molokai, including Penguin Bank, but excluding the area within 3 nautical miles of the upper reaches of the waves on the shore of Kahoolawe Island...." In addition, "the deep-water area of the Pailolo Channel from Cape Halawa, Moloka'i to Nakalele Point, Maui and southward...." and the "one hundred meter isobath adjoining the Kilauea National Wildlife Refuge on the island of Kauai...." was included. This bill also leaves open the possibility of boundary modifications to include the waters surrounding Kaho'olawe and other areas and resources **after** sanctuary designation. Presently, NOAA and the State are in the process of developing a management plan for the sanctuary.

The eventual success of the Nation's newest national marine sanctuary is yet to be determined. Public comment, public participation, and a clear understanding of the needs the *kohola*, the State and NOAA will remain the major points that must be considered in striving to develop the most effective management plan for the sanctuary.

### SUMMARY

Both Congress and the public have renewed their interest in providing protection to Hawaii's humpback whale population beyond that afforded by the Marine Mammal Protection Act and the Endangered Species Act. The designation of the Hawaiian Islands Humpback Whale National Marine Sanctuary indicates Congress' commitment to protecting a significant endangered species. Many in Hawai'i see the protection of the *kohola* and its habitat as vital and symbolic to the national and international recognition of the importance of recovering and maintaining the Hawaiian culture.

The *kohola*, Hawai'i's native born giant, and the Hawaiian culture are endangered. As part of a cultural reawakening, people are asking: What is the significance of the nation's newest *pu'uhonua* to Hawai'i and the nation? How will Hawai'i's culture and its marine resources benefit from sanctuary designation? How can the people of Hawai'i, as *konohiki* (overseer) of their island environment, contribute to the long-term survival of the *kohola*? The answers to these and many other questions depend on the ability of NOAA, the State, and the people of Hawai'i to cooperatively manage a nationally and internationally significant marine resource.

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# CORAL REEF ISLANDS IN A PERIOD OF GLOBAL SEA LEVEL RISE

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## ABSTRACT

Unnecessary concern has been raised amongst low-lying island nations regarding the possible consequences of a greenhouse-induced sea level rise over the next century. A process approach to the problem suggests that far from disappearing, many coral islands will increase in size at least during the first 100 years of sea level change. Similarly, the application of more realistic groundwater models, to predict the future of potable freshwater resources on reef islands, suggests that the resource may actually increase in some areas during the period of sea level rise. Greater problems may result from the lack of mature soils, though plant growth may be aided by CO<sub>2</sub> enrichment, especially as many reef island crops belong to the C<sub>3</sub> group. Marine resources may also be replenished by greater circulation in lagoons, although the possibilities of some eutrophication must also be taken into account. It is suggested that the present pressures on reef islands due to population increases, and already occurring natural phenomena are more important for the planning process than the potential sea level rise of the next 100 years. Maintenance of healthy reef systems will be important in allowing these positive responses to global change.

## INTRODUCTION

Concerns about global changes produced by the greenhouse effect during the 1980's quickly focused attention on the effects of sea level rise on particularly vulnerable coastal areas. Statements were made, by those who knew very little about coral reef processes, which suggested that some island nations may disappear altogether, e.g., "It is estimated that a 60 cm rise around the Maldives in the Indian Ocean would cover these coral islands and displace 177,000 people." (Falk and Brownlow, 1989)

The popular press were quick to take up this doomsday theme. For example, the *Pacific Islands Monthly* had as a feature article a special report entitled, "The Greenhouse Effect -Where Have All The Islands Gone." The report argued that "atoll states are the most helpless of all nations in face of the Greenhouse Effect" and concluded with the forecast "some of the most recently populated islands in the world may be depopulated ... and some of its most recently formed islands may disappear forever." (Roy and Connell (1989) and McLean (1989))

Not surprisingly there was an immediate political response. For example,

If the Greenhouse Effect raises sea levels by 1 metre, it will virtually do away with Kiribati... if what the scientists say now is going to be true, in 50 or 60 years my country will not be there.

-President I. Tabai  
Kiribati, Sept. 1988

The environmental change caused by industrial progress in the developed world may slowly drown this unique paradise in its entirety.

—President M. Gayoom  
Maldivé Islands, 1988

Subsequently, consultants were employed to assess what measures would be required to save these nations. For example, the Delft Hydraulics Laboratory estimated that 34.3% of the national economy of the Maldives would be required to give adequate protection and 18.8% for Kiribati, 14.4% for Tuvalu, and 11.1% for Tokelau (UNEP, 1990).

Unfortunately, many of these reports did not examine the processes involved in the formation and maintenance of coral islands, two types of which with completely different origins are recognised.

1. Coral cays, usually formed on the leeward side of reefs and dominated by sand-size sediments. These can be found on all types of reef, including fringing reefs.
2. Motus, shingle based islands found on the windward margins of reefs and most particularly around the outer margins of many atolls.

A process approach to an assessment of the hazards suggests that existence of reef islands will not be the problem within the next century, but that other environmental effects of global change will need consideration and planning. Paradoxically, some of the effects may be beneficial.

#### **WAVE ACTION ON REEFS - THE FORMATION OF CORAL CAYS**

In 1988, Hopley and Kinsey suggested that a rise in sea level in the period of 50-100 years would result in an increase of sediment supply to coral reef cays. They suggested that at the present time there was an overabundance of sediments on reef flats of the Great Barrier Reef (but also elsewhere in the world) which have been at sea level for a period of more than 5,000 years. The major problem is one of transporting the sediment to the cay, a process which can take place only at high tide when there is sufficient wave power passing across the reef flat. They further suggested that a small rise in sea level would see greater productivity of reef flat areas increasing from a present yield of about  $0.5 \text{ kg m}^{-2} \text{ yr}^{-1}$  to as much as  $4 \text{ kg m}^{-2} \text{ yr}^{-1}$ , and, therefore, the potential to supply even more sediment towards the nodal point of wave refraction. (See also Kinsey and Hopley (1991) for quantitative estimates.)

Little work has been carried out on the processes of sediment transport on reef tops, particularly in association with coral cays, but what little there is support this contention (Hopley (1981, 1982), Flood (1986), and Gourlay (1990)). Studies have shown that even under tradewind conditions of up to 25 knots, at low tide waves across reef flats of the Great Barrier Reef may be insufficient to move sediment. Sediment movement is therefore restricted to less than 50% of the time when water levels are sufficiently deep over the reef flat to allow waves of significant size, and therefore transportational ability, to pass over the reef. This is particularly prominent in areas of significant tidal range, such as the Great Barrier Reef, but is also a factor on mid-oceanic reefs where tidal range is negligible. Many of these reefs have developed reef flats at sea levels higher than present (Hopley, 1987; Nunn, 1991). As upward reef growth will almost certainly lag behind a rise in sea level it is considered that a rise of up to 0.5 m may unlock reef flat sediments for longer periods and allow them to be moved towards the coral cay. The end result is thus an increase in the size of the sand store which, under normal weather conditions has the potential for further island construction.

Most published observations on both sediment movement on reefs and of wave action support this conclusion. For example, Hopley (1982) has indicated that time of maximum sediment movement on reefs of the Great Barrier Reef varies according to tide height, wave height and location on the reef flat. Under normal winter conditions of southeasterly winds of approximately 20 knots, the period of maximum turbidity on reef flats close to coral cays occurred when tidal levels were either flooding to, or ebbing from, a high water position with waves breaking close to the cay. As maximum sediment movement takes place just seaward of the wave breakpoint (King, 1972), the point of breaking of the transmitted wave on the reef flat becomes a critical factor in determining sediment mobility. Under the 20 knot southeasterly conditions experienced on the Great Barrier Reef, with deep water wave heights of about 2 m, high water waves break directly on the cay beach, but at lower tidal levels the point of breaking is more distant from the cay. Maximum sediment movement thus occurs in a zone on the reef flat that oscillates about the cay according to the tide height and the height of the reformed waves crossing the reef flat. The question arises as to whether or not the net direction of sediment movement is towards the island and if it can result in an increase in beach height.

As waves move into shallow water, towards their break point, there is an increase in discrepancy between the forward orbital motion under wave crests and the slower return flow beneath troughs. The forward movement is short in duration, but high in velocity and may lead to the selective movement of coarser sediments in the direction of wave propagation, i.e., towards the cay, while finer materials that may also be moved by the slower return currents will readily move almost an equal distant in both directions. For movement of sediment of any particular size, the forward orbital velocity must exceed the required entrainment velocity. Bottom velocity has been shown to be a function of wave height and water depth (Inman and Nassu, 1956) and thus on a reef flat will vary at different stages of the tide, hence producing the noted periodicity in sediment movement.

A higher sea level will thus produce water depths which will cause greater movement of sediment towards a coral cay. Buildup of the cay itself will depend on the nature of the waves which break on the cay beach. The height of the constructed beach berm is dependent upon wave runup. Numerous studies (CERC, 1984) show that runup height varies with the wave height, wave steepness, beach slope, shape of the beach profile and roughness and permeability of the beach material.

Although most beach models and empirical formulae suggest that given adequate sediment supply (not a problem on reefs), a higher water level will produce a higher beach, there have been few applications to coral islands. However, Gourlay and Hacker (1991) working on Raine Island on the northern Great Barrier Reef found that the relative wave runup height varied in a consistent manner with the ratio of the breaker height to water depth over the reef flat, consistent with the fact that the wave heights are limited by shallow water breaking conditions over the reef flat. Gourlay and Hacker indicate that the height of the beach berm is determined by the runup height of the dominant wave action. This could be expected to occur at the highest spring tides. A beach berm elevation of 4 m could be built by small flat waves of 0.5 m height breaking directly onto the beach at the tide level as low as 2.3 m. They also showed that similar heights could be attained by the maximum breaking waves of 1.6 m, at an extreme tide level of 3 m.

Although further work is required, these data suggest that a small rise in sea level without any responding buildup of reef flat level, would result in the attainment of greater berm heights under most weather conditions, i.e., a build up of the island by an amount which could exceed the amount of increase in water level. For example, in the case of Raine Island quoted above, Gourlay and Hacker (1991) suggest that with a 0.6 m

rise in sea level, the larger 1.6 m waves would increase berm height by a further 0.8 m and 0.5 m waves would increase berm height by 1.2 m, i.e., to 4.8 m and 5.2 m respectively.

Additional to a rise in sea level, increasing incidence and intensity of tropical cyclones, hurricanes and typhoons is also quoted as a major threat to the existence of tropical coral cays. Whilst such storms can already cause catastrophic damage to reef islands, there is ample evidence to suggest that the majority of higher elevations on cays (as well as on motus, see below) are the result of emplacement during these high energy events. For example, on the Great Barrier Reef highest elevations of between 3-4 m above mean high water springs of many reef islands is not produced by any wind blown sand but largely by wave deposited materials. In the past, these high sand ridges have been attributed to higher sea levels. However, strong arguments have been put forward for emplacement during high energy events. Even the highest reef islands may be overtopped by exceptional storm waves causing major ecological disturbance and occasionally loss of life. It is unlikely that the small increase in sea level now forecast for the next 100 years will greatly increase the risk. The outer edge of coral reefs will still form a protective barrier from storm surges, the increased severity of which will be due only to changes in the inverted barometer effect (see below). This will produce only a few centimetres of extra sea level height. Whether or not this is critical for the reef islands and their human populations depends to a large extent on local conditions.

### ATOLL MOTUS

Cyclonic action is even more important in the construction of atoll motus and other shingle dominated islands. The coarse detrital materials of atoll motus cannot be moved by normal wind generated waves of local origin. Major tropical storms are required for their emplacement and although atoll motus are found in low latitudes where tropical cyclones do not generate, such locations can still experience large swells generated by storms at higher latitudes. Whilst knowledge of normal wave action on reefs is limited, not surprisingly data for high energy extreme events is totally absent. Nonetheless, observations made subsequent to such events and the application of empirical methods confirm these conclusions.

The most spectacular example of island construction by a tropical cyclone was the new rampart formed on Funafuti by hurricane Bebe in 1972 (Maragos, et al., 1973; Baines, et al., 1975; Baines and McLean, 1976). On the southeastern side of this atoll, a ridge 19 km long, 30-40 m wide and up to 4 m high was formed during this single storm from material dredged up from up to 20 m depth on the reef front. On more sheltered areas discontinuous low rubble tracts formed. Under normal weather conditions since 1972, the Funafuti ridge has altered its original convex profile to a concave one, migrated 10-20 m shoreward and significantly reduced in height. In some areas, it now remains only as a rubble zone and in its migration has left large coral heads as residual reef blocks. Nonetheless, the longterm result has been a building of Funafuti motus.

Further evidence on the response of reef islands come from the Holocene record. For example, Bayliss-Smith (1988) has suggested that storms during the mid Holocene in the Solomons were more frequent and intense than at present and that at that time islands increased in size. It is also notable that in the Caribbean, where, for isostatic reasons the Holocene sea level record is one of continuous rise up to the present and therefore continuous upward growth and evolution of reef flats (Hopley, 1982), on reef complexes such as the Belize barrier reef, coral cays are more frequent than on many Indo-Pacific reefs, possibly because of the lower level of the reef flats and more continuous sediment movement over them.

A greater risk of inundation from storm surges, associated with cyclone activity on mainland and high island coastlines, is not likely to increase dramatically on open-ocean reef islands where amplification of the surge, by shoaling and funnelling effects does not take place. In the open ocean surges are essentially limited to the inverted barometer effect (1 cm for every hPa of pressure reduction) and to wave setup on the margins of the reef. An example is given by Hopley (1972) in a report on Cyclone Emily which crossed over the southern Bunker and Capricorn islands of the Great Barrier Reef in 1972. Falling from a central pressure of 945 hPa, it passed over Heron Island with a central pressure of 985 hPa, and over the adjacent mainland at 992 hPa. Nonetheless, the surge of almost 2 m on the mainland south of Gladstone was significantly higher than the figure of <0.8 m at Heron Island.

The general conclusion is that the application of temperate coastal erosion theories, such as that proposed by Bruun (1988) are not applicable to coral islands and their application previously suggesting erosion rates of 1-2 m per year as a result of greenhouse-induced causes (Roy and Connell, 1989) is misleading. Those who have worked on reef processes generally agree that in the short term of 50-100 years reef islands may in fact increase in size, e.g.,

Thus it is possible that with rising sea level the broad sediment laden reef flats of Kiribati will see substantial re-working of the surficial sediment which could result in the formation of new islands and expansion, through the accretion of existing islands, at least until the existing sediments surplus is exhausted.

A new phase of island building is therefore envisaged. This will be aided by the presence of the existing islands and the natural beachrock and conglomerate 'seawalls' and 'groynes' which will serve to trap and stabilise mobilised sediment (McLean, 1989).

and

At least over the next 50-100 plus years coral islands seem relatively secure even if, (or especially if) reef platforms become progressively inundated. Increased tropical cyclonic activity, combined with maximum growth rates and new coral habitats will ensure sediment supply and increased water depths will increase sediment transport efficiency (Parnell, 1989).

Existing beachrock, conglomerate and other cemented island deposits such as phosphatic cay sandstone will certainly retard even changes in locations of islands. Moreover, there is sufficient evidence (in the form of very recent artefacts contained within beachrock) to suggest that the cementation processes are so rapid that they will be effectively contemporaneous with the addition of new material to reef islands. Raised tidal levels will result in higher levels of cementation, superimposed over the top of existing beachrocks. Availability of land, is therefore, not the problem for the low lying island nations over the next century as has previously been suggested.

## **OTHER POTENTIAL CHANGES TO CORAL REEF ISLANDS**

### **Ground Water Resources**

Concerns have been expressed for the ground water resources upon which both island peoples and vegetation depend. In general, such concerns have resulted from the

application of the now outmoded Ghyben-Herzberg model (Miller and Mackenzie, 1988). This assumes homogenous materials and that the outflow, or loss of freshwater, occurs at island margins in, or below, the intertidal zone producing a predominantly horizontal flow. Although some of the fresh water remains above sea level, the majority of it (40 units of depth for every unit of head) will reside below sea level. This model produces a great depletion in the potential for ground water resources if island size is reduced. Freshwater lenses may not occur on islands that are less than 300 m wide. However, the recently discussed layered aquifer model (Wheatcraft and Buddemeier, 1981; Herman, Buddemeier and Wheatcraft, 1986; Oberdorfer and Buddemeier, 1988; and Buddemeier and Oberdorfer, 1990) has much greater applicability to real world situations though it does suggest that the overall freshwater resource may be less than in the Ghyben-Herzberg model. The model presumes two basic geological layers possessing distinct porosities: a surficial layer, of Holocene age, of low permeability overlying deposits of high permeability, of Pleistocene age, separated by a solution unconformity at relatively shallow depths of 7-25 m. Primary mechanism for loss of freshwater is not outflow at island margins, but loss to degradation by downward mixing into the saline water in the Pleistocene deposit below. This creates a broad transition zone of brackish water.

However, this model is far less sensitive to island size and a threshold island width figure of 120 m, has been suggested for retention of the freshwater resource. Moreover, if the island size remains constant, Oberdorfer and Buddemeier (1990) have suggested that rising sea level has a counter intuitive effect on total freshwater resource for islands possessing a layered aquifer. An increase in sea level makes available more of the low permeability aquifer for retention of freshwater, increasing the total freshwater resource. However, as Parnell (1989) has noted "under current recharge conditions, the potable freshwater resource is reduced by a small amount. It is possible that recharge rates will decrease with higher temperatures and higher evapotranspiration, but if recharge increases (which is possible given increased rainfall and perhaps better land use practices) the model shows a significant increase in both potable and total freshwater resources."

Thus, a rise in sea level may not be disastrous for island ground water resources. Indeed, if accompanied by an increase in island size as seems likely and increases in rainfall as is predicted for some areas of low latitudes, ground water resources may actually increase.

### **Soils and Plant Growth**

By definition, reef island soils are young. For example, Fosberg (1954) identified three soil series on atolls with increasing maturity:

- Shioya soil series found on the youngest sediments, deficient in almost every element essential for plant growth,
- Arno soil series with a more developed 'A' horizon and some bonding by organic matter, and
- Jemo soil series found under mature island forests and in which much organic matter is incorporated.

It is these latter soils which provide the basis for most agriculture on many reef islands. Unfortunately, even though islands may increase in size during the next 100 years, the soils on the new land area will be of the younger immature type. The major concern is that changes to the shape and orientation of islands which may result from

changes in wind directions, may lead to the erosion of at least part of the older core areas of the islands on which the agricultural soils are found.

Most concern however, has been for rising saltwater ground tables and salt contamination of low lying vegetation (e.g., Hughes and McGregor, 1990). As indicated above, this may not necessarily be so and the future for sustainable agriculture and maintenance of mature vegetation on reef islands may not be as grim as has been forecast in the past. Indeed, there may be a significant increase in the productivity of many tropical crop species found on reef islands. Crops with a  $C_3$  photosynthetic pathway have higher magnitude physiological responses to  $CO_2$  enrichment and with a doubling of  $CO_2$  concentration in the atmosphere may have crop yields increasing by as much as 33%. Amongst the  $C_3$  crops are casava, sweet potato, taro, yam, banana, papaya and coconuts (Jacobs, 1990). There have also been suggestions that  $CO_2$  enrichment will lead to a reduction in stomatal conductance and transpiration and an increase in water use efficiency by plants. If this takes place, then even in areas where a reduction in total rainfall is predicted, there may be some offsetting for agriculture.

### Marine Resources

Rejuvenation of coral growth as suggested by Hopley and Kinsey (1988) and Kinsey and Hopley (1991) should also bring about the replenishment of many of the natural marine resources, upon which island nations depend. On relatively open atolls, a slight rise in sea level may do much to increase lagoon circulation with beneficial effects. However, on atolls where few hoas (lagoon exits) exist, increasing sedimentation through building up of shingle ridges may completely close off lagoons. Such a situation occurred at Taiaro Atoll in the Tuomotus as described by Salvat, et al. (1977). Although partial closure of the lagoon took place as the result of a slight uplift, complete isolation occurred during the 19th century as the result of blocking of the remaining exit by a boulder rampart, deposited during high seas. Corals were initially killed by the uplift, but subsequently hypersaline conditions (about 43 ppt) have developed and only *Porites lobata* survives, compared to about 14 species prior to the lagoon being closed. Other fauna have been similarly restricted.

Deterioration in lagoon and near-reef water quality may also occur if nutrients are released into the marine environment during the period of global change (e.g., Hallock and Schlager, 1986). A release of nutrients can result from rising water tables producing a greater leaching of island soils which can also be aggravated if water table fluctuations reach into septic tanks and rubbish tips. Remobilisation of naturally occurring phosphate deposits, produced through the accumulation of guano, may also take place as water tables rise through island soils. A full assessment of these changes to nutrient status, and whether or not eutrophication will occur, needs further investigation.

### CONCLUSION

There is no doubt that reef island environments are precarious and extremely vulnerable to environmental change. However, kneejerk reactions as have occurred as recently as two years ago, with so-called scientific assessments suggesting reactions as drastic as mass resettlement for particular island nations are excessive (Roy and Connell, 1989). There will be some local land losses and changes to the ecology of the islands, but there may well be as many gains from global change as there are losses. McLean's (1989) survey of Kiribati is an example of a true scientific approach towards assessment of the future risk. Although further work is required, particularly on the

sedimentation processes occurring on coral reefs, and also on ground water hydrology, McLean's summary for Kiribati is probably pertinent to many other reef island situations.

On the face of it the low atolls and islands of Kiribati appear particularly vulnerable to any future rise in sea level, and while this is to a large extent true, several factors suggest that the most probable outcomes will not be as substantial nor as devastating as initially envisaged ... And yet, in addition to or regardless of any Greenhouse induced changes the population is likely to have to cope with large natural variations in physical phenomena such as fluctuations in water level, freshwater lens volume, rainfall incidence and drought for example, which will have a profound effect on land and livelihood in the future ... It should also be stressed that there is no obvious immediate danger from Greenhouse induced causes; these will take decades to have any major impact on any but the most vulnerable locations (Buddemeier and Oberdorfer, 1989). But this does not mean that the government should not capitalise on the international support for Greenhouse related environmental matters because there is a very real need to address the questions of long term planning and preparation.

As predictions for sea level rise become more conservative, e.g., no more than 25 cm by the middle of the next century, concerns about the island nations may diminish. However, as McLean has shown, the environmental problems existing on many reef islands already necessitate careful planning and management. Only by maintaining (or in some instances restoring) reef systems to a healthy state will they be able to respond to global change in the positive directions suggested in this paper. Such a policy, requiring economic, demographic and sociological as well as scientific input, is necessary even if global changes to environment were minimal. Concentration on island carrying capacities, sustainable use of resources, maintenance of water quality and widening of island nations' economies by, for example, strategic planning for the beneficial use of the 200 nm EEZ will be far more productive than design of breakwaters, rockwalls and groynes and plans for mass migration. However, it is important to remember that the costs may not be all that different and that the interest raised in the island nations at the present time should be redirected towards the planning issues raised above. In the long term (>100 yrs) if no reversal to global change trends can be achieved, then some of the more sensational forecasts may well occur, but at that stage the implications for other parts of the world, including coastlines of the most developed nations, would also be severe.

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# AUSTRALIAN INITIATIVES IN SEA LEVEL AND CLIMATE MONITORING

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## ABSTRACT

This paper outlines a major Australian initiative to monitor rising sea level trends on behalf of the Forum Island Countries of the South Pacific. The specifications demanded by the GREENHOUSE mechanism lead to high resolution instrumentation with a focus upon datum control. Since sea level measurements are essentially relative to survey marks on land, a supporting program of geodetic survey is required in this tectonically active region.

## INTRODUCTION

Long term monitoring of marine variables has always been seen to be a worthy pursuit yet rarely practised. The hazards of climate change have brought greater emphasis upon such activities, partly due to promotion by the Intergovernmental Oceanographic Commission through a series of large scale international programs such as GLOSS (Global Sea Level Observing System), TOGA (Tropical Ocean/Global Atmosphere), WOCE (World Ocean Circulation Experiment), etc. and more recently by GOOS (Global Ocean Observing System) and GCOS (Global Climate Observing System). Major commitments by Australia to establish regional high-resolution monitoring arrays for sea level and associated meteorological variables fall neatly into this plan.

A twelve-station array around the Australian coastline is almost complete and preparatory work is well-advanced for an eleven station array established on behalf of the Forum island countries of the South Pacific (Figure 1). The latter initiative is sponsored by the Australian International Development Assistance Bureau (AIDAB) which has also begun a feasibility/design study for the Maldives in the Indian Ocean. Other work on long term sea level signals continues in the ASEAN region, the Southern Ocean and more recently in Antarctica.

## INSTRUMENTATION

Given that the general consensus of scientific opinion is that the historic sea level trends are of a magnitude  $1.5 \pm 0.5$  mm per year, a program with aspiration to identify future trends should have a resolution somewhat smaller, and possibly sub-millimetre in scale.

It was considered, based upon experience with traditional float-operated tide gauges, that these would be inadequate in this respect (Lennon and Mitchell, 1992).

For example, analysis of the historic sea level trend, based upon the Australian network, covers a wide range of results including some of negative sign, despite the fact that the Australian mainland has the reputation of conforming to a relatively stable crustal block. However, if one can assume such stability, and so consider each gauge

result as an independent attempt to measure the regional trend, one may be justified in proceeding, through averaging, to estimate the regional value. Such a luxury is denied to the Pacific because of the widespread tectonic motion over a range of spatial scales. Consequently averaging processes would have no place here so that the requirement is to search for even higher accuracy with a desirability to strive for absolute sea level.

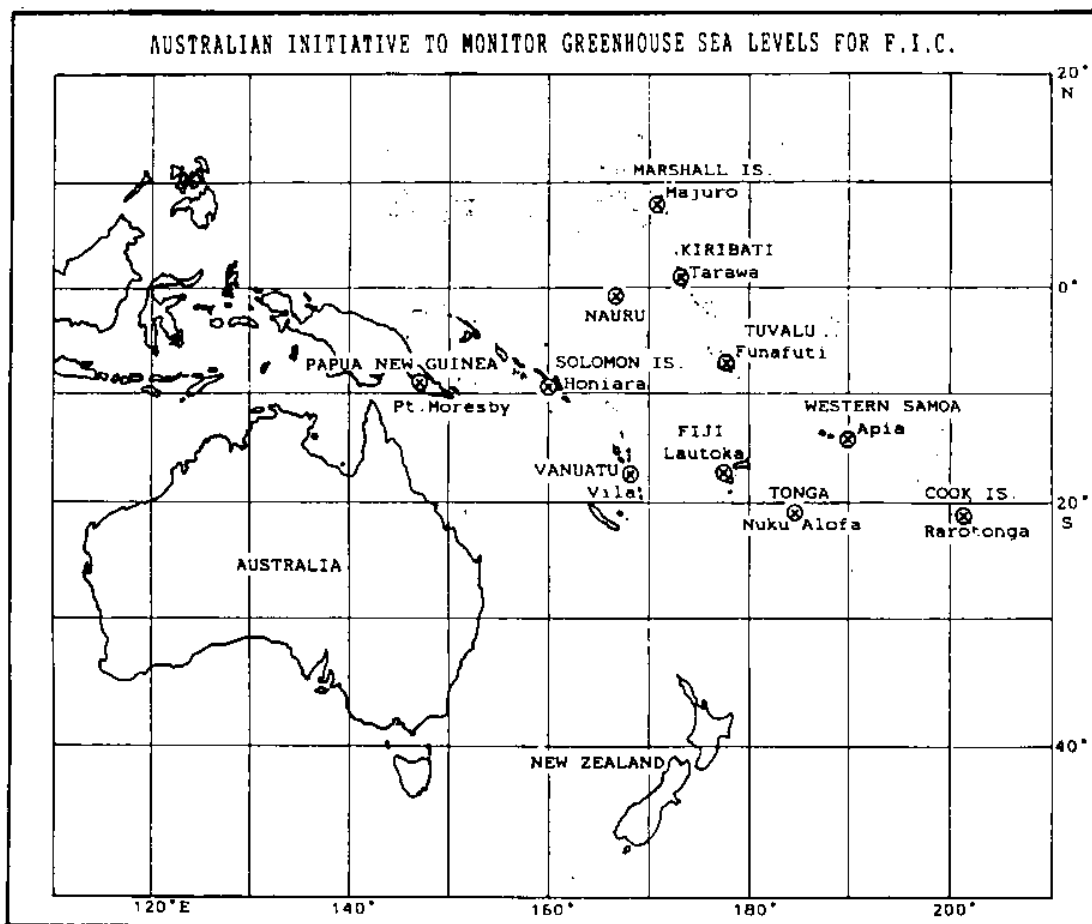


Figure 1. The array of SEAFRAME stations planned for the Pacific region

The selection process for suitable instrumentation focussed upon the acoustic Aquatrak sensor and the sophisticated 9000 series station controller and logger produced by Sutron Ltd. An important factor in this choice is the ability of this sensor to maintain a stable datum which, furthermore, is conveniently accessible to survey and geodetic procedures. A novel self-calibrating system for the time of flight of each acoustic pulse is a further attraction. The choice then is almost identical to that adopted by the National Oceanic and Atmospheric Administration (NOAA) of the U.S.A. This choice has been reinforced by experience. For example, if one takes a long time series of sea level from a float-operated gauge, one is accustomed to viewing systematic signals, such as the tides, emerging from a continuum of background noise which is suspected to be due to inferior instrumental performance and human interaction. The latter is now confirmed since a

power spectrum of a time series from the new stations shows a noise level considerably less than that for a float-operated gauge, and consequently much clearer identification of the periodic and quasi-periodic signals is possible even in the all-important low-frequency band (Lennon, Woodland, and Suskin, 1992).

The name now coined for the Australian stations is SEAFRAME (Sea Level Fine Resolution Acoustic Measuring Equipment). Figure 2 shows the main elements of a typical station, which also incorporates supplementary sea level monitoring by a submerged pressure sensor, together with the relevant meteorological parameters:

Barometric Pressure  
 Wind Speed and Direction  
 Air and Water Temperature

The primary water level is sensed at a one second sampling interval but logged at six-minute intervals as the mean of 180 samples. The supplementary sensors are logged at hourly intervals.

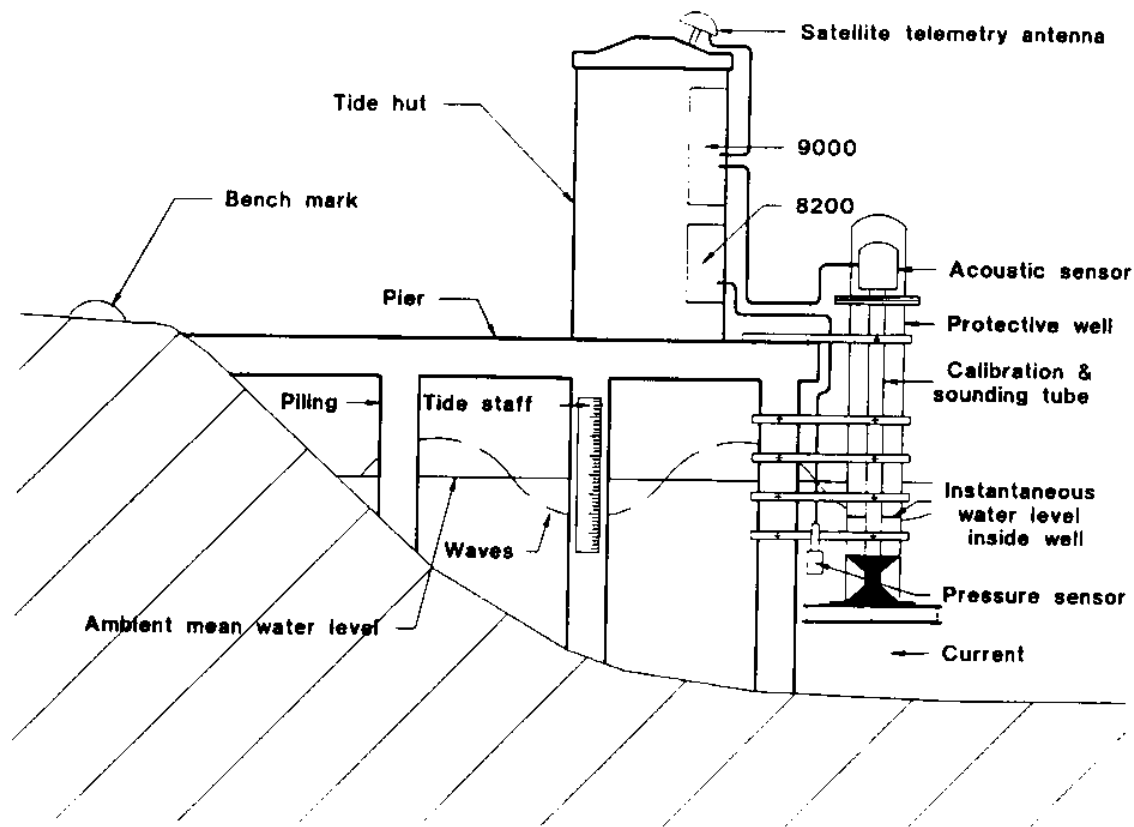


Figure 2. A SEAFRAME station

Figure 3 gives a power spectrum comparison of simultaneous data from a SEAFRAME installation and from a traditional float-operated gauge at the same site. This diagram shows the lower noise level in the low frequency band as mentioned above, and also in the high frequency band as experienced in the SEAFRAME record.

### DARWIN ANALOGUE AND SEAFRAME SPECTRA

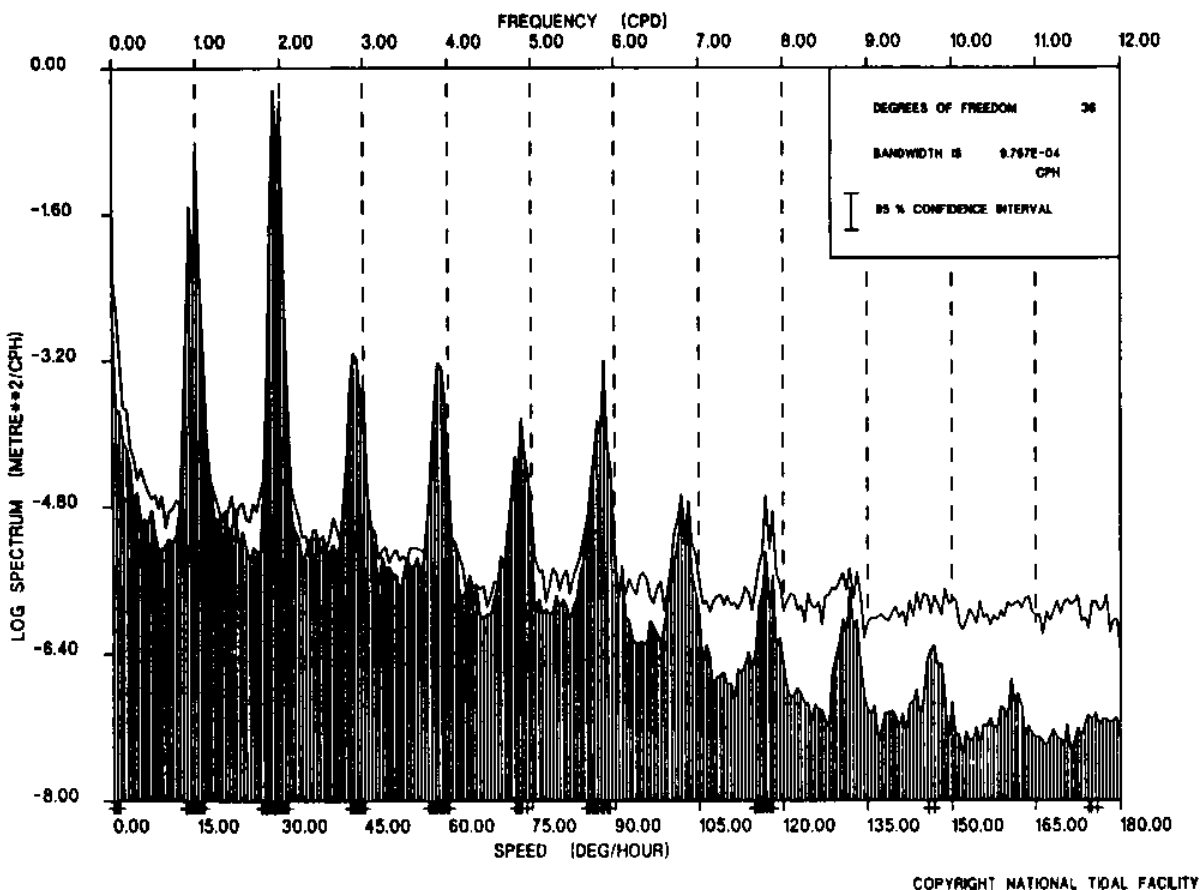


Figure 3. A comparison by power spectrum of simultaneous data from a float-operated gauge and a SEAFRAME system at Darwin. The blank plot is a spectrum of the float gauge data. The shaded plot is the equivalent from the SEAFRAME data.

The traditional gauges were always known to have unfortunate nonlinear characteristics but it can now be confirmed that, in the past, a significant contribution to the higher frequency signals has not represented true shallow-water tides but rather imperfections in an instrument based upon stilling well design.

## PROJECT PHILOSOPHY

The Pacific project will gain much from its more crustally-stable Australian neighbour, but it is still necessary to consider in depth the basic argument upon which the interpretation of trends will be based.

Certain facts are clear:

- Because of its geophysical environment, the Australian case is less complex and it is possible to claim that if the true GREENHOUSE trend is identifiable anywhere, then it will be identified in Australia (Mitchell, 1992).
- For the Pacific, the project aims to establish a reference station in each of eleven countries. These stations will support a variety of products and will provide groundtruth for future satellite altimetry missions. However, in terms of GREENHOUSE trends, the initial information which they will give, but only after twenty or more years of observation, will be a simple point value, identifying the relative movement of land and sea at the site.
- Whatever the outcome, it is necessary to give due care to survey and geodetic procedures, not only to the sea level measurements referred to fixed marks on land, but also, perhaps by the Global Positioning System (GPS) and other altimetric means, to determine the relative motion of the land across each national region (Jacksa, Gilliland, and Tan, 1992). Note here that local sea level trends are the result both of oceanographic and of land level trends. Plans for the survey/geodesy program are currently under discussion (Warhurst, 1992).
- Although GPS techniques are developing rapidly at this stage, it is still uncertain as to whether vertical determination can yet be achieved, over the 1,000 Kms or so which separate some adjacent stations in the array, with a sub-centimetre accuracy necessary to maintain a role in 'GREENHOUSE' studies. There is however a prospect that field and computational procedures will soon make this possible. Meanwhile the aim is to establish a reference network on national scales.
- Attention must also be given to tidal motions of the local earth's crust in response to marine tidal loading, and other similar perturbations to survey procedures (Baker, 1992).
- The GREENHOUSE mechanism may prove to be dominated by the addition of mass to the ocean in the form of melt water, or alternatively by steric adjustment resulting from thermal change, but more likely by a combination of the two. One carries the implication of warping the regional crust, while steric effects do not suffer the same implication. Again climate change may prove to be associated with lateral shifts in the thermal zones of the ocean with a consequent shift in surface topography. Given time, it is possible that these features may be identified, thus allowing an assessment of the component parts of the sea level signal, and in particular the separation of the tectonic trends at the reference stations from the true oceanic trend.

There remain many obstacles to be surmounted and in fact, in many aspects, the program is operating at the threshold of what is physically possible so that what appears to be a routine monitoring task assumes the characteristics of a multi-faceted research program.

## INFORMATION AND TRAINING

The program in the Pacific contains provision for information and training and already has a Climate Change Information Officer, in position with SPREP. The intention is to develop structures to identify and fill the needs for information about both long and short term features of climate change for a range of beneficiaries from the general public to representatives of government.

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# SEA LEVEL RISE VULNERABILITY CASE STUDY MAJURO ATOLL, REPUBLIC OF THE MARSHALL ISLANDS

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## ABSTRACT

A possible future concern for coastal land areas is the impact of accelerated sea level rise (ASLR) as a result of global environmental changes. Study and planning for ASLR is being accomplished by the World Meteorological Organization and the United Nations Environment Programme, and Majuro Atoll was selected as a Pacific Islands case study site. This paper presents a brief summary of the oceanographic and coastal engineering considerations applicable to the evaluation of ASLR and its potential impact on a low-lying atoll island. The investigations include determination of scenario wave and sea level conditions, analysis of wave runup and inundation of the atoll land area and other coastal impacts, and assessment of possible response strategies and shore protection measures.

## INTRODUCTION

Increasing awareness is evident in general news reports and scientific journals regarding the growing concern about possible global environmental changes, such as global warming, and the potential impact on human populations. Scientists report of possible accelerated sea level rise (ASLR) as a result of global warming, and, although there is still considerable debate and uncertainty about the magnitude of possible ASLR, or even if it will occur at all, many nations are taking the possible threat very seriously and are investigating the potential impacts of ASLR and how to deal with them.

The World Meteorological Organization and the United Nations Environment Programme jointly formed the Intergovernmental Panel on Climate Change and its Coastal Zone Management Subgroup (IPCC-CZMS), to assess the vulnerability of coastal areas and response strategies for adaptation to sea level rise (IPCC, 1990; 1991). The overall study effort is being coordinated by the Ministry of Transport and Public Works of the Netherlands and the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA). The IPCC-CZMS has recommended that coastal countries (1) assess their vulnerability to ASLR and other potential impacts of global climate change, and assess the assets at risk; (2) start the planning process for appropriate response strategies; and (3) develop comprehensive coastal management programs to reduce their vulnerability to ASLR.

Majuro Atoll was selected as a case study site to develop a methodology for assessing the physical, social, economic and environmental vulnerability to sea level rise, and to evaluate possible response strategies. Majuro is a typical atoll, composed of a ring shaped reef system enclosing a salt-water lagoon. The atoll is elongate in shape, 25 miles from east to west, and 6 miles from north to south. There are 64 islets located on the encircling reef, which vary in width from about 0.1 miles to 0.5 miles. The total dry land area is about 4 square miles, and the average land elevation is less than 8 feet above mean sea level. The lagoon has a surface area of about 125 square miles, with an average depth of about 150 feet.

The study was accomplished as a joint effort between NOAA, the Republic of the Marshall Islands Environmental Protection Authority (RMIEPA), the South Pacific Regional Environment Programme (SPREP) and Sea Engineering, Inc. (SEI). The case study involved the following general steps:

- 1 - delineation of the vulnerability zones;
- 2 - inventory of study area characteristics;
- 3 - determination of future development factors;
- 4 - assessment of physical changes and natural responses; and
- 5 - formulation of response strategies and assessment of their costs and impacts.

SEI was tasked with determining the physical vulnerability of the study area to ASLR, assessing the condition and characteristics of the shoreline, and formulation of shore protection alternatives. This paper briefly summarizes the methodology and results of the coastal engineering investigations, and how these results may impact Majuro Atolls future.

## METHODOLOGY

Storm wave runup on the shoreline and coastal inundation limits, and shore protection design parameters, were determined for the study area using existing available climatic, oceanographic and topographic data for Majuro Atoll, supplemented by a site visit to field check the condition and characteristics of the shoreline. Numerical modeling techniques were used for the analysis, based on models previously developed by SEI for hurricane vulnerability analysis in Hawaii. Parameters determined included wave heights, water levels, and runup elevations/inundation limits for three scenario wave events and three sea level scenarios, as follows:

Scenario Wave Events: annual, 50-year return period and model typhoon conditions,

Scenario Sea Levels: ASLR0 - existing sea level  
ASLR1 - 0.3 m (1 ft.) rise  
ASLR2 - 1.0 m (3.3 ft.) rise

General methods for shore protection, erosion control and shoreline flood protection were evaluated for applicability to the study area. Primary study areas on Majuro were the commercial and population center at the east end of the atoll (commonly known as Dalap-Uliga-Darrit or just D-U-D), and the important ground water and agriculture area located at Laura at the west end of the atoll. Of the approximately 20,000 people living on Majuro, about 15,000 of them live in the D-U-D area.

### Accelerated Sea Level Rise (ASLR)

A number of studies have shown that the earth has warmed by about 0.53°C (1°F) during the last century, and the earth's average surface temperature has been predicted to possibly warm by at least 1.5°C to 4.5°C in the next century (Edgerton, 1991). The atmospheric warming could cause a melting of glacier ice and the thermal expansion of

ocean water, and ultimately a global sea level rise. Analysis of the past 100 years of tide gauge records around the world shows that the global sea level has been rising at a rate of 1 to 2 millimeters annually (Edgerton, 1991). Several sources have estimated future rises in sea level due to atmospheric warming. The U.S. Environmental Protection Agency has estimated that the sea level would rise 0.5 to 2 meters globally by the year 2100. A 1987 National Research Council report estimated a global rise in sea level of 0.5 to 1.5 meters by 2100. For this case study project, the IPCC-CZMS mandated that the assessment of the vulnerability of coastal areas and evaluation of strategies for adaption to sea level rise consider ASLR of 0.3 m (1 foot) and 1.0 m (3.3 feet) by the year 2100.

### Storm Waves

Estimated annual and 50-year return interval deepwater wave heights for Majuro were determined based on a statistical analysis of wind and wave data contained in the Summary of Synoptic Meteorological Observations - Area 8 (U.S. Weather Service Command) and the Local Climatological Data (NOAA) for Majuro. A scenario typhoon event was determined based on a review of historical tropical cyclones in the vicinity of the Marshall Islands, defined by a central pressure of 964 mbs and maximum sustained winds of 75 knots, a radius of maximum wind of 15 nm, and a forward speed of 12 knots. Design significant wave heights (H, feet) and periods (T, seconds) applicable to the ocean side of the atoll were as follows:

Annual	50-Year	Typhoon
H T	H T	H T
13 13	19 13	27 11

### Stillwater Level Rise

An important step in determining storm wave runup and inundation limits is to determine the stillwater level rise along the shore. The rise in stillwater level along the shoreline during extreme wind and wave events is generally a function of three components: (1) the astronomical tide, (2) storm surge due to reduced atmospheric pressure and wind stress setup, and (3) wave setup due to momentum flux changes in a train of waves of changing amplitude. These components are considered together with the ASLR scenarios to obtain the total design stillwater levels, summarized as follows for the ocean side of the atoll in feet above MSL:

	Annual	50-Year	Typhoon
Astronomical Tide	2.6 feet	2.6 feet	2.6 feet
Pressure Drop Setup	0.3	0.4	1.7
Wind Stress Setup	0.0	0.0	0.0
Wave Setup - ASLR1	1.8	3.0	4.0
ASLR2	1.6	2.7	3.7
Total - ASLR1	5.7 feet	7.0 feet	9.3 feet
ASLR2	7.8 feet	9.0 feet	11.3 feet

### Wave Runup

The vertical height to which waves will run up on a shoreline slope determines the elevation over which inland flooding by waves will occur. Experimental wave runup relationships which determine significant wave runup heights for random waves on

gentle and impermeable slopes, corrected for slope roughness and composite slopes, have been found to give reasonable runup values. The total vertical height to which water will reach along the shore is determined by adding the wave runup to the total stillwater level rise.

## RESULTS

### Flooding and Inundation

Calculated results of the stillwater levels and wave runup elevations and resultant backshore flooding are as follows for the D-U-D and Laura areas (EL = total elevation to which water will rise, D = distance inland the runup will extend from the MSL shoreline, and (FL) or FL = partial flooding or complete flooding, respectively, due to extensive inundation distance or the stillwater level exceeds the beach crest):

	Annual	50-Year	Typhoon
<b>ASLR0</b>			
D-U-D area	EL 7' D 80'	(FL)	FL
Laura	EL 6' D 60'	EL 8' D 90'	FL
<b>ASLR1</b>			
D-U-D area	EL 8' D 90'	FL	FL
Laura	EL 8' D 80'	EL 9.5' D 130'	FL
<b>ASLR2</b>			
D-U-D area	FL	FL	FL
Laura	(FL)	FL	FL

As can be seen, the significant wave runup nearly reaches the shoreline crest even during an annual wave event with no ASLR. With even the lower ASLR1 all of the D-U-D area would be flooded by any wave occurrence greater than an annual event. With ASLR2 the study areas would be flooded annually. An idea of the flooding frequency can be estimated by plotting the predicted runup elevations for the annual and 50-year events on semi-log paper. Flooding being defined by the wave runup exceeding a typical "critical" beach crest elevation. Ocean-side flooding frequency estimates are as follows:

	Critical Flooding Frequency (times/years)			
	Beach Crest EL	ASLR0	ASLR1	ASLR2
D-U-D area	7.5 feet	1/30	1/5	>10/1
Laura	11.0 feet	<1/100	<1/100	1/1

### Shoreline Erosion

More than 70% of the world's sandy coastline has experienced net erosion over the past few decades, and the remaining 20% to 30% have remained stable or shown no measurable changes. The erosion is partly due to a sea level rise of about 1 to 2 mm per year, and a sea level rise of 1 meter during the forthcoming century would be a major

factor causing recession of sandy shorelines. Bruun (1962) devised a rule governing shoreline erosion, which states that a beach that has attained equilibrium with coastal processes will respond to a rise in sea level by losing sand from the upper part of the beach profile and gaining it in the nearshore area until a new equilibrium is established. Thus, the coastline will retreat (1) as the direct result of the sea level rise, and (2) as a result of the beach erosion. Using generalized shoreline profiles and conditions the shoreline retreat due to ASLR and the dry land area which would be lost can be estimated.

	Shoreline Retreat (feet)		Dry Land Lost (acres)	
	ASLR1	ASLR2	ASLR1	ASLR2
D-U-D area	20 - 80	70 - 260	50	160
Laura	20 - 130	70 - 420	45	140

Existing dry land in the D-U-D area is about 510 acres and in Laura about 740 acres, so as much as 10% to 30% of the D-U-D area and 6% to 19% of the Laura area could be lost with ASLR of 1 foot and 3.3 feet, respectively.

### Water Resources

The present water system that supplies the heavily populated D-U-D area relies upon airstrip catchment of rain water and ground water from Laura. A promising ground water area is found in the Laura area, reported potable fresh ground water storage ranged from 450 to 550 million gallons during 1984 and 1985, with an estimated sustainable yield of 400,000 gallons per day. ASLR may affect the loss of ground water resources in two ways. One is the increased frequency of flooding due to storm waves and high water levels. Storm flood damage is not necessarily permanent, but it may make the ground water resource unusable at a critical time. The second threat is from island area loss, either by frequent inundation of low-lying areas or by erosional loss of shoreline. Using the results of the erosion and land loss estimated by this study, and procedures for estimating the resultant reduction of the ground water lens developed by Miller and Mackenzie (1988), the loss of lens area in Laura is estimated to be:

	Lens Area (feet <sup>2</sup> )	Percent Loss
ASLR0	150,000	0
ASLR1	135,000	10%
ASLR2	105,000	30%

### RESPONSE STRATEGIES

Potential response options to ASLR as identified by the IPCC include protection, accommodation and retreat. For an atoll environment the accommodation options are limited, with the most viable being to raise existing structures on pilings and plan new structures with raised first levels to accommodate occasional flooding and help to minimize property damage during storms. It would be desirable to raise the general ground elevation of the atoll above the possible future still water level, however the only source of fill material would be to dredge material from the lagoon at considerable cost and potential environmental impact. Retreat to naturally occurring higher ground is not possible on low, uniform elevation atolls. In extreme conditions, and in the absence of creating higher ground which is habitable under extreme conditions, the only retreat option may be to abandon the atoll.

Atoll islets are primarily composed of unconsolidated coralline material and their shorelines require stabilization and protection against erosion by wave action which would increase with ASLR. Shore protection can also be used to prevent flooding of the backshore area by storm waves. Rock revetment can be constructed by quarrying the hard, consolidated fringing reef limestone for armor and underlayer stone. In lieu of reef flat material, revetment can be constructed using manmade concrete armor units. Coral aggregate and sand for use in the concrete mix can be obtained directly from the lagoon or old reef flat quarry sites.

In order to prevent flooding by storm waves, the revetment crest elevation should be designed to prevent significant wave overtopping despite the water level rise and severity of wave attack. In some cases, however, it is not feasible and/or economically justifiable to construct a non-overtopping structure. For example, ASLR2, when combined with the 50-year and typhoon wave conditions, results in a water level exceeding most of the land elevation of Majuro. This high water level, coupled with storm waves, makes shore protection impractical for the worst case ASLR2 scenario considering any waves greater than the annual wave event.

An illustration of the required crest elevation and approximate cost for rock revetment shore protection around the 58,000 linear feet encompassing the D-U-D area for ASLR1 and the three scenario wave events is as follows:

	ASLR1 + Wave Event		
	Annual	50-Year	Typhoon
Crest El. (Ft. MSL)	9	10	14
Cost (Million US\$)	35.0	46.0	105.0

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