

THE INTEGRATED GROWTH RESPONSE OF CORAL REEFS TO
ENVIRONMENTAL FORCING: MORPHOMETRIC ANALYSIS OF
CORAL REEFS OF THE MALDIVES

by

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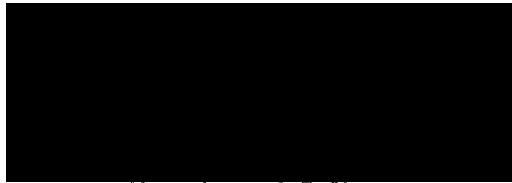
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ABSTRACT

Coral reefs are bioherms whose structure comprises a dynamic mixture of geologically inherited and environmentally forced morphologies. The major debate of coral reef history is over the relative importance of antecedent, erosional and recent, constructional processes in controlling the pattern and pace of reef growth. Landscape scale studies of reef morphology enable us to distinguish between these two morphological lineages on modern reefs. This thesis quantifies empirical relationships among spatial patterns of coral reef growth, geomorphology and environmental forcing in the archetypal atoll nation of the Maldives. The main hypothesis is that asymmetric ocean wave forcing interacts with antecedent reef platform structure to produce characteristic growth configurations and predictable reef morphologies during the Holocene (at least). The hypothesis is tested by regressing a set of reef growth morphometrics derived for every single coral reef larger than 1 ha on impinging wave energy for the entire archipelago ($n = 2041$). The methods involved the classification of eight Landsat-7 Enhanced Thematic Mapper Plus (ETM+) satellite images covering all reefs of the Maldives, and the calculation of morphometric indices using a geographical information system (GIS). The spatial pattern of coral reef growth, as defined by the distributions of distinct reef geomorphologies, was quantified by multiple morphometrics of well-defined geomorphic zones: reef slope, reef crest, coral rubble, sand flats, reef lagoons and reef islands. These features were delineated with an overall accuracy of 81%. The total area all coral reef and lagoon habitats that comprise Maldives is 21,372.72 km². A total of 2,041 ± 10 distinct coral reef structures larger than 0.01 km² occupy a vertically-projected surface area of 4,493.85 km². Smaller areas of coral reef substratum cover another 19.3 km², bringing the total area of coral reef to 4,513.14 ± 135.40 km². Islands occupy only 5.1% of the total reef area. Spatial gradients in environmental forcing (i.e., southern ocean swell and monsoon wind-wave fields) were characterized and quantified along the same dimensions as the reef geomorphology, and statistically related to the reef morphometrics. Non-parametric Multidimensional Scaling (MDS) and Analysis of Similarities (ANOSIM) procedures identified statistically significant differences among groups of reefs located on atoll rims that were exposed to nine differing hydrodynamic regimes. The widths of rim reef slopes, crests and flats widths were significantly related with incident wave power ($r^2 > 0.07$, $p < 0.01$, $n=488$), with the largest reef growth zones facing the major monsoon wind direction, and the smallest facing the relatively calm Maldives Inner Sea. The hydrodynamic openness of the 16 complex atolls of the Maldives was quantified by a rim aperture index (range from 0.03 to 0.35). The total area of various reef growth forms in atoll lagoons (i.e., patch reefs, knolls and *faros*) was significantly positively related with the aperture index ($r^2 > 0.62$, $p < 0.001$, $n=16$). The extensive, detailed and accurate data provided by this study for the first time on the exact numbers, sizes, shapes and areas of reef features of the entire Maldivian archipelago demonstrates the value of synoptic technologies to seascape ecology, supports the hypothesis that the spatial patterns of coral reef growth predominantly reflect recent hydrodynamic forcing, and provides a sound basis for predictive modelling and management decision support in a developing nation of 300,000 people living on coral reefs and confronted with rising sea level.

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Chapter 1

1. GENERAL INTRODUCTION

Reef scientists have tried, with varying degrees of success, to determine the factors controlling the development of coral reef morphologies seen in the modern day. Several comprehensive theories have been erected within the last 150 years to explain coral reef formation (Darwin 1889; Dana 1890; Daly 1915; Hoffmeister and Ladd 1944; MacNeil 1954; Purdy 1974). Reviews of these theories and surface morphologies of modern atolls lead us to believe that there are two temporally separated phases in reef development: *geologically controlled erosional phases* and *environmentally controlled constructional periods*. The time scales at which these two phases occur are such that it may be possible to separate the physical processes affecting growth on modern day reefs from the antecedent controls. No work has been done on this at the spatial scales necessary (i.e., at the scale of entire reef systems or atolls), although the controlling environmental factors are thought to be well known (Roberts et al. 1992).

Coral reefs reflect control by physical processes (Roberts et al. 1992). In particular, wave direction and power (functions of near and far-field wind stress) determine patterns of reef productivity and shape reef morphology as well as benthic community structure (e.g. Munk and Sargent 1954). Lateral reef growth in shallow water reef systems is characterized by sequences of geomorphologic zones parallel to the contours of the seaward reef slope or the shore of the adjacent land where present (Fagerstrom 1987). Spatial variation in hydrodynamic forcing exerts the major control over shallow reef zonation (Bradbury and Young 1981), which is best developed on the windward sides of oceanic atolls. It is postulated that the peripheral morphology of atoll rim reefs expresses the integral of lateral growth, which can be inferred by quantifying their zonation patterns.

Oceanic atoll reef complexes maybe regarded as a system of related ecological structures with common environmental processes operating on and around them. Reef structure, morphology and growth may be investigated by two basic methods: surface mapping of geomorphology and interpretation of borehole samples. Borehole data reveals the reef framework of reefs and Holocene growth patterns that vary both vertically and laterally (Montaggioli 2000; Kennedy and Woodroffe 2002). Mapping of reef morphology provides a means to understand the modern surficial processes at play in the growth of reefs. Reef slopes and reef crest adjacent to the slope as well as back reef sand flats on the windward side of reefs are the most prominent morphological growth zones on reefs (Hubbard 1997).

The Maldives is one of the largest, but least well-studied atoll groups in the world. They are uniquely located in the monsoon wind regimes of the Indian Ocean that provide the opportunity to investigate new environmental forcing functions, not explored to date in any atoll group in the world. Atoll rim reefs of the Maldives display asymmetric geomorphological zonation in their arrangement on the atoll rims, a characteristic noted for many atolls around the world (Wiens 1962; Guilcher 1988). The rim reefs on the ocean-facing (east and west) rims are broader and more continuous than those on the rims facing the Maldives Inner Sea. This pattern of reef development has attracted scientific attention for a long time (Darwin, 1889; Gardiner 1902; Agassiz 1903; Purdy and Bertram 1993), but no convincing explanation has been offered. I postulate that reversing monsoon winds and southern Indian Ocean swells, the predominant hydrodynamic forcing functions in the northern Indian Ocean, interacts with antecedent reef platform structures to produce characteristic growth configurations and predictable Holocene reef morphologies in the Maldives' atolls.

An evaluation of the literature on atoll reef morphology indicates a huge gap in our knowledge of Indian Ocean atolls. Few studies have been carried on the Maldivian atolls since ground-breaking surveys by Gardiner (1901) and Agassiz (1902) a century ago.

Recent insights into the morphology of the Maldives' atolls were provided by Preu and Engelbrecht (1991), Woodroffe (1992) and Bianchi et al. (1997). These studies concentrated on very few reefs in one or two atolls, and their conclusions are deduced from measurements made at the scale of sections and zones of the individual reefs they investigated in the atolls. In order to understand the geomorphology and the pattern of reef formation in atolls and archipelagos, and to compare them across biogeographical regions of the world, I believe (in keeping with the precepts of landscape ecology, Brown 1999) that quantitative, synoptic maps of reef morphology are needed for major atoll groups at appropriate scales and resolutions. The Maldives group of atolls remains the least studied in this respect.

Early studies of atolls (e.g. Wiens 1962) posed hypothetical questions on atoll growth morphology in relation to environmental forces, especially wind and waves. The majority of the early coral reef surveys (excepting Gardiner's in 1902 and Agassiz's in 1903) were conducted in Pacific atolls using navigational charts and, on a few occasions, aerial photos. The measurements made were mostly crude estimates and are unsuitable for statistical analysis.

Today, we have new techniques and advanced tools that can be used effectively to analyze patterns of reef growth as reflected in atoll reef morphology at the characteristic scales of variation in major environmental forcing functions (i.e., across biogeographical regions). Remote sensing from space provides a uniform, quantitative survey technique for remote coral reefs such as the atolls of the Maldives (Green et al. 1996; Hatcher et al. 1997; Knight et al. 1997; Mumby and Harborne 1999; Mumby et al. 1998; Holden and LeDrew 1998). Satellite imagery of most of the world's atolls is now available at suitable spatial resolutions to depict reef morphology in a synoptic format (e.g. Landsat 7 Enhanced Thematic Mapper plus; ETM+). These images are cost effective to acquire and can be analysed by people with good computer expertise (Green et al. 1997). Advanced satellite image processing and GIS tools allow us to quantify reefs over large domains and analyse them spatially.

In this thesis I will attempt to map and quantify surface coral reef geomorphology on atoll rim reefs and lagoon reefs of the Maldives using the most recent Landsat 7 ETM+ satellite imagery and Geographic Information System tools. The quantified data will be used to test hypotheses relating to coral reef geomorphology and environmental forcing during the Holocene.

1.1 Aims and Objectives

The aim of the research presented in this thesis is to enhance our understanding of atoll reef growth and development in relation to predominant environmental processes that operate around them. This aim will be achieved by the detailed mapping of coral reef geomorphology on the Maldives's reefs (both on rim reefs and lagoon reefs), and relating them to environmental processes. The objective is to develop new approaches to understanding atoll reef morphology and reef growth.

The specific objectives of this thesis are to make the following contributions to coral reef science:

1. Provide a comprehensive review of the literature on geological and ecological models of coral reef growth and development,
2. Develop and demonstrate methods to map and quantify coral reef geomorphology at archipelagic scales using remote sensing and GIS tools,
3. Calculate the accurate total coral reef area for the Maldives using Landsat 7 imagery,
4. Characterize individual reef components of the Maldivian atolls spatially and develop a geomorphological database,
5. Test hypotheses about environmental forcing of reef growth patterns using quantified geomorphological data.

Based on existing knowledge (Chapter 2) and the examination of the surface geomorphology and growth patterns of atoll rim and lagoon reefs of the Maldives (Chapter 4), the following hypotheses are erected to explain the spatial patterns of growth of the atoll reefs of the Maldives.

- *The integrated growth of atoll rim reefs (as defined by total reef surface area, total reef flat area, reef slope width, reef crest width, reef flat width, proportion of reef flat and lagoon) is a function of incident wave power.*

This hypothesis stems from the very earliest observations and intuitions of environmental controls on the patterns of atoll growth (Darwin 1889), and builds on the pioneering work of Munk and Sargent (1946). The underlying mechanistic explanation is that the metric of wave energy integrates both the positive effects of mixing and the delivery of new nutrients to reef surfaces and interstices (Hamner and Wolanski 1988), and the negative effects of erosion and off-reef transport (Hubbard 1997). In the Northern Indian Ocean, the wave field is the result of the dominant monsoon climatology and the northward propagation of ocean swell from the major storm centres in the southern Indian Ocean (Fein and Stephens 1987).

- *The integrated growth of atoll lagoon reefs (as defined by total reef surface area, total reef flat area) is a function of atoll rim aperture.*

This hypothesis stems from the common observation that gaps in fringing, barrier and atoll rim reefs are often backed by lagoon reefs whose growth axes are apparently oriented towards the inflow of water through the gap (Wiens 1962). Hatcher (1997) and Andréfouët and Payri (2000) expand this observation to the concepts of atoll “closure” or “aperture” (resp.) and derive relationships with many metrics of reef ecosystem structure and function. The putative mechanism controlling reef growth rates and their resulting morphological expression is again the degree of lagoon exchange mixing with the ocean waters surrounding the reef and the advective delivery through opening in the atoll

perimeter of essential elements and nutrition to the organisms responsible for reef accretion.

These hypotheses are rigorously tested using quantitative statistical analysis of a database of metrics of more than 2,000 individual reefs of the Maldives.

1.2 Overview

Chapter 2 provides a comprehensive review of the ecological and environmental models that exist to explain coral reef growth on atolls, and contrast these to ideas behind antecedent controls of atoll morphology. Key questions addressed are the extent to which antecedent morphologies have been masked by modern environmental and ecological processes.

Chapter 3 justifies the hypotheses posed in this thesis and explores the ideas based on a few reefs from the northern three atolls. Initial results, findings and the methods of morphometric analysis will be introduced in this chapter. This chapter has been published in the Proceedings of the 9th International Coral Reef Symposium and, was co-authored by Dr. Bruce G Hatcher, who contributed ideas and editorial revisions to the paper. The research outlined in this chapter is fully developed in chapters 4 and 5.

Chapter 4 presents the methods used to map and quantify coral reef geomorphology, and derives morphometric variables for reefs from the quantified data. Reef geomorphology is mapped and quantified by the classification of satellite imagery, and the spatial analysis of these classifications is done using Geographical Information Systems (GIS) tools. The procedures used and developed to acquire and process the satellite imagery, quantify the reef morphology using GIS tools, and analyze the resulting morphometrics are described in detail. A comprehensive database for atoll reefs is the major output of this chapter.

Geomorphological variations of rim and lagoon reefs in the 16 great atolls of the Maldives are presented.

Chapter 5 presents the full tests of the hypotheses posed in this thesis. Monsoon and swell generated wave data are analyzed to characterize the climatology affecting reefs of the Maldives. Non-parametric multivariate statistics and parametric methods are used to rigorously test hypotheses relating patterns of coral reef growth to wave energy at archipelagic scales.

Chapter 6 uses the remotely sensed data and geospatial analysis to derive the most accurate and detailed estimates of the Maldives' reef areas to date, and compare our results with the current benchmark. This chapter been submitted to the Coral Reefs Journal and is currently under review. It is co-authored by Dr Bruce Hatcher who contributed ideas, suggestions and editorial revisions.

Chapter 7 wraps up the research presented in the thesis in a summary conclusion.

Chapter 2

2 THE CONSTRUCTIONAL MORPHOLOGY OF MODERN CORAL REEFS: ANTECEDENT VERSUS RECENT ENVIRONMENTAL CONTROLS ON THE PATTERNS OF GROWTH

2.1 Introduction

Corals have persisted on this planet for over 200 million years and thus must be considered extremely successful in evolutionary terms (Veron, 1986; Wood 1998). Corals, together with other calcium-secreting organisms, construct the greatest structures made by life on earth. These coral reefs, which are ubiquitous in the tropical oceans, occupy about 0.2% of the earth's ocean (Kleypas 1997), an area equivalent to United Kingdom. There have been attempts, with varying degrees of success, to determine the factors controlling the development of coral reef morphologies seen in the modern day. Several comprehensive theories have been erected within the last 150 years to explain coral reef formation (Darwin 1889; Dana 1890; Daly 1915; Hoffmeister and Ladd 1944; MacNeil 1954; Purdy 1974).

Three types of coral reefs are recognized after Darwin (1842): fringing reefs, barrier reefs and atolls. Fringing reefs are those that grow along continental or high island coastlines. Barrier reefs are separated from land by a deep lagoon (e.g. the Great Barrier Reef). Atolls have a coral reef rim encircling a lagoon of variable depth. Historically atoll formation has been the central theme in addressing the coral reef problem, yet, very few studies have been dedicated to understanding atolls. Wiens's (1962) study represents the most comprehensive study on atoll biology, ecology and their environments to date, but the emphasis was only on Pacific atolls. This research will focus on the Holocene growth

and surficial morphology of atoll type reefs at sea level in the atolls of the Maldives in the Indian Ocean.

Early coral reef theories suggest that coral reefs can grow from a suitable foundation upwards to form atolls, with vertical movements of the land or glacial sea level changes (Darwin 1899; Daly 1915). Others believe that atolls just display characteristics of the foundation on which the reef established itself (MacNeil 1954, Hoffmeister and Ladd 1944). It is not easy, if not impossible, to determine how atolls evolved to display their general shapes and the reefs they encompass today. However, atolls at modern sea level display distinct surficial morphological traits, which appear to be related to the prevailing environmental processes. The key to unravel modern atoll morphology and coral reef growth patterns may be found in studies of large-scale environmental processes that mold Holocene reefs at sea level.

Reviews of coral reef theories and external morphologies of modern atolls (Wiens 1962; Guilcher 1988) lead us to believe that there are two temporally separated phases in reef development: geologically controlled erosional phases and environmentally controlled constructional periods. The time scales at which these two phases occur are such that it may be able to separate the physical processes affecting growth on modern day reefs from the antecedent controls. No work has been done on this at the spatial scales necessary (i.e., at the scale of entire reef systems or atolls), although the controlling environmental factors are well known. Here, I will review the ecological and environmental models that have been developed to explain surficial features of atolls and contrast these to ideas behind antecedent controls of atoll morphologies.

The majority of the world's 425 atolls (Stoddart 1965) are oceanic in existence (e.g. atolls of the Maldives, Tuamotus and Marshall Islands) and they occur in the Pacific and Indian Oceans. The structure and morphology of a generalized oceanic atoll is shown in Fig 2.1. An atoll consists of 2 components: the rim and the lagoon. The rim may consist of a single continuous reef with few or no reef passes (deep openings) to the ocean or it may consist of many individual reefs with several passages to the ocean (Chapter 3). The morphology of atoll rim reefs may be complex with reef islands, sand bars, reef lagoons of

variable depths and extensive coral, rubble and sand flat formations. The atoll lagoon (20 – 80 meters deep) may consist of scattered patch reefs and knolls. A feature of special interest on the Maldivian atolls is the occurrences of annular reefs on the rims and within lagoons that are known as '*faro*' – a Maldivian term coined by Gardiner (1902). A *faro* is defined as a ring shaped reef with a central lagoon. The examination of numerous *faros* in the Maldives show that *faros* may in fact form many different shapes in addition to being ring shaped. Although they are physically similar, atolls and *faros* are clearly distinct in dimensions, as *faros* are distinctive parts of an atoll.

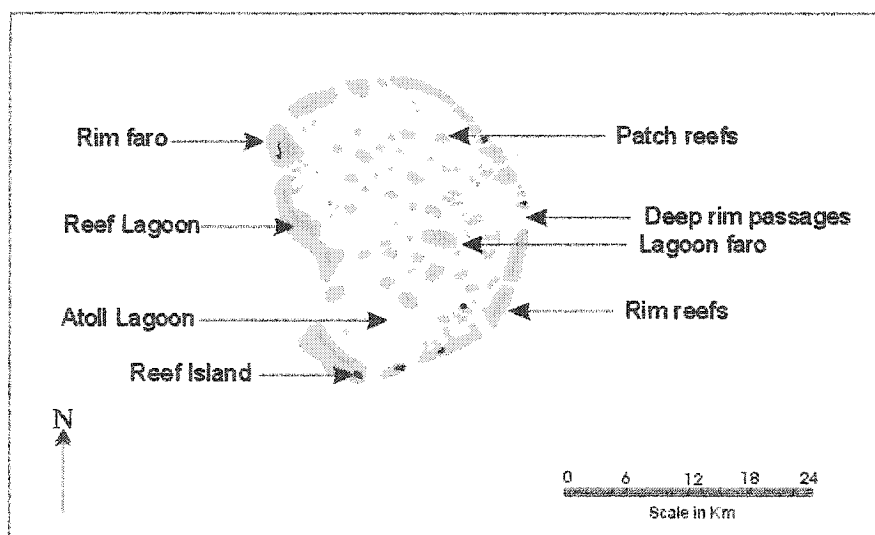


Figure 2.1 Structure and morphology of an atoll.

In the research described in the consecutive chapters, I will use quantitative morphological data (Chapter 4) derived from atoll reefs (both rim reefs and lagoon reefs) of the Maldives to develop new approaches to understanding atoll reef morphology and reef growth (see Chapter 5). The Maldives are one of the largest but least studied atoll groups in the world and they are uniquely located in the reversing monsoon wind regimes of the Indian Ocean that provides the opportunity to investigate new environmental

forcing functions not explored to date in any atoll group in the world. The atolls of the Maldives span about 900 km north to south in the Indian Ocean, extending roughly from the equator to seven degrees north latitude. The atolls are arranged in a way that they have a double chain of atolls in the central region, tapering off towards the north and south to single atolls (Fig 2.2). Atoll rim reefs of the Maldives display asymmetric geomorphological zonation in their arrangement on the atoll rims, a characteristic noted for many atolls around the world (Guilcher 1988). Reefs on the oceanward rims of atolls have wider and more extensive reef flats than those lining the rims facing the sea between lines of atolls. I hypothesize that these characteristics reflect broad-scale spatial variation in time-averaged, physical-biological control of reef growth, rather than antecedent structure, but the relationship has not been quantified. It is postulated that monsoon winds and southern Indian Ocean swells, the predominant hydrodynamic forcing functions in the northern Indian Ocean, interact with antecedent reef platform structures to produce characteristic growth configurations and predictable Holocene reef morphologies in the Maldives' atolls.

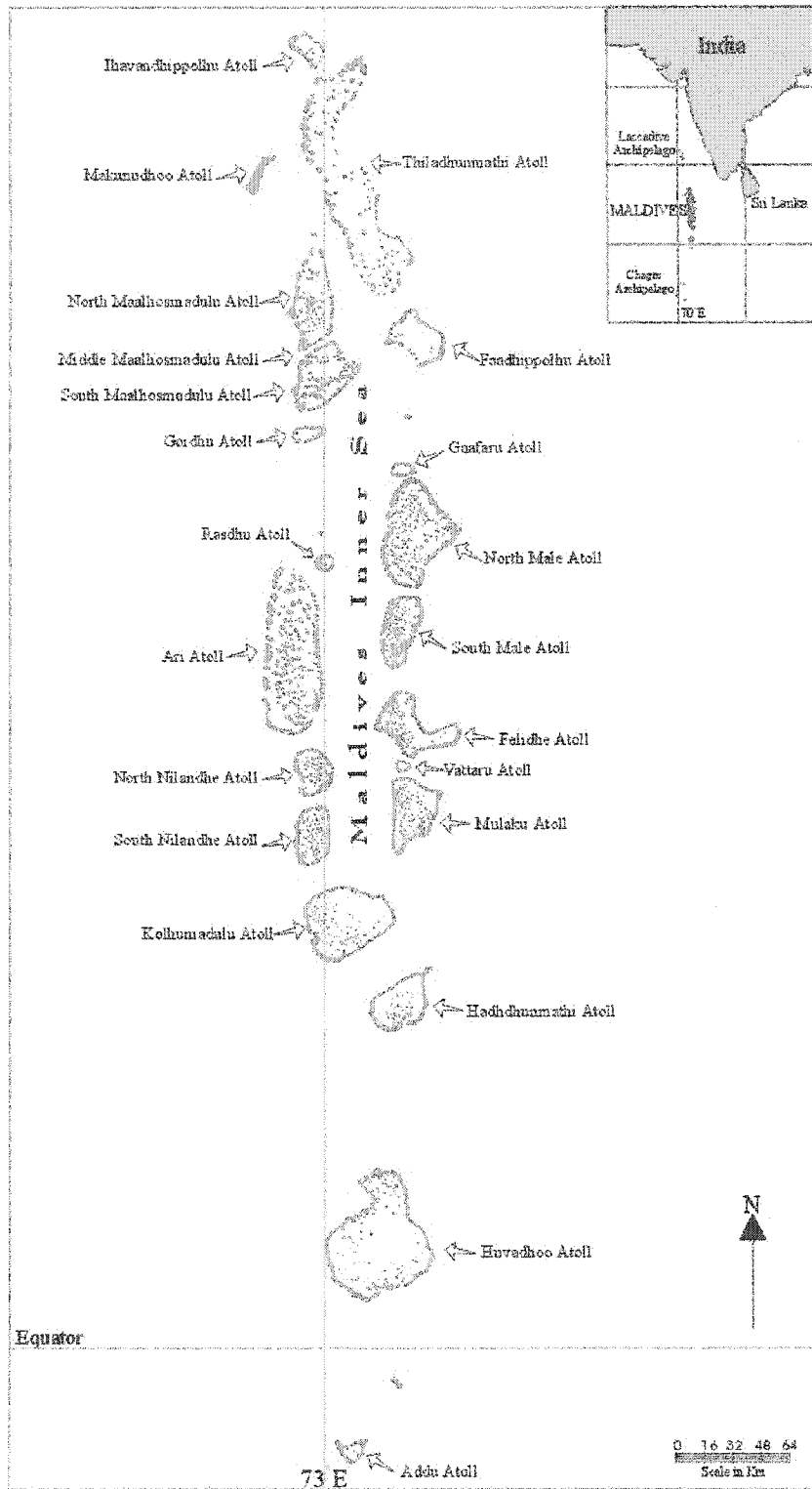


Figure 2.2 The location, structure and arrangement of atolls of the Maldives

2.2 Geological models of atoll formation

2.2.1 Defining Theories:

During the last 150 years, coral reef theory has been developed in relation to three well established geological events as controlling factors for atoll formation: *plate tectonics, glacial sea level changes and sub aerial erosion* (Stoddart 1973). Tectonic control relates to vertical movement of land relative to sea, of which subsidence is the key process for atoll formation. Glacial and sea level control refers to Pleistocene sea level changes and their effects on the formation of modern atolls (Daly 1915). Sub-aerial erosion occurs when reefs are emerged either by tectonic moments or by a drop in sea level (Purdy 1974). The popular theories of reef formation have become synonymous with these geologic forces to explain reef development and atoll formation. The most striking concept is the genetic transformation of fringing reefs around subsiding volcanic islands into barrier reefs and thence into atolls and the consequent shapes they assume (Darwin 1889). It is usually assumed that the whole process can happen by biological growth of skeletal reef organisms.

2.2.2 Tectonic control

Darwin (1889) was the first to suggest a comprehensive theory for atoll formation. His popular theory (still widely used in texts) is based on the subsidence of land relative to the sea surface. The basic postulation of the theory is that coral reefs first fringe around a subsiding oceanic volcanic island. As the island subsides by crustal movements, the reef grows, first to become a barrier reef, and then to an atoll. The evidence for tectonic events is unquestionable, as can be seen in many modern reef formations (Guozhong 1996; Ota 1996; Scoffin and Dixon 1983; Guilcher 1988).

As the depth and structure of atoll foundations became known from deep drilling and seismic studies, the geological events controlling the formation reefs became better appreciated. Drilling under atolls in the Indian (Aubert and Droxler 1992) and the Pacific Ocean (Stoddart 1973) has proven Darwin's primary postulation that oceanic reefs began growth on subsiding volcanic foundations now deep beneath atolls, that much subsidence has taken place, but not that all such reefs developed from fringing reefs around oceanic islands to atolls. At the same, time such drilling and seismic work has revolutionized our perceptions of reef theories and led to alternative models for atoll development (Aubert and Droxler 1990; Purdy and Bertram 1993).

2.2.3 Glacial / Sea level Control

Daly (1915) rejected subsidence as the control of atoll formation and came up with his glacial control theory of coral reefs. The theory states that during glacial sea level lowstands, oceanic reefs and islands were levelled by the action of waves to form platforms. During deglaciation, when sea level rose, corals grew on the edges of these levelled platforms upwards to form atolls. It was suggested that corals thrived better on the rims (of the wave planned platforms), facing wave action, and that growth was inhibited towards the center of the platform. The result will be an atoll.

Evidence for sea level changes is widespread on many modern reefs (Harvey and Hopley 1981; Hopley 1982) but there is much criticism on the postulations of the glacial control theory of atoll formation (Ladd and Hoffmeister 1936; Guilcher 1988). Bianchi et al. (1997) described submarine terraces and caves at various depths on the outer atoll slopes in the Maldives. These were interpreted as features resulting from Quaternary shorelines at a time when sea level was lower than today. The authors also suggested that the high dolomite content of sea floor sediments and karst phenomena in caves and patch reefs were evidence of past emergence and weathering of the atolls. Similar erosion features

were observed at other atolls while investigating reported reef cracks in the Maldives (Risk and Sluka 2000). Anderson (1998) described terraces and cliffs around the atolls of the Maldives, which suggested sea level lowstands during the Pleistocene.

Terraces around modern atolls are indications of sea level still stands. Such terraces perhaps provide evidence that reefs do grow laterally at stable sea levels. It has also been suggested that such terraces may have been formed by wave action and erosion. Williams (1994) described a terrace of 50m to 2km width at Cocos Keeling Islands with well-developed spur and groove morphology on the windward reef. Similar terraces have been described for other atolls (Glynn et al. 1996).

2.2.4 Antecedent platform and Sub-aerial erosion control

Some workers believed the origin of coral reefs to be a combination of both biological and geological processes, and that there was undeserved support for the subsidence and glacial control theories, which dictate a totally constructional (biological growth of skeletal organisms and accretion) scenario for atoll formation (Hoffmeister and Ladd 1935). It was also pointed out that many elevated coral reefs have a foundation of non-coraliferous limestone, discounting the postulations of the subsidence theory (Hoffmeister and Ladd 1935).

Hoffmeister and Ladd (1944) suggested that coral reefs could grow up from any suitable foundation to become atolls. They claimed it wasn't necessary for subsidence or sea level to vary and thus proposed the antecedent platform theory for coral reefs. MacNeil (1954) went further to develop the karstic saucer or the subaerial erosion theory of atoll formation, which was later developed by Purdy (1974). MacNeil (1954) pointed out that all three previous theories (subsidence, glacial, antecedent platform) had some merits but argued that atolls display shapes and sizes relating to the foundations on which they grow. The view was that during the Pleistocene low sea levels, coral reefs and reef platforms or

limestone were eroded subaerially to produce karst morphologies with marginal rims and central depressions. It is implied that once emerged, the old reef or limestone structure becomes karstified by rainfall and percolating water. Examples of karst erosion features on modern reefs are 'blue holes' (cylindrical deep depressions on reefs) and '*faros*' (Purdy 1973). Numerous examples of modern day limestone solution forms support this hypothesis, with particular reference to Okinawa limestone (MacNeil 1954). Purdy (1974) provided many examples from modern day investigation of limestones that support this theory.

Woodroffe and McLean (1998) showed that Christmas atoll in the Pacific exhibited a form similar to Pleistocene or earlier by karstification during sea level low stands. The Holocene reef of Christmas atoll forms a minor veneer of coral over older, sub aerially eroded lime stone surfaces, such that the erosional morphology is retained in the modern form.

Bloom (1974) noted that karst erosional morphology is widespread around world and that it demonstrates that the result of weathering and erosion during Pleistocene glaciation was not to plane off the foundations at wave base as Daly (1915) suggested, but rather produced rugged karst landscapes. Bloom (1974) judged from the depths and extents (diameter) of the blue holes in the Bahamas and Honduras that the potential for development of significant solution relief (atolls) seems considerable. The larger and deeper passages on atoll rims are considered drainage channels created by the flow of meteoric waters during sea level low stands (Purdy and Bertram 1993). Similarly *faros* and spurs and groove formations were believed to be formed by subaerial erosion processes. The subsidence theory explains passage formation in terms of the inhibition of reef growth by freshwater streams during the fringing reef stage of development (Darwin 1889).

2.2.5 Summary

Despite the attempts by early authors to come up with a universal theory of coral reef growth, none are accepted universally and there is still much controversy as to how reefs have developed their shapes, sizes and features both in the modern environment and in ancient times. Darwin himself recognized the difficulty of synthesizing a universal reef theory. The atolls and associated reefs (e.g. *faros*) of the Maldives were particularly troublesome for explanation in the Darwinian context as seen from the originator's own words: "*I can in fact point out no essential difference between these little ring-formed reefs (meaning faros) (which, however, are larger, and contain deeper lagoons than many atolls that stand alone in the open sea), and the most perfectly characterized atolls, excepting that the ring formed reefs are based on a shallow foundation instead of on the floor of the open sea, and that instead of being scattered irregularly they are grouped closely together.*" The problem was one of scale, in that these small, ring reefs (i.e., *faros*) are essentially atolls within atolls.

Morphologies resulting from sub aerial erosion are, unfortunately often very similar to the classical constructional growth forms (e.g. central depressions surrounded by raised rims, deep regular channels of outer flanks). This can lead to misinterpretation in the absence of core and seismic data. There is much uncertainty about how much of the reef structure observed today is geologically controlled (subsidence, glacial eustasy, subaerial erosion) and how much is the result of modern physical environmental controls of growth processes.

Today, the coral reef "problem" is addressed from a range of different perspectives, with particular emphasis on the analysis of coral growth and reef accretion (Buddemeier and Kinzie 1976; Buddemeier and Smith 1988; Davies 1983), Holocene reef morphology (Camoin et al. 1977; Harvey and Hopley 1981; Collins et al. 1996) and sea level history

(Neumann and MacIntyre 1985; MacIntyre and Adey 1990) complimented by modern field and laboratory techniques. Holocene reef thickness has been determined for many reefs around the world (Woodroffe et al. 1994; Woodroffe 1992; Woodroffe and McLean 1998; Camoin et al. 1997; Montaggioni et al. 1997; Cabioch et al. 1995).

The Deep Sea Drilling program has been instrumental in establishing the geological structure and age of the foundations under modern reefs (Backman et al. 1988). Reefs of the Maldives in the Indian Ocean, for example, are now known to have developed on top of a 2000-meter thick carbonate platform of non-reefal origin (Aubert and Droxler 1992) and have been interpreted to display little evidence of subsidence during their formation (Purdy 1981). Similar structures have been found under atolls in the Pacific (Stoddart 1973).

In summary, the quest for a universal theory of coral reef growth had been a scientific endeavour for almost 200 years, and despite much work it still remains elusive. Both the subsidence and the glacial control theories of atoll formation were based on the fact that reefs grow upward to keep up with the sea level. They could explain horizontal pattern only in terms of the lateral transition from attachment to non-reefal substratum to free standing structures as sea level fell. Many reefs do not fit this pattern. It has been suggested that reef formation can be explained only in terms of the interaction among biological, geological, and physical environmental processes (Stoddart 1969; Hopley 1978). The current crisis of anthropogenic reef degradation moves the resolution of the coral reef problem from the realm of academic exercise to that of urgent priority.

2.3 Ecological model of atoll reef morphology

2.3.1 Coral Reef Growth

The growth and formation of coral reefs are complex phenomena resulting from the interaction of a variety of chemical, physical, biological, and geological factors (Fagerstrom 1987). The geological factors (e.g. tectonics, glacial) controlling reef development were described earlier.

2.3.2 Vertical Reef Growth

During the Holocene transgression, reefs have grown vertically in response to rising sea levels (Kennedy and Woodroffe 2002; Braithwaite et al. 2000). Reef frame growth is initially determined by reef community diversity, patterns of coral growth and distribution (Grigg 1983; Buddemeier and Smith 1988; Buddemeier and Kinzie 1976). Calcification rates of skeletal organisms and accretion rates affect vertical reef growth and depend on many physical and biological factors (Fagerstrom 1987). It has been suggested that fast growing branching corals such *Acropora* species may be instrumental in the growth spurts of some reefs (Braithwaite et al. 2000; Camoin et al. 1997).

While some studies have shown the strong constructional (coral growth, calcification and accretion) components of Holocene reef growth and framework formation (e.g. Montaggioni 2000; Bianchi et al. 1997; Brown and Dunne 1980), others argue that few if any constructional features are evident on modern reefs (Purdy and Bertram 1993). The presence of recent corals in growth position (Woodroffe et al. 1994; Camoin et al. 1997)

and sediment sequences of recent origin on reef frameworks from core drilling confirm that modern reef frameworks are to a large extent constructional. Bianchi et al. (1997) concluded from extensive underwater observations that reefs in the Maldives were constructional down to 50 meters depth.

Diaz et al. (1997) characterized the reef types and morphology in the lagoons of 4 atolls in the San Andres and Providencia Archipelago (Columbia) and concluded that both ecological and geomorphological reef types show definite patterns of development and distribution within lagoon settings mainly in response to hydrodynamic and geomorphological factors. The authors suggested that the entire reef configuration in the lagoons today has developed in Holocene times, and these reefs have grown up from a base level at around the present maximum depth found in the lagoons (about 25 m).

Numerous drilling and coring studies have been conducted on Holocene reefs and carbon dating has been performed on core samples (e.g. Davies and Marshall 1979, from the Great Barrier Reef) to estimate the ages of stratigraphic sequences. It is now widely known that Holocene reefs form veneers of up to 40m thick on older Pleistocene structures (Scoffin et al. 1978; Stoddart 1969; Marshall and Davies 1984; Hatcher 1997). Davies (1983) stated that Holocene reef growth has added only a thin veneer of modern reef rock, which varies between 3-33 meters. The ages of the Holocene reef formations are also widely known (Camoin et al. 1997; Montaggioni et al. 1997; Davies 1983; Webster et al. 1998; Montaggioni 2000).

Camoin et al. (1997) analyzed Holocene reef sequences recovered in drill cores at Mauritius, Réunion and Mayotte and reconstructed sea level changes and reef growth patterns in the Holocene from the core samples. Holocene reef sequences recovered were 16-22 meters thick. Vertical accretion rates were estimated to be 0.9 to 7 mm per year for the Holocene.

Most studies relating to Holocene reef growth originate from the Great Barrier Reef, where emphasis is laid on the integrated effects of geological and physical factors in the formation of reefs (Stoddart 1978; Harvey and Hopley 1981; Hopley 1983; Davies 1983).

Studies have also been carried out in atoll environments to determine the extent of Holocene growth. Growth of the Holocene section on reefs in the Maldives was initiated about 6000 years BP, and grew upwards in a catch up mode to accumulate sections about 15 to 20 m thick (Woodroffe 1992; Risk and Sluka 2000).

Grigg (1998) reported that in the Hawaiian Islands, Holocene vertical reef growth is limited by wave exposure. Reef growth and accretion was measured along a gradient in wave energy from minimum to maximum exposures to wave action. Results showed that coral growth rates were similar at all stations (7.7 –10.1 mm per year) but reef vertical accretion occurred only at wave-sheltered stations. At sheltered sites in Kanehoe Bay, Holocene reef accretion was estimated to be of order of 10-15 meters. At exposed sites only a thin veneer of living corals, resting on antecedent Pleistocene limestone foundations, represents Holocene accretion. The patterns of Holocene reef growth described by Grigg (1998) contradict the model developed so far: greater reef growth on exposed reef margins (i.e., windward reefs). While it cannot be generalized to other regions (e.g. Indian Ocean), the fact that little accretion has occurred for exposed substrates disproves a simple exposure control of accretion hypothesis. There may be other factors such as coral diversity, temperature and light that may be responsible for this pattern of variation in reef growth.

2.3.3 Lateral Reef Growth

When reefs reach sea level they must shift to a predominantly lateral mode of growth, because they cannot grow upwards from the water (Montaggioni 2000). If a reef framework develops during a period of stable sea level, or during a slow sea level rise, it develops a cross sectional profile of its own, reflecting the pattern of horizontal growth and sediment deposition (Fig 2.3).

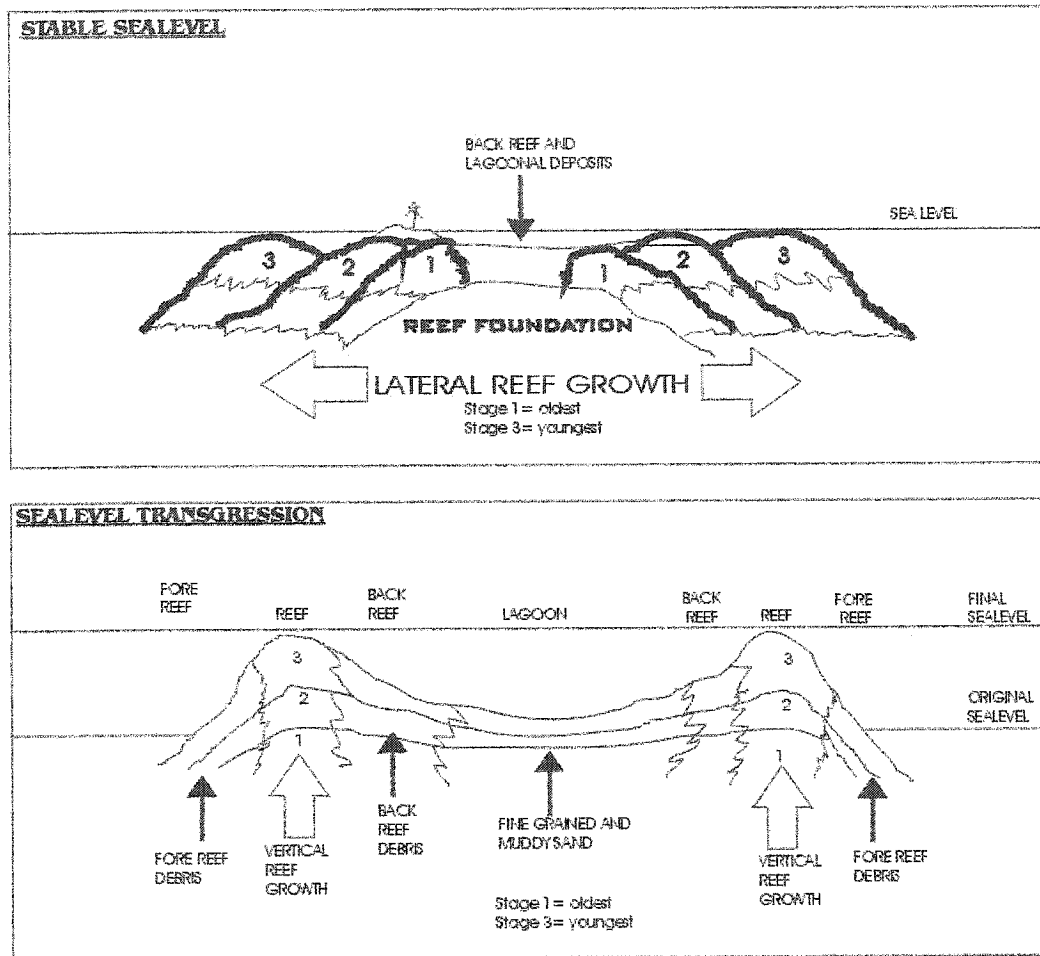


Figure 2.3 Reef growth responses to stable sea level and transgression (Redrawn from Longman 1981).

The lateral mode of reef growth is somewhat analogous to the growth mode assumed by microatolls in shallow subtidal reef flats (Woodroffe and McLean 1990). Microatolls are coral colonies, which are dead on top, but has a living around its perimeter. Their upward growth is constrained by exposure and sea level (just as modern reefs at sea level are) but they grow outwards horizontally in the normal way by calcification. In shallow water reef systems lateral growth is characterized by sequences of geomorphologic zones parallel to the contours of the seaward reef slope or the shore of the adjacent land where

present (Fagerstrom 1987). Reef islands, for example, are products of extended periods of lateral growth of reefs.

As most reefs at sea level today have been so for about 4000-6000 years (Digerfeldt and Hendry 1987; Davies 1983 and others) it is reasonable to conclude that they have grown laterally to a substantial extent. However, few studies have shed much light on lateral reef growth, yet it is this growth which has created the distinct, repeatable morphological zonations observed on modern reef flats, as well as many of the unique sedimentary and ecological characteristics of Holocene coral reefs. Pirazzoli et al. (1987) found that lateral reef growth in Reao Atoll, Tuamotu Islands, has proceeded at the rate of 0.03mm to 0.1 mm per year for the last 3-4000 years. On reefs in the Great Barrier Reef, lateral reef growth is markedly less on the windward margin than the leeward margin where most accretion takes place (Scoffin et al. 1978; Davies 1983).

Van Woerik and Done (1997) looked at the relationships between the extent of Holocene reef development and the ecological structure of the associated reef slope coral communities. They found evidence to conclude that the condition of corals on the reef's outer margin is related to horizontal reef advance during stable sea levels. Their postulation was that differences in the cumulative production of reef building materials should reflect differences in the dynamics of benthic communities and populations over the last 5000 years.

2.3.4 Reef framework

The most important process in all Holocene reefs is the construction (organic production and calcification) of the reef framework by skeletal organisms, especially scleractinian corals (Davies 1983; Braithwaite et al. 2000). The reef framework is a rigid organically built framework with potential to resist waves (Longman 1981). In an atoll, the reef framework represents the mass just in front of the reef crest, and is both the site for

abundant carbonate sediment production and a wave baffle to allow reef associated sediment to be deposited in adjacent areas (Longman 1981). The reef framework results from two structural components: mass of large colonial inter-grown skeletal organisms and sediments (originating from corals, calcareous algae, mollusks and many other calcareous invertebrates) and marine calcareous cement (from coralline algae) that unites organisms and reef sediments (Fagerstrom 1987). These two components combined form a rigid framework. The reef framework represents only a few percent of the mass of an atoll, whereas the larger expanses of the atoll rim consists of rubble and sediment (derived from the reef framework) deposited both on the fore reef and back reef zones (Longman 1981).

2.3.5 Reef growth controlling factors

2.3.5.1 Chemical factors

Coral reefs flourish in warm tropical waters where the *salinity* ranges from 34 –36 parts per thousand and very few reefs can withstand salinities out of this range (Kleypas et al. 1999). The association of unicellular photosynthetic algae (zooxanthellae) in their tissues characterizes reef-building corals. This symbiotic relationship is crucial for corals and reef growth on modern reefs. Optimal levels of *oxygen and carbon dioxide* are essential for carbon fixation by photosynthesis of zooxanthellae. They are also needed for the general smooth running of physiological functions of corals and other reef organisms.

Optimal levels of *dissolved nutrients* in the form of nitrates and phosphates are also required by zooxanthellae for growth, maintenance and reproduction, but higher levels of nutrients promote macro algal growth which can drastically reduce the potential for reef growth by coral algal competition for space. *Carbonate saturation* levels in seawater have been suggested as a major control on calcification rates and reef development

around the world (Kleypas et al. 1999). It is suggested that the entire surface of the ocean is supersaturated with respect to carbonates but the degree of saturation is higher at lower latitudes. Laboratory experiments indicate that calcification rates of corals and calcareous algae decline as aragonite saturation state in seawater is reduced (Gattuso et al. 1999).

2.3.5.2 Physical factors

Temperature is the major controlling factor for Holocene reef growth and has its effects on both photosynthesis and calcification in coral reefs. Corals have a low temperature range and the optimal temperature for calcification is 26-27 degrees Celsius. However, coral reefs do exist at temperatures below 18 degrees Celsius and as high as 34 degrees in some parts of the world (Kleypas et al. 1999). At low or higher temperatures calcification of corals is affected adversely (Gattuso et al. 1999). *Water turbulence* around coral reefs is essential for optimal reef growth. Turbulence refers to water movement principally by waves. Generally high rates of turbulence are found in oceanic atoll reef environments. This maintains the levels of salinity, temperature, dissolved gases and nutrients for optimal coral growth. The diversity of reefs in turbulent conditions is well documented (Stoddart 1969). Directional turbulence creates geomorphological zonation, which are best developed on windward reefs.

Stoddart (1971) reviewed the significance of physical environmental factors in Indian Ocean reef structure and outlined the major influencing factors: wind systems, storms, tides and rainfall. Of these the predominant influencing forces in the modern day are those generated by wind systems: waves, swells and storms. Hydrodynamic forcing on atolls determines patterns of reef productivity, and community structure (Hamner and Wolanski 1988; Chappell 1980) as well as marked morphological patterns in relation to physical processes (Munk and Sargent 1954, Hopley 1982, Roberts et al. 1992, Shinn et al. 1981). Spatial variation in hydrodynamic forcing exerts the major control over

shallow reef zonation, which is best developed on the windward margins of oceanic atolls (Bradbury and Young 1981).

Turbidity is another important control of coral growth and refers to the concentration of suspended solids (inorganic and organic) in a unit volume of seawater. Reef areas are remarkably low in turbidity in tropical waters despite high turbulence levels. Low turbidity has important physical and biological consequences for reefs. Turbidity indirectly affects photosynthetic rates (by affecting light levels) and calcification rates.

2.3.5.3 Biological factors

The existence of distinct *biogeographic* provinces for coral reefs is well known (Veron 1986). The diversity and growth of communities in these biogeographic units are controlled by local environmental parameters such as temperature, salinity, and turbulence and turbidity as well as geological factors. In situations where gradients of these parameters exist and are steep, biogeographic boundaries can be determined. The best examples of these are the distinction between Atlantic, Caribbean and Indo-pacific biogeographic provinces, in terms of generic coral diversity (Porter 1974; Veron 1986). Taxonomic diversity differences between corals and calcareous algae are considered to be an important factor in reef growth in these provinces (Fagerstrom 1987). For example, encrusting coralline algae are of major importance to Pacific reefs, less importance in the Indian Ocean, and are of generally minor importance in the Atlantic (Fagerstrom 1987). The most important attribute of reef communities is their high *taxonomic diversity* and is well known for the Indo pacific (Davies et al. 1971; Scheer 1971; Veron 1986).

Reef *biomass* is an important biological component determining reef growth rates which may be measured as coral tissue (Fagerstrom 1987). It is suggested that high biomass in reef systems is due to the occupation by small animals of microhabitats in the reef

framework. The greater the surface area (i.e., the complexity of the reef habitat (rugosity) in terms of caves, caverns, tunnels, spur and grooves), the higher the potential biomass.

Coral reefs are characterized as high *productivity* areas. High productivity (measured as carbon fixation) of reefs results from the highly efficient symbiotic relationship between zooxanthellae and corals. Other sources of primary productivity on reefs include filamentous algae, calcareous and non-calcareous algae, grasses and phytoplankton. Primary production is highest on the reef crests and coral knolls, intermediate on flats and lagoons and lowest on the deep seaward slopes.

The chief biological process of reef growth in the Holocene is the production of calcium carbonate or calcification by skeletal organisms. *Reef Calcification* refers to the precipitation of CaCO_3 (a by-product of metabolism of reef corals and calcareous algae) both organically as skeletons and inorganically as sediment. In most reefs, the greatest influence over the rate of calcification is the rate of precipitation of calcium carbonate into skeletons (corals and calcareous algae) on the reef framework organisms. Skeletal growth rates depend on the allocation of energy to production, consumption, reproduction and skeletal growth. Massive coral growth rates range from $4\text{-}15\text{mm.yr}^{-1}$ whereas for branching *Acropora spp.*, branch elongation can be $100\text{-}150\text{mm.yr}^{-1}$ and can exceed 200 mm in some cases (Davies 1983).

Interspecific and intraspecific *competition* is a major biological factor influencing the composition and structure of reef communities. It operates with other ecological factors such as biomass, light, nutrients, skeletal growth etc. In reefs the main form of competition are for space and energy (sunlight and food). Topographic complexity of reefs tends to decrease competition and enhance opportunities.

2.3.5.4 Geological factors

The dominant geological controlling factor for reef growth in the Holocene is rate of the transgression (Davies 1983; Stoddart 1973; Guilcher 1988). It is known that during the last regression, sea level dropped by about 100 meters in the late Pleistocene or early Holocene and it is widely accepted that during the Holocene transgression, sea level rose variably at the rate of 0.1 - 1 cm per year (Stoddart 1973). Sea level reached its present position around 6000 years BP (Davies 1983). Other factors affecting Holocene reef growth are the depth of the Pleistocene surface (which may be affected by tectonic movements) and the level of subaerial erosion of Pleistocene reefs during the sea level stillstand. It is estimated that reefs grew at the rate of 0.1- 0.5 cm per year in the Holocene (Stoddart 1973; Davies 1983). The rate of vertical reef growth was affected by the rates of sea level rise in the Holocene which resulted in 3 main types of reef growth: *keep-up reefs*, *catch-up reefs*, *give-up reefs* (Neumann and MacIntyre 1985). For instance, the main Holocene transgression took place at the rate of 1 cm per year (Stoddart 1973) and some reefs would not have been able to keep up with the rapidly rising seas (as their rate of growth was lower) and drowned. Those with higher rates of growth (comparable to the rates of transgression) would have *kept up* with the rising seas, while other slow-growing reefs would have *caught up* with the sea levels once its rise slowed down or growth rate exceeded rise rate. There are many examples of apparently drowned atoll or reefs (e.g. Chagos bank, Indian Ocean) and others that are still actively in catch-up mode (e.g. many *faros* within some atolls of the Maldives) as sea levels became stable.

2.3.6 Wind-wave forcing and reef morphology

Modern atolls maybe dependent on the configuration of the basement topography for many of their features, but these undergo various modifications of form or condition

during the construction of the overlying veneer through the influence of unequal exposure to waves, oceanic or local currents and the presence of fresh or impure waters (Dana 1890). Gardiner (1902) noted that atoll rim reefs facing the windward ocean side were larger than those facing the shelter of the Maldives Inner Sea. It was suggested that such variations may arise as a result of variations in growth on the windward reefs but no causation was suggested. It was also noted that smaller atolls consistently had continuous rims in the Maldives, while larger atolls had more channels, but again no reason was suggested for this variation. Darwin (1889) noted the presence of *faros* in some atoll lagoons in the Maldives, and their absence in others, and attributed this to the openness of the atoll lagoon i.e., the number and width of the deep channels on the atoll rim. He postulated that where the channels are broader, lagoon reefs would develop within the atoll. This implies that lagoon circulation above some threshold is necessary for patch reef and *faro* growth within atoll lagoons, but the hypothesis has not been quantified or tested. Guilcher (1988) suggested that the number of lagoon patch reefs is not necessarily related to the openness of the atoll and showed examples of atolls (both closed and open) that do not fit this pattern of lagoon reef growth. However this does not rule out a relationship between environmental forcing and lagoon reef growth, which remains to be tested by rigorous quantitative analysis. The postulation of environmental control can then be inferred for atoll lagoon reefs. Empirical studies of lagoon reefs, their morphology, location and orientation may provide clues as to the controls on reef growth within atoll lagoons in relation to prevailing wind-wave and hydrodynamic regimes.

Several studies have pointed out the apparent eco-morphological adaptations of coral reefs to physical oceanographic processes, particularly wave fields (e.g. Roberts et al. 1992; Van Woesik and Done 1997; Hamner and Wolanski 1988; Bradbury and Young 1981). However few studies have tied growth processes to environmental forcing in a quantitative manner (e.g. Munk and Sargent 1954). Munk and Sargent (1954) showed that the length and spacing of spur and groove formations on Bikini Atoll were related with the distribution of wave power around the atoll. The implication is that these are growth features, molded by the time-integral of the wave forcing. An alternative

hypothesis is that spur and groove topography results from sub-aerial exposure and erosion during low sea level stands (Purdy 1974).

The reversing monsoon winds are known to affect the atoll hydrodynamics inducing strong upwelling and variations in plankton abundance in atolls of the Maldives (Preu and Engelbrecht 1991). Yamano et al. (1998) showed that circulation in reversing monsoon areas are seasonal and that coral and reef zonation appears to reflect this pattern. Scoffin and LeTissier (1998) showed that the fossil reefs in Ko Phuket, Thailand commenced to grow about 6000 years ago in a reversing monsoon climate. Guozhong (1996) suggested that the characteristics of coral atolls in the South China Sea are controlled either by the tectonic history or by the monsoons of East Asia. Comparative studies of the large-scale geomorphology of reefs of the Maldives using remote sensing imagery (Naseer and Hatcher 2001) demonstrates that the widths of windward reef slopes, crests are correlated with the wave energy resulting from the reversing monsoons.

Wind and waves appears to be the primary driving mechanism of lagoon flushing and circulation on coral atolls (Atkinson et al. 1981; Hamner and Wolanski 1988; Kench 1994). Within the lagoon, the surface water is moved primarily by wind, whereas deeper water is moved by tides. Many of the biological and ecological events that occur within the lagoon are regulated by the residence time of water within the lagoon (Hatcher et al. 1987). Smithers (1994) noted that water flow through shallow channels (between reef islands on the rim) at Cocos Keeling atoll was predominantly unidirectional into the lagoon and that these were driven by southeasterly trade winds, which prevail for most of the year. The main construction process in this instance was pointed out as the infilling of the atoll lagoon.

Specific growth features of windward reefs have been related to hydrodynamics in some studies (Munk and Sargent 1954; Roberts 1974; Shinn et al. 1981; Guilcher 1988; Roberts et al. 1992). Several biophysical factors on reefs (coral diversity, sediment distribution, lagoon infilling, nutrient flow) are dominated by wave energy (Hubbard 1997). Kench (1998) pointed out that wave set-up at the windward reef crest maybe responsible for an identified 0.1 m higher water level in the windward reef flat of an atoll, which promotes

higher reef flat growth. At Cocos Islands the reef flat is best developed at its windward margin (1500m wide in the south as opposed to less than 100 meters on the east and west), where the zone of most active coral growth and reef flat development corresponds to the zone in which greatest wave energy is incident at the reef edge (Kench 1998). The reef flat at Clipperton atoll was widest (up to 200 meters) on the exposed southern side, and was only 50 meters wide on the northern leeward side (Glynn et al. 1996).

Reef islands, which are major morphological features on modern day reefs, form as a direct result of wave action on reefs which have reached sea level during the Holocene (Gourlay 1988). Reef terraces are wider, with continuous peripheral reefs on the windward sides of atolls and ill developed on the leeward sides, resulting in lagoons that are open toward the ocean along their leeward margin (Diaz et al. 1997).

Bradbury and Young (1981) investigated the topographic complexity of the reef structure as a function of wave energy on Heron Reef. The reef is exposed in the north (to cyclones) but is sheltered from the southeast trade winds by an adjacent reef. Reef morphology and coral community structure each responded substantially but independently to the wave forcing function. The deposition of sediments derived from the reef crest and transported across the reef flat, and form of the reef structure, reflect these two dramatically different sources of wind generated wave energy.

Brown and Dunne (1980) studied 31 patch reefs in British Virgin Islands in relation to the prevailing currents (in a trade wind area) and concluded that corals show clear and consistent distribution patterns on the reef in relation to currents. They stated that variations in lagoon patch reef shape are primarily controlled by differential growth of the reef building biota in response to bathymetric and hydrological influences. The currents also appear to be responsible for the orientation, and asymmetrical elongation of patch reefs in a northwest to southeast direction in the lagoon.

2.3.7 Morphology of atoll rim reefs

Ecological zonation of coral communities on modern reefs has been well studied by many workers (Done 1983; Massel and Done 1993; Davies 1971; Scheer 1971; Scheer 1974). Stony corals are able to modify their environment by creating rigid reef structures in response to environmental forcing which results in reef zonation and segregation of organisms in terms of coral species diversity, area of cover, colony size, density and spatial pattern. Distinct windward and leeward sides are recognizable on reef flats in terms of coral communities with directional wind dominance (Stoddart 1969; Davies et al. 1971; Wells 1954; Done 1983).

In the same manner as for coral communities, geomorphological zonation is very conspicuous on modern reefs. Geomorphological zonation however, cannot be examined only in terms of the skeletal species living amongst the zones, for such species maybe absent from many of these zones (Buddemeier et al. 1975; Stoddart 1969); rather it will be the topographical complexity and textural characters of the benthic habitat which will need to be taken into account in the study of these zones. Surface morphology has been described for common reef forms and biogeographic regions of the world (Battistini et al. 1975; Holthus and Maragos 1995; Kuchler 1986).

One of the main difficulties in the study of reef morphology is the lack of a generally accepted and standardized terminology for morphological categories (Mumby and Harborne 1999). This makes it very difficult to compare morphological categories across wide geographic regions. Current morphological classifications for Indo pacific reefs are based on detailed descriptions of relatively small numbers of "characteristic" reef types, extended to large reef tracts by inspection, association, and assumption rather than by quantitative analysis. Battistini et al. (1975) provided some 112 morphological categories for Indo pacific reefs, yet they are rarely used in agreement to describe reefs features in general. Kuchler's (1986) review of reef terminology generated over 240 terms. Despite the discrepancies in terminology there are widely agreed morphological zones of atolls

that include categories such as the reef slope, reef crest, algal ridge, spur and groove formations, reef flat, rubble zones, conglomerate platforms, beach rock, lagoons, beaches and reef islands and sand flats. It seems that reef scientists have a high agreement or consensus for some reef terms such as reef slope, reef front, reef flat, beach, sand flats etc. but the problem is further complicated by the use of local terms such as '*hoa*', '*motu*' and '*faro*'.

A prominent feature of reefs in the Cocos Keeling atoll is the coral conglomerate that underlies most of the reef islands, and continues onto the atoll rim (Woodroffe and McLean 1994). This structure, which is inundated by the highest tides, is found exposed on the ocean-facing sides of the reef islands, and is a Holocene fossil reef flat. Extensive reef flats occur on many atoll and barrier rim reefs. The width of rim reefs described for reefs in the Great Barrier Reef range from 150 to 500 m (Kuchler 1986) and 300 to 500 m in the Pacific atolls (Wiens 1962). Reefs in the Great Barrier Reef rise from about 20 meters depth on the continental shelf where as atoll of the Pacific rise from 1000's of meters from the ocean floor. In contrast, atoll rim reefs in the Maldives rise from about 40 – 60 meters from a submarine ridge and have reef flats with an average width of 800 meters.

2.3.7.1 *Faros*

Faros are special reef types found in the atolls of the Maldives. Their unique characteristics have always attracted the attention of reef scientists and geographers. Gardiner (1902) thought that *faro* formation was a result of the dissolution of the inner lagoon. Guilcher (1988) suggested that the pronounced reversal of the monsoon winds is important in the formation of *faros*. Stoddart (1971) postulated some underlying variability in rates of reef growth, which explains *faro* occurrence to the north but not to the south. The latest view (Purdy and Bertram 1993) is that *faros* are inherited forms

reflecting antecedent topography and solution processes. Risk and Sluka (2000) believed that the upward accretion during the Holocene transgression under conditions of ever shifting wind directions could result in *faros*. It is generally noted that *faros* are more common in the northern atolls of the Maldives (Darwin 1889; Gardiner 1902; Stoddart 1971; Woodroffe 1992) and some have related this to the strength of the monsoon from north to south (Risk and Sluka 2000). There is no agreement on the control processes which formed *faros*.

2.3.7.2 Reef Islands

Reef islands are the most conspicuous geomorphological features of modern atolls at sea level and they have formed during the last 3000 to 4000 years (Woodroffe 1992). In the Society and Tuamotu Islands, the low isles on atolls are principally or exclusively on the windward side of atolls (Guilcher 1988) whereas in atolls of the Maldives, they are located on the eastern and southeastern rims of atolls predominantly and are not apparently related to windward hydrodynamics. Woodroffe (1992) noted that reef island formation and the morphology of the adjacent reef flat are strongly affected by the occurrence of storms. He predicted that where storms are rare, reef island structure would be predominantly of sand whereas in stormy regions the structure would consist of boulder deposits and the modern reef flat would also display storm related depositional structures such as rubble ramparts. Andréfouët et al. (2001a) suggested strong relationships between exposure to swells and rim structure including reef islands on rim reefs.

2.3.7.3 Reef Lagoons and Infilling

Reef lagoons are diagnostic features in the study of reef morphology, which may help us infer the extent of inherited characteristics. Hopley (1983) suggested that reefs growing from the shallowest platforms will, assuming no temporal differences related to the establishment of a living veneer, have reached sea level earliest and are more likely to have the greatest lateral growth (as opposed to vertical growth), masking the underlying morphology. Reefs that have reached sea level long ago have extensive reef flats and also complex morphologies created by infilling lagoons.

Purdy and Bertram (1993) pointed out that modern atolls represent arrested stages of lagoon infilling caused by lowstands in Pleistocene. In stable sea level conditions accretion would be lateral and in rising sea level conditions accretion would be vertical. It was suggested that the end product of this type of carbonate deposition is not the Holocene morphology of emergent rims and central lagoons, but the development of flat-topped carbonate banks commonly seen in the geologic record.

Sediment generated from the windward reef margins is probably the main source of material that fills up atoll lagoons. Therefore the rate and pattern of atoll lagoon filling will depend on the type of coral community and the flux of materials generated from rim reefs. In the Maldives, many reefs have lagoons, (10-20 meters deep) derived from either Pleistocene solution or vertical growth of the rim in the Holocene, and being actively infilled today. Sediments generated from the reef front will pass over the atoll rim reef flat, fill up any lagoons present on the reef flat, and will spill over into the atoll lagoon. The spill over of sediments is seen dramatically in some Maldivian atolls where the sand flats extend well into the atoll lagoon. The morphology of modern reef lagoons is certainly affected by Holocene reef growth and cannot be explained only by Pleistocene solution depressions. Reef lagoons at various stages of infill are very prominent on atoll rim reefs in the Maldives.

2.4 Antecedent vs. modern environmental controls of atoll morphology

There is little dispute that glacial sea level variations and sub-aerially formed Pleistocene foundations beneath modern atolls have affected their Holocene morphology (Purdy 1974; Hopley 1983; Purdy and Bertram 1993). Reef lagoons and blue holes on modern atoll rim reefs are features that provide the strongest evidence to support the antecedent karst theory of reef formation. Perhaps the best of such karst morphology comes from *faros* (ring shaped reefs with a central lagoon) in the Indian Ocean. Purdy and Bertram (1993) used aerial photographs taken in 1965 of numerous *faros* in the Maldives to argue effectively for the sub-aerial erosion theory and karst morphology of modern reefs. While their argument was convincing, it is also noted that the lagoons of these *faros* are continuously being filled (perhaps some have already filled completely) by modern, windward reef-generated sediments, and that their morphology is being altered so much that the inherited morphologies will eventually disappear to be replaced completely by modern growth and accretion.

Stoddart (1971) reviewed the significance of environmental factors broadly defined in Indian Ocean reef morphology. He described the physical environment in terms of winds, storms, tides and rainfall, and stressed the need to distinguish modern reef growth as influenced by hydrodynamics from inherited features. Since most modern atolls have been at sea level for 4000-6000 years and the essential features of the climate and weather systems affecting them have also remained fairly stable for much if not all of that period, they are likely to show geomorphologic features that may be considered partially or wholly under the control of the existing environment. The reef structures resulting from growth during this period may or may not have disguised the antecedent relief depending on the thickness of accretion, matching of modern to past patterns of environment forcing and the extent of sub-aerial erosion of the antecedent platform. This really depends on the reef in question, its location, and its growth potential.

It is universally agreed that once reefs reach stable sea level, their morphology is strongly influenced by winds, waves and hydrodynamics. On atolls of the Maldives for example, where there was extensive reef accretion during the Holocene on antecedent platforms (Woodroffe 1992, Risk and Sluka 2000), and lateral reef growth has proceeded for 3-4000 years under the influence of the periodically reversing monsoon climate regime. Thus, the environment and history of reefs in the Indian Ocean more than those in any other location, (Stoddart 1971) lead us to expect those morphological features most indicative of lateral growth processes (reefs slopes, crests and lagoon sand flats) reflect the modern conditions of reef growth as influenced by hydrodynamic conditions. Stoddart (1969) considered atolls as geologic structures inheriting features from older reefs in the geologic past while being constantly modified environmentally by reef growth in the present. He noted the emphasis on surface features of coral reefs in early works in order to describe atolls (e.g. Darwin 1889; Dana 1890).

A widely debated morphological trait on atolls is the atoll lagoon. Darwin (1889) suggested that lagoons of some atolls are deeper due to greater subsidence, while Daly (1915) believed that the observed variation in depth was due to postglacial inhibition of reef growth. Purdy and Bertram (1993) suggested that increased rainfall permitted greater solution deepening of lagoons through sub aerial exposure during glaciations. Woodroffe (1992) speculated that contrasts in the morphology of atoll lagoons in the Maldives might be due to different factors controlling reef growth and sediment production during the Holocene. Only Purdy and Bertram (1993) had related lagoon characteristics statistically to rainfall patterns ($r=0.91$), while others have only speculated on possible causes. Thus, the critical question of the relative importance of antecedent vs. recent environmental control of atoll lagoon morphology remains wide open.

It is suggested that algal ridges on atoll rims are important constructional features on Pacific and Atlantic trade wind belt reefs (e.g. Marshalls and Tuamotus and Belize Barrier Reef) but of less importance in the Indian Ocean (Stoddart 1969; Woodroffe 1992). These differences imply that atoll morphology is strongly affected by the modern physical environment.

Examination of the internal framework of Atlantic reefs show that reefs that have *kept up* or *caught up* with rising sea levels during the Holocene transgression consisted of fast growing *Acropora* species (Neumann and MacIntyre 1985). Camoin et al. (1997) found that branching coral facies systematically predominated over the coral head facies throughout the Holocene reef sequences, in Indian Ocean reefs, suggesting that *Acropora* is the main frame builder among branching forms. Risk and Sluka (2000) made similar conclusions for reefs of the Maldives where *Acropora* was the dominant branching form on reef slopes. This is also supported by the fact that dredging projects in the Maldives consistently yield large quantities of loose *Acropora* rubble with sediments. Circumstantial evidence therefore indicates that fast growing *Acropora* species may play a central role in the vertical and lateral growth of atoll type reefs and infilling of reef lagoons under moderate weather conditions. We also know that the Pacific is usually stormier than the Indian Ocean (Wiens 1965; Maldives Metrological Data). The difference in storminess maybe the reason why Indian Ocean atolls have a loose, less well-cemented framework than Pacific reefs (Woodroffe 1992). Storminess of the Pacific have generated more dramatic reef morphologies on its atolls than those in the moderate conditions in the Indian Ocean (Battistini et al. 1975).

The geomorphology of Indian Ocean atolls and reefs had been described in great detail by some early studies (Gardiner 1902; Agassiz 1902; Sewell 1932). These early, qualitative studies provided interpretations of patterns and controls on reef growth based on visual surveys of a few reefs extended to the archipelago from the inspection of navigation charts. More recent subsurface geological studies of the Chagos-Laccadives ridge (Aubert and Droxler 1992) demonstrate that the gross arrangement of the atolls reflects the topography of the highest peaks of a carbonate platform which has been radiometrically dated to 57 million years, itself resting on volcanic peaks rising from the depths of the Indian Ocean (Duncan and Hargraves 1990). Thus, at the larger, longer scales of atolls (i.e., 10's of km and millions of years) and the entire archipelago, antecedent control on the geomorphology is incontrovertible. However, the

geomorphology of individual reefs within atolls clearly expresses modern features in their shape and zonation.

Morphological differences between Pacific and Indian Ocean atolls are many. *Hoā* (Stoddart and Fosberg 1994), conglomerate platform (Woodroffe and McLean 1994) and algal ridges are examples (Table 2.1).

	Indian Ocean	Pacific Ocean	Atlantic Ocean
Atoll structure	<ul style="list-style-type: none"> * Asymmetric morphologies * Proportion of land on the rim is less? * Vegetated land (islands) occurs on both the leeward reefs of the atolls as well as windward reefs. * Atoll rim less continuous * Lagoon depth approx from 50 - 80 meters 	<ul style="list-style-type: none"> * Asymmetric morphologies * Proportion of land on rim is high * Vegetated land (islands) are located frequently on the windward sectors of the atoll rim * Atoll rim more continuous * Lagoon depth range from 30 - 90 meters 	<ul style="list-style-type: none"> * Asymmetric morphologies * No significant land on the rims * Lagoon depth 5 - 10 meters
Reef lagoons	* Very common	* Rare	* Blue holes
Reef Islands	<ul style="list-style-type: none"> * Located asymmetrically around the rim * Islands composed of loose fine sand and rubble derived from coral 	<ul style="list-style-type: none"> * Located asymmetrically around the rim * Islands composed of coral shingle, and well cemented boulder conglomerates 	<ul style="list-style-type: none"> * Located asymmetrically around the rim
Reef slope	* Windward spur and grooves	* Windward spur and grooves	* Windward spur and grooves
Algal ridge	* Absent or poorly developed	* Present on windward margin	* Present on windward margin
Reef flat	<ul style="list-style-type: none"> * Rubble deposits and boulders rare * Many submerged * Transverse stripes common * Simple surface morphology 	<ul style="list-style-type: none"> * Rubble deposits and boulders common * Slightly emerged and terraced * Transverse stripes uncommon * Complex surface morphology 	* Rubble deposits

Table 2.1. Morphological variation between atolls of different biogeographic regions.

Pacific atolls are characterized by the presence of large storm deposits, higher amounts of coral rubble, tidally exposed reefs with crustose coralline algae, and a windward spur and groove zone (Glynn et al. 1996). One major difference between atolls of Pacific and Indian Ocean appears to be the lack of storm deposits on Indian Ocean atolls, and rim reef continuity of atolls in the Pacific (Stoddart 1969; Woodroffe 1992). Such statements have been made based on qualitative observations in most instances, and there are no quantitative data available to prove the putative differences between Pacific and Indian Ocean atolls.

An evaluation of reef morphology in Pacific and Indian Ocean atolls leads us to believe that the variation in their morphologies are strongly related to both geological and environmental phenomena (Guilcher 1988). Large areas of atoll rims in the Indian Ocean are submerged or at sea level (Stoddart 1971; Dumbraveanu and Sheppard 1999) whereas many Pacific atolls appear to be slightly elevated (Guilcher 1988). It has been suggested that the *catch up* strategy of reef growth has been extremely predominant in both Pacific and Indian Ocean atolls (Guilcher 1988; Woodroffe 1992). It is quite possible that some of the reefs of the atolls in the Maldives have still not reached sea level and are actively growing vertically to reach sea level (pers obser.). Pacific atolls show more relief and topographic complexity as well as morphological diversity than Indian Ocean reefs. Pacific atolls also appear to have been infilled more extensively than Indian Ocean atolls. This scenario may have been affected by tectonic activity causing slight elevations of atolls in the Pacific in the Holocene or Pleistocene and perhaps more subsidence in the Indian Ocean (Woodroffe and McLean 1998). One explanation for the morphological differences between Pacific and Indian Ocean atolls (e.g. lack of rim reefs with lagoons in the Pacific) is that Pacific atolls perhaps reached sea level earlier than Indian Ocean atolls. The other explanation would be the differences in environmental setting between the two regions. Comparative studies of Indian and Pacific atoll morphology maybe the key to understanding atoll type reef formation during the last 10,000 years.

2.5 A new model of atoll reef morphology: Research premise

There seems to be little doubt that subsidence, sea level changes, subaerial erosion and environmental factors all have contributed significantly to the development of coral reefs in the earth's geological past (Stoddart 1973). Understanding how much each of these factors contributed to the morphology of any modern reef is a complex issue demanding interdisciplinary approaches. Geologists usually study the reef framework in the context of paleo-climate, whereas biologists strive to understand the living, surficial veneer of the reef in the context of the prevailing physical environment. The latter approach provides the key to understanding modern day reef growth, but it may not explain modern reef morphology if the antecedent pattern of growth differed from the present, or if subaerial erosion erased or modified that pattern.

It appears that the uncritical use of surficial gross morphology of atolls (atolls, *faros*, microatolls) to explain modern reef formation (e.g. Darwin 1889, Daly 1915, Stoddart 1965, MacNeil 1954) has been a real weakness in efforts to explain the processes controlling atoll formation. Historically, coral reef theory was based only on morphologies interpreted from crude navigational charts and on extensive soundings conducted on coral reef areas. In order to understand how modern reefs develop, and to predict the patterns of reef growth in space and time, we have to quantify the processes which control the development of reefs during the Holocene, and separate these from the processes that resulted in the antecedent morphology. There is a clear need to devise surveying and quantifying techniques for whole reefs at regional scales, and to relate them to physical forces at similar scales. Most early work and even recent studies have been carried out at the scale of individual reefs, or smaller sub units, which are unsuitable to understand growth morphology and separate it from erosional morphology in the context of ocean climate. It is also necessary to implement studies that bridge the gap between the structural geology and the growth biology of coral reefs using innovative

multi-scale measurement techniques and analytical approaches (e.g. Naseer and Hatcher 2001; Andréfouët et al. 2001a). The results will improve our understanding of the fundamental processes controlling the patterns of reef growth, resulting morphologies and susceptibility to environmental change.

Physical factors affecting reef morphology across biogeographic regions may be compared by the examination of the prevalent weather patterns in the respective regions. Two prominent weather systems are noted in coral reef areas: trade winds and monsoons. Trade winds create a temporally constant spatial pattern of winds and waves (although the magnitude varies), whereas monsoons create seasonally reversing patterns. Reefs in trade wind areas of the world experience unidirectional wind continuously pounding on their windward reefs. The resulting morphologies are dramatic (Battistini et al. 1975). Most of the 425 atolls distributed in the world's oceans are located in the tropics, and may be divided into three major biogeographic divisions: Pacific atolls, Indian Ocean Atolls and Atlantic atolls. All atolls in both the Pacific and Atlantic are affected by unidirectional trade winds but the northern Indian Ocean atolls are affected by seasonally reversing monsoons. The contrasting reef geomorphology of these groups of atolls, which emerge in relation to their respective climate regimes, has not been investigated yet. Quantitative comparisons of reefs from unidirectional trade wind and oscillating monsoon areas using satellite imagery provide powerful analytical tools for quantifying the role of hydrodynamic forcing of atoll and reef structure. The atolls of the Maldives are the only coral reef group in the world that can provide gradients in physical forcing across groups of reefs with uniform geological history and in sufficient numbers to rigorously test hypotheses relating to physical forcing and reef growth.

The most promising tools currently available for such studies are remote sensing and geostatistical analysis. Morphological variation and pattern arising from gradients of physical forcing (e.g. wind-waves and swells) impinging on atolls can be quantified using satellite imagery. Satellite images (e.g. Landsat 7 ETM+) appear to be the only viable option for mapping reefs at the nested scales of entire atolls, banks, ridges and provinces. Satellite sensors have been used by a limited number of studies to map reef

geomorphology (Bour 1988, Kuchler et al. 1986, Kuchler et al. 1988, Ahmad and Neil 1994). Andréfouët et al. (2001a)'s work on atoll rim typology represents one of the first to develop quantitative geomorphological classification of atolls using remote sensing methods. They mapped atoll rim morphology using satellite images and showed that rim morphology and hydrodynamics were related to lagoon flushing, but also implied that such methods can be used to map reef morphology across the scale of atolls and to compare and correlate morphology to physical forcing. Zonation on Heron reef was mapped by Ahmad and Neil (1994) using Landsat TM data, which generated thirteen reef classes. Concentric patterns of ecological and geomorphic zonation were identified on Heron reef which included the raised algal rim, rubble zone, coral zone and sandy zones.

Most quantification of atoll morphology use data derived from navigational charts, and in a few cases aerial photos have been used (Wiens 1965; Woodroffe 1992; Purdy and Bertram 1993). Woodroffe (1992) made some useful quantitative measurements of atolls in the Maldives that could be used in a matrix analysis of atoll and reef morphology. He highlighted the north-south variations of certain morphological characteristics such as depth of atolls, patch reef diversity within atoll lagoons, and atoll rim continuity. The problem with such measurements is that they are of variable accuracy, spatially inconsistent, and collected from dated navigational charts. While the latest admiralty charts have utilized satellite imagery for accuracy, the scale at which the charts are available (1:300,000) is insufficient to transcribe morphological features accurately. To quantify lagoon and reef morphology as a function of atoll hydrodynamics, large numbers of replicate measurements of sample atolls, must be made with consistent accuracy. Satellite observations are the only means of doing this in a cost effective manner.

Stoddart (1969) rightly pointed out that much confusion in coral reef morphological studies has resulted from attempts to explain inherited form by present processes and modern forms by past processes (a temporal-scaling problem), and by attempts to explain first order reef features such as atolls by observations of coral colonies and small reef segments (an up-scaling problem). We know that modern reefs form veneers on older structures, and we know the thickness and ages of the veneers in most cases. Little is

known, however, of the patterns of lateral growth of reefs during the Holocene. Observed differences in the surface features of reefs and how much modern growth has been successful in masking older surfaces depend on the vigor of reef growth in the modern day. Quantifying the "growth potential" of the reef in terms of windward reef slopes and correlating these to depths of reef lagoons and their physical dimensions may provide clues to interpret environmentally controlled morphologies of reefs.

Hatcher et al. (1987) outlined the importance of interdisciplinary research on coral reefs and described techniques that can be used in process related research. They recognize the problems that arise as a result of scale mis-matches and logistic limitation related to up-scaling from lower levels of organization (e.g. organisms and communities) to entire reef ecosystems. The availability of satellite imagery at fine spectral and spatial resolution has the potential to solve these problems of scale. The focus of research needs to shift from deductive approaches based on theoretical models to inductive approaches based on rigorous analysis of empirical measurements of reef structure and function.

Understanding of coral reef growth in the future will surely depend less on the application of general models to individual reefs (as done historically), and more on quantitative modeling of processes now widely known, and rigorous testing of these models using statistical analysis of multiple reefs. Although many studies have convincingly related hydrodynamic conditions to patterns of lateral reef growth (expressed as surface morphology), most of the investigations were done at spatial scales far too small to be useful for interpreting the roles of climate process and phenomena operating in biogeographical reef provinces. Quantitative data at the scale of entire atolls need to be rigorously analyzed to investigate environmental processes on coral reefs and to make clear distinctions between geologically inherited (antecedent) morphology and environmentally controlled reef growth on modern day reefs.

Chapter 3

3 ASSESSING THE INTEGRATED GROWTH RESPONSE OF CORAL REEFS TO MONSOON FORCING

3.1 Introduction

The growth and formation of coral reefs are complex phenomena resulting from the interaction of a variety of biological, physical, chemical and geological factors (Fagerstrom 1987). Coral reef structures reflect control by physical processes. In particular, wave direction and power (functions of near and far-field wind stress) determine patterns of reef productivity and shape reef morphology as well as community structure (e.g. Munk and Sargent 1954; Hopley 1982; Roberts et al. 1992). Lateral reef growth in shallow water reef systems is characterized by sequences of geomorphologic zones parallel to the contours of the seaward reef slope or the shore of the adjacent land where present (Fagerstrom 1987). Spatial variation in hydrodynamic forcing exerts the major control over shallow reef zonation (Bradbury and Young 1981), which is better developed for windward sides of oceanic atolls. It is postulated that the peripheral morphology of atoll reefs expresses the integral of lateral growth, which can be inferred by quantifying their zonation patterns.

Several geomorphological classifications have been erected for Indo-Pacific reefs (Battistini et al. 1975; Hopley 1982; Kuchler 1986; Holthus and Maragos 1995). They are based on detailed descriptions of relatively small numbers of "characteristic" reef types, extended to large reef tracts by inspection and association rather than by quantitative analysis. With the availability of high quality remote sensing, a few attempts have been made to quantify zonation at the scale of entire reefs (e.g. Andréfouët et al. 2001a), but the number of reefs mapped has been too small to allow multivariate analytical methods.

The coral reefs of the Maldives (northern Indian Ocean) are ideal for developing the morphometric analytical approach because of their location, extent and the marked asymmetry of their arrangement on the atoll rims. The reefs on the ocean-facing (east and west) rims of the double chain of atolls are broader and more continuous than those on the rims facing the Maldives Inner Sea. This pattern of reef development has attracted scientific attention for a long time (Darwin 1889; Gardiner 1902; Agassiz 1903), but no convincing explanation has been offered. In the research introduced here, quantitative analysis of controls on reef growth is attempted by mapping morphometric asymmetries of the Maldives using satellite imagery, and relating them statistically to climatic-oceanographic forcing.

Monsoons are the dominant weather systems in the Indian Ocean and have blown consistently throughout the Quaternary and probably earlier (Haq 1985). In contrast to predominantly unidirectional trade wind regimes in the Pacific where most atolls occur, the monsoons reverse seasonally from east to west every year (Webster 1981; Fig 3.1).

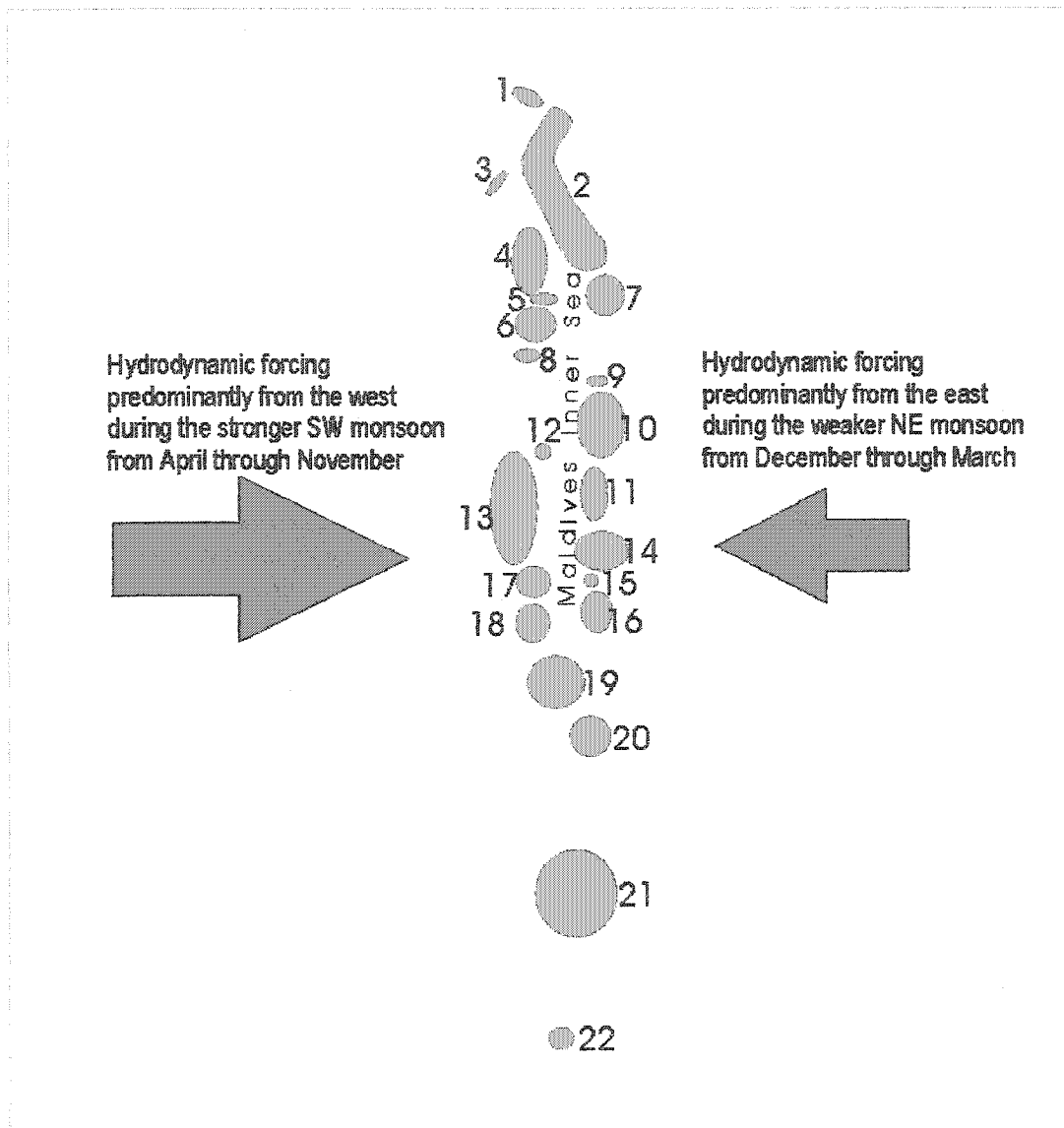


Figure 3.1 Schematic diagram of the Maldivian atolls (1-22) to illustrate the monsoon reversal and characteristics of the NE and SW monsoon

The research presented in this thesis aims to test the hypothesis that monsoon-driven environmental forcing (i.e., swell and wind-wave fields) interacts with antecedent reef platform shape to produce characteristic and predictable reef morphologies and growth configurations in the Holocene. Well-defined gradients in monsoon forcing and antecedent platform structure across and along the north-south axis of the archipelago provide a sampling matrix suitable for multivariate analysis of a set of morphometrics derived from remotely sensed images of hundreds of “replicate” reefs spread along these gradients. The objective is to characterize individual reef components of the Maldivian atolls spatially, statistically determine empirical relationships among patterns of geomorphology and environmental forcing, and then use these relationships to predict patterns of reef growth under varying environmental conditions. This chapter outlines the hypothesis and presents the initial findings and the methods of morphometric analysis which is further expanded and developed in subsequent chapters.

3.2 Study Area

The atolls of the Maldives lie in the Indian Ocean ($00^{\circ} 45'S$ to $7^{\circ} 06'N$ latitude and $72^{\circ} 33'E$ to $73^{\circ} 47'E$ Longitude) about 480 km south west of India (Fig 2.2). The length of the archipelago is about 900 km north to south and 130 km east to west. It comprises 22 atolls consisting of hundreds of individual reefs and approximately 1200 low reef islands (Table 3.1).

The gross structure is a double chain of atolls tapering to lines of single atolls towards the north and south (Fig 3.2). This peculiar arrangement results in a somewhat sheltered ocean area in the central part of the archipelago (the Maldives Inner Sea; Fig 3.2). Depths in the Maldives Inner Sea ranges from 200 to 600m and there are no near-surface reefs within the sea. Just outside the oceanward rims of atolls on the west and east of the archipelago water depths are 1000's of meters.

#	ATOLL	AREA (km ²)	# of REEFS (Approx)	# of RIM REEFS (Approx)	# of REEF ISLANDS (Approx)	LAGOON DEPTH (Max. m)
1	Ihavandhippolhu Atoll	286	17	9	26	49
2	Tiladhunmathi- Miladhunmadulu	3850	151	72	177	58
3	Makunudhu Atoll	139	3	3	4	31
	Double Chain of atolls					
4	North Maalhosmadulu Atoll	1168	130	41	88	49
5	Middle Maalhosmadulu Atoll	135	15	14	15	46
6	South Maalhosmadulu Atoll	940	75	30	53	55
7	Faadhippolhu Atoll	699	46	23	67	55
8	Goidhu Atoll	105	1	1	8	42
9	Gaa Faru Atoll	82	2	2	1	40
10	North Male Atoll	1565	233	39	55	69
11	South Male Atoll	535	153	18	34	58
12	Rasdhu Atoll	59	4	3	5	37
13	Ari Atoll	2252	196	49	76	69
14	Felidhu Atoll	1021	188	39	18	68
15	Vattaru Atoll	43	1	1	1	35
16	Mulaku Atoll	956	111	22	48	73
17	North Nilandhe Atoll	594	84	17	16	66
18	South Nilandhe Atoll	739	85	15	63	68
	Single chain of Atolls:					
19	Kolhumadulu Atoll	1617	100	11	60	79
20	Hadhdhunmathi Atoll	881	48	4	83	73
21	Huvadhu Atoll	3152	180	33	278	82
22	Addu Atoll	158	7	4	50	79

Table 3.1 Geographical characteristics of the 22 atolls of the Maldives (modified from Purdy and Bertram 1993). Note: Numbers of reefs and reef islands were estimated from 1993 Navigation Charts.

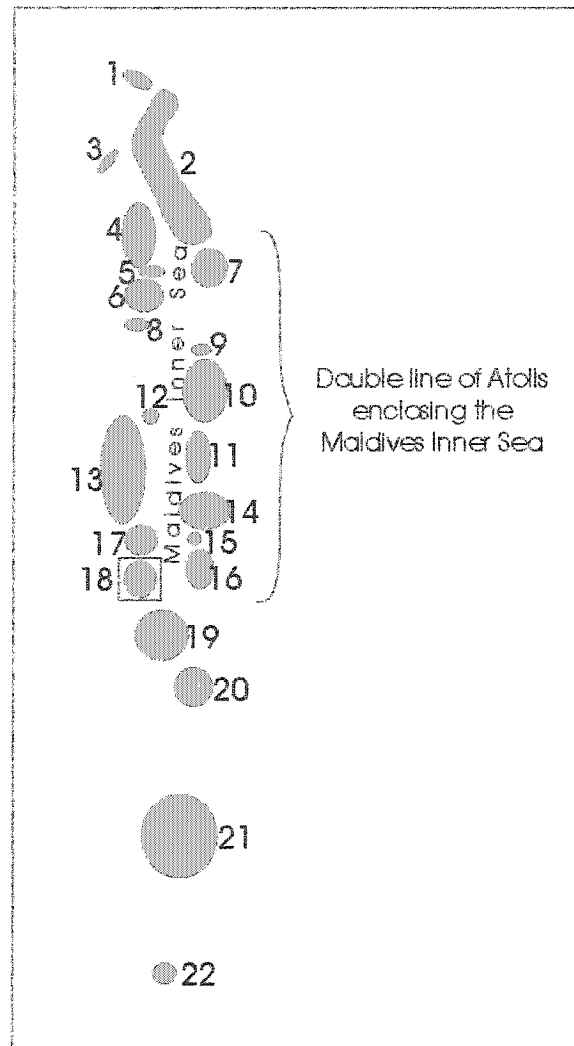


Figure 3.2 Schematic diagram to illustrate the gross arrangement of the Maldives' 22 atolls (1-22) displaying the single and double line of atolls and the sheltered Maldives Inner Sea within the double chain of atolls.

The Maldivian atolls and associated reefs vary tremendously in their formation, size and physical setting (Wells 1988; Table 3.1). Some atolls are relatively open systems (e.g. North Malé Atoll; Fig. 3.3) with numerous discontinuous rim reefs, patch reefs and knolls around the atoll rims and in the atoll lagoon. Others are almost closed systems (e.g. Kolhumadulu Atoll; Fig 3.4) with a more continuous rim and few to sometimes no reefs in the lagoon. The depths of atoll lagoons range from 30 to 80 meters (Table 3.1).

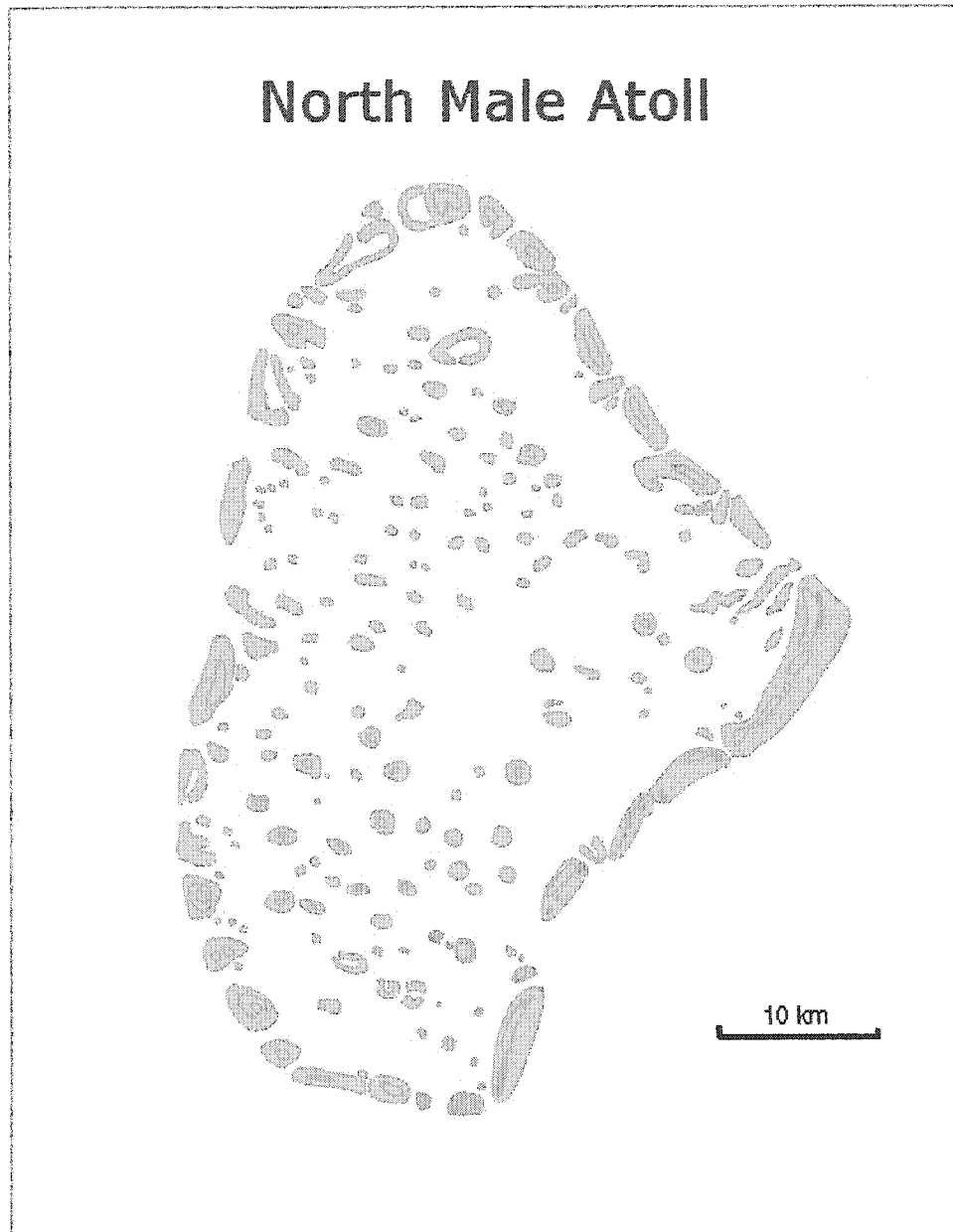


Figure 3.3 North Male atoll is an example of a relatively “open atoll” with numerous deep passes along its rim and many lagoon patch reefs in its center.

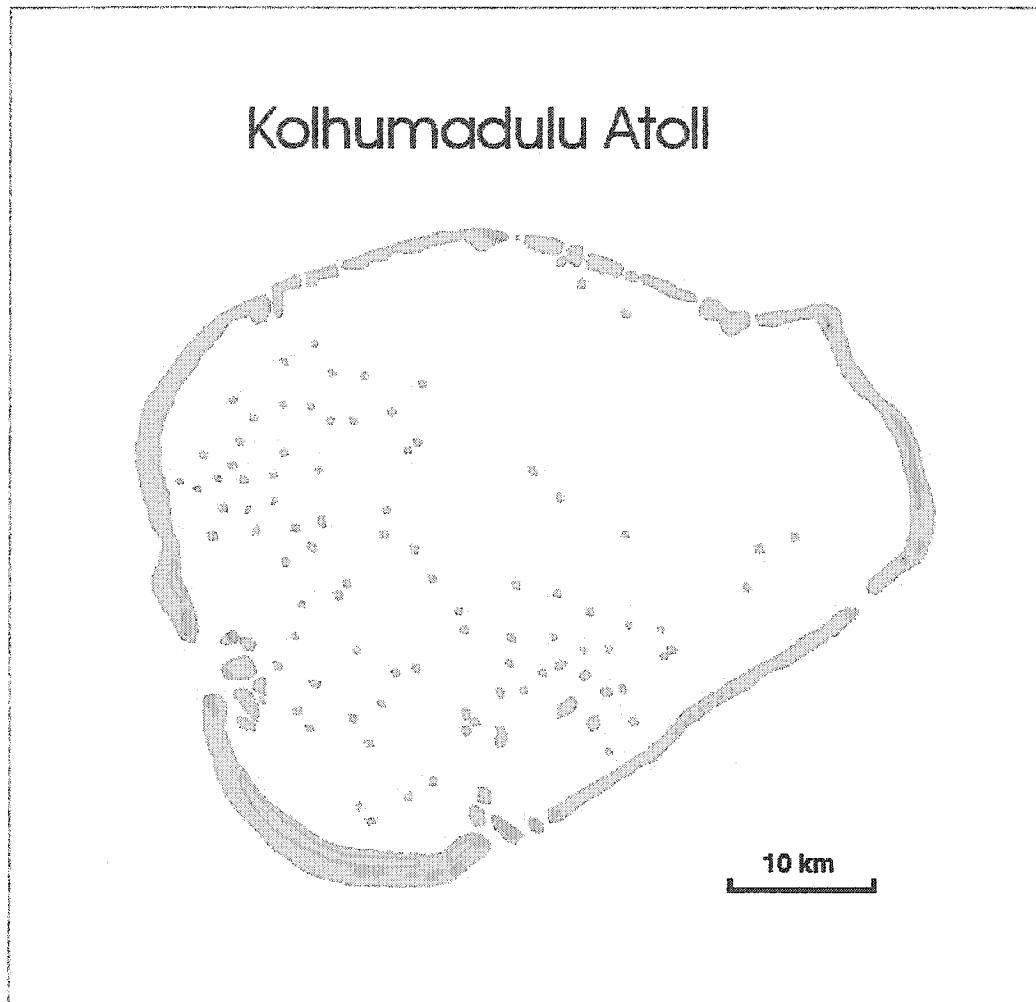


Figure 3.4 Kolhumadulu Atoll in the south of the Maldives is good model of a less open atoll. It has few deep passes on its rim and rim reefs are thinner and elongated. Few knolls and patch reefs are found in its central lagoon.

The reversing pattern of the monsoons imposes an asymmetry of physical forcing across the east-west axis of the archipelago (Fig 3.1). The stronger SW monsoon blows predominantly from the western sectors during April through November, producing continuous, high-amplitude waves and currents on the western ocean-facing reefs of the Maldives. The weaker, shorter NE monsoon blows less consistently from the eastern sectors during the rest of the year. Consequently, exposure to the dominant hydrodynamic forcing shifts onto reefs along the eastern margins of the Maldives' atolls. Reefs facing the Maldives Inner Sea and those within atoll lagoons are also exposed to these asymmetries of forcing, but at intensities variably reduced by the fetch and degree of shelter offered by reefs on the ocean-facing rims of the atolls.

3.3 Materials and methods

Based on the geographic setting (Figs 3.1 and 3.2) and monsoon climatology of the Maldives (Fig 3.5), it is hypothesized that reefs growing along the rims of the atolls facing the *western Indian Ocean margin*, *eastern Indian Ocean margin*, and the *Maldives Inner Sea* have predictable reef morphologies, which can be quantified by morphometrics derived from satellite imagery at 30-meter spatial resolution, and statistically related to climatic and oceanographic data at similar spatial scales.

Monthly wind direction and frequency in Central Maldives

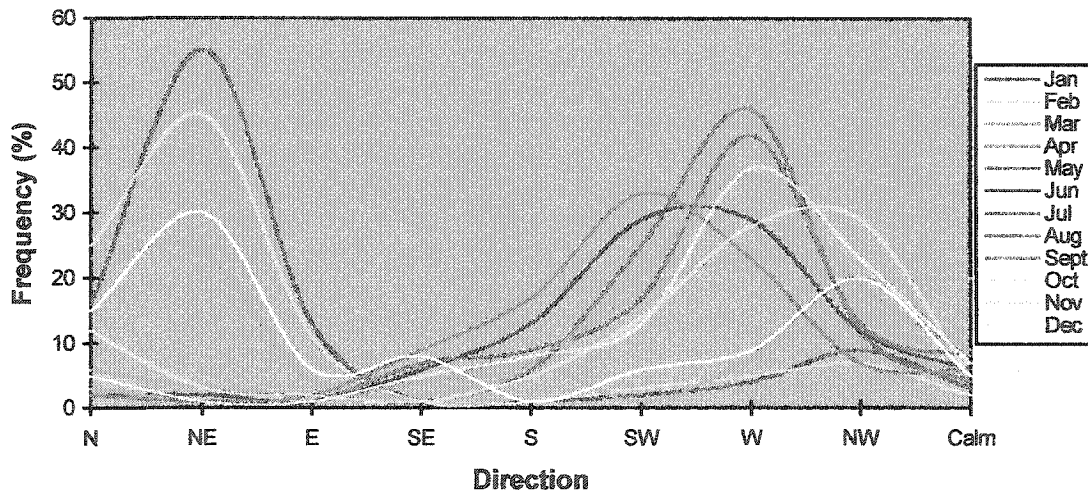


Figure 3.5 Wind direction frequencies in central Maldives over 20 years to show the consistency and regularity of the Indian Ocean monsoon winds affecting reefs of the Maldives. Direction indicates where the dominant winds are from (i.e., meteorological wind direction).

3.3.1 Satellite image analysis

Reef components of atoll rims and lagoons were sampled using images produced from the latest Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite

(<http://landsat.gsfc.nasa.gov/>). (Fig 3.6)

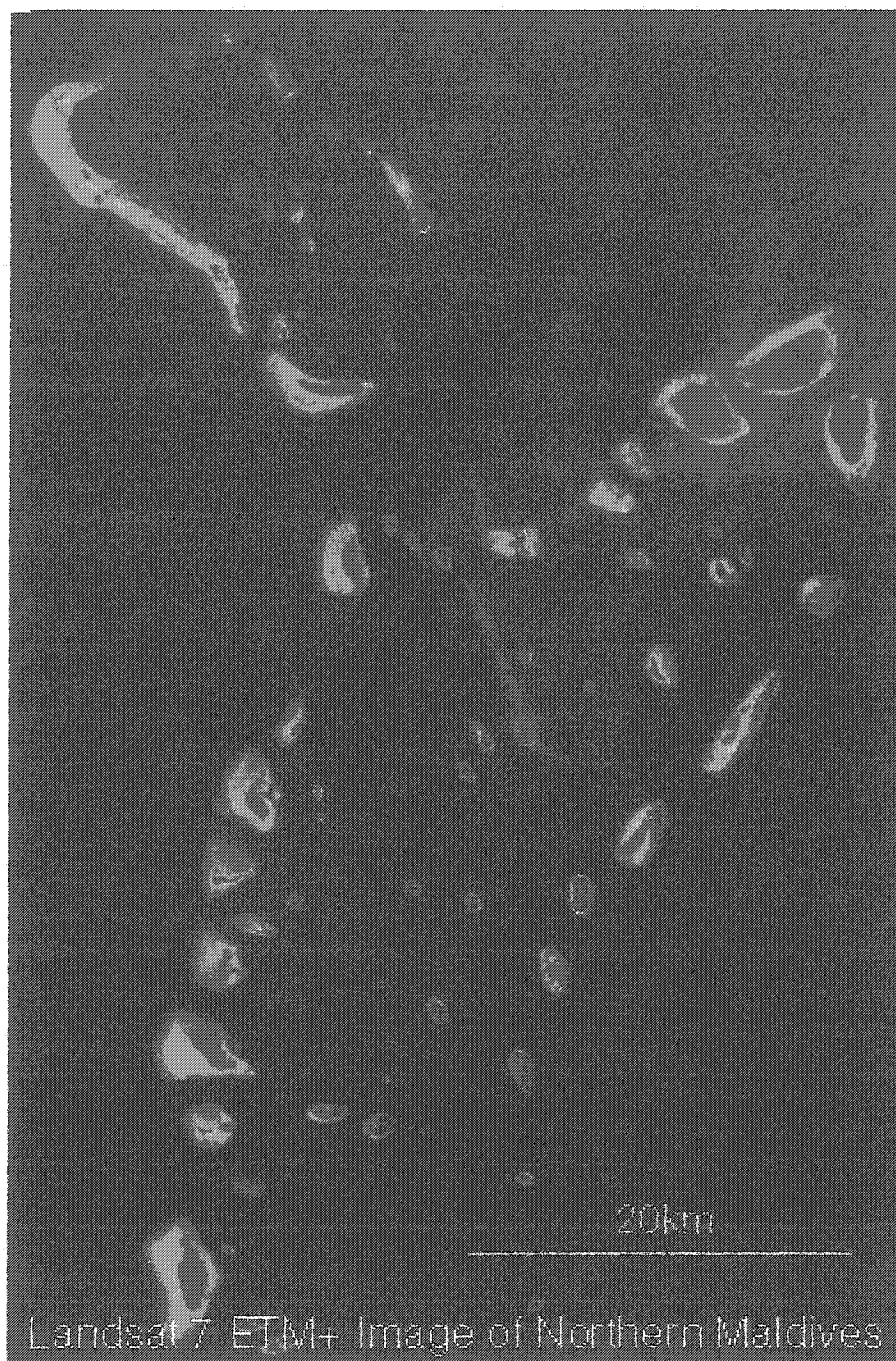


Figure 3.6 Landsat ETM+ Composite image of the northern Maldives. The top part of the image is a single atoll and the bottom half shows half of the largest atoll in the Maldives.

Two radiometrically and geometrically corrected images of the northern atolls of the Maldives (path 146 row 55 and path 146 row 56 captured on Nov 7th 1999 and May 1st 2000 respectively) were obtained from the US Geological Survey, EROS Data Centre (<http://landsat7.usgs.gov/>). These two images included four of the 22 atolls of the Maldives. Image analysis was done with PCI GEOMATICA Software from PCI Geomatics (<http://www.pcigeomatics.com/>). ETM+ satellite data were supplied in 8 spectral channels at 30x30m pixels, four channels of which (Band 1- Band 4) were used to classify the images (Table 3.2). Based on local knowledge of the study area, supervised classifications were performed (using the maximum likelihood classifier in PCI) on image subsets covering each of four atolls to generate several (5-7) morphological categories: reef slope, the wave-breaking reef crest, reef flat, back-reef sand flats, deep and shallow reef lagoons and reef islands. A total of 300 (approx) individual reefs were thus classified. As more Landsat 7 ETM+ scenes become available, this research aims to ultimately map and classify every single coral reef within all 22 atolls of the Maldives. The methods of image processing and, quantifying reef geomorphology are described in detail in Chapter 4.

Band	Spectral Range (μm)	Reef Islands	Sand Flats	Reef Lagoon	Reef Crest	Reef Slope	Shallow Lagoon	Deep Ocean
1 (blue)	0.450 to 0.515	104.28	194.27	118.04	116.29	92.95	162.44	83.52
2 (green)	0.525 to 0.605	86.73	167.55	66.24	93.10	55.55	126.35	45.08
3 (red)	0.630 to 0.690	76.36	101.65	29.70	64.29	31.54	54.84	32.88
4 (NIR)	0.750 to 0.900	143.72	28.10	15.56	17.76	16.40	15.80	18.64

Table 3.2 Landsat ETM+ Sensor characteristics as applied to the classification of reef morphology in the Maldives showing the mean DN values of the features classified from the images.

3.3.2 Reef Morphometrics

A basic series of morphometrics were determined for each reef in the classified images using the distance and area measuring tools in PCI-ImageWorks (Table 3.3). Not all

zones occurred or were measurable in all reefs sampled, and so the sample sizes for the different zones are unequal (n ranges from 15 to 50).

MORPHOMETRIC	UNITS
Atoll-scale metrics:	
* Atoll surface area	m ²
* Rim perimeter	m
* Number of reefs on atoll rim	-
* Number of reefs on atoll lagoon	-
* Number of deep channels on rim	m
* Mean width of deep channel	m
* Lagoon area	m ²
Reef-scale metrics:	
* Reef surface area	m ²
* E-W and N-S width of reefs	m
* Reef perimeter	m
* Outer slope width and area	m and m ²
* Crest width and area	m and m ²
* Outer flat width and area	m and m ²
* Sand flat area	m ²
* Lagoon area	m ²
* Reef island area	m ²

Table 3.3 Morphometrics selected to quantify the Holocene growth structures of 123 reefs in the northern Maldives.

From the basic morphometrics of each reef, ratios are derived to capture critical aspects of the geomorphology, growth patterns and causal mechanisms. For example, the aspect ratio of reef slope to flat area reflects the potential for lateral accretion; the exchange index of lagoon volume to channel area reflects the flushing rate of the reef lagoon. Ratios enable us to make analytical comparisons among reefs. Dimensionless ratios are scale-independent, allowing reefs of different sizes to be used in multivariate analyses of shape and function (Reyment et al. 1984; Hatcher et al. 1987).

3.3.3 Environmental Variables

Regional climatological and oceanographic data on sea surface temperature, salinity, dissolved oxygen and inorganic nutrients, and chlorophyll have also been obtained at one-degree scale from the 1998 World Ocean Atlas CD-ROM (National Oceanographic Data Center – <http://www.nodc.noaa.gov/>). Spatial variation in forcing may be derived from these environmental data at scales comparable to those ranging from individual reefs to the entire Maldives archipelago. Spatial correlations of these patterns with reef geomorphology may be used to infer patterns of reef growth during the Holocene. In this chapter, focus is on the asymmetrical pattern of monsoon-forced gravity waves that impinge on reefs facing the open ocean and the Maldives Inner Sea.

Meteorological data relevant to monsoon forcing (i.e., air temperature, rainfall, hours of bright sunshine, day length and wind velocity and direction) were obtained for the North, Central and Southern region of the Maldives dating from 1945 to present (Maldives Dept. of Meteorology). Much of this data consisted of monthly means except for the northern station for which daily means were available. The 1992 daily mean wind velocities recorded in the north Meteorological station were used here for preliminary comparisons and, to explore the climatological relationships with reef growth. The wind data were input to the nomograms of Bretschneider (1965) to estimate the significant wave heights impinging on the reefs facing the Maldives Inner Sea (fetch \approx 25km), and integrated over

each of the two monsoon seasons to calculate the total wave energy in kWh^{-1} per m of reef perimeter. The wave energy impinging on the ocean-facing reefs was estimated directly from long-term observations of significant wave height in the north Indian Ocean under both monsoons (Bigelow and Edmondson 1947). Details of wave energy and wave power calculations using long-term climatological data are presented in Chapter 5.

3.4 Results

Reef features in as much as 20-30 m (based on ground verification of Navigational charts) water depth were apparent in suitably classified Landsat 7 ETM+ images at 30-meter resolution, allowing accurate mapping of the nominated reef zones in the 123 reefs analyzed (Fig 3.7). The average and overall accuracies of the classification based on Maximum Likelihood Statistics was 92.00 % (KAPPA coefficient = 0.9). Ratioed spectral bands (band1/ band 2; and band 1/ band 3) had the greatest power to separate different reef zones (Fig 3.8). The average Separability was 1.95; maximum 2.0; and minimum 1.5 for the reef slope and reef lagoon signature pair. Ordinal values in the confusion matrix ranged from 88.32 to 97.35, with the maximum cross-class value of 3.27 (sand flat vs. shallow lagoon). The spectral separation of the classes is shown in Fig 3.8.

The classified images clearly resolved the topographic complexity of the floor of the atolls, revealing here-to-for undescribed connections between adjacent reefs, and lagoon features unmapped on the best available charts (British Admiralty 1993 @ 1:300,000 scale).

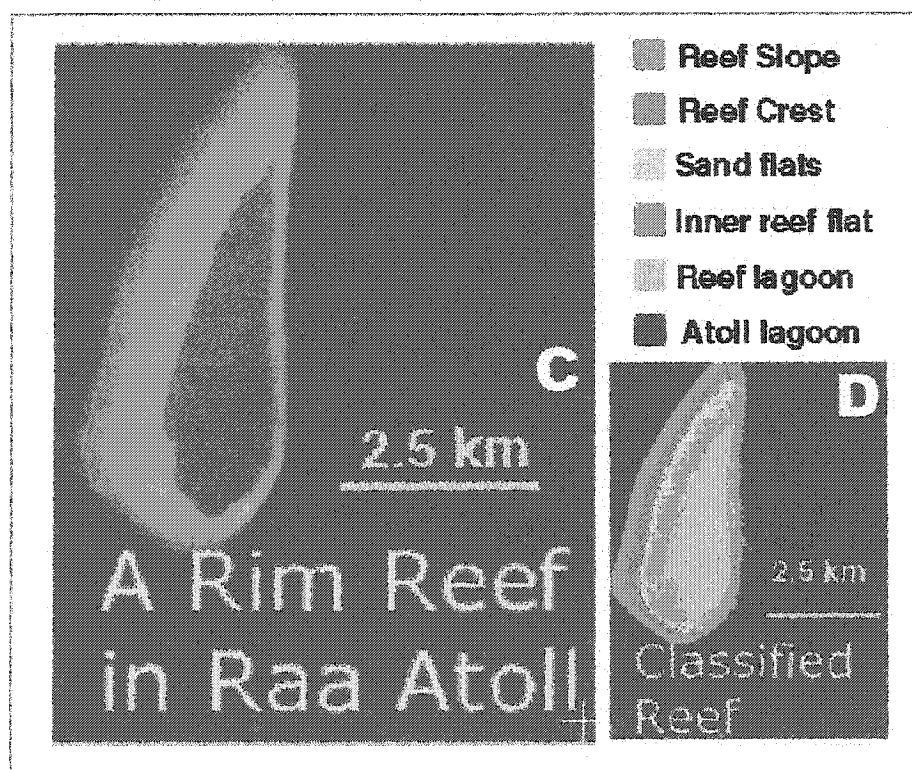
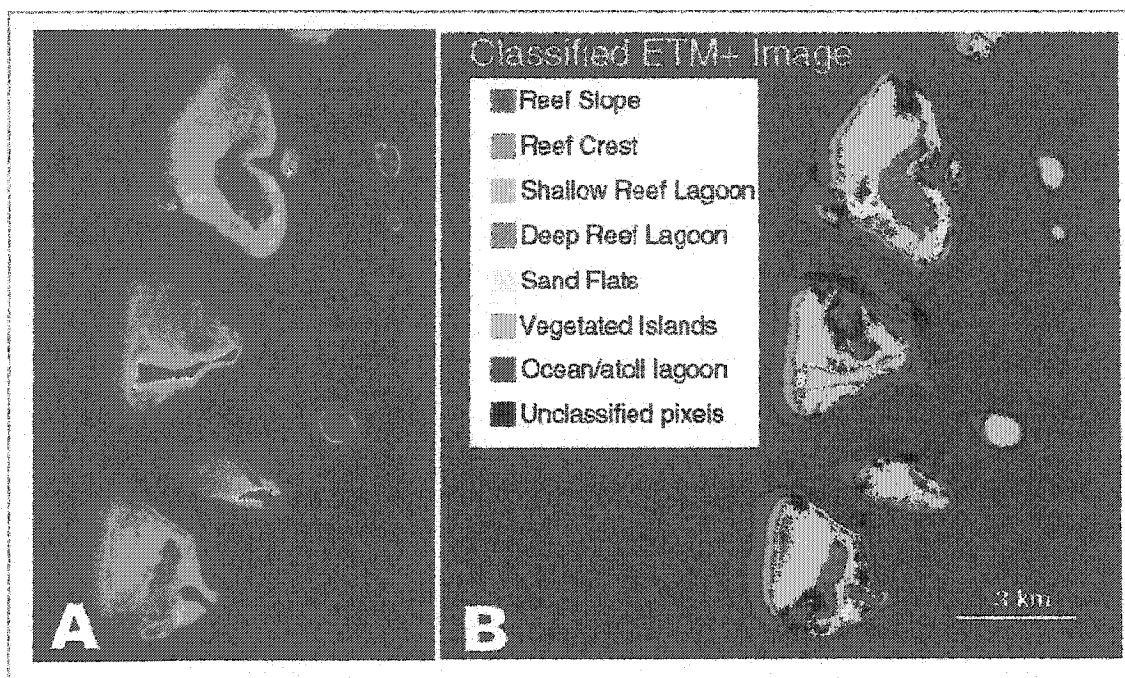


Figure 3.7 Parts of classified ETM+ imagery of reefs from Northern atolls of the Maldives. (A = Composite image, B = Same image classified, C = Composite rim reef, D = Same reef classified).

Reefs on the eastern and western atoll rims facing the ocean and the Maldives Inner Sea exhibit very different morphologies of reef slopes and flats. Reef slopes facing the western ocean are 1.5 times wider than those facing the eastern ocean, and 2.1 to 2.5 times wider than those facing the Maldives Inner Sea. The corresponding ratios for the reef crest widths show the same pattern, but the values are considerably (up to 5-times) higher. The west-east differences in the morphology of reef margins facing the Maldives Inner Sea are not as large or consistent as for those facing the open ocean. The mean width of the western-facing reef crests is about 1.5 times that of the eastern-facing crests on the Inner Sea, but the reef slopes on the Inner Sea do not differ significantly in width. Notably, the crests of reefs facing the eastern ocean (NE monsoon with unlimited fetch) are only half as wide as those facing the narrow Inner Sea, but exposed to the stronger SW monsoon. The mean widths of slope and crest do not differ significantly on ocean-facing reefs, or on west-facing reefs on the Inner Sea, but the average slope on the east-facing reefs of the Inner Sea is almost 3.7 times wider than the adjacent reef crest.

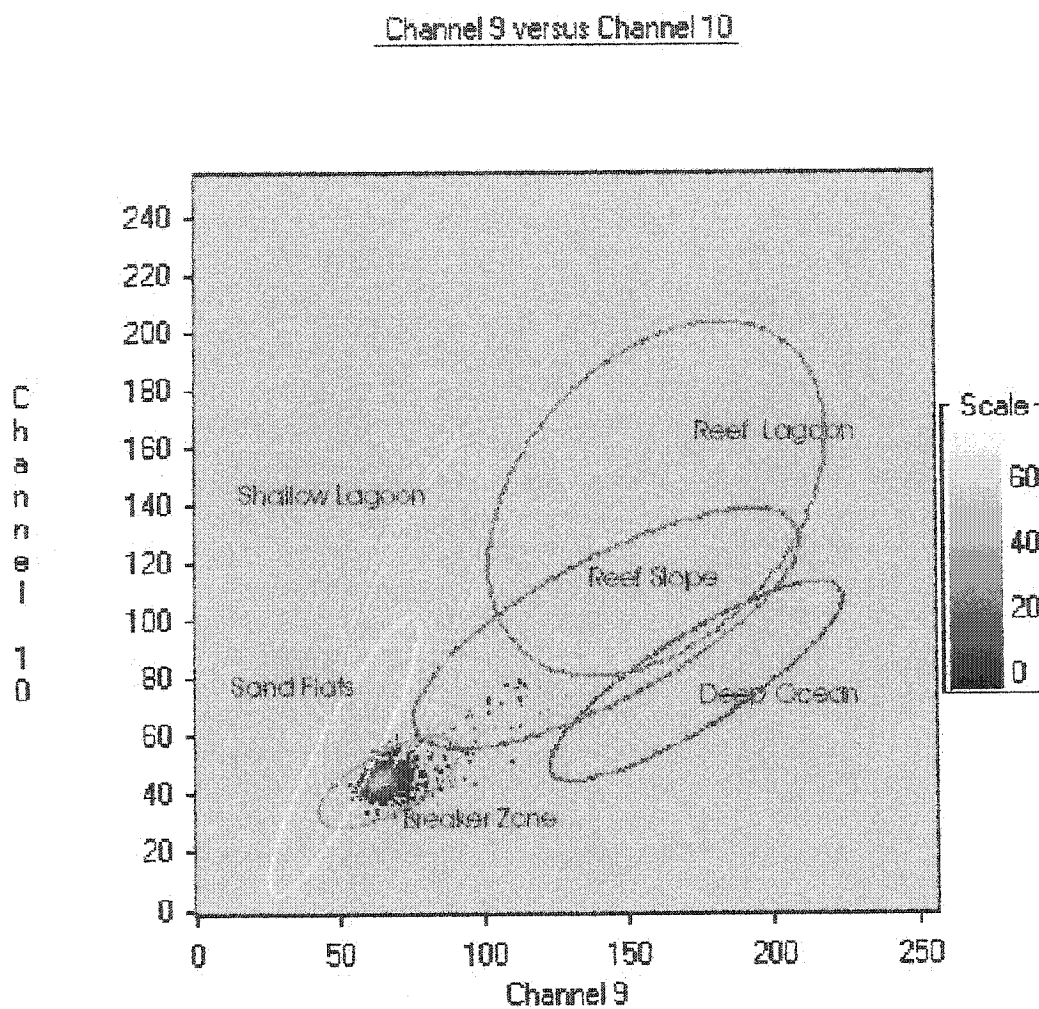


Figure 3.8 Spectral plot of band ratios (Channel 9 = band1/ band 2; Channel 10 = band 1/ band 3) which displays the integrity of the spectral classes. The greatest overlap is between the Reef lagoon class and the Reef slope class. As reef slope drops to more than 30 meters it becomes spectrally very similar to reef lagoon at similar depth.

REEF ORIENTATION	SLOPE WIDTH m (SEM,n)	CREST WIDTH m (SEM,n)	SLOPE: CREST RATIO	FETCH Km (range)	WAVE ENERGY kW.m ⁻¹ (SEM,n)
West Ocean	274.	260.	1.05	3000	0.38
– SW Monsoon	(6.1, 45)	(6.4, 52)		(2500-3700)	(0.02, 3)
East Inner Sea	131.	134.	0.978	25	0.08
– SW Monsoon	(8.8, 14)	(9.7, 15)		(15-35)	(n.a.)
East Ocean	176.	48.3	3.64*	500	0.08
– NE Monsoon	(9.4, 29)	(6.0, 29)		(400-700)	(0.09,3)
West Inner Sea	110.	91.7	1.20	25	0.03
– NE Monsoon	(6.4, 27)	(9.0, 21)		(15-35)	(n.a.)
West: East	O: 1.55*	5.38*			4.88
Ratio	I-S: 1.19	1.46*			2.67
Ocean: Sea	SW: 2.09*	1.95*			4.75
Ratio	NE: 1.60*	0.53*			2.67

Table 3.4. Comparison of morphometrics derived from satellite image analysis for the perimeters of 123 reefs in the northern Maldives averaged over each of the two Monsoon seasons. SEM = Standard Error of the Mean of n observations. * = means used in ratios differ at $p = 0.05$.

The large east-west differences in the width of reef slopes and crests facing the open ocean reflect the far greater total wave power estimated to impinge on western-facing reefs subjected to the SW monsoon (Table 3.4). The morphometrics of the reef crests facing the Inner Sea reflect the asymmetry of monsoon forcing, but the slopes do not. Further refinement of both the morphological and environmental measurements modified these preliminary results (see Chapter 4 and 5).

3.5 Discussion

The research premise introduced here is predicated on two assumptions. Firstly, that satellite imagery can accurately map the surficial reef morphology of the entire Maldives archipelago, and secondly, that the observed patterns of morphology reflect the time-integrated response of reef growth to environmental forcing. The preliminary findings do not refute these assumptions, and are concordant with the prediction that asymmetries in reef zonation will mirror asymmetries in monsoon forcing. These assumptions are rigorously tested using multivariate models Chapter 5.

Remote sensing and GIS tools, although technically challenging, can be confidently applied to the study of coral reef geomorphology (Chapter 4). The coverage, and the spatial and spectral resolution of the Landsat 7+ ETM imagery is adequate to quantify the morphometrics of major reef habitat of the Maldives' reefs with an accuracy suitable for the hypotheses posed. The only significant limitation is the maximum lower depth limit of reflected light penetration (30m) in the blue part of the visible spectrum. Marine geomorphological research is progressing from models based on the survey description of individual structures to those based on the statistically rigorous quantification of seascapes. It is clear that remote sensing is the only method that can generate the type of data required for large-scale studies, and it is only with GIS that the consistent measurement of thousands of reef structures becomes feasible.

The geomorphology of the Maldives' atolls and reefs has been described in great detail (Gardiner 1902; Agassiz 1903; Sewell 1932; Davies et al. 1971). These early, qualitative studies provided interpretations of patterns and controls on reef growth based on visual surveys of a few reefs extended to the archipelago from the inspection of navigation charts. More recent subsurface geological studies of the Maldives ridge (Purdy and Bertram 1993; Aubert and Droxler 1992) demonstrate that the gross arrangement of the atolls reflects the topography of the highest peaks of a carbonate platform which has been

radiometrically dated to 57 million years, itself resting on volcanic peaks rising from the depths of the Indian Ocean (Aubert and Droxler 1992). Thus, at the larger longer scales of atolls and the entire archipelago, antecedent control on the geomorphology is incontrovertible. This is not necessarily true, however, for the geomorphology of individual reefs within atolls, as expressed by their shape and zonation.

Whilst several studies have pointed out the apparent morphological adaptations of reefs to physical and biological processes (particularly wave fields, e.g. Roberts et al. 1992, van Woerik and Done 1997), few studies relate growth processes to environmental forcing in a quantitative manner. Munk and Sargent (1954) showed that the length and spacing of spur and groove formations on Bikini Atoll were related with the distribution of wave power around the atoll. The implication is that these are growth features, molded by the time-integral of the wave forcing. An alternative hypothesis is that spur and grooves develop from sub-aerial exposure during low sea level stands (Purdy 1974). In the Maldives, where there is extensive reef accretion during the Holocene on near-surface antecedent platforms (Woodroffe 1992), lateral reef growth has proceeded for several thousand years under the influence of the periodically reversing monsoon climate regime. Thus, the environment and history of reefs in the Indian Ocean (Stoddart 1971) lead us to expect those morphological features most indicative of lateral growth processes (reef slopes, crests and lagoon sand flats) to reflect modern conditions of reef growth as influenced by hydrodynamic conditions. The similarity of the ratios of simple reef morphometrics and crude wave forcing across exposure gradients in the northern Maldives (Table 3.4) do not disappoint, and this relationship is rigorously analyzed in Chapter 5 of this thesis. This research is designed to bridge the gap between the structural geology and growth biology of coral reefs using innovative measurement techniques and analytical approaches. The results will hopefully improve our understanding of the fundamental processes controlling the growth, morphology and productivity of the Maldives' reefs, and may be extended to coral reefs elsewhere in the Indopacific.

The Maldives (as well as many other archipelagic nations) is faced with the uncertainties of sea level rise, and consequent loss of land in addition to dealing with anthropogenic reef degradation (Souter et al. 2000; Wilkinson 2000). Reefs may keep up with the rising sea levels if the conditions are favourable for vertical accretion (Buddemeier and Smith 1988), but in most instances we have no knowledge of the reef building capacity of a given area. Extensive maps displaying gradients of change in reef morphometrics with respect to physical process provide a basis for comparing the growth characteristics of reefs, and predicting their capacity to keep up with sea level rise. Techniques envisioned here can be applied to risk analysis in the Maldives as the people attempt to prepare for the inevitable.

Chapter 4

4 QUANTIFYING CORAL REEF GEOMORPHOLOGY: DEVELOPING A REEF DATABASE FOR THE MALDIVES

4.1 Introduction

The only formal database on coral reefs of the world is maintained currently at Reefbase (www.reefbase.org). A large variety of biological, ecological and geological data pertaining to coral reefs exists in this database, but lacks, or provides inadequate quantitative data on the major atoll groups of the world. Data on individual atolls and reef dimensions derived from historical and recent literature are not yet available. Most of the data on coral reefs of the world at this database is from the book “World Atlas of Coral Reefs” by Spalding et al. (2001). One of the main objectives of this research is to develop a comprehensive geomorphometric database for coral reefs of the Maldives. Here, focus is on reef geomorphology and their metrics, but this can be developed further to include many biological and ecological parameters for the same reefs.

The primary objective of this research is to test hypotheses relating wind-wave forcing and coral reef growth in the Maldives (see Chapter 5). To rigorously test hypotheses at the scale of the archipelago, it is necessary to quantify the geomorphology of individual rim and atoll lagoon reefs in atolls that best reflect reef growth. Many studies indicate that reef geomorphology is the appropriate level of analysis to examine patterns of coral reef growth (Roberts 1974; Bradbury and Young 1981; Fagerstrom 1987; Guilcher 1988; Hopley 1982). Reef geomorphology was mapped and quantified in this study by the classification of satellite imagery and the spatial analysis of these classifications using Geographical Information Systems (GIS) tools. This chapter is dedicated to the methods of remote sensing, image analysis and GIS tools used in this research to map and quantify coral reefs of the Maldives. An atoll reef database is the output of this analysis.

An evaluation of the literature on atoll reef morphology indicates a huge gap in our knowledge of Indian Ocean atolls (Chapter 2). Wiens (1962) gave excellent descriptions of Pacific atolls and their geomorphology. A number of other studies around this time concentrated on Pacific atolls (Tracy et al. 1948). More comprehensive recent studies of many Pacific atolls have also been made (Andréfouët et al. 2001a; Dufour 2001). Indian Ocean reefs and atolls were described by Guilcher (1988) and Woodroffe (1994). Few studies have been carried on the Maldivian atolls since ground-breaking surveys by Gardiner (1901) and Agassiz (1902) a century ago. The most recent insights into the morphology of the Maldives' atolls was by Preu and Engelbrecht (1991), Woodroffe (1992) and Bianchi et al. (1997). These studies concentrated on very few reefs in one or two atolls, and their conclusions are deduced from measurements made at the scale of sections and zones of the individual reefs they investigated in the atolls. In order to understand the geomorphology and the pattern of reef formation in atolls and archipelagos, and compare them across biogeographical regions of the world, quantified maps of reef morphologies of major atoll groups of the world are needed. The Maldives group of atolls remains the least studied in this respect.

Remote sensing from space provides a uniform, quantitative survey technique for remote coral reefs such as the atolls of the Maldives. The Maldives group of atolls and their reef constituents are scattered over 180,000 km² of Indian Ocean. Remote sensing has increasingly been used to assess coral reefs, map habitats, and to detect changes at larger scales than possible using conventional survey methods (Green et al. 1996; Hatcher et al. 1997; Knight et al. 1997; Mumby and Harborne 1999; Mumby et al. 1998; Holden and LeDrew 1998). It is the only cost effective survey tool available currently to obtain a synoptic view of large reef domains at a given time. While time series of reef images can be used to infer rates of change over time, synoptic views can be used to study large-scale physical environmental processes on reefs. Major limitations of the use of remote sensing appear to be the lack of continuity in data availability, cloud cover and sensor specifications (Green et al. 1996). Most sensors currently in use for high spatial resolution (<1km²) coastal mapping (such as coral reef mapping) are not specifically

designed for marine work. However, with better sensors, software and algorithms constantly being developed there is reason to believe that remotely sensed imagery will be the preferred choice to study large-scale processes on coral reefs in the near future.

Studies of atoll morphology in the Pacific are the first large scale studies carried out using remote sensing tools (Andréfouët et al. 2001a). These studies have generated accurate morphological data for atolls, and laid down the first steps towards a comprehensive atoll reef morphological database. The research presented in this chapter aims to map and quantify the gross geomorphology of all atoll reefs of the Maldives. A complete and consistent satellite image database will be generated for the Maldives, the major group of atoll reefs in the Indian Ocean.

In anticipation of this research, evolving series of Landsat products: the Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and the Enhanced Thematic Mapper Plus (ETM+) images were all considered for analysis. The aim was to obtain a complete set of suitable images that covers the entire Maldives archipelago and associated reef system (eight Landsat footprints). Image data archives at major Landsat download centres were thoroughly searched for images covering the Maldives. The best coverage of Landsat TM images was found at the Ground Receiving Station at Hyderabad, India. With three bands in the visual spectrum at 30m pixel dimension, TM imagery is suitable to depict habitat information at the spatial scales of reef geomorphological zones. Although cloud-free images were available for the area at the time of enquiry in 1998/9, their acquisition cost of ~ \$2000 per image made them economically unfeasible for use in this research. A few low cost Landsat MSS images of selected atolls were available from the USGS MSS Archives at the EROS Data Centre, and one image was acquired and analyzed as a preliminary assessment. At 80m-pixel dimension, the MSS images were considered too coarse to depict reef geomorphology at the spatial resolution required to address the questions posed in this thesis.

The latest of the Landsat series, the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) was launched in April 14, 1999. The ETM+ sensor replicates the capabilities of its

predecessors, the TM instruments on Landsat 4 and 5. It also includes new features that make it a more versatile and efficient instrument for whole earth observation including studies of global change, land cover monitoring and assessment, and large area mapping (<http://landsat7.usgs.gov/index.php>).

One of the missions of the Landsat 7 program was to provide images for the NASA Long Term Acquisition Plan (LTAP) to support scientific research (Gasch et al. 2000). Several coral reef locations worldwide have been integrated in the LTAP data set (Arvidson et al. 2001). To improve the coverage of coral reefs zones, specified target reefs endorsed by coral reef research groups worldwide were also added to the list of potential sites. All sites in the LTAP list were to be imaged at least one time a year (Gasch et al. 2000). For this research, we successfully requested and included the Maldives in the LTAP data acquisition plan under Landsat ETM+ program in the early stage of its genesis. The Landsat ETM+ sensor has consistently collected images of the Maldives since April 1999 and these are now available at the Landsat 7 archives (<http://glovis.usgs.gov/>). A complete set of 8 reasonably cloud-free images for the Maldives was captured during the period April 1999 to June 2002. These images were acquired and atoll reef morphologies were mapped using image analysis techniques (see below).

Figure 4.1 vividly displays the spectrally distinct morphological zones of an atoll lagoon reef in the Maldives. The crystal clear waters and the shallowness of reefs at sea level make them ideal for mapping using satellite and airborne remote sensing. The surface areas and other dimensions (see later) of these morphological features of the reef can be measured from classified satellite images with high accuracies.

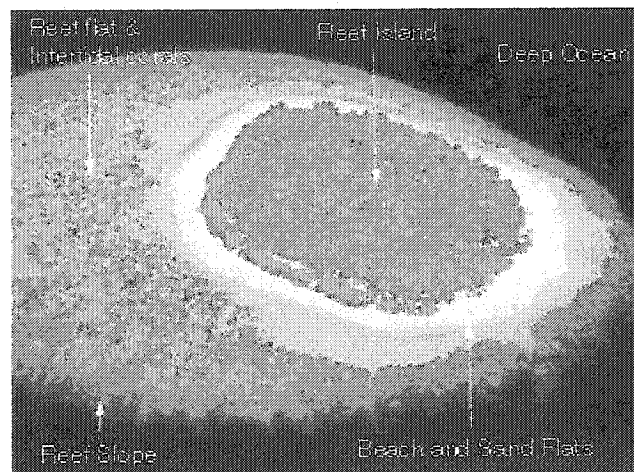


Figure 4.1 Lagoon patch reef in the Maldives displaying the prominent morphological features and zonation (photo reproduced from www.visitmaldives.com).

4.2 Materials and Methods

4.2.1 Study Area

The atolls of the Maldives lie on a submarine ridge aligned north to south in the Indian Ocean, stretching from 1-degree south latitude to 7-degrees north latitude. The 73rd meridian of East longitude runs directly through the central axis of the atoll archipelago (Fig. 4.2). The surface and subsurface geology of these atolls and the carbonate foundation on which they stand, were described in detail by Aubert and Droxler (1992) and Purdy and Bertram (1993). The length of the archipelago is 900 km north to south and 130 km east to west. It comprises 16 large, complex atolls, 5 smaller, simple atolls or *oceanic ring reefs* and 4 oceanic reef islands (Fig 4.2).

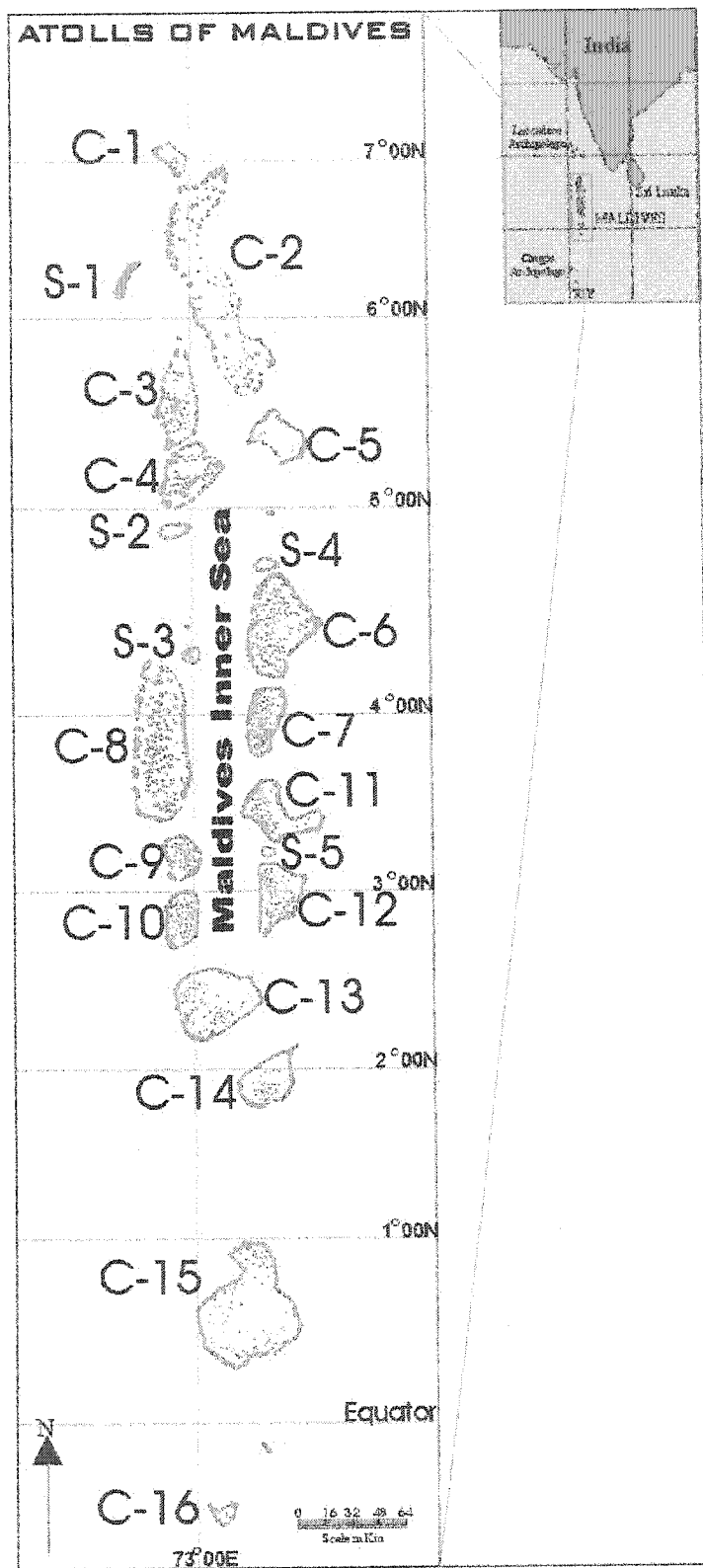


Figure 4.2 Locations and types of atolls in the Maldives. C 1-16= Complex atolls. S 1-5 = Simple atolls.

The gross structure of the archipelago comprises a double chain of atolls in the central region, tapering to lines of single atolls towards the north and south (Fig 4.2). This arrangement results in an ocean area of limited fetch in the central archipelago - the Maldives Inner Sea (MIS). Depths within atoll lagoons range from 30 to 80 meters, while water depths within the Maldives Inner Sea range from 200 to 600 m. There are no near-surface reefs within the MIS. Just outside the oceanward rims of atolls on the west and east of the archipelago water depths are 1000-4000 meters. The detailed structure, shapes and sizes of the 16 atolls mapped and quantified for the reef database in this chapter are shown Fig 4.3. Local names of these 16 atolls and atoll identification codes used throughout this chapter are shown in Table 4.1.

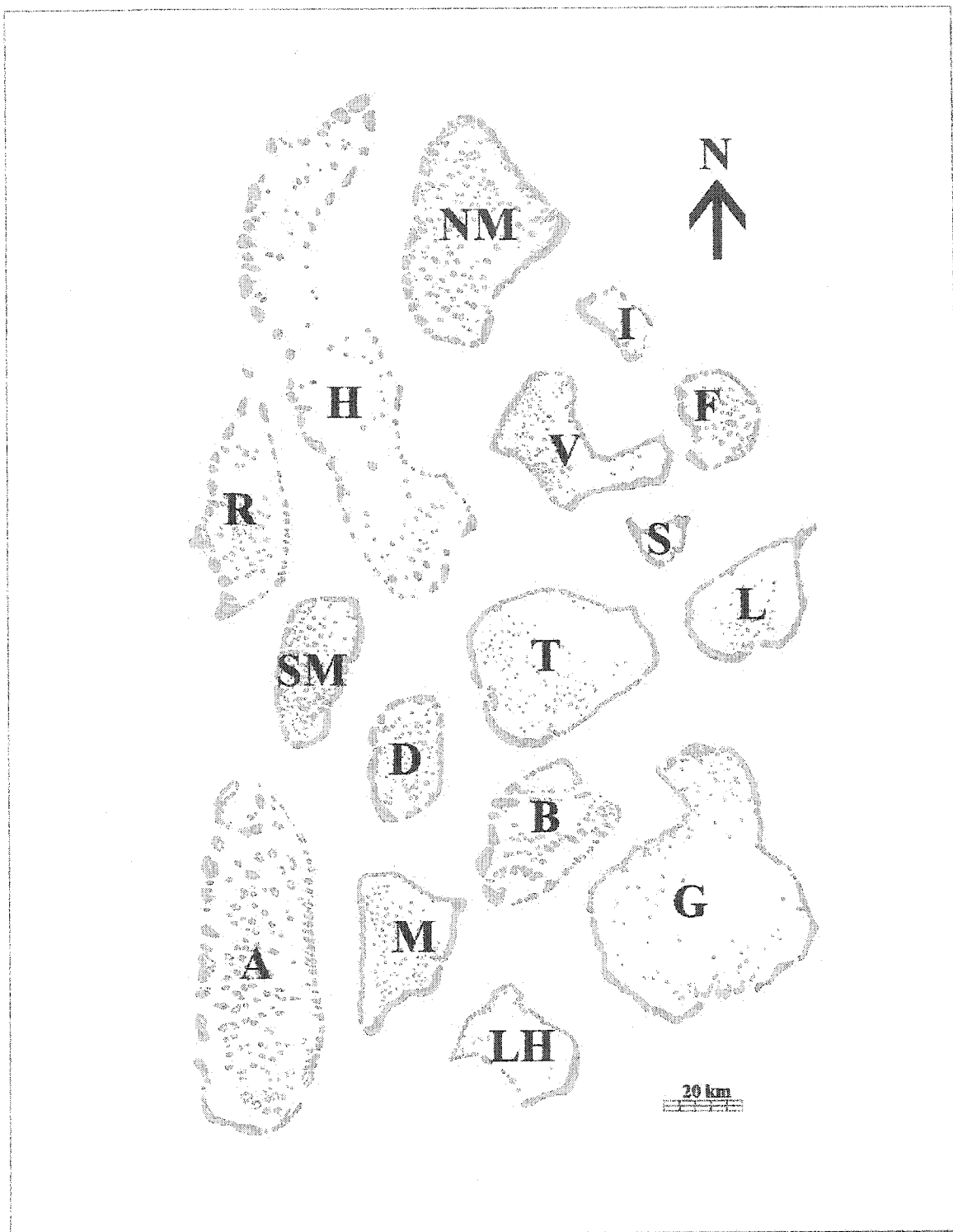


Figure 4.3 Detailed structure, diversity of shapes and sizes of the 16 atolls and associated rim and lagoon reefs mapped in this chapter to quantify reef morphology. See Table 4.1 for details of atoll names of corresponding letter codes here. (N.B. This is not a true geographic representation of the atolls).

Atoll number	Atoll Code	Common mixed names adopted in this study	Formal geographic names of atolls in the Maldives
1	I	Ihavandhippolhu atoll	Ihavandhippolhu atoll
2	H	Haa atoll	Thiladhunamthi-Miladhunmadulu atoll
3	R	Raa atoll	North Maalhosmadulu atoll
4	B	Baa atoll	South Maalhosmadulu atoll
5	LH	Lhaviyani atoll	Faadhippolhu atoll
6	NM	North Male atoll	North Male atoll
7	SM	South Male atoll	South Male atoll
8	A	Alifu atoll	Ari atoll
9	V	Vaavu atoll	Felidhoo atoll
10	M	Meemu atoll	Mulaku atoll
11	F	Faafu atoll	North Nilandhoo atoll
12	D	Dhaalu atoll	South Nilandhoo atoll
13	T	Thaa atoll	Kolhumadulu atoll
14	L	Laamu atoll	Hadhdhunmathee atoll
15	G	Gaafu atoll	Huvadhoo atoll
16	S	Seenu atoll	Addu atoll

Table 4.1 Names of the 16 atolls mapped and the identification codes used in this study. Two levels of naming are used for atolls in the Maldives: administrative names and geographic names. The names in the 3rd column are predominantly derived from administrative names. An administrative name may not explain a natural atoll, as it can be only part of an atoll.

4.2.2 Atoll reef geomorphology

An atoll is best characterized by its *rim* and the central *lagoon*. Two types of reefs may be distinguished on an atoll: *rim reefs* and *lagoon reefs* (Fig 4.4). These reef types have both differences and similarities. The basic difference is that they are subject to very different hydrodynamic regimes. Reefs within the atoll lagoon are sheltered from high energy, wave and swell regimes to which all rim reefs are constantly subject, depending, in the northern Indian Ocean, on the status of the monsoon. The geomorphological categories of the two reef types are quite different. Lagoon reefs generally do not have the extensive, sharply zoned reef crests and flats of the rim reefs, and display a circular symmetry rarely evident in rim reefs (compare reefs in Fig 4.1 and Fig 4.4). The patterns of growth of both reef types, and hence their emergent morphologies is, however, dependent on the time integrated response of a complex assemblage of organisms to light and nutrient supply, as regulated by local hydrodynamics and modulated by sea level change and antecedent topography. The relative importance of the recent environmental forcing and the antecedent substratum in controlling the present morphologies of atoll reefs is a matter of unresolved debate (see full discussion in Chapter 2).

Based on established criteria (Battistini et al. 1975; Hopley 1982; Kuchler 1986; Holthus and Maragos 1995), seven morphological zones were identified *a priori* in each reef type for the purposes of this study. These zones have distinct boundaries known to be related to the hydrodynamic regime, and can be readily interpreted from the Landsat 7 ETM+ imagery (Fig 4.5 and Fig 4.6).

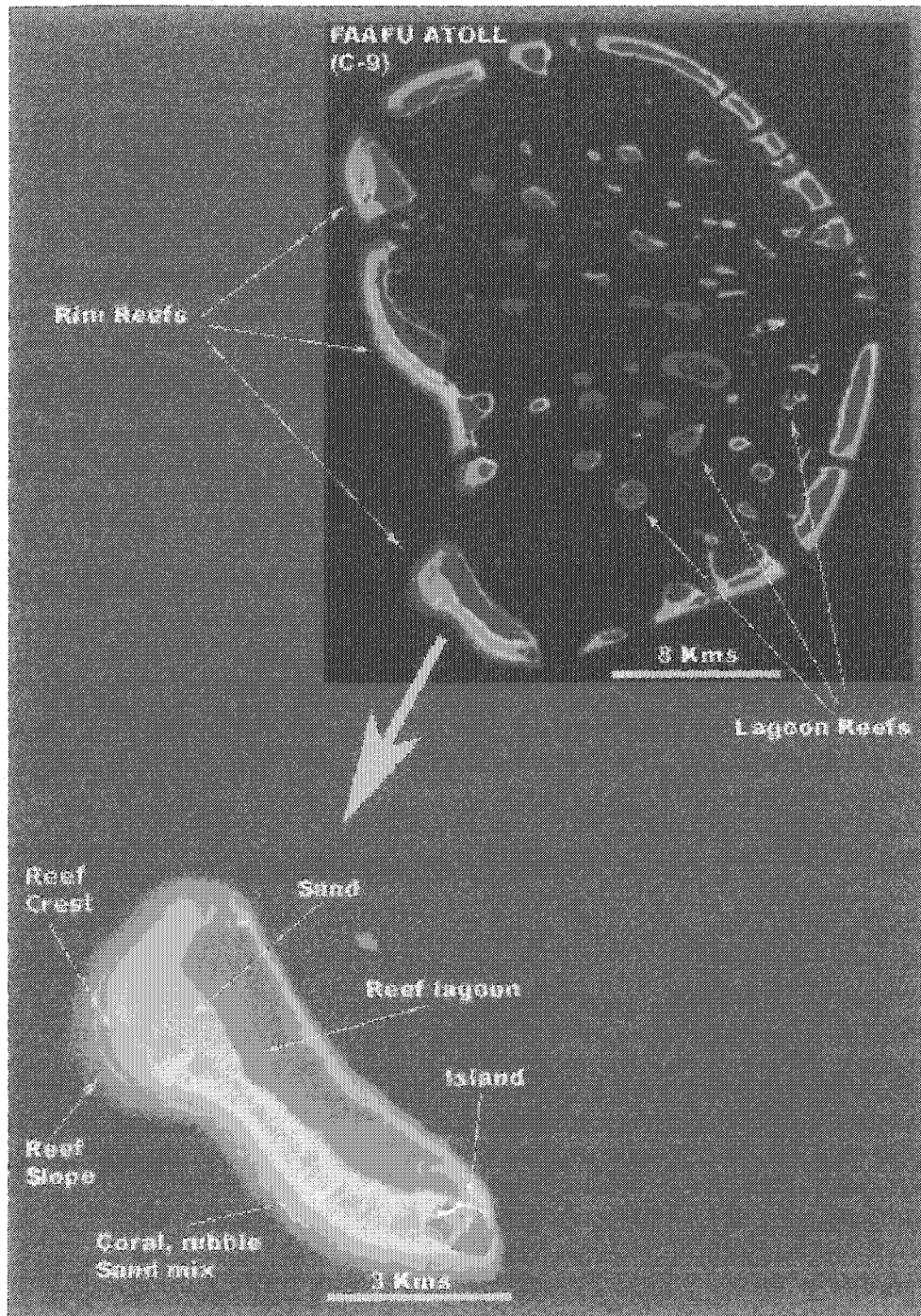


Figure 4.4 Satellite image of Faafu atoll in the Maldives to illustrate the main geomorphic components of a typical Maldivian atoll. The inset shows a rim reef and the six geomorphological classes chosen for mapping reefs.

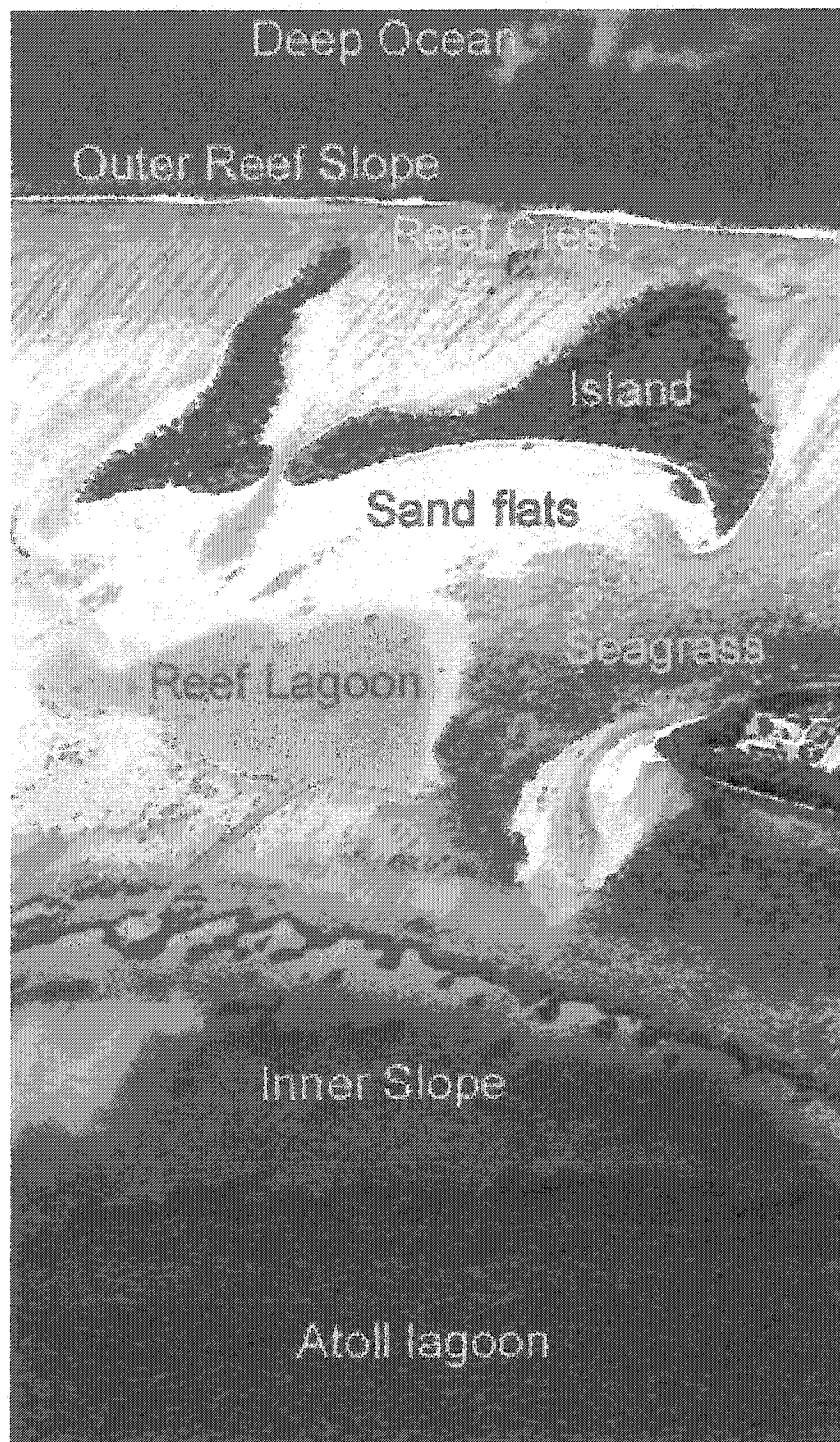


Figure 4.5 Oblique aerial photo taken from air, to emphasize the structure of a rim reef in an atoll in the Maldives displaying the seven geomorphological classes mapped using interpreted satellite imagery.

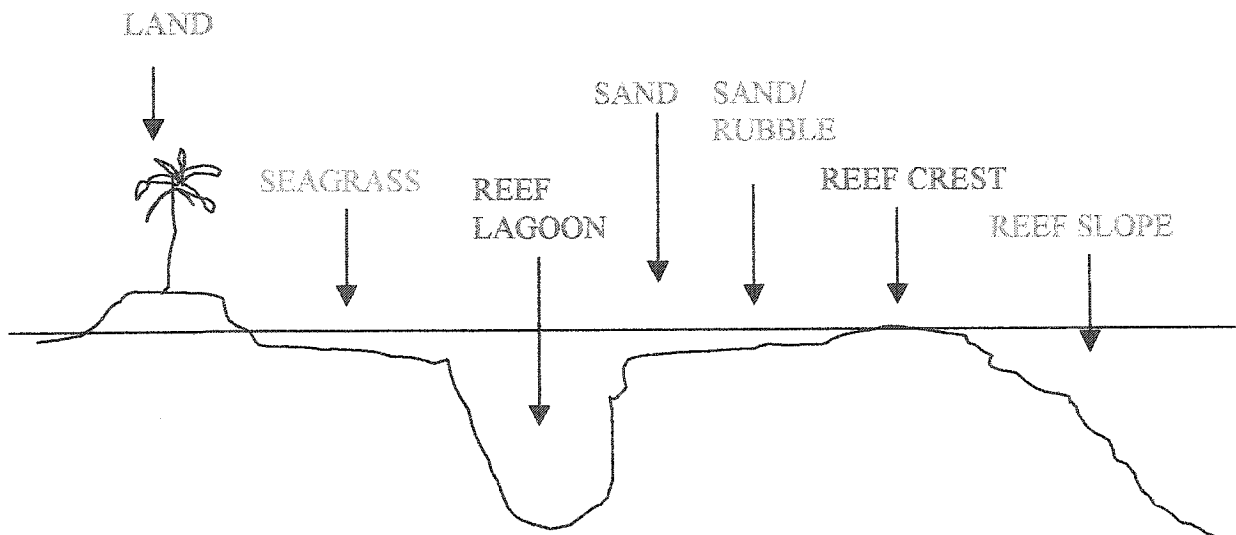


Figure 4.6 Schematic cross sectional diagram of a Maldivian rim reef system to define the seven classes mapped using satellite imagery.

The *Reef slope* can form the inner or outer margin of a given rim reef as it falls away into deep water. The inner reef slope usually consists of an upper 10-20 meters of coral zone, and then continues to the atoll lagoon floor as a sandy slope. The outer reef slope (facing the ocean) is the area of strong wave action where the greatest density and coverage of live coral occurs, and the fastest reef growth and productivity takes place. On atoll lagoon reefs, the zonation of the reef slope is usually less well defined and the zone of high coral abundance does not extend as deep down the windward and leeward slopes as on rim reefs.

The *Reef crest* is the algal ridge or the coralline pavement where wave energy is dissipated in breakers. Lagoon reefs do not usually have such a zone (unless positioned down weather of a passage through the atoll's rim reefs), and the equivalent zone on a lagoon reef will be the intertidal zone characterized by coral and or rubble. The reef crest on a rim reef will usually have a coralline algal platform, but this feature is less well defined for Indian Ocean reefs in general, and is variably represented in the Maldives' reefs, being most obvious in southern atolls. The reef crest is also defined well by rubble, boulders and sturdy corals. Overall, this zone can be mapped with confidence from satellite imagery given its location and spectral distinction. It can occasionally be confused with seagrass (see results).

The *Sand and coral rubble mixed zone* is just inside (i.e., downstream) of the reef crest, and is a mixed zone of coral, rubble and sand. This zone is separated from the adjacent sand flats by its spectral characteristics associated with hard substrata. Since it is a mixed zone there is difficulty in identifying it homogeneously on all images. It may be confused sometimes with sand flats. This is the zone of flow-parallel striations commonly described for Indian Ocean reefs (Battistini et al. 1975; Guilcher 1988). The zone may also be overgrown with seagrass on reef platforms that support reef islands.

Sand flats can be easily identified as they have the highest spectral reflectance. Extensive, prograding sand flats are found on rim reefs of the Maldives' atolls, where they reflect hydrodynamic transport of carbonate sediments generated on the reef slopes, crest and flats. Sometimes a sand flat can flow over the back of the reef platform into the atoll lagoon, where it forms an inner reef slope.

The *Reef lagoon* is a very well defined geomorphological feature on reefs in the Maldives. They are found on both rim reefs and lagoon reefs. They are generally interpreted as solution-formed karst structures on modern reefs (e.g. Purdy 1974). A reef lagoon in this study is defined as one that has a minimum depth of at least 3 - 5 meters. Other areas with sandy bottom of similar characteristics on a reef were identified as sand flats. A reef lagoon can be identified and classified with confidence based on its location on the reef. It is only confused with reef slope domains because of spectral overlap.

Seagrass is common on rim reefs of the Maldives especially in southern atolls. It is classified here not because it is a geomorphological component of the reef, but because it forms an ecological habitat of interest on reef flats. It is very distinct spectrally in the reef context because of its very low reflectance in the blue band, giving it the spectral properties of deep ocean.

Reef islands are scattered on rim reefs on the Maldives, and it is estimated that there are 1200 reef islands in the archipelago. Most of them are very small, and only a few being larger than 2 km². Reef islands are thought to be products of hydrodynamic deposition of coral rubble during the final phase of Holocene development (Gourlay 1988; Woodroffe and McLean 1994), and are known to be dynamic structures.

The geomorphological classes mapped for rim reefs were: 1) the Windward slope, 2) the Reef crest/ boulder zone, 3) the Coral/rubble and coral/sand mix zones, 4) the Sand flat, 5) the Reef lagoon, 6) the Seagrass beds and 7) the Reef islands.

For lagoon reefs the classes were similar in number but differ in the morphology of the first 2 classes: 1) the Reef slope, 2) the Intertidal zone, 3) the Coral/sand/rubble zone, 4) the Sand flat, 5) the Reef lagoon, 6) the Seagrass beds and 7) the Reef islands.

Figure 4.7 shows an idealized diagram of a typical Maldivian rim reef to display the landscape-scale morphological features of interest and the metrics derived for this study. There is a great variety of sizes and shapes of reefs on atoll rims and lagoons of atolls in the Maldives: most reefs will display the common features in this figure. These morphological features can be readily recognized and mapped from Landsat 7 ETM+ (and TM) satellite images.

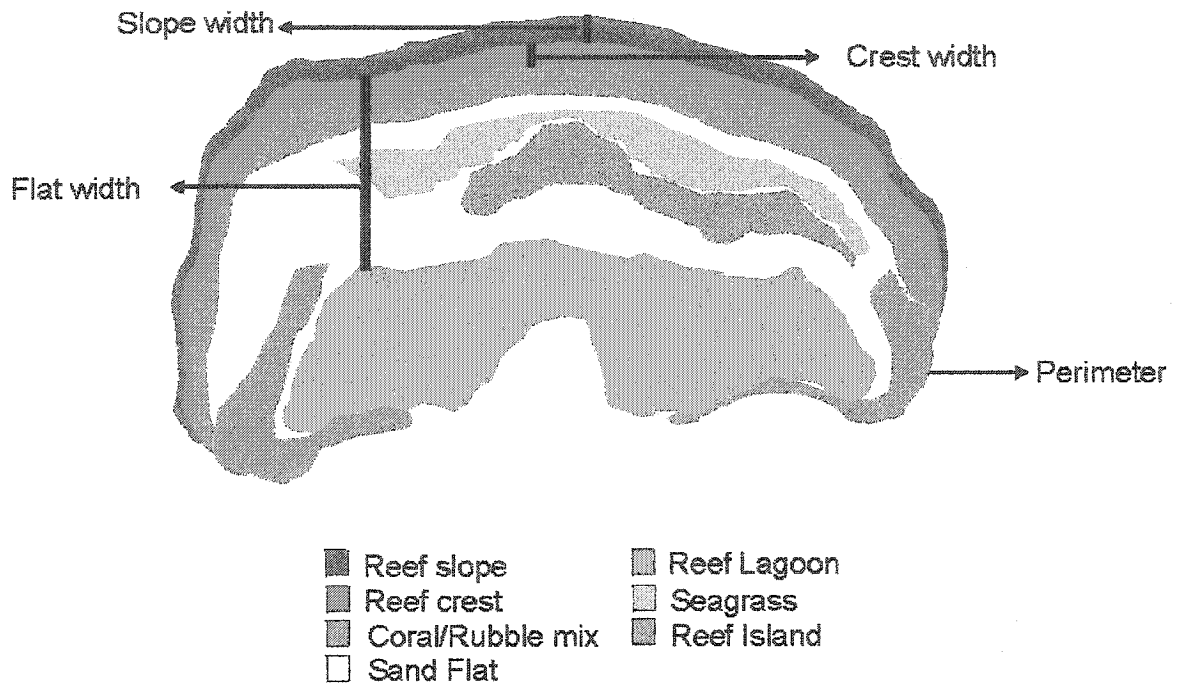


Figure 4.7 Schematic diagram of a reef to show the seven geomorphological classes that were mapped on each reef, and four of the morphometrics that were derived from these classified images. The areas of each class were also calculated, and the total area of the reef is the sum of all the classes.

Individual reefs (rim reefs and lagoon patch reefs) in each of the 16 complex atolls of the Maldives were mapped from classified remotely sensed images. For each reef the following variables were derived to reflect lateral reef growth and morphological development. In addition, the centroid of every reef was determined by summing the geographic coordinates along the reef rim at regular intervals and calculating the average of these coordinates. This centre-point of the reef was taken as the geographic location of the reef on the atoll rim or lagoon.

4.2.2.1 Geometric variables measured from the classified images

4.2.2.1.1 X- distance

This is the maximum extent (in meters) of the reef in the East-West direction. This variable was calculated by determining the eastern and western point of the reef in Universal Transverse Mercator (UTM) coordinates. As UTM coordinates are in meters, by knowing coordinate Eastings, the extent of the reef in the East-West direction can be determined (See Fig 4.8). In other words if a reef is enclosed by a rectangle, the X-direction will represent the length of the rectangle in the East-West direction.

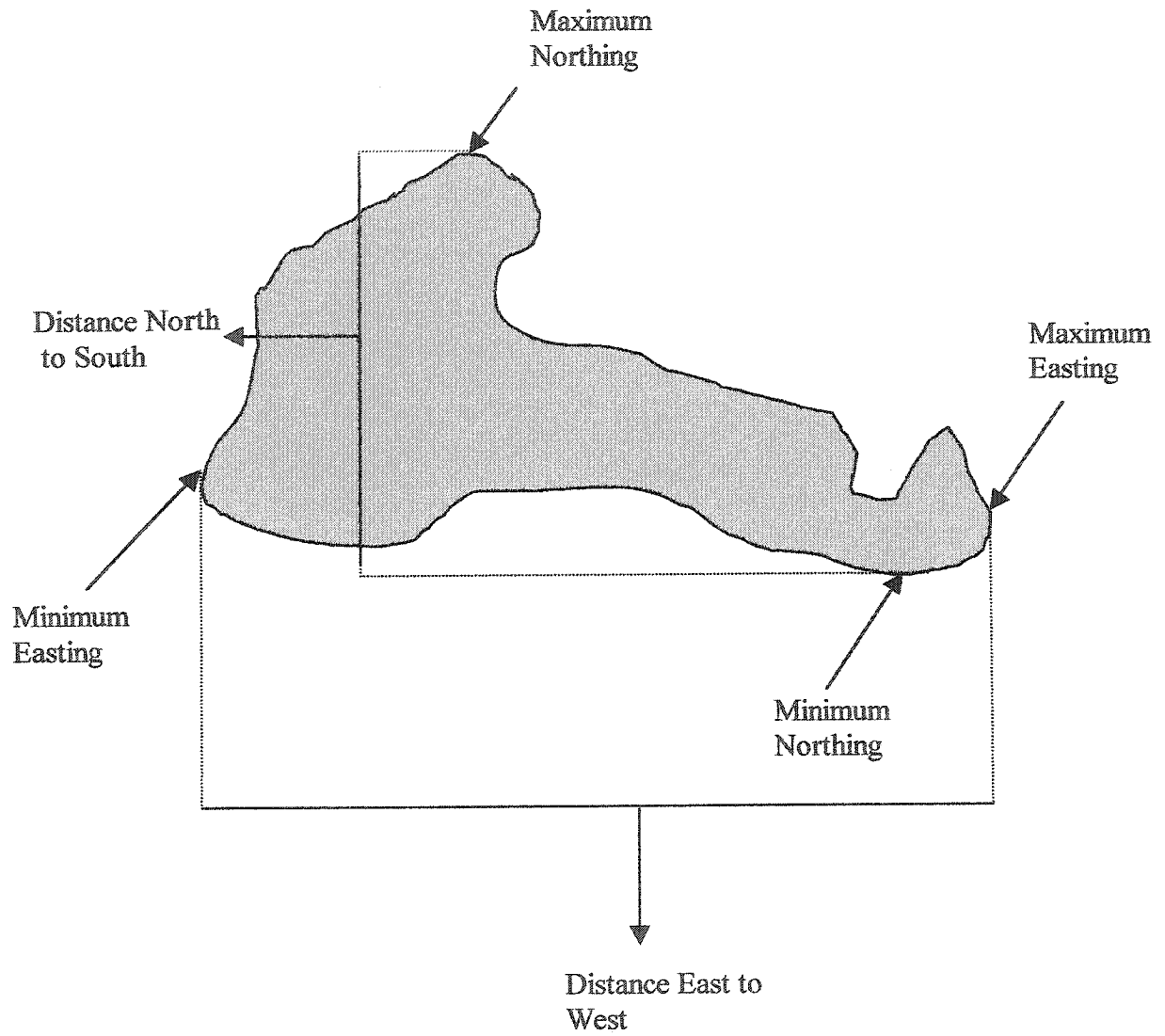


Figure 4.8 Schematic diagram of a reef to show the maximum extent (distance in meters) of the reef in the East-West and North-South directions.

4.2.2.1.2 Y - distance

This is the extent (distance in meters) of the reef in the North-South direction. Knowing the coordinates for Northing in UTM this was calculated for each reef as for the X-distance (above). This will be the North to South length of the side of the rectangle, which encloses the reef.

4.2.2.1.3 Total surface area of the reef

The total surface area (km²) for each reef was calculated for each rim reef and lagoon reef in the entire Maldives archipelago. The area encompasses all seven classes of each reef in the classified image (Fig 4.7).

4.2.2.1.4 Perimeter of the reef

The perimeter of every reef is the outermost line around the reef beyond all the classes, including the outer reef slope (Fig 4.7)

4.2.2.1.5 Reef slope, crest and reef flat widths

The widths of the reef slope, reef crest and reef flat were taken perpendicular to the edge of the reef (Fig 4.7). For each reef, many measurements (n= 1 to 60 depending on the size of the reef) of the respective widths were taken, and the mean width of slope, crest, and flat was calculated for every rim reef. Crest width here is defined as the width of the crest or boulder zone taken perpendicular to the reef edge (Fig 4.7). Reef flat width was measured normal to the reef edge from the outer edge of the reef crest to the inner edge of the reef lagoon or atoll lagoon, whichever was predominant on the given reef (Fig 4.7).

4.2.2.1.6 Surface Area of reef classes

There are seven classes mapped on every reef (Fig 4.7). The total surface area for each of these seven classes for every reef was calculated using GIS tools.

4.2.2.2 Derived variables

4.2.2.2.1 Shape ratios

Three shape ratios were calculated for each reef: compactness ratio, thinness ratio and roundness. Each is derived from the area and perimeter of a given reef. These shapes explain the overall shape of objects in terms of their circularity or perimeter complexity (Davis 1986; Northern Eclipse Help Reference: www.empix.com).

The compactness ratio is a ratio of how compact (i.e., how circular) the reef is. Compact reefs tend to be rounder. The ratio ranges between 0 and 1. Rounder reefs are close to unity, and thinner reefs approach zero. The expression used to calculate the compactness ratio is:

$$C = \sqrt{(A_p/A_c)}, \quad (4.1)$$

where C is the compactness ratio, A_p is the area of the polygon calculated, and A_c is the area of a circle having the same perimeter as that of the polygon calculated.

The Thinness Ratio or Circularity Ratio gives an indication as to the object's shape and is defined by:

$$T = 4\pi A/P^2 \quad (4.2)$$

Where T is thinness, A is the area and P is the perimeter. Circles will have the greatest area to perimeter ratio. Perfect circles will be approach unity and long thin shapes will have value close to zero.

Roundness (R) for an object may be defined by:

$$R = (P^2) / 4\pi A, \quad (4.3)$$

where P is the perimeter and A the area. This gives the reciprocal value of the circularity ratio. A circle will have a value slightly greater than or equal to unity. Other shapes will increase in value.

Another ratio that can be determined for an object is its Equivalent Circular Diameter, which is defined by the expression:

$$2\sqrt{(A/\pi)} \quad (4.4)$$

where A is the area. This is the diameter of the circle that would have the equivalent area as this object.

Thread Length is an estimation as to the true length of a thin, and thread-like object (e.g. a ribbon reef), and is defined by the expression:

$$P + (\sqrt{(P^2 - 16A)})/4, \quad (4.5)$$

where P is the perimeter and A is the area. The assumption here is that the object to be measured is thread-like in form. It should be noted that this is an estimate only. The expression was used to estimate reef width for all reefs independently of the transect method described above.

Thread Width is an estimation of the width of a thin, thread-like object, defined by:

$$P - (\sqrt{P^2 - 16A})/4 \quad (4.6)$$

where P is the perimeter and A is the area. It is an estimation of the true width of a threadlike object (e.g. reef width), and assumes that the object to be measured is thread-like in form. It should be noted again that this metric will return unrealistic measures for compact (i.e., rounded) reefs. It provides an estimate only, and was used as an alternative estimate of the width of reefs.

4.2.2.3 Atoll measurements

For each of the 16 atolls analysed, the Total Surface Area and Perimeter were calculated using GIS tools. The perimeter of the atoll was taken as the length of the line running along the outer edge of the rim of atolls and across the mouths of the deep passes of the atoll. The total surface area of the atoll was calculated as the total area of the rim reefs and the atoll lagoon combined.

The Aperture of an atoll is described as the ratio of the total cross-sectional widths of the deep channels between reefs on the atoll rim to the perimeter of the atoll (as calculated above). This metric provides an index of the exchange circulation in an atoll lagoon (Hatcher 1997; Andréfouët et al. 2001a), and perhaps also an indication of the density of patch reefs in the lagoon.

4.2.3 Remote sensing methods: Reef classification and mapping

The questions of causal relationships between environmental forcing and atoll reef growth posed in this thesis (see chapter 5) necessitate the accurate large-scale quantification of growth-related geomorphological features of coral reefs. This has never been attempted before at the archipelagic scale and with a number of reefs suitable for rigorous statistical analysis. Most geomorphologic studies focus on single reefs (Storlazzi et al. 2001). It is impractical to map and quantify large numbers of coral reefs and their morphologies using conventional methods: only remote sensing is appropriate for such studies. (Green et al. 1996).

Appropriate remote sensing and GIS tools were used in this research to map and quantify coral reefs of the Maldives. The methods are described in detail in the following sections. Standard marine and coastal image processing methods were adopted to classify satellite imagery (Green et al. 2000).

4.2.3.1 Landsat 7 ETM+ Satellite Images – Acquisition and characteristics

Landsat 7 carries the ETM+ sensor and acquires remotely sensed images of the Earth's land surface and surrounding coastal regions (<http://landsat7.usgs.gov/index.php>). Passive satellite sensors such as the Landsat 7 ETM+ offer a useful means to map coral reef geomorphology in clear tropical waters. The sensor can detect benthic features from as deep as 30 meters in ideal water and atmospheric conditions. With a spatial resolution of 30 meters, and spectral bands in the blue, green, red and Infrared segments of the electromagnetic spectrum, ETM+ is a good compromise tool for mapping gross geomorphic features on shallow coral reefs.

Worldwide locations of Landsat imagery are identified by their path and row numbers. Eight Landsat 7 ETM+ scenes covered the atolls of the Maldives, where each scene is 30,000 km² (Fig 4.9)

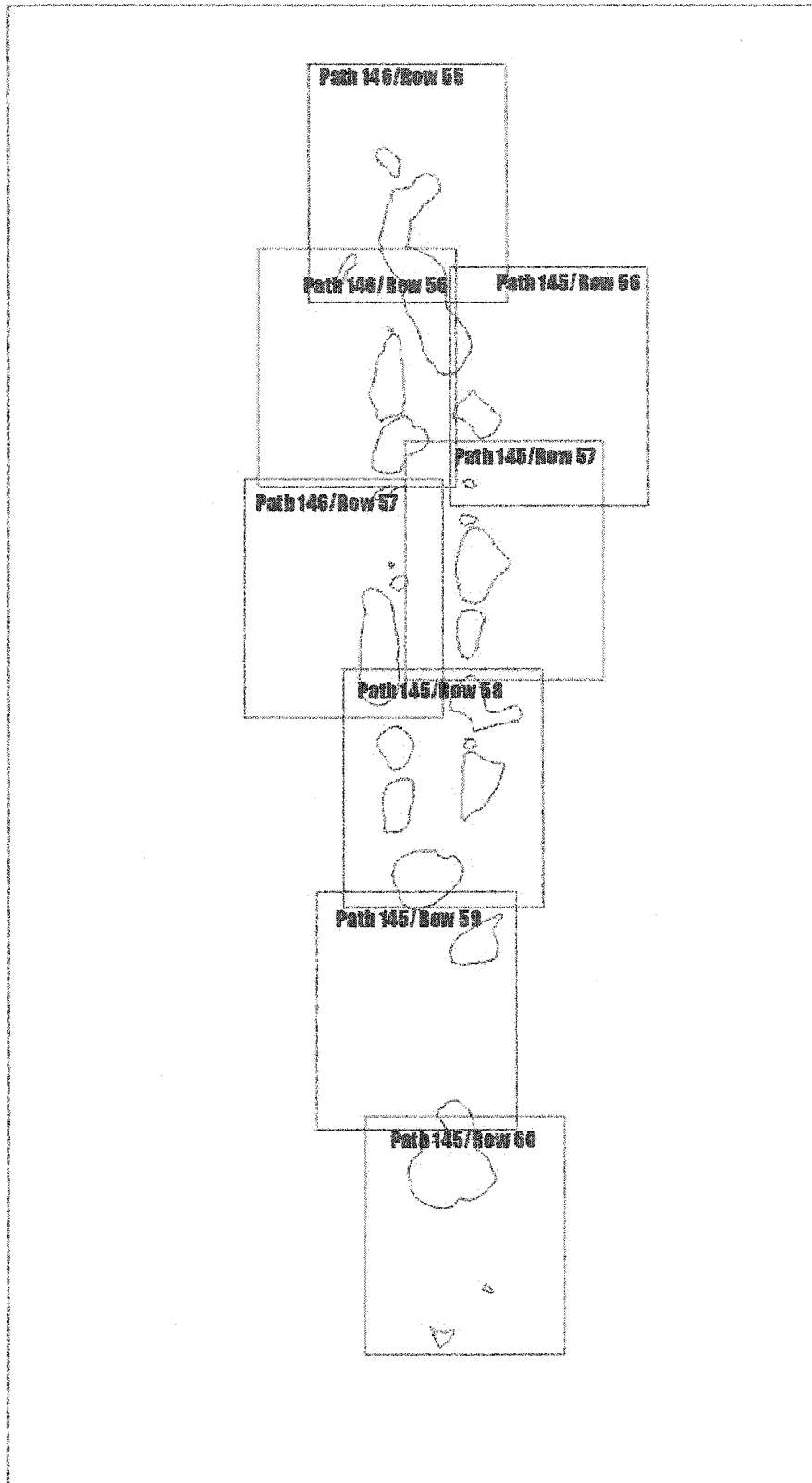


Figure 4.9. Landsat 7 ETM+ scene coverage of the Maldives' atolls.

The Landsat 7 ETM+ satellite has collected images of the Maldives since 1999, which can be browsed at <http://glovis.usgs.gov/>. The image database has been visited continuously over the last 3 years to select cloud-free images. Due to the climatic conditions of the study area in the tropical Indian Ocean, there are very few cloud-free scenes for the study area. Out of 100's of images collected so far, only a fraction is usable due to heavy cloud cover. The last of eight reasonably cloud-free images usable for this study and covering the entire domain became available only by May of 2002. These were acquired from US Geological Survey, Earth Observing System (EOS) Data Gateway (<http://edcimswww.cr.usgs.gov/pub/imswelcome/>) as radiometrically and geometrically corrected data (Level 1G) on CD-ROMs.

Landsat 7 ETM+ data are subject to 3 levels of processing: Level 0R (raw uncorrected), Level 1R (radiometrically corrected), and Level 1G (radiometrically and geometrically corrected). The Level 1G product ordered here was radiometrically and geometrically corrected (systematic) by the data processing centre, to the user-specified parameters including output map projection, image orientation and pixel size (http://landsat7.usgs.gov/l7_processlevels.html). According to the Landsat 7 documentation, the resulting product was free from distortions related to the sensor (e.g. jitter, view angle effect), satellite (e.g. altitude deviations from nominal), and Earth (e.g. rotation, curvature). It was claimed that residual error in the systematic L1G product is less than 250 meters in flat areas at sea level. On the images acquired for the Maldives' atolls, the geometric error was in fact 30-60 meters in most cases. The systematic L1G correction process does not employ ground control points to attain absolute geodetic accuracy. The characteristics of ETM+ data are given in Table 4.2

Landsat 7 ETM+ Sensor Spectral Bands		
Band	Spectral range (μm)	Spatial Resolution
1 (Blue)	0.450 to 0.515	30 m
2 (Green)	0.525 to 0.605	30 m
3 (Red)	0.630 to 0.690	30 m
4 (IR)	0.750 to 0.900	30 m
5 (IR)	1.550 to 1.750	30 m
6 (Thermal)	10.40 to 12.50	60 m
7 (IR)	2.090 to 2.350	30 m
8 Pan	0.520 to 0.900	15 m

Landsat 7 ETM+ Technical Specifications

Spatial resolution	15/30/60 m
Spectral range	0.45-12.5 μm
Number of bands	8
Temporal resolution	16 days
Size of image	183 x 170 km

Table 4.2 Characteristics of Landsat 7 ETM+ data

There was considerable variability amongst the eight images in terms of their digital number (DN) values, due mainly to atmospheric variability. Every image was considered as a separate entity, and classifications were carried out for each individual atoll cropped from the scenes. The spectral characteristics of the homogenous areas of deep ocean in all the images selected for this study are given in Table 4.3. The variability between the images are low, but all the images had varying cloud cover and haziness, which challenge creation of a uniform classification.

Image	Date acquired	Mean Ocean DN for comparison		
		Blue (N,sd)	Green (N, sd)	Red (N,sd)
Path146/Row55	11 July 1999	76.56 (23384,1.22)	39.45 (23884,0.96)	27.29 (23384,1.23)
Path146/Row56	01 May 2000	95.76 (3717,1.13)	57.60 (3717,0.84)	48.92 (3717,1.1)
Path146/Row57	12 Jan 2001	69.67 (5616,1.38)	39.94 (5616,1.04)	28.99 (5616,1.36)
Path145/Row56	21 Jan 2001	74.66 (990,1.29)	41.94 (990,0.96)	29.63 (990,1.3)
Path145/Row57	21 Jan 2001	79.61 (3306,1.4)	46.64 (3306,1.03)	34.61 (3306,1.37)
Path145/Row58	24 Jan 2002	72.56 (4473,1.3)	39.65 (4473,0.99)	27.41 (4473,1.30)
Path145/Row59	07 Mar 2000	78.53 (7544,1.38)	44.29 (7544,1.00)	32.84 (7544,1.41)
Path145/Row60	20 Dec 2000	77.52 (6364,1.38)	44.28 (6364,1.08)	32.34 (6364,1.49)

Table 4.3 Scene details of the 8 images processed for the Maldives. N = number of pixels sampled, sd = standard deviation)

In most cases it was possible to crop individual atolls from scenes for classification. Some atolls were covered by two scenes, however, in which case each portion was classified separately. No attempt was made to mosaic the parts of an atoll that were spread across two scenes for the purposes of classification. Mosaics of such atolls were created after the classification process in order to get morphometrics for the whole atoll. For classifications it was necessary to separate *lagoon reefs* and *rim reefs* of an atoll, as these are structurally very different, but the spectral signatures of the geomorphological classes were similar. For example, lagoon reefs do not have a wide slope and a reef crest, while rim reefs do. A set of masking procedures was developed to separate lagoon reefs and rim reefs. Altogether 40 individual classifications (20 rim + 20 lagoon) were carried out on scenes containing atolls and sections of atolls (Fig 4.10).

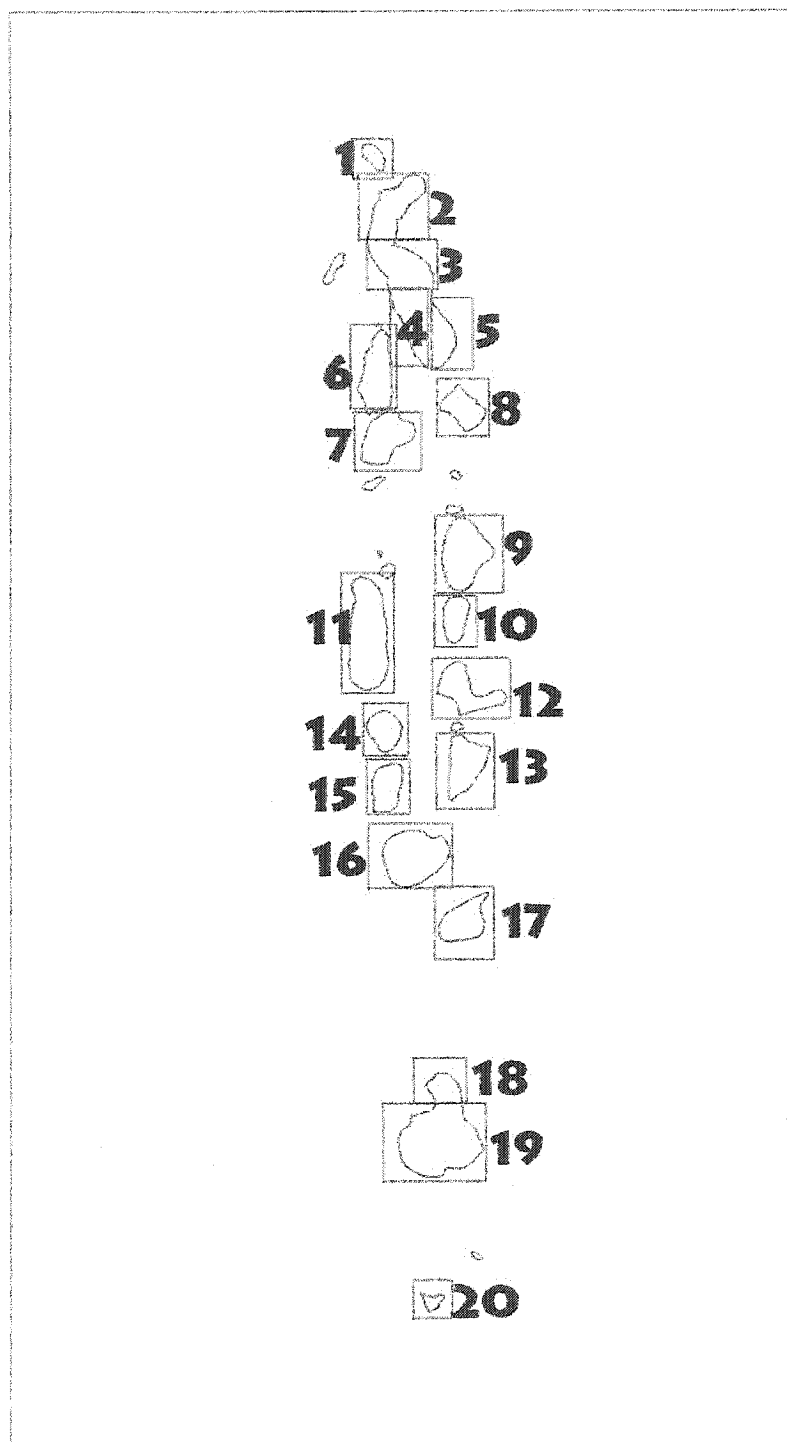


Figure 4.10 Cropping (1-20) of views from the 8 Landsat satellite scenes covering the Maldives' atolls to prepare them for classification. These crops discarded the large areas of open ocean from the images and made the classification area as small as possible. Crop numbers 2,3,4 and 5 covers atoll C2 and crop numbers 18 and 19 covers atoll C15. All remaining crops cover one single atoll. All images were classified separately.

4.2.3.2 Image processing procedures

Image analysis, interpretations and classifications were performed using programs within PCI GEOMATICA version 8.1.1 (www.pcigeomatics.com) (See Appendix 1). Raw images (HDF and GEOTIFF formats) were first read into PCI format, and images were then cropped and prepared for classification (see below).

4.2.3.3 Image Preparation

The eight Landsat 7 ETM+ scenes obtained for this study were initially cropped into sections of smaller, manageable sizes (mostly into single atolls in scenes, ranging from seven to 80 megabytes per file). An exception was made for the two largest atolls (C-2 and C-15, see Fig 4.2), which were covered by more than one scene. Hence there was more than one scene section for the two largest atolls. The remaining 14 atolls were classified as single atolls. Fig 4.10 shows the cropping of individual atoll scenes and sections of large atolls prepared for classification. For the entire Maldives archipelago there were 20 smaller images (scenes) to be processed and classified. Atoll lagoon reefs and rim reefs were classified separately based on the criteria described above. Thus, there were 40 classifications altogether: 20 for lagoon reefs and 20 for rim reefs. Rim reefs and lagoon reefs were separated and classified by creating separate masks for each reef type in each cropped image. An elaborate masking procedure was developed to separate reef types and to mask ocean, clouds and land on the images, which is summarized in Fig 4.11.

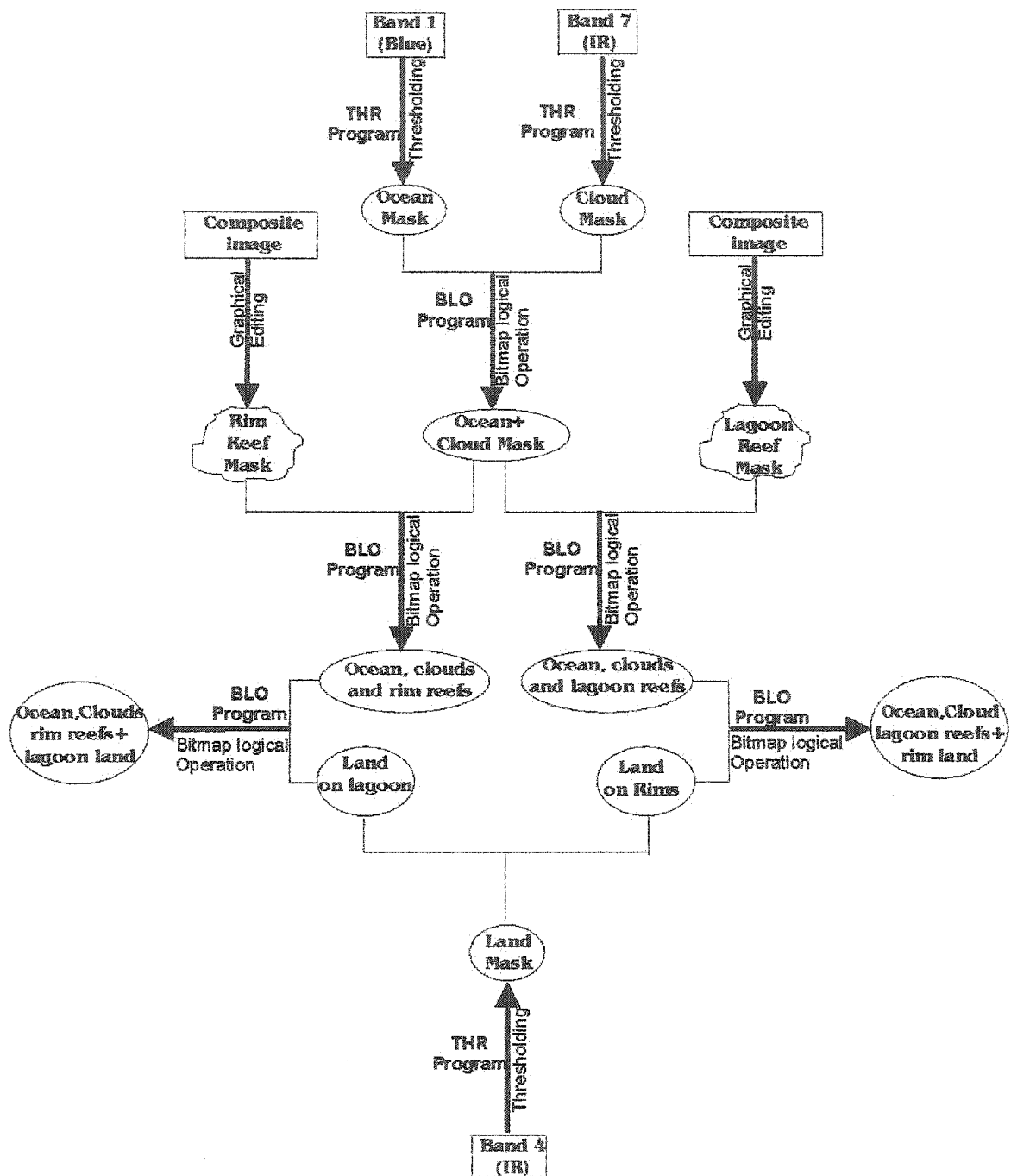


Figure 4.11 Summary flow diagram for masking Landsat ETM+ imagery of the Maldives in preparation for classification using PCI GEOMATICA.

4.2.3.4 Masking deep water, clouds and reef islands

Individual bands of images were explored using the Pseudocolour option in PCI ImageWorks. This option was suited to examine the intensity of DN values according to morphological thresholds on reefs. It also assists in the selection of maximum and minimum DN values for thresholding the different spectral bands. Pixels of an area of a given band were sampled by using a graphical mask and studying the histograms under these masks to determine statistics. Observing an image under Pseudocolour option in individual bands enabled edge detection clearly (for example reef edges). Coupled with ground truthing studies for reef edge detection and careful observations of band 1 DN's, masks were developed for images in order to produce better classifications. The objective was to mask ocean, clouds and reef islands before running a classification.

It was also necessary to mask *all rim reefs* or *all lagoon reefs* for a given atoll so that only lagoon reefs or only rim reefs will be classified in the final stages of a classification routine in PCI. Such a mask cannot be created easily, as there was no way to threshold a single band to achieve this. It appears initially that this can be done by just creating an outline for all the atolls, but this would still leave a lot of ocean pixels around the reefs, presenting a problem in quantifying reef morphology. In order to create a *Rim Reef Mask* and a *Lagoon Reef Mask*, it was necessary to create several other masks objectively, and combine them with Bitmap logical operations in PCI (Fig 4.11).

4.2.3.4.1 Cloud Mask

To achieve good classifications of the 20 images it was crucial to create masks of unwanted pixels on the images. The first problem was to deal with cloud cover. There were varying amounts of clouds ranging from thick “popcorn” to thin haze on all images. It was necessary to either assign a class to clouds and classify them, or mask them from classification. The first option was tried but was not a suitable strategy given the variations and confusion which result. Most clouds could be accurately masked using ETM+ Infrared (IR) band 7. Cloud pixels were very bright on an image with heavy cloud, usually having the highest DN value. Masks were developed using the THR program (see Appendix 1) in PCI GEOMATICA. The minimum and maximum threshold values of the cloud mask were determined by sampling an area of ocean pixels on the image in ETM+ Band 7. Theoretically in Infrared band 7, most light should be absorbed in water and very little is reflected. Therefore ocean areas appear very dark and the bright clouds are seen clearly. A bitmap mask of an area over water was sampled and the mean DN value was established for the area under the mask along with maximum and minimum values for the whole band. The histogram statistics developed here would be for the areas not covered by clouds (i.e., from the ocean areas). The cloud mask was created using these statistics. Occasionally the cloud mask would result in masking areas of reef islands with bright pixels but this was corrected using Bitmap editing tools in ImageWorks.

4.2.3.4.2 Ocean Mask

The second mask created for each atoll image was an ocean mask. On average, more than 90% of the pixels in all images were in the deep ocean, and were not necessary for the purposes of the reef classifications. Initially the ocean was treated as a separate class, but this created much confusion in the classes. For example, some reef island DN values were similar to ocean values and also seagrass beds were easily confused with deep ocean pixels. Ocean masks for each image were crucial for a good classification for the reef zones.

Ocean masks were created using the blue band. In oceanic coral reefs areas such as the Maldives, water clarity is generally very high. The blue band sensor detects reflected light from a maximum of 20-30 meters depth in ideal conditions. Deepwater ocean pixels had the lowest DN values (Table 4.3) in the blue band around coral reef areas. On shallow reefs, the DN values were very high (Table 4.4 and 4.5). Therefore it was possible to develop a mask for deepwater by thresholding the blue band. The maximum and minimum threshold values to be used in the THR program were determined by carefully examining the images and by sampling pixels over ocean under a bitmap mask. Histograms statistics of these values were then used to determine the maximum and minimum threshold values. It was possible to develop a reasonably accurate mask for all images this way. As DN values over ocean varied considerably (Table 4.3) it was necessary to establish the maximum and minimum THR values for all 20 images separately.

Some reef island areas have similar spectral properties to ocean pixels and get covered by the final ocean mask. These anomalies were corrected using Bitmap editing tools so that the resulting mask would be just ocean. The final outcome is a bitmap mask, which covers all ocean areas, revealing only reefs (Fig 4.11).

The *Ocean Mask* and *Cloud Masks* were combined using the Bitmap Logical Operations (BLO) program (see Appendix 1) in PCI. The resulting *ocean and cloud mask* covered most areas not necessary for the classification of coral reef morphologies and zones.

4.2.3.4.3 Land Mask.

The third mask created was the land (reef island) mask (Fig 4.11). For the purposes of this study it was necessary to calculate the total reef island area for every given reef. Attempts were made to take reef islands as a separate class in early classifications. But this proved to be too confusing: there was much confusion between ocean pixels and reef slope pixels and reef island pixels. So, it was better to mask reef islands. This was very straightforward using the infrared band 4. When the image is observed in band 4, all water areas appear black indicating total absorption in the infrared band, and land appears very bright. By carefully examining the land water boundary pixels and observing the bimodal histogram of the band, maximum and minimum threshold values were determined for the THR program. The resulting mask some times did also cover small areas of clouds which had high DN values, but they were corrected by editing the bitmap mask using editing tools. In this way a bitmap of all reef islands was created for every image. This land mask was later integrated into the classified image in order to calculate the reef island area on all atolls.

So far we have two masks: an *ocean and clouds mask* and a *land mask*. It is now necessary to create two temporary masks: one that covers *all lagoon reefs* and another that covers *all rim reefs* of a given atoll. This was done manually using Bitmap editing tools.

4.2.3.4.4 'Lagoon Reef Mask' and 'Rim Reef Mask'

A free hand trace-and-close line was drawn, using graphical editing tools in PCI, to cover all reefs inside the atoll lagoon (Fig 4.11). By flood filling the area inside the hand drawn trace-and-close line graphic, a mask was completed which covers all lagoon reefs on a

given image of an atoll. Similarly a mask was created for all rim reefs of the same atoll using free hand editing tools to cover reefs encircling the atoll rim.

4.2.3.4.5 Combining Ocean and Clouds Mask and Lagoon Reef Mask

In this step, the *ocean and clouds mask* and *lagoon reef mask* were combined by Bitmap Logical Operations (BLO) (see Appendix 1) in PCI. The resulting bitmap mask is one that covers ocean, clouds and all lagoon reefs of a given atoll. The only reefs uncovered by this combined mask will be *rim reefs*. This mask can now be used to classify only rim reefs of an atoll. However, this is still incomplete for use in the final classification as the *land on rim reefs* need to be masked as well (see later).

4.2.3.4.6 Combining Ocean and Clouds Mask and Rim Reef Mask

Next, *ocean and cloud mask* was combined with the *rim reef mask* using BLO (Fig 4.11). The resulting bitmap mask covered ocean, clouds and all rim reefs of a given atoll. The only reefs not covered with this combined mask will be *lagoon reefs*. This mask can now be used to classify only lagoon reefs of an atoll. This mask is, however, incomplete yet as it is again necessary to mask land on the lagoon reefs for final classification.

We now have two masks: one that covers ocean, clouds and all rim reefs and another that covers ocean, clouds and all lagoon reefs of an atoll.

4.2.3.4.7 Creating masks for Land-on-Rim reefs and Land-on-Lagoon reefs.

In order to complete the final *lagoon reef mask* and *rim reef mask* it was necessary to obtain separate bitmaps for land on rim reefs and lagoon reefs. Since a land mask had been created for the entire atoll earlier using IR band 4, it was simply a matter of creating two separate masks from this using Bitmap editing tools in PCI. The result was two masks: one of “land on rims” and another of “land on lagoons”.

Finally *land-on-rim reefs mask* was combined with the *ocean, clouds and rim reef mask* and *land-on-lagoon reefs mask* was combined with the *ocean, clouds and lagoon reef mask*. The result is two bitmaps: one which covers ocean, clouds, rim reefs, and land on lagoon reefs and another which covers ocean, clouds, lagoon reefs and land on rim reefs. These two masks can now be used in the final stages of the classification to eliminate rim reefs or lagoon reefs as well as clouds, ocean and land from any given classification of coral reef habitat.

This complex masking procedure was crucial for classifications of the 20 images, given that less than 10 percent of each image contained reefs and needed to be classified. The procedure was necessary not only because it results in a better classification, but because it was necessary to classify rim reefs and lagoon reefs separately for the purposes of this study, and this can only be effectively done by developing separate masks as outlined here. A summary of all the masking procedures is shown in Fig 4.11.

4.2.3.5 Band Selection

Eight bands of data are available in the Landsat ETM+ sensor (Table 4.2). Based on established works, (Green et al. 1996; Mumby 1997; Andréfouët et al. 2001b) and the spectral Separability of class signatures, four bands (blue, green, red, infrared) were chosen for the classifications in this study.

4.2.3.6 Field work / Ground Truthing

Ground truthing is a critical field procedure in remote sensing used to verify and calibrate the classes represented on an image. It is considered an integral part of any study based on remotely sensed images. Processing remotely sensed imagery requires varying levels of fieldwork depending on the objectives of the study and the level of classification of the habitats in question. The amount of ground-truthing to be undertaken also depends on the level of understanding of the study area by the image analyst, and the amount of

confusion among classes identified in unsupervised classifications. Four levels of ground truthing were employed in image processing for this study: 1) recollection of extensive personal knowledge of coral reefs in all atolls of the Maldives, 2) examination of 1:10,000 scale aerial photographs of all atolls exposed from 1965 to 1999, 3) examinations of a large collection (approx 100) of oblique aerial photos of selected reefs and 4) field visits to six selected atolls and reefs where 15 georeferenced spot dives and 10 underwater transects were conducted using SCUBA.

It must be noted that the area under investigation in this study is very large (total surface area of all atolls= 20,900 km²). It would be impractical to launch a field campaign that covered even a significant part of this area. Further, it is beyond the scope of a PhD study to undertake such a task. Consequently, local knowledge and aerial photos were heavily relied on in developing training sets for image classification and consequent error assessments. The geomorphological classifications at the levels of organization and spatial resolutions attempted in this research can be done very confidently with little or no fieldwork because our knowledge of reef zonation is so extensive and complete (Mumby and Harborne 1999; Mumby 2000).

Nevertheless field assessments were made to characterize the seven reef categories for this study and also to determine the maximum discernible depth of the reef edge on reef slopes on outer atoll slopes. Selected reefs were investigated in six atolls (Atolls LH, NM, V, L, G, S, Fig 4.2) by snorkel and SCUBA. In many cases shallow reef areas were surveyed by small boat and GPS readings were taken of the bottom classes. Classes were identified and marked with GPS coordinates, which were later identified on images. GPS coordinates were also taken of selected landmark points in some atolls to verify the geometric accuracy of images. The geometric accuracy of the images was determined to be 30-60 meters. This would allow the classes to be confidently located on the images as the accuracy of the GPS used was seven meters.

Maximum discernible depths at reef edges both inside and outside the atoll were investigated by running SCUBA transects perpendicular to the reef edge on reef slopes.

With a line to which a floating buoy is attached, a diver ascended up the reef slope from a depth of approximately 40m (a depth at which the sensor certainly does not see the bottom), recording depths and seabed composition at regular intervals. Each time depth is recorded a signal was made to the observer above the water by means of the floating buoy and line. The diver was followed by boat on the surface and GPS coordinates were recorded for every depth record using a Garmin E-trex GPS receiver (exhibiting a typical positional accuracy of 7m). At the same time depths were also recorded using a hand held depth sounder. Independent transects were also run by boat across reef slope and depths were recorded by depth sounder. Depth and seabed composition data, and its associated location coordinates were imported into a PCI GEOMATICA channel for easier viewing and interpretation.

4.2.3.7 Supervised Classification and Training

In remote sensing methodology, classification is defined as the process of identifying image pixels with similar properties, organizing them into groups (usually statistically but not always) and assigning labels (e.g. habitat names) to those groups (Green et al. 2000). Theory and technical concepts behind processing digital satellite imagery and image processing methodology are described in many standard texts (Curran 1985; Campbell 1996). In this study, the parametric Maximum Likelihood Classifier (MLC) in PCI GEOMATICA was used to perform supervised classifications on the imagery. Studies have demonstrated the effectiveness of supervised MLC clustering in image classifications (Mumby 1997; 1998). MLC classifies all image data using a set of spectral signatures (see below) as specified by the input image channels during the classification procedure. Signature data pertaining to a particular class are created and stored in the image database. The result of the classification is a theme map that encodes each class with a unique gray level. The value used to encode a class is specified when the class signature is created. When the theme map is directed to the computer display, a pseudo-colour table can be created and loaded so that each class is represented by a different colour.

Supervised classification relies on the ‘training’ of the image data to achieve the desired classification. Training is the process of defining the spectral envelope of each class (Green et al. 2000). The term ‘training sites’ in image processing signifies the identification of pixels or groups of pixels within known (i.e., field validated) classes, which are used to develop spectral signatures for the imagery. It is important to ascertain that the spectral properties of the training sets are statistically representative of the classes (i.e., benthic habitats) investigated. MLC is a parametric statistical procedure that requires the data in the training sets to be normally distributed. Attempts were made to ensure normality of the ground truth data collected for this study, although this was not always the case. Fig 4.12 shows the blue band histogram of a training set developed for the reef slope class in ‘LH’ atoll for reference. Table 4.4 and 4.5 show the details of the training sets developed for image classifications in this study.

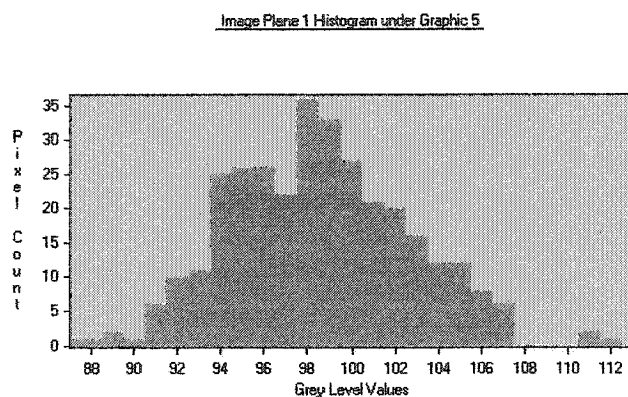


Figure 4.12 Histogram of training sets for the reef slope class.

	Reef slope	Reef Crest	Coral/rubble	Sand Flat	Lagoon	Seagrass
Band1	98.85	121.01	152.98	198.38	111.40	82.15
Band2	65.57	101.70	129.56	173.59	64.80	58.24
Band3	40.02	77.10	80.55	108.26	36.40	43.67
Band4	14.62	18.10	14.80	16.07	14.19	18.02
# of Pixels	21583	22514	18028	26526	23483	6715

Table 4.4 Class (benthic habitat) training sets and mean DN values for four Landsat 7 ETM+ spectral bands across all images for rim reef classes of the Maldives atoll reefs.

	Reef slope	Intertidal	Coral/rubble	Sand Flat	Lagoon	Seagrass
Band1	95.08	112.46	136.29	184.10	109.21	83.27
Band2	56.33	78.99	103.26	155.75	63.52	60.29
Band3	37.60	48.92	57.34	93.19	38.48	47.00
Band4	14.88	15.41	15.66	17.04	14.91	31.34
# of Pixels	11408	6985	5448	6892	11909	71

Table 4.5 Class (benthic habitat) training sets and mean DN values for four Landsat 7 ETM+ spectral bands across all images for lagoon reef classes of the Maldives atoll reefs.

4.2.3.8 Spectral signatures

Spectral signatures are the end results of training sample assessment and can be evaluated in many ways. Figures 4.13 and 4.14 show the spectral plots of the signatures for rim reef and lagoon reef classes. It is seen that most of the classes can be separated from each other. The classes that have the greatest similarity are reef slope and lagoon and seagrass. The confusion between these classes can be easily dealt with by contextual editing, however, as all three are confined to different geomorphologic zones of the reefs and none of them occurs in close proximity to the others.

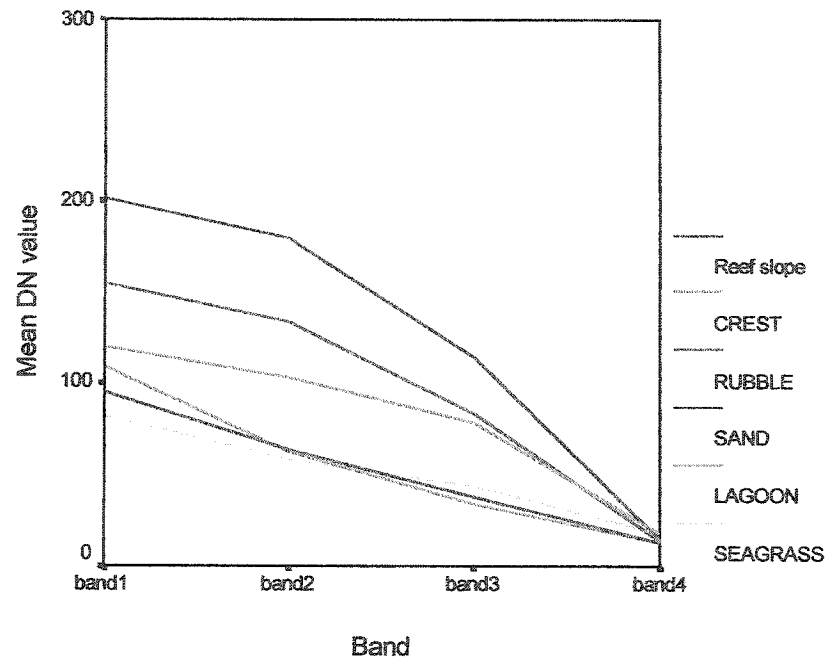


Figure 4.13 Spectral plot of digital numbers in four spectral bands (Band 1-4) of the Landsat 7 ETM+ sensor for six geomorphological classes of rim reefs in the Maldives.

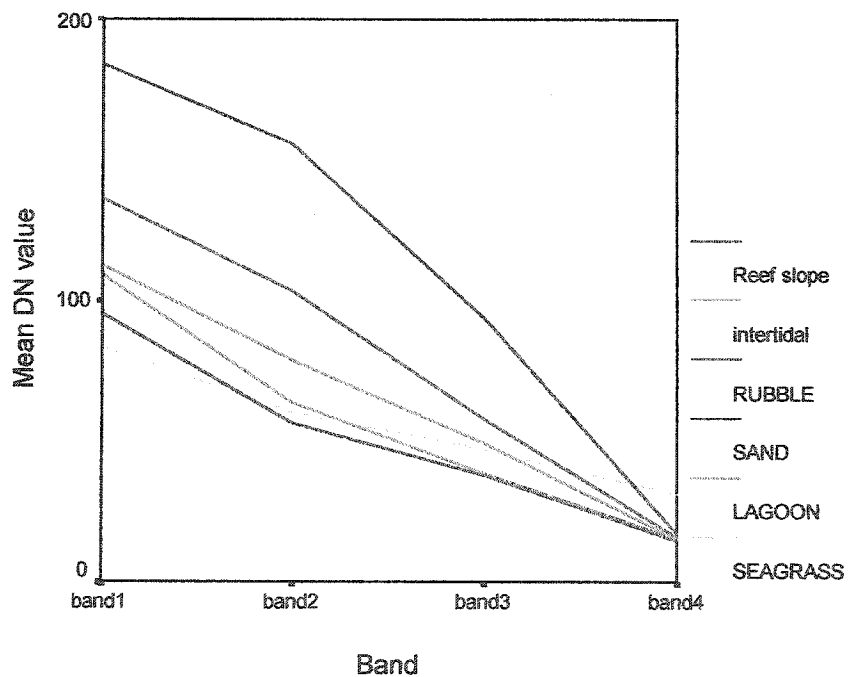


Figure 4.14 Spectral plot of digital numbers in four spectral bands (Band 1-4) of the Landsat 7 ETM+ sensor for six geomorphological classes of lagoon reefs in the Maldives.

4.2.3.9 Confusion Matrix

The evaluation of the confusion matrix (i.e., contingency table) gives an indication of how well separable are the signatures of the various classes. Table 4.6 shows the pooled confusion matrix for all 20 rim reef classifications in this study.

	Slope	Crest	Rubble	Sand Flat	Lagoon	Seagrass
Slope	94.52	1.07	0.00	0.00	3.93	0.49
Crest	0.25	97.42	1.58	0.02	0.69	0.02
Rubble	0.01	0.66	98.20	0.65	0.45	0.06
Sand Flat	0.00	0.00	1.05	98.78	0.01	0.00
Lagoon	3.18	0.22	0.05	0.00	96.34	0.28
Seagrass	1.05	0.50	0.00	0.00	0.07	98.36

Table 4.6 Confusion matrix for rim reef classifications.

4.2.3.10 Signature Separability

Spectral distance between signatures is another statistical measure of the reliability of the training sets developed for each spectral class. The measure is based on divergence, transformed divergence or Bhattacharyya distance (Green et al. 2000; PCI GEOMATICA help documents). Separability measures yield values between 0 and 2, where 0 indicates complete overlap between signatures and a value of 2 indicates a complete separation between classes. The following guides are suggested in PCI GEOMATICA documentations: $0.0 < x < 1.0$ (very poor separability), $1.0 < x < 1.9$ (poor separability), $1.9 < x < 2.0$ (good separability).

The spectral separabilities between signatures for a rim reef classification as calculated with the PCI GEOMATICA software are reported in Table 4.7. This gives a representative picture for all imagery. The highest degree of confusion (hence the lowest measure of separability) was noted between the 'reef slope' class and 'lagoon' class in all

classifications. More complex classification routines were required to reduce this confusion. Ancillary data such as depth channels and water column corrections may have solved this confusion to a large extent but this was not attempted due to lack of data and expertise. It should also be noted that the confused classes (slope and lagoon) can be dealt conveniently as the two classes in question do not occur together. Consequently a large part of this confusion can be overcome by contextual editing.

	Reef slope	Reef Crest	Rubble/coral	Sand Flat	Lagoon
Reef Crest	1.99				
Rubble/coral	2.00	1.94			
Sand Flat	2.00	2.00	1.94		
Lagoon	1.75	2.00	2.00	2.00	
Seagrass	1.91	1.99	2.00	2.00	1.98

Table 4.7 Separability measures for the Maldives' rim reef classes based on Bhattacharyya distance. Average separability = 1.97, minimum separability = 1.75 (Lagoon and Reef slope).

4.2.3.11 Image editing for known problems: contextual editing

Some amount of image editing was undertaken before subjecting the images to GIS analysis. Many images had dense "pop corn" clouds on them that obscured the signals from reefs underneath them. The masks created for clouds ensured they were not classified. They can be easily observed in the final images as black "holes". Given the scale of these classifications, non-classified areas under clouds can be easily located on classified images. In most cases they fell on homogenous areas. It was decided that to leave these unclassified areas on images would be a loss of data for the final reef quantification and analysis. Therefore wherever possible, classified images were carefully examined for such unclassified "cloud holes" and they were manually edited (i.e., cloud holes changed to the underlying respective classes) using image editing facilities in ImageWorks, PCI GEOMATICA. This would enhance the quality and accuracy of the final data quantified for all reefs (Green et al. 2000). The other option would have been to discard the cloud affected reefs from analysis. But this was not

necessary as clouds were a minor problem on most reefs classified. Confused classes with homogenous areas were also corrected systematically.

4.2.3.12 Combining land and seagrass masks with the classifications.

The 40 classified images generated from supervised MLC in PCI GEOMATICA, supplemented with contextual editing, generated six reef classes in all: 1 = reef slope; 2 = reef crest or intertidal; 3 = coral/sand/rubble mix; 4 = sand flat; 5 = lagoon; 6 = seagrass. These classified images had to undergo further processing before they could be used in the GIS analysis. In particular it was necessary to encode land (which was developed as bitmap masks as described above) back into classified image channels. Although seagrass was classified as a separate class in MLC, some seagrass areas were also created manually and masks were created for them. It was also necessary to put these back on the classified images, before importing the images to the GIS, as land (reef island) area was one of the morphometrics that was desired to be quantified from the imagery.

In order to accomplish these corrections it was necessary to take extra steps. The two land bitmap masks (*land on rim reefs* and *land on lagoon reefs*) (see Section on masks, Fig 4.11) were encoded using the MAP module in PCI GEOMATICA. This results in two new channels with land information in them. Care was taken to give a class value to land that was not found in the classified images. Classified images had six classes (i.e., slope, crest, rubble/coral, sand flat, lagoon, seagrass) and therefore land was given a value of seven when it was encoded. The encoded bitmaps were then multiplied with the respective rim or lagoon classification using the ARI module (see Appendix 1) of PCI GEOMATICA, so that land will be incorporated into the classification. Now these land-incorporated images can be exported into GIS in *.TIF or IDRISI raster format for analysis.

4.2.4 Geographical Information System (GIS) methods: Reef quantification

Classified satellite images were quantified using IDRISI32 GIS software. IDRISI32 is a raster-based GIS software published by Clark Labs within the Graduate School of Geography at Clark University (www.clarklabs.org). It is particularly useful for its raster analytical capabilities, which makes it ideal for geospatial analysis.

For most tasks IDRISI has a set of modules that are stand-alone programs. Each module processes one or more input raster images such as a classified satellite imagery and outputs a raster image in most cases. Each module performs a specific function such as overlay, filtering, distance calculations and image reclassification. There are also modules implementing basic "map algebra" operations: arithmetic with grids, statistics, and other operations. A brief explanation of the IDRISI32 modules used for reef quantification here is given in Appendix 2.

4.2.4.1 Quantifying geomorphology

The problem of measuring and quantifying 40 classified images totalling more than 2000 classified reefs each with seven classes was not trivial. One option was to manually obtain the data for each reef, but this would be very tedious, laborious and above all highly subjective. No documentation or direction was found in the literature that describes a method of how this can be done in an automated fashion. Solutions were developed in IDRISI32 raster GIS.

The module-based raster analytical function presented by IDRISI32 was a critical component in the development of a GIS-based model for the quantification of reef morphology in this study. Drawing from a variety of modules, systematic models were developed in IDRISI for semi-automated quantification of classified imagery and to obtain geographic coordinates of reefs (Fig 4.15). Similar models were developed for the

calculation of other metrics such as reef slope, crest and flat widths. IDRISI macros were then written to automate the model for the 40 classified images (see Appendix 3).

4.2.4.1.1 Surface areas of reef geomorphological classes

This was the main numerical component in quantifying reef geomorphology. The surface areas of seven reef classes were calculated (reef slope, reef crest, shallow coral/rubble, sand flat, lagoon, seagrass and reef island) for every reef. Fig 4.15 shows the GIS model developed for these calculations. This model enabled the calculation of the seven reef class areas on each classified image and derives other metrics (see below) for reef habitat polygons.

Figure 4.15 Cartographic model for semi automated area measurement of classes of reef geomorphology using IDRISI GIS. The model was run for each classification individually.

4.2.4.1.2 Reef Area and Perimeter

These were quite straightforward and can be calculated directly using the AREA and PERIM modules (see Appendix 2). Using the model (Fig 4.15) the AREA and the PERIMETER module was run on each reef polygon and the program calculates the area based on the reference system parameters of the classified image's documentation file.

4.2.4.1.3 Reef slope, reef crest and reef flat width

These measurements were first drawn on the images using vector tools in PCI GEOMATICA. For each reef many width measurements were made at equal intervals. Vector layers of width measurements were created in this way for every reef in each atoll. The vector layers were then imported into the IDRISI GIS where the mean width was calculated for each reef (Fig 4.16).

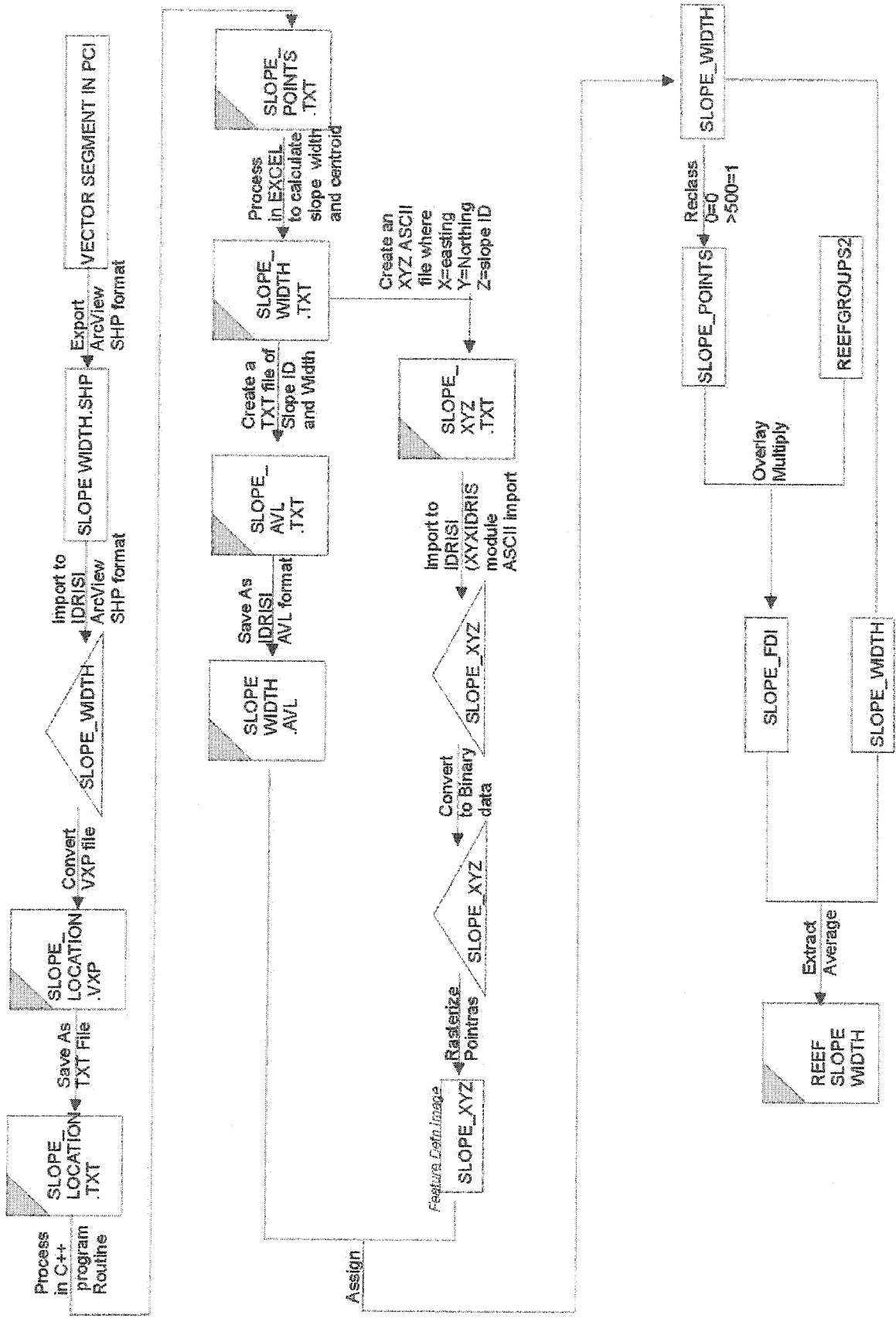
4.2.4.1.4 Compactness ratio

The compactness ratio of polygons can be calculated in IDRISI by the CRATIO module. It is a ratio calculated by comparing the area of a polygon to that of a circle having the same perimeter as the polygon. The formula used to calculate the compactness ratio is

$$C = \sqrt{(A_p/A_c)}$$

where C is the compactness ratio, A_p is the area of the polygon being calculated, and A_c is the area of a circle having the same perimeter as that of the polygon being calculated. This gives an indication how compact an object is.

Figure 4.16 Cartographic model for width measurement of reef slope, reef crest and reef flat classes using IDRISI GIS. The model was run for each classification individually



4.2.4.1.5 Reef Location

When vectorized reef polygons are exported in text format, the polygon is defined precisely by its geographical coordinates for each reef. The data output can be used to measure the extent of X and Y direction for each reef. This will allow the definition of an enclosure for each reef in terms of its X and Y distances. The vector data allows the determination of the location of each reef by averaging the location of all the vertices of the polygon. The end result is the centroid, the central location of the reef polygon.

4.2.4.1.6 Output from GIS

While the output of GIS data as text files was simple for some parameters (such as the reef area, perimeter and ratios), it was in awkward formats for the areas of the seven reef classes and for location coordinates of individual reefs. The simple parameters can be directly read into a spreadsheet but the larger, complex text files (such as those of reef location and enclosure) needed to be interpreted and rearranged into the spreadsheet data format. This would be a difficult task to attempt manually. Two simple programs (a windows scripting program and a C++ routine) were written to automate these two tasks. The location data (Northing and Easting) for each reef was read in UTM coordinates. The X and Y-distances of enclosure for each reef was also measured in UTM.

4.3 Results

4.3.1 Image Classification Results

The final classifications of all 40 scenes depicted the rim and lagoon reefs clearly in interpreted maps generated by multispectral supervised classification and completed by contextual editing and encoding mask-generated reef island and seagrass classes. The thematic maps are attached as bitmap images on the CD-ROM included in the appendices of this thesis. Fig 4.17 shows the classified reefs of Ari atoll for illustration. A thematic map of this nature needs to be accompanied by a level of accuracy reflecting the correspondence between the class labels and the true class, which is defined as what is observed on the ground during field surveys (Campbell 1996; Mumby and Green 2000). PCI GEOMATICA software provides a module for formal accuracy assessment. An accuracy assessment was performed on the classified images using this module with a set of data (100 sites) independent of those used for classification of the imagery. An error matrix best presents the output of an accuracy assessment. Table 4.8 shows the error matrix for a rim reef classification.

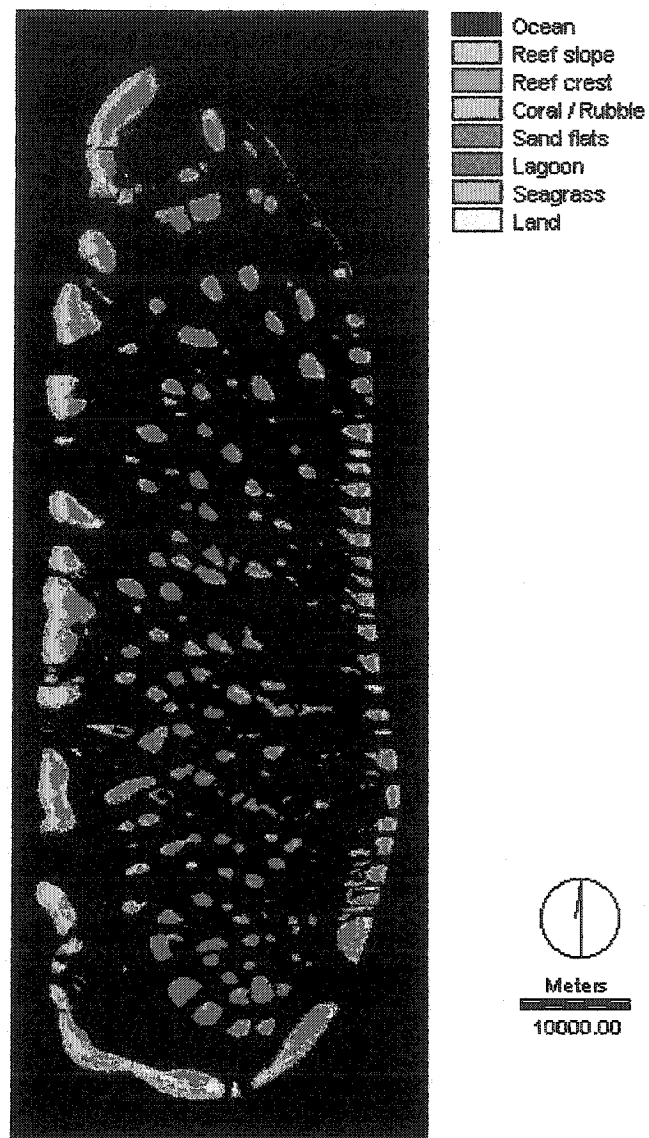


Figure 4.17 Classified thematic map of Ari Atoll. The class "Ocean" refers to deep (>30m) water.

Classified Data	Reference Data							Totals
	Reef slope	Reef crest	Rubble/coral	Sand flat	Lagoon	Seagrass	Reef island	
Reef slope	28	0	1	0	2	1	0	32
Reef crest	1	11	2	0	0	0	0	14
Rubble/coral	0	4	17	0	0	0	0	21
Sand flat	1	0	3	11	0	0	0	15
Lagoon	3	0	0	0	7	0	0	10
Seagrass	0	0	0	0	0	1	0	1
Reef island	0	0	0	1	0	0	6	7
Totals	33	15	23	12	9	2	6	100

$$\text{Overall Accuracy} = (28+11+17+11+7+1+6)/100 = 81\%$$

Class Name	Producer's Accuracy		User's Accuracy		Kappa Statistic
Reef slope	28/33	84.85%	28/32	87.50%	0.81
Reef crest	11/15	73.33%	11/14	78.57%	0.75
Rubble/coral	17/21	73.91%	17/21	80.95%	0.75
Sand Flat	11/12	91.67%	11/15	73.33%	0.70
Lagoon	7/9	77.78%	7/10	70.00%	0.67
Seagrass	1/2	50.00%	1/1	100.00%	1.00
Reef island	6/6	100.00%	6/7	85.71%	0.85

Table 4.8 Error matrix for the thematic map output generated by supervised multispectral classifications complemented by contextual editing and mask-generated reef island and seagrass classes. Classified data categories are in rows and ground referenced data in columns. Overall accuracy is the number of correctly classified pixels (diagonals) divided by the total number of reference points. Producer's accuracy is the correctly classified pixels (diagonal values) divided by column totals. User's accuracy is the correctly classified pixels (diagonals) divided by the row totals.

The overall accuracy of the classification Dhaalu atoll was 81% (95% Confidence Interval = 72.81%, 89.19%) i.e., 81 of 100 reference pixels were correctly classified. The overall KAPPA statistic was 0.76. Producer and user accuracies for individual classes are shown in Table 4.8. Producer accuracy is the probability that individual classes were correctly classified by the classifier whereas the user accuracy is probability that the individual classes on the ground are correctly classified. The level of overall accuracy reported here is in agreement with most studies reporting accuracies of thematic maps generated from Landsat satellite imagery at comparable resolutions (Ahmed and Niel 1994; Green et al. 1996, Mumby et al. 1997; Mumby and Harborne 1999; Andréfouët et al. 2001b)

4.3.2 Reef Morphometrics

The atolls of the Maldives consist of 16 large morphologically complex atolls, 5 oceanic ring reefs (i.e., simple atolls) and 4 oceanic reef islands (Fig 4.2). The metrics described here are for the 16 large atolls only. The remaining reefs (oceanic ring reefs and oceanic reef islands) were mapped and quantified separately in order to get accurate reef area for the Maldives' atolls (see Chapter 6). Table 4.9 shows prominent metrics of the 16 complex atolls mapped in this study. The complete descriptive statistics of all reef morphometrics are reported on the CD-ROM included in the appendices of this thesis.

Atoll #	Atoll ID	Surface Area (km ²)	Perimeter (km)	Aperture	Total rim reef area (km ²)	Total lagoon reef area (km ²)	Total reef area (km ²)	# of rim reefs	# of lagoon reefs	Total # of Reefs
1	I	289.8	93.4	0.14	112.8	6.8	119.6	10	20	30
2	H	3788.7	494.9	0.31	330.6	93.9	424.4	72	80	152
3	R	1184.3	196.9	0.26	182.6	40.9	223.6	42	113	155
4	B	1126.9	173.6	0.24	123.5	75.1	198.6	29	50	79
5	LH	701.4	147.8	0.08	143.3	14.7	158.0	26	58	84
6	NM	1568.2	206.7	0.17	257.6	91.4	349.0	47	142	189
7	SM	536.3	114.6	0.14	137.0	38.7	175.7	23	89	112
8	A	2271.7	261.6	0.35	269.3	219.7	489.0	62	204	266
9	V	1090.9	213.4	0.13	218.9	37.1	256.0	51	152	203
10	M	983.9	164.2	0.06	179.6	17.7	197.4	25	86	111
11	F	597.2	121.3	0.16	118.1	33.2	151.2	22	64	86
12	D	736.4	128.3	0.15	147.6	31.9	179.5	17	81	98
13	T	1695.8	200.8	0.06	219.3	24.4	243.7	20	131	151
14	L	884.6	165.5	0.03	190.3	13.4	203.8	7	49	56
15	G	3278.6	326.4	0.09	301.5	53.3	354.7	31	171	202
16	S	157.2	77.5	0.03	70.2	0.1	70.4	4	3	7

Table 4.9 Metrics of the 16 complex atolls of the Maldives. Refer to Fig 4.3 and Table 3.1 for atoll names and atoll ID. Atolls are numbered from North to South, with 1, 2 and 13-16 forming the single atoll chains in the north and south respectively, and 3-12 forming the double chain.

Atoll surface areas (including the rim and the lagoon) in the Maldives ranged from 157.2 km² to 3788.7 km². The two largest atolls in the Maldives have a total surface area of 3788.7 km² (atoll H, Fig 4.3) and 3278.6 km² (atoll G, Fig 4.3). These are also the two largest coral atolls in the world (www.reefbase.org). The smallest complex atoll mapped here had a surface area of 157.2 km² (S atoll, Fig 4.3). Depending on the definition of atoll used, there may be smaller atolls in the Maldives that were not mapped for the development of the atoll metrics presented here (see Chapter 6 on reef area). Here, these small, atoll-shaped reefs are considered as “oceanic ring reefs” or *faro*. There is a real need to re-evaluate our definitions of “atoll” in order to generalize views on comparative studies of atolls. What is considered to be just an annular ring reef (e.g. a *faro*) in the Maldives is commonly defined as an atoll in many Pacific regions. The results of this study enables us to make interesting comparisons with major Pacific groups of atolls. Andréfouët et al. (2001a) reported that atoll area in Tuamotu, French Polynesia ranged from 6.1 km² to 448.8 km². Atoll area (measured in terms of total lagoon area) in the Marshall Islands ranges from 8.4 km² to 2173.8 km² (Spennemann, (1998); URL: <http://life.csu.edu.au/marshall/html/atolls>). The point of interest here is that there are many “atoll shaped” reefs (in other words: atolls within atolls) in the Maldives, which have areas much larger than the smallest of the atolls in the Pacific. The question then is; are these atolls or simply ring shaped reefs?

Total reef area was greatest in atoll ‘A’ with an area of 489.0 km², followed by atolls ‘H’ and ‘G’, which measured 424.4 and 354.7 km² respectively. Atoll ‘A’ also had the most reefs on it. Atoll surface area was highly correlated with total area of all rim reefs within the atoll ($r = 0.92$, $p = 0.001$, $n = 16$; Fig 4.18). Only a poor correlation was found, however, between atoll surface area and total lagoon reef area ($r = 0.55$, $n=16$). This indicates that reef growth in the atoll lagoon is not a simple function of the size of the atoll. It may be related to the aperture (hydrodynamic openness) of the atoll rim, as investigated in detail in Chapter 5. The proportions of the seven reef habitat classes were determined for each of the 488 rim reefs and 1493 lagoon reefs mapped in 16 atolls of the Maldives (Tables 4.10 and 4.11).

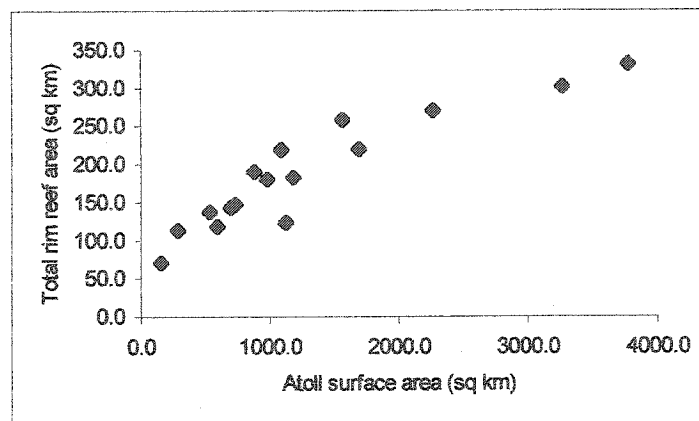


Figure 4.18 Scatterplot of atoll surface area and rim reef area for 16 large atolls of the Maldives (Pearson correlation; $r = 0.92$, $p = 0.001$, $n = 16$).

Atoll #	Atoll ID	No of rim Reefs	Mean reef area (km ²)	Mean Slope proportion	Mean Crest proportion	Mean Rubble proportion	Mean Sand Flat proportion	Mean Lagoon proportion	Mean Seagrass proportion	Mean Reef island proportion
1	I	10	11.28	0.41	0.12	0.17	0.10	0.05	0.01	0.15
2	H	72	4.59	0.31	0.12	0.16	0.11	0.07	0.00	0.22
3	R	42	4.35	0.32	0.11	0.16	0.12	0.10	0.00	0.19
4	B	29	4.26	0.26	0.21	0.08	0.19	0.13	0.00	0.12
5	LH	26	5.51	0.35	0.21	0.19	0.06	0.08	0.03	0.08
6	NM	47	5.48	0.26	0.19	0.19	0.06	0.23	0.00	0.05
7	SM	23	5.95	0.22	0.21	0.22	0.03	0.29	0.00	0.02
8	A	62	4.34	0.16	0.16	0.23	0.02	0.37	0.01	0.05
9	V	51	4.29	0.19	0.19	0.34	0.03	0.24	0.00	0.02
10	M	25	7.19	0.13	0.19	0.28	0.12	0.26	0.01	0.02
11	F	22	5.37	0.14	0.17	0.35	0.08	0.21	0.01	0.04
12	D	17	8.68	0.16	0.16	0.28	0.09	0.27	0.00	0.03
13	T	20	10.96	0.17	0.16	0.21	0.08	0.31	0.01	0.06
14	L	7	27.19	0.15	0.15	0.26	0.09	0.17	0.08	0.11
15	G	31	9.73	0.17	0.23	0.18	0.11	0.16	0.07	0.08
16	S	4	17.56	0.21	0.23	0.17	0.03	0.15	0.06	0.14

Table 4.10 Mean proportions (area) of each of seven habitat classes mapped for 488 atoll rim reefs in 16 atolls of the Maldives. Atolls are numbered from North to South, with 1,2 and 13-16 forming the single atoll chains in the north and south (respectively), and 3-12 forming the double atoll chain.

Atoll #	Atoll ID	No of lagoon Reefs	Mean reef area (km ²)	Mean Slope proportion	Mean Intertidal proportion	Mean Rubble proportion	Mean Sand Flat proportion	Mean Lagoon proportion	Mean Seagrass proportion	Mean Reef Island proportion
1	I	20	0.34	0.84	0.09	0.04	0.02	0.00	0.000	0.02
2	H	80	1.17	0.35	0.17	0.06	0.04	0.12	0.003	0.26
3	R	113	0.36	0.46	0.22	0.10	0.10	0.05	0.000	0.06
4	B	50	1.50	0.12	0.25	0.04	0.32	0.16	0.000	0.11
5	LH	58	0.25	0.80	0.10	0.09	0.01	0.00	0.000	0.00
6	NM	142	0.64	0.28	0.26	0.13	0.07	0.23	0.000	0.02
7	SM	89	0.44	0.26	0.25	0.12	0.16	0.19	0.000	0.01
8	A	204	1.08	0.19	0.19	0.10	0.05	0.45	0.000	0.01
9	V	152	0.24	0.31	0.17	0.14	0.30	0.08	0.000	0.00
10	M	86	0.21	0.65	0.17	0.09	0.08	0.01	0.000	0.00
11	F	64	0.52	0.27	0.28	0.13	0.18	0.12	0.000	0.01
12	D	81	0.39	0.35	0.21	0.08	0.17	0.16	0.000	0.03
13	T	131	0.19	0.52	0.33	0.09	0.03	0.02	0.000	0.01
14	L	49	0.27	0.68	0.15	0.14	0.03	0.00	0.001	0.01
15	G	171	0.31	0.37	0.27	0.16	0.15	0.02	0.000	0.03
16	S	3	0.04	0.74	0.26	0.00	0.00	0.00	0.000	0.00

Table 4.11 Mean proportions (area) of each of seven habitat classes mapped for 1493 atoll lagoon reefs in 16 atolls of the Maldives. Atolls are numbered from North to South, with 1,2 and 13-16 forming the single atoll chains in the north and south (respectively), and 3-12 forming the double atoll chain.

The most striking difference between rim and lagoon reefs is the high proportion of deep reef (slope) areas on lagoon reefs. Atoll lagoon patch reef growth appears to be dependent on rim aperture, and it is predicted that patterns of atoll lagoon reef growth (in terms of reef slope and emerged reef flat domains) will reflect the lagoon circulation and exchange, which are governed in large part by atoll aperture (Atkinson et al. 1981). Waves do not generally break on atoll lagoon reefs unless they face in-coming swells just inside the mouth of a deep rim pass. Hence they do not have well defined reef crests. Instead, a coral flat of variable width defines the shallow margin of the reef.

Lagoon reefs support few extensive seagrass beds (Table 4.11). Seagrass was most abundant on rim reefs in the 3 southern most atolls (Table 4.10). Their distribution reflects the different hydrodynamic and nutrient regimes of lagoon reefs compared to rim reefs. Miller and Shuka (1999) reported that seagrass abundance around reef islands in the Maldives is related to human settlements and fishery-derived nitrification of island beach and shallow lagoon areas on a given reef.

Atoll lagoon reefs were considerably smaller in their total surface area when compared to rim reefs. The area of lagoon reefs ranged from 0.02 to 6 km² whereas rim reefs ranged between 0.06 and 83 km². Mean area for rim reefs was 6.15 km² and 0.5 km² for lagoon reefs (Tables 4.10, 4.11).

The X and Y- distance variables (Fig 4.8) for rim reefs were significantly correlated ($R=0.81$, $n = 488$) at the 0.01 level (Fig 4.19). The pattern of scatter in Fig 4.19 is not a true indication of the predominant preference for growth in terms of the east-west and north-south extent of reefs. These two variables are measures of reef enclosure (in the east-west and north-south directions) and therefore do not reflect the orientation of the reef and the growth axis of the reef. Further analysis of reef orientation in terms of its major and minor axis may generate better interpretations in terms of preferential growth directions of rim reefs.

Scatter plots of all the main dimensional metrics of rim reefs (X-distance, Y-distance, Area, Perimeter) show high correlations, as expected because of their inherent interdependence (R ranged from 0.81 to 0.97, $p = 0.01$, $n = 488$; Fig 4.20)

Scatterplot of X_distance against Y_distance

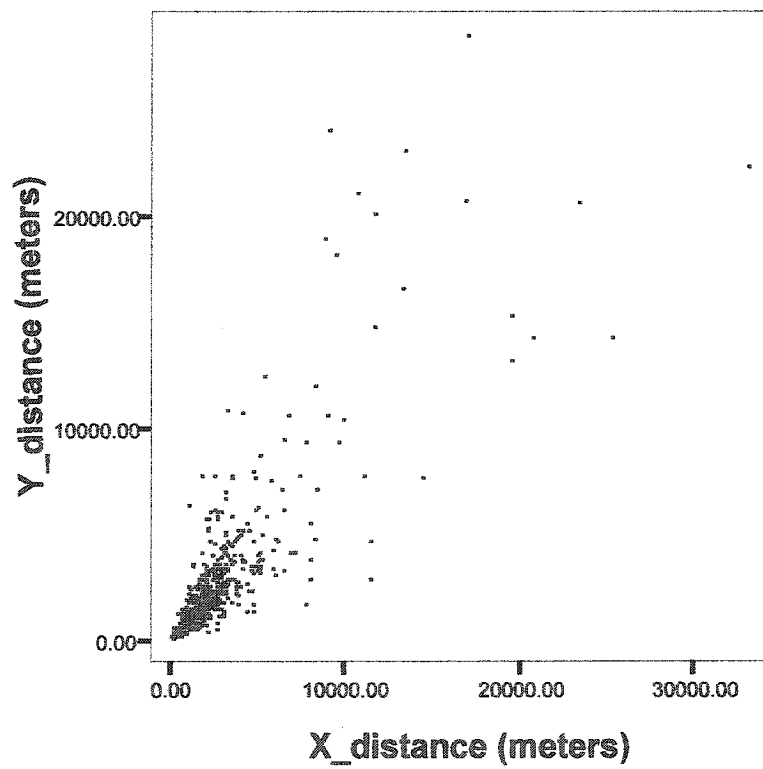


Figure 4.19 Scatter plot of X-distance (extent of the reef east to west) against Y-distance (extent of the reef north to south)

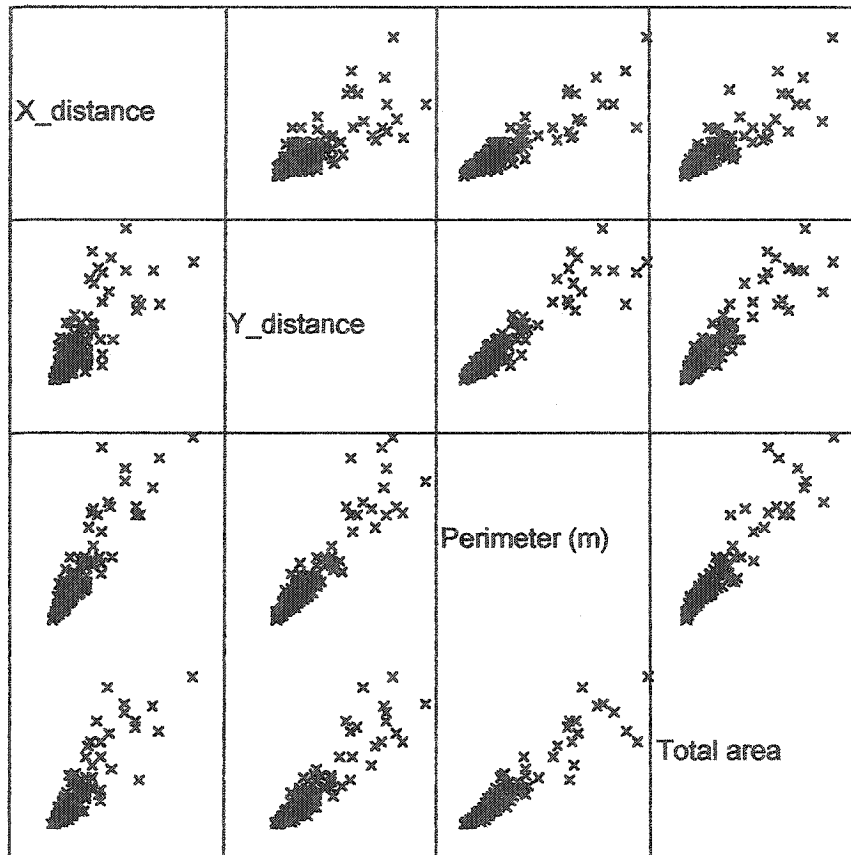


Figure 4.20 Scatterplot matrix of X-distance, Y-distance, Reef perimeter and Reef Area of 488 rim reefs in 16 atoll of the Maldives. Pearson correlation coefficients are given for each relationship ($r > 0.81$, $n = 488$, $p = 0.01$)

The reef slope, reef crest and reef flat on rim reefs are structures that best reflect hydrodynamic forcing on a reef (Roberts et al. 1992). Windward slopes and crest dissipate most of the wave energy reaching a reef. With this in mind, the widths of reef slope, reef crest, and reef flat were measured on classified imagery to examine wave-forcing relationships on rim reefs (Fig 4.7). Slope width, crest width and reef flat were significantly correlated at the $p = 0.01$ level (for crest vs. flat, $r = 0.41$, $n = 466$; slope width vs. flat width, $r = 0.42$, $n = 452$ and Slope vs. crest, $r = 0.38$, $n = 451$; Fig 4.21). The variation of widths of reef slopes and crest among the 16 atolls are shown in Fig 4.22.

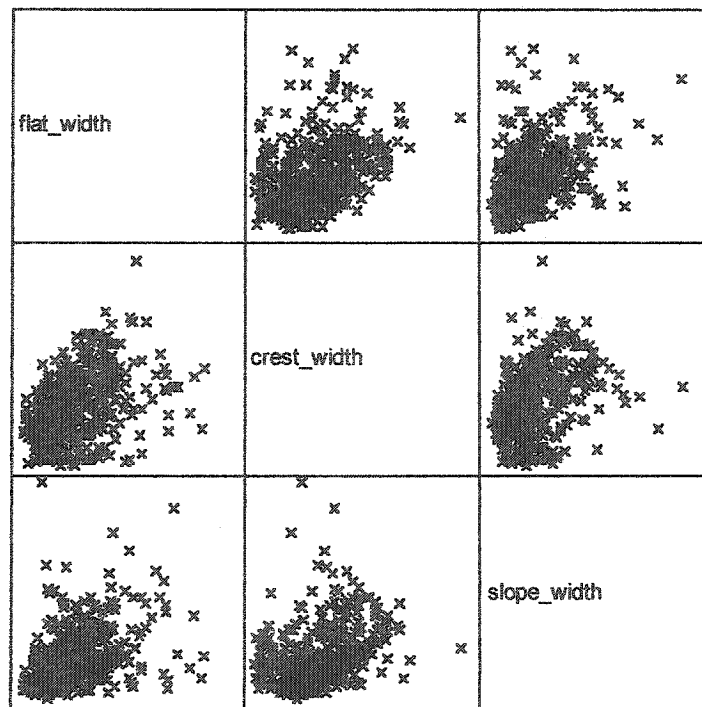


Figure 4.21 Scatterplot matrix of reef flat, slope and crest widths of 488 rim reefs in 16 atolls of the Maldives. Pearson correlation coefficients for each relationship ($r > 0.38$, $n > 450$, $p = 0.01$) are given in the text.

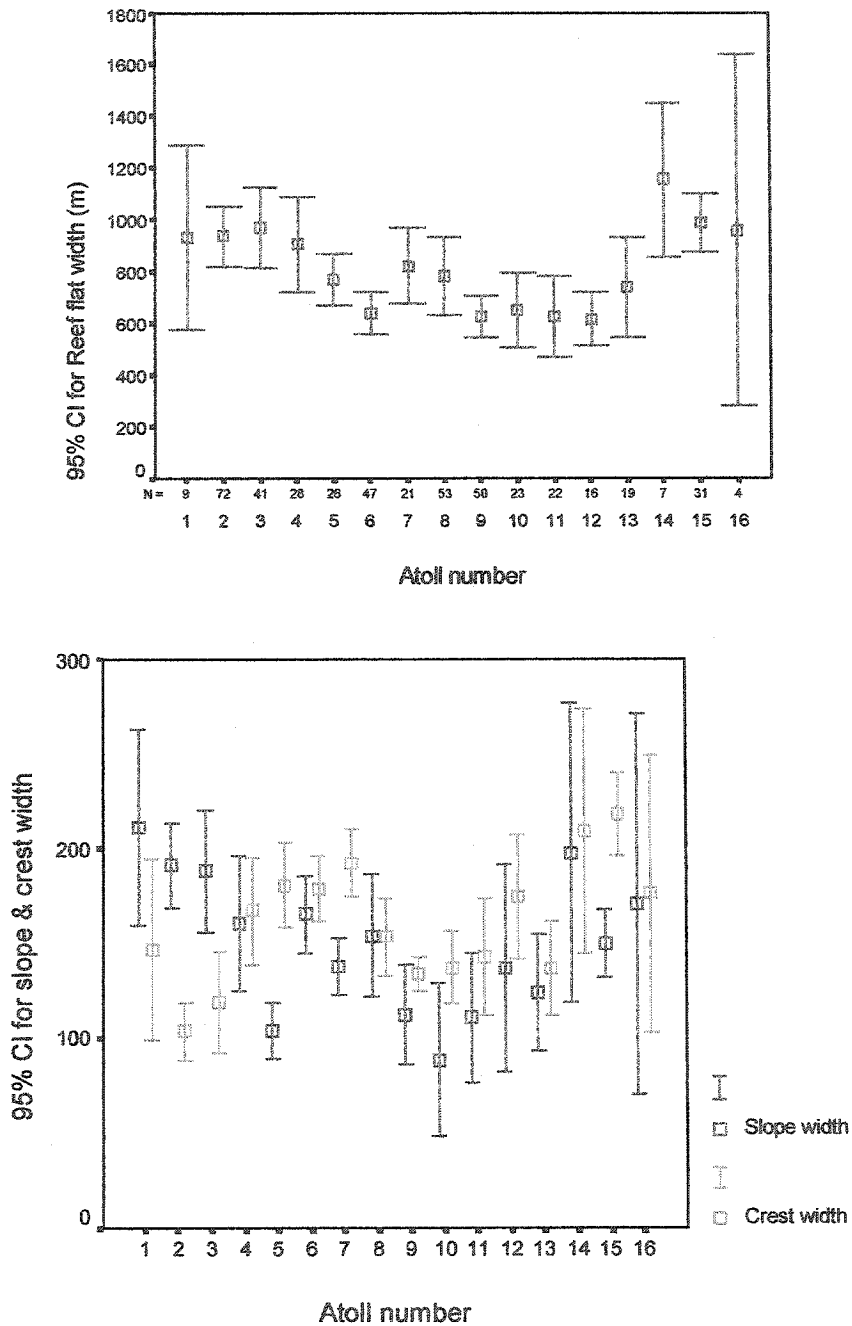


Figure 4.22 Mean widths of reef flat (upper plot) slope and crest (lower plot) on 488 rim reefs in 16 atolls of the Maldives. Atolls are numbered from North to South, with 1,2 and 13-16 forming the single chains in the north and south (respectively), and 3-12 forming the double atoll chain. Error bars are 95% confidence intervals about the mean.

Distribution of reefs across the entire Maldives archipelago indicates that the largest reefs of the system exist towards the eastern and southern regions of the atolls (Fig 4.23). The reefs are also longer and more ribbon-like towards southern and south-eastern regions.

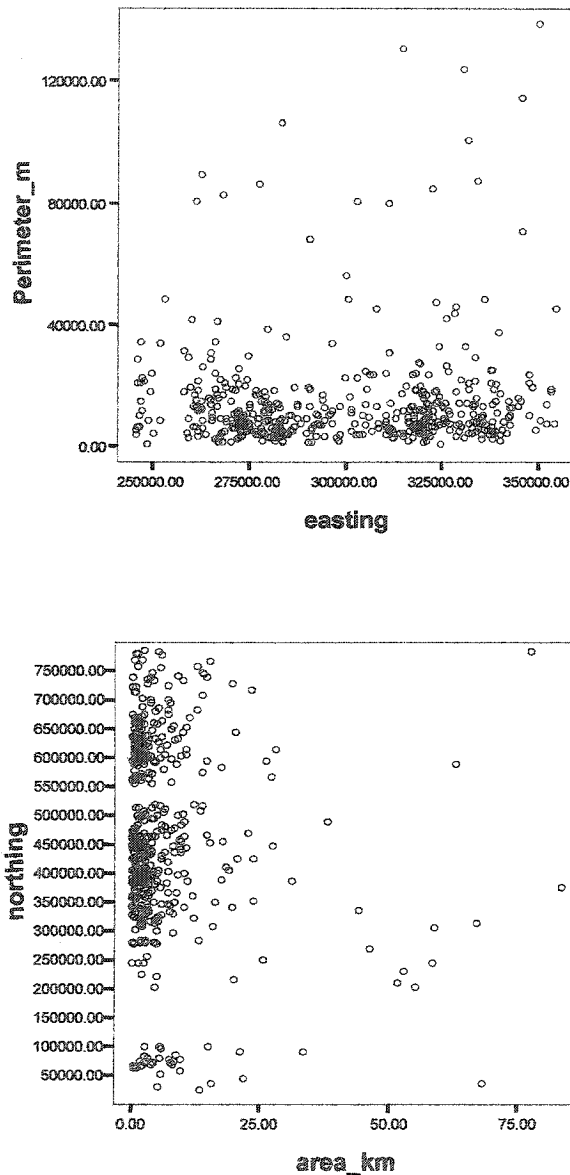


Figure 4.23 Distributions of reef area and perimeter in the east-west (Easting: upper plot) and north-south (Northing: lower plot) directions (resp.) for 488 rim reefs in 16 atolls of the Maldives. The largest reefs occur towards the south and eastern regions of atoll chain (from which direction come the predominant Indian Ocean swells; Chapter 5).

Total areas of reef habitat classes given in Table 4.12 and 4.13 should be interpreted with caution when generalizing these results to the atolls of the Maldives and for other comparisons. Not all habitats in every reef on every atoll or all other, non-atoll reefs were mapped in developing this database. A small proportion of rim and lagoon reefs in some atolls were not fully mapped due to cloud cover. But all reefs were mapped to get the best estimate of total reef area for the Maldives (Chapter 6). In particular, the apparent absence of seagrass classes from some atolls (Table 4.12) may not be real, because seagrass beds smaller in extent than the spatial resolution of the Landsat 7 ETM+ imagery (30m x 30m) may not be mapped. Therefore many small seagrass areas, which are quite common around reef islands, may have been missed. For example it is known that 'B' atoll (Fig 4.2) has seagrass beds but none were mapped here. The spectral signature of sparse seagrass is also quite similar to another reef class (sand/rubble), and hence it may again be misclassified. There is also the possibility that a reef or reefs on which seagrass does occur was not mapped due to cloud cover.

Atoll #	Atoll ID	Total Reef Slope area (km ²)	Total Crest area (km ²)	Total Coral/rubble area (km ²)	Total Sand Flat area (km ²)	Total Reef Lagoon area (km ²)	Total Seagrass Island area (km ²)	Total Reef area (km ²)
1	I	43.0	10.3	14.2	30.2	9.0	0.7	5.4
2	H	86.7	30.4	78.0	56.8	39.9	1.9	37.2
3	R	38.5	20.4	44.8	22.0	48.4	0.5	9.0
4	B	22.8	16.8	18.0	27.3	35.1	0.0	3.2
5	LH	41.2	25.2	28.6	21.2	18.1	1.9	7.1
6	NM	51.2	41.4	54.6	23.6	76.3	1.9	8.6
7	SM	18.0	20.3	39.5	11.1	45.5	0.7	1.8
8	A	40.1	36.2	84.9	9.0	91.1	1.2	6.8
9	V	27.2	34.0	72.3	15.2	69.3	0.0	0.9
10	M	18.5	33.2	45.8	32.9	43.2	1.9	4.2
11	F	15.7	14.9	45.2	10.1	30.2	0.3	1.8
12	D	20.5	22.2	38.6	16.7	45.8	0.5	3.3
13	T	38.1	31.9	56.0	25.8	54.7	3.7	9.1
14	L	21.4	29.7	45.7	25.2	29.8	15.6	23.0
15	G	36.4	62.2	49.3	46.4	58.9	23.3	24.9
16	S	10.8	14.2	10.4	1.5	10.8	7.9	14.7

Table 4.12 Total areas (km²) of seven reef classes mapped on atoll rim reefs from satellite imagery. Atolls are numbered from North to South, with 1,2 and 13-16 forming the single atoll chains in the north and south (resp.), and 3-12 forming the double atoll chain.

Atoll #	Atoll ID	Total Reef slope area (km ²)	Total Intertidal area (km ²)	Total Coral/rubble area (km ²)	Total Sand Flat area (km ²)	Total Reef Lagoon area (km ²)	Total Seagrass area (km ²)	Total Reef Island area (km ²)
1	I	4.9	0.8	0.5	0.3	0.0	0.0	0.3
2	H	29.6	17.0	8.9	4.8	10.7	0.4	22.5
3	R	11.3	8.6	7.0	8.0	2.5	0.0	3.9
4	B	6.9	14.3	4.9	21.3	25.3	0.0	2.3
5	LH	10.7	1.5	2.3	0.2	0.0	0.0	0.1
6	NM	20.7	19.2	13.4	7.2	30.2	0.0	0.8
7	SM	7.4	6.9	4.9	7.5	11.8	0.0	0.2
8	A	24.2	36.9	24.6	9.4	123.3	0.0	1.4
9	V	7.9	4.8	5.1	12.6	6.5	0.0	0.0
10	M	12.5	2.4	1.3	1.1	0.5	0.0	0.0
11	F	4.2	7.9	5.1	5.7	10.0	0.0	0.4
12	D	7.5	5.6	2.7	7.4	7.6	0.0	1.1
13	T	11.3	6.6	3.2	2.1	1.1	0.0	0.2
14	L	7.8	1.8	2.7	0.8	0.0	0.1	0.3
15	G	15.2	11.2	9.5	11.6	3.6	0.0	2.2
16	S	0.1	0.0	0.0	0.0	0.0	0.0	0.0

Table 4.13 Total areas (km²) of seven reef habitat classes mapped on atoll lagoon reefs from satellite imagery. Atolls are numbered from North to South, with 1,2 and 13-16 forming the single atoll chains in the north and south (resp.), and 3-12 forming the double atoll chain.

Atoll lagoon reefs in general had very little land on them except in 'H' atoll, where lagoon reefs supported 22.5 km² of reef islands. This may be related to the openness of this very large atoll. Otherwise most land in the atolls was found on rim reefs. In the 16 atolls mapped, total land (reef islands) on lagoon reefs was 35.7 km² and on rim reefs the total was 161 km². Land on lagoon reefs thus accounted for only 18 % of the total land area of the atolls. The 'V' atoll had the least land area at just under 1 km². Interestingly this atoll with so very little land had the fifth largest reef area (256 km²) in all the 16 atolls. This atoll also had the largest rim reef in all of the Maldives at 83.5 km². Total land area was correlated with atoll area (R=0.75).

Shapes of reefs were investigated using well-established morphometric ratios (Davis, 1986), which use both area and perimeter of an object to give shape estimations. Three variants of shape expressions were used, all of which were closely correlated so that any one of them is sufficient to describe the shapes of reefs. The thinness ratio increased with how compact or how circular a reef is (Fig 4.24). In other words the lower the ratio, the thinner the reef is.

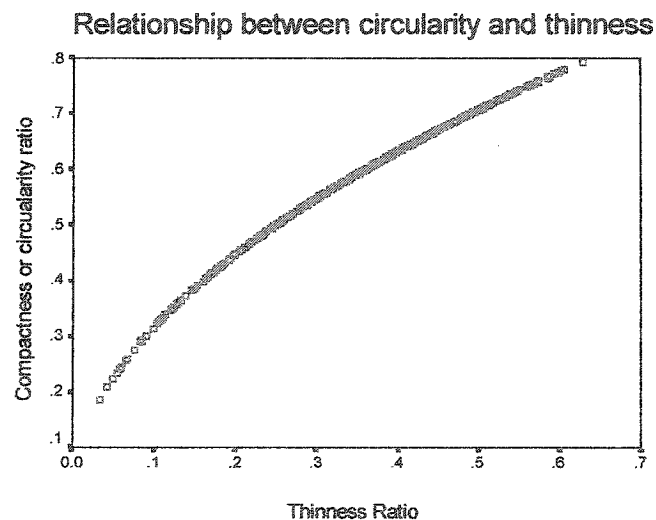


Figure 4.24 Relationship between Compactness ratio and Thinness ratio for 488 rim reefs of the Maldives.

Rim reefs appeared to be rounder in northern and central western atolls than southern and central eastern atolls. Thinner and more ribbon-like reefs occurred on the rims of southern atolls (Table 4.14, Fig 4.25). It is predicted that that southern and southern eastern facing reefs receive more swell and high-energy waves, and hence rim reefs are more linear in shape than northern and western reefs, which does not receive swell waves. This prediction will be tested in Chapter 5.

Atoll #	Atoll ID	Atoll location (latitude)	Circularity Ratio	Thinness Ratio
1	I	7.00	0.58	0.35
2	H	6.25	0.66	0.45
3	R	5.58	0.67	0.45
4	B	5.25	0.63	0.40
5	LH	5.40	0.59	0.36
6	NM	4.40	0.57	0.34
7	SM	4.00	0.53	0.29
8	A	3.80	0.56	0.32
9	V	3.50	0.55	0.32
10	M	3.00	0.58	0.36
11	F	3.20	0.60	0.37
12	D	2.80	0.56	0.32
13	T	2.40	0.53	0.30
14	L	1.90	0.40	0.19
15	G	0.50	0.51	0.28
16	S	-0.60	0.44	0.21

Table 4.14 Mean shape ratios of rim reefs in atolls of the Maldives. Atolls are numbered from North to South, with 1,2 and 13-16 forming the single atoll chains in the north and south (resp.), and 3-12 forming the double atoll chain.

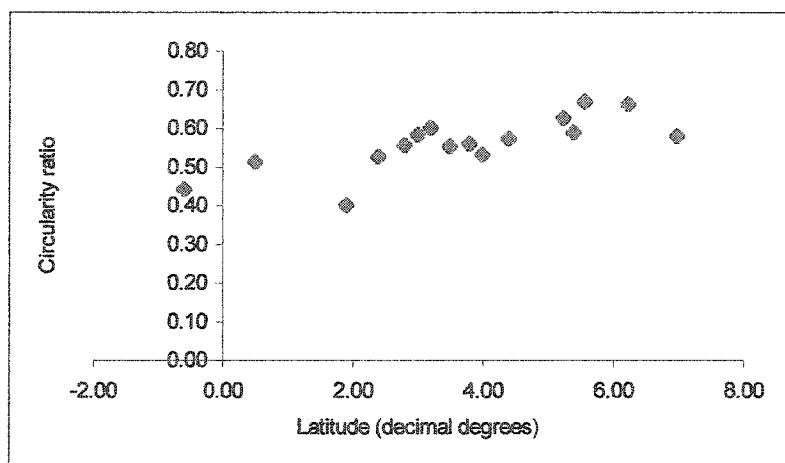


Figure 4.25 The north-south pattern of reef shape displayed in terms of mean circularity of rim reefs in 16 atolls of the Maldives. N ranges from 4 to 72 per atoll.

In Fig 4.25 Low reef circularity ratios are observed in some atolls around 4 degrees latitude. These atolls are located on the eastern part of the double chain where they are exposed to heavy swells.

Atoll #	Atoll ID	Atoll location (latitude)	Circularity Ratio	Thinness Ratio
1	I	7.00	0.72	0.52
2	H	6.25	0.71	0.51
3	R	5.58	0.68	0.47
4	B	5.25	0.69	0.48
5	LH	5.40	0.70	0.49
6	NM	4.40	0.67	0.45
7	SM	4.00	0.68	0.46
8	A	3.80	0.64	0.42
9	V	3.50	0.70	0.50
10	M	3.00	0.70	0.50
11	F	3.20	0.69	0.48
12	D	2.80	0.68	0.47
13	T	2.40	0.70	0.50
14	L	1.90	0.68	0.46
15	G	0.50	0.69	0.49
16	S	-0.60	0.71	0.51

Table 4.15 Mean shape ratios of lagoon reefs. Note the similarity of ratios in all atolls. Atolls are numbered from North to South, with 1,2 and 13-16 forming the single atoll chains in the north and south (resp.), and 3-12 forming the double atoll chain.

The mean shape ratio for all lagoon reefs is 0.69 ($n = 1423$) and for all rim reefs the mean is 0.58 ($n = 488$). The shapes of lagoon reefs are very similar across the 16 atolls (Table 4.15 and Fig 4.26). They were also rounder (a circularity ratio closer to 1) than rim reefs. Lagoon reefs grow in very different hydrodynamic conditions compared to atoll rim reefs, which take the all the force of waves and swells. Here, we have circumstantial evidence that reefs, which grow in lower hydrodynamic regimes (i.e., in atoll lagoons), have more circular shapes than reefs than those that receive high wave energy.

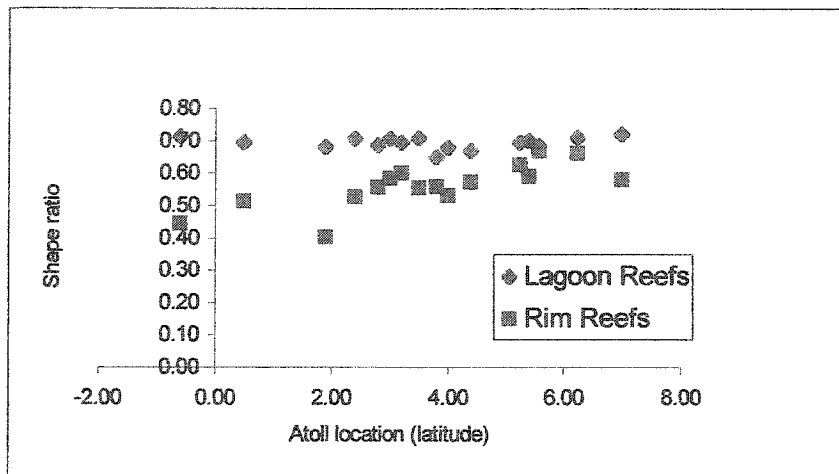


Figure 4.26 Variation of mean shape ratios of lagoon reefs and rim reefs in 16 atolls plotted against atoll location in the Maldives. N ranges from 4 to 72 for rim reefs and 3 to 204 for lagoon reefs per atoll.

4.4 Discussion

This research has demonstrated the usefulness of satellite remote sensing and GIS as tools for mapping and quantifying a wide variety of morphometric and habitat attributes of remote coral reefs spread over vast areas of ocean space. Shallow, geomorphological reef zones covered with optically clear water can be detected and demarcated confidently using data from satellite sensors calibrated with sound local knowledge of representative reefs. Landsat ETM+ imagery provides suitable spectral and spatial resolutions at an affordable price to map coral reef geomorphology at whole reef province scales. Large-scale quantitative data are prerequisites for scaling analysis of coral reefs and interdisciplinary research (Hatcher et al. 1987; Mumby et al. 2001). Reef features such as the reef slopes (30 to 200 m width), reef crests (30-300 m width) reef flats (100 m to 2 km width) and lagoons (200 m to many km) were consistently and accurately mapped from ETM+ imagery. Many hundreds of reefs spanning an area 900 x 200 km (180,000 km²) in the central Indian Ocean were mapped and classified at 30 x 30m (0.0009 km²) spatial resolution at a cost of ~ \$ 9000 for the data products. At the scale of gross geomorphological features (i.e., 10's to 100's m) good accuracies (81% overall) were obtained from maximum likelihood classifications with minimal ground truthing.

Applications of remote sensing to coral reef studies have shown varying results depending on the objectives and application (Green et al. 1996). Sensor resolution is probably the most important issue in many studies (Andréfouët et al. 2002). There has been a considerable increase of remote sensing applications to coral reefs in recent years, and a few of these focused entirely on research relating to coral reef geomorphology or zonation (Andréfouët et al. 2001; Millennium Coral Reef Mapping Project).

Given the broad geomorphological classes mapped here, certain assumptions and decisions were made on the levels of accuracy that would be tolerated in the classifications. The interest here is to map the zonation of reef morphologies that reflect

the long-term integration of reef growth processes. Therefore, sub pixel variation within the broad morphological zones was not a concern. For example there are patch reefs of a few pixels size (30 to 100 m across) within reef lagoons on individual reefs, but they were forcibly classified (both with image training and contextual editing) as part of the lagoon rather than a separate morphological category or members of the existing classes. It was not necessary to classify them as a separate class for the purposes entailed here. Similarly there are small patches of corals on otherwise homogenous sand flats, which were not mapped as separate classes. The objective here was to assign all surface components of a reef to one of the seven classes under investigation without a null class.

Most geomorphological work on coral reefs consists of studies of a few individual reefs, the results of which are generalized to large biogeographical regions (Hopley 1982; Guilcher 1988). The use of remote sensing provides an effective research tool that can be used to build comprehensive reef databases for hundreds and even thousands of reefs over extensive areas using uniform methods, thereby allowing us to investigate physical and biological processes at the required scales. A world-wide project on mapping of coral reef geomorphology is currently underway (Millennium Coral Reef Mapping project, <http://imars.marine.usf.edu/corals/seascape.html>). When completed, this initiative will provide the most up-to-date information on structure and pattern formation in atoll reef systems worldwide.

Remote sensing studies have been directed at coral reefs for at least 30 years (Smith et al. 1975; Pirazzoli 1982; Armstrong 1983; Classen and Pirazzoli 1984; Bour et al. 1986). But large-scale applications are virtually lacking (Green et al. 1996). There are no published studies in which reefs of even a single geographic province or reef system have been completely mapped using satellite imagery. Inventories of coral reefs and associated habitats have been at best estimated from crude navigational maps. The most comprehensive and exhaustive study of coral reef areas in the world today (Spalding et al. 2001) was largely based on navigational charts of different scales. This is perhaps indicative of the continuing uncertainties and misgivings researchers have in the use of remote sensing as a mapping tool, despite much advances over the last two decades. The

experiences gained in the research presented here indicate that coral reefs can be mapped using space borne imagery with a considerable investment both in terms of training and expertise, software and hardware. If these requirements are met fully, remote sensing and GIS are the ideal tools for coral reef mapping and quantification at sensor-specific scales. It is interesting to note that very few studies based on satellite imagery have been initiated by governments of coral reef countries in order to map and quantify reefs, despite their expediency for both reef science and for management.

The major constraint to mapping reefs is the availability of good imagery. A complete set of cloud free images for this study was only available within three years after the Landsat 7 ETM+ sensor started collecting imagery of the Maldives. Availability of atoll reef imagery has been made possible by NASA's LTAP program, which pledges to a regular long-term collection of coral reef imagery. Older Landsat imagery (TM and MSS) was not regularly collected for oceanic coral reefs. A search for the Maldives' atolls did not generate a complete set of cloud free TM or MSS images. Another major constraint has been the cost of imagery but the sudden drop in cost for Landsat 7 ETM+ imagery has largely solved this. A complete set of eight Landsat images covering all the atolls the Maldives can be purchased for approximately US \$ 3800.00. This is a fraction of the cost of Landsat TM imagery.

High resolution reef maps generated from satellite image can be used for management purposes (Green et al. 1996; 2000). Quantitative maps simplify reef management and depictions of "reef-use". Useful management metrics for atolls and reef islands currently in use (e.g. atoll area, lagoon depth, reef island size, etc.) have been developed from old survey charts, and are unreliable for many management needs. Geomorphologically defined habitats on reefs such as lagoons and reef islands are better suited for resource inventories. They can be used in conjunction with species data to assess and estimate fishery yields and harvests (e.g. Hatcher 2003). The maps can also be used in a GIS to plan research and in the selection of marine protected areas (Mumby et al. 1995). The data obtained from satellite-based maps are quantitative per reef, and can be used to answer questions relating to large-scale processes on coral reefs (see Chapter 5).

There are many global and regional initiatives to monitor the world's coral reefs (Wilkinson 2002). Most are summaries of many small scale studies based on a few transects at best, and are well coordinated by regional centres using standardized survey methods. The lack of a base map that describes the extent of coral reefs places a major constraint on monitoring reef resources and health in many coral reef countries and regions. Many times lack of detailed base maps hinders sound planning at the beginning of programs. If a global and regional effort, equivalent to the Global Coral Reef Monitoring Network (GCRMN; Wilkinson 2002) for example, can be developed to map and quantify coral reefs of the world in a collaborative fashion with standardized methods, it would be a valuable service to coral reef management globally. Data from such centres can be conveniently managed at existing centres of excellence (e.g. coral reef database at www.reefbase.org). Base maps of reef data are vital to complement regular national data collected at higher resolutions, such as coral cover, fish abundance and lagoon infilling on individual reefs. The dataset presented here is one of the first of its kind for an entire reef system, will prove extremely valuable to the coral reef nation of the Maldives, and could easily be extended for the entire Indian Ocean region.

Chapter 5

5 THE INTEGRATED GROWTH RESPONSE OF ATOLL CORAL REEFS TO ENVIRONMENTAL FORCING: MORPHOMETRIC ANALYSIS OF REEFS OF THE MALDIVES.

5.1 Introduction

The earliest known non-scientific accounts of physical descriptions of the Maldivian atolls and their climatology come from the historical writings of the French traveler Francois Pyrard de Laval, who was literally washed on to these reefs in 1602 (Gray 1887; Owen 1832). Pyrard was shipwrecked in the Maldives and lived there for 5 years. He called the atolls 'atollons', and talked of a 'great stone wall' (meaning coral reefs) surrounding the atollons. Some accounts of reefs, their shapes and physical characteristics were given by Pyrard. He said "it is extraordinary to see these 'atollons' environed by a great stone wall, in such wise as no space of dry ground even could be so well closed and protected by walls as they are" – indicating the prominence of atoll rim reefs and hydrodynamics in effect.

The formation of reefs of the Maldives has been at the centre of the coral reef debate since Charles Darwin's popular theory of atoll formation (Dana 1890; Davis 1969). The structure and arrangement of the Maldivian atolls, with a double chain in its central part (Fig 4.2), on a linear submarine ridge rising from the ocean floor, has always made them difficult to explain in a strict Darwinian context. Many theories have been suggested for the formation of coral reefs of the Maldives.

5.1.1 Current theories on the formation of the Maldives' atolls and reefs

Darwin (1889) devoted a section entitled "Atolls of Maldiva Archipelago - the Great Chagos Bank" to describe the Maldives' reefs and their formations in his famous book "The structure and distribution of coral reefs". He acknowledged that the formation of the Maldives did not fit his well-defined atoll formation theory. It is difficult to relate individual Maldivian atolls in a true fringing reef to barrier reef to atoll succession due to their peculiar arrangement and geological structure. In trying to explain the unusual reef formations, Darwin (1889) suggested that reefs of the Maldives might have grown around a subsiding mountain range similar to that of modern day New Caledonia: as the mountain range subsided atolls formed on the peaks. This, he thought, explains the structure and arrangement of atolls as we see today, based on his subsidence theory. Darwin wrote on the variations between reefs of the northern and southern atolls of the Maldives Archipelago and speculated on the possible causes on this. Atoll morphology, including the size and shape of rim reefs and reef islands, reef passes, and the depths of the atoll lagoons and the seas between them were discussed. The ring-shaped reefs (termed '*faro*' by Gardiner, 1902) of the northern atolls were described in great detail.

Daly (1915) suggested that the flatness of atoll lagoons of the Maldives (also noted by Darwin, 1889) is evidence of wave planation during glacial low stands of sea level, providing support for his Glacial Control theory. Daly selected many examples from the Maldivian atolls to elucidate his theory. He suggested that small atolls, such as *Vattaru* (not studied as an atoll this study), filled up with debris more rapidly than larger atolls. He showed that small atolls consistently had shallow lagoons using the relationship between maximum lagoon depths and width of the reef platform. He argued that if subsidence were the control for reef development then the lagoons of atolls would not agree so well all over the world in terms of depth.

Gardiner (1902) thought reefs of the Maldives have 'somehow' grown to the surface from a common plateau levelled by oceanic and tidal currents. He suggested that reefs were "growing outwards" (laterally) on all sides, the lagoons increasing in size. He further

suggested that atolls owe their existence to the fusion of reefs on their rims and the "washing away" of reefs in the interiors.

Hass (1962) came up with yet another theory for atoll formation in the Maldives. He called this the "Central Subsidence" theory. There is very little agreement for this theory among reef scientists.

5.1.2 Geological history of the Maldives' atolls and their foundations

Drilling and seismic studies on the Maldives ridge (Aubert and Droxler 1992; Purdy and Bertram 1993) explains the origin and evolution of the foundation on which the atolls of the Maldives stand in the modern day. These studies described the 55 Ma history of the evolution of the Maldives based on the results of the Ocean Drilling Program (ODP) leg 115, an oil exploration well drilled in North Male Atoll, and large number of seismic profiles.

The volcanic ridge, on top of which the Maldives carbonate system has been established, represents a segment of a hotspot trace (Duncan and Hargraves 1990). At present, this active hotspot is located beneath the Island of Réunion. The structure and ages of basalts recovered from ODP sites have suggested that the volcanic ridge under modern day Laccadives, the Maldives, Chagos, Mascarene Plateau and the islands of Mauritius and Réunion were all part of the Réunion hotspot trace (Duncan and Hargraves 1990). These basalts have been traced northwards to the Deccan Traps of India.

The Réunion hotspot began its activity at about 67 Ma with the rapid eruption of the massive flood basalts of the Deccan Traps (Duncan and Hargraves 1990). During the Palaeocene and Eocene interval (about 55 Ma) the hotspot generated the Chagos-Maldives-Laccadives ridge, successively forming the volcanic basement underlying the carbonate systems of the Laccadives, the Maldives, and Chagos. Complex tectonic movements over millions of years has led to the migration of the basalts northwards to display the modern day distribution and location of the respective carbonate systems.

Samples of the basalts drilled from the Maldives were dated to be 57.2 Ma (Duncan and Hargraves 1990). It has also been found that the ages of basalts recovered from the sites along the Hotspot track (northwards from Réunion to the Deccan Traps of India) increase systematically from south to north with Réunion being the youngest at 2 Ma, Mauritius at 1-7 Ma, Mascarene Plateau at 31-45 Ma, Chagos at 49 Ma, Maldives at 55 Ma and Deccan basalts 67 Ma (Duncan and Hargraves 1990). The age structure along with the characteristics of the basalts confirms the hotspot activity during their Cenozoic evolution.

Once the volcanic basement established itself, carbonate deposition took place, capping the volcanic edifices. Complex geologic processes must have modified the platform many times in its history, resulting in the form and structure we see today. Long-term sea level changes, tectonic subsidence, periodic sub-aerial exposure and erosion, have all affected the development of the Maldives carbonate system. In summary, the modern day atolls form the surface of a 2000 m thick carbonate platform, which has a 55 Ma year history.

5.1.3 History of exploration and early surveys

The atolls and reefs of the Maldives were first properly surveyed and documented by R. Moresby in 1834-6 (Anon 1836; Spray 1966). Many coral reef specific expeditions have been launched to the Maldives since then to better understand its reefs and how they may have formed, and much has been published on these early works (Gardiner 1902; Agassiz 1903; Sewell 1932; Kohn 1964; Hass 1964, Scheer 1971; Scheer 1974; Stoddart 1966; Davies et al. 1971; Rice 1986). Most early surveys and reef descriptions were based on what people knew from old British Admiralty charts and soundings made by Moresby in 1834-6. With recent insights into the geology of the atoll foundations (Purdy and Bertram 1993) we have begun to appreciate reef formations with new perspectives.

Some studies suggest that the modern gross morphology of atolls and reefs in the Maldives is largely inherited from the shapes of the limestone foundation on which they have grown (Purdy 1981). It seems that the foundation has undergone sub aerial erosion and solution during times of lower sea levels. When sea level rose corals have re-established and continued to grow on the eroded platforms (Purdy and Bertram 1993). The atoll reefs are also thought to be young in inception. Ages of coral reef islands of the Maldives have shown them to be in the order of about 3000 to 4000 years old (Woodroffe 1992).

5.1.4 Processes of reef growth during the Holocene

Oceanic atoll reef complexes such as the Maldives reef system maybe regarded as a system of related ecological structures with common environmental processes operating on and around them. Reef structure, morphology and growth may be investigated by two basic methods: surface mapping of geomorphology and interpretation of borehole samples. Borehole data reveals the reef framework of reefs and Holocene growth patterns that vary both vertically and laterally (Kennedy and Woodroffe 2002; Montaggioni 2000). Mapping of reef morphology provides a means to understand modern surficial processes at play in the growth of reefs. Reef slopes and reef crest adjacent to the slope as well as back reef sand flats on the windward side of reefs are the most prominent morphological growth zones on reefs.

Modern coral reefs are characterized by large amounts of loose biogenic sediment (Montaggioni 2000). Reefs grow as a result of their ability to produce carbonate on windward margins, much of which is subsequently eroded by the mechanical action of waves on windward reef face and transported into back reef flats as prograding sand flats and thence into lagoons where it accumulates (Fagerstrom 1987). Sediment is also created *in situ* by algae and bio eroders, but the predominant sand flat prograding into lagoons results from physical forcing. Sediments are continuously produced, transported on reef flats and deposited in lagoons and around reef islands. The pattern of the sand flat spread across the reef flat thus reflects the growth process of a reef in relation to weather

and hydrodynamics. It is the predominant mechanism of masking antecedent (karst) morphologies on modern reefs. Similarly the pattern of rubble and live coral zones on the reef flat is primarily driven by modern processes (Done 1983).

Reef lagoons appear to be indicators of antecedent karst topography on modern reefs (Purdy 1974). On reefs of the Maldives, lagoons on individual rim reefs as well as lagoon reefs are very common in many atolls. Reef islands represent visually prominent visual Holocene morphological features on modern reefs.

Atoll rim reefs display process-driven morphologies prominent on all modern reefs (Chapter 4). There are differing views over the processes that produce modern day reef morphologies. Some findings implicate antecedent Pleistocene basement structure of reefs to explain their morphology, while others demonstrate the importance of weather and climate processes in controlling growth on modern reefs (Chapter 2). Relationships between environmental processes and patterns of reef growth can be adequately investigated by quantitative analysis of reef morphology at spatio-temporal scales that allow regressions on environmental processes. Whilst it is well accepted that spatial patterns of reef growth and the resulting morphologies are controlled primarily by environmental forcing, no quantitative studies have been done on a scale that allows determination of the relationship between coral reef growth and environmental forcing. Atoll reefs of the Maldives provides an ideal setting to develop and test environmental models of coral reef growth by treating 100s of individual reefs at the same scale using satellite imagery and GIS tools.

Early studies (Darwin 1889; Gardiner 1902; Agassiz 1903; Davis 1969; Dana 1890; Wiens 1962) posed hypothetical questions on atoll morphology in relation to environmental forces especially wind and waves. The majority of the early studies (excepting Gardiner's in 1902 and Agassiz's in 1903) were conducted in Pacific atolls using navigational charts and, on a few occasions, aerial photos. The measurements made were mostly crude estimates and are unsuitable for statistical analysis. Today we have new techniques and advanced tools that can be used effectively to analyze patterns of reef

growth as reflected in atoll reef morphology at the characteristic scales of variation in major environmental forcing functions (i.e., across biogeographical regions). Satellite imagery of most of the world's atolls are now available at suitable spatial resolutions to depict reef morphology (e.g. Landsat 7 ETM+; Chapter 4). These images are cost effective to acquire and can be analysed by people with basic computer expertise (Green et al. 1997). Advanced remote sensing and GIS tools allow us to quantify reefs over large domains and analyse them spatially with an accuracy and completeness heretofore unknown.

Excellent reviews of the growth of fringing and barrier reefs during the Holocene have been published recently (Montaggioni 2000; Kennedy and Woodroffe 2002). There appears to be a need to develop research on atoll rim structure and growth dynamics. A review of atoll reef geomorphology and growth in light of new techniques and recent research is needed (Naseer and Hatcher 2001; Andréfouët et al. 2001a, Dufour et al. 2001). Wiens' (1962) pioneering and comprehensive book on (predominantly Pacific) atolls is very dated in many aspects. The same is true of other major writings on atoll reefs (Guilcher 1988; Stoddart 1965; Stoddart 1969; Stoddart 1973).

The research presented in this thesis is aimed at updating and filling critical gaps in our knowledge of atolls, especially those of the less-well studied Indian Ocean, and to better understand the processes that shape modern reefs of the Maldives.

Based on existing knowledge (Chapter 2) and the examination of the surface geomorphology and growth patterns of atoll rim and lagoon reefs of the Maldives (Chapter 4), the following hypotheses are erected to explain the spatial patterns of growth of the atoll reefs of the Maldives.

- *The integrated growth of atoll rim reefs (as defined by total reef surface area, total reef flat area, reef slope width, reef crest width, reef flat width, proportion of reef flat and lagoon,) is a function of incident wave power.*

This hypothesis stems from the very earliest observations and intuitions of environmental controls on the patterns of atoll growth (Darwin 1889), and builds on the pioneering work of Munk and Sargent (1946). The underlying mechanistic explanation is that the metric of wave energy integrates both the positive effects of mixing and the delivery of new nutrients to reef surfaces and interstices, and the negative effects of erosion and off-reef transport. In the Northern Indian Ocean, the wave field is the result of the dominant monsoon climatology and the northward propagation of ocean swell from the major storm centres in the southern Indian Ocean (Fein and Stephens 1987).

- *The integrated growth of atoll lagoon reefs (as defined by total reef surface area, total reef flat area) is a function of atoll rim aperture.*

This hypothesis stems from the common observation that gaps in fringing, barrier and atoll rim reefs are often backed by lagoon reefs whose growth axes are apparently oriented towards the inflow of water through the gap (Wiens 1962). Hatcher (1997) and Andréfouët and Payri (2000) expand this observation to the concepts of atoll “closure” or “aperture” (resp.) and derive relationships with many metrics of reef ecosystem structure and function. The putative mechanism controlling reef growth rates and their resulting morphological expression is again the degree of lagoon exchange mixing with the ocean waters surrounding the reef and the advective delivery through opening in the atoll perimeter of essential elements and nutrition to the organisms responsible for reef accretion.

Here, I test these hypotheses rigorously using quantitative statistical analysis of a database of more than 20,000 metrics of more than 2,000 individual reefs of the Maldives.

5.2 Materials and methods

5.2.1 Climatology

Monsoons of the Indian Ocean govern the climatology of the Maldives' atolls. Monsoon wind reversal plays a significant role in weather patterns. Two monsoon seasons are observed: the NE and the SW monsoon (Fein and Stephens 1987). Monsoons can be best characterized by wind and rainfall patterns. Here wind data was comprehensively analysed to characterize the seasonality of the monsoons affecting the Maldives' atolls. Wind data was then used to calculate wave energy and power affecting atoll reefs.

5.2.2 Wind data

Wind data for the Maldives are available for three regions (Fig 5.1):

1. Hanimaadhoo Domestic Airport (location: 73°09'54" E/ 6°45'03.8"N)
2. Hulhule International Airport (location: 73°31'40.9"E/ 4°11'42.6"N)
3. Gan Domestic Airport (location: 73°09'06.0"E/ 0°41'31.0S)

The stations are widely enough spaced (300 to 400 km) for the analysis of regional wind patterns across the Maldives archipelago. For central and southern stations data were available for 27 and 24 years respectively, whereas for the northern station data were only available for 10 years. These data sets are short for many analytical purposes, but analysis of long term (200 year monthly winds) historical data suggests the reliability of the local daily meteorological wind data for long term analysis.

Raw data from these stations were obtained, digitized and analysed to characterize monsoon wind patterns. Daily average wind speed and direction from the three stations were organized in Excel spreadsheets and descriptive statistics were obtained using analytical tools in Excel and SPSS version 10 software. The local met data was compared

with an analysis of ship-based wind data for 200 years in eight, 2-degree grid squares (Fig 5.1) obtained from the Comprehensive Ocean-Atmosphere Data Set (COADS, <http://www.cdc.noaa.gov/coads/>). These archives of observations at sea represent an excellent proxy to verify key monsoon wind characteristics derived from the shorter winds records collected at the land-based Meteorological stations in the Maldives. To corroborate and confirm that wind speed records from local meteorological stations conform to the actual wind speeds at the sea surface, the COADS historical data were analysed over a grid area for which the upper left hand corner was at 72 degrees east longitude and 8 degrees north latitude and the lower right hand corner was at 76 degrees east longitude and 0 degree latitude (Fig 5.1). COADS dataset for each 2-degree grid square consisted of monthly wind speed and direction. The data were organized in Excel and SPSS software to obtain descriptive statistics for wind speed and direction and correlations with the local meteorological datasets.

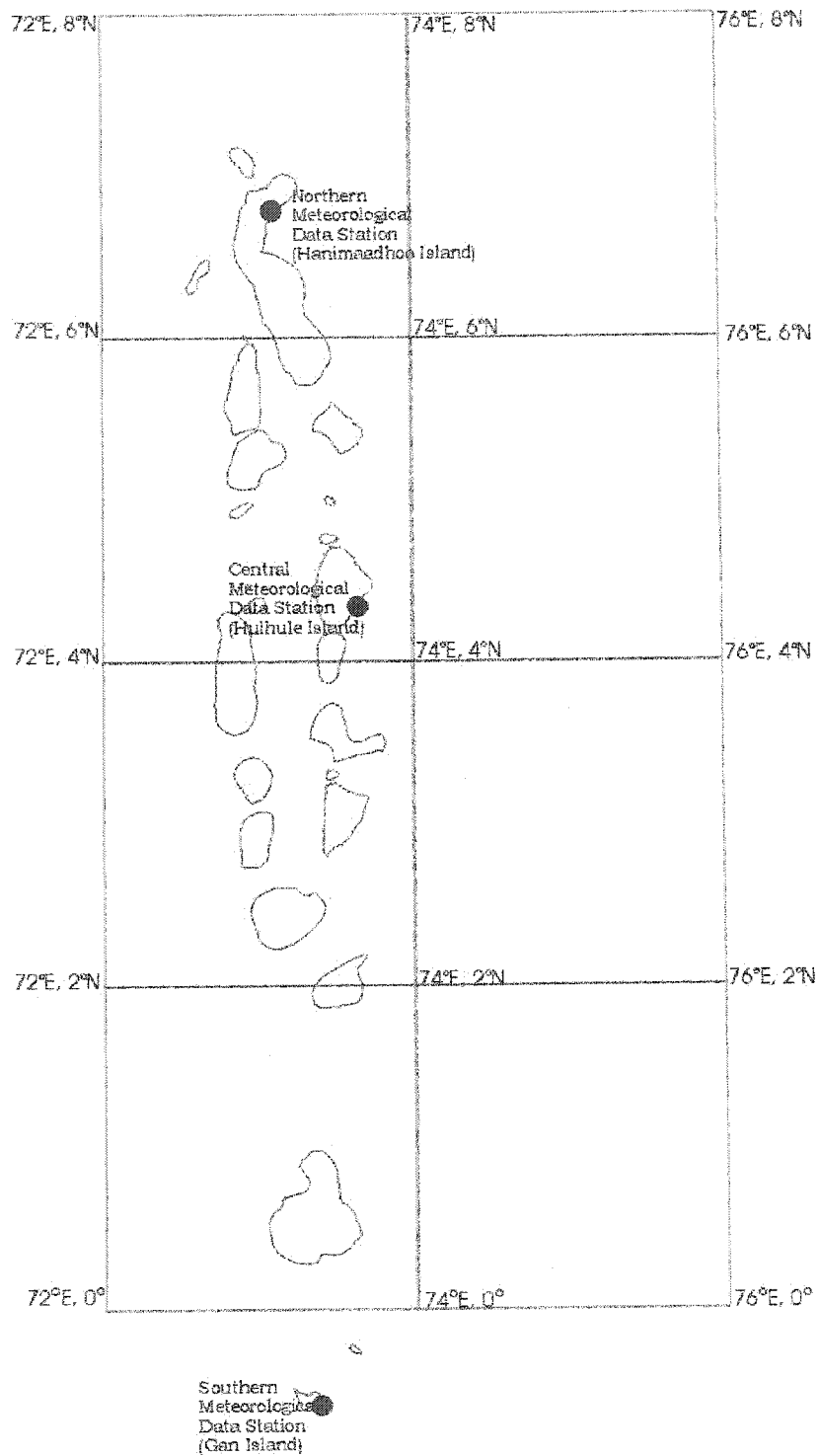


Figure 5.1 Location of northern, central and southern meteorological data stations in the Maldives and the geographic extent for which the COADS historical wind data was analyzed to verify local wind data

5.2.3 Exposure regimes of atoll rim reefs

Ideally, it would be desirable to have wind and wave data at the same spatial resolution as individual rim and lagoon reefs (i.e., approx. 10km length scale). This would allow a separate calculated wave power for each reef, at many degrees of freedom in the statistical tests of hypothesis. This is, however, impossible to achieve with the resolution of the wind data available (i.e., greater than 2-degree grid squares). Based on wind-wave analysis for northern, central and southern Maldives, and estimates of swells reaching the Maldives from the southern oceans, two spatial scales of wave exposure regimes were identified for all rim reefs of the Maldives (Table 5.1). The exposure regimes were developed primarily based on reef location, orientation and fetch in relation to the prevailing wind-wave/swell direction, such that each of 488 rim reefs of the Maldives were assigned to one of five or nine exposure regimes (depending on the spatial scale, Fig 5.2).

The direction of propagation and significant, deep-water wave height of the southern swell was determined from web-posted reports for well-established, internationally known surfing sites (“breaks”) in the Maldives. Average shallow-water (breaking) swell heights and wave characteristics are well known for these surf locations. Storm-generated swells from the southern Indian Ocean reach south and southeast facing reefs of the Maldives in a consistent manner (Knox 1987). In order to check the accuracy of these observational swell data, the synoptic wave model (NOAA WAVEWATCH III; <http://polar.ncep.noaa.gov/waves/historic.html>) was run to produce 7-day predictions of Hs for waves greater than eight second period in the middle of the both monsoon seasons and in the middle of both transition between monsoons.

Exposure scale I

Regime	Reef location to Prevailing wind direction	Code
1	Reef facing the Maldives Inner Sea on the west side	WI
2	Reefs facing the Maldives Inner Sea on the east side	EI
3	Reefs facing the ocean on the eastern side of the Maldives ridge	EO
4	Reefs facing the ocean on the western side of the Maldives ridge	WO
5	Reefs facing the southern Indian Ocean swells	SO

Exposure scale II

Regime	Reef location to prevailing wind direction	Code
1	Reefs facing the ocean on the eastern side of the Maldives ridge in northern Maldives	NEO
2	Reefs facing the ocean on the western side of the Maldives ridge in northern Maldives	NWO
3	Reefs facing the ocean on the eastern side of the Maldives ridge in central Maldives	CEO
4	Reefs facing the ocean on the western side of the Maldives ridge in central Maldives	CWO
5	Reefs facing the Maldives Inner Sea on the west side in Central Maldives	CWI
6	Reefs facing the Maldives Inner Sea on the east side in Central Maldives	CEI
7	Reefs facing the ocean on the eastern side of the Maldives ridge in southern Maldives	SEO
8	Reefs facing the ocean on the eastern side of the Maldives ridge in southern Maldives	SWO
9	Reefs facing the southern Indian Ocean swells	SSO

Table 5.1 Two sets of exposure classifications of rim reefs of the Maldives at two spatial scales: I. Archipelagic scale (approx. 800 km) and II. Atoll group scale (approx. 200 km). The classifications were created to group reefs according to their exposure to monsoon wind-wave and swell for the purposes of statistical analysis of the affect of wave-forcing on patterns of atoll reef growth.

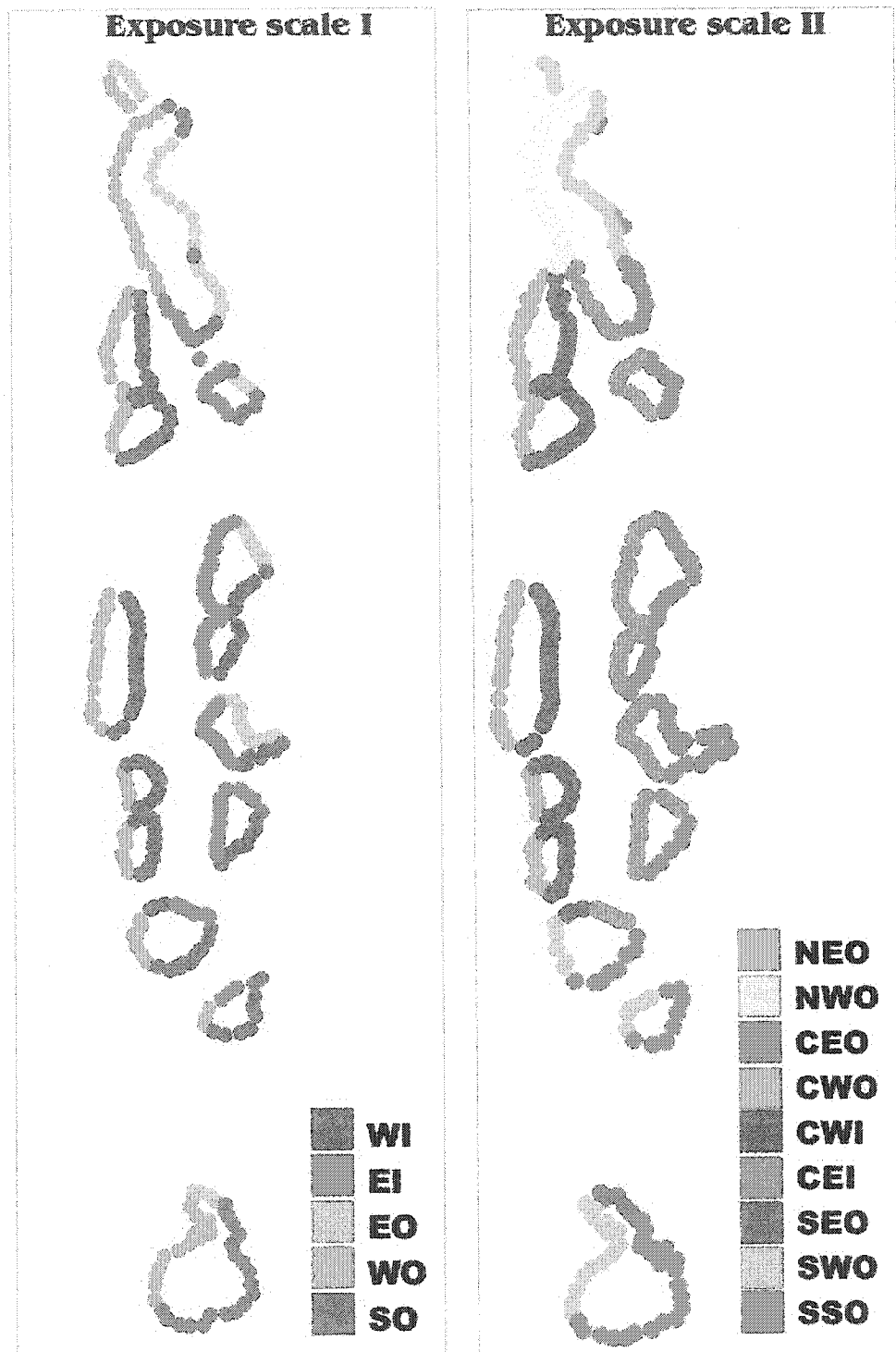


Figure 5.2 Two spatial scales of classifications of wind-wave and swell exposure regimes for atoll rim reefs of the Maldives. Refer to Table 5.1 for details of exposure codes.

5.2.4 Wind generated waves and calculation of wave power for the nine exposure regimes

Analysis of seasonal wind velocities was used to calculate wind-generated wave energy for all rim reefs that make up the atolls of the Maldives. Winds at the surface create gravity waves as a function of wind duration, fetch and speed. Significant wave heights and wave periods can be estimated from wind speed (Kinsman 1965; SWAMP Group 1985; Teng and Liu 2000). Wind and wave characteristics are well correlated in the Indian Ocean: a one-year study of wind and waves simultaneously in the vicinity of the Maldives showed that highest wave heights are found in the regions of highest wind speeds (Quartly et al. 2000).

Since winds blow consistently from the SW to W quadrants during the SW monsoon, and from the NE to E quadrants during the NE monsoon, most wind-wave fields propagate normal to the vast majority of rim reefs in the north-south aligned Maldives archipelago. Daily wind speed records from the Met stations in the north, central and south regions of the archipelago (Fig 5.1) were used to calculate significant wave heights and periods for each twenty-four hour period through the entire wind record for each of the nine exposure regimes of scale II outlined in Table 5.1 and Fig 5.2. Winds blow very infrequently from sectors other than those defined for a monsoon. Therefore we can conveniently divide the wind data set from a given Meteorological station into two sectors (east and west) based on wind directions to define monsoon seasonality. Thus the wind dataset for each Met station was structured seasonally and daily wind generated wave energy and wave power for nine wind-wave regimes (Fig 5.2) calculated. Days with wind speeds of zero values were excluded from the analysis for all regions.

For wave power calculations it was generally assumed that if the wind blows at a constant speed for 24 hours, the sea is fully developed. This period is also the maximum temporal resolution of the local wind data (i.e., daily average wind) available for the three Met stations in the Maldives. For the oceans-facing exposures of the Maldives (i.e., exposure

regimes 1-4, 7 and 8) the fetch is considered unlimited, and it is assumed that waves will be fully developed with a wind duration of 24 hours at unlimited fetch. For the Maldives Inner Sea, the fetch is limited to 15 to 50 km, and the wind-wave height generated in these regions will be lower than in conditions of unlimited fetch.

For west and east, ocean facing reefs in the north, central and south of the archipelago (NEO, NWO, CEO, CWO, SEO, SWO; Fig 5.2), local wind speed was used assuming infinite fetch to compute wave height (H_s) and period (T_p) from Pierson-Moskowitz (PM) relations for equilibrium sea states (SWAMP Group 1985). Only winds that were “onshore” with respect to the Maldives outer coastlines were used. The PM equilibrium total wave energy and wave frequency are defined by:

$$EPM = 3.64 \times 10^{(-3)} \times U_{10}^4 g^{(-2)} \quad (5.1)$$

$$fPM = 0.13/U_{10} \quad (5.2)$$

Where “EPM” is the equilibrium total wave energy, U_{10} is the wind speed at 10 m reference height, and g is the acceleration due to gravity, and fPM is the equilibrium peak frequency of the wave spectrum. From these equations we can estimate wave height (H_s) and period (T_p) as follows:

$$H_s = 4 \sqrt{EPM} \quad (5.3)$$

$$T_p = 1/fPM \quad (5.4)$$

For reefs facing the Maldives Inner Sea (MIS) on the east and west (CWI, CEI) (Fig 5.2), the waves do not reach equilibrium state and are always in the growing mode. Hence fetch limited relations are required to estimate significant wave height and period. The fetch relations of Hasselmann et al. (1973) were used to estimate wave energy and frequency reaching reefs of the MIS:

$$E_{tot} = 1.6 \times 10^{(-7)} X \quad (5.5)$$

$$f_p = 3.5 X^{(-0.33)} \quad (5.6)$$

Where E_{tot} is dimensionless total energy, fp is dimensionless peak frequency, and X is dimensionless fetch. Dimensioning these equation gives:

$$E_{tot} = E_{tot_} [\text{dimensional}] g^2 / U_{10}^4 \quad (5.7)$$

$$Fp = fp_ [\text{dimensional}] U_{10}/g \quad (5.8)$$

$$X = X_ [\text{dimensional}] g / (U_{10}^2) \quad (5.9)$$

Where $X_ [\text{dimensional}]$ is the width of the Maldives Inner Sea from east to west. From dimensional total wave energy and frequency, wave height (H_s) and period (T_p) can be estimated can be again estimated from the following relations:

$$H_s = 4 \sqrt{(E_{tot_} [\text{dimensional}])} \quad (5.10)$$

$$T_p = 1/fp_ [\text{dimensional}] \quad (5.11)$$

Knowing wave height and periods for each wind sector, wave power for each of the nine exposure regimes were calculated from the following expression by Munk and Sargent (1954):

$$\text{Wave power} = (1/32\pi) \rho g^2 H_s^2 T \quad (5.12)$$

where wave power was originally expressed in units of horsepower per linear foot of reef crest normal to the direction of wave propagation, but can equally be calculated as watts per linear meter using SI unit, ρ is the density of water, g is the acceleration due to gravity, H_s is the significant wave height and T is wave period.

Total daily wave power for a given regime was summed for the number of years of wind data available (10 to 27 years) and divided by the number of years to get the average annual wave power impinging on any meter of a given rim reef within that exposure

regime. The same was done to calculate swell-wave power impinging on south-facing portion of rim reefs, totaled for one calendar year.

5.2.5 Atoll aperture

An atoll is spatially defined by its rim and the central lagoon. Deep passes or channels between rim reefs connect the ocean and the atoll lagoon, which contains lagoon reefs (Fig 5.3). Lagoon water circulation patterns, the residence time of water in the lagoon, and the rate of exchange of lagoon water with the surrounding ocean is largely defined by the number and cross-sectional area of these passes through the atoll rim (Atkinson et al. 1981; Hatcher et al. 1987; Dufour and Harmelin-Vivien 1997; Dufour 2001), which can be expressed as a dimensionless morphometric of atoll “openness”, “closeness” or rim “aperture” (Andréfouët et al. 2001a; 2001c). The methods used to determine atoll aperture were described briefly in Chapter 4. These methods were adopted from Andréfouët et al. (2001a). Aperture (A) for an atoll is defined by the ratio of total length of deep channels (or passes) on the rim divided by the perimeter of the atoll (Fig 5.3). Rim aperture (%) was calculated for all 16 atolls of the Maldives.

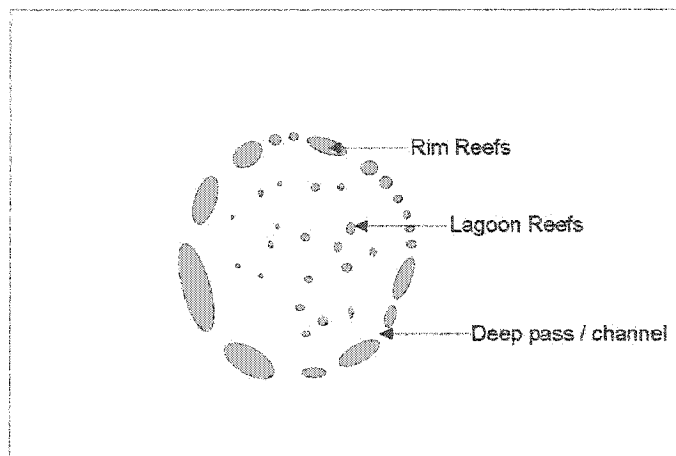


Figure 5.3 Schematic diagram to show atoll reef structures used for calculation of rim aperture.

5.2.6 Rim and lagoon reef growth data (quantification of reef geomorphology)

To evaluate the patterns of reef growth in response to spatial variations of wave power in the Maldives, geomorphologic data were collected for all rim reefs affected by the nine, high-resolution wave regimes. Methods used to map and, quantify reef growth data are described in detail in Chapter 4.

5.2.7 Data analysis and hypothesis testing

Descriptive statistics, parametric statistics, calculations of wave power, correlations among parameters and regressions of reef data on wave power were computed using analytical procedures in Microsoft Excel 2000 and SPSS 10.0 statistical software.

Spatial patterns of reef growth data derived from the geomorphological data (presented in Chapter 4) were analysed using non-parametric, multivariate statistical procedures in the PRIMER (Plymouth Routines in Multivariate Ecological Research) package version 5 developed by the Plymouth Marine Laboratory, UK (Clarke and Warwick 1994; Clarke and Gorley 2001). The analyses used here to search for pattern and test hypotheses (i.e., Multidimensional Scaling and Analysis of Similarities) are based on similarity coefficients calculated between each pair of samples. The resulting similarity matrices are used to classify samples into groups of similarity, or to make an ordination plot in which reefs are visually displayed in two or more dimensions (Clarke and Warwick 1994). The similarity commonly used are Bray-Curtis or Euclidean distance.

Non-parametric multidimensional scaling (MDS) is a procedure that arranges objects in space as a two (or more) dimensional graphical representation of the similarities of samples in the data set (in this case for 488 rim reefs). The distance between samples on the plot reflects the degree of similarity between samples depending on the measure used (Clarke and Warwick 2001). The 'goodness of fit' of the MDS plot is measured by the stress formula. If the stress is large the plot is a poor representation of real relationships among samples, while a low stress value indicates a representative relationship among the

samples. Clarke and Warwick (1994) suggest that a stress value between 0.05 and 0.1 indicates a good ordination with no real prospect of a misleading interpretation.

The analysis of similarity (ANOSIM) test utilizes the same similarity matrix as that used to create the MDS plot to test for differences among and within *a priori* groupings (Clark and Warwick 2001). The groupings should obviously not be derived from the MDS plot. The null hypothesis that can be tested using ANOSIM is that there are no differences among groups (similar to the use of a parametric ANOVA). A test statistic (Global R) is computed that reflects the differences between and within groups. The R-value must lie within the range -1 to +1 technically (Warwick 1994), and is usually between 0 and +1. When R=1, all samples within a group are more similar to each other than samples from other groups. R is approximately 0 when similarities between and within will be the same on average, which is the case when the null hypothesis is true. The Global R statistic indicates the similarities among all groupings. It is a useful comparative measure of the degree of separation of groups, but the main interest for hypothesis testing is whether it is significantly different from zero.

The assumption in the tests performed here is that reefs experiencing similar physical processes controlling their growth (i.e., growth environments) would exhibit similar geomorphology, reflecting similarities in patterns resulting from time-integrated reef growth. The ANOSIM rigorously tests the degree of similarity. Two levels (i.e., spatial scales) of exposure regime (i.e., groups) were created based on the wind data analysis (Fig 5.2 and Table 5.1) in order to perform tests of similarity. Exposure level I has 5 groups and Exposure level II has 9 groups of rim reefs encompassing all the atolls of the Maldives. Non-parametric MDS ordinations were first run on the rim reef data set in PRIMER. Running ANOSIM procedure in PRIMER tested the null hypothesis of no difference between exposure groups.

The contributing variables to reef groups ordinated by the MDS and tested by the ANOSIM were explored by the similarity percentage (SIMPER) procedure in PRIMER. The SIMPER procedure indicates what variables are principally responsible for

differences between sets of samples that have been defined *a priori* and are confirmed to differ in community structure (Warwick 1994)

5.3 Results

5.3.1 Wind data analysis

The NE monsoon blows consistently from the N to E quadrants for 4 months from Dec to March (Fig 5.4 and 5.5). During the SW monsoon, winds blow predominantly from the NW to SW quadrants for eight months from April to November (Fig 5.4 and 5.5).

Wind was uniform in speed and direction over the past twenty-plus monsoon seasons in the Maldives. The highest wind speed recorded in the northern reefs for the period 1992 to 2001 was 12.3 m.s^{-1} . Wind speed was usually higher in the central region during both monsoons, with a maximum wind speed recorded at 18 m.s^{-1} for the period 1975 to 2001. In the south of the archipelago the maximum wind speed recorded was 17.5 m.s^{-1} during the period 1978 to 2001. Mean wind speed was highest during the months of June and July in the north, January and June in the centre. Wind speed was in general lower and more uniform throughout the year in the south, but reefs in the south are largely exposed to the southern Indian Ocean swells. Wind analysis indicated that the monsoon was considerably weaker in the south. During the peak months of the SW monsoon, the southern regions have a weak wind blowing from the south and south-eastern sectors. However this is the time of high swell energy reaching the south facing reefs in the south and southeast-facing reefs on the eastern coast of the archipelago.

Monthly wind direction analysis from the three stations showed consistent patterns with little annual variations (Fig 5.5). These patterns were corroborated by the 200-year COADS wind records. Fig 5.6 shows the comparison of Met station data and COADS long-term data for corresponding grid squares.

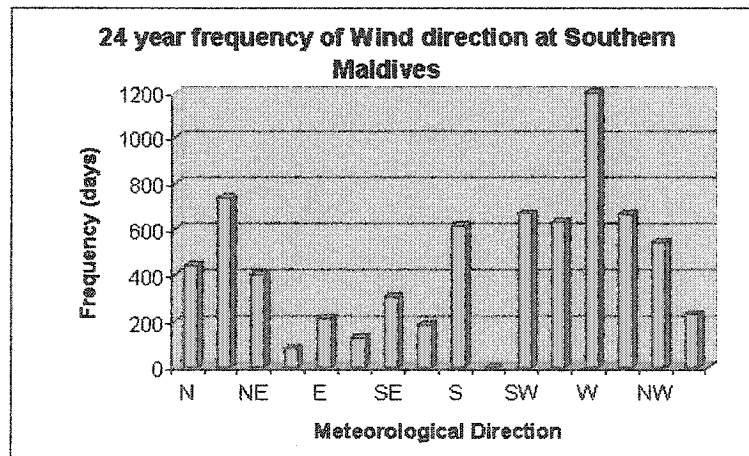
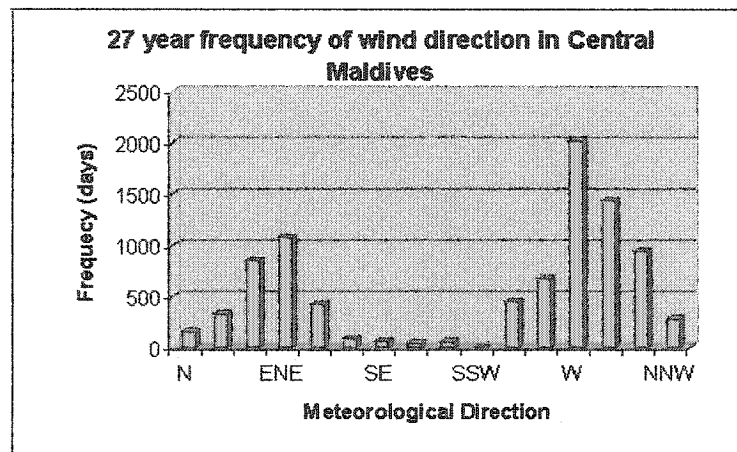
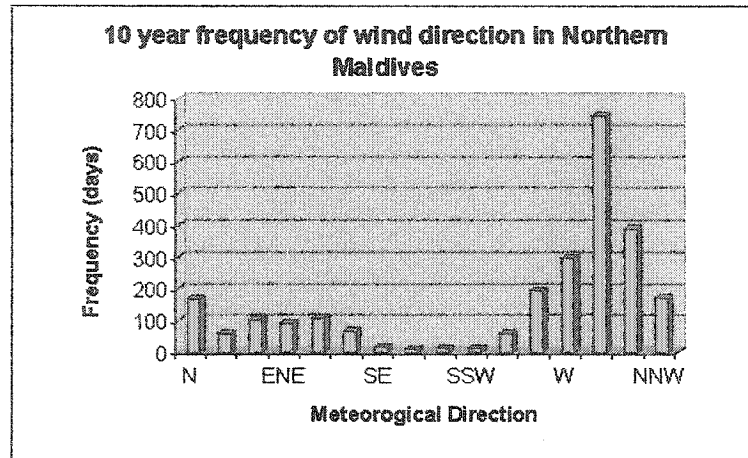


Figure 5.4 Frequencies of wind direction for north, central and southern Maldives.

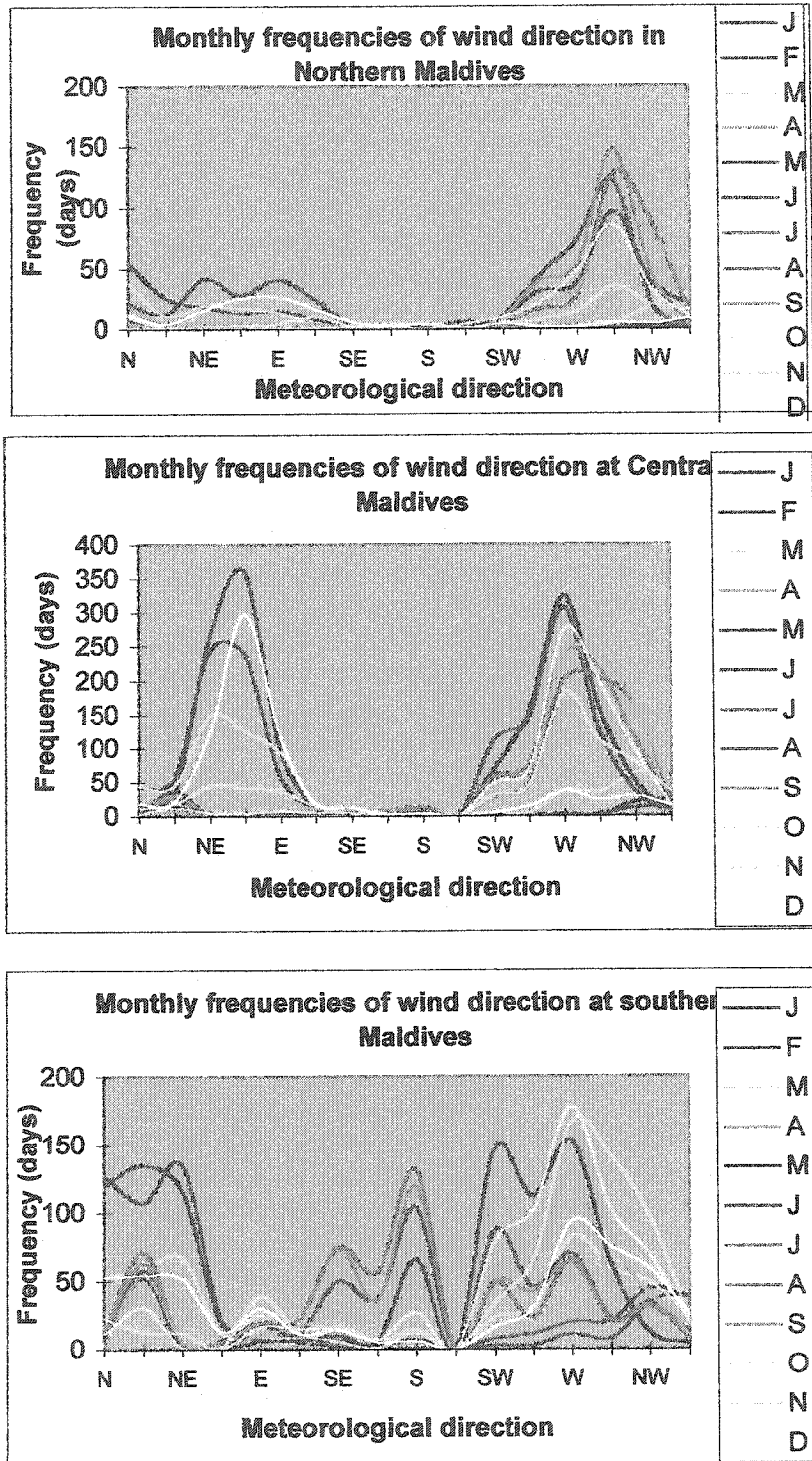


Figure 5.5 Monthly frequencies of wind direction in north, central and southern Maldives from Metrological stations.

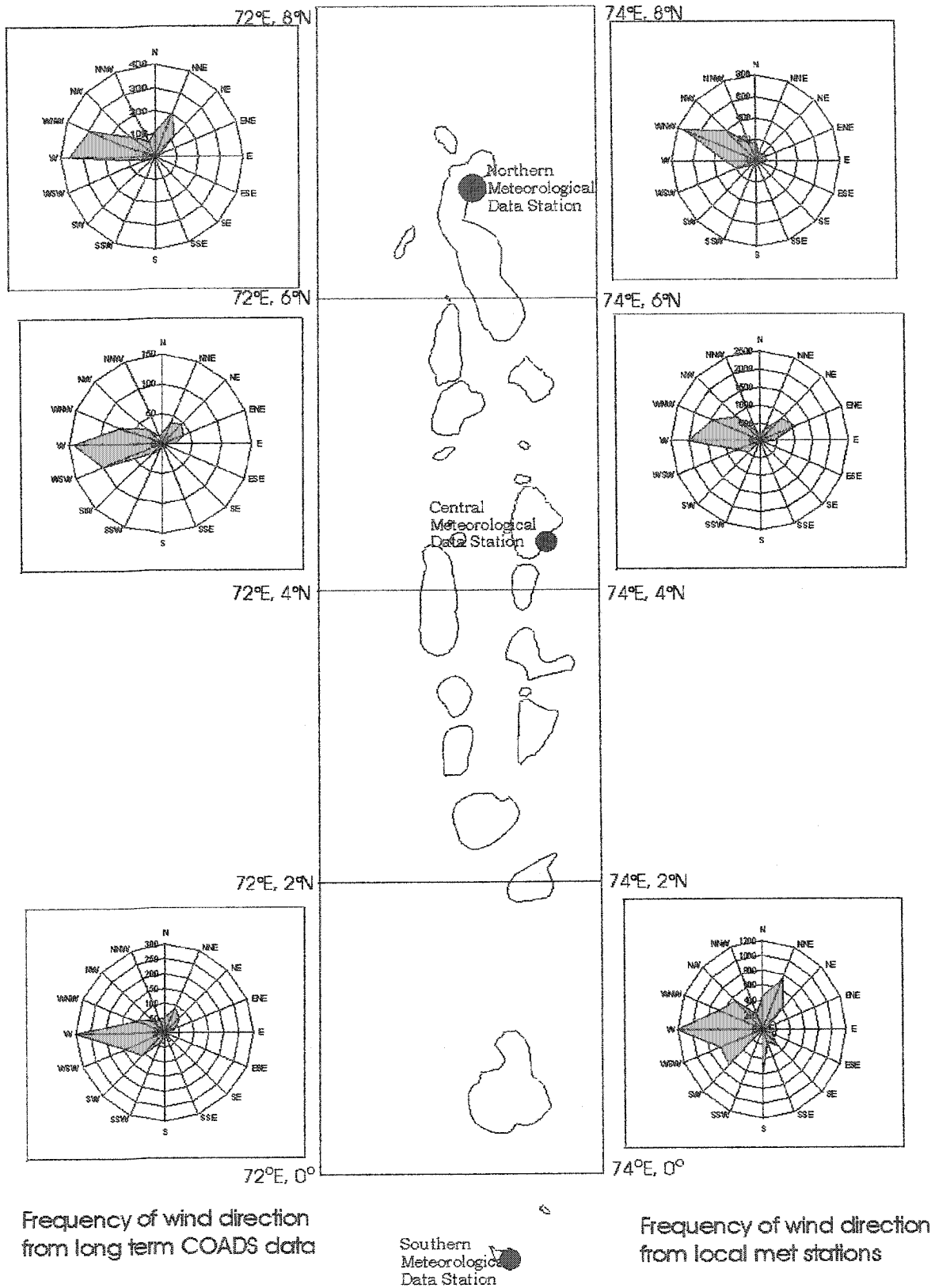


Figure 5.6 Comparison of local and long-term wind frequencies

Wind speed from the three meteorological stations were analysed to detect patterns comparable to wind direction and to complete seasonal local wind characteristics. Monthly wind speed and direction from the three Met stations are summarized in Fig 5.7. Seasonal patterns in wind speed in the three regions are more prominent when we consider daily mean speeds for the periods which data are available (Fig 5.8).

Analysis of COADS sea wind data from the large grid area (Fig 5.1) verified that land based meteorological stations reflect real seasonal wind patterns at sea around the Maldives (Fig 5.6). The local Met station datasets and the 200-year ship-based records of wind speed from the COADS were highly correlated ($R=0.97$). Consistent seasonal patterns of wind direction and speed make this dataset suitable for analyses of wave power and hydrodynamic forcing on atoll rim reefs of the Maldives.

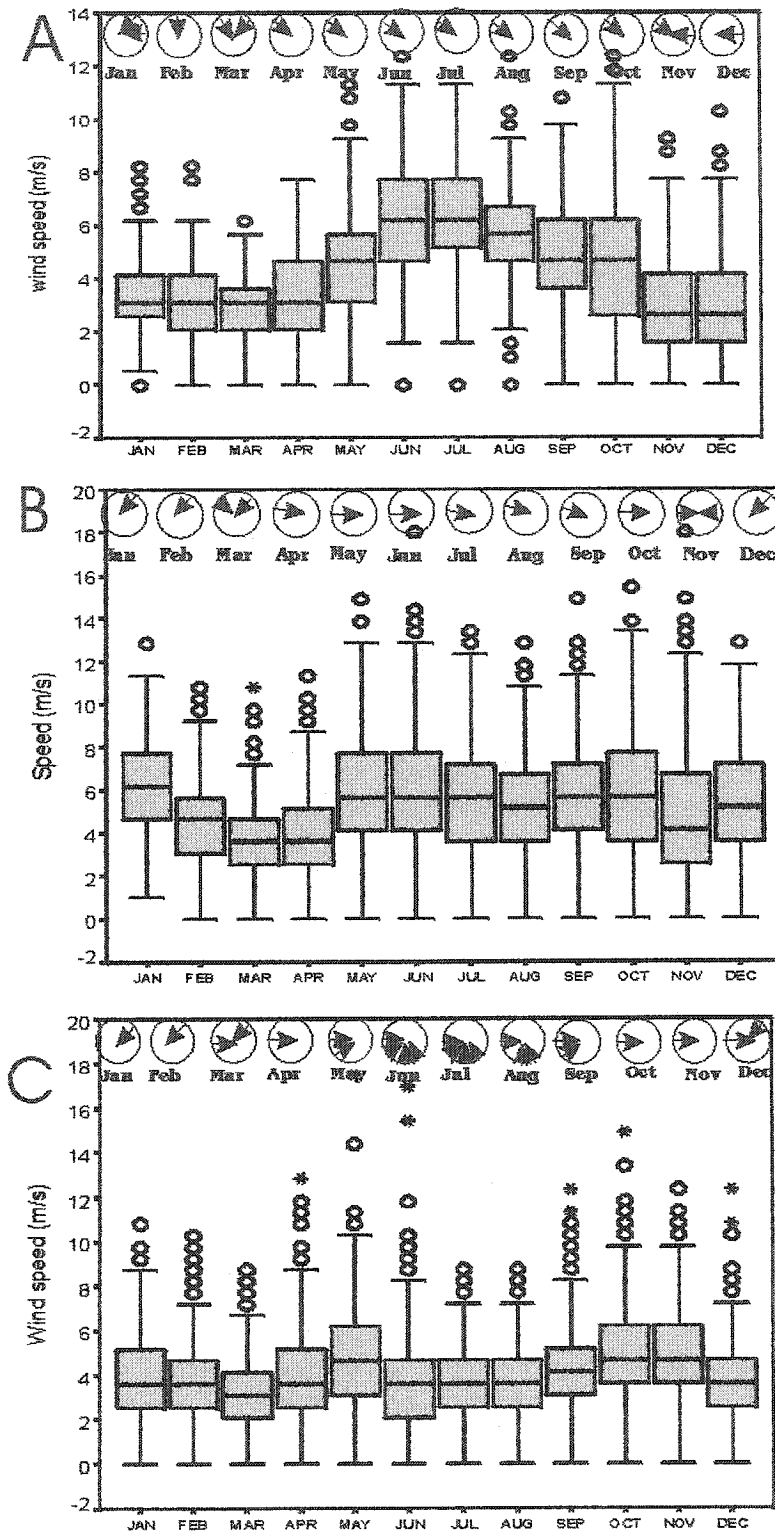


Figure 5.7 Description of wind speed data for North (A), central (B) and south (C) Maldives. Super imposed circles with arrows indicate predominant meteorological wind directions.

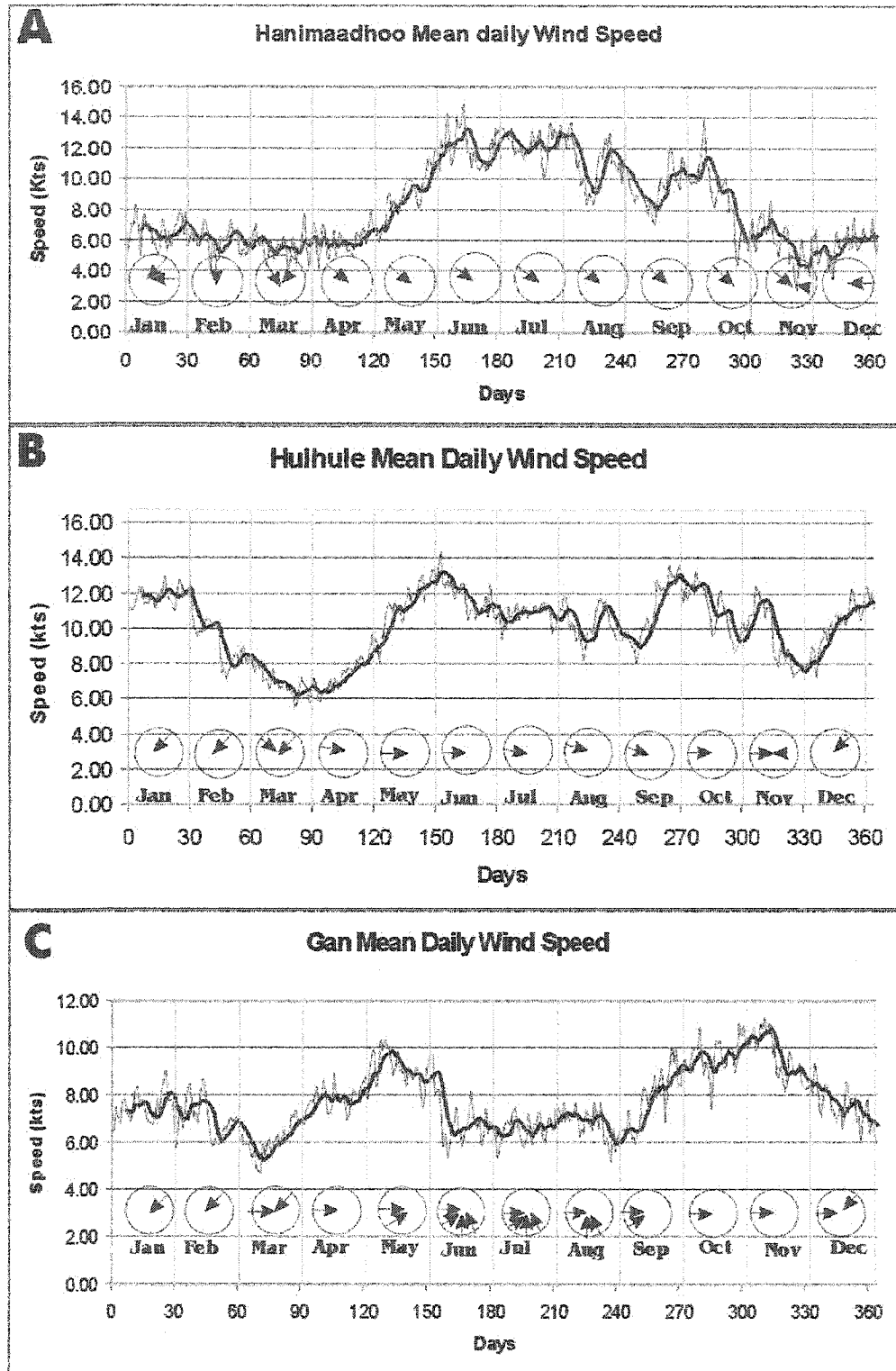


Figure 5.8 Mean daily wind speed and direction for A= North (Hanimaadhoo), B=Central (Hulhule), C= South (Gan) met stations. Arrows indicate dominant wind direction.

The climatology quantified here defines the environment in which reefs of the Maldives grow. As reef growth is a slow process (typical vertical accretion rates of 1-10mm y^{-1} , Kennedy and Woodroffe 2002), it is important to know how long the recent pattern of monsoon wind forcing can be assumed to have prevailed in the past. Paleoclimatological research demonstrates that the northern Indian Ocean monsoons have been blowing in a consistent manner as described here for thousands if not millions of years (Haq 1985; Fein and Stephens 1987). Recent paleoceanographic research on the Maldives ridge provides new insights to monsoon variability (Rostek et al. 1994; Beaufort 1996) during the last 200,000 years. These studies strongly suggest that the monsoon has been blowing with little variability throughout the Holocene. So, based on these paleoenvironmental studies and local wind data analysis it is assumed that monsoon wind-generated waves have affected reefs at various meteorological wind sectors in the Maldives' atolls seasonally (NE and SW monsoons) since the last glacial maximum.

5.3.2 Non parametric multivariate analysis

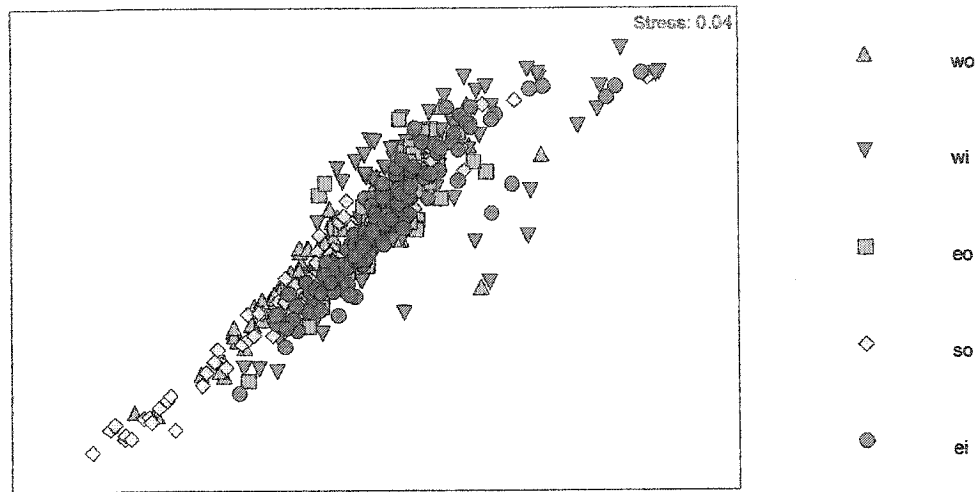
5.3.2.1 Multidimensional Scaling (MDS)

The MDS routines were run on the rim reefs to determine how well atoll rim reef groups are separated in relation to the predicted wave regimes in exposure level I (EO, WO, EI, WI, SO), using the morphometric variables developed in Chapter 4. The first ordination is based on the Bray-Curtis similarity matrix and the second on Euclidean Distance matrix (Fig 5.9). Stress levels of 0.04 and 0.1 (resp.) show that the both ordinations are reliable representations of relationships among groups of rim reefs and exposure regimes, with little uncertainty of interpretation.

Both MDS ordinations indicate that reef groups based on exposure are significantly separated statistically, but that there is also a high degree of similarity. There is a significant overlap of the reef groups. Rim reefs facing the western ocean (SW Monsoon) and southern ocean swell are more similar to each other than those reefs facing the inner sea (WI, EI), which themselves overlap to a large extent. Rim reefs seem to be separated

by their geomorphologic characteristics with respect to prevalent hydrodynamic conditions integrated over the past two decades. Further analysis and hypothesis testing was performed to determine the similarity of the reef groups.

A

MDS of rim reefs using Bray-Curtis similarity matrix

B

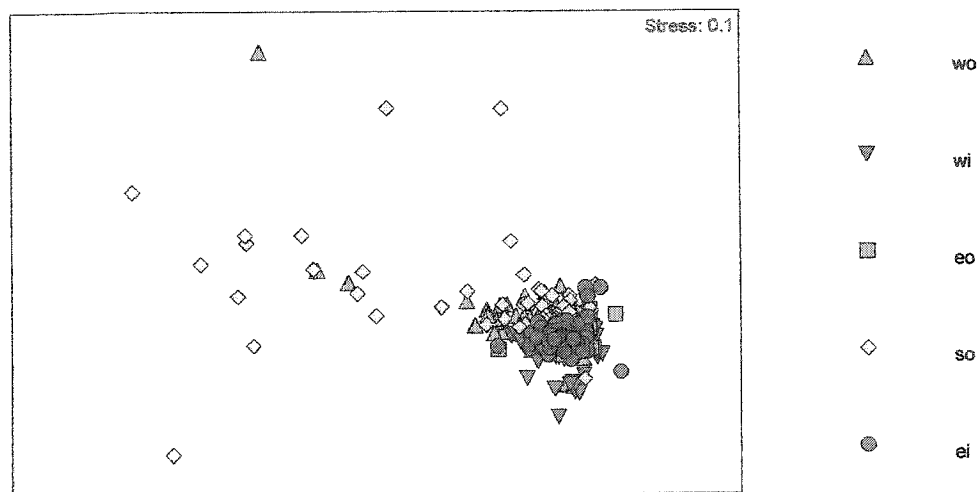
MDS of Rim reefs using normalised Euclidean Distance

Figure 5.9 MDS ordinations of rim reefs on the Maldives' atolls. A= ordination plot derived using Bray-Curtis similarity matrix, B= plot derived using Euclidean Distances. For details of exposure groups see (Fig 5.2 and Table 5.1).

5.3.2.2 Analysis of Similarity (ANOSIM)

The ANOSIM routine performed using normalized Euclidean distances between sample pairs identified significant differences among reef groups affected by varying levels of wave energy, both in simple (Exposure level I) and complex (Exposure level II) groupings of exposure regimes. For exposure level I the Global R is 0.22, which is significant at $p=0.001$ level. Pairwise tests for exposure level I groups are shown in Table 5.2. The distribution of Global R under the null hypothesis is shown in Fig 5.10. The lowest separation was between reefs on the east ocean and west inner sea ($R=0.09$) i.e., these groups had little differences between them in terms of the measured morphometrics. Reefs facing the southern swells and those facing the eastern inner sea had the highest significant R-value indicating that they are the most different of groups.

Analysis of similarities between wave regimes in Exposure level II gave a Global R value of 0.24 which was significant at $p=0.001$ level. Pairwise tests between these groups and the distribution of R values under the null hypothesis are given in Table 5.3 and Fig 5.11 respectively. Negative R values indicate possible incorrect groupings. At this complex level of classification some groups are poorly separable by the ANOSIM procedure, but overall the majority of the groups are significantly different to each other.

The similarity percentages (SIMPER) analysis showed that rim reef groups based on Exposure level I were best characterized by dimensional variables of reefs and their morphologies: e.g. perimeter, reef length, width, reef flat width, slope width, crest width and reef area. The average similarity within reef groups in Exposure level I ranged between 88.73 % and 92.4 %. The average dissimilarity between pairwise coefficients in Exposure I groups ranged from 8-11% with the variables reef flat width, slope width and crest width contributing to the greatest dissimilarity between groups.

Groups	R Statistic	Sig Level %
wo, wi	0.22	0.1
wo, eo	0.27	0.1
wo, so	0.28	0.1
wo, ei	0.35	0.1
wi, eo	0.09	0.1
wi, so	0.30	0.1
wi, ei	0.10	0.1
eo, so	0.21	0.1
eo, ei	0.12	0.1
so, ei	0.42	0.1

Table 5.2 Pairwise ANOSIM tests for individual rim reef groups of the Maldives in exposure level I. (See Table 5.1 and Fig 5.2 for details of exposure regime groupings).

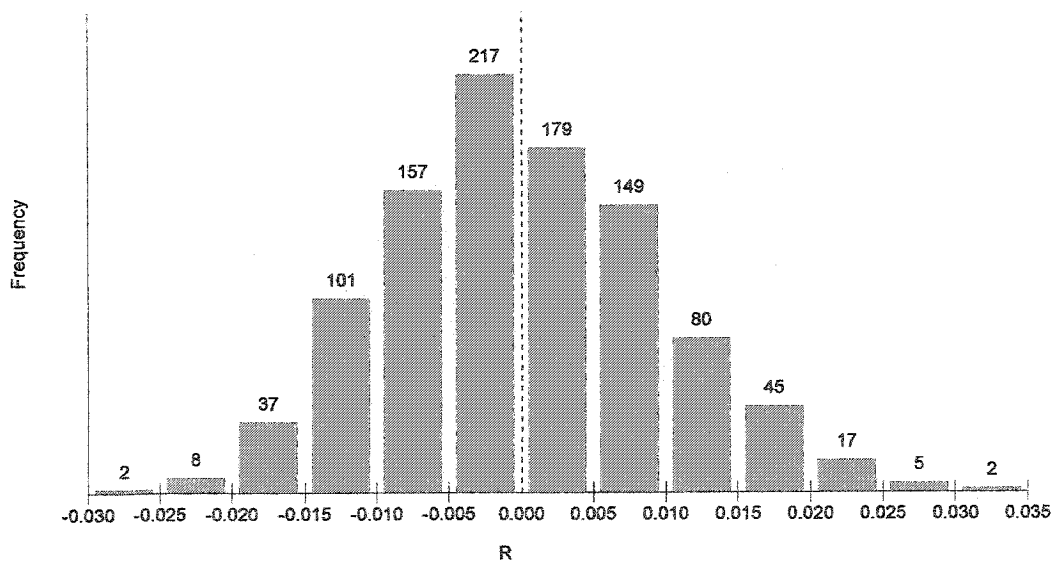


Figure 5.10 Frequency distribution of ANOSIM Global R values under the condition that null hypothesis is true for Exposure Level I classification of rim reefs of the Maldives' atolls. (See Table 5.1 and Fig 5.2 for details of exposure regime groupings).

Groups	R Statistic	Sig Level %
cwo, cwi	0.25	0.10
cwo, swo	0.21	1.10
cwo, seo	0.21	18.00
cwo, sso	0.17	0.10
cwo, nwo	0.11	0.90
cwo, neo	0.46	0.10
cwo, ceo	0.40	0.10
cwo, cei	0.48	0.10
cwi, swo	0.13	6.40
cwi, seo	-0.16	75.70
cwi, sso	0.30	0.10
cwi, nwo	0.18	0.40
cwi, neo	0.19	0.80
cwi, ceo	0.05	12.50
cwi, cei	0.09	0.10
swo, seo	0.03	40.80
swo, sso	-0.14	96.10
swo, nwo	0.51	0.10
swo, neo	0.67	0.10
swo, ceo	0.29	0.10
swo, cei	0.28	0.20
seo, sso	-0.26	93.50
seo, nwo	0.32	7.90
seo, neo	0.57	0.90
seo, ceo	0.08	34.10
seo, cei	-0.03	50.00
sso, nwo	0.03	28.50
sso, neo	0.06	14.90
sso, ceo	0.10	0.10
sso, cei	0.42	0.10
nwo, neo	0.36	0.10
nwo, ceo	0.43	0.10
nwo, cei	0.48	0.10
neo, ceo	0.45	0.10
neo, cei	0.55	0.10
ceo, cei	0.03	23.80

Table 5.3 Pairwise ANOSIM tests for individual rim reef groups of the Maldives in exposure level II. (See Table 5.1 and Fig 5.2 for details of exposure regime groupings). Negative R values indicate possible incorrect groupings.

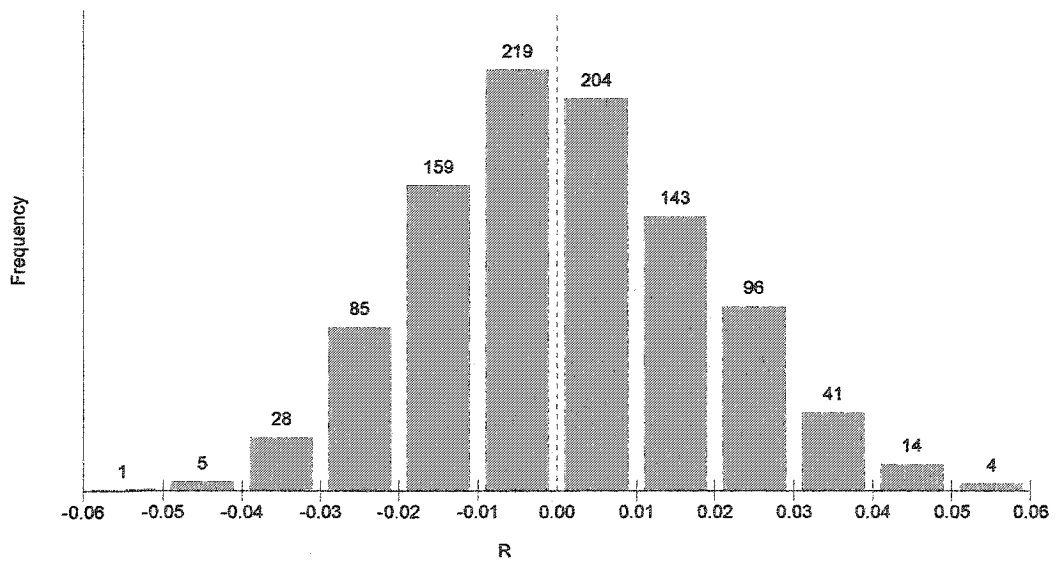


Figure 5.11 Frequency distribution of ANOSIM Global R values under the condition that null hypothesis is true for Exposure Level II classification of rim reefs of the Maldives' atolls. (See Table 5.1 and Fig 5.2 for details of exposure regime groupings).

5.3.3 Wave Power

Wave power calculated for the nine regimes (Exposure level II) are given in Table 5.4. Wave heights generated using Pierson-Moskowitz (PM) relations for equilibrium sea-states (SWAMP Group 1985) agree well with real observations and correlations of wind and wave heights in the Indian Ocean (Quarty 2000). The greatest, local, wind-generated wave energy reached reefs along west-facing ocean exposures of the archipelago (Table 5.4). The lowest wave energy reached reefs along the east-facing ocean exposures and those facing the Maldives Inner Sea. In general, wave power calculations show that wind-wave forcing was highest during the SW monsoon, and hence on the western ocean side of the atolls. Wave power calculations presented here are in agreement with worldwide ocean wave energy estimates made using TOPEX/POSEIDON altimeter data (Krogstad et al. 1997)

Exposure Regime	Annual average Wave Power (Watts.m⁻¹)	Annual average Wave Power (KW.m⁻¹)	Number of observations (days)	Total Wave Power (Watts.m⁻¹)
1. North East Ocean	80582.21	0.02	1677	805822.1
2. North West Ocean	1221693.52	0.34	1877	12216935.2
3. Central East Ocean	639458.86	0.18	3743	17265389.3
4. Central West Ocean	2182136.27	0.61	5964	58917679.2
5. South East Ocean	144433.08	0.04	3948	3466393.9
6. South West Ocean	806561.80	0.22	4313	19357483.2
7. Central West Inner Sea	123540.34	0.03	3743	3335589.1
8. Central East Inner Sea	295212.47	0.08	5964	7970736.8
9. Southern Ocean**	5916634.74	1.64	365	

Table 5.4 Wave power calculated from local wind and swell height data ** for each of the exposure regimes confronting atoll rim reefs of the Maldives. Annual averages were calculated by dividing the sum of the entire, integrated wind-wave power over the period of observation by the number of years for which the data was available. ** Swell-generated wave power for southern ocean was estimated from the average swell wave height reported at international surf sites over one calendar year.

The greatest wave power reached reefs facing the southern swells and the least wave power reached reef facing the northeast ocean facing reefs and those facing the Maldives Inner Sea. Wind-wave power was greatest for reefs facing the western ocean. The wind-generated wave power among the reef groups was highly variable with a factor of 30 difference in the wave power delivered to different reef groups. The swell generated wave power is three to 80 times greater than the monsoon wind-wave power.

5.3.4 Rim reef growth and wave power analysis

The reef metrics that portray the pattern of atoll rim reef growth (Fig 5.12) are positively and significantly related to incident wave power: reef area ($r^2 = 0.21$, $p < 0.01$, $n = 488$), reef slope width ($r^2 = 0.07$, $p < 0.01$, $n = 453$), reef crest width ($r^2 = 0.16$, $p < 0.01$, $n = 468$) and reef flat width ($r^2 = 0.12$, $p < 0.01$, $n = 469$). Relationships between wave power and the mean widths of reef slopes, crests, flats and total reef area at both exposure scales are summarized in Tables 5.5 and 5.6. Interestingly, the *proportions* of reef flat and reef lagoon per reef were not significantly related with wave power ($r = 0.05$, $r = 0.006$ (resp., $n = 488$, $p > 0.01$).

Rim reef slope width was significantly correlated with crest width ($r=0.38$, $p = 0.01$, $n = 451$) and flat width ($r=0.42$, $p = 0.01$, $n = 452$). It follows that a wider reef slope would produce a wider reef crest and a wider reef flat as well. Reef shape in terms of its thinness and roundness (Fig 5.13) was significantly related to wave power (Fig 5.14). Reef thinness was negatively related to wave power ($r^2 = 0.09$, $p < 0.01$, $n = 485$), while reef roundness was positively related ($r^2 = 0.14$, $p < 0.01$, $n = 488$). Reefs that were exposed to high swell wave energy were thin and elongated, whereas reefs that were exposed to moderate monsoon wind generated wave energy were rounder (Fig 5.13).

Regression equations that best describe the linear relationships between metrics of reef growth and incident wave power are shown in Fig 5.14 and 5.15. Regression coefficients range from 0.07 (slope width) to 0.21 (reef area), indicating that wave power never explains more than 21% of the measured variability in a metric.

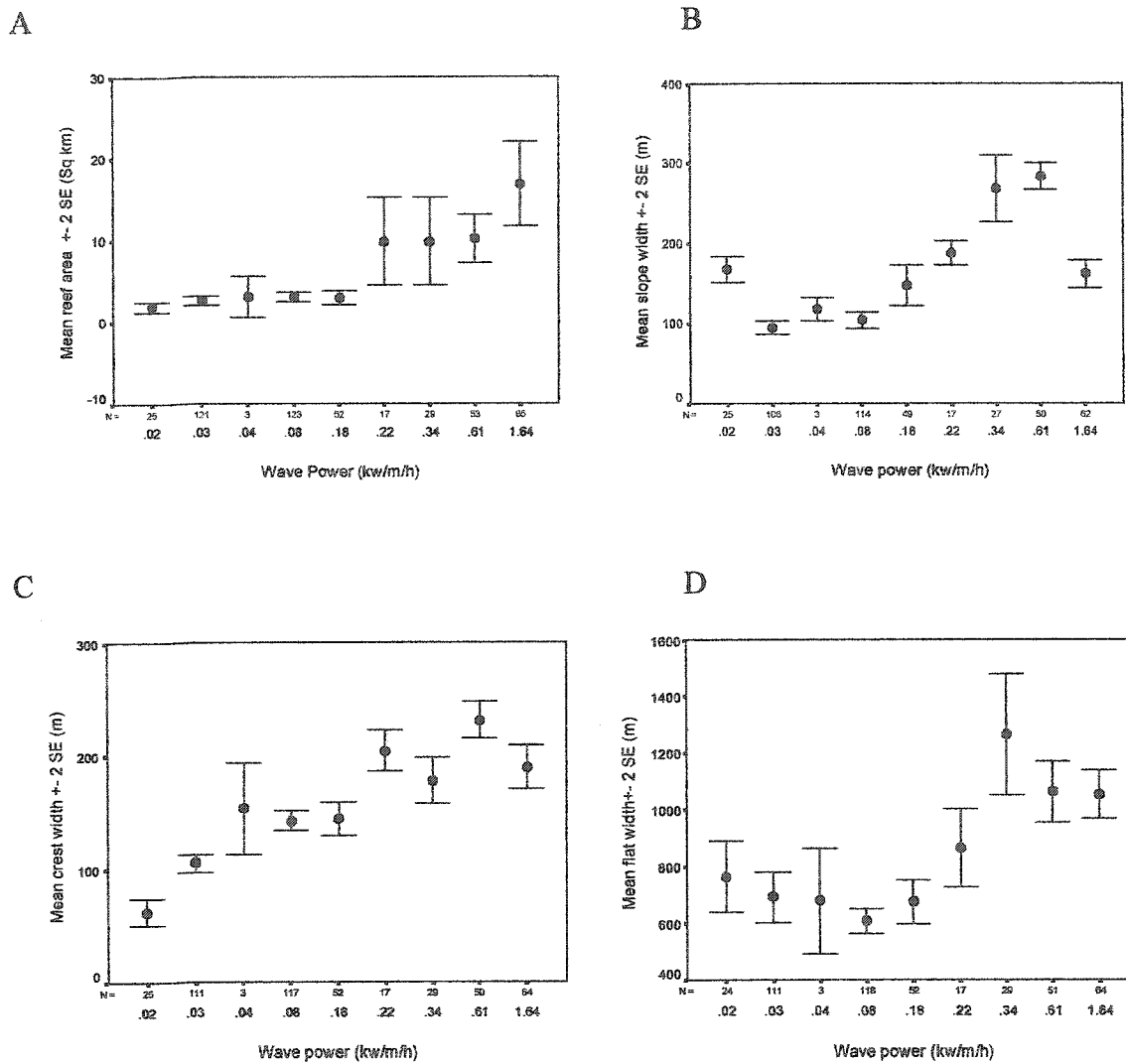
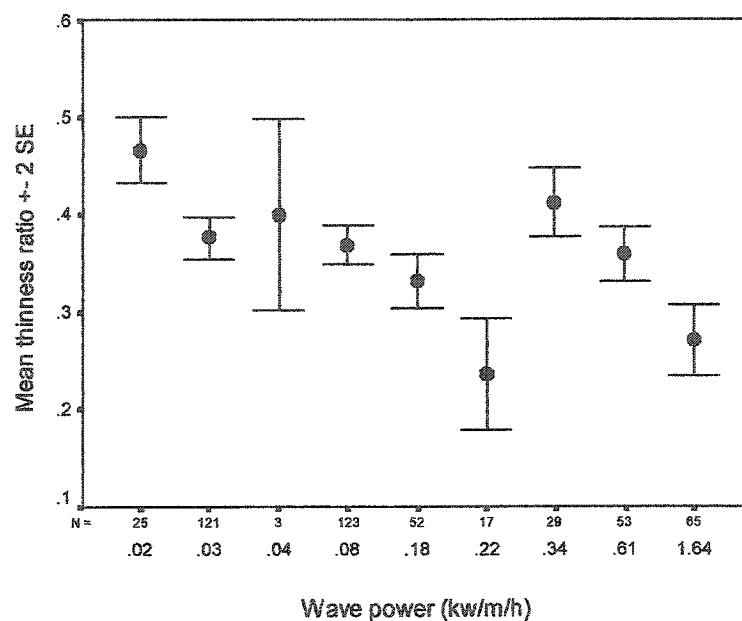


Figure 5.12 Statistical relationships between wave power and morphometrics of integrated reef growth of atoll rim reefs of the Maldives: total reef area (A); reef slope width (B); reef crest width (C); and reef flat width (D). Mean values of the dependent variable and standard error of the mean are shown.

A



B

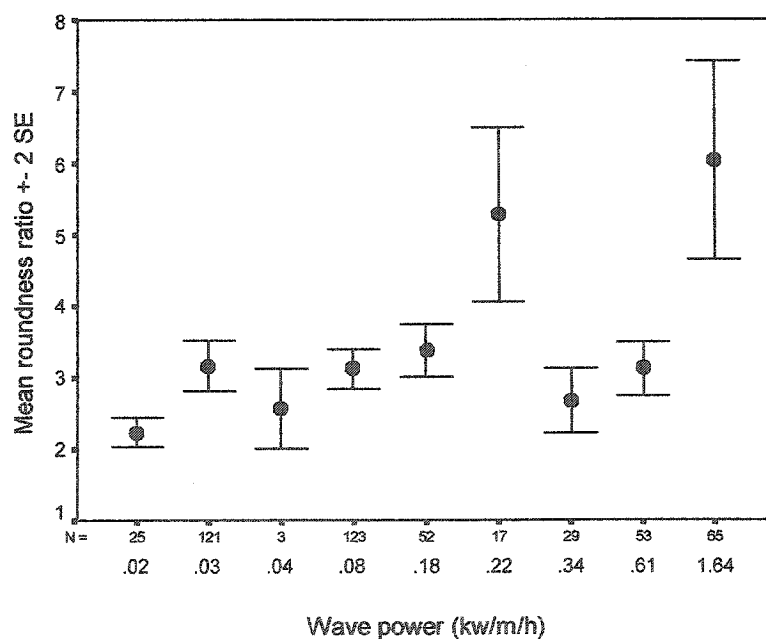


Figure 5.13. Variation in patterns of reef shape in relation to wave power for 488 rim reefs of the Maldives' atolls. (A) With increasing wave power reefs were thinner and elongated. (B) Reefs with moderate wave energy were rounder with a ratio closer to one. N.B. Ratios higher than unity indicates less round reef shapes.

Exposure Code Scale I	Wave Power (KW.m ⁻¹)	Mean Reef area (Km ²) (SEM,N)	Mean Slope width (Meters) (SEM, N)	Mean Crest width (M) (SEM,N)	Mean Flat width (M) (SEM,N)
WI	0.03	2.6 (0.28,122)	95.3 (4.3,106)	105.9 (4.0,112)	691.3 (45.1,112)
EI	0.08	3.1 (0.28,126)	106.4 (5.4,117)	142.0 (4.3,120)	607.7 (21.8,121)
EO	0.08	2.66 (0.30,80)	153.1 (8.3,77)	118.8 (6.7,80)	701.9 (31.9,79)
WO	0.38	10.31 (1.23,95)	264.8 (8.5,91)	213.9 (5.8,92)	1107.2 (46.7,93)
SO	1.50	16.92 (2.56,65)	162.9 (8.8, 62)	189.6 (9.8,64)	1054.1 (42.7,64)

Table 5.5 Comparison of reef growth metrics and wave power among reef groups of Exposure Scale I (See Table 5.1 for exposure scale codes). SEM= Standard Error of the Mean, N = number of reefs used in the analysis.

Exposure Code	Wave Power Scale II (KW.m ⁻¹)	Mean Reef area (Km ²) (SEM, N)	Mean Slope width (M) (SEM, N)	Mean Crest width (M) (SEM, N)	Mean Flat width (M) (SEM, N)
NEO	0.02	2.0 (0.3,25)	168.0 (8.1,25)	61.9 (6.0,25)	765.0 (62.6,24)
CWI	0.03	2.6 (0.3,121)	95.3 (4.3,106)	105.3 (4.0,111)	691.4 (45.5,111)
SEO	0.04	3.1 (1.2,3)	117.9 (7.6,3)	153.5 (20.2,3)	679.3 (92.7,3)
CEI	0.08	3.1 (0.3,123)	104.3 (5.3,114)	142.6 (4.4,117)	607.1 (22.3,118)
CEO	0.18	3.0 (0.4,52)	147.6 (12.3,49)	144.1 (7.3,52)	674.1 (38.4,52)
SWO	0.22	9.8 (2.7,17)	188.1 (7.9,17)	204.1 (9.3,17)	862.7 (68.7,17)
NWO	0.34	9.8 (2.7,29)	269.3 (20.9,27)	178.2 (10.0,29)	1263.6 (106.5,29)
CWO	0.61	10.2 (1.5,53)	283.9 (8.4,50)	231.3 (8.0,50)	1063.4 (53.1,51)
SSO	1.50	16.9 (2.6,65)	162.9 (8.8,62)	189.6 (9.8,64)	1054.1 (42.7,64)

Table 5.6 Comparison of reef growth metrics and wave power among reef groups of Exposure scale II. (See Table 5.1 for Exposure codes). SEM= Standard Error of the Mean, N= number of reefs used in the analyses.

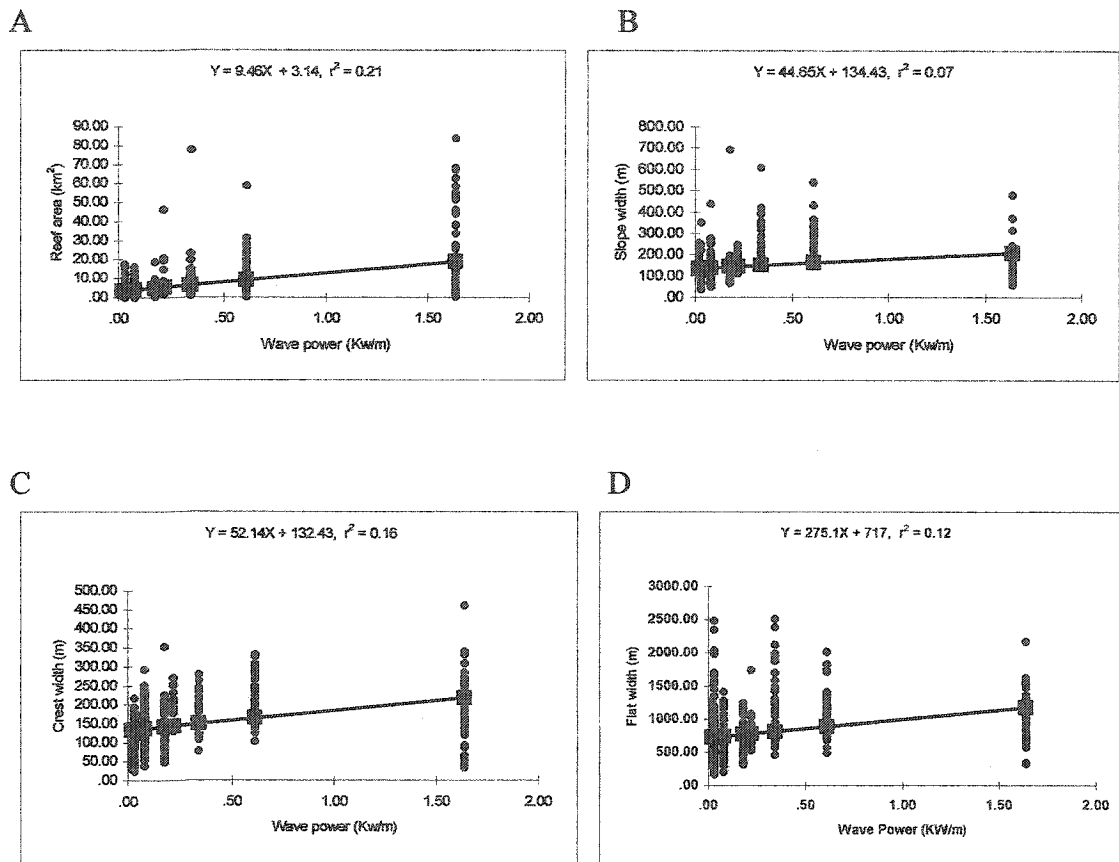


Figure 5.14 Relationships between reef growth metrics and wave power. A. Reef area, B. Reef slope width, C. Reef crest width, and D. Reef flat width.

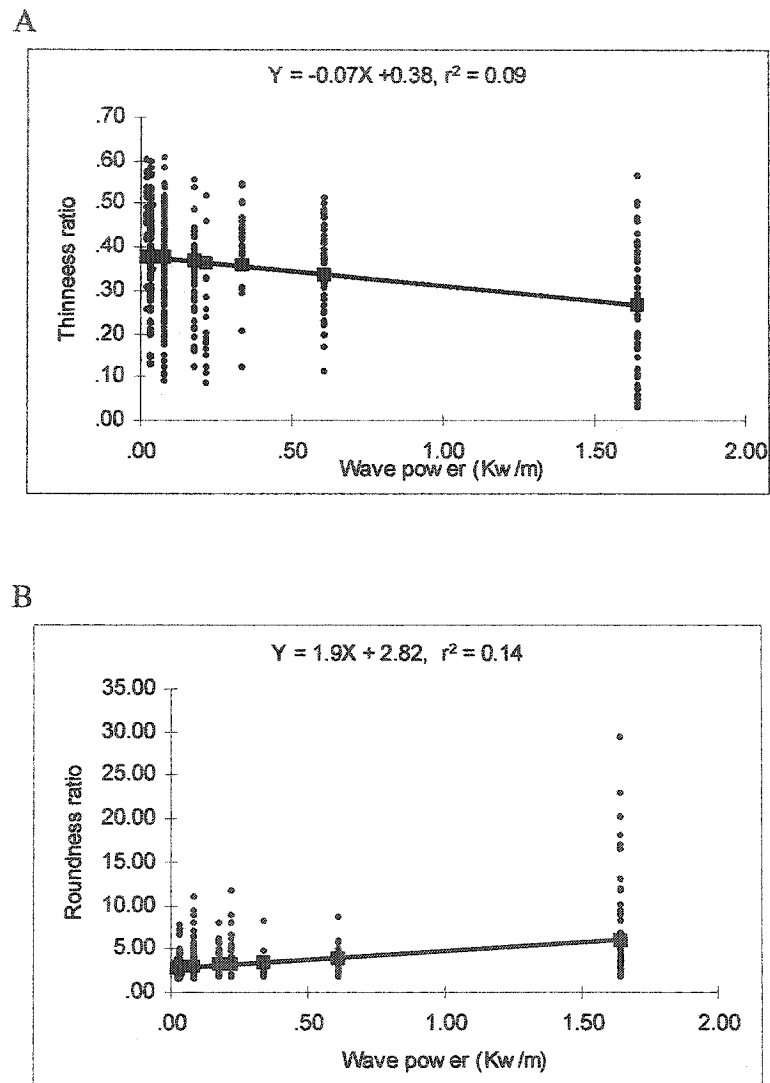


Figure 5.15 Relationship between reef shape and wave power. A. Reef thinness, B. Reef roundness. Thinner reefs have a lower ratio and roundness ratio increases for circular reefs.

5.3.5 Relationship between reef lagoons and wave exposure

Based on the hypothesis that wave power is related to the overall growth and accretion of the reef, it was predicted that the surface area of reef lagoons on individual reefs would be inversely related to impinging wave power i.e., reefs exposed to higher wave energy will have less lagoon area as a result of sediment infilling. Fig 5.16 shows the mean proportion of reef lagoon on rim reefs within exposure level I.

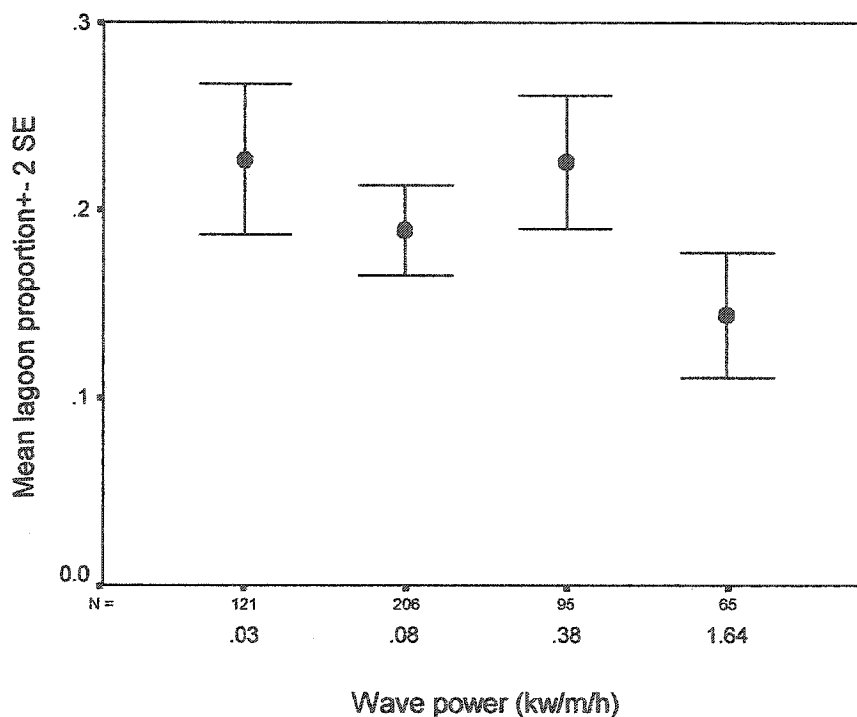


Figure 5.16 Mean reef lagoon proportions of total rim reef area in atolls of the Maldives as a function of wave exposure regimes in the simple exposure scale (Exposure level I). Error bars show mean \pm 2 Standard Errors of the Mean.

As predicted, the proportion of reef lagoons is least on reefs facing the southern ocean swells. These reefs receive the highest amount of energy from swell waves. This result supports the hypothesis that reefs exposed to high wave energy progressively less lagoon area due to rapid infilling.

Total lagoon area on all rim reefs in each wave power regime (within Exposure level I) showed a better relationship between hydrodynamic forcing and lagoon infilling (Fig 5.17). Here reef lagoon area across wave regimes is expressed as a % of the total reef area in each regime. As predicted the % lagoon area is least in the highest exposure regimes. It is concluded that of the 2000 or so reefs in the Maldives, those that are subject to the highest hydrodynamic energy results in greater infilling of these reefs.

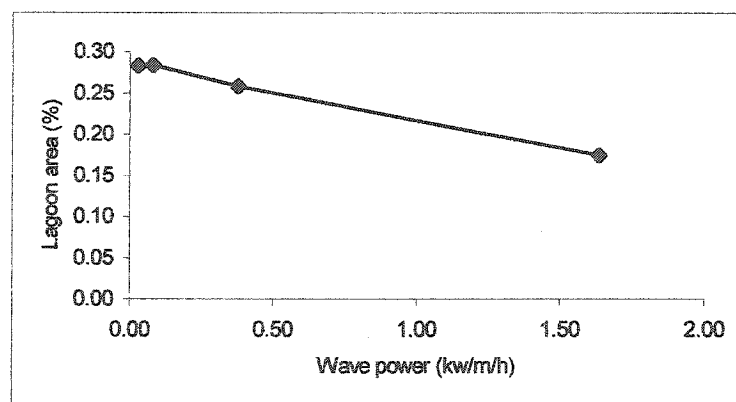


Figure 5.17 Mean percent reef lagoon area (in proportion to total reef area) of rim reefs of the Maldives atolls located in wave regimes classified under Exposure Scale I.

5.3.6 Lagoon reef growth and aperture analysis

Atolls are characterized by a rim and a central lagoon. The structure and function of rims of atolls has been a long debated issue. Studies suggest functional relationships between the atoll rim and the lagoon (Dufour 1997; 2001). The atoll rim structure varies within biogeographic coral reef regions of the world. Some rims consist of a completely closed wall with no deep openings to the surrounding ocean (e.g. Hull atoll; Wiens 1962). Others have a few deep channel openings to the ocean. Yet others have rims made up of many individual reefs separated by many deep channels. (Fig 4.3, Chapter 4).

Atoll aperture is defined here as the openness of an atoll in terms of the number and width of the rim channels on the atoll. Aperture was simply the width of channels divided by the atoll perimeter:

$$A = C/P, \quad (5.13)$$

Where A is the aperture, C is the total length in meters of all the deep channels on the rim and P is the perimeter of the atoll. Table 5.7 shows the aperture and other metrics for 16 atolls of the Maldives.

Atoll	Code	Aperture	Number of Lagoon reef		Atoll area (km ²)	Ratio:
			Lagoon Reefs	area (km ²)		Lagoon Reef area/Atoll area
Ihavandhippolhu	I	0.14	20	6.7	289.81	0.023
Haa	H	0.31	80	93.8	3788.71	0.025
Raa	R	0.26	113	40.9	1184.31	0.035
Baa	B	0.24	50	75.1	1126.95	0.067
Lhaviyani	LH	0.08	58	14.7	701.42	0.021
North Male	NM	0.17	142	91.4	1568.18	0.058
South Male	SM	0.14	89	38.7	536.33	0.072
Ari	A	0.35	204	219.7	2271.75	0.097
Faafu	F	0.16	64	33.2	597.15	0.056
Dhaalu	D	0.15	81	31.8	736.46	0.043
Vaavu	V	0.13	152	37.1	1090.97	0.034
Meemu	M	0.06	86	17.7	983.92	0.018
Thaa	T	0.06	131	24.4	1695.79	0.014
Laamu	L	0.03	49	13.4	884.63	0.015
Gaafu	G	0.09	171	53.2	3278.59	0.016
Seenu	S	0.03	3	0.12	157.22	0.001

Table 5.7 Atoll metrics for the 16 atoll of the Maldives analyzed for lagoon reef growth and rim aperture relationships.

The issue investigated here is the relationship between the atoll rim structure (in terms of aperture) and the growth of patch reefs in the atoll lagoon. Even Darwin (1889) suggested a possible relationship between the size and number of atoll rim channels and atoll lagoon patch reef growth. Wiens (1962) indicated that where the rim is more complete the less likely is the lagoon to have coral knolls, pinnacles and other reef patches. It is suggested that where rim reef passes in atolls are large, deep and numerous, the sedimentation of the lagoon floor is reduced by the sweeping action of the moving water. The reduction of sedimentation encourages patch reef growth in the lagoon.

Guilcher (1988) found that there is apparently no relation between the *occurrence* or *number* of pinnacle reefs in the atoll lagoon and the degree of connection between the lagoon and the ocean (aperture). This is quite possible. An open atoll may have few *numbers* of reefs but a greater reef area indicating higher growth in open atolls. Similarly an atoll with a lower degree of aperture may have a higher *number* of reefs but these reefs maybe small in size and in term of growth they may not be significant. In this study there was a significant but weak relationship between the number of reefs and the atoll aperture (Fig5.18, $r = 0.36$, $p = 0.001$, $n = 16$).

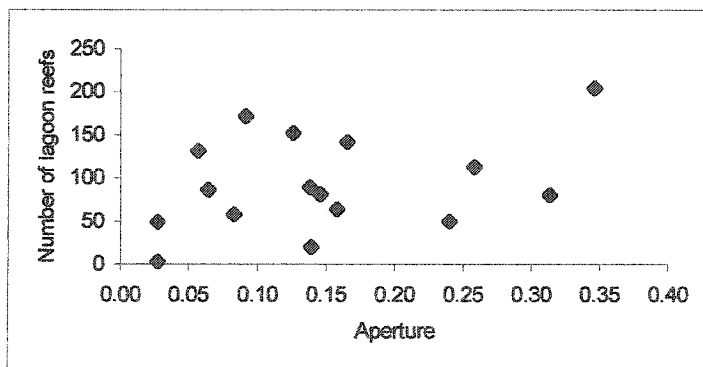


Figure 5.18 Relationship between number of atoll lagoon patch reefs and atoll aperture for 16 atolls of the Maldives.

So, the degree of atoll aperture and its lagoon reef growth is a matter open to discussion and remains to be tested using quantifiable lagoon reef growth metrics. While many have debated the issue, none has analyzed lagoon reef growth data quantitatively to conclusively show a relationship between lagoon reef growth and rim morphology. Here it is hypothesized that open atolls will have more lagoon reef area than closed atolls and this is tested by correlating atoll aperture to lagoon reef area.

A highly significant positive relationship ($r^2 = 0.62$, $p < 0.001$, $n = 16$) exists between the total area of lagoon reefs within an atoll and its aperture (Fig 5.19). It was also observed that in general, larger atolls had greater lagoon reef area (Fig 5.20), but larger atolls did not necessarily have larger apertures and the correlation between aperture and atoll size was poor (Fig 5.21, $r = 0.40$, $p = 0.001$, $n = 16$).

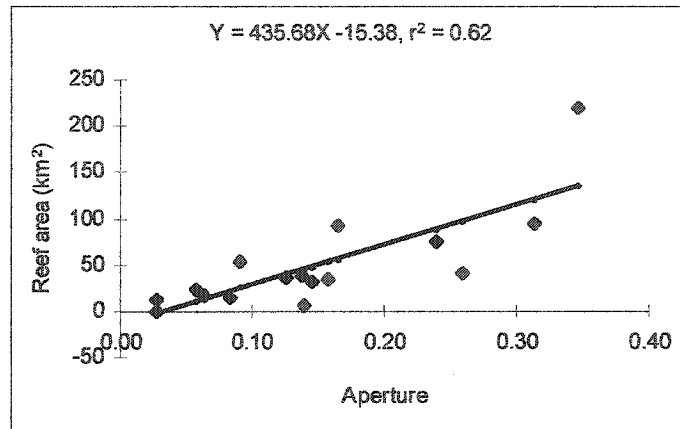


Figure 5.19 Scatterplot of the relationship between the lagoon reef area and aperture for 16 atolls of the Maldives ($r = 0.79$, $p < 0.001$). The regression line which best describes the relationship is shown.

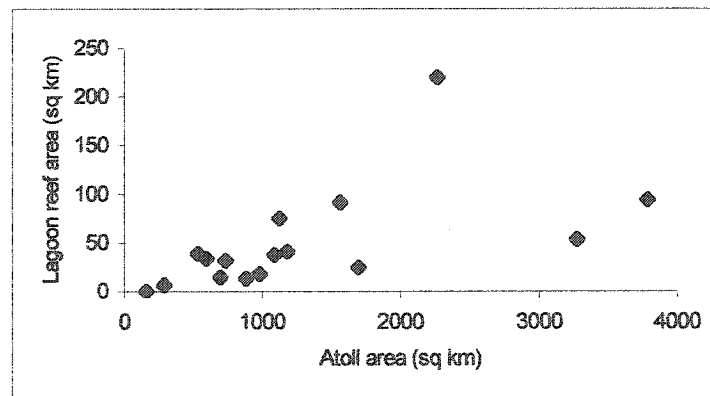


Figure 5.20 Scatterplot of atoll area and lagoon reef area for 16 atolls of the Maldives.

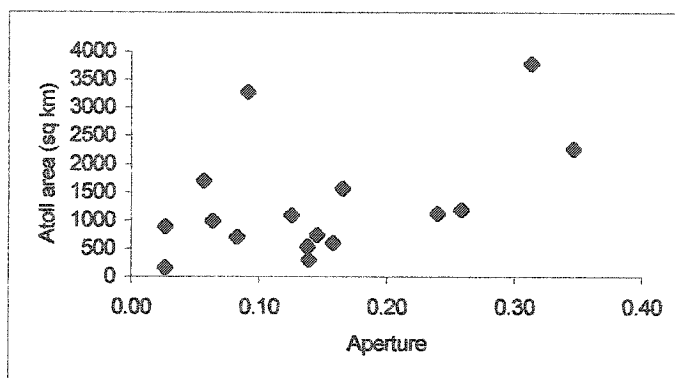


Figure 5.21 Scatterplot of atoll aperture and atoll area for 16 atolls of the Maldives ($r = 0.40$, $p = 0.001$, $n = 16$). Smaller atolls did not necessarily have smaller apertures.

The shallow reef flats on lagoon reefs showed a an even stronger relationship to atoll aperture ($r^2 = 0.72$, $P < 0.001$, $n = 16$), suggesting reefs that have reached or are continuing to reach sea level grow at a faster rate in open atolls than closed atolls (Fig 5.22).

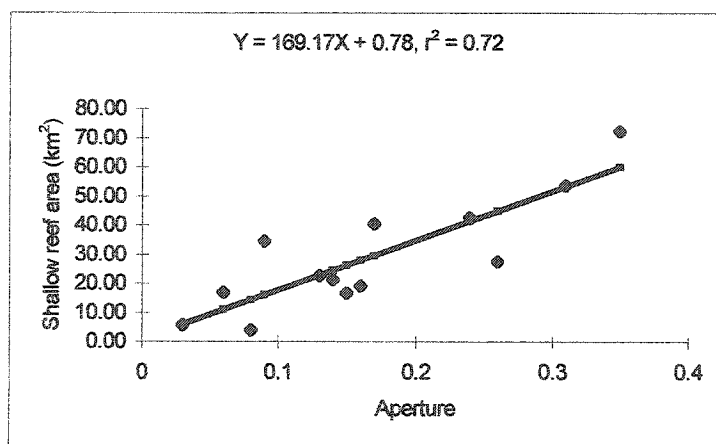


Figure 5.22 Scatterplot of atoll aperture versus shallow reef area of lagoon patch reefs in 16 atolls of the Maldives ($r = 0.85$, $p < 0.001$). The regression line which best describes the relationship is shown.

5.4 Discussion

The sizes, shapes and benthic habitat zonation patterns of 488 individual coral reefs located on the rims of the Maldives' 16 great atolls are largely explained by a single metric of hydrodynamic forcing. Multiple morphometric expressions of the time-integrated growth of these reefs ordinate strongly along axes of exposure to impinging wave fields, group at a high level of dissimilarity according to their geographic location relative to the main directions of Monsoon wind-wave and swell forcing, and are highly correlated with long-term averages of wave power dissipated on them. These results support the long-standing, but never-tested hypotheses that coral reef growth is controlled by hydrodynamic forcing functions (Hamner and Wolanski 1988), and provide the first detailed and rigorously defensible explanations for the asymmetrical growth morphologies of the world's most complex atoll reef province: the Maldives archipelago. The conclusion applies both to the atoll rim reefs and the patch reefs and *faros* of the great atoll lagoons. Analysis at the spatial scale of an entire reef province, and at a level of replication equalling the entire complement of the Maldives' reefs was made possible only with remote sensing and GIS technologies. The opportunities to further develop and test hypothesis posed at the scales of reefscapes using these technologies are immense. This study has only tapped that potential.

While the results strongly support the concept that the modern configurations of the Maldives' reefs reflect the net integration of constructional processes operating throughout much of the Quaternary under hydrodynamic forcing similar to today's, they do not unequivocally resolve the tension between antecedent (erosional) and recent (constructional) controls on reef morphology. There are certainly indications of the interplay between inherited reef morphology and modern environmental processes in reef growth in the Maldives. The fact that the proportion of reef flat and reef lagoons resulted a non-significant correlation in this research is perhaps indicative of the inherited nature

of some reef lagoon depressions and even some of the reef flat areas. Modern growth processes alone cannot explain all the variation in morphologies measured at the scale of entire atolls (e.g. atoll shape), or within individual reefs (e.g. fore-reef “lagoons”). But at the intermediate scales of entire reefs, the measured morphologies are entirely consistent with net constructional processes responding to current patterns of hydrodynamic forcing. The regressions of horizontal dimensions (slope with, crest width, flat width) of reef morphology on wave power demonstrate directional forcing on the patterns of lateral reef growth. Understandably, the strongest relationship exists between reef crest width and wave power. This is the area of highest wave energy dissipation and maximum rates of corraline algal growth. More comparative studies of this nature across coral reef systems of the world are needed to differentiate modern environmental processes from geological processes in shaping coral reefs.

The wave power calculations critical to this research was predicated on the analysis of local wind data over a reasonably short period of time (10-27 years). The necessary assumptions concerning the wind duration required to fully form seas, the temporal pattern of monsoon wind directions and the identification of exposure regime groupings of individual reefs are all subject to a risk error because of the limitations of the data. A basic tenant of ecology is to match the scales of various observations to those of the putative forcings controlling pattern (Levin 1992; Kay and Schneider 1994; Brown 1999). Data with higher spatial and temporal resolution (e.g. modelled wave data in 0.25x0.25 degree resolution grids hindcast over decades using the NOAA WAVEWATCH III; <http://polar.wwb.noaa.gov/waves/historic.html>) would likely result in significant refinement of the methods and results presented here. A further refinement of the methods for wave power analysis is to determine the orientation of each individual reef in relation to wind-wave and swell directions. Thus resolving the directional wind-wave components and unique wave power impinging on each reef would greatly increase the degrees of freedom in the various statistical analyses. The derivation of such data was beyond the scope of this research because of limitations of time and resources, which were correctly focused first on the derivation of the reef morphometrics from the

remotely-sensed data. Detailed studies of a single reef using complex wave modeling coupled with benthic studies requires considerable research effort (Storlazzi 2001).

This research highlights the relevance and application of scaling methods in process-related studies of coral reefs (Hatcher et al. 1987; Smith and Kinsey 1988; Hatcher 1997; Murdoch and Aronson 1999; Mumby 2001). Whilst several studies have pointed out the apparent morphological adaptations of individual or small groups of reefs to physical processes (particularly wave fields, e.g. Bradbury and Young 1981, Roberts et al. 1992, van Woerik and Done 1997), few studies relate growth processes to environmental forcing in a quantitative manner across entire systems of reefs. This begs the question of up-scaling from few, high-resolution studies to generalizations about processes operating over large domains. Most reef studies have been carried out on few “representative” reefs, and the results extrapolated to explain processes over entire reef systems (e.g. the Great Barrier Reef: Hopley 1982). Munk and Sargent (1954) showed that the length and spacing of spur and groove formations on an atoll in the Marshall Islands were accurately predicted by the distribution of wave power around the atoll. This early study provided clear signs of a quantitative relationship between patterns of reef growth and hydrodynamics, but the pioneering work was not extended to other atolls, much less entire atoll systems until the detailed work of Storlazzi et al. 2001 and this study, despite a greatly improved understanding of the physics of wave-reef interactions (Symonds et al. 1995; Hearn 2001; Hearn et al. 2001). Perhaps the relationship is simply taken for granted by reef ecologists, and not considered worthy of further research. Hopefully, the power of the analyses presented here will re-awaken the interest in spatially-explicit but generalizable models of modern reef growth that extend beyond the geological model of sea level change as the dominant control on reef growth rates and patterns (Montaggioni 2000; Kennedy and Woodroffe 2002).

The dearth of quantitative studies of coral reef morphology and surficial growth at the scales of entire systems of reefs undoubtedly reflects a logistical constraint on the collection of synoptic data throughout the history of coral reef research: you had to be there to make observations, getting there was difficult, and measurements were made by

direct inspection and labour-intensive sampling. It is time consuming and expensive to study large ecosystems this way, but that has been the reef research tradition. We now have tools and techniques to overcome the challenges of synoptic sampling of reef geomorphology and even communities (Chapter 4). Environmental data are becoming available at finer spatial resolutions with better accuracies and at higher frequencies via satellites and ocean observing networks now. Wind, wave, sea surface temperature, chlorophyll and many more parameters are now regularly collected by sensors in space. Effective use of such data can provide crucial results to compare and contrast coral reef systems across the biogeographical regions of the world.

Comparative studies of major atoll groups of the world are critical to answer the two major questions of modern coral reef growth: Antecedent, sub-aerial or current, submarine control of reef structure? Physical or biotic control of reef function? Compared to Pacific atolls, the Maldives' atolls are relatively landless and their reefs have a very high proportion of deep reef lagoons on them compared to reefs on Pacific atolls. These differences maybe interpreted as a direct result of differences in climatological conditions between the two settings (i.e., Pacific vs. Indian Ocean). Many Pacific atoll rim reefs appear to be more mature than those of the Indian Ocean, having broader reef flats and larger debris fields (including low reef islands, boulder ramparts and rubble deposits; Wiens 1962; Stoddart 1969b; Battistini 1975; Guilcher 1988). The reef lagoons of Pacific atolls also appear to be infilled more rapidly perhaps due to stronger hydrodynamic forcing in the trade wind belts (Pichon 1981). The Maldives has not reached this stage of atoll reef growth. Reefs are probably actively growing upwards and outwards in many areas, and infilling is proceeding at a much lower rate compared to Pacific. This maybe the reason why reef flat: reef area ratios are not well-related to wave power in the Maldives' rim reefs, despite the fact that the absolute dimensions of the outer reef slopes and reef flats are significantly related with impinging wave power. Comparative studies of hydrodynamic forcing functions across biogeographic reef provinces experiencing different wind-wave regimes based on the type of research presented in this thesis, may contribute to a better understanding of modern coral reef growth. This is certainly a direction for future research.

Distinct asymmetries in the structure of atoll rim reefs of the Maldives have much to say about the relative importance of antecedent versus modern controls on patterns of reef growth. The rim sectors of atolls lining the east and west of the Maldives Inner Sea and those lining the ocean sides of the same atolls on the east and west were morphologically (and statistically) distinct (Figure 5.2, Table 5.5). The rim sectors lining the Maldives Inner Sea have smooth edges, while the rims facing the western and eastern ocean have rugged, irregular edges: some reefs and parts of reefs having extended laterally much further upstream than other. The contrast indicates that over the growth periods integrated in the currently expressed morphologies, the rims facing the stronger, more variable hydrodynamic conditions of the outer oceans, grew faster and more variably in response to that forcing. On the other hand those rims facing the Maldives Inner Sea were subject to wave powers an order of magnitude lower and lesser extremes of weather variability, as they were sheltered on both sides. The predicted reef growth response to these hydrodynamic conditions is, far less lateral extension of reefs having much steeper slopes. Hence, reef alignment along the Maldives Inner Sea is virtually a straight line, from which may be inferred a close correspondence to the antecedent structure of the atolls' inner rims, perhaps a result of the volcanic basement morphology or sub-aerial erosion during periods of sea-level low stand. On the more rapidly growing outer rim slopes, these antecedent features (including lagoon on these atoll rim reefs) are largely masked by constructional sub-marine process of reef growth.

The shapes of atoll rim reefs on both the ocean and the Maldives Inner Sea sides will of course have been affected during times of lower or variable sea levels, but the effects would not have been symmetrical. As sea level fell the ocean facing rims would have experienced relatively little change in wave exposure compared to those on the Inner Sea side. The Inner Sea became more sheltered from wind-waves and swell as the connections to the surrounding ocean diminished (analogous to the atoll aperture arguments presented earlier). As sea levels again rose the discrepancies in exposures between the Maldives Inner Sea and ocean-facing reefs would diminish, but, as the data presented in this study demonstrate, even at the present-day high stand, it is still very

great. The discrepancy in wave forcing would have been further attenuated during the global sea level high-stand of about 1-2m approximately 4.5 kA B.P. (Woodroffe 1992; Kennedy and Woodroffe 2002), but this event appears to have been too small and short-lived to allow reef growth processes to significantly reduce the striking differences between the reef growth morphologies of the inward and outward-facing rims of the great atolls of the Maldives. Thus, the multi-scale shapes of rim lines on the atolls facing the open ocean and the Maldives Inner Sea quantified and classified in this study provide circumstantial evidence of environmental forcing of reef growth and the shaping of atoll rim reefs during the Quaternary.

Metrics of the net, time-integrated growth of patch reefs and *faros* within the lagoons of the 16 great atolls of the Maldives are strongly related to the apertures of those atoll rims. Directional wind, waves and wind-driven currents around oceanic atolls create ideal conditions for reef productivity (Hamner and Wolanski 1988; Wolanski 2000). It follows that the growth of atoll lagoon reefs is dependent on rim aperture, the hydrodynamics of rim reef flats and passes, and patterns of lagoon circulation (Atkinson et al. 1981). It is postulated that open atolls would create better ecological conditions for lagoon reef growth than closed atolls. Deep rim passes in many Pacific atolls were described by Wiens (1962). A total of 118 passes were noted for Pacific atolls, of which 44 were in 28 atolls of the Marshalls, 34 in 30 atolls of Carolines and 33 in the 72 atolls of the Tuamotus. The average number of deep passes per atoll ranged from 0.46 to 1.5 in the various Pacific atoll groups. In contrast, the 16 great atolls of the Maldives contain 467 deep (i.e., navigable) channels detected using the classification scheme developed for this study (Chapter 4), which constitutes an average of almost 30 passes per atoll. A total of 17% of the total rim length (i.e., perimeters) of the Maldives' 16 great atolls was occupied by deep channels. This large aperture of the Maldives' atolls is postulated as the causal explanation for the remarkable density and complexity of lagoon reefs in the Maldives' atolls compared to Pacific atolls. The location of passes was reported to be more frequent on the leeward side of atolls in the Pacific: 85 % of passes lie on leeward sectors (Wiens 1962). This was also the case for the Maldives' atolls. Although not quantitatively investigated, it was noted that passes were more frequent on the sheltered sides (i.e., those

experiencing low wave power) of atolls. Lagoon reef growth was more prominent at the mouths of lagoon passes than at inner extents of the atoll lagoons. Lagoon reefs in close proximity to rim channels will receive considerably higher wave energy and better conditions for reef growth which will result in larger reef areas. Presumably reefs would then also grow faster to the sea surface in these regions of the atoll lagoon.

Clearly atoll rim growth patterns have major differences in the two environmental settings of the Pacific and Indian Oceans. The ecological significance of this difference for coral reef structure and function has yet to be properly investigated.

Hatcher (1997) expressed the importance of understanding ecosystem processes at equivalent spatial and temporal scales in coral reefs, and specified the level of measurements necessary to address the outstanding coral reef research questions. The type and scale of data analyzed here appear to be at the right scales to address ecosystem processes on coral reefs. Coral reef research is still predominantly confined to studies of individual reefs. Diverse interdisciplinary research methods are necessary to address process related coral reef studies. This research has demonstrated the feasibility of such complex research undertakings by combining satellite image analysis and GIS tools with rigorous, quantitative statistical analysis of coral reef morphometrics and environmental data, in order to investigate lateral coral reef growth across one of the largest atoll reef systems of the world.

Chapter 6

6 INVENTORY OF THE MALDIVES' CORAL REEFS USING MORPHOMETRICS GENERATED FROM LANDSAT 7 ETM+ IMAGERY

6.1 Introduction

The area of seabed occupied by coral reef communities is an essential metric for understanding coral reef ecology across a broad range of spatial scales. Population densities and metabolic rates of reef communities are scaled to the surface area of a habitat or reef zone (Hatcher et al. 1987). Tropical marine reserves are designed and zoned on the basis of aerially-scaled habitat criteria (Possingham et al. 2000). Regional evaluations of reef health (Rajasuriya et al. 2000), and global estimations of reef productivity and yields (Crossland et al. 1991, Kleypas 1997) depend on aggregate measures of reef area at appropriate scales. There is considerable (i.e., an order of magnitude) uncertainty around the global number, with at least seven published estimates ranging from about 100,000 to almost 4,000,000 km² (Smith 1978, Spalding and Grenfell 1997). Three sources of error may contribute to variability in estimates of reef area: errors of attribution (a function of the definition of coral reef used and the cartographer's or the software's ability to identify reefs), errors of demarcation (a function of accuracy of mapping reef boundaries), and errors of scaling (a function of mapping resolution or map scale). The relative contributions of the error terms, and sign and magnitude of error propagation varies with the type and scale of the source data (predominantly bathymetric charts), and the method of up-scaling from the source data to aggregative measures (i.e., the area integration algorithm). Spalding and Grenfell (1997) observed large and inconsistent discrepancies in both sign and magnitude of change in estimates of reef area as they altered the resolution and scale of regional and global reef mapping. The authors concluded that differences in the definition of what constituted a coral reef area were the

major source of variation amongst different author's estimates of global reef area, and that increasing the resolution of mapping substantially reduces aggregate estimates of reef area at regional scales because less inter-reef area is included. The implication for coral reef science and management is that the world has less coral reef resource than previously thought, and new methods are required for accurate reef area calculations over large spatial domains. The interpretation of remotely sensed data is the best tool currently available for this task (Andréfouët et al. 2001a, Green et al. 2000).

The Maldives archipelago is the historical archetype of a coral reef province. Sparsely populated by humans since at least 500BC and formally studied since 1840, they provide the key test system for models of reef response to the ocean environment (Darwin 1889, Daly 1915, Gardiner 1902, Agassiz 1903, Sewell 1932, Stoddart 1965, Woodroffe 1992, Purdy and Bertram 1993, Naseer and Hatcher 2001). Urgent concern for the fate of the Maldives' coral reefs and their people in the Millennium global greenhouse (Kleypas et al. 2001) implore the urgency to provide the best possible estimates of the actual areas of coral reef habitats over the entire archipelago at a spatial resolution that matches or subceeds the area of the minimum management unit (i.e., the smallest area of marine space that can be effectively managed, Hatcher 2001). The benchmark is provided by the pioneering cartography of Moresby during 1834-6 (Spray 1966) and the meticulous digitization of Spalding et al. (2001), manifest in the web-distributed estimate of 8,920 km² for the total area of shallow reef (nominally down to 30m depth) in the Maldives (Spalding et al. 2001, Oliver and Noordeloos 2002). This chapter presents the use of satellite remote sensing data and geospatial analysis to derive the most accurate and detailed estimates of the Maldives' reef areas to date, and compare our result with the benchmark.

6.2 Methods

The Maldivian archipelago extends 900km from 7° 06'N to 00° 45' S latitude and 130 km from 72°33'E to 73° 47'E longitude in the north central Indian Ocean (Wells 1988). It comprises 16 atolls, 5 oceanic *faros* (ring-shaped reefs exposed to the open ocean that are not atolls) and 4 oceanic platform reefs (reefs lacking lagoons that are exposed to the open ocean, Fig.6.1). Water depths outside the atolls drop steeply to 100s of metres in the Maldives Inner Sea and 1000s of meters in the surrounding ocean. The atolls and their associated rim reefs lagoons and lagoon reefs vary tremendously in their formation, size and physical setting (Purdy and Bertram 1993, Naseer and Hatcher 2001). The depths of the atoll lagoons range from 30 to 80 meters.

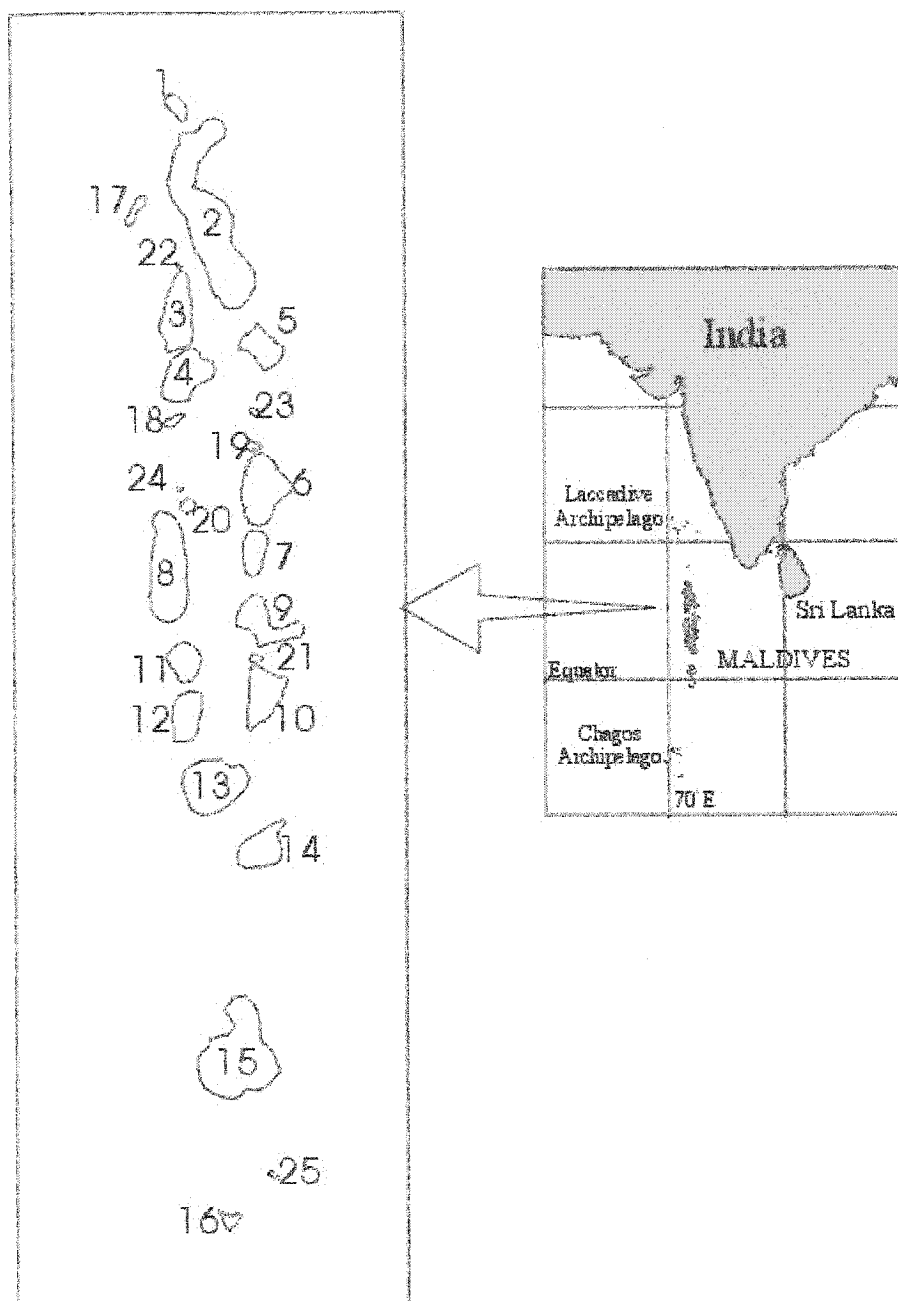


Figure 6.1 Location and diagrammatic outlines of the major coral reef features of Maldives. Items 1-16 = complex atolls, 17-21 = oceanic *faros*, 22-25 = oceanic platform reefs. See Table 6.1 for atoll statistics.

6.2.1 Image Analysis

The morphology of the atoll reefs and lagoons were classified on the basis of the spectral signatures of their various habitats using images produced from the latest NASA Landsat 7 Enhanced Thematic Mapper Plus (ETM+, <http://landsat.gsfc.nasa.gov/>). Eight radiometrically and geometrically corrected images of the Maldives (path 146/row 55, path 146/row 56, Path146/Row57, Path145/Row56, Path145/Row57, Path145/Row58, Path145/Row59, Path145/Row60) captured between July 1999 and January 2002 were obtained from the US Geological Survey (USGS), EROS Data Centre (<http://landsat7.usgs.gov/>). The data were supplied in 8 spectral channels ranging from 15m to 60m square pixels, four channels of which (Bands 1 to 4 at 30x30m pixel resolution) were used to classify the images using PCI-GEOMATICA™ software (version 8.2.1) from PCI Geomatics Ltd. (<http://www.pcigeomatics.com>). Each scene was processed separately, and no attempt was made to intercalibrate spectral signatures among scenes.

Deep water (>30m depth) pixels were identified and masked using Band 1 (Chapter 4) to delineate the threshold between submerged reef pixels and deep-water pixels. The remaining (reef) pixels delineated polygons equivalent to the outer boundaries of coral reef areas. The depth at which submerged reef features (outer reef slopes, deep lagoon patch reefs) could be reliably detected and classified from the imagery was determined by SCUBA diving down-slope transects to 40m depth (i.e., beyond the possible limits of detection of a bottom-reflected signal by the Landsat sensor), and collecting GPS positions of simultaneous benthic and depth data along the transect. The slope depth data were overlaid on image channels, in which the maximum discernible depth was determined to be 25 to 30 m, depending on scene and location.

Supervised classifications trained with ground-truth data were performed using the maximum likelihood classifier (MLC) on eight images individually to generate seven morphological categories: submerged reef (i.e., outer and inner reef slopes, sub-surface

lagoon patch reefs), wave-breaking reef crest, reef flat, back-reef sand flats, reef lagoons (i.e., contained within reef structures, not atoll lagoons), sea grass meadows and reef-top islands. Ground truthing and image analysis methods are described in detail in Chapter 4.

6.2.2 Reef inventory

Individual reef areas of two types (atoll rim reefs and lagoon reefs) were demarcated and enumerated within each atoll by analysing the classified Landsat 7 images (polygons above) using a customized model written in the IDRISI™ GIS software (www.clarklabs.org). It selected reef areas larger than 1 hectare in area (i.e., 12 pixels or more) having all adjacent (i.e., outer perimeter) pixels classified as deep water. Reefs having any part of their perimeter on the outer edge of an atoll or facing the open ocean were designated as atoll rim reefs. All other reef structures were identified as atoll lagoon patch reefs by masking the rim reefs. The area module in IDRISI was used to determine the area of each of the seven habitat classes within each reef unit (not all classes occurred in all reefs), and to sum these to determine the total surface area of that reef. Additionally, the total area of the seven habitat classes was derived for the entire dataset (i.e., including reef structures less than 1 ha.) to yield a maximum estimate of reef area. The spatial resolution of this reef mapping and area-determining process was the 30x30m (900m²) pixel of the Landsat 7 ETM+ data. No correction of these area estimates was made for sloping seabed or sub-pixel topography (i.e., rugosity), so the actual surface area of steeply sloping or very rough terrain (e.g. spur and groove) may be as much as twice the vertically projected area that is the accepted metric.

Error components

The error of attribution associated with the measures of reef class areas was calculated as 19 % from accuracy assessments of classifications reported by the MLC routine in PCI-GEOMATICA™. This error term applies to aerial estimates of different reef habitat classes, but not to the estimates of individual reef areas because only the accuracy of

classification of pixels occurring on the perimeter of reefs will affect the estimate of individual reef area, and this is dealt with in calculating the demarcation error.

The error of demarcation is expressed as the ratio of the total number of single contiguous pixels forming the perimeter of all reef polygons in an atoll to the total number of pixels that make up the total area of that atoll. Assuming there is an ambiguity in the location of the reef edge of ± 1 pixel, the error of demarcation was calculated as 3.0 %. This error term is relevant to the estimates of individual reef areas using IDRISITM, and also to the estimate of the total number of individual reefs within atolls and entire archipelago.

The error of scaling in this analysis is zero because no up-scaling was done from the resolution of the source map (i.e., the Landsat image) to a coarser resolution (i.e., smaller scale) map. The numbers of reefs greater than 1 ha. Within an atoll are determined without ambiguity or error. Statistical analyses (Pearson correlation analysis) of derived reef data (reef numbers and areas) were done using the SPSSTM software package.

6.3 Results

The Maldives archipelago contains $2,041 \pm 10$ distinct coral reefs of greater than 1 ha. area (Table 6.1). Of these, 529 are located on the rims of the 16 atolls, 5 form the rims of the 5 ocean *faros*, and 4 form oceanic platform reefs, also rising from deep water but lacking a lagoon. These rim reefs were all large and distinct enough to be enumerated without error. The remaining $1,503 \pm 10$ reefs are lagoon patch reefs scattered throughout the lagoons of the atoll. The number of reefs varies greatly among atolls, ranging from only seven in Seenu to 268 in Ari atoll. Very small lagoon patch reefs may be obscured by cloud or included with larger reefs due to errors of demarcation.

MAJOR REEF STRUCTURES	Total surface area (km ²)	No. of Reefs	Reef area (km ²)	Reef Island area (km ²)
Complex Atolls (16):				
Ihavandhippolhu	289.81	30	119.50	5.70
Haa	3788.71	164	500.70	68.70
Raa	1184.31	155	223.50	12.90
Baa	1126.95	105	262.90	5.50
Lhaviyani	701.42	84	158.00	7.20
North Male	1568.18	189	349.00	9.40
South Male	536.33	112	175.60	2.00
Ari	2271.75	268	489.40	8.30
Faafu	597.15	86	151.30	2.20
Dhaalu	736.46	98	179.40	4.40
Vaavu	1090.97	203	251.10	0.92
Meemu	983.92	111	197.30	4.20
Thaa	1695.79	154	243.70	9.30
Laamu	884.63	56	203.70	23.10
Gaafu	3278.59	210	437.90	34.30
Seenu	157.22	7	70.32	15.00
Oceanic Faros (5):				
Makunudhoo	142.48	1	142.48	0.96
Goidhoo	112.61	1	112.61	2.20
Gaafaru	88.05	1	88.05	0.19
Rasdoo	61.84	1	61.84	0.62
Vattaru	46.72	1	46.72	0.01
Oceanic platform reefs (4):				
Alifushi	4.38	1	4.38	0.71
Kaashidhoo	9.54	1	9.54	2.89
Thoddoo	4.75	1	4.75	1.62
Foahmulah	10.18	1	10.18	5.13
MALDIVES TOTAL	21372.72	2041	4493.85	227.45

Table 6.1 Reef area statistics for the Maldives derived from classified Landsat-7 ETM+ imagery. Total surface area of the major reef structures includes all reef area plus atoll lagoons. The number of reefs is based on those having a total area greater than one hectare, while the actual reef areas are derived from all pixels in seven classes of habitat (including reef islands) within each atoll to a depth of approx. 25-30m. Reef-top island area is a subset of the reef area (i.e., class 7).

The total surface area of the major reef structures of the Maldives (all coral reef and lagoon habitats of atolls) is $21,372.72 \pm 641.20 \text{ km}^2$ (Table 6.1). This value includes the vast areas of the world's largest atoll lagoons, much of which is too deep to support coral growth. Only 21.1% of this area ($4,493.85 \pm 134.80 \text{ km}^2$) is actually occupied by distinct coral reefs as defined in this study (i.e., contiguous reef areas $>1 \text{ ha}$. including reef passes, enclosed reef lagoons, areas of unconsolidated sediments and reef-top islands down to a water depth of approximately 30m, hereafter referred to as reef platforms). Rim reefs comprise the greatest area of reef platform ($3,221.4 \text{ km}^2$), while the ocean *faros* occupy 451.70 km^2 and the ocean platform reefs only 28.85 km^2 (together equalling only 10.64% of the total area of reef platform. The remaining 791.92 km^2 of reef area (17.5% of the total) forms patch reefs in the 16 atoll lagoons. To this area is added the 19.3 km^2 of smaller patches of lagoon reef (often well below the surface) detected and mapped in the classified imagery but not enumerated as distinct reef platforms. This brings the total estimate for the reef area of the Maldives to $4,513.14 \pm 135.40 \text{ km}^2$. From this must be subtracted the small area ($227.45 \pm 6.82 \text{ km}^2$) of reef islands that currently emerge from the reef platforms, to yield the most accurate estimate of productive marine reef habitat in the Maldives: $4,285.69 \pm 128.57 \text{ km}^2$. This is the number that is used for comparative purposes and to scale reef ecosystem processes, goods and services.

The numbers and areas of reefs in the Maldives atolls are both well-correlated with the total surface area of the atoll ($r = 0.70$, and $r = 0.93$ resp., $p=0.01$, $n = 16$), while reef island area is only poorly correlated with reef area ($r = 0.65$, $p = 0.05$, $n = 25$).

The costs of the results presented here are calculated at $8 \times \text{US}\$600.00$ for the Landsat-7 ETM+ images, plus $\text{US}\$3,500.00$ for the software, plus $\text{US}\$11,800.00$ for the 2 week ground-truthing trip, plus 1 year of RS-GIS technician time @ $\text{US}\$55,000.00\text{y}^{-1}$. The total of $\text{US}\$75,100$ is equivalent to $\text{US}\$16.64$ per km^2 of reef area mapped.

6.4 Discussion

Satellite-borne multi-spectral remote sensing coupled with geospatial analysis has allowed to produce the most accurate maps and area calculations of the Maldives coral reefs ever compiled, at very modest cost. The spatial resolution of the maps approximates or is finer than the characteristic spatial scales of the major reef zones and features required. The depth of reef boundary delineation (~ 25-30m) corresponds to the lower extent of productive reef in many locales (Vecsei 2001). The additive errors of attribution and demarcation around the estimates of reef area are less than 5%. The cost per unit area is a small fraction of the cost of a ship-borne hydrographic and underwater survey, and yields equal or greater accuracy (Mumby et al. 1999). It is concluded that remote sensing and geomatics software is the key technology for the accurate mapping and area estimate of coral reefs. These results and conclusions are supported by a growing body of literature on the theory and application of remote sensing in coral reef ecosystems (Green et al. 2000). It is predicted that the techniques employed here will soon allow a complete assessment of the world's coral reef areas at an unprecedented level of accuracy and precision (Gasch et al. 2000, Mumby 2001).

The Maldivian archipelago has long been remarkable for the size, pattern of development and morphological diversity of its atoll reefs (Darwin 1842, Stoddart 1965), which have spawned major and as yet unresolved controversy concerning the relative importance of antecedent sub-aerial and current environmental forcing (Woodroffe 1992, Purdy and Bertram 1993). The quantitative classification of the absolute area of zones of accretion and erosion for every single reef in the entire archipelago ($n = 2041 \pm 10$) allows statistical testing of geomorphological hypothesis with unprecedented rigour (Naseer and Hatcher 2001). For example, the weak statistical relationships between the total surface area of an atoll and the total areas of reef platform and reef island (Table 6.1) indicate that factors other than the extent of antecedent platform contribute to the frequency and intensity of reef growth upon it. Both the uneven spatial distribution and the small magnitude of reef island area (only 230 km² - fully 23% less than currently used planning value of 300 km²,

Spalding et al. 2001) throughout this archipelagic nation of 310,000 people requires extremely detailed land-use planning in the face of global climate change that is well-served by the analytical products presented here.

The fact that the estimate of the total area of coral reef habitat in the Maldives ($4,493.85 \pm 134.80 \text{ km}^2$) is only 50.4% of the current best estimate of $8,920 \text{ km}^2$ (Spalding et al. 2001) demonstrates the combined effects of poor source data and low-resolution up-scaling in over-estimating reef area. Both estimates share the same basic definition of coral reef, so simple errors of attribution cannot be the source of the discrepancy. Spalding and Grenfell (1997) determined that generic global estimates of reef area decreased by 60 to 95% as the size of the resolved unit (i.e., spatial resolution) was decreased from a $2 \times 2 \text{ km}$ (4 km^2) estimation grid (pixel) size to a 0.5×0.5 (0.25 km^2) size (Table 6.2). The effect is consistent in sign and magnitude with the difference of -50% between total reef area derived by Spalding et al. (2001) using a 1 km^2 grid and that derived using our measurement grid of $30 \times 30 \text{ m}$ (0.0009 km^2). If the effects were linear then the discrepancy should be much larger, but a scaling error is not incurred from this source data (because no up-scaling was done by increasing the size of the grid unit). Furthermore, the far greater ability of the remotely sensed data to resolve small reef areas than the 1:300,000 navigational charts (British Hydrographic Office 1993) provide an offsetting, positive effect on the total reef area estimates. This effect is seen in some (but not all) cases when up-scaling is done using navigation charts at different scales (Table 6.2), perhaps because the larger scale charts are often derived from remotely sensed imagery (e.g. aerial photographs). In other cases, however, the use of charts drawn at 1:250,000 or 1:300,000 result in no significant difference in estimates of reef area derived from charts drawn at 1:1,000,000 (Table 6.2). This outcome would be expected when the larger-scale chart is derived from the small-scale chart.

Smaller scale	Larger scale	Sign	Magnitude	Case	Reference
2x2 km	1x1 km	-	30-50%	Global	Spalding and Grenfell (1997)
1x1 km	0.5x0.5 km	-	30-45%	Global	"
1x1 km	0.03x0.03 km	-	50%	Maldives	This study
1:1,000,000	1:250,000	-	7%	Philippines	Spalding and Grenfell (1997)
1:1,000,000	1:300,000	+	4%	Maldives	"
1:1,000,000	<1:50,000	+	35%	Seychelles	"
1:1,000,000	1:250,000	+	47%	Great Barrier Reef	"

Table 6.2. Up-scaling effects of map resolution on global and regional estimates of coral reef area (derived from Spalding and Grenfell 1997). Smaller scale maps have lower (coarser) spatial resolution, while larger scales have higher (finer) spatial resolution. The sign and magnitude of differences in estimates of total reef area are shown for five scale contrasts.

The main benefit of using the high-resolution maps derived from remotely sensed data to estimate reef area is the reduction of a positively biased (i.e., towards overestimation) error of demarcation of the margins of reefs (Fig 6.2). By using a 1x1 km grid to digitize reef area, Spalding et al. (2001) consistently extend the margins of reef features into deep water. For very large features relative to the grid size (e.g. entire atolls of many 100s km² area) the overestimation will be proportionally small. For example, the areas of the two largest atolls (Haa and Gaafu) as calculated here are within 5% of the areas reported from the digitization of nautical charts (Spalding et al. 2001), indicating that the dimensions of the very large reef features are accurately estimated by the 1 km gridding method. At the scale of individual reefs of a few km² (the mean area of individual Maldivian reefs is only 2.19 km²) however, the overestimation error associated with 1 km² pixels is substantial (Fig. 6.2).

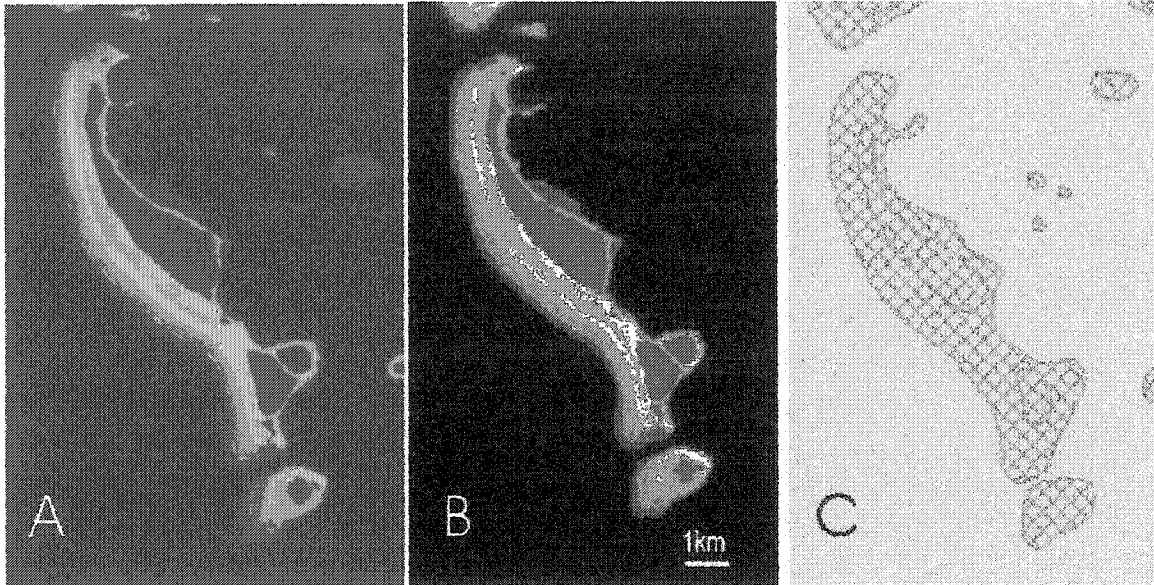


Figure 6.2 Three images of an atoll rim reef in Faafu Atoll ('F' atoll), Maldives. A. Landsat ETM+ composite image shown in natural colour. B. Classified image showing reef habitats ($n = 7$ classes) in false colour as used for area measurement (this study). The total area of all reef classes on the largest reef rim platform is calculated to be 23.60 km^2 . C. Digitized image of Admiralty chart #1013 (British Hydrographic Office 1993) for the same area of reef showing the digitizing grid (0.25 km^2 squares), produced by Spalding et al. (2001) and obtained from the interactive GIS map at www.reefbase.org (Oliver and Noordeloos 2002). The total calculated area of the reef in C. is 38.5 km^2 (63.1% larger than the reef area in B.). The several lagoon patch reefs evident in image A. were masked for the rim reef classification in B. Note the discrepancies with the charted reefs in C.

The shape of the digitized reef in Fig. 6.2C shows ambiguities of attribution and sources of demarcation error in perimeter delineation. The smoothed curves of the digitized map clearly extend well beyond existing reef substrata, leading to overestimations of reef area. The bay near the southeast corner of the reef and edges of the enclosed reef lagoons are markedly different from the satellite image. The southern of the two lagoon patch reefs along the eastern margin of the image, and two smaller ones along the northern margin are not captured in the digitized image, while two small patch reefs are plotted which do not now exist. This is just one of more than 2000 reefs of the Maldives. Many others show similar discrepancies. The overall effect is a variable and significant exaggeration of the true area of reef structures by digitizing small-scale nautical charts.

While such an approach to estimating coral reef area may be adequate for global models and calculations, it can lead to significant type-II errors when testing hypothesis concerning reef processes at regional scales, and potentially serious mis-assessments of coral reef resources at national and local scales. The need for accurate metrics of coral reefs is greatest in national and regional planning and management agencies, where policy based on the repeated promulgation of incorrect information often leads to failures of implementation. The tools to do the job properly now exist and this has been consistently demonstrated in the research described here.

Chapter 7:

7. CONCLUSIONS AND FUTURE WORK

7.1 General conclusions

The research presented in this thesis was designed to enhance our understanding of modern controls on coral reef growth at the regional scale using cutting edge tools and technologies for seascape ecology. Two key innovations were developed in the course of the research. Firstly, remotely-sensed metrics of surficial geomorphology were used to infer time-integrated patterns of reef growth in response to quantified environmental forcing. Secondly, customized geospatial analysis and novel statistical analysis were used to explore and categorize metrics of size, shape and symmetry for hundreds of reefs, and to rigorously test hypotheses concerning the roles of modern versus antecedent controls on reef growth morphology. The outcomes of the research include new methods to map, classify and quantify large reef domains, new insights to old models of reef growth, and valuable management planning tools for the vulnerable reef nation of the Maldives.

Heretofore underutilized research methods of multi-scale measurement and analysis have been successfully extended and demonstrated to be useful for investigating the link between structural geology and the growth biology of coral reefs. Developing and applying these techniques to a large and remote ecosystem occupied a great deal of the research period, thereby limiting the range of analyses and investigations that could be undertaken. Further analysis of the results presented here will lead to improvements in our understanding of the fundamental processes controlling the spatial patterns of coral reef growth, the resulting reef morphologies, and their susceptibility to environmental change at regional and global scales.

Physical factors affecting reef morphology across biogeographic reef provinces can be compared by the examination of the prevalent hydrodynamic regimes in the respective regions: particularly wind-wave and swell energy fields. In most instances the weather and climatology data are readily available and well studied (e.g. monsoons, trade winds and long-period swell regimes). In many cases, the paleoclimatology is also adequate to describe the marine forcing that applied during the major periods of coral reef construction in the late Quaternary (e.g. Rostek et al. 1994, Beaufort 1996). The lacking data, which need to be generated, are standardized geomorphological databases for the reefs that grew in various climatic regions and regimes. This thesis establishes guidelines and a benchmark for such research by developing innovative methods for quantifying the growth morphology of coral reefs, and by creating a reef database for one of the largest atoll reef groups of the world. It is possible now to extend the approach to other coral atolls systems of the world (e.g. the Tuamotus of French Polynesia).

There seems to be little doubt that environmental processes have contributed significantly to the pattern and pace of growth of coral reefs during the Holocene in Maldives (Woodroffe 1992, Hatcher and Naseer, 2001). Understanding the mechanism of this contribution and extending it across reef provinces of the world requires a major research undertaking, obviously demanding interdisciplinary approaches. The various global reef mapping projects currently underway (Spalding et al. 2001; Millennium Coral Reef Mapping project) are indicative of the investment in this potential.

Better understanding and prediction of broad scale patterns of coral reef growth in the future will surely depend less on the generalization of qualitative models developed from detailed study of individual reefs (as done historically), and more on quantitative modeling of known bio-physical processes (e.g. Kleypas et al. 1997), and the rigorous testing of these models using statistical analysis of multiple reefs (this study). Although many studies have convincingly related hydrodynamic conditions to patterns of lateral reef growth (expressed as the surface morphology of habitat zones with known growth rates), most of the investigations were done at spatial scales far too small to be useful for interpreting the roles of climate process and phenomena operating at the scale of

biogeographical reef provinces. The methods of obtaining quantitative, geometric data for hundreds of individual reefs in a large domain presented in Chapter 4 and the testing of hypothesis in Chapter 5 lead the way to making clear distinctions between geologically inherited (antecedent) morphology and environmentally controlled growth morphology on modern day reefs.

The results presented here demonstrate that the growth patterns of individual rim reefs and lagoon reefs of the Maldives' 16 great atolls are largely explained by the amount of wave energy impinging on them. The structure of atoll rims in terms of the barrier they present to the impinging wave and flow field (i.e., hydrodynamic closure, Hatcher 1997), largely explained the patterns of reef growth manifested in the atoll lagoons. Multiple morphometric expressions of the time-integrated growth of these reefs ordinate strongly along axes of exposure to impinging wave fields, are significantly related to long-term averages of wave power dissipated on them, and group at a high level of dissimilarity according to their geographic location relative to the main directions of monsoon wind-wave and swell forcing. The primary zones of reef accretion, the outer reef slopes and reef flats are 1.5 to 2.8 times wider on the ocean margins of atolls that face the stronger monsoon than those reefs facing the Maldives inner sea which experience wave energies 5 to 12 times lower than ocean-facing reefs. Similarly, the morphometrics resulting from the growth of patch reefs and *faros* within the lagoons of the 16 great atolls of Maldives are statistically consistent with a calculated index of the apertures of those atoll rims.

These results support the long-standing, but never-tested hypotheses that coral reef growth is controlled by hydrodynamic forcing functions (Hamner & Wolanski 1988), and provide the first detailed and rigorously defensible explanations for the asymmetrical growth morphologies of the world's most complex atoll reef province: the Maldives archipelago. The conclusion applies both to the atoll rim reefs and the patch reefs and *faros* of the great atoll lagoons. I conclude that most of the outer structure of reefs located both on the rims and in the lagoons of Maldives' atolls is the result of variable patterns of vertical and lateral accretion controlled primarily by the long-term integral of wave energy delivered to them during the major periods of reef growth in the late

Pleistocene and Holocene sea level transgressions and still-stands. That is: the structure of Maldives' reefs at the reef-scale is primarily the result of recent constructional processes. At the smaller scale of lagoons within individual reefs, and at the larger scale of entire atolls, the patterns of occurrence, sizes and shapes of morphological features are more consistent with inherited, antecedent structure resulting from processes of sub-aerial erosion during sea level regressions and low-stands. These conclusions are consistent with the few geological studies of Maldives that allow reconstruction of individual reef growth and atoll basements from coring (Bianchi et al. 1997; Woodroffe 1992; Purdy and Bertram 1993).

The characterization of climatology around coral reefs is vital to study environmental growth patterns on reefs. Data with higher spatial and temporal resolution (e.g. modelled wave data in 0.25 x 0.25 degree resolution grids hindcast over decades using wave models; NOAA WAVEWATCH III: <http://polar.wwb.noaa.gov/waves/historic.html>) would result in significant refinement of the methods and results presented here. While the derivation of such data was beyond the scope of this research because of limitations of time and resources, such data will be pursued in the near future to make better predictions on reef growth in Maldives.

Mapping the surface geomorphology of the Maldives' reefs, spanning an area 900 x 200 km (180,000 km²) in the central Indian Ocean, was made possible using Landsat 7 ETM+ satellite imagery. Remote sensing and GIS tools, although technically challenging, are the most promising tools currently available for mapping and quantifying coral reef geomorphology. Morphological variation and pattern arising from gradients of physical forcing (e.g. wind-waves) impinging on atolls can be conveniently quantified by satellite imagery. Landsat 7 ETM+ satellite images appear to be a viable option for mapping reefs at the nested scales of individual reefs, entire atolls, banks, ridges and biogeographical provinces. New methods had to be developed to quantify coral reef geomorphology of hundreds of reef in a consistent manner using raster GIS tools.

The analysis Landsat 7 ETM+ imagery coupled with geospatial analysis has allowed me to produce the most accurate maps and area calculations of Maldives' coral reefs ever

compiled to date. The spatial resolution of the habitat maps approximates or is finer than the characteristic spatial scales of the major reef zones and features required. It is concluded that remote sensing and geospatial analysis is the key technology for the accurate mapping and area estimation of coral reefs.

7.2 Future work and management implications

The large database generated in Chapter 4 is not limited to addressing the questions posed in this thesis. The opportunities to further develop and test hypothesis posed at the scales of reefscapes using these data are immense. This study has only tapped that potential. It is envisaged that the data will be used in future to investigate other ecological relationships on reefs of the Maldives. For example, it is known that human settlements and activities on reefs lead to nitrification of the reef flat and lagoons and changes in the algal and seagrass biomass (Miller and Sluka 1999). Seagrass beds were mapped in this study (Chapter 4) not as a geomorphological class, but because it was a prominent ecological habitat on many rim reefs. This quantitative data can be used to test hypotheses about anthropogenic impacts and ecological relationships on reefs on a countrywide scale. The potential for future uses of this data for reef management tasks, such as the setting up of a network and marine protected areas, is immense.

Comparative studies of hydrodynamic forcing functions across biogeographic reef provinces experiencing different wind-wave regimes based on the type of research presented in this thesis, may contribute to a better understanding of modern coral reef growth. This is certainly a direction for future research. Much synoptic environmental data are now available to make such large scale comparisons practicable. For example, ocean scale global models of wind-wave data (NOAA WAVEWATCH III; <http://polar.wwb.noaa.gov/waves/historic.html>), sea surface temperature and bleaching predictions (NOAA Pathfinder AVHRR; <http://podaac-www.jpl.nasa.gov/sst/>) and

biogeochemical data and models of coral calcification (Kleypas et al. 1999; 2001) are available. The scales of such data match the resolution at which productive areas on reefs (e.g. reef slope) can be accurately mapped as shown in this study. Matrices of such data can be used to model and predict the effects of climate forcing on reef growth.

The availability of land (reef islands) per reef is not only important for human settlements and the development of coral reef countries. Reef-top islands represent the most dynamic geomorphic features on modern reefs, which are strongly related to hydrodynamics (Ali 2000). In light of perceived climate change scenarios and forecasted sea level rise, the data presented in this thesis can be used to investigate the potential vulnerability of human populations and communities resident on coral reef islands to these perceived threats. For example, island morphodynamics can be investigated and related to climatology with spatial data collected in this research (Ali 2000).

Maldives (as well as many other archipelagic nations) is faced with the uncertainties of sea level rise, and consequent loss of land area in addition to dealing with anthropogenic reef degradation (Souter et al. 2000; Wilkinson 2000). Reefs may keep up with the rising sea levels if the conditions are favourable for vertical accretion (Buddemeier and Smith 1988), but in most instances we have no knowledge of the reef building capacity of a given area. Maps generated at the geomorphological level in this thesis, displaying spatial gradients of change in reef morphometrics with respect to physical process provide a basis for comparing the growth characteristics of different classes of reefs, or even individual reefs, and predicting their capacity to keep up with sea level rise. The techniques envisioned here can be applied to risk analysis in Maldives as the people attempt to prepare for the inevitable.

High resolution reef maps generated from satellite image can be effectively used for management purposes (Green et al. 2000). Quantitative maps simplify reef management and depictions of “reef-use”. For coral reef nations with more reef than land, “reef-use” is sometimes more relevant to management decision-support than land-use. Useful management metrics for atolls and islands currently in use (e.g. atoll area, lagoon depth,

island size, etc.) has been developed from old survey charts, and are unreliable for many management needs. Geomorphologically-defined habitats on reefs, such as flats, lagoons and islands are better suited for resource inventories. They can be used in conjunction with species data to assess and estimate fishery yields and harvests (e.g. Hatcher 2003). The maps can also be used in a GIS to plan research and in the selection of marine protected areas (Mumby et al. 1995).

There are many global and regional initiatives to monitor the world's coral reefs (Wilkinson 2002). These are summaries of many small scale studies based on a few 50m transects at best, that are well coordinated by regional centres using standardized survey methods. The lack of good quality base maps that describe the extent and distribution of coral reefs and the various habitats places a major constraint on the monitoring of reef resources and health in many tropical and regions. Often, the lack of detailed base maps hinder sound planning at the beginning of reef research programs. If a global and regional effort, equivalent to the Global Coral Reef Monitoring Network (GCRMN; Wilkinson 2002) for example, can be developed to map and quantify coral reefs of the world in a collaborative fashion with standardized methods, it would be a valuable service to coral reef management globally. Data from such centres can be conveniently managed at existing centres of excellence (e.g. coral reef database at www.reefbase.org). Base maps of reef data are vital to complement national data regularly collected at higher spatial resolutions, such as coral cover, fish abundance and lagoon infilling on individual reefs. The data set presented here is the first of it kind for an entire reef system. It will prove extremely valuable to the coral reef nation of Maldives, and could easily be extended for the entire Indian Ocean region.

We now have tools and techniques to overcome the challenges of synoptic sampling of reef geomorphology and even benthic communities. Environmental data are becoming available at finer spatial resolutions with better accuracies and at higher frequencies via satellites and ocean observing networks now. Sensors in space now regularly collect wind, wave, sea surface temperature, chlorophyll and many more parameters. Many oceanographic parameters are collected regularly and distributed (e.g. NOAA AVHRR

Pathfinder temperature data, SeaWiFS chlorophyll data). Although the temporal range of most of these data sets is short, they will progressively produce high-resolution datasets for future research. Effective use of such data can provide crucial results to compare and contrast coral reef systems across the biogeographical regions of the world.

Despite that fact that remote sensing studies have been directed at coral reefs for at least 30 years (Classen and Pirazzoli 1984), large-scale applications are virtually lacking (Green et al. 1996). There are no published studies in which reefs of even a single geographic province or reef system have been completely mapped using satellite imagery. Inventories of coral reefs and associated habitats have been at best estimated from crude navigational maps (Spalding et al. 2000). This is perhaps indicative of the continuing uncertainties and misgivings researchers have in the use of remote sensing as a mapping tool, despite much advance over the last two decades. It is expected that the geomorphological data presented in this thesis will be used as the base maps upon which to build resource inventories for coral reefs of Maldives. This will be an important contribution of this thesis for coral reef management in the country.

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APPENDICES

Appendix 1. PCI GEOMATICA Programs used

PCI GEOMATICA is an advanced image processing software suitable for various forms of space and air borne image analysis. PCI has many programs for different functions. In this research ImageWorks, which is part of PCI's image analysis software, was most extensively used for image processing. ImageWorks is an image display and manipulation program. ImageWorks presents easy-to-use tools for editing, visualizing, exploring and manipulating geospatial data (e.g. imagery, vectors, graphical bitmaps, etc.) at multiple resolutions. It also provides many stand-alone programs to perform varying tasks related to image processing. ImageWorks provides extensive tools for image exploration such as histograms, scatter plots, spectral plots and linear-distance measuring tool and enables a variety of image classification procedures. PCI GEOMATICA also presents a bank of algorithms for various image processing and analytical tasks. The following algorithms were used in this study.

THR

THR is a program which creates threshold bitmap segments from a set of assigned bands or image channels. For each input pixel value between the minimum and maximum threshold gray values inclusive, corresponding bits are turned ON in the output bitmaps. For each input pixel value outside this range, the corresponding bits are turned OFF. If the maximum threshold value is not specified, every pixel above the minimum threshold value will be turned ON. This is a very useful routine to create as many masks as necessary for preparing images for classification so that areas of the image under the mask or outside the mask can be excluded from the final classification. For the purposes of this study many masks were developed using this program (Fig 4.11).

BLO (Bitmap Logical Operations)

This is a program which performs specified logical operations on one or two bitmap masks created by the THR program and stored within the image file. This is a useful routine to combine bitmap masks in many situations. For this study for e.g. bitmap masks were created using the THR program for clouds and deep ocean and these were combined by BLO program (Fig 4.11).

ARI (Image Arithmetic)

ARI performs arithmetic or a logical operations on image data stored in two image channels and/or a constant. The result is saved in a specified new output channel. Image data can be added, subtracted, multiplied by this algorithm. This program was used to combine the land data, which was developed as bitmap masks, into the classified image channels before images were quantified.

MAP

This is a program which creates image channels from graphical bitmaps. Bitmaps are encoded by setting the image area under each bitmap to the appropriate gray level value. Values which are not under the bitmap remain unchanged. This is a useful routine when bitmaps of known classes are developed and need to be encoded into image channels and can be used in final classifications. Any number of bitmap segments can be encoded on an image channel. The gray level value used for encoding each bitmap can be specified during the process. In this study it was necessary to encode bitmaps of land, which were created in infrared band 4 using the THR program. These land bitmaps needed to be integrated and encoded into the final reef classifications so that they can be quantified in the GIS. MAP allowed this procedure.

REVERSEBITS

ReverseBits performs a logical function on one bitmap layer so that the result will be a 'logical complement' (i.e., reverse) of the original bitmap. This was sometimes a useful procedure. For example, if in a given image the oceans were masked, and only reefs were shown, then when the bitmap is reversed with this program, a new mask would be created for all the reefs.

Appendix 2. IDRISI 32 programs used to quantify classified images

FILTER MODULE

FILTER creates a new image in which each pixel's value is based on its value and those of its immediate neighbours of an input image. The nature of this operation is determined by the values stored in a 3 x 3, 5 x 5, 7 x 7 or variable-sized template that is centered over each pixel as it is processed. For all filters except the median, mode and adaptive box filter, the pixel and its neighbours are multiplied by the values stored in the corresponding positions of the template, and the resulting values are summed to arrive at a new value for the pixel. Filtering is used for a variety of purposes. In this analysis the median filter was used for random noise removal. Satellite images show much variability of pixels and when images are classified there is much noise all over the image. This is the last step in the preparation of the classified images for analysis.

RECLASSIFICATION

This module reclassifies the image data or attribute values into new integer categories. Reclassification can be implemented by equal intervals, division of the data range, or by the application of user-defined limits. This module was generally used to reclass a multi theme image to create Boolean images for separating reefs from ocean for example.

GROUP

GROUP module determines contiguous groupings of identically valued integer cells in an image. Cells belonging to the same contiguous grouping are given a unique integer identifier, numbered consecutively in the order found. It was using this module that individual reefs were grouped and identified (by an integer) from Boolean images created for reefs.

AREA

This module measures the areas (in a unit specified) associated with each integer category (for e.g. categories created using the GROUP module) on an integer image. The output of this module can be in the form of a new image where each pixel takes on the area of the category to which it originally belonged. The output can be also sent to a text file called an "attribute values file" in IDRISI. This values file can be exported from IDRISI as a text file. This module was used to measure the area of every reef and the seven classes within the reef.

OVERLAY

The OVERLAY module produces a new image from the data of two input images. New values result from applying one of the many possible operations (addition, subtraction, multiplication etc.) to the two input images, referred to as the first and second images during program operation. The module was used in instances where pixel-to-pixel arithmetic was necessary between two input images. Most commonly in raster models an area of an image, for example, may need to be made zeros in which case it can be multiplied with a suitable Boolean image. Similarly pixels can be added by overlaying to create a new image.

SCALAR

SCALAR carries out scalar arithmetic on images by adding, subtracting, multiplying, dividing or exponentiating the pixels in the input image by a constant value. This may be essential when, for example, implementing a mathematical equation using a set of raster images.

INITIAL

INITIAL creates a new raster image with the same user-defined value in each cell. This was used in the model for assigning the pixel area (i.e., the satellite spatial resolution) to a new image created.

EXTRACT

This module extracts summary statistics (usually in the last stages of a model) to either a table or an "attribute values file" from an existing image file. It uses two files, an image file and a feature definition file. The summary output statistics can be the minimum, maximum, total, average, range, or standard deviation of all cells in the analyzed image for each identifier in the feature definition image. The attribute values file to which extracted data are written can be exported as a text file.

PERIM

PERIM measures the perimeter of each category in a grouped integer image using the **GROUP** module. The perimeter of every reef was measured this way.

POLYVEC

This module vectorizes IDRISI raster polygon images. Options exist to produce vector polygon files, vector arc files and vector point files of polygon locators from a raster polygon image. In this analysis reef polygons created by the **GROUP** module were vectorized so that they have the outline of the reefs as vector polygons. The output image file is stored as a vector file. This was necessary so that geographic coordinates of the polygon (or reef) edges can be exported into a text file. Reef centroids can be calculated

from this exported reef edge coordinates by taking the mean locations around the polygon.

CONVERT

CONVERT converts files between all possible combinations of IDRISI 32 data and file types supported for image and vector files. Using the module vector polygon data for reefs were exported as text files and processed in MS Excel to obtain the centroid locations of every reef.

CRATIO

CRATIO computes the compactness ratio of polygons (e.g. reef polygons) by comparing the area of a polygon to that of a circle having the same perimeter as the polygon, for all cells identified (using GROUP) as part of the polygon. This is a useful shape ratio that can be used to compare reef morphologies.

Appendix 3: IDRISI Macro file developed for automating Tasks

```
filter x smale_1*smaleatoll_1*2
reclass x I*smaleatoll_1*notocean*2*0*0*0*1*1*8*-9999
group x notocean*Y*groups
area x groups*1*2*areas
overlay x 3*areas*notocean*notoceanareas
reclass x I*notoceanareas*reefs*2*0*0*2*1*2*20000*-9999
group x reefs*Y*reefgroups
overlay x 3*reefgroups*reefs*reefgroups2
scalar x reefgroups2*reefgroupid*3*10
overlay x 3*reefs*smaleatoll_1*classifiedreefs
overlay x 1*classifiedreefs*reefgroupid*reeffaciesid
initial x pixelarea*2*1*900*1*smale_1*m
extract x reeffaciesid*pixelarea*1*3*faciesareas
perim x reefgroups2*2*2*perimeter
area x reefgroups2*2*6*reeffareas
polyvec x reefgroups2*1*reefpolygons*Y*0
convert x reeppolygons*location*v*1*1*2
perim x reefgroups2*1*2*perimeter
area x reefgroups2*1*4*areas2
cratio x areas2*perimeter*cratio
extract x reefgroups2*cratio*1*1*cratio
scalar x areas2*4*piarea*3*12.56637061
scalar x perimeter*perimeter2*5*2
overlay x 4*4*piarea*perimeter2*tratio
extract x reefgroups2*tratio*1*1*tratio
overlay x 4*perimeter2*4*piarea*roundness
extract x reefgroups2*roundness*1*1*roundness
scalar x areas2*areatopi*4*3.141592654
scalar x areatopi*areatopi_root*5*0.5
scalar x areatopi_root*equi_diameter*3*2
extract x reefgroups2*equi_diameter*1*1*equi_diameter
scalar x areas2*area16*3*16
overlay x 2*perimeter2*area16*area16_peri
scalar x area16_peri*area16_peri_root*5*0.5
overlay x 1*area16_peri_root*perimeter*perim3_area16
scalar x perim3_area16*reef_length*4*4
extract x reefgroups2*reef_length*1*1*reef_length
overlay x 2*perimeter*area16_peri_root*perim2_area16
scalar x perim2_area16*reef_width*4*4
extract x reefgroups2*reef_width*1*1*reef_width
```

CD-ROM: Forty (40) Thematic maps of individually-classified atolls of the Maldives and descriptive statistics for reef morphometrics.

Note: Atoll rim reefs and atoll lagoon reefs are classified separately. The names of files signify rim reefs or lagoon reefs for the same atoll or part of the atoll (For e.g. "Addu_r" means rim reefs of Addu atoll and "Addu_l" means lagoon reefs of the same atoll). Descriptive statistics are found in a Microsoft Word file (Descriptive Statistics.doc)

