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IMPACT ASSESSMENT OF CYCLONE SALLY ON THE ALMOST ATOLL OF AITUTAKI (COOK ISLANDS) BY REMOTE SENSING

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ABSTRACT

Damage from tropical cyclones can have major consequences for coral reef structure and ecology, as well as for human communities and human uses of coral reef resources. Remote sensing with high resolution multispectral satellite images can be used to assess large scale cyclone damage on coral reef areas. SPOT images of the almost atoll of AITUTAKI, Cook Islands, taken in June 1986 and in February 1987 after the passage of Cyclone Sally near the island in January, were transformed and subjected to a textural analysis, and then compared to assess damage to the reef and lagoon. New shallow sand and rubble deposits showed increased reflectance, while lower reflectance seemed associated with damage to reef structure, scouring in the lagoon, deposits of terrestrial sediments, and rapid algal regrowth on damaged surfaces. One third of the whole shallow surface (0-3 m) of the reef and lagoon of Aitutaki showed such changes after the cyclone at a scale detectable by satellite remote sensing.

INTRODUCTION

Remote sensing with satellites such as SPOT makes it possible to obtain data on natural phenomena relatively rapidly in even the most remote parts of the world and the most inaccessible environments. For instance, shallow coastal areas are difficult of access from both land and sea, particularly for large scale surveys, so satellite images offer great advantages in areas where aerial photography is not cost effective. One useful application is in the analysis of the effects of natural disasters such as severe storms on coaslines and shallow marine resources in areas far form other means of surveillance.

Coral reefs and cyclones

Coral reefs are unique features on the surface of the planet because they are constructions on a geological scale built by biological activity. Recent reefs are dynamic features undergoing constant change as they adapt to fluctuating sea levels and other changes in the land-sea interface. Coral reefs are often subject to cycles of construction and destruction, with the destructive phases often helping to consolidate the reef framework by redistributing material and filling interstices. Tropical cyclones (hurricanes or typhoons) are among the major destructive force for reefs in regions where they occur. They are intermittent and sometimes rare events in any particular locality, by many reefs bear permanent marks of their passage.

Most effects of cyclones on reefs result from wave action, although heavy fresh water inputs may be important in localized areas, and the winds may affect terrestrial vegetation and sediment. On Funafuti Atoll, wave action during tropical cyclone Bebe in 1972 built a coral rubble rampart (storm beach) 18 km long, 37 m wide and averaging 3.5 m in height above the reef flat (Maragos et al. 1973 ; Baines et al. 1974). A small cyclone that hit the raised coral island of Niue ine 1979 produced waves that broke over the top of the 18 m cliffs surrounding the island, leaving reef fish in the hotel swimming pool.

Cyclones are a major mechanisms for the construction (or removal) of raised land areas on reef platforms. Storm rampart such as that at Funafuti become permanent island features, and are widespread on both atolls and the reef platforms of high islands such as Rarotonga. The production and redistribution of reef sediments during cyclones represent major effects with important consequences for the reef system and for human uses of the land and reef areas.

Cyclone damage must inevitably have a major consequences for the coral reef ecology as well as its structure. Much of the living surface may be damaged or removed, changing the available surface area (Dahl 1972) and the habitats or shelter for many reef organisms. There may be a selective removal or more fragile or vulnerable species, or an advantage given to species that can regenerate rapidly, thus changing the population structure. Much new surface is made availalble for colonization, although rubble and sediment deposits may take time to be stabilized enough. The arbitrary occurence of cyclones relative to tidal, lunar or seasonal factors regulating reproduction in reef organisms may result in widely different primary colonizers and successional patterns depending on the chances of timing, possibly leading to new reef communities quite different from those that they replaced.

Depending on the location of the reef, cyclone damage may be frequent, leading to a relatively "adapted" or "resistant" ecosystem, or it may only occur once in 50 or 100 years. Such rare extreme events may be an important determinant of reef structure and function for decades even though this may not be immediately apparent to the casual observer.

Man and island

In the tropical cyclone belts, most islands are built on coral reefs or are sourrounded by them, and these reefs resources are important for human subsistence and development. Islands are also a special case for environmental management, with limited resources in often diverse environments with high environmental gradients (Dahl, in press.). Islands are also particularly vulnerable to cyclones, and man has not always developed them with this threat in mind, leading to great economic damage and loss of life. During cyclone Bebe on Funafuti, for instance, a storm surge 4m high destroyed many buildings and took several lives, but this did not keep planners from wanting to put housing in the area affected. On Rarotonga, protective rubble ramparts and coastal vegetation were bulldozed to give homes an ocean view. Many coastal construction projects interfere with coastal dynamics and increase vulnerability during storms.

Cyclones also affect fisheries, damaging the productivity of coastal fishing areas, not to mention fishing vessels and port facilities. The cyclone on Niue obliterated the port facilities and destroyed almost every boat and canoe on the island including a new fisheries research vessel. Given the importance of island fisheries for both subsistence and commercial purposes, advanced planning is important to minimize eventual damage, and rapid assessment of storm damage can help to plan remedial actions. Many traditional island fisheries included such provisions, including reserving certain less vulnerable areas or species for use after cyclones while the rest of the reef was recovering.

There are of course also cyclone effects on island terrestrial resources such as agricultural areas, tree crops, forests, water supplies and infrastructure that also need to be evaluated.

Remote sensing

Remote sensing with satellite multispectral images and digital processing offers considerable adavantages for certain types of studies. Islands present many critical management problems which require careful planning and environmental monitoring, yet obtaining reliable current information on island environments is still very difficult. Of over a thousand islands recently reviewed in Oceania only 18 could be said to have complete and recent information available (Dahl 1986). Most oceanic islands are too remote for frequent aerial photographic coverage, and where it exists it may be decades out of date. Island terrain, whether terrestrial or marine, is often difficult and diverse, making on-site survey methods labour intensive and logistically complex, while producing masses of detail than may be difficult to situate and analyse.

Obtaining satellite images of islands does present some problems. Limitations of recorder capacity of reception by ground stations reduce potential coverage, particularly since many islands are far from continent-based reception facilities. High islands also have frequent orographic cloud cover that makes obtaining cloud-free images difficult. Another important problem is the scale of image resolution relative to the scale of the island or reef features of interest. A resolution of 80 metres shows little of interest on a small island. However the new high-resolution images such as those produced by SPOT, with 20 m resolution in multispectral mode and 10 m in panchromatic, can show many island features of interest, including the major zones on coral reefs

AITUTAKI

Aitutaki is an almost-atoll in the Cook Islands (18°52'S, 159°48'W) 225 km north of Rarotonga. It consists of a small volcanic island of 16.8 sq. km and a maximum altitude of 119 m surrounded by a large lagoon of 66 sq. km enclosed by a roughly triangular barrier reef, hence the term "almost-atoll". There are 13 low coral islets totalling 2.2 sq. km on the 600-1000 m wide barrier reef. The lagoon has a maximum depth of 10.5 m and is mostly under 4.5 m, with numerous patch reefs in some areas. The population of about 3,000 lives mostly from agriculture and fishing, with some small-scale tourism. Tridacna maxima is common on the reefs and forms the basis of a major food-gathering and commercial industry (IUCN, in press). There have been efforts to improve the revenues from the island's marine resources, including the introduction of Trochus in 1957, now harvested commercially, and recent trials of Tridacna derasa, Turbo marmoratus, and Eucheuma. The status of the lagoon and reef resources is thus of economic as well as scientific importance. Aitutaki was studied in detail by an expedition in 1969 (Stoddart & Gibbs 1975). Lagoon sedimentation has been described by Summerhayes (1971) and more recently by Collotte (in press.) the reefs by Stoddart & Pillai (1973). A brief marine environmental survey was made in 1976 (Dahl, 1980). Recent information on the reefs has been summarized by IUCN (in press).

Remote sensing study of Aitutaki

A SPOT multispectral (20 m resolution) was aquired on 23 June 1986. The first goal was, in the framework of the CCOP/SOPAC IOC STAR remote sensing study group, to develop a demonstration project to show the potential use of high resolution satellite data for shallow water mapping and mineral prospection.

The first step was to delineate the lagoon automatically in the image by thresholding XS3 and XS1 respectively for elimination of emerged land and determination of deep water. Fig. 1 (Jupp et al. 1985) shows the spectral performance of various type of bottom according to bathymetry on XS1 (x) versus XS2 (y) wavelengths.

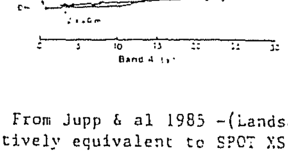

Fig. 1 : From Jupp & al 1985 -(Landsat band 4 and 5 respectively equivalent to SPOT XS1 and XS2.)

This figure demonstrates the potential use of these spectral bands to caracterize the type of bottom and the bathymetry, and to describe in particular, the difference in light penetration between band XS1 (20 m and more) and band XS2 (5 to 7 meters).

The calculation starts with the formula linking $R_{i(z)}$ radiance as measured in the wavelength (i) to the depth (z) :

$$(1) \quad R_{i/z} = R_{i\infty} + (0{,}545 R_i^f - R_{i\infty}) e^{-2K_i z}$$

$$R_{i(z)} = \frac{L_{i(z)}}{E}$$

$L_{i(z)}$ = Luminance at the observed point
E = Illumination

Where :

- i = Wavelength or spectral band
- 0,545 = Transmission coefficient at the land-sea interface
- $R_{i(z)}$ = Reflectance of an observed point where the bottom is situated at a depth of z (meters)
- $R_{i\infty}$ = Reflectance of the water mass with infinite depth
- R_i^f = Natural reflectance of the bottom
- K_i = Attenuation coefficient in channel i

Therefore :

$$(2) \quad z = \frac{1}{2K_i} \ln \frac{0{,}545 R_i^f - R_{i\infty}}{R_{i(z)} - R_{i\infty}}$$

Of the three original channels XS1, XS2 and XS3, only the firsts can be used as the third does not penetrate through water (absorption of the near infrared). The correllation coefficient, calculated on 250.000 pixels in the lagoon as defined here, is 0,90.

Transforming the cartesian coordinates (XS1), XS2) of fig. 1 to polar ones :

$$(3) \quad \rho = \sqrt{(XS1)^2 + (XS2)^2} \qquad \theta = \mathrm{Arctg}\,(XS1/XS2)$$

induces a decorrelation (r = 0,23) due to the fact that for a definite depth the distance (ρ) varies according to the bottom type while for a definite bottom type in shallow waters the angle (θ) varies according to the bathymetry (see fig. 1).

Because the bottom of the Aitutaki lagoon is covered in places with coral heads and branching ribbons of coral knolls showing as discontinuous zones on the image, we have created a third neo-channel (texture) created by replacing the original digital value at each point on the image with the result of the computation of a local standard deviation within a 3x3 pixels window. This method, already described by Jupp et al. 1985, uses the shortest wavelength channel. We applied it (Loubersac 1987) using the ratio (XS1)2 /XS2 which is a good descriptor for shallow waters (Ben Moussa 1987).

Two new maps : a bathymetric one and a map of the sediment distribution in the lagoon have been produced by CCOP/SOPAC using SPOT imagery. The satellite imagery appears to offer considerable advantages for those types of study. About 75 % of the bathymetric map (see figure 2) were drawn using the SPOT image with little need for field calibration.

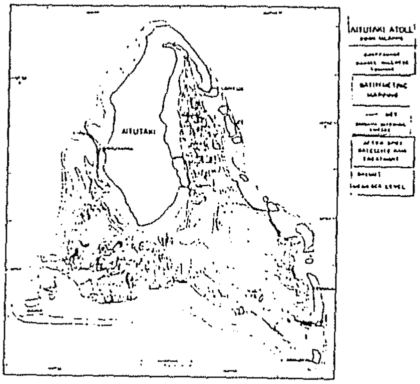

Fig. 2 : Bathymetric map of Aitutaki

The color composition ρ in red, θ in green and texture in blue has been also used by CCOP/SOPAC in conjuntion with ground truth measurements to make a morphological study of the lagoon (Collotte, 1988).

Lyzenga (1981) shows that through the following transformation of raw data :

$$x_i = \ln (L_i - L_{si})$$

Where L_i = Luminance measured in channel
L_{si} = Luminance of deep water in channel

The resulting neo-channels are linear functions of the water depth and are linearly related to each other. So on a bidimentional histogram of (X_{XS1}) plotted against (X_{XS2}), the pixels will fall along straigth lines whose slope is KXS2/KXS1 (KXS1 being the irradiance attenuation coefficient in band XS1). If the bottom reflectance changes, the corresponding pixels points will fall along a parallel line. The displacement between the two parallel lines corresponds to a bottom reflectance change which can be detected even if the bathymetry is not known.

Lyzenga demonstrated that this displacement is related to the bottom reflectance as follows :

$$(4) \quad Y_i = Y_{i0} \frac{k_j \ln r_i - k_i \ln r_j}{\sqrt{k_i^2 + k_j^2}}$$

Where r_i = bottom reflectance in band i
Y_{i0} = a constant for fixed illumination and atmospheric conditions

So disregarding the constants Y_{i0} and $\sqrt{k_i^2 + k_j^2}$ one may write :

(5) Y_i as homologous to $\ln r_i - (k_i/k_j) \ln r_j$

Using the SPOT image and bathymetric data obtained by the CCOP/SOPAC Technical Secretariat (Richmond & al, 1986), one may compute the K XS1/K XS2 ratio. Note that the CCOP/SOPAC ground truth campain took place from 5 May to 7 July of 1986 in conjunction with the SPOT overpass of 23 June.

Engel (1988), comparing three SPOT images (Heron island, Moorea and Aitutaki), showed that for Aitutaki 23.6.86 : is homogeneous to 15 ln (XS1) - 3 ln (XS2) and found, by representing Yi as a monochrome image, eight bottom types in the lagoon.

Using a contingency table combining the bottom types defined from the images and ground truth parameters, it is possible to map the distribution of both the terrigeneous fine sediments, occuring mostly in the N.E. zone as well as in the adjacent lagoon, especially in the deep basin, and the biogenic coarser sediment, predominating everywhere else and accumulating primarily in the eastern and southern area.

IMPACT ASSESSMENT OF CYCLONE SALLY

Tropical cylcone Sally formed in the Northern Cook Islands on 26 December 1986 and passed through the Cook Island on a southeastward track before declining south of the Austral Islands on 5 January 1987 after maintaining hurricane intensity for nearly a week (Kishore 1987). It made a loop north of Aitukati before passing 60 km to the west on its way south, and thus subjected the island to a prolonged period on high winds and heavy seas. The winds on Aitutaki first reached gale force December 31 at 00h, declined to near gale force for 24 hours during the cyclone's loop, returned to gale force on 1 January at 12th, and reached storm force on 2 January at 00h before accelerating to the south where the eye passed over Rarotonga bringing waves of 10 m on the reef and winds gusting to 93 knots. At the height of the storm on Aitutaki (2 January, 5h to 8h), the winds gusted to 70 knots and the minimum sea level pressure reached 983 Mb. There was damage to housing, coconut trees and other vegetation, and the high seas and heavy swells damaged the wharf and cargo shed. The effects on Rarotonga were disastrous (Cowan & Utanga 1987).

IFREMER was alerted by CCOP/SOPAC on 7 January, leading to an immediate request for a new SPOT image of Aitutaki. After some problems with cloud cover, a good quality image in XS mode with only slight cloud cover was obtained on 17 February for comparison with the reference image of 23 June 1986. Both images were taken, at the same tide level (high tide), which reduced to some extent the information potentially available on the shallow reefs.

COMPARISON OF IMAGES BEFORE AND AFTER THE CYCLONE

The two images of 23 June 1986 and 17 February 1987 were preprocessed for radiometric and geometric corrections.

The image obtained after Cyclone Sally was processed (level S) at CRIS (Centre de Rectification des Images Spatiales) in Toulouse (France) so that each pixel could be superimposed on the equivalent pixel of the reference image of 23 June 1986.

The radiometric corrections were performed as follows :

Following Begni (1986) and Duinguirard (1986), the digital counts Ni (i for XS1, XS2 and XS3) can be converted to luminance Li :

$$Li = Ai\ Ni$$

where $Ai = 1{,}056\ w.m^{-2}\mu m^{-1}$ for XS1
$= 1{,}011\ w.m^{-2}\mu m^{-1}$ for XS2
$= 1{,}020\ w.m^{-2}\mu m^{-1}$ for XS3

and to reflectance Ri $= \dfrac{L_i}{f.E_i.\sin h}$

where f is a coefficient for correcting the variations of distance between sun and earth (William & al., 1985).

Ei = mean value of incident solar illumination
h = sun angle

According to Tanre et al (1981), atmospheric corrections may be performed as follows :

$$R_i = \frac{T_i\ R_i^{SOL}}{1 - S_i R_i^{SOL}} + R_i^{ATM}$$

with Ti the atmospheric transmitting factor computed with 5S software (Tanre et al, 1985).

Ri ATM the atmospheric reflectance deduced from the lowest value observed in the open ocean.

Si the spheric albedo of the atmposphere.

The image of 23 June 1986 was acquired under optimal atmospheric conditions, while the image of 17 February 1987 has some clouds, mostly in the south west part of the atoll. Before comparing the images, clouds and their shadows were eliminated using bidimentional histogram thresholding deduced from the radiometric behaviour of the clouds and shadows on XS3 and XS2. Interactive elimination had to be added since the automatic methodology was not efficient enough to eliminate all cloud and shadow pixels.

The radiometrically and geometrically corrected images were first compared visually. Such a detailed comparison let the interpretator to give a first assessment of the zones affected by the cyclone (Lemaire et al, 1987). Among the clearly visible impacts of Sally one can find ; mostly on the reef flats and around the main island :

- Coastal erosion of the mainland and islets, mostly in the north-west and north-east parts of the atoll.

Major modifications of sand bank patterns in the south-east and south-west parts of the atoll.

- The presence of crevices in the coral reef, mostly in the eastern part.

After polar transformation as described above, major differences are apparent mostly in the shallow waters. Significant changes occur in the unconsolidated sediments and some areas of hard bottom with a strong textural component were replaced by soft areas with little texture.

Since the potential advantages of remote sensing for impact studies include not only synoptic description but also quantification and prediction, we directed the study toward two goals :

a) the quantification of the area of the shallow water bottoms which were altered or removed.

b) The quantification of the erosion of low lying coastal areas which can threaten permanent housing and the conclusions which can be derived from such an analysis to minimise the risks of future damage to housing.

For the first goal, a), the methodology, based on a multitemporal approach, uses radiometric comparison which can be summarized as follows :

is the reflectance of the bottom on XS1 and XS2 after the cyclone higher (lighter) than lower (darker) than the same as before ?

If one considers the distribution of the pixels in the two bidimentionnal spaces defined by the axis XS1 before and after, and XS2 before and after, three main classes can be observed (Fig. 3) :

- The class of the pixels strongly correlated (no changes) belonging to the first principal component axis after PCA
- The class of the pixels lighter after the cyclone.
- The class of the pixels darker after the cyclone.

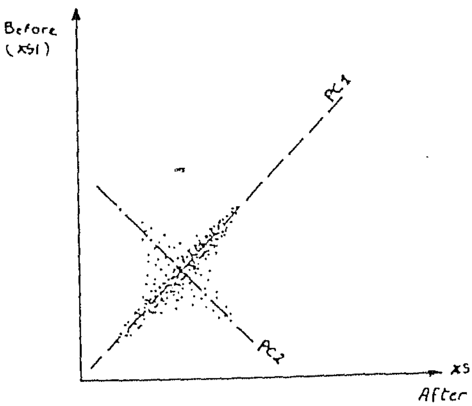

Fig. 3 : multitemporal comparison of shallow water pixels before and after cyclone Sally.

Fig. 4 (see back page) summarizes the differences observed after the passage of the cyclone. One coding shows areas that have increased reflectance as the result of the cyclone, such as new, reworked of shallower sand deposits. A second indicates areas that became darker since the passage of the cyclone. These changes could be variously due to deposits of terrestrial (volcanic) sediment eroded from the high island, increased depths from scouring or the removal of blocks of reef framework, or the rapid growth of algal cover on disturbed surfaces in the 1 1/2 months between the cyclone and the recording of the second image.

The differences in reef and lagoon areas shallower than 3 meters depth were then quantified for the whole of Aitutaki. Lighter areas covered 15.2 % of the bottom, and darker areas 17.0 %. Thus one third of shallow marine bottom surfaces on the almost-atoll were severely altered or removed by the cyclone.

For the second goal (b) the methodology is based on the fact that the signature of the erosional effect of Sally on coastal low lying areas corresponds to a modification of the coastal vegetation limit.

So applying a vegetation index (Compton 1979) to the form of XS3/XS2 on the two radiometrically calibrated images one can detect the vegetation pixels from the no vegetation ones and so can detect the coastal limits of the terrestrial vegetation.

Fig. 5 (see back page) shows the coastal limits between sand and vegetation before the cyclone (black line) and the modifications induced by Sally after the cyclone (dotted line). Fig. 5 shows major areas of coastal erosion in the north-west of the main land where sand reaches up to 70 meters inland and where a big part of the airstrip has been invaded by sediments. This can be also seen in the north-east and east where the band of destroyed vegetation averages 40 m in width and reaches 60 m at Tavaerua so as in the south-west at Maina.

In can be concluded that housing in the Anauga district on the coastal border of the road leading to the airstrip has to be carefully planned since the low lying coastal zone is particularly vulnerable to future storm damage.

Table 1 (see hereafter) gives (in percent) the regression of the vegetation cover on the islets of Aitutaki (Mainland not included because of cloud cover).

CONCLUSION

This preliminary study has demonstrated the potential of remote sensing techniques for identifying large-scale changes in coastal and shallow marine areas, such as those produced by a tropical cyclone, by comparing images before and after the event. There is clearly potential for the further development of such techniques. For studies of the medium and large scale sediment dynamics, it would have been desirable to have panchromatic SPOT images with their 10 m resolution. More could be done to analyse changes in the exposed hard surfaces of the islets and coastal areas. Since whole reef zones should suffer major cyclone effects, it should be possible to identify their status in the images. One would expect a drastic reduction in living coral cover and the image "texture" produced by patchiness or relief on the reef, followed by stages in algal recolonization such as those observed by Loya (1976). There should be a spectral evolution of damaged and regenerating reef zones that should be identifiable from a series of satellite images, depending on the lapse of time between the event and the images. However, it will take some accumulated experience before such interpretation will be possible.

CCOP/SOPAC is developing a comparison between aerial photographs taken in 1955 and the two SPOT images. A drastic reduction in number of pinnacles has been observed in the south-west part of the lagoon. This could be correlated to the fact that the southern and eastern reef flats being the major stock of the sediment of the atoll have been considerably eroded by the wave action. Because sediment cannot be evacuated by the Arutanga passage there is continuing infilling in the lagoon. This has been observed for more than 30 years by the population, mostly the fishermen who are preoccupied by fish fauna changes.

There are clearly many potential applications of this technique. A satellite image of an affected area makes it possible to orient ground-level impact surveys more efficiently. The large-scale evaluation and quantification of certain types of cyclone damage visible in the images can help in planning emergency aid or help for reconstruction. The analysis of vulnerable areas seen in the images can help in planning and siting land uses, developements and coastal infrastructure to minimize the risks of future damage. Remote sensing may help in following large scale reef phenomena such as coral bleaching or die-offs. On a broader scale, this could become a new tool to assist in monitoring the state, extent and capacity of fisheries resource areas (Bour et al, 1986), and in providing the kinds of data required for island environmental management.

The value of image comparisons makes clear the importance of developing data banks of reference images to be used for future comparisons. In the case of Aitutaki, we were fortunate to have an image taken a few months before the passage of the cyclone. The systematic collection and archiving of remote sensing images according to carefully selected criteria balancing potential scientific of human interest with rigorous economy is a pressing need, particularly at a time when the planet is being subjected to increasing large-scale changes produced by development, pollution, climate change, sea level rise, etc. Only when this problem is solved will the type of study reported on in this paper move from a chance occurence to a systematic tool for scientific research and human betterment.

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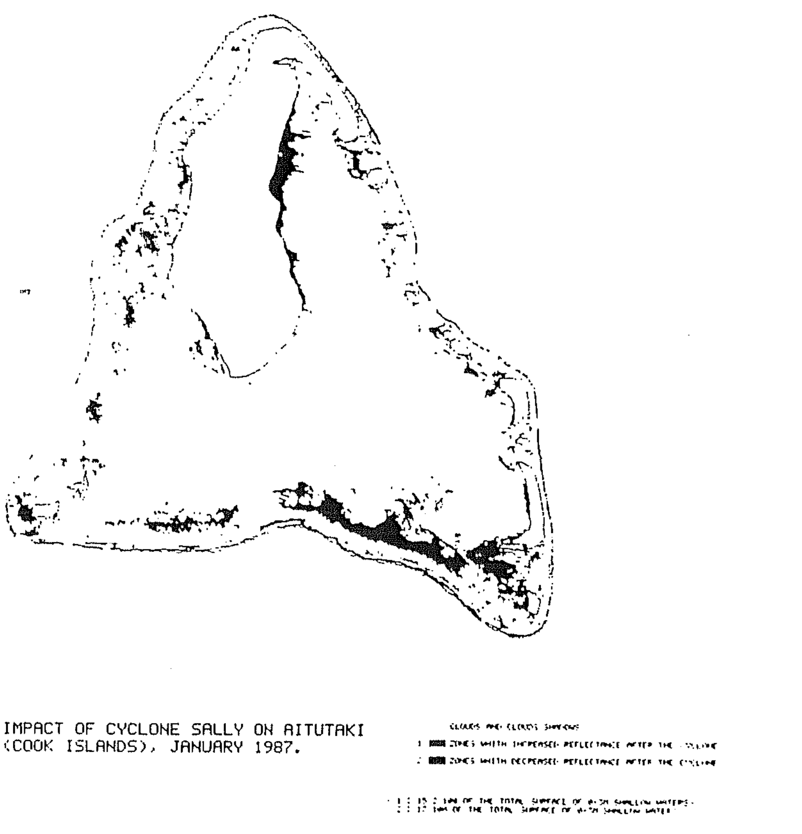

Fig. 4 : Map of radiometric changes in the shallow waters.

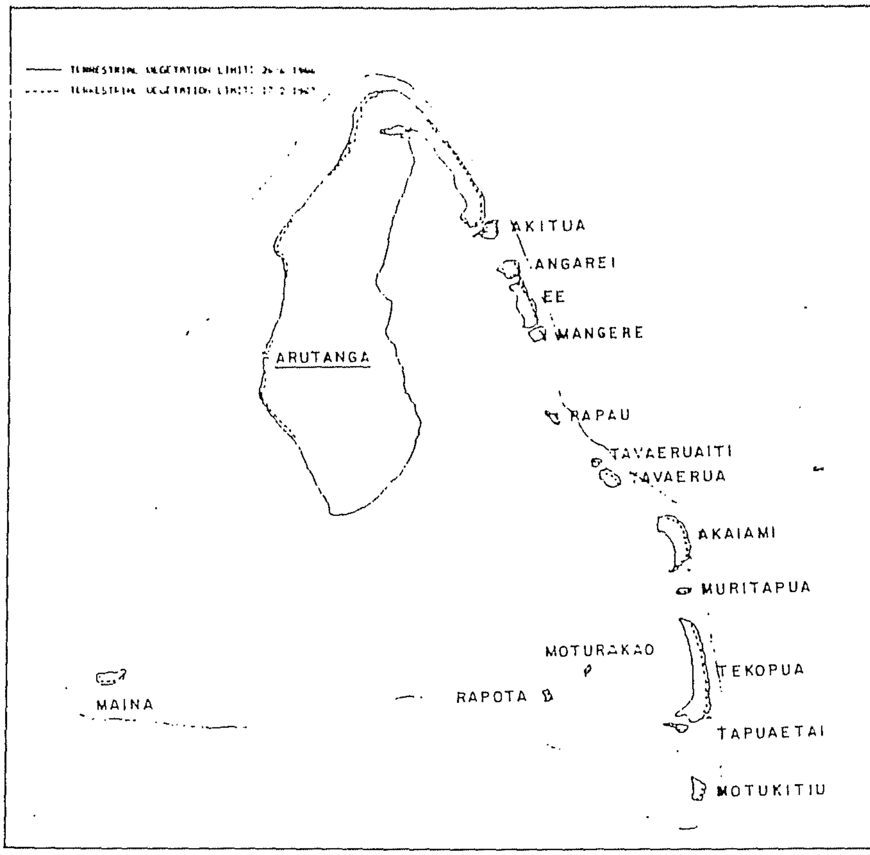

Fig. 5 : Map of coastal erosion.

NAME OF ISLET	REGRESSION OF VEGETATION COVER (%)
Akitua	31,3
Angarei	23,4
Ee	15,8
Mangere	21,5
Papau	24,2
Tavaeruaiti	36,4
Tavaerua	29,1
Akaiami	11,7
Muritapua	17,6
Tekopua	6,6
Tapuaetai	15,6
Motukitiu	10,6
Moturakao	18,3
Rapota	25,4
Maina	25

Table 1 : Regression of vegetation cover (percent) on the islets of Aitutaki.