MAURITIUS RESEARCH COUNCIL

A RAPID ASSESSMENT OF THE EXTENT OF CORAL BLEACHING IN MAURITIUS AFTER THE 1998 SEAWATER WARMING EVENT

Final Report

November 1999

MAURITIUS RESEARCH COUNCIL

Address:

Level 6, Ebène Heights,
34, Cybercity,
Ebène 72201,
Mauritius.

Telephone: (230) 465 1235
Fax: (230) 465 1239
Email: mrc@intnet.mu
Website: www.mrc.org.mu

This report is based on work supported by the Mauritius Research Council under award number MRC/RUN-9909. Any opinions, findings, recommendations and conclusions expressed herein are the author's and do not necessarily reflect those of the Council.

A RAPID ASSESSMENT OF THE EXTENT OF CORAL BLEACHING IN MAURITIUS AFTER THE 1998 SEAWATER WARMING EVENT.

By
Emily Hardman

November 1999.

School of Ocean Sciences,
University of Wales, Bangor.

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science (MSc.) in Marine Environmental Protection at the University of Wales, Bangor.

Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed (candidate)

Date

Statement 1

This dissertation is being submitted in partial fulfilment of the requirements for the degree of Master of Science.

Signed (candidate)

Date

Statement 2

This dissertation is the result of my own independent work/investigation, except where otherwise stated. Other sources are acknowledged in the text and a full reference list provided.

Signed (candidate)

Date

Statement 3

I hereby give consent for my dissertation, if accepted, to be available for photocopying and for inter-library loan, and for the title and abstract to be made available to outside organisations.

Signed (candidate)

Date

Rapid Assessment of the Extent of Coral Bleaching in Mauritius After the 1998 Seawater Warming Event.

Emily Hardman School of
Ocean Sciences, University
of Wales, Bangor

bstract

ring 1997-1998 coral reefs throughout the tropics were subjected to the most igraphically widespread bleaching event in recorded history. In Mauritius, Sea Surface nperature (SST) anomaly charts produced by NOAA show that SST was raised 1-1.25°C ıve the climatological maximum for this region during February 1998, however, the level bleaching in Mauritius was poorly known. This study investigated whether the coral reefs vlauritius had suffered a mass bleaching event during 1998. A rapid assessment was made the degree of coral bleaching on reefs around the whole coast of Mauritius during April 19. Surveys were made by snorkelling and SCUBA diving and assessments made by direct ervation, underwater video transects and underwater photography. Underwater videos were lysed to confirm the results from the field surveys and the community data were analysed ag the PRIMER statistical software. Results were displayed within a Geographical ormation System (GIS). Meteorological data for the period January 1997 to April 1999 e also analysed. The results indicate that the coral reefs in Mauritius were healthy, vever, all sites showed some signs of degradation particularly from boat and anchor aage and cyclone damage. The coral reefs appear, however, to have escaped the mass aching event of 1998. There were no large areas of dead standing coral other than at site 29 the Barrier Reef. Mean bleaching was <10% at all and in all cases was only partial aching. It is suggested that Mauritius escaped the mass bleaching event due to the effect of lone Anacelle, which produced cloudy, unsettled weather during February 1998. The tor bleaching episode observed during this survey is thought to be a frequent and normal nt relating to large environmental fluctuations experienced within the lagoon. With the ential threat of increasing mass coral bleaching events it is suggested that Mauritius needs ct quickly to protect its coral reefs from further degradation.

cknowledgements

vould like to thank my supervisor, John Turner, for giving me the opportunity to visit iuritius and for his help throughout the project.

vould also like to thank everyone at the University of Mauritius who made this work ssible, especially Jhoomuch and Seetiah for their excellent organisational skills; Sharveen sands and Ranjeet Baghooli for their help with the data collection. Also Olivier Tyak from p Divers, Mick Frederic from Aquarius Diving and our boatmen for taking us to the reefs, driver for taking us everywhere, Madame Manikam for her wonderful cooking and the iuritius Research Council for providing the funding for the trip.

Jig thank you also to Rebecca Klaus for her help with data collection in Mauritius and all GIS help and to Dave Roberts for the use of his computer and video advice.

ially, I would like to thank NERC for my funding throughout the year (award '03/98/235/MS).

Table of Contents

List of Figures

List of Tables

1.0 Introduction

1.1 Overall Goal

During 1997-1998 coral reefs throughout the tropics were subjected to the most geographically widespread and probably most severe bleaching event in recorded history. In Mauritius Sea Surface Temperature (SST) anomaly charts produced by NOAA show that SST was raised 1-1.25°C above the climatological maximum for this region during February 1998, however, the level of bleaching in Mauritius was poorly known. The aim of this study was, therefore, to investigate whether the coral reefs in Mauritius had suffered a mass bleaching event as a result of the sea warming in 1998.

The following sections describe the possible causes of coral bleaching, its affects on coral reefs and the bleaching event of 1997-1998. In addition an introduction is given to Mauritius and the present status of its coral reefs.

1.2 Coral Bleaching

Since extensive coral bleaching across the Pacific Ocean was first described by Glynn in 1984 there has been an increasing incidence of reports of coral bleaching throughout the tropics. Coral bleaching has occurred in the Caribbean, Indian and Pacific Oceans on a regular basis (Brown, 1997) and repeated bleaching has been reported on reefs in French Polynesia (Fagerstrom and Rougerie, 1994; Hoegh-Guldberg and Salvat, 1995), Jamaica (Gates, 1990; Gareau and Macfarlane, 1990), the Galapagos (Glynn, 1993; Podesta and Glynn, 1997), Thailand (Brown *et al.*, 1996), Panama (Glynn and D'Croz, 1990; Podesta and Glynn, 1997) and the Great Barrier Reef (Harriott, 1985; Berkelmans and Oliver, 1999).

Coral bleaching occurs when the density of zooxanthellae declines sharply and/or when the concentration of photosynthetic pigments within the zooxanthellae is reduced. Bleaching causes corals to tum white or pale because the low concentration of pigments allows the limestone skeleton to become visible through the transparent tissue (Gareau and Hayes, 1994). Bleaching is not limited to scleractinian corals, but also occurs in hydrocorals, soft corals, sea anemones, bivalve molluscs (Williams and Bunkley-Williams, 1990) and sponges that host photosynthetic cyanobacteria (Vicente, 1990).

1.21 Mechanisms of Coral Bleaching

Coral bleaching originally referred to the loss of brown pigment by corals (Yonge and Nichols, 1931). More recently, research has shown that coral bleaching may result through either loss of zooxanthellae by corals (Hoegh-Guldberg and Smith, 1989; Glynn and D'Croz, 1990; Lesser *et al.,* 1990; Le Tissier and Brown, 1996) and/or the loss of photosynthetic pigment per zooxanthella (Hoegh-Guldberg and Smith, 1989; Lesser *et al.*, 1990).

In laboratory studies Hoegh-Guldberg and Smith (1989) showed that when *Stylophora pistillata* and *Seriatopora hystrix* were exposed to water temperatures >30°C bleaching resulted due to a temperature dependent loss of zooxanthellae. When the same coral species were exposed to high irradiance, however, bleaching occurred due to a loss of photosynthetic pigment per zooxanthella. Jones (1997) found that loss of zooxanthellae in *Acropora spp*. could occur without decreases in zooxanthellar chlorophyll concentrations. He showed that in the 2 colonies losing zooxanthellae during a bleaching event the zooxanthellar chlorophyll concentrations actually increased.

Recent studies have investigated the cellular mechanisms involved in the reduction of zooxanthellae numb

ers during coral bleaching events. Gates *et al.* (1992) suggested that the primary bleaching mechanism in temperature-stressed corals and anemones involved host-cell detachment, whereby entire animal endodermal cells, their zooxanthellae and accompanying vacuolar membranes were discharged into the coelenteron. Hayes and Bush (1990) show that during bleaching the loss of algal cells causes disruption of the gastrodermis and mucus accumulates in the gastrovascular cavity. It is suggested that the mucus might alter gastrodermal function and contribute to the release and/or degeneration of zooxanthellae. In the field Brown *et al.* (1995) identified three different mechanisms that could potentially lead to a reduction in zooxanthellae. The most important mechanisms appeared to be a degradation of the zooxanthellae *in situ.* A second mechanism involved the release of zooxanthellae from the endoderm into the coelenteron. The final mechanism involved the release of intact endodermal cells containing intracellular zooxanthellae.

1.22 Fate of Coral Reefs affected by Bleaching

The immediate effects of bleaching on the host are a decline in zooxanthellae density, loss of chlorophyll pigments, an increase in respiration rate and a decline in coral protein, lipid and carbohydrate (Glynn and D'Croz, 1990; Glynn *et al.*, 1985; Coles and Jokiel, 1977; Hoegh-Guldberg and Smith, 1989; Goreau and Macfarlane, 1990; Szmant and Gassman, 1990; Jokiel and Coles, 1990). In addition, there are a number of non-lethal responses, which may have long-term effects. These include a decrease in coral growth and calcification (Goreau and Macfarlane, 1990), impairment of reproduction (Szmant and Gassman, 1990), and tissue necrosis (Glynn and D'Croz, 1990).

Long-term effects can lead to reduced cover of important reef-building species and to an increased abundance of species that erode reef frameworks. Reduced growth of bleached corals could decrease the capacity of corals to compete favourably for space with other reef benthos such as algal turf, coralline algae, macroalgae, sponges, bryozoans and tunicates (Glynn, 1993). If the intensity of the bleaching event is not great then many corals will recover after a few weeks. An intense episode can, however, cause massive bleaching and the death of corals and other reef organisms (Glynn, 1985). Many of the faster branching coral species with high metabolic rates are more susceptible to bleaching and these species may be replaced by the less susceptible slower growing species (Brown and Suharsono, 1990; Jokiel and Coles, 1990; Williams and Bunkley-Williams, 1990). When bleached corals die, space becomes available and is often colonised by non reef-building organisms such as algal turf, macroalgae, sponges and tunicates. The dead reef framework also provides shelter and grazing surfaces for many potentially destructive organisms such as boring sponges and mussels, sea urchins and fishes resulting in severe bioerosion of the reef (Glynn, 1991). The coral framework will eventually collapse and degenerate into a pile of rubble. This rubble provides very limited hiding places for fish and poor substrata for new coral recruitment. As a result fish productivity will fall slowly and remain low until there is reasonable recovery of reef structure (Wilkinson *et al.*, 1999}.

Furthermore, it has been suggested that an increased incidence of ciguatoxic fishes may occur on reefs where bleaching events have caused significant coral mortality (Kohler and Kohler, 1992). Ciguatera poisoning is associated with blooms of toxic epiphytic dinoflagellates, which live on coral reefs after environmental disturbances (Quod *et al.,* 1994).The toxins that cause ciguatera are ingested by herbivorous fish, which feed on marine algae and are then passed up the food chain to humans eating reef fish (Hales *et al.,* 1999). Kohler and Kohler (1992) found that dead sections of bleached corals in the US Virgin Islands and British Virgin Islands quickly became colonised by filamentous algae harbouring the dinoflagellates implicated in ciguatera fish poisonings. In the Galapagos Islands, Hales *et al.* (1999) found a strong positive correlation between the annual incidence of ciguatera poisoning and local warming of the sea surface during El Nifio. In recent months the level of ciguatera poisoning in Reunion and other French islands in the Indian Ocean has increased, apparently as a result of the bleaching disturbance (Quod, in Wilkinson *et al.,* 1999).

1.23 Recovery of **Coral** Reefs

The rate of coral reef recovery is often related to the scale and severity of the bleaching event but varies greatly with location. Rapid recovery has been observed in areas where the presence of coral survivors nearby could serve as seed populations facilitating recruitment (Endean and Stablum, 1973). Low rates of recovery may occur in coral communities that experience unusually frequent disturbances or continued predation (Endean and Cameron, 1990). In the Thousand Islands, Java Sea, 5 years after a mass bleaching event in 1983 recovery was not complete and coral cover was still 50% of its former level (Brown and Suharsono, 1990; Warwick *et al.,* 1990). Coral cover finally attained pre-bleaching levels in 1990 at one site and 1994 at the other site (Brown, 1997). Recovery patterns at the two sites were very different despite their close proximity and initially similar community structure. This highlights that the ability to predict the recovery of reefs affected by bleaching depends on a number of factors. These include successional sequence and diversity of the reef; past and present dynamics of the community; environmental tolerances and life history strategies of dominant species; secondary disturbances such as predation and erosion and the magnitude of the disturbance (Brown and Suharsono, 1990).

1.24 Causes of Coral Bleaching

Coral bleaching is a general stress response that may result from a variety of environmental conditions and anthropogenic stresses. A variety of different stresses have been suggested as being potentially responsible for causing coral bleaching. Localised bleaching events have been associated with bacterial and other infections (Kushmaro *et al.,* 1996), solar radiation (Fisk and Done, 1985; Harriott, 1985), sea level drops (Glynn, 1976), reduced salinity (Gareau, 1964), increased turbidity (Bland, in Williams and Bunkley-Williams, 1990) and temperature changes (Coles and Jokiel, 1978). In most cases the key environmental variables remain poorly defined. Recent work however, highlights increased sea surface temperatures and solar radiation (including UV radiation) as the most common factors believed to be responsible for large scale coral bleaching.

1.241 Solar radiation

A number of studies in both the field and laboratory have shown that solar radiation can cause bleaching of both reef corals and anemones. Fisk and Done (1985) and Harriott (1985) suggested that increased solar radiation caused shallow water bleaching of corals on the Great Barrier Reef during 1982. Although no measurements of UV radiation level were made bleaching occurred only on the upper and unshaded surfaces of colonies and occurred during a summer of unusually low rainfall and higher than average hours of sunshine (Harriott, 1985).

Gleason and Wellington (1993) transplanted *Montastrea annularis* in the Bahamas from 24 m to 12 m. At each depth colonies were either exposed or protected from UV. The study found that transplanted colonies of *M. annularis* exposed to UV radiation at 12 m depth showed visible signs of bleaching within seven days of exposure. In contrast, changes in colony colour were not observed in UV-protected colonies. It was suggested that UV radiation (280-400 nm) alone caused the bleaching effect. Dunne (1994) however, suggests that photosynthetically active radiation, PAR (400-700 nm) may in fact have caused the bleaching. Brown *et al.* (1994) showed that solar radiation was the primary factor responsible for bleaching of *Goniastrea aspera* in Thailand. They were unable to attribute the bleaching response to a specific component of the solar radiation, however, they suggested PAR as a possible candidate for further investigation. High levels of PAR and UVB radiation were found to affect *Agaricia agaricites* planulae (Gleason and Wellington, 1995). PAR was found to cause

a significant reduction in chlorophyll concentrations while the UVB caused a decrease in survivorship of the larvae.

Bleaching was induced in *Stylophora pistillata* in laboratory experiments by sudden exposure of colonies previously grown at 25% sunlight to full sunlight (Hoegh-Guldberg and Smith, 1989). Kinzie (1993) showed that in *Montipora verrucosa* elevated UV radiation stressed the symbiotic algae causing a reduction in areal zooxanthellae density. Bleaching responses were initiated as a result of exposure to PAR and UV radiation in the zoanthid *Palytlioa caribaeorum* (Lesser *et al.*, 1990) and the sea anemone *Aiptasia pallida* (Lesser and Shick, 1990).

1.242 Elevated sea temperature.

Many tropical marine organisms, including corals, live near their upper thermal tolerance limits. Small increases in sea temperature (1-2°C) over several weeks or large increases (>4°C) over a few days will lead to coral mortality (Coles and Jokiel, 1978; Glynn, 1984). There is significant evidence both from field and experimental studies that sea temperatures are associated with bleaching events.

In 1991 and 1995 there were two incidences of extensive coral bleaching in the Andaman Sea. Both 1991 and 1995 are years when the highest seasonal temperatures were recorded suggesting that bleaching occurs when average temperature rises above a local threshold (Brown *et al.,* 1996). Analysis of monthly mean Sea Surface Temperature (SST) records from Puerto Rico for the thirty year period 1966-1995 indicates that severe bleaching occurred when temperatures exceeded the long term mean during the period of maximum annual temperature. It is suggested that prolonged heat stress may be an important precondition for bleaching to occur, with sharp temperature changes acting as an immediate trigger (Winter *et al.,* 1998). SST records from 1970-1994 in Panama and 1973-1994 in the Galapagos Islands indicate that in both areas all bleaching events were associated with El Nifio warming events. The data support the idea that an absolute SST threshold needs to be reached for bleaching to occur. The combined effect of SST anomalies and their duration is another factor potentially relevant in determining the occurrence of bleaching, as is the timing of the anomaly.

In laboratory experiments colonies of *Pocillopora damicornis* kept at slightly elevated sea temperatures (30-32°C) exhibited severe bleaching, accompanied by a progressive loss of zooxanthellae and mortality after 5 weeks. In contrast, zooxanthellae loss was insignificant in colonies kept at normal temperatures (26-28°C). These high temperature experiments resulted in mortality similar to that observed during the 1982-1983 El Nifio event (Glynn and D'Croz, 1990). Lesser *et al.* (1990) showed that increases in seawater temperature significantly reduced the total number of zooxanthellae per polyp in the zoanthid *Palythoa caribaeorum.*

Drollet *et al.* (1994) suggest that severe bleaching events occur when high total solar irradiance coincides with elevated seawater temperature. This indicates that bleaching is a synergistic interaction between temperature and UV-B radiation, possibly associated with total solar irradiance. Indeed many workers (e.g. Glynn, 1991; Brown and Suharsono, 1990; Williams and Bunkley-Williams, 1990; Goreau and Hayes, 1994) have observed bleaching during periods of low wind velocity, calm seas and low turbidity when conditions favour heating of shallow waters and high solar penetration.

1.243 Other factors

A wide range of other factors have been observed to cause coral bleaching at a more localised level. Extreme low tidal exposure and sudden sea level lowering preceded coral bleaching on shallow reef flats in French Polynesia and the Tokelau Islands (Glynn, 1984). In Jamaica, localised bleaching was observed after torrential rain and increased river discharge lowered the salinity of inshore waters (Goreau, 1964). High turbidity may have complicated and intensified the 1987 bleaching event in the Bahamas (Bland, in Williams and Bunkley• Williams, 1990) and at Mayotte (Faure, in Williams and Bunkley-Williams, 1990). Examination of bleached corals has revealed large aggregations of bacteria (Brown, 1997) and in the laboratory high doses of bacteria have been shown to produce bleaching (Kushmaro *et al.,* 1996)

1.25 Past Bleaching Events

Since 1980 there has been a significant increase in the number of reported large-scale coral bleaching events (Winter et al., 1998), indeed between 1979 and 1990, 60 major coral bleaching events were reported (Williams and Bunkley-Williams; Glynn, 1991). Many of these events occurred over large geographical areas and in 1982-1983 and 1986-1987 coral bleaching was reported in all tropical oceans. These events affected shallow and deep corals across large regions including reefs remote from local stresses (Williams and Bunkley-Williams, 1990). El Nino can partially explain this pattern and 1983 and 1987 were both El Nino years, however bleaching also occurred in non-El Nino years. In almost all cases it was observed that mass bleaching followed extended periods of high temperature, low wind, low cloudiness and low rainfall. *In situ* observations combined with NOAA satellite-derived sea surface temperature records show that at 7 sites in the Caribbean mass bleaching events took place when the monthly mean temperature was approximately 1°C above average during the warmest months (Gareau and Hayes, 1994).

In 1982-83, a very strong El Nino event resulted in widespread ocean warming in the equatorial eastern Pacific, the western Pacific, the Indian Ocean and the Caribbean. Severe bleaching occurred with mass mortality of corals around Costa Rica, Panama, Colombia and Ecuador. Bleaching resulted in 51% coral mortality in Costa Rica, 75-85% mortality in Panama and 97% mortality on reefs around the Galapagos Islands. Mortality was greatest among the fast-growing branching colonies of *Pocillopora spp.* and *Millepora spp.* and some species disappeared from sites where they had formerly been abundant (Glynn, 1984; Glynn and Colgan, 1992). On the Caribbean side of Panama many scleractinian and hydrozoan hard corals, as well as gorgonians, sea anemones and zoanthids bleached during June 1983 (Glynn, 1984). Extensive coral bleaching and mortality were also observed in French Polynesia (Salvat, in Glynn, 1984), Southern Japan (Yamaguchi, in Glynn, 1984), the Florida Keys (Jaap, in Glynn, 1984) and the Bahamas (Smith, in Glynn, 1984). In Indonesia, coral bleaching resulted in the mortality of 80-90% of the shallow corals of the Thousand Islands (Brown and Suharsono, 1990) and a reduction in coral coverage from 50% to <1% in the Pulau Seribu Islands (Brown, 1987). Mass bleaching of shallow water corals was also observed at Lizard Island and other locations on the Great Barrier Reef with mortality rates of up to 58% (Harriott, 1985).

During the 1986-1988 bleaching event bleaching occurred throughout the Indian, Pacific and Atlantic Oceans and at new sites, including reefs throughout the Red Sea and the extended Caribbean region. In the Atlantic the north central Caribbean, Bahamas and south Florida appeared to be the most intensely bleached area. Bleaching was recorded in both intertidal and sub-tidal reefs, down to depths of 91.4m (Lang, in Williams and Bunkley-Williams, 1990) and on inshore and offshore reefs. Widespread bleaching began in Puerto Rico in August 1987 resulting in extensive partial mortality of coral species (Winter *et al.,* 1998). In the Indo-Pacific, bleaching on the Great Barrier Reef was the most extensive and intense reported to that date (Oliver, in Williams and Bunkley-Williams, 1990). Bleaching was also reported in the Andaman Islands (Wood, in Williams and Bunkley-Williams, 1990), Reunion (Nairn, in Williams and Bunkley-Williams, 1990), Kenya (McClanaham, in Williams and Bunkley-Williams, 1990) and the Maldives (Wood, in Williams and Bunkley-Williams, 1990). The eastern Pacific however, bleached less in 1987 than in 1983 (Williams and Bunkley-Williams, 1990).

In addition to these two bleaching events, other mass bleaching events have occurred throughout the tropics. In 1989-1990 coral bleaching occurred throughout the Caribbean region (Glynn, 1991). In Jamaica many areas were heavily affected by mass bleaching. On the north coast of Jamaica 80% of corals were bleached and by the end of 1991 most coral species were overgrown by algae, such as *Halimeda* and *Dictyota* or outcompeted by sponges and soft corals (Goreau, 1992). In Puerto Rico severe bleaching occurred in September 1990 with most corals being bleached over their entire surfaces. Some of the shallow-water *Millepora* and scleractinian colonies were killed almost immediately and extensive partial and total colony mortalities followed (Winter *et al.,* 1998).

Extensive coral bleaching occurred in intertidal and subtidal coral colonies in Southern Thailand in 1991 and 1995 (Brown *et al.,* 1996). Mass bleaching also occurred in the central and western Pacific in 1991 (Gleason, 1993) and was recorded in French Polynesia in 1994 (Fagerstrom and Rougerie, 1994; Hoegh-Guldberg and Salvat, 1995). In Moorea corals were bleached down to 25 m and between 39.6 and 72.4% of live coral colonies were affected (Hoegh-Guldberg and Salvat, 1995). In the Society Islands 95% of anemones were fully bleached and up to 90% of hard corals were bleached (Fagerstrom and Rougerie, 1994). An extensive coral bleaching event occurred in 1996 in Papua New Guinea. 54% of all corals were bleached and bleaching occurred on the shallow fringing reef and to depths of 20m on the reef slope (Davies *et al.*, 1997).

Despite many reefs in the Caribbean suffering from repeated bleaching events the reefs of Belize did not suffer a widespread bleaching event until the summer of 1995. During this time 52% of corals were affected by bleaching, with *Agaricia tenuifolia* suffering 43% partial mortality. The effects of the mass bleaching event had subsided by May 1996 however, this bleaching event was unprecedented in this area (McField, 1999). Similar effects were observed in other Caribbean reefs during this event with 55% of bleached corals experiencing partial tissue mortality in Bonaire, 50% in Discovery Bay, Jamaica, 45% in Grand Cayman and 16% in Curacao (CARICOMP, 1997).

1.26 The 1997-1998 Bleaching Event

During 1997-1998 coral reefs throughout the tropics were subjected to the most geographically widespread and probably most severe bleaching event in recorded history. There was unprecedented bleaching in coral reefs throughout the Indian Ocean, the Middle East, Southeast and East Asia, the Caribbean, the Far West and Far East Pacific and the Atlantic Ocean (Wilkinson *et al.*, 1999). Many reefs previously regarded as pristine were seriously affected. The global mean surface temperature in 1998 was the highest on record, with sea surface temperatures reaching up to 40°C in some areas (Wilkinson, 1998). There appears to be some correlation between this bleaching event and one of the strongest El Nino events of the century. In many areas sea surface temperatures rose 2°-3°C above the normal seasonal maximum and in some locations 4°-6°C increases were recorded. Warm surface waters were first observed in the Indian Ocean in satellite images from NOAA in January 1998. The first bleaching was reported off the east coast of Africa and Madagascar one month later (Wilkinson *et al.*, 1999). This warm pool of water increased in size and moved northwards during the first six months of 1998, causing bleaching throughout the Indian Ocean (Figure 1). The start of bleaching in the Indian Ocean in February 1998 coincided with a large El Nifio event. Bleaching then started in Southeast and East Asia as the South China Sea and Pacific Ocean started to heat up, coinciding with a strong La Nifia in June (Wilkinson, 1998).

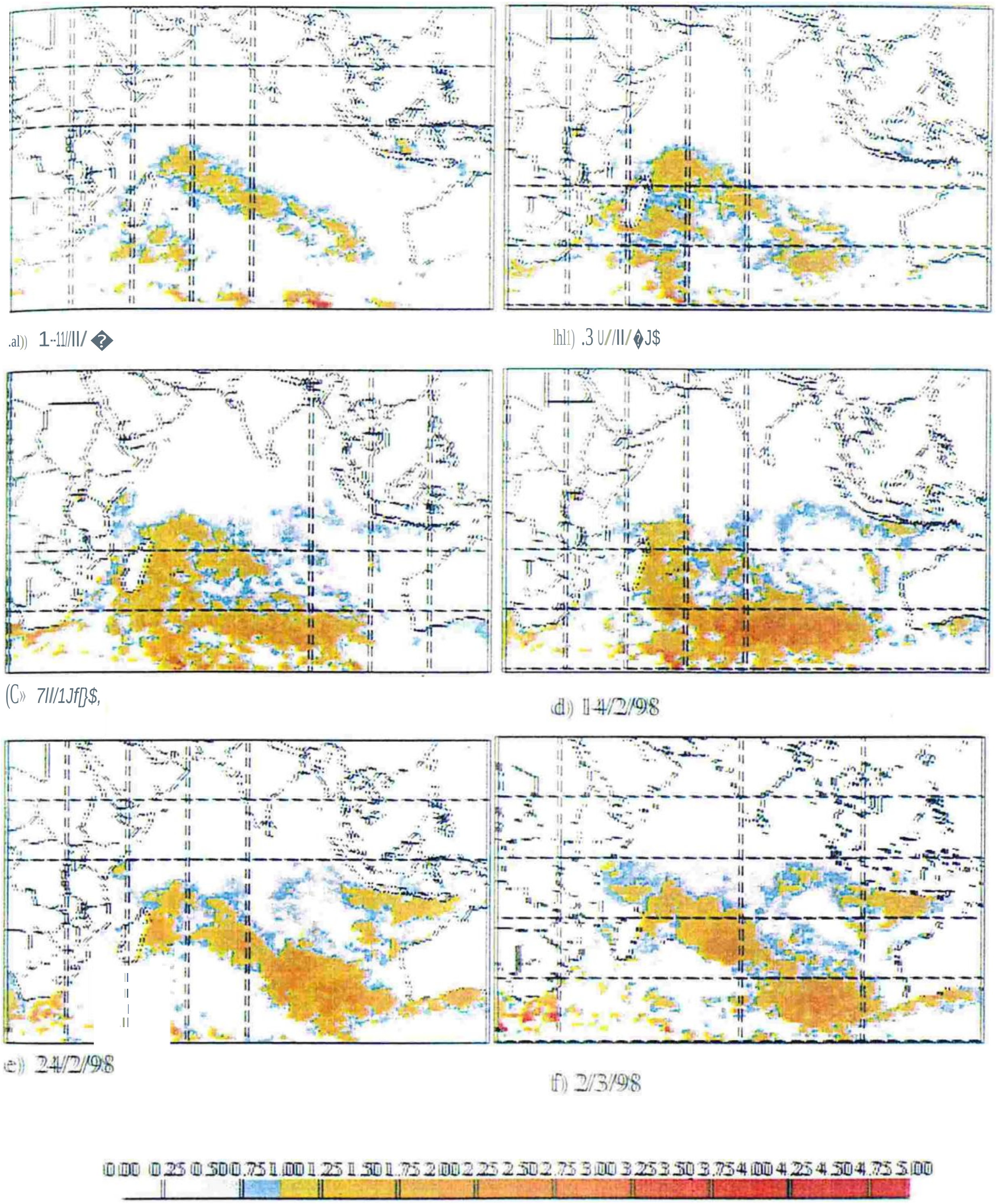


Figure [illegible] NOAA/NESDIS [illegible] Sea Surface [illegible]

J

The most severe bleaching ever reported in the Indian Ocean occurred around the islands of the Maldives, the Seychelles and Sri Lanka and on the coasts and islands of India, Kenya and Tanzania. The bleaching affected 90% or more of the living corals many of which subsequently died. Bleaching was most pronounced in shallow water, less than 15 metres deep and particularly affected fast-growing species such as *Acropora*, *Echinopora* and *Montipora*. Bleaching was also observed in *Astereopora*, *Galaxea*, *Lobophyllia*, *Millepora*, *Pocillopora* and *Seriatopora*. Slower growing species such as *Porites* also bleached, however, many recovered within 1 to 2 months (Wilkinson *et al.*, 1999). Soft corals, anemones, tridacnid clams and some sponges were also affected. By 1999, 80 to 90% of the bleached corals in the more severely affected areas had died, including previously resistant species and many of the remaining corals were still bleached or had reduced colour. It is predicted that this bleaching event has reduced the proportion of live to dead coral across the whole Indian Ocean from 80% live; 20% dead in 1997 to 64% live; 36% dead (Wilkinson *et al.*, 1999).

In Kenya and Tanzania bleaching started in March and continued during April. Bleaching was most extreme in shallow water (90-100%) but was also 50% or more at 20 m. Coral mortality was high, reefs have been reduced to between 10 to 50% of previous levels and algal cover has increased up to 200% (Linden and Sporrong, J999). The Maldives experienced relatively

severe, rapid bleaching between late April to May. 80% of corals were totally or partially bleached in shallow water and 30-45% at depths of between 10 and 30 metres. Reports indicate that 95% of mostly *Acropora* communities were dead and soft corals, anemones and giant clams were partially bleached. Some recovery began in May, but this was not rapid (Wilkinson *et al.*, 1999). There was extensive bleaching throughout the Seychelles and 75% of corals within the Seychelles Marine Park system were recorded dead. Soft corals, anemones and giant clams also bleached (Wilkinson, 1998). Bleaching in Sri Lanka started in mid April and by late April 80% of species on the reef flat were bleached. Some recovery was seen in June, but most branching and tabulate *Acropora* and *Pocillopora* colonies were dead (Wilkinson, 1998). In India there was 90% mortality of corals on the outer-atoll seaward slopes of the Lakshadweep Islands and in the Andaman Islands more than 90% of massive corals and more than 75% of branched corals were bleached (Ravindram *et al.,* 1999). In Socotra corals bleached in May and by November all shallow tabular and branching corals were dead and coral rubble was washed ashore (Turner, 1999.).

In Mauritius SST anomaly charts produced by NOAA show that SST was raised 1-1.25°C above the climatological maximum for this region on 31st January 1998. SST rose to 1.25-1.50C above normal between 10th and 14th February 1998 and remained 1-1.25°C above normal until 28th February. It is highly probable that extensive bleaching occurred in Mauritius during this time. The level of bleaching in Mauritius however is poorly known. Extensive bleaching was observed to be beginning in April 1998. Up to 25% of *Acropora formosa* thickets were partially bleached but in most cases alive. Some *Acropora cytherea* was bleached and some *Porites* and small favids were bleached, some completely, but most partially. Anemones were also bleached (Turner, 1999). A report by the Albion Fisheries Research Centre, Mauritius concluded that bleaching affected 39% and 31% of live corals in Balaclava marine park and Blue Bay marine park respectively. Partial bleaching was 27% in both areas and total bleaching in Balaclava and Blue Bay was 12% and 4% respectively (Goorah *et al.*, unpubl.). It seems unlikely, however, that Mauritius escaped mass coral reef bleaching when bleaching was so severe throughout the Indian Ocean.

1.27 Implications for the Future

Large areas of the reefs in the Maldives, the Seychelles, Sri Lanka, Kenya and Tanzania were severely damaged and may take between 25 and 50 years to recolonise. The dead reefs will be initially colonised by algae, resulting in losses of some fish species that depend on live corals. Bioerosion will cause a massive weakening of the reef structure causing the coral framework to collapse. This would result in a decrease in fish productivity. These countries are very densely populated and are dependent on the reefs for fisheries and tourism. The recent bleaching event will, therefore, have a severe impact on the people of the Indian Ocean. In the worst case scenario, the bleaching event may result in major losses in tourism income and employment; fish productivity may fall considerably, resulting in reduced catches for fishermen and major loss of income and there will be a loss of the protective barrier function of the reef, resulting in greater coastal erosion (Wilkinson *et al.*, 1999). Thus, in addition to biological impacts, a severe bleaching event can also have a major negative socio-economic impact on the countries affected.

Computer models have predicted that as a result of global warming, sea surface temperatures will increase by 1-2°C on average by AD 2030-2050 (Manabe *et al.*, 1991). If this were the case we would expect an increase in the severity and scale of coral reef bleaching around the world. Modelling results indicate that all coral reef regions between approximately 25°N and S would experience temperature increases of between 1 and 2°C. These regions would experience sustained warming that falls within the lethal limits of most reef-building coral species. Especially at risk would be mid- to high latitude coral reefs in the western Pacific (Bonin Islands, Ryukyu Islands, Taiwan), central Pacific (north-western Hawaiian Islands) and western Atlantic (Bermuda, Bahamas, Florida Keys). Some Indian Ocean coral reefs including Madagascar and Mauritius would also experience relatively high sea temperatures (Glynn, 1993).

Individual coral colonies living in high temperature environments can survive and photosynthesise at temperatures a few degrees higher then the same species living in colder environments (see Jokiel and Coles, 1990 for review) and some individual colonies have the capacity to acclimate physiologically to higher temperatures. However, even corals normally exposed to high temperatures such as those in the Arabian Gulf and Gulf of Oman, bleach during excessive and prolonged periods of warming (Glynn, 1993). If sea warming does occur then in order for coral reefs to survive coral species will need to evolve rapidly to cope with this environmental change. The fossil record indicates, however, that coral reef ecosystems have survived through many warming periods over geological time (Glynn, 1991) and thus in the long term it is likely that some corals will be able to adapt to life in warmer seas.

1.3 Mauritius

1.31 General Characteristics

Mauritius is located in the Indian Ocean at an altitude of 20° South and a longitude of 57° East, approximately 1000km off the coast of Madagascar. It is the central island in the Mascarene group of islands, which stretches from Reunion in the south to the Seychelles in the north. The Republic of Mauritius comprises the main island of Mauritius together with the islands of Rodrigues, Cargados Carajos Shoals (St. Brandon Islets) and Agalega Islands as its dependencies. Mauritius also claims sovereignty of Diego Garcia and Tromelin. The island of Mauritius is 60km long by 40km wide and has a total area, including several much smaller adjacent islands of 1865 km^2 (Figure 2).

a)

b)

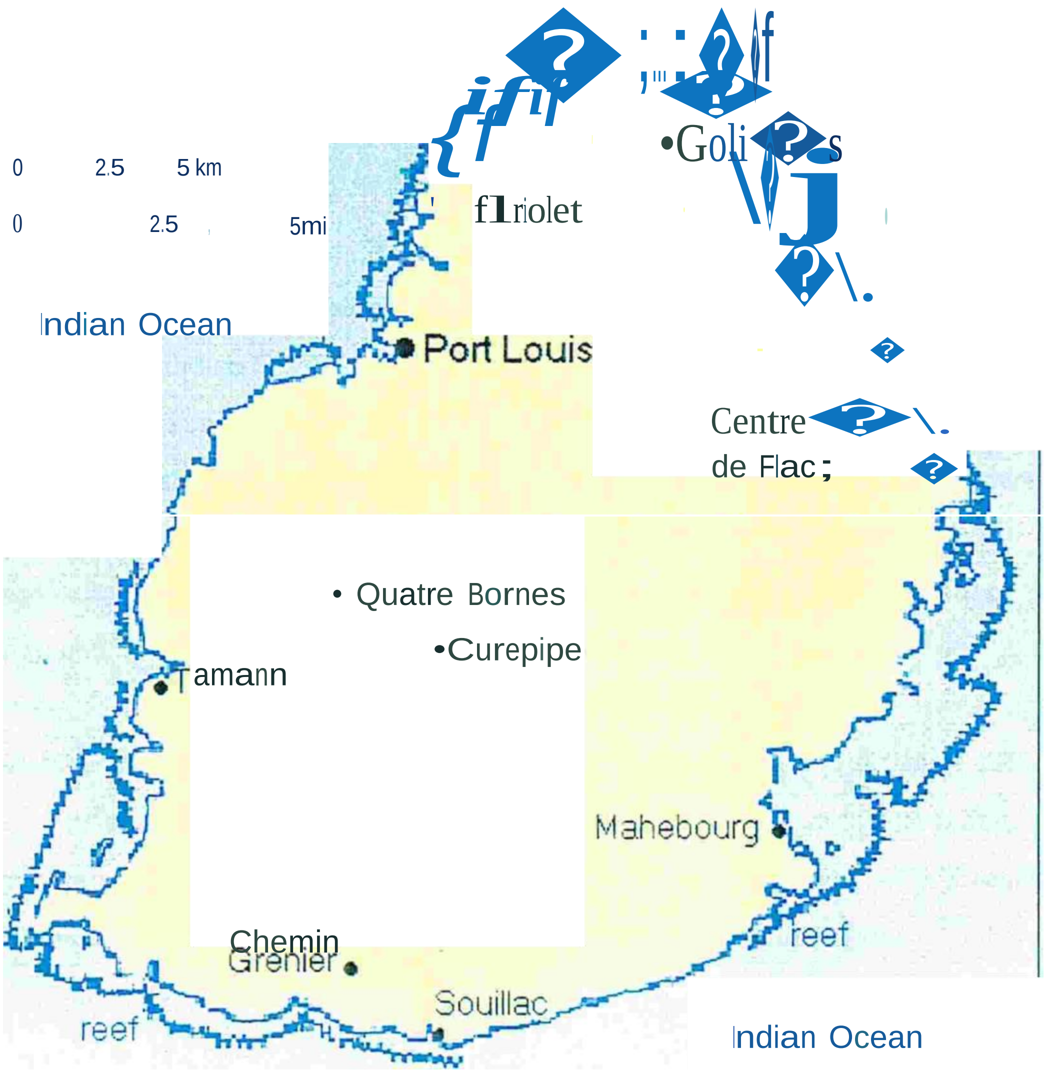


Figure 2. a) the posuion of vlauritius in the Indiar Ocean (adapted from <http://ww,v.o<lci.gov/cia/publications/facthok/mp.hrnl»). b) the island of Mauritius (adapted from <http://www.maurinet.com/>).

Mauritius is of volcanic origin and was formed by a series of collapsed calderas filled with lava (doleritic basalts) during two major volcanic phases (Pichon, 1971). It is the oldest of the Mascarenes islands having initially arisen 7-8 million years ago and has since been modified by a series of volcanic eruptions from 3.5 million years to between 0.7 and 0.17 million years ago (Faure, 1975). The coastline of Mauritius, formed by the seaward flow of the lava, is 200 km long. It is surrounded by 150 km of narrow fringing coral reefs enclosing a lagoon area totalling 243km^2(UNEP, 1984).

Mauritius has a subtropical climate and the temperature at sea level ranges from 25°C in August to 33°C in February (MTPA, 1998). It is located in the south-east trade winds belt and the predominant wind direction is east south east. As a result the coast is predominantly affected by swell from the south-east. The trade winds blow most of the year, but especially during the cool season (May-November). Mean wave heights on the south coast have been recorded as ranging from 1.67m in the summer to 2.86m in the winter (Fagoonee, 1990).

Annual rainfall varies from 1200mm on the north coast to 3,600mm on the central plateau. Mauritius is affected by cyclones each year. Cyclones originate in the lower latitudes of the South western Indian Ocean during November to March, with the highest frequency occurring in January and February. Strong winds (up to 200krn/hr), high rainfall and heavy swell always accompany these cyclones (Pichon, 1971). Tides are sernidiumal and have a very small tidal range of 0.6m at springs and 0.5m at neaps (Fagoonee, 1990). The sea surface temperature varies seasonally between 23°C in the winter (September) and 27°C during the summer (February) with a mean of 25.7°C (Hartnoll, unpubl.).

Mauritius has a population of 1,168,256 (July 1998 est.) and a growth rate of 1.2% (1998 est.) (CIA, 1998). The population density was 554 persons/km^2 in 1995 (Hing, 1999). The population is multi-racial and comprises of 68% Inda-Mauritians, 27% Creole, 3% Sino• Mauritians and 3% Franco-Mauritians (CIA, 1998).

1.32 Economy

Until it achieved independence in 1968 the economy of Mauritius was traditionally dependent on sugar production. The Export Processing Zone (EPZ) was, however, established in 1970 to attract foreign capital through tax incentives and facilities (Lutz, 1994). In the early 1980s the government launched a successful programme aimed at developing economic development through export-led industrialisation, agricultural diversification and expansion of the tourism industry (EPZDA, 1997). As a result, the past decade has witnessed rapid economic growth of between 5 and 6% per annum (CIA, 1998). This has been reflected in increased life expectancy, lowered infant mortality and improved infrastructure. The rapid industrialisation of Mauritius has however put stress on the natural environment and has caused land-use conflicts and pollution in the lagoons (Lutz, 1994).

Mauritius now makes its living on sugar cane agriculture, light industry and textiles, tourism, fishing (reef fishing and offshore bank fishing) and offshore banking (Hing, 1999). In 1997 the highest share of the Gross Domestic Product (GDP) came from the manufacturing sector (24%) followed by the wholesale, retail trade and tourism (18%) and the finance group (17%) (Hing, 1999).

1.33 Coral Reefs in Mauritius

The reefs surrounding a great part of the Mauritius coastline are discontinuous, forming a series of lagoons. There are 150km of fringing reef around the island which is cut by surge channels and river mouths, but is otherwise only absent from two areas: a 15.5 km stretch on the south coast and two sections totalling 10.5km on the west coast. Thirty six genera of hermatypic corals have been recorded from Mauritius (Pichon, 1971).

Salm (1976) describes three main types of reef that occur in Mauritius: peripheral fringing reefs, sheltered fringing reefs and lagoonal coral patches. He, however, omits the small barrier reef which is located at Mahebourg. Most of the reefs are well-established spur and groove reefs with an algal ridge, although the spur and groove zone is sometimes replaced by dead coral flagstone (Fagoonee, 1990). The reef flat is usually less than 25 metres wide and is exposed at low tide. The width of the lagoons varies greatly from a few km to a few 100m, with wider lagoons generally occurring on the east coast (up to 4 nautical miles) than on the west coast. The lagoons are usually only 1-2m deep, but reach depths of up to 6 metres in the north (Pichon, 1971).

The peripheral fringing reefs consist of the fore reef, reef crest and back reef. The fore reef consists of the spur and groove zone and is colonised by encrusting corals such as *Montipora*, *Pocillopora*, *Echinopora*, *Leptoria*, *Favia*, *Favites* and *Porites* as well as soft corals. The reef crest is dominated by massive coral colonies and the back reef by macro-algae *(Turbinaria ornata* and *Sargassum sp.)* and *Echinometra mathaei* (Fagoonee, 1990). Sheltered fringing reefs, which border surge channels and sheltered bays within the peripheral reef, are characterised by a dense cover of large colonies of staghorn and tabular *Acropora* and foliaceous *Montipora*. The lagoon substrate is composed of coral rubble, dead standing coral, patches of fine sand and seagrass. Lagoonal patch reefs have a high cover of staghorn or tabular *Acropora* and *Pavona* (Pichon, 1971). The barrier reef, at Mahebourg, is 400-600m wide, 9km long, 3-5km offshore and shelters a lagoon 15-30m deep (Faure, 1977). The reefs in Mauritius are heavily degraded by pollution, eutrophication and overfishing.

1.34 Uses of **the Coastal Zone**

Fisheries are exploited in lagoons and off-lagoons by over 3,900 artisanal fishermen (Fagoonee and Daby, 1993) and through mariculture in small walled areas of lagoon known as barachois (Fagoonee, 1990). Artisanal fishermen use a combination of lines, basket traps and seine and gill nets. The main fishes caught include groupers, rabbitfish, siganids, emperorfish, goatfish, parrotfish and mullets. Octopus, squid and coastal mud crabs are also caught (Fagoonee, 1990). In the barachois finfish and to a lesser extent shellfish, such as crabs and oysters are raised on a small scale (Fagoonee, 1990). Commercial fishing takes place offshore off the Banks on the Mauritius-Seychelles ridge (MEQL, 1990).

Sand is extracted from the lagoons at Trou d'Eau Douce and Ile d'Ambre. Sand mining provides a source of raw materials for local construction work and for water purification. Approximately 100,000 tonnes of sand is removed from lagoons each year (Fagoonee and Daby, 1993). Coral and shells have been removed for sale to tourists. The removal of corals from the sea was, however, banned in 1988 (Bhuiyan, 1994).

Tourism development began in the early 1960s in Mauritius and the sector has grown steadily over the years and now ranks as the third largest source of income for Mauritius after agriculture and industry. Between 1990 and 1998 the number of tourists visiting the island increased from 291,550 to 558,195 (Hing, 1999). Mauritius has made a clear choice for high• quality, expensive hotels by limiting the number of hotel rooms and banning charter flights (Lutz, 1994). Hotel and other tourists developments are concentrated on the coast with 90% of hotels situated there (Fagoonee, 1990). The hotels are concentrated in the north around Grand

Baie with the rest located on the eastern coast at Trou d'Eau Douce and Belle Mare and the western coast at Trou aux Biches and Le Mome. There are a number of diving and snorkelling centres operating from the larger hotels.

Agriculture in Mauritius occupies approximately 100,000 hectares of land. Sugar cane is the principle agricultural product and is grown uu [illegible] -od land area, which is 45% of the total land area (Fagoonee, 1990). Other agricultural products grown in Mauritius include tea, com, potatoes, bananas, pulses, cattle, goats and fish (CIA, 1998).

Mauritius has undergone rapid industrial development in the past decade. Industries include food processing (largely sugar milling), textiles, chemicals, metal products, transport equipment, non-electrical machinery and tourism (CIA, 1998). More than 50% of industrial sites have been located on the coast (Fagoonee, 1990).

1.35 Impacts to Coral Reefs

The marine environment in Mauritius is under stress from industry, tourism and the over-exploitation of natural resources.

1.351 Human Impacts

The lagoon fishery is being exploited to the maximum and may already be overexploited. There has been a decreasing trend in the annual catch from 2200 tonnes in 1970 to 1500 tonnes in 1990 despite a six fold increase in fishing effort (Paul, 1988).

Despite a ban on the removal of marine organisms from the waters surrounding Mauritius shell collectors have been observed around the coast of Ile aux Aigrettes collecting cowries and private boat owners have been observed taking marine organisms, mainly molluscs illegally (Bhuiyan, 1994). Tour operators and visitors have also been observed taking fish and large shellfish form the Ile Plat lagoon (Bhuiyan and Bell, 1995).

Coral colonies are killed by fishermen walking over the reefs and by the keels, motors and anchors of their pirogues and coral is often deliberately broken to find fish and octopus. In the lagoon at Ile Plat many fishermen have been observed walking over the reef at low water spearing fish and octopus. Owners of yachts and speed boats also walk across the coral to secure their boats in the deeper water of the central lagoon (Bhuiyan and Bell, 1995). The indiscriminant placing of mesh fishing traps and the weights used to anchor them causes direct physical damage to coral colonies. Permanent buoys placed in the lagoon at Ile Plat by tour operators also destroy corals both by the weights used and the attached mooring chains (Bhuiyan and Bell, 1995).

Cerfs are already seriously eroded, possibly as a result of sand mining activities (Fagoonee and Daby, 1993).

Tourism development in Mauritius has had a number of negative impacts on the coastal zone. Land clearing, reclamation and construction activities have caused an increase in sedimentation in the lagoons, which smothers the coral reefs (MEQL, 1990). The construction of coastal structures such as jetties, piers breakwaters, seawalls and groins alters the water circulation causing beach erosion. Increased tourism also causes problems of sewage pollution.

There are 4 sewer networks in operation in Mauritius which discharge untreated effluent at very shallow depths at or near the reef edge. This has caused an increase in turbidity of the water and floating sewage has been observed on the water surface. This affects the coral reefs and poses a serious health risk for people using the lagoon (Hartnell, unpubl.). Some hotels around the island discharge raw sewage into the lagoons (Fagoonee and Daby, 1993). Gendre

Sand mining has an negative impact on environmentally sensitive habitats such as coral reefs and seagrass beds as well as the local tourist industry. Direct impacts of sand mining include mechanical damage to the seagrass beds due to poor site selection and an increase in the concentration of suspended sediment in the water column, causing damage to coral reefs. In addition, excessive sand removal could alter the hydrodynamic regime resulting in erosion of nearby tourist beaches. The sand beaches on the east side of Ile aux et al. (1994) found high levels of coprostanol in the sediments of Trou d'Eau Douce lagoon, suggesting severe faecal contamination. In Trou aux Biches lagoon enrichment of the lagoon from sewage has lead to eutrophication, causing dense algal growth (Daby, 1999).

Water pollution also arises from the industries situated in the coastal zone. Untreated sugar industry wastes contaminate the lagoon with flyash, alkaline wastewater, traces of oil and other organic effluents (Fagoonee and Daby, 1993). Other forms of industrial contamination include the effluent from dye-houses, printing, tanning, paint manufacture, for example inorganic pollution by heavy metals, effluents from chemical and other industries and sewage. The majority of pollutants accumulate in estuarine and lagoon sediments (Fagoonee and Daby, 1993).

Agriculture causes erosion due to the reduced stability of soils and an excessive discharge of freshwater from irrigation and increased natural surface run-off. Agricultural practice in Mauritius often includes an indiscriminant use of fertilisers (MEQL, 1990). It has been estimated that fertiliser consumption in Mauritius averages 600kg/hectare and pesticide use has an application rate averaging 44kg/hectare, both of which are extremely high in comparison to international application rates (Fagoonee and Daby, 1993). Near Port Louis eutrophication has caused the increased growth of seaweeds which are choking the nearby reefs and increasing turbidity in western lagoons such as Grand Baie is indicative of high nutrient content and possibility of eutrophication (Daby, 1990).

1.352 Natural Impacts

In addition to the damage caused by human activities the coral reefs in Mauritius are also under threat from natural impacts. There have been serious outbreaks of the crown-of-thorns Starfish *(Acanthaster planci)* over the last 20 years. The population at Trou aux Biches increased 13-fold between 1971 and 1980, from 30 to 416 starfish per $100m^2$. It is possible that this increase is due to a decline in the population of the main predator of *A. planci*, the gastropod mollusc *Charania tritonis*, due to extensive collection of its shell and possibly pesticide pollution (Fagoonee, 1990). Explosive increases in the population of sea urchins, *Tripneustes gratilla* and *Echinometra mathaei* in the early 1970s on parts of the east coast caused destruction of the seagrass beds and reef areas (UNEP/IUCN, 1988). A very high abundance of *E. mathaei* was also observed at Balaclava during a survey in 1991 (Done *et al.*, 1991). These increases are thought to be caused by the overfishing of predators of their larvae, such as oysters (UNEP/IUCN, 1988).

Mauritius is affected by cyclones each year. These cyclones cause physical damage to the reefs and transport silt into the lagoons smothering corals. Recent cyclones to hit Mauritius include Cyclone Gretelle in 1997, Cyclone Anacelle in 1998 and Cyclone Davina in 1999 which generated winds of up to 173 km/hr.

1.36 Coastal Zone Management in Mauritius

Mauritius is an island country and the coastal zone is an important socio-economic resource, providing food and income. Rapid development or the coastal zone, however, is causing degradation of the coastal ecosystems and preservation of the coral reefs is vital. In the past Mauritius has introduced very little legislation to protect the marine environment, however significant progress has been made in managing the reef resources in recent years.

Under the Fisheries Act (1980) six Fishing Reserves, in which large net or gill fishing is prohibited were defined (UNEP/IUCN, 1988). This act also made the removal of corals, collecting of live molluscs and the use of spearguns within the lagoons illegal (Bhuiyan, 1994). In 1988 the Mauritian government established the Environmental Investment programme (EIP) to deal with the policy, institutional, legislative and infrastructure aspects of preventing further environmental degradation (Fagoonee and Daby, 1993) and a Marine Environment Management Plan has been prepared by the Ministry of Fisheries and Marine Resources (Salm *et al.,* 1998).

Since the early 1970s Baie de l'Arsenal, Flat Island/Gabriel and Blue Bay have been recommended to the Mauritius government for the establishment of marine parks (Procter and Salm, 1974). These recommendations were not implemented due to problems of co-ordination between the different government agencies concerned (UNEP/IUCN, 1988). Blue Bay and Balaclava have however now been declared Marine Parks and are monitored by the Albion Fisheries Research Centre, Mauritius.

t.37 Rationale for the Study

If Mauritius was affected by the mass coral bleaching event of 1998, then coral mortality could result in socio-economic impacts, including a further decrease in lagoon fish stocks and a decline in the number of tourists visiting the island. The coral reefs in Mauritius are already degraded by both human and natural impacts, making the reefs more susceptible to coral bleaching and more likely to suffer mortality (Wilkinson et al., 1999). It is therefore, important that the degree of bleaching and the current health of the coral reefs in Mauritius is known, in order that adequate management measures can be taken to favour rapid recovery of the coral reefs and offer greater protection in the future.

The aim of this study was therefore, to assess the extent of coral bleaching in Mauritius following the seawater warming event of 1998. The hypothesis to be tested was that the coral reefs in Mauritius would have been subjected to extensive bleaching during this warming event. One year later coral reefs would be dominated by dead standing coral and overgrown by macro- and filamentous algae.

1.4 Objectives

The principle objective of this study was:

- To investigate whether the coral reefs in Mauritius had suffered a mass bleaching event as a result of the sea warming in 1998 by making an assessment of coral bleaching, macroalgal growth and dead standing and recovering coral around the coast of Mauritius.

The secondary objectives were:

- To investigate which species and/or life-forms were most severely bleached.
- To investigate whether different size colonies were differently affected by bleaching.
- To determine whether there was any geographical pattern in the extent of bleaching around the coast of Mauritius.
- To investigate the climatic factors influencing Mauritius during the period of sea warming.
- To determine what other stresses (natural and human-induced) coral reefs in Mauritius are subjected to.
- To present the results within a Geographical Information System (GIS).

2.0 Materials and Methods

2.1 Field Surveys

A rapid assessment of the degree of coral bleaching was carried out on coral reefs in Mauritius between 9th – 13th April 1999. Surveys were carried out at 34 sites around the coast of Mauritius. Reefs were studied on all aspects of the island both within and outside the lagoons (Figure 3, Table 1).

Reefs to be surveyed were identified using supervised and rectified Landsat 4 TM images classified by Klaus (1995), aerial photographs and habitat maps produced by Montagionni and Faure (1980). The precise location of the reef was obtained using a hand-held Global Positioning System (GPS) (Magellan NAV 5000D, datum set to WGS-84). Wooden boats fitted with a small outboard motor and manned by local fishermen were used as transport within the lagoons. Outside the lagoons surveys were carried out in collaboration with local dive operators and their dive boats were used as transport.

Timed surveys of between 15 and 70 minutes were carried out across the reef by snorkelling in shallow areas (<5m depth) and by SCUBA in deeper areas. The length of each survey varied depending on the size of the reef structure being surveyed and time limitations. Assessments of coral bleaching were carried out by three different methods: direct observation, underwater video and underwater photography.

Visual surveys were carried out by between 4 and 5 observers and notes were made in waterproof notebooks. Observers swam from the boat across the reef at a distance of approximately 5 metres apart so that the same section of reef was only surveyed once. The survey was only carried out on the outward swim (and not on the return swim). Within the lagoon observers usually swam across the reef towards the reef flat.

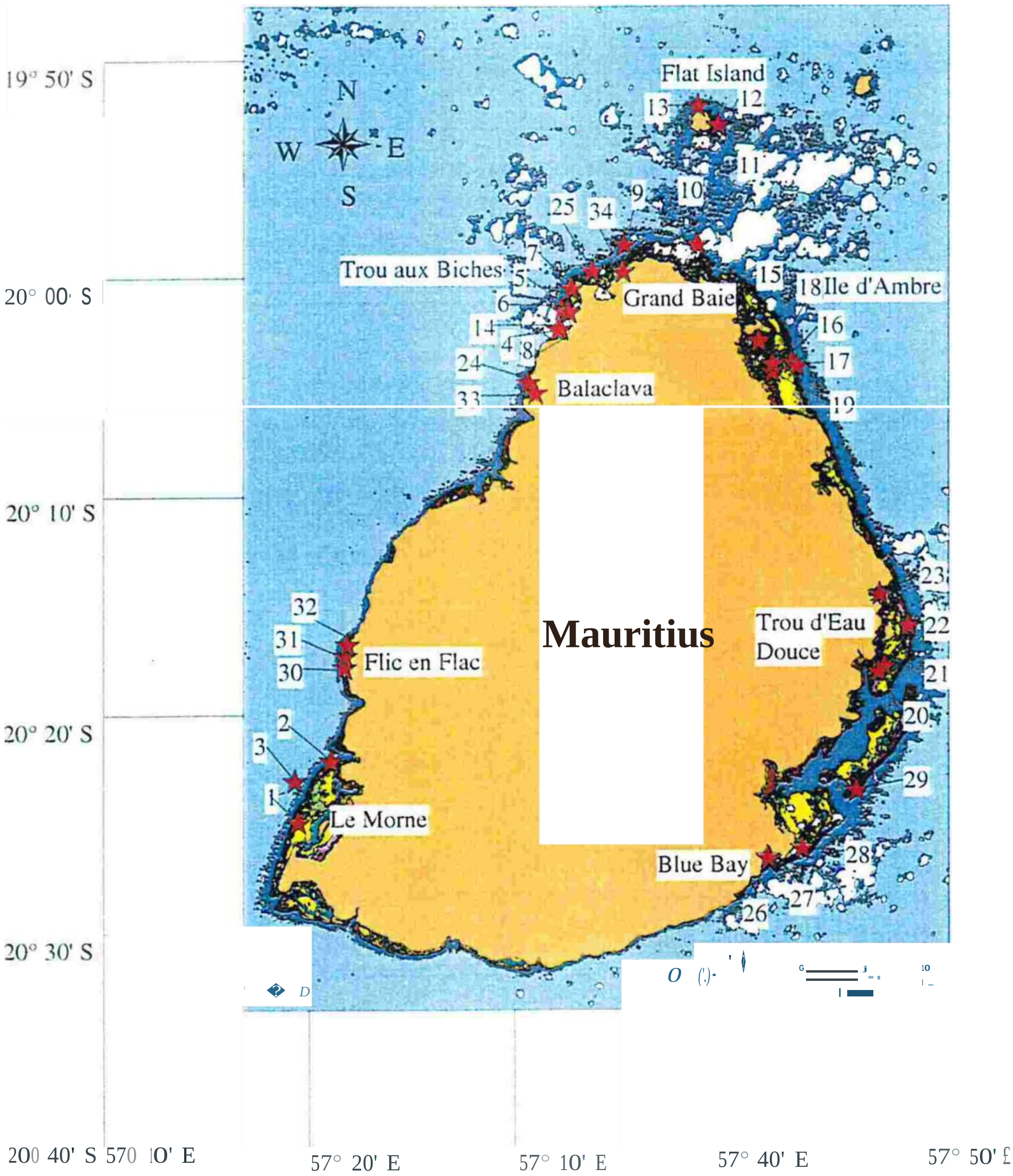


Figure 3. The position of the 34 survey sites around the coast of Mauritius. No GPS fix was made for sites 3 and 13 and so the approximate position of these sites is shown.

Table 1. Site description and GPS position of the 34 sites surveyed around the coast of Mauritius. GPS positions were obtained using a hand-held Magellan NAV 5000D, datum set to WGS-84.

Site	Name	Date Surveyed	GPS (South)	GPS (East)	Depth (m)	Description
1	LeMorne	08/04/99	20 24.937	57 19.499	0.5-2	Lagoonal patch reel
		08/04/99	20 24.950	57 19.371		
2	Point Harmonie	08/04/99	20 22.077	57 21.119	0-7	Lagoonal patch reel
3	Le Morne (Cannion)	08/04/99	NoGPS	NoGPS	5-13.8	Fore reef
4	Trou aux Biches	09/04/99	20 02.292	57 32.296	0-10	Fore reef
		09/04/99	20 02.399	57 32.346		
5	Trou aux Biches	09/04/99	20 01.383	57 32.339	0-10	Fore reef
		09/04/99	20 01.399	57 32.346		
6	Trou aux Biches	09/04/99	20 01.432	57 32.643	0-3	Lagoonal patch reel
		09/04/99	20 01.417	57 32.635		
7	Trou aux Biches	09/04/99	20 00.442	57 32.809	0-3	Lagoonal patch reef
8	Trou aux Biches	09/04/99	20 01.523	57 32.701	0-3	Lagoonal patch reef
9	Perybere	10/04/99	19 58.452	57 35.377	5-17	Fore reef
		10/04/99	19 58.648	57 35.361		
10	Calodyne Reef	10/04/99	19 58.447	57 38.972	5-15	Fore reef
11	Flat Island South	11/04/99	19 53.007	57 39.979	0-2	Lagoonal patch reef
12	Flat Island North	U/04/99	19 52.937	57 39.991	0-2	Reef crest
13	Flat Island	11/04/99	NoGPS	NoGPS	0-2	Fringing reef
14	Trou aux Biches	11/04/99	20 02.284	57 32.136	5-19	Fore reef
		11/04/99	20 02.220	57 32.248		
		11/04/99	20 02.198	57 32.193		
15	Ile d'Ambre	13/04/99	20 02.859	57 41.972	0-2	Lagoonal patch reef
16	Ile d'Ambre	13/04/99	20 03.830	57 43.539	0-2	Reef crest
17	Ile d'Ambre	13/04/99	20 04.007	57 43.794	0-2	Reef crest
18	Ile d'Ambre	13/04/99	20 04.268	57 42.625	0-2	Lagoonal patch reef
		13/04/99	20 04.280	57 42.636		
19	Ile d'Ambre	13/04/99	20 03.923	57 42.643	0-2	Lagoonal patch reef
20	Trou d'Eau Douce	14/04/99	20 17.796	57 48.019	0-4	Lagoonal patch reef
		14/04/99	20 17.800	57 48.055		
21	Trou d'Eau Douce	14/04/99	20 18.044	57 47.746	0-2	Lagoonal patch reef
		14/04/99	20 18.036	57 47.676		
22	Trou d'Eau Douce	14/04/99	20 15.969	57 49.143	0-2	Lagoonal patch reef
23	Trou d'Eau Douce	14/04/99	20 14.505	57 47.783	0-2	Lagoonal patch reef
		14/04/99	20 14.521	57 47.821		
24	Balaclava	1.5/04/99	20 04.728	57 30.698	0-3	Lagoonal patch reef
25	Grande Baie Aquarium	15/04/99	19 59.650	57 33.822	5-14	Fore reef
26	Blue Bay	16/04/99	20 26.170	57 42.622	0-8	Lagoonal patch reel
		16/04/99	20 26.667	57 42.471		
27	Blue Bay (shallow)	16/04/99	20 26.591	57 42.385	0-2	Lagoonal patch reel

Site	Name	Date Surveyed	GPS (South)	GPS (East)	Depth (m)	Description
28	Ile aux Aigrettes	17/04/99	20 26.170	57 44.065	0-3	Lagoonal patch reef
		17/04/99	20 26.112	57 44.055		
		17/04/99	20 25.644	57 44.278		
29	Barrier Reef	17/04/99	20 23.533	57 46.677	0-3	Barrier Reef
		17/04/99	20 23.433	57 46.831		
30	Flic en Flac (south)	19/04/99	21 17.800	57 21.759	0.5-2	Lagoonal patch reef
31	Flic en Flac (middle)	19/04/99	20 17.281	57 21.801	0-2	Lagoonal patch reef
32	Flic en Flac (Baie Dangereux)	19/04/99	20 16.763	57 21.900	0-2	Lagoonal patch reef
		19/04/99	20 16.763	57 21.900		
33	Balaclava Maritime Hotel	20/04/99	20 05.206	57 31.037	2-7	Lagoonal patch reef
		20/04/99	20 05.162	57 31.037		
34	Hibiscus Hotel	20/04/99	19 59.675	57 35.313	5-7	Lagoonal patch reef
		20/04/99	19 59.647	57 35.310		

Underwater video was recorded using 90 minute Video-8 format tapes in a Sony 8mm video camera (Model CCD TR55E) placed in an Amphibico housing. The video camera was held at 45° to the substrate and the operator swam slowly across the reef following the contour of the substratum. Video recording was confined to before 4pm due to the lack of light and so could not be carried out at all sites. Underwater still photographs were taken using Nikonos V and Nikonos III underwater cameras equipped with a 28mm Nikon lens and ASA 200 Kodachrome film. Natural light was used whilst snorkelling and synchronised flash was used on SCUBA dives.

The visual survey consisted of two sections, which were carried out simultaneously. The first section described the general features of the reef. Notes were made about the percentage cover of 6 physical and 7 biological attributes of the reef (Table 2), the presence of other symbiotic organisms, such as anemones or *Tridacna* clams and any general impacts to the reef, such as bleaching, *Acanthaster planci*, anchor and storm damage. At the end of the timed swim results of all observers were combined. A scale was established in order to provide semi-quantitative percentage cover data of the biological and physical attributes (Table 3).

Table 2. Description of the physical and biological attributes used during the rapid assessment to describe the general reef characteristics.

Physical Attributes	Descri tion	Biological Attributes	Descri tion
Continuous Pavement	A large, unbroken section of substrate (rock/coral)	Hard Substrate	Any hard substrate such as rock or dead coral that is worn down and no longer recognisable .
Large Blocks	Blocks of substrate (rock/coral) >lm in diameter.	Hard Coral	Living hard coral including *Millepora sp.* and *Heliopora sp.*
Small Blocks	Blocks of substrate (rock/coral) <Irn in diameter	Soft Coral	Living soft coral species including zoanthids
Rubble	Broken sections of coral or rock <30cm in diameter.	Dead Coral	Dead standing coral which is still recognisable and only partially overgrown by algae.
Sand	Sediment that is deposited on the bottom if disturbed.	Turf Algae	Algae that does not rise more then 1cm above the substrate
Silt	Sediment that remains in suspension if disturbed.	Macro-algae	Fleshy algae whose fronds are projected more than 1cm above the substrate.
		Coralline Algae	Species that are generally hard to the touch. Encrusting species may occur as a hard smooth pavement n the substratum.

'he second section involved a more detailed description of the species composition of the eef. All hard and soft corals and macro-algae were identified to genus or species level where ossible. The size of hard and soft coral colonies was recorded using four size intervals (1-Dem; 11-25cm; 26-50cm; >50cm). The abundance of all species was recorded on the same .mi-quantitative scale of 0-5 as for the biological and physical attributes. The percentage eaching observed in each species was also recorded on the same scale of 0-5, where each score represented the percentage of that species bleached. At the end of the timed swim results of the different observers were combined.

Table 3. Abundance scale of 0-5 and the corresponding percentage cover(%).

Scale	Corresponding percentage cover(%)
0	0
1	1-10
2	11-30
3	31-50
4	51-75
5	76-100

2.2 Video Analysis

Underwater videos were analysed to confirm results from the field surveys and to correct observer bias. The videos were watched and the time shown on the video clock at the beginning and end of each tape was recorded in order to calculate the time interval. Videotapes were analysed using the random point sampling technique (Foster *et al.*, 1991), which involves pausing the tape at randomly spaced intervals and placing sample points at random locations on the monitor screen. The number of tape pauses was calculated by dividing the duration of the video recording, in seconds, by 5 (see Osborne and Oxley, 1997).

Five points were sampled at each pause (Osborne and Oxley, 1997).

In order to calculate when to randomly pause the tape the "time of day" displayed on the video counter was used and random times chosen using Minitab (version 12.1). A grid 155mm by 215mm was drawn on a clear plastic sheet, with gridlines every 10mm. The random sampling points were calculated in Minitab by randomly choosing 5 x- and 5 y-co-ordinates for each site. Due to the 45° angle of the video, points were only utilised from the lower half of the grid.

A Sony Video 8 Trinitron colour monitor (Model TV EV-DT1) was used to play back tapes on a personal computer with a video capture card. The computer programme Win/TV

(Hauppauge Win/TV 4.5) was used for video image capture. The video image was frozen at the calculated random times and the grid placed over the screen. The benthos occurring under each of the five points was identified to species level, where possible using Veron (1986) and Richmond (1997). Any additional species not noted during the visual survey were also recorded.

The video data were converted to percentage cover data by summing up the points for each benthic category/species and expressing it as a percentage of the total number of points in the transect.

$$\text{Percentage cover} = \frac{\text{Total number of points for benthic category}}{\text{Total number of points for transect}}$$

The percentage cover was attributed a score on a scale of 0-5 as in the initial surveys. Video data were combined with the results from the visual surveys. Data from the video analysis were given a 75% weighting and data from the initial surveys given 25% weighting. Results from the video analysis were given greater weighting due to the greater accuracy of abundance measurements. Species observed during the initial survey, but not observed during video analysis were given a score of 1 on the abundance scale.

2.3 Photography

The 35rnrn slides obtained during the initial surveys were used to provide a permanent archival record of the health of the coral reefs and the degree of bleaching observed on the reefs. These images could be used in long-term studies to compare coral health over time. The slides were also used to confirm species identification and help in identifying species, which could not identified in the field. In addition, the slides were captured digitally and included within the Geographical Information System.

2.4 Statistical Analysis

A number of ecological indices were used to describe the species composition at each site. Species richness was first calculated as the number of hard coral species per site. Species diversity was calculated as the Shannon-Weiner Diversity Index H' where:

$$H' = \Sigma p_i \ln p_i \qquad \text{and } P_i = (n_i/N_i)$$

n_i = % cover score for each species

N = sum of all % cover scores for each site

Evenness at each site was calculated using Pielou's Index of Evenness where:

$$J = (H'/\ln S)$$

H' = Shannon-Weiner Diversity Index for that site

S = the number of species present at that site.

Finally Simpson's Dominance Index was calculated using the equation

$$SI = \Sigma(n_i(n_i - 1)/(N(N - 1))$$

n_i = % cover score for each species

N = the number of species present at that site.

The PRIMER statistical software.was used to perform multivariate analyses of the community data (Clarke and Warwick, 1994). A cluster analysis using the Bray-Curtis similarity index was performed on 4th root transformed data and dendrograms formed using the group-average clustering method. To establish which species contributed most to either the similarity or dissimilarity between groupings of data the SIMPER programme was carried out.

2.S Development of a Geographical Information System (GIS)

Results from the original survey and video analysis were displayed within a Geographical Information System (GIS) using the software Maplnfo Professional (version 4.5). A supervised and rectified Landsat 4 TM image classified by Klaus (1995), was translated from the original raster image into a vector file by R. Klaus using the longitude/latitude-WGS 84 projection to produce the base map. The original 28 classifications were combined to produce 17 classifications (Figure 4). The positions of the 34 survey sites, acquired using a GPS were added straight to the base map and a grid of longitude and latitude created using the MapBasic function gridmakr.mbx.

The biological, physical and bleaching data were displayed within a thematic overlay as pie• charts. The "Queryc-Select" function on the main tool bar, which highlights sites, which meet certain pre-determined criteria, was used to identify geographical patterns in the degree of bleaching and the general health of the coral reefs around the coast of Mauritius. This was achieved by determining criteria for the percentage cover of particular key biological attributes or species diversity and richness. The "Querye-Select" function was then used to highlight those sites with a higher or lower percentage cover, species diversity or species richness than specified in the query.

A series of 35mm slides showing a representative image of particular sites, bleaching and impacts to the reef were digitally captured in 36-bit colour at 150 dpi using a Nikon 35mm film scanner (model LS-1000) within Adobe PhotoShop (version 5.0). Final images were converted to 8-bit colour. The image files were then linked to the relevant survey site using the MapBasic tool pixshow.mbx.

2.4 Analysis of Meteorological Data

Meteorological data for the period January 1997 to April 1999 were provided by the Mauritius Meteorological Office. Sea surface temperature and mean significant wave height data were obtained from a Waverider Buoy, located off Blue Bay. Other data were obtained from various sites around the island. The data were analysed in Minitab (version 12.1) in order to investigate whether climatic conditions during the period of sea warming were unusual.

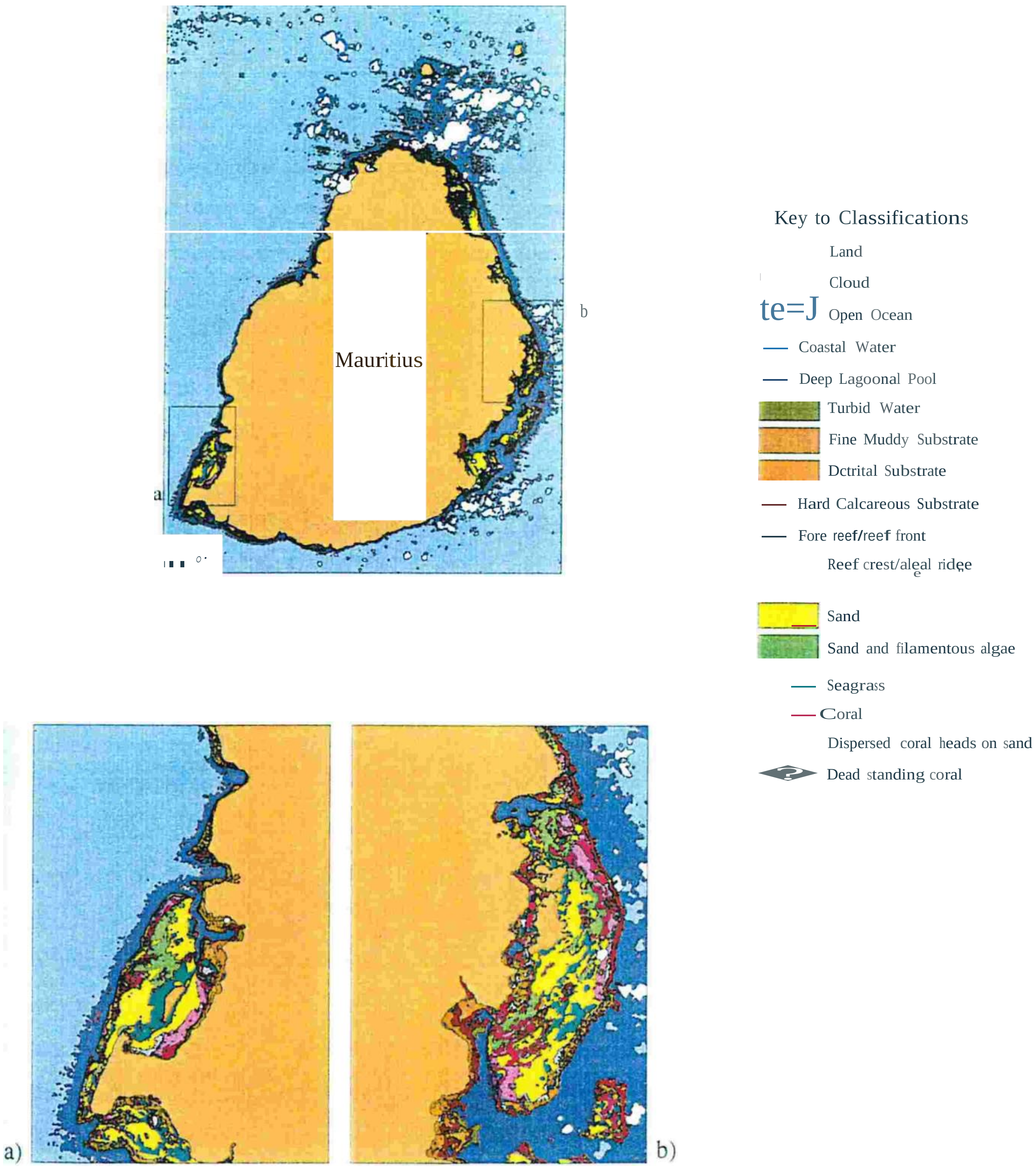


Figure 4. Biotope classification of the coastal zone of Mauritius developed from a supervised and rectified Landsat 4 TM image by R. Klaus. illustrating detail of a) Le Morne lagoon and b) Trou d'Eau Douce lagoon.

3.0 Results

3.1 Reef Composition

The coral reefs surveyed in Mauritius were in general healthy, however, all sites showed some sign of degradation. Fifty four species of hard coral were observed during the surveys (including *Millepora sp.* and *Heliopora sp.)*. Hard coral cover was >50% at 16 of the sites studied and >75% at 4 of the sites. Soft coral cover was <10% at 31 sites. Dead coral cover was <10% at 16 sites but was >30% at 6 sites and was >50% at the Barrier Reef 29 (south-east). Macroalgal cover was <10% at 25 sites, although turf algal cover was <10% at only 12 sites it was >50% at Calodyne Reef 10 (north) and Ile d'Ambre 16 (north-east). Rubble was <10% at 23 sites and 0 at Trou aux Biches 14 (north-west) and Grand Baie 25 (north). It was >30% at only two sites: Flat Island 12 (north) and Blue Bay 27 (south-east) (Figures 5 and 6).

ASEAN-Australia Living Coastal Resources uses a classification system where reefs with coral cover >75% are considered 'Excellent' and reefs with coral cover 74-50% are considered 'Good' (Chou, 1998). Unspoilt coral reefs in Southeast Asia are generally more diverse than those in Mauritius, however if we apply these criteria to Mauritius it can be seen that 12% of the reefs surveyed can be classified as 'Excellent' and 27% as 'Good'. It does not follow, however, that reefs with low hard coral cover are in poor condition or degraded as some reefs have a naturally low coral cover due to environmental conditions. The composition of reefs in Mauritius will, therefore, be described, depending on the zoomorphological zone of the reef being studied.

Within the lagoons, sites with >50% hard coral cover were found at Le Marne 1 and 2 (south-west), Balaclava 24 and 33 (north-west), Flat Island 11 (north), Ile d'Ambre 15, 18 and 19 (north-east), Trou d'Eau Douce 21 and 23 (south-east), Blue Bay 26 and 27 (south-east) and Ile aux Aigrettes 28 (south-east) (Figures 7 and 8). Le Morne 2 (south-west) also had <10% dead coral cover, <10% turf algal cover and <10% macro-algal cover. Ile d'Ambre 15 (north-east) and Blue Bay 26 (south-east) had hard coral cover >75% and <10% dead coral cover, <10% turf algal cover and <10% macro-algal cover, indicating healthy sites with little degradation. Lagoonal patch reefs with <50% coral cover were found at Trou aux Biches 6, 7 and 8 (north-west), Flat Island 13 (north), Trou d'Eau Douce 20 and 22 (south-east), Flic en Flac 30, 31 and 32 (south-west) and Perybere 34 (north) (Figure 7). Flic en Flac 30 (south-west) and Trou d'Eau Douce 22 (south-east) show some signs of degradation as site 30 had al cover <30%, dead coral and macro-algae >30% and site 22 had coral cover <30%, dead al cover>30% and turf algae >30%.

Of the reef crest sites Flat Island 12 (north), Ile d'Arnbre 16 and 17 (north-east) had a coral cover of <50% (Figure 9). These sites are exposed to wave action and coral growth is limited by exposure to air. These sites therefore have a naturally low cover of hard coral colonies. Flat Island 12 (north) had a low percentage cover of dead coral (11-30%), turf algae and macro-algae (1-10%). Ile d'Arnbre 16 and 17 (north-east) also had a low percentage cover of dead coral (1-10%) and macro-algae (<31 %), however, site 17 had >30% turf algal cover and site 16 had >50% turf algal cover (Figure 10) The Barrier Reef site (south-west) had a coral cover >30%, but was dominated by dead coral (>50%) and turf algae (>30%), suggesting degradation on a large scale. We cannot, however, conclude that these sites are degraded by human activities as they are exposed to more extreme conditions than the patch reefs within the lagoons.

Of the fore reef sites Le Morne 3 (south-west), and Trou aux Biches 4 and 5 (north-west) had hard coral cover <50%. Trou aux Biches 14 (north-west), Grand Baie 25 (north), Perybere 9 (north) and Calodyne Reef 10 (north) had coral cover <30%. These sites are naturally composed of small massive and encrusting coral colonies, soft coral and a high percentage cover of hard substrate (>50% in all cases, except Trou aux Biches 14 (north-west), where hard substrate >30%) (Figure 11). Le Morne 3 (south-west), Trou aux Biches 4 and 5 (north-west) and Grand Baie 25 (north) had 1-10% dead coral, turf algae and macro-algae cover. Perybere 9 (north), Calodyne Reef 10 (north) and Trou aux Biches 14 (north-west) had >30% turf algae cover. Soft coral cover was 11-30% at Perybere 9 (north), Calodyne Reef 10 (north) and Grand Baie 25 (north) (Figure 12).

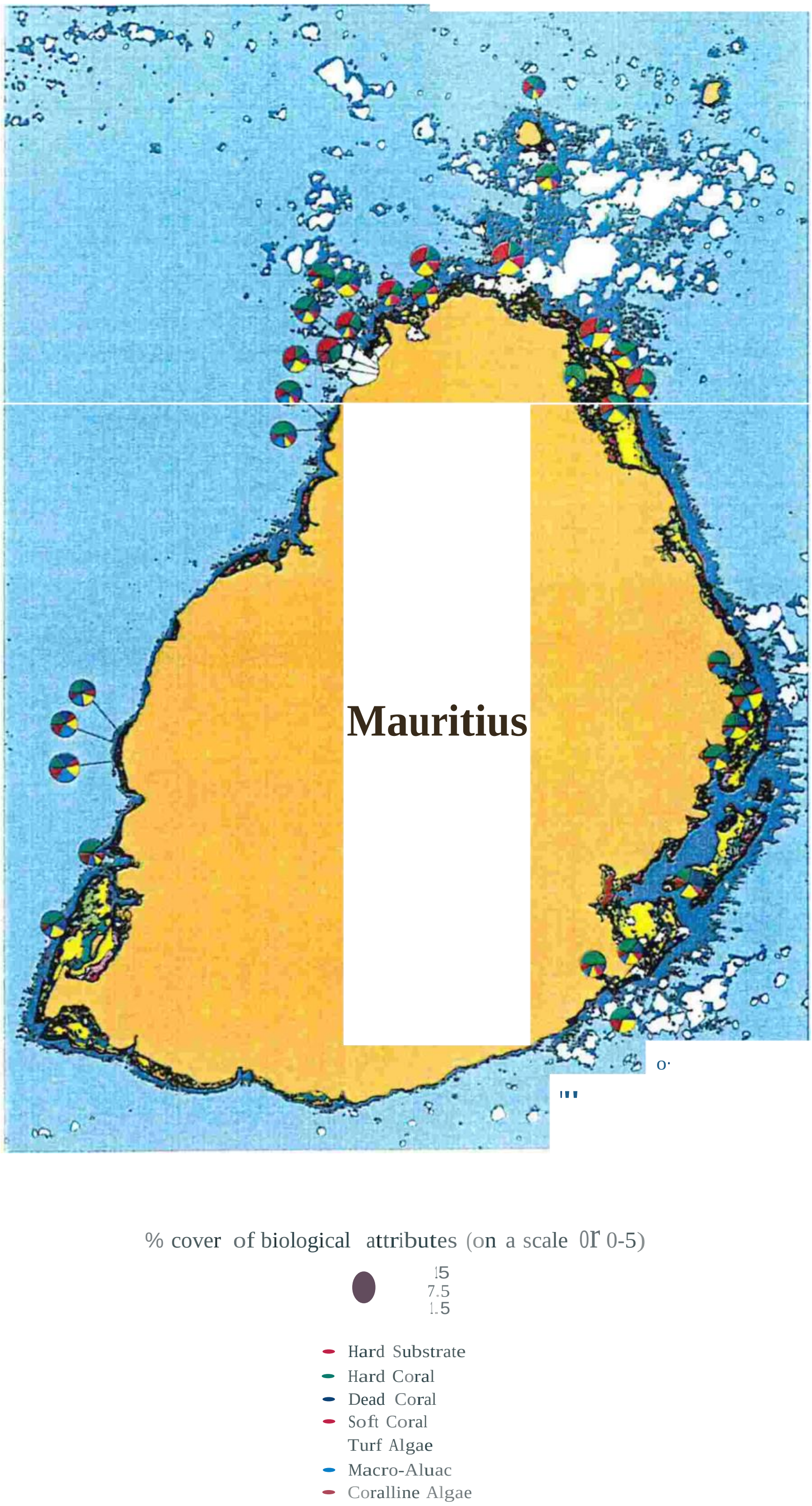


Figure 5. Pie charts of the % cover of biological attributes of each site surveyed, based on a scale of 0-5, where 0 = 0%, 1 = 1-10%, 2 = 11-30%, 3 = 31-50%, 4 = 51-75% and 5 = 76-100%. The larger the pie chart, the greater the total % cover.

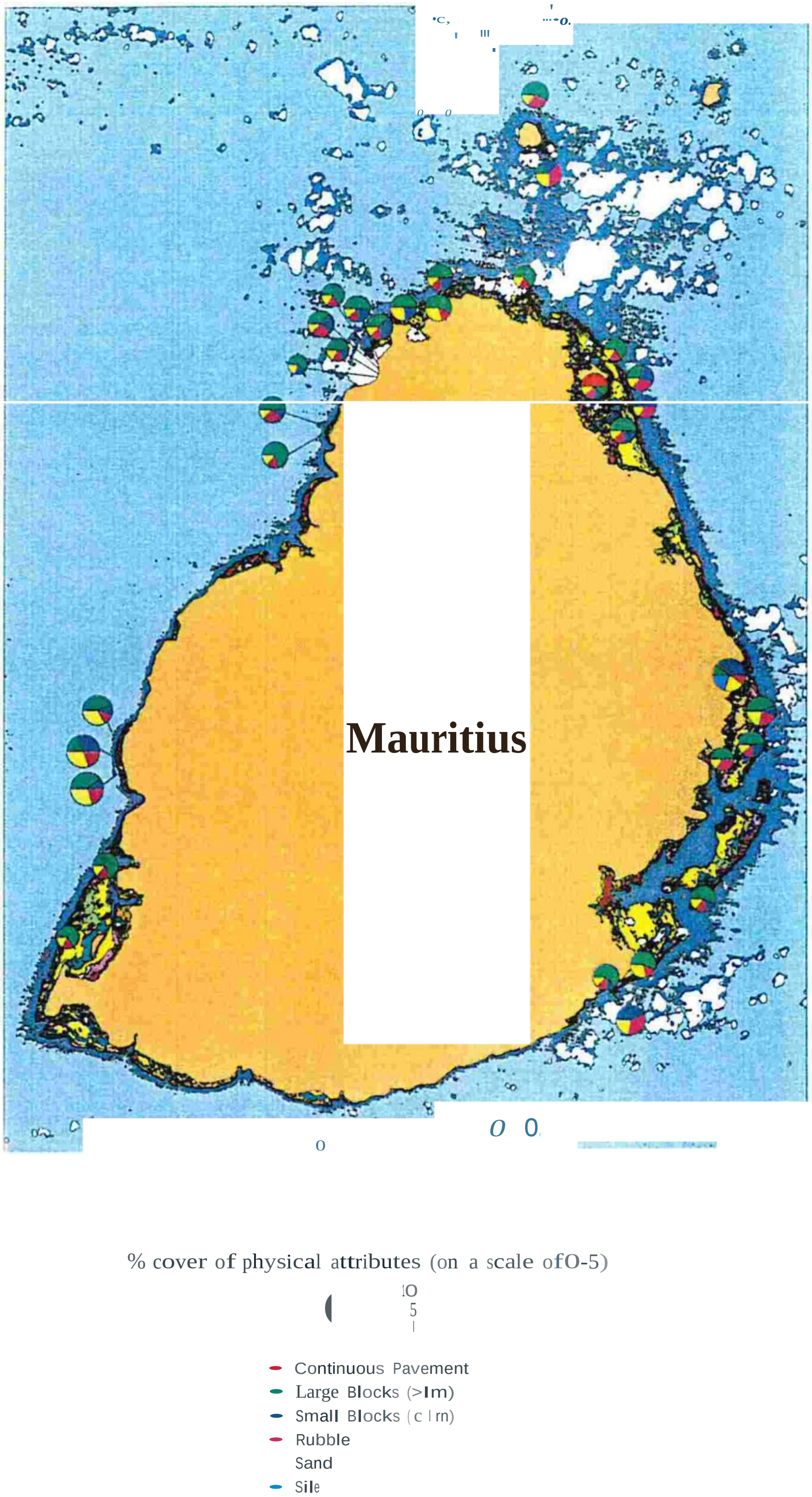
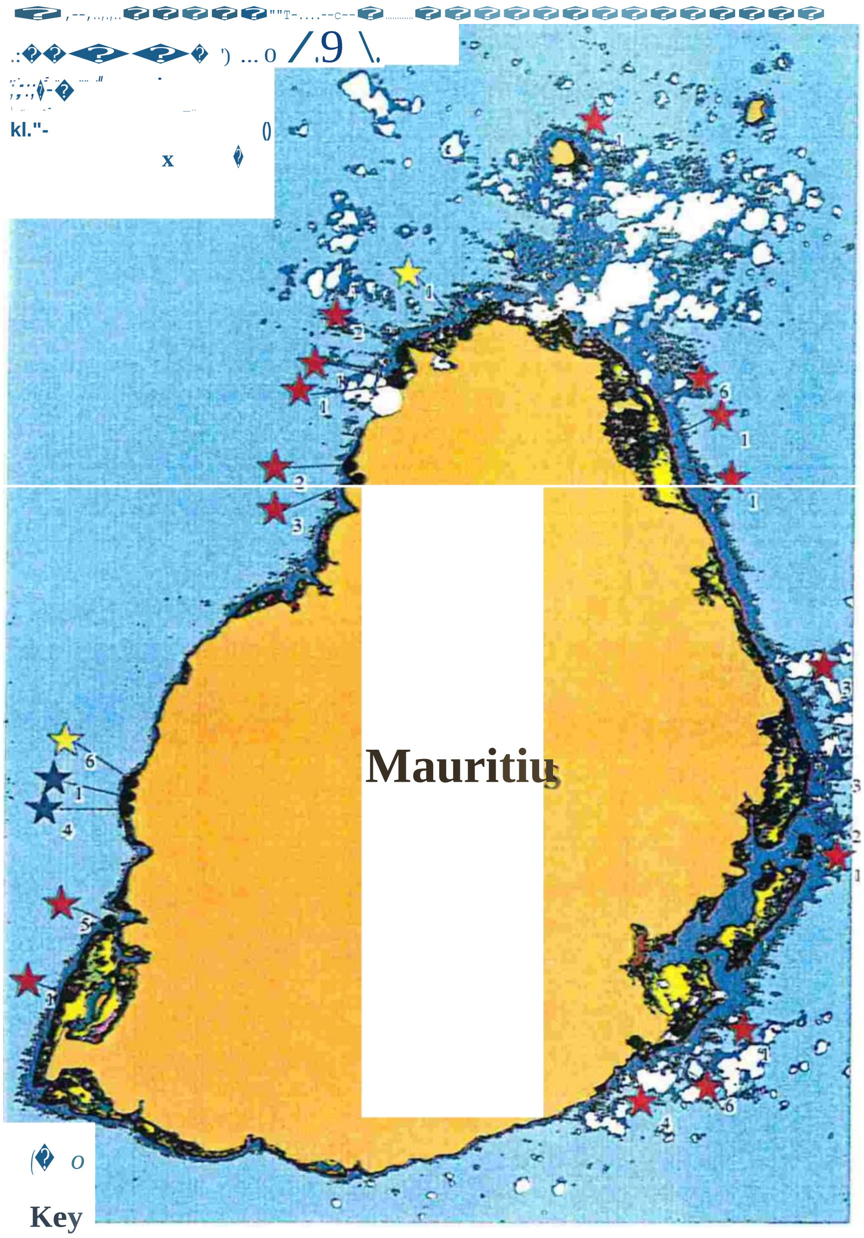


Figure 6. Pie charts of the % cover of physical attributes of each site surveyed, based on a scale of 0-5, where 0 = 0%, 1 = 1-10%, 2 = 11-30%, 3 = 31-50%, 4 = 51-75% and - = 76-100%. The larger the pie chart, the greater the total % cover.



Key

High coral cover

* 1 HC>3. MA<2
* 2 HC>3. T..\>2
* 3 HC>?. OC<l. TA<2
* 4 HC>3, DC<2, TA<2
* 5 HC>3. 0C<2. \L\<2. T.-\<2
* 6 HC>-4. OC<l. \I.\<2. T:\<2

Intermediate coral cover

- 1 HC>2
- 2 HC>_. DC<2

Low coral cover/high dead coral cover

* 1 HC<3. MA>2
* 2 OC>2, TA>–
* 3 HC<3. OC>2, TA>2
* 4 HC<3. 0C>2. MA>–

Figure 7. Biological anributes or the lagoon- al h reefs. HC = Hard Cora. DC= Dead Coral. TA= Turf Algae. ;\,!A= Macro-Algae Cb over is ased on a scale or 0- - . where 0 = 0%, l = l–1 OC10. 2 = 1 1–30S:. 3 = 3 l - -oq.. -l- = - l–, - q. and 5 = 76-1 00?.

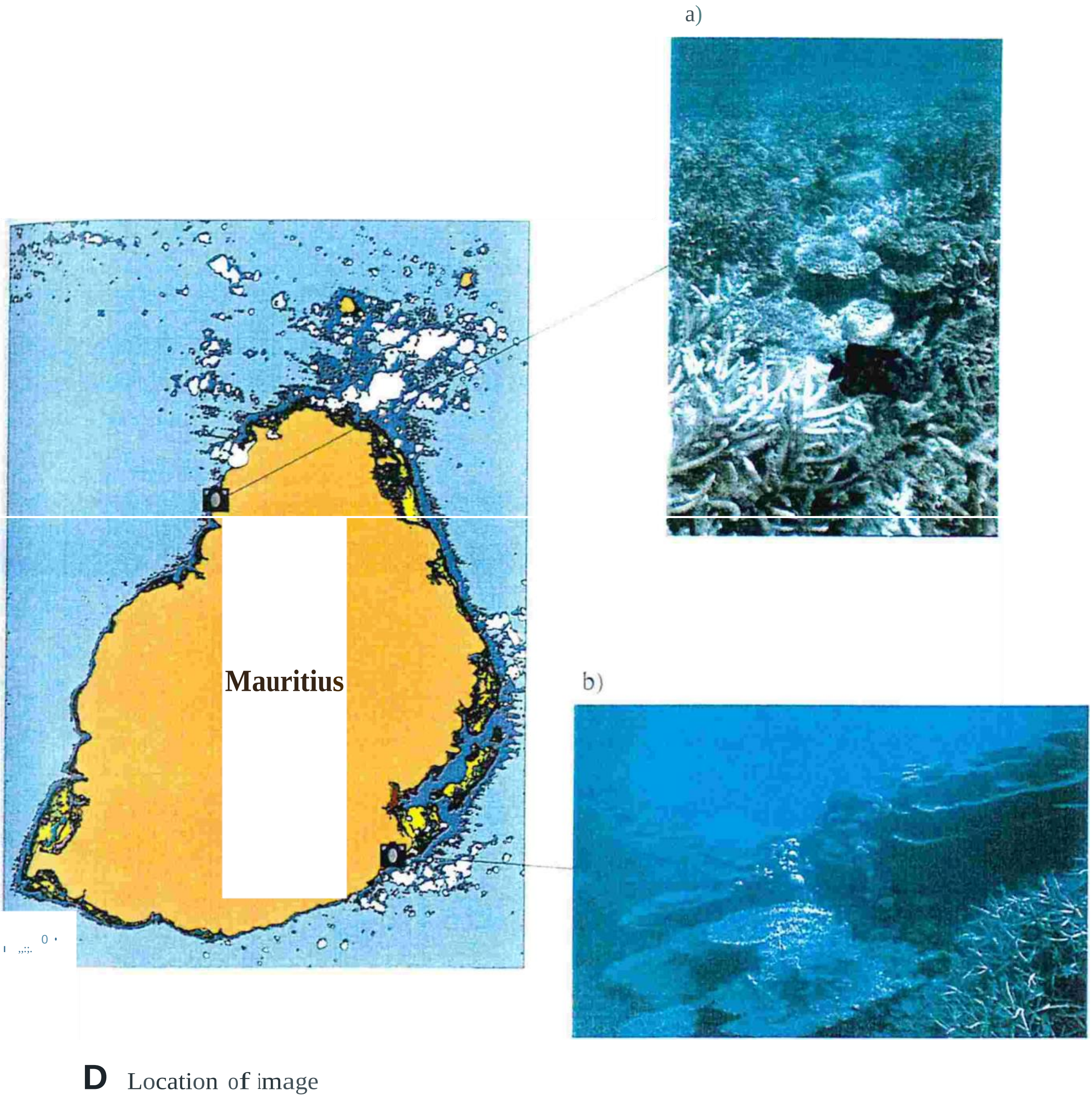
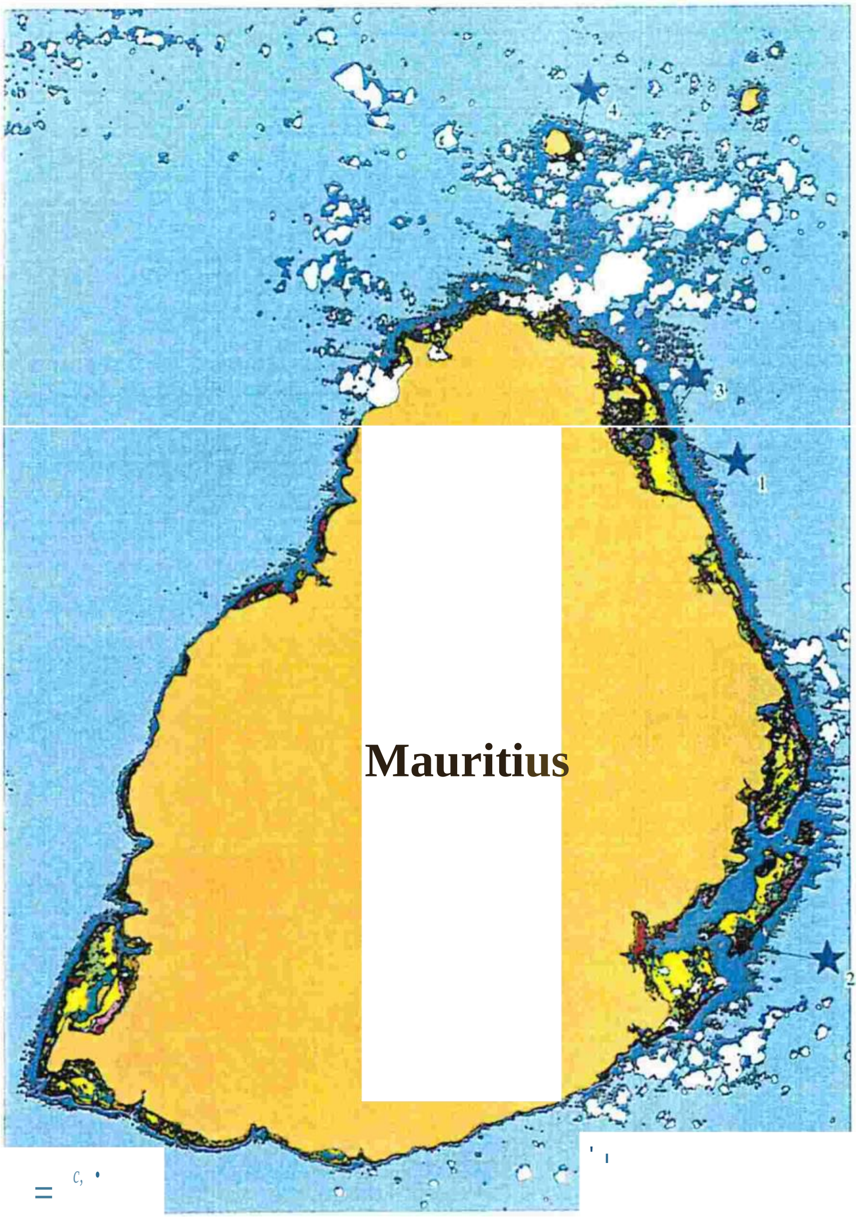


Figure 8. Two examples of lago nal parch reefs. a) Balaclava 2-J.. b) Blue Bay 26. Both sites have a high diver .ity of hard coral species and are characterised principally by large colonies of branching and tabular Acropora ill·



Key

*1 HC>2. TA>2
*2 HC>2. DC>1
*3 HC<1. TA>2
*4 HC<1. RB>2

Figure 9. Biological and physical attributes of the reef crest sites and Barrier Reef 29. HC = Hard Coral. DC= Dead Coral. TA= Turf Algae. RB= Rubble. % cover is based on a scale of 0-5. where 0 = 0%. 1 = 1-10%. 2 = 11-30%. 3 = 31-50%. 4 = 51-75% and 5 = 76-100

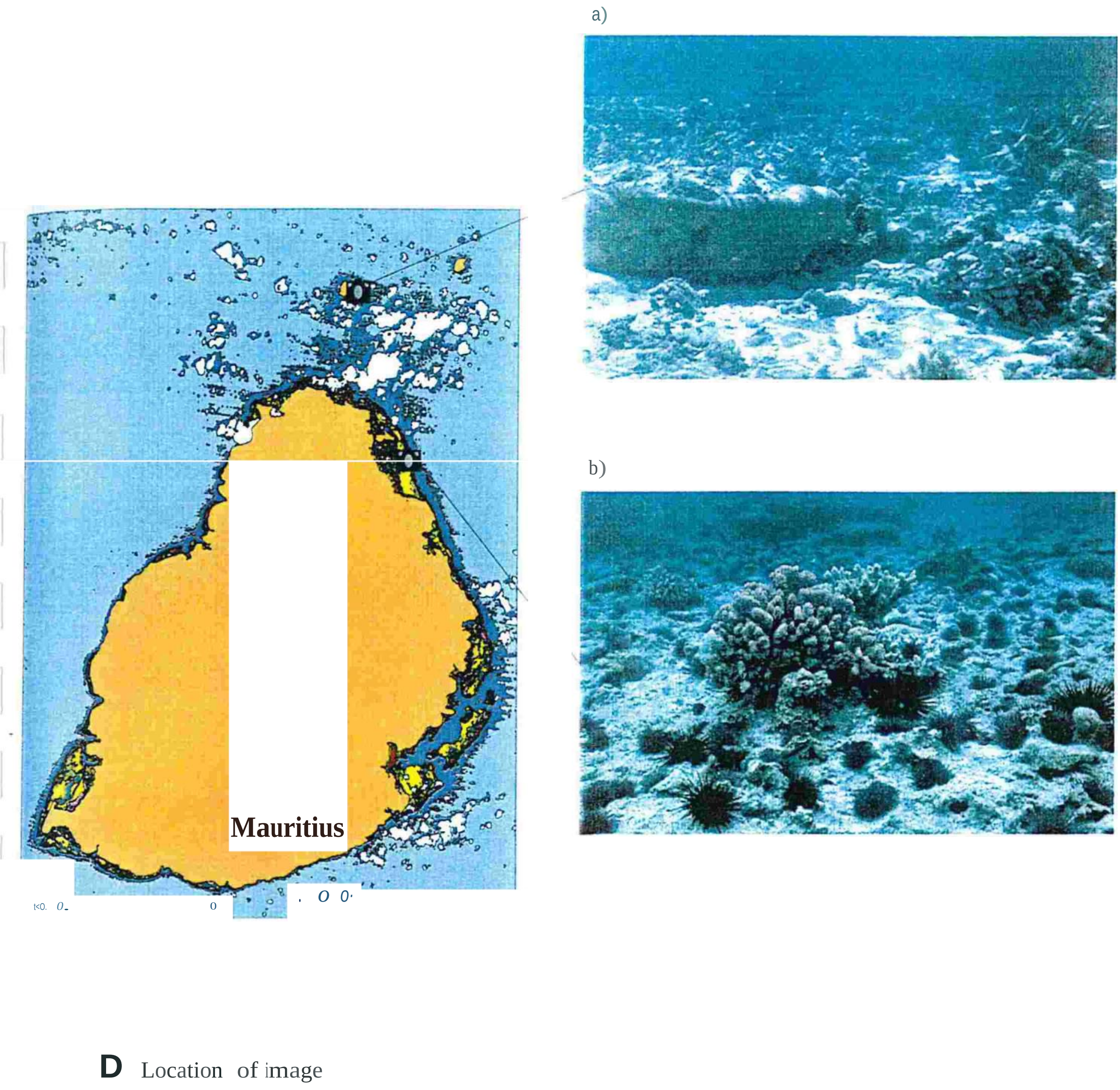
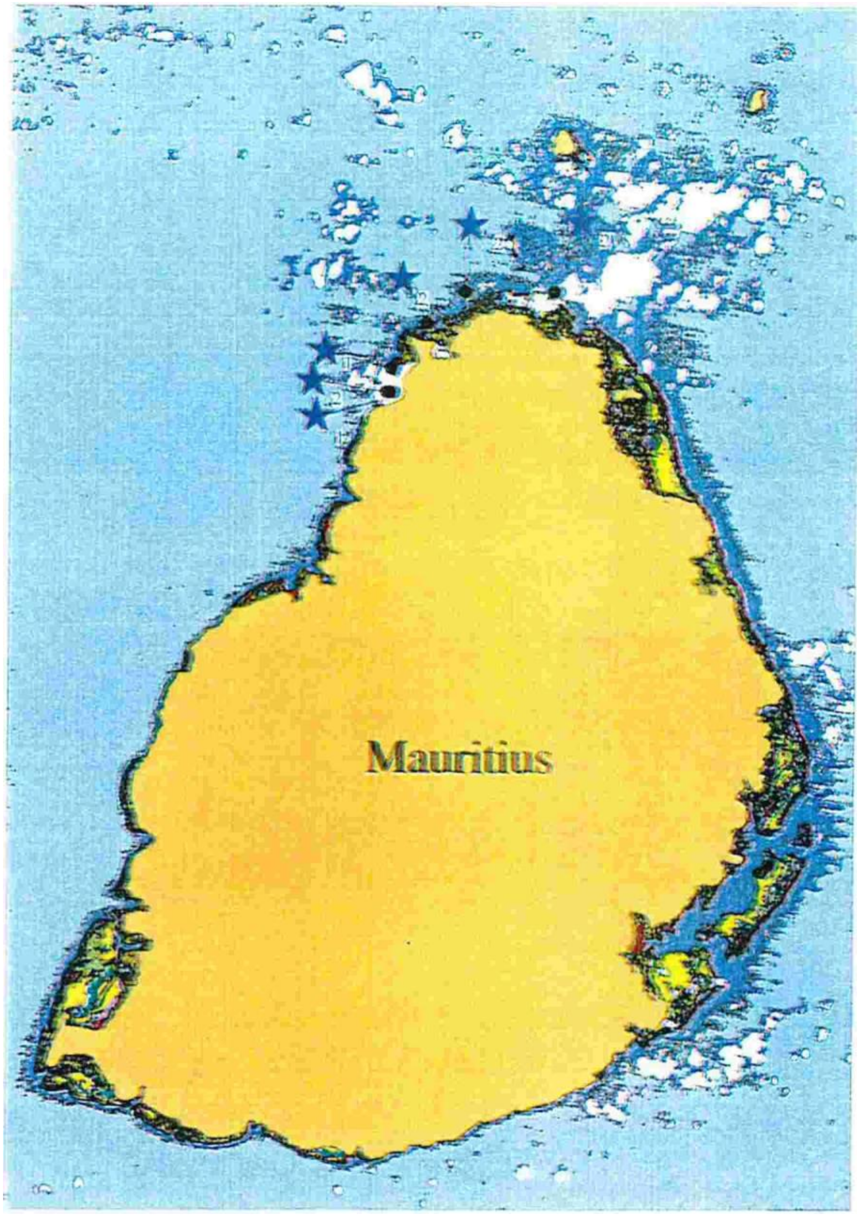
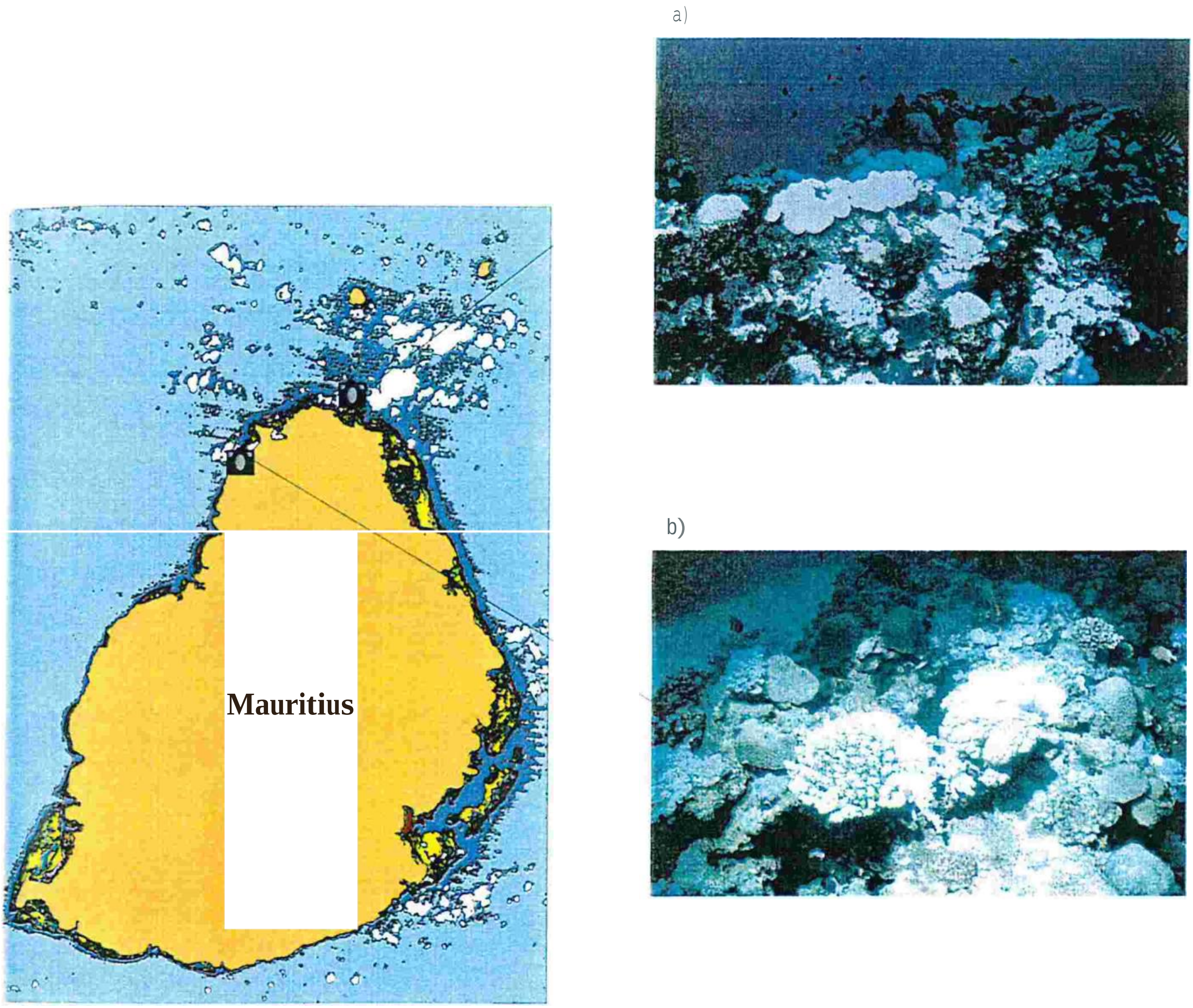


Figure 10. Two examples of reef crest sites. a) Flat f.land 12. characterised by small colonies of Acropora sp, Millepora �- and small massive species b). Ile d'Arnbre 16, characterised by small colonies of Pocillopora �-· Montipora �- and small massive species



★ HC<3. DC<2. TA<2. MA<

igure 11. Biological attributes of the fore reef sites. HC = Hard Coral. D = Dead Coral. TA = Turf Algae. MA = Macro-Algae.



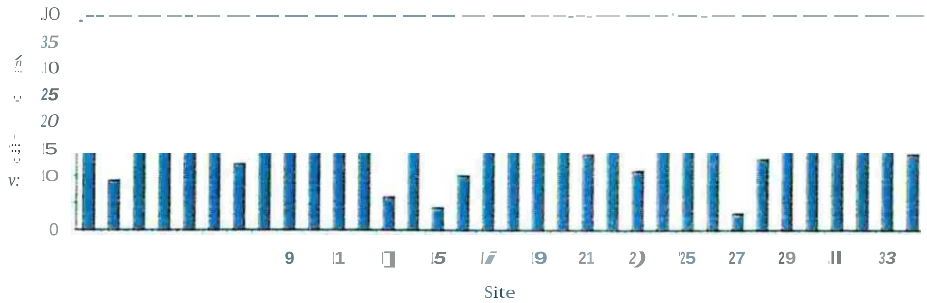
D Location of image

Figure 12. Two examples of fore reef sites. a) Calodyne Reef 10. b) Trou aux Biches 14. Both sites are characterised by small massive and encrusting hard coral species (for example [illegible] Lobophyllia sp. and Goniastrea sp.) and soft coral species.

Species richness was generally high but ranged from 3 species at Blue Bay 27 (south-east) to b species at Trou aux Biches 14 (north-west). Species richness was >20 at 14 of the sites studied. Species diversity also tended to be high and ranged from H' = 1.1 at Ile d'Ambre 15 (north-east) to H' = 3.5 at Trou aux Biches 14 (north-west). Species diversity had a H' value >3.0 at 12 of the sites studied. Evenness ranged from J = 0.80 at Ile d'Ambre 15 (north-east) to J = 1.1 at Trou aux Biches 5 (north-west) and dominance ranged from 0 at Ile d'Ambre 16 (north-east) and Grand Baie 25 (north) to 2.33 at Blue Bay 27 (south-east) (Figure 13).

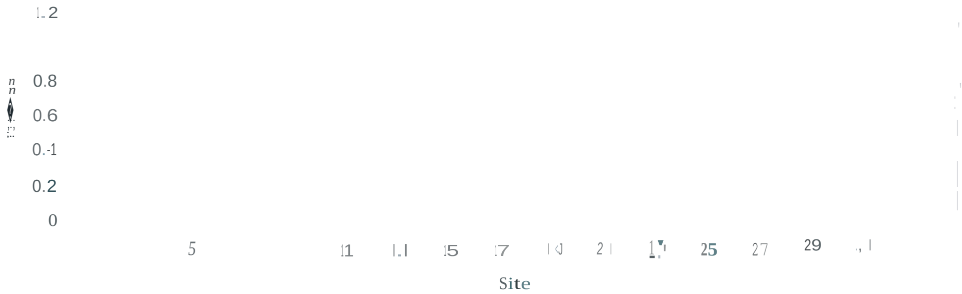
If we consider, in this case, high species richness to be >20 species, high species diversity to be H'>3.0, high evenness to be J>0.96 and low dominance to be Sl<0.05, it can be seen that within the lagoons high diversity and low dominance was found at Flat Island 11 (north), Balaclava 24 (north-west) and Blue Bay 26 (south-east). Flic en Flac 30 (south-west) had a high species richness, fairly high species diversity (2.5-3.0), high evenness and a low dominance, Balaclava 33 (north-west) had very high species richness (>25), high species diversity and evenness, but a high dominance (>0.09), suggesting a site dominated by a number of different species. Low species diversity and high dominance was found at Ile d'Ambre 15 (north-east), where species richness was <10, species diversity was <2.0, evenness was <0.91 and dominance was >0.99. Low species diversity and high dominance was also found at Le Mome 2 (south-west), Trou aux Biches 7 (north-west), Trou d'Eau Douce *13* (south-east), Blue Bay *17* (south-east) and Ile aux Aigrettes *2g* (south-east) (Figure 14).

On the reef crest all 3 sites showed high evenness (J>0.96) and low dominance (Sl<0.05). Species richness and species diversity were high at Flat Island 12 (north) (species richness>25, H'>3.0), but species richness was low at Ile d'Ambre 16 and 17 (north-east) (≤20). On the Barrier Reef 29 (south-east) species richness was high (>20), species diversity was >2.4, evenness was high (>0.96) and dominance was low (<0.05) (Figure 15). Species diversity was high and dominance low on all the fore reef sites. All sites had a H' value >3.0, J>0.96 and Sl<0.05 and all sites except Trou aux Biches 5 (north-west) had a species richness >20 (Figure 16).

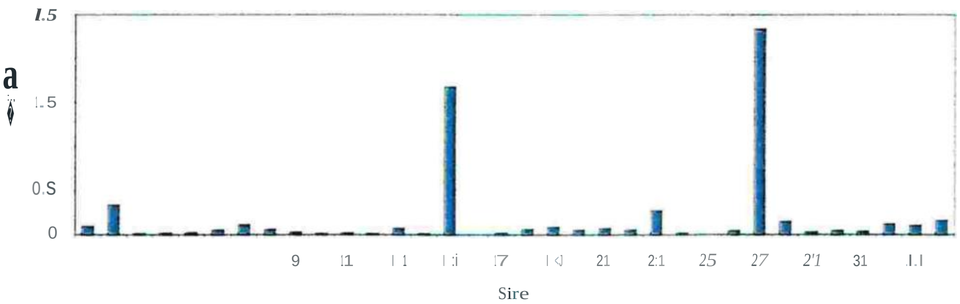


a)

b)

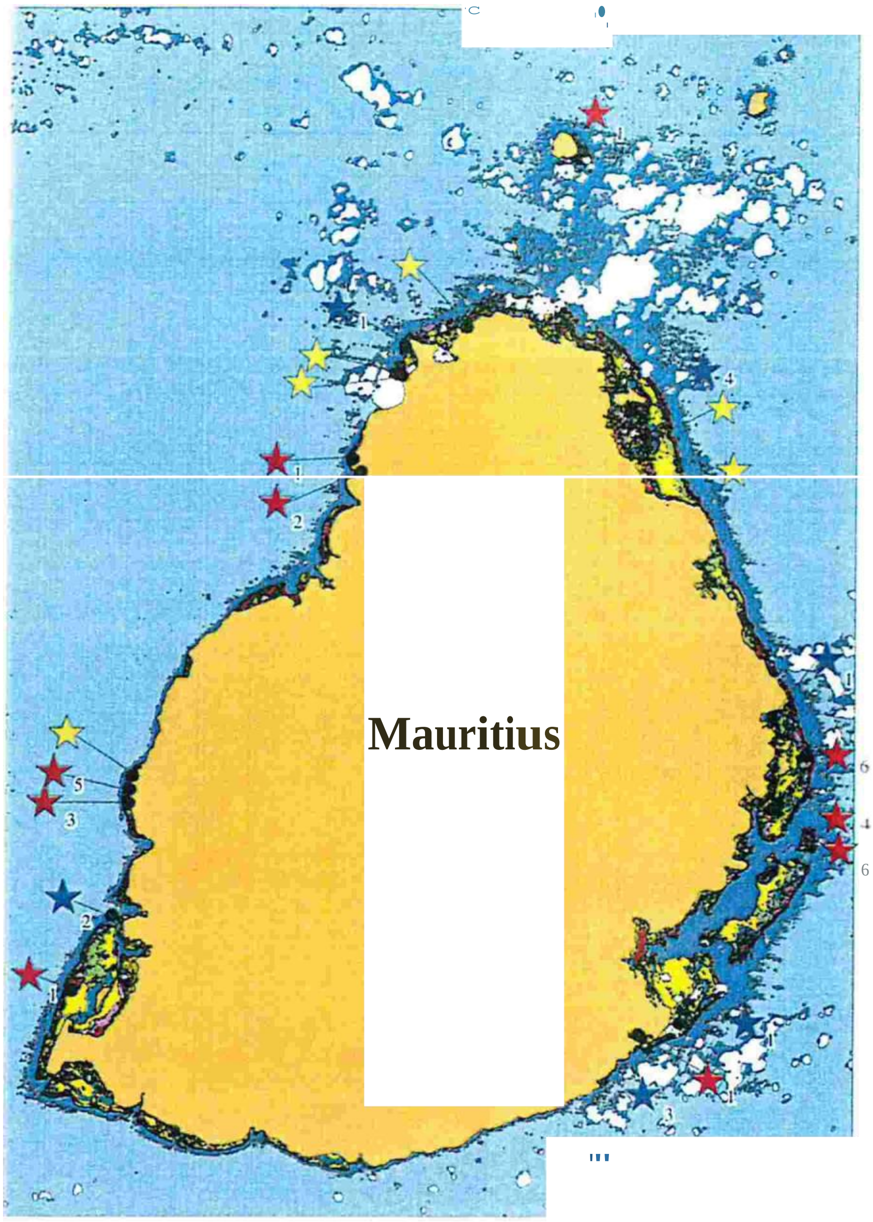


c)



d)

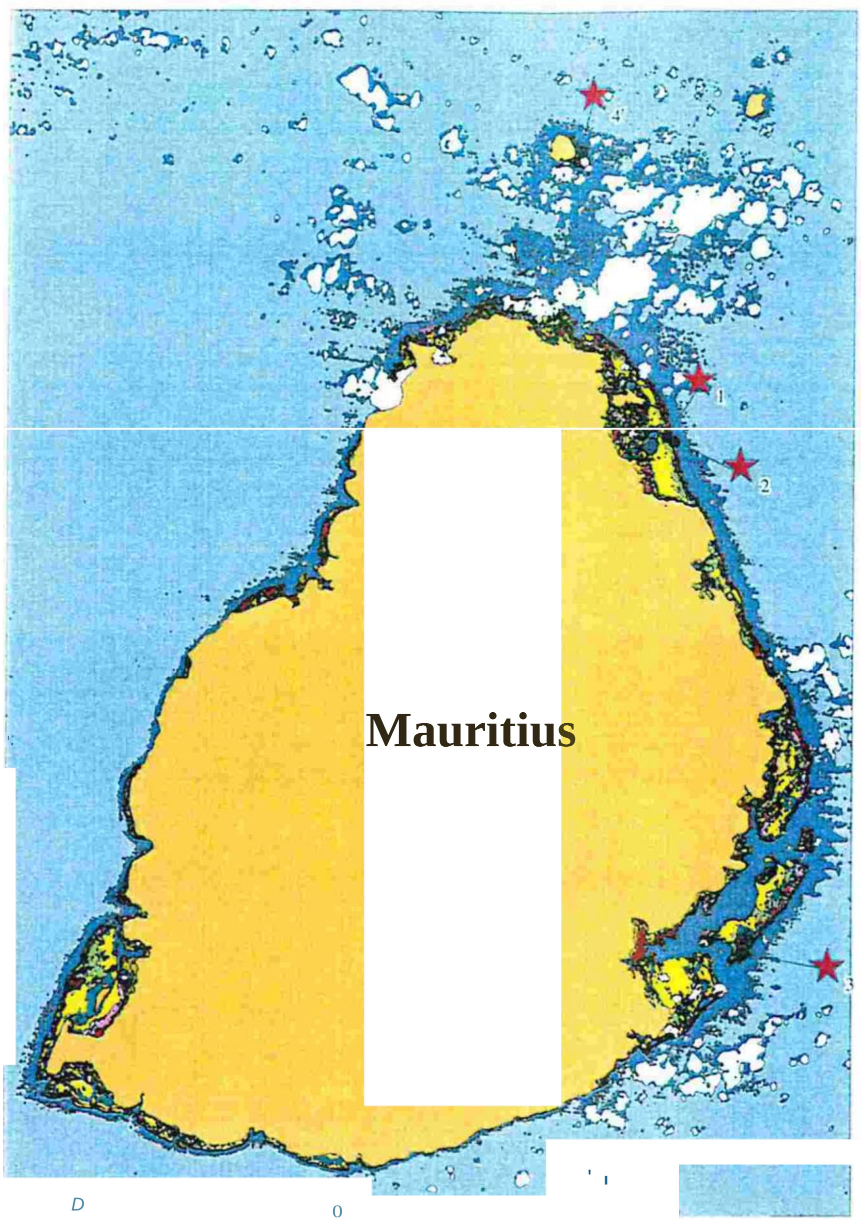
Figure 13. Ecological indices describing hard coral community composition at the 33 sites surveyed around the coast of Mauritius. a) Species richness (number of hard coral species per site). b) Species diversity, calculated using the Shannon-Weiner Diversity Index. c) Evenness, calculated using Pielou's Index of Evenness and d) Dominance, calculated using Simpson's Dominance Index.



Key

High species diversitv and/or low dominance	Intermediate	Low species diversity and hi⧫h dominance
1 5>21. H'>3. J>0.96. Sl<0.05	5<21. H'>2. 1<0.99. 51>0.05	1 S=IO-20. H'=2-2..l-9. 1<0.97. SI=0.1O-0.99
2 5>21. H'>1. J>0.96. 51=0.1O-0.99		2 S<IO. H'=2-2.49.1<0.97. Sl=0.1O-0.99
3 5>21. H'=2.5-3. 1>0.96. 51<0.05		3 S<IO. H'<2. J>0.96. Sl>0.99
4 5>21. H'=2.5-3. 1<0.96. 51=0.05-0.09		4 S<10. H'<2. 1<0.91. Sl>0.99
5 5<21. H'=2.5-3. J>0.96. 51<0.0–		
6 5<21. H'=2.5-.1. 1>0.96. l=0.05-0.09		

Figure 14. Species richness (S;. .pecies diversity (H'), evenness (J) and dominance (S [) of the lagoonal parch reefs.



Key

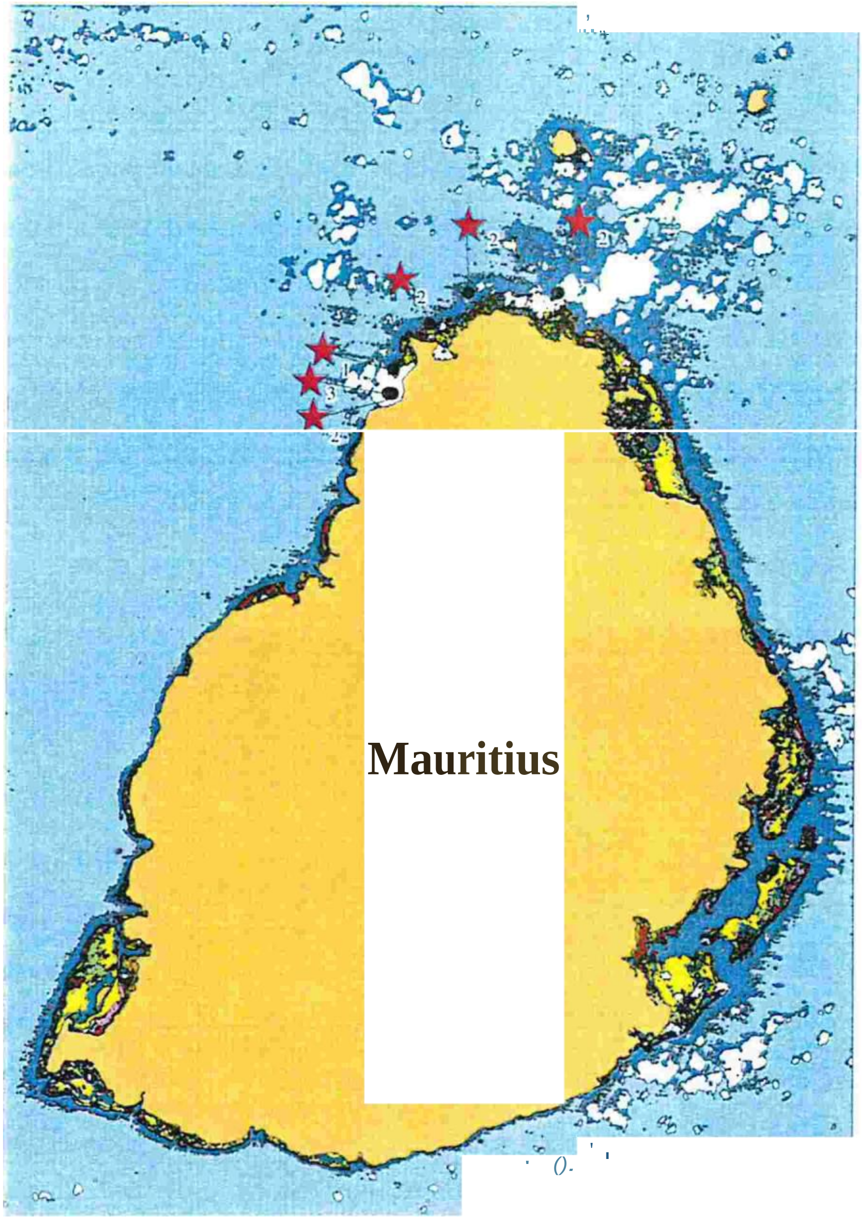
*1 S=IO-20. H'=2-2..J.9. J>0.99. Sk0.05

*2 S=IO-20. H'=2.5-3.0. J=0.97-0.99. ?1<0.05

*3 S=2 l-25. H'=2.5-3. J=0.97-0.99. Sl<0.06

*4 S>25. H'>3. J>0.99. Sk0.0:i

Figure 15. Species richness (S). species diversity (H'). evenness (J) and dominance (SI) of the reef crest sites and Barrier Reef 29.



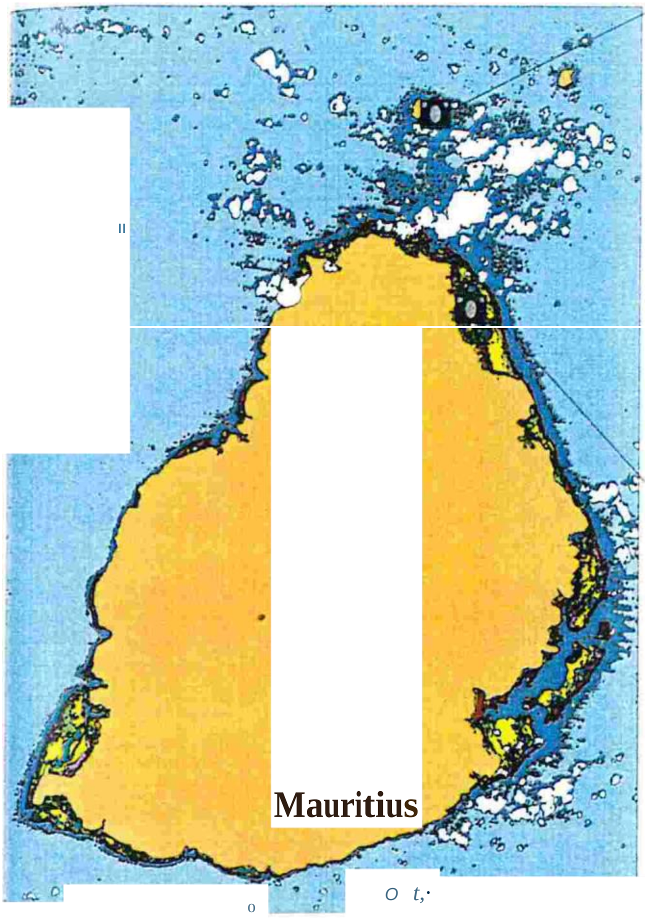
Key

*1 S=10-20, H'>3. J>0.96. Sl<0.05
*2 S=21-25. H'>3. J>0.96, Sl<0.05
* 5>26. H'>3. J>0.96. Sl<0.05

Figure 16. Species richness (S), species diversity (H'), evenness (J) and dominance (Sl) of the fore reef sites.

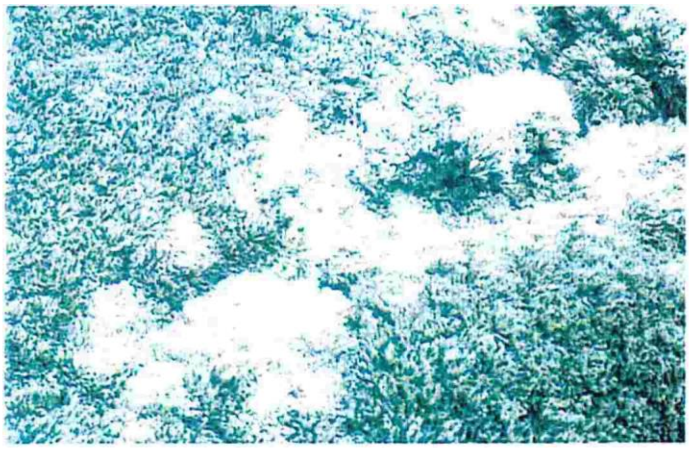
Of the sites with >50% hard coral cover only Balaclava 24 (north-west), Flat Island 11 (north) and Blue Bay 26 (south-east) showed a high species diversity and low dominance. This highlights Blue Bay 26 (south-east) as a particularly healthy site with high coral cover, low dead coral cover, macroalgal and turf algal cover and a high species diversity and low dominance. Other sites with hard coral cover >50% tended to have low species diversity (H' <2.0) and a high dominance, indicating sites dominated by large colonies of one or two species: Trou aux Biches 7 (north-west) *(Acropora cytherea);* Ile d'Ambre 15 (north-east) *(Galaxea sp,);* Trou d'Eau Douce 23 (south-east) *(Pavona cactus);* Blue Bay 27 (south-east) *(Pavona spp.)* and Ile aux Aigrettes 28 (south-east) *(Acropora formosa)* (Figure 17). In contrast, sites with low hard coral cover such as Perybere 9 (north), Calodyne Reef 10 (north), Flat Island 12 (north), Trou aux Biches 14 (north-west), Grand Baie 25 (north) and Flic en Flac 30 (south-west) tended to consist of small coral colonies and have a higher species diversity and lower dominance.

The classification analysis for species abundance at the different sites can be seen in figure 18. Balaclava 24 (north-west) and Flic en Flac 30 (south-west), Trou aux Biches [illegible] (north-west) and Ile d'Ambre 19 (north-east), Trou aux Biches 4 and 5 (north-west) and Perybere 9 (north) and Grand Baie 25 (north) show the greatest Bray-Curtis similarity (89%, 88%, 87% and 87%, respectively). Barrier Reef 29 (south-east) and Trou d'Eau Douce 20 (south-east) showed a Bray-Curtis similarity of [illegible]%. The fore-reef sites were all clustered into a distinct group at 63%. The Barrier Reef 29 (south-east) and the reef crest site, Flat Island 12 (north) were clustered with the lagoonal patch reefs of Flic en Flac 30 (south-west), Trou aux Biches 6 (north-west), Trou d'Eau Douce 20 (south-east), Blue Bay 26 (south-east), Flat Island 11 (north) and Balaclava 24 and 33 (north-west) at 62%. At 50% Blue Bay 27 (south-east), Ile d'Ambre 15 and 16 (north-east), Trou d'Eau Douce 21 and 23 (south-east), Flat Island 13 (north), Le Mome 2 (south-west); Flic en Flac 32 (south-west) and Perybere 34 (north) were distinctly different from any of the other clusters.



a)

b)



D Location of image

Figure 17. Two examples of sites with low species diversity (H'<2.0) and low species richness (<I 0). a) Flat Island 11. an example of a site dorninat J by Acropora formosa (for example sire 28). b) Ile d'Arnbre 15. dominated by Galaxea iR· (astreata'').

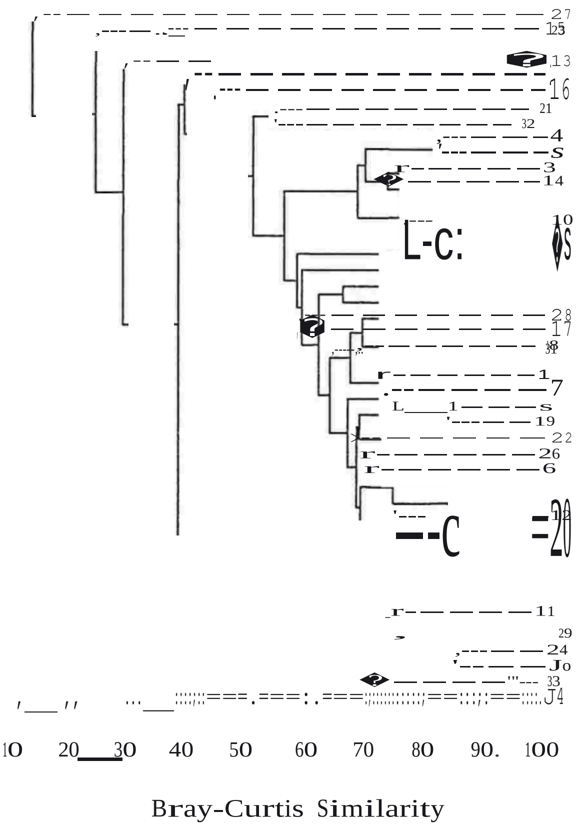


Figure 18. Dendrogram for the group-average clustering of Bray-Curtis similarities between the 34 sites around the coast of Mauritius (√√-transformed).

The lagoonal patch reefs showed an average similarity of 46.14%. *Acropora formosa, Acropora cytherea, Pocillopora damicornis, Montipora sp.* (foliose) and *Pavona cactus* corunouieu muse lO me s1m11ar1ut?s wurun me group anu li. *jormosa* ana IL *cytnerea* were identified as indicator species for the lagoonal patch reefs (Table 4). On the fore reef sites, which showed a similarity of 70.24%, important species in terms of abundance included *Porites sp., Pavona clavus, Platygyra sp., Favia sp.* and *Goniastrea sp.*. These species were all identified as indicator species for the fore-reef sites. The reef crest sites showed a similarity of 46.31 %. The most important species in terms of abundance were *Porites sp., Lobophyllia sp., Platygyra sp., P. damicomis* and *Favites sp.*. These species were also identified as indicator species.

Table 4. Average abundance (based on a scale of 0-5) and percentage contribution of the five species that account for the greatest similarity in the different geomorphological zones of the reef identified by SIMPER analysis. * indicates an indicator species of this zone, determined as a species with a ratio >1.5.

Reef Type	Species	Average Abundance	Ratio	Cumulative %
Lagoonal patch reef	*Acropora formosa**	2.39	1.52	11.05
	*Acropora cytherea**	1.87	1.54	21.05
	Pocillopora damicomis	1.09	1.37	29.01
	Montipora sp. (foliose)	1.39	1.19	36.28
	Pavona cactus	1.09	0.97	42.97
Fore reef	*Porites sp.**	2.00	7.46	6.19
	*Pavona clavus**	1.43	7.05	12.02
	*Platygyra sp.**	1.29	9.28	17,73
	*Favia st).**	1 14.	R QR	?11Q
	*Goniastrea sp.**	1.00	8.98	29.05
Reef crest	*Porites sp.**	1.00	4.14	12.13
	*Lobophyllia sp.**	1.00	4.14	24.26
	*Platvovra sp.**	L00	4.14	36.38
	*Pocillopora damicomis**	1.00	4.14	48.51
	*Favites sp.**	1.00	4.14	60.64

A. formosa and *P. clavus* contributed most to the dissimilarities between the lagoonal patch reefs and the fore reefs (Table 5). *A. formosa* was in greater abundance on the lagoonal patch reefs, whilst *P. clavus* was in greater abundance on the fore reefs. Other important species in terms of dissimilarity were *Acropora robusta* and *Acropora valida,* which were more abundant on the fore reefs and *Pavona cactus,* which was more abundant on the lagoonal patch reefs. *A. cytherea* and *Favites sp.* contributed most to the dissimilarities between the lagoonal patch reefs and the reef crest sites. *A. cytherea* was more abundant on the lagoonal patch reefs, whilst *Favites sp.* was more abundant on the reef crests. Other important species were *A. formosa* and *Acropora humilis,* which were more abundant on the lagoonal patch reefs and *Lobophyllia sp.,* which was more abundant on the reef crest. *P. clavus* and *Acropora robusta,* contributed most to the dissimilarities between the fore reefs and the reef crest sites. *P. clavus* and *A. robusta* were in high abundance on the fore reefs, but were not present on the reef crest. *A. humilis* and *A. cytherea* were also more abundant on the fore reefs, whilst *A. formosa* was abundant on the reef crests, but not present on the fore reefs.

Table 5. Average abundance (based on a scale of 0-5) and percentage contribution of the five species that most discriminate between reef type dissimilarity identified by SIMPER analysis.

Species	Average Abundance		Cumulative %
	Fore reef	Lagoonal patch reef	
Acropora formosa	0.00	2.39	4.73
Pavona clavus	1.43	0.26	8.95
Acropora robusta	1.14	0.17	12.80
Pavona cactus	0.00	1.09	16.23
Acropora valida	1.00	0.30	19.48
	Reef crest	Lagoonal patch reef	
Acropora cytherea	0.33	1.81	4.46
Favites sp.	1.00	0.39	8.22
Acropora formosa	1.33	2.39	11.81
Lobophyllia sp.	1.00	0.43	15.15
Acropora humilis	0.33	0.87	18.48
	Reef crest	Fore reef	
Pavona clavus	0.00	1.43	5.37
Acropora robusta	0.00	1.14	10.04
Acropora humilis	0.33	1.14	13.79
Acropora formosa	1.33	0.00	17.16
Acropora cytherea	0.33	0.86	20.44

3.2 Coral Bleaching

The coral reefs surveyed in Mauritius appear to have escaped the mass bleaching event of 1998. There were no large areas of dead standing coral that could be attributed to the bleaching event other than at the Barrier Reef 29 (south-east). This site was dominated by dead coral (>50%) covered in turf algae and consisted of small colonies of regenerating corals with healthy tips. Damage of this scale is unlikely to be caused by the Crown-of-thorns Starfish *(Acanthaster planci)* and thus indicates a site of possible mass bleaching.

Bleaching was observed at 29 of the sites surveyed but in all cases was only partial bleaching. Mean bleaching was <10% at all sites surveyed and was 0 at 5 sites. Le Morne 1 (south-west) showed the highest mean bleaching value (0.67), however there was no pattern in the sites bleached and no significant difference in mean bleaching value between the 34 sites studied (Kruskall-Wallis: $H = 9.00$, $df = 33$, $p>0.05$). If the sites are combined into geographical areas Grand Baie (north) shows the highest mean bleaching value (0.79) (Figure 19), however, again there is no significant difference between the areas (Kruskall-Wallis: $H = 3.05$, $df = 9$, $p>0.05$). Bleaching occurred on the lagoonal patch reefs, on the fore reefs and on the reef crest. Sites where no bleaching occurred were located in the lagoons at Le Mome 2 (south-west), Blue Bay 27 (south-east), Flat Island 13 (north) and Trou d'Eau Douce 23 (south-east) and on the reef crest at Ile d'Arnbre 16 (north-east) (Figure 20).

Nineteen species were observed to show partial bleaching. The number of species bleached at each site ranged from 6 at Le Mame I (south-west) and Calodyne Reef 10 (north) to 0 at Le Mame 2 (south-west), Flat Island 13 (north), Ile d'Arnbre 16 (north-east) and Trou d'Eau Douce 23 (south-east), Of the 19 species *Galaxea fasicularis*, *Acropora formosa* and *Platygyra sp.* were the species most observed to be partially bleached. G. *fasicularis* was bleached at 21 of the sites studied; *A. formosa* at 19 of the sites and *Platygyra sp.* at 14 of the sites. The mean bleaching value was also highest for G. *fasicularis* (1.52), *Platygyra sp.* (1.15) and *A. formosa* (0.96) (Figure 21). Bleaching in G. *fasicularis* and *Platygyra sp.* occurred mostly in shallow water (<10m deep) and ranged from a value of 1 (<10%) to 4 (51 - 75%). Bleaching of *A. formosa* ranged from a value of 1 (<10%) to 2 (11 - 30%). Partial bleaching of *A. fonnosa* occurred only on the upper surfaces of horizontal branches. G. *[asicularis* and *Platygyra sp.* showed partial bleaching on their upper surfaces only and

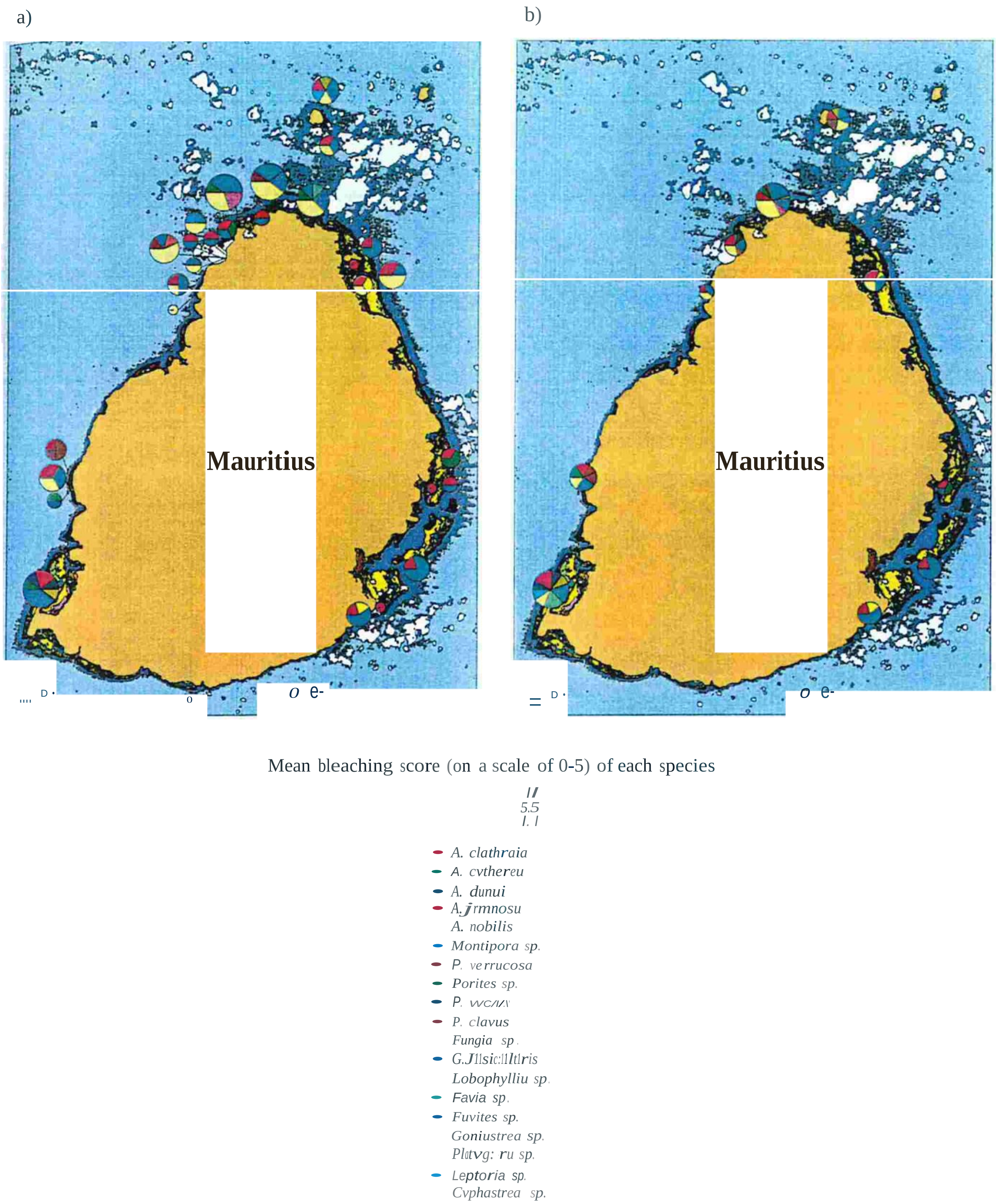
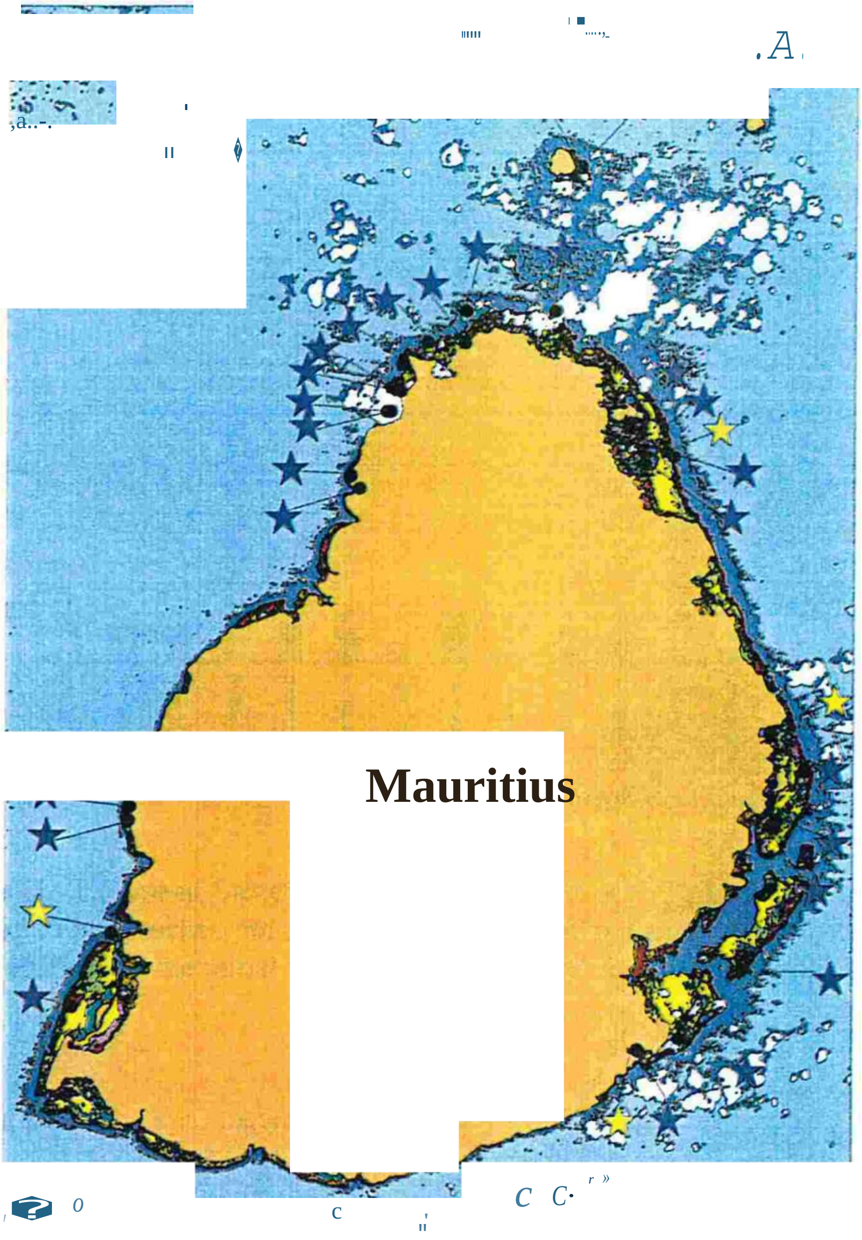


Figure 19. Mean bleaching score of the species bleached at a) each site and b) each area. Bleaching score is based on a scale of 0-5, where 0 = 0% of that species bleached, 1 = 1-10%, 2 = 11-30%. 3 = 31-50%, 4 = 51-75% and 5 = 76-100%. The larger the pie chart, the greater the total % cover.



* Bleaching = 0
* Bleaching >0

Figure 20. The presence and absence of coral bleaching at the 34 sites surveyed around the coast of Mauritiu .

appeared pale rather than fully bleached (Figure *22)*. Bleaching was patchy and bleached colonies were often observed adjacent to unbleached colonies of the same species.

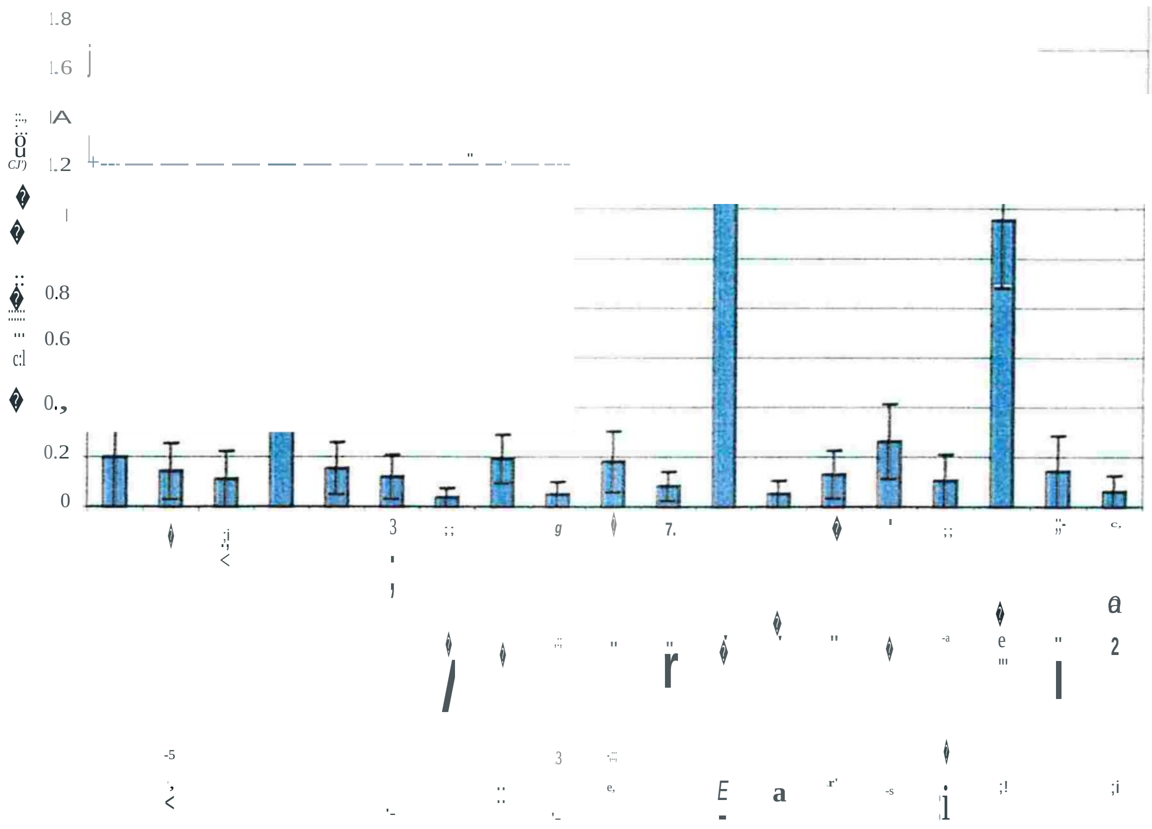


Figure 21. The mean bleaching score (on a scale of 0-5) ± SE of the 19 species of coral observed to be bleached around the coast of Mauritius (n = 365). The values are based on the results obtained in the initial surveys combined with observations from the video analysis.

There appears to be no pattern in the extent of bleaching of *A. formosa*, *Platygyra sp.* and *G. fasicularis* (Figure 23). *A. formosa* bleached in the lagoons at Le Morne (south-west), Flic en Flac (south-west), Balaclava (north-west), Trou aux Biches (north-west), Flat Island (north), Ile d' Ambre (north-east), Trou d'Eau Douce (south-east) and Blue Bay (south-east) and on the Barrier Reef (south-east). *G. fasicularis* bleached with *A. formosa* in all the above areas as well as on the fore reef at Grand Baie (north), Perybere (north) and Calodyne Reef (north). *Platygyra sp.* bleached with *A. formosa* and G. *fasicularis* in the lagoons at Flic en Flac (south-west), Balaclava (north-west), Flat Island (north) and Ile d' Ambre (north-east) and with G. *jasicularis* in the lagoon at Trou aux Biches (north-west) and on the fore reef at Grand Baie (north), Perybere (north) and Calodyne Reef (north).

J

J

J

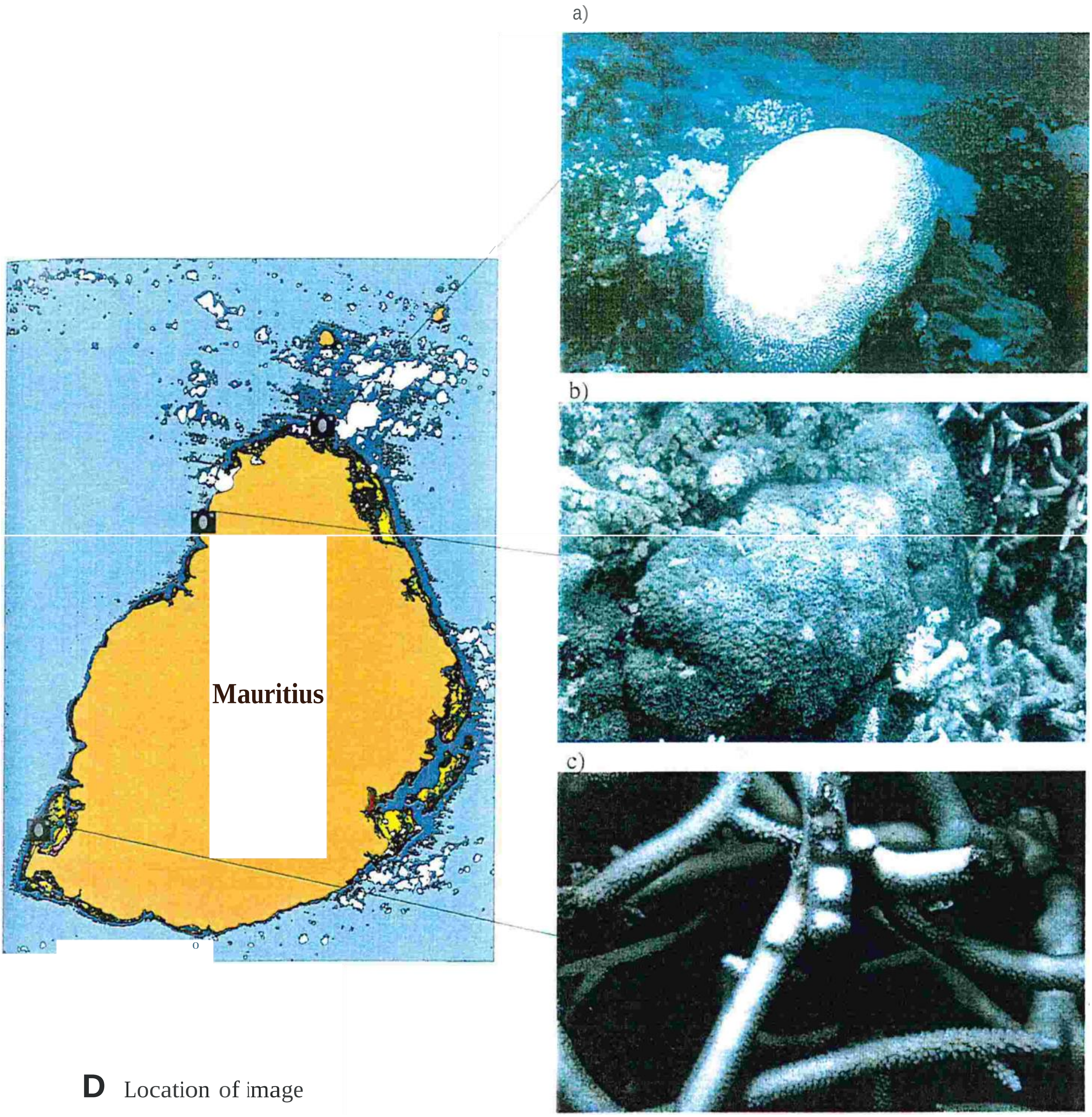
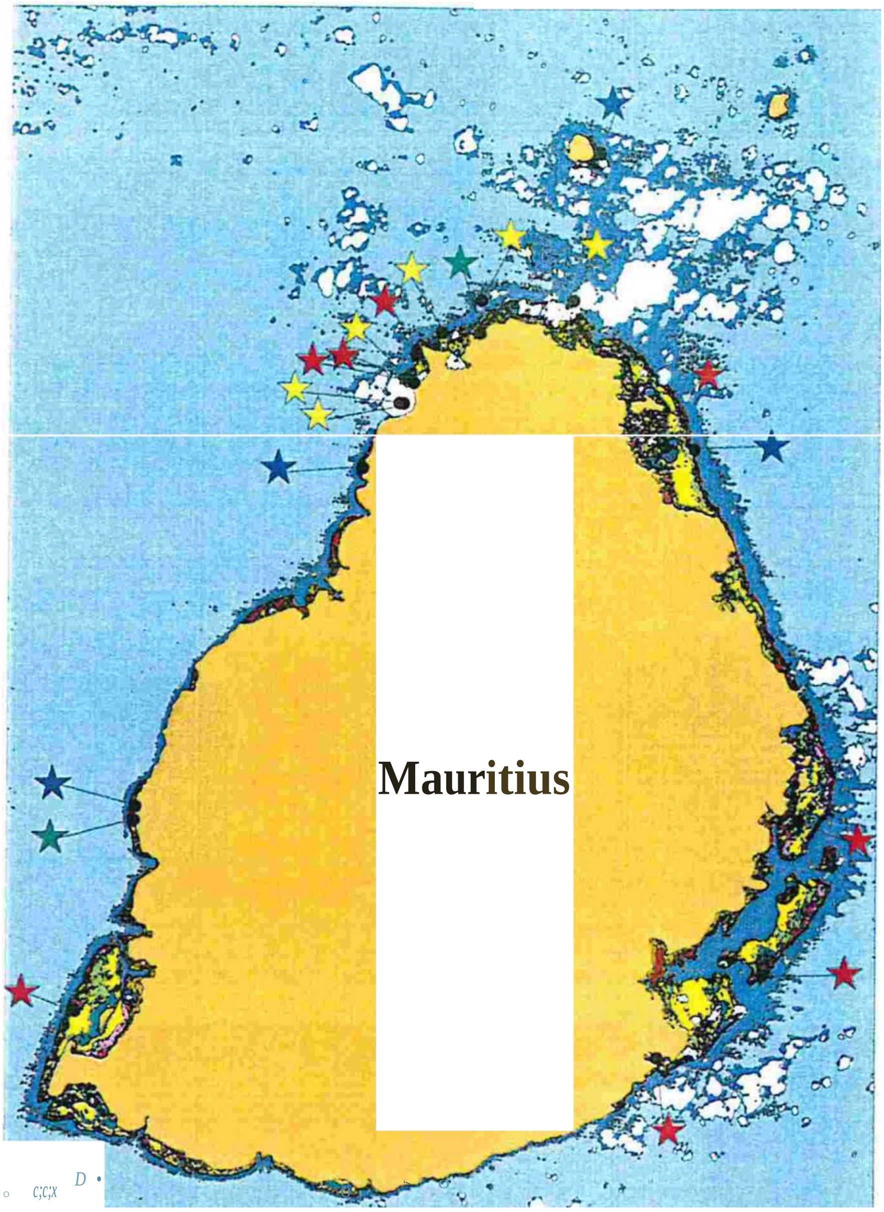


Figure 22. Three examples of partial bleaching of a) Platvgvra _fil2. (Calodyne Reef 10).
b) Galaxea fasicularis (Balaclava *24)* and c) Acrooora formosa (Le Marne l).



<;;;. fasicLilaris bleached
t.. formosa and G.. fasicularis bleached
G. fasicularis and Platvgvra il2· bleached
t,.. forrnosa, (;. fasicularis and Platv'.!vra sp. bleached

Figure 23. The geographical distribution of coral bleaching in the three species most commonly observed to be bleached during the 1999 survey.

If the sizes of those species bleached are compared it can be seen that the mean bleaching value appeared to increase with colony size (Figure 24): small colonies (<10cm) showed the lowest mean bleaching value (1.00) and large colonies (>50cm) the highest bleaching value (1.89). However, the difference in the mean bleaching value of the different sized colonies is not significant (Kruskall-Wallis: H = 6.43, df = 3, p>0.05).

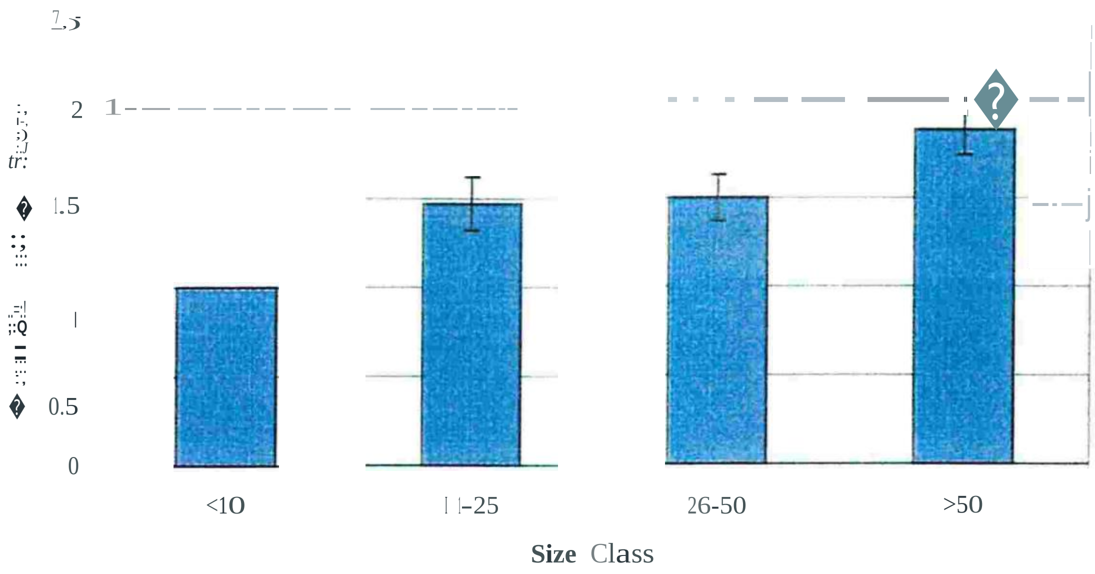


Figure 24. The mean bleaching score (on a scale of 0-5) ± SE of the four different size classes of bleached coral colonies (n = 73). The data are based on observations from the initial surveys only.

3.3 Other Impacts

In addition to bleaching other impacts, both human and natural were observed at all of the sites studied. Human impacts were common and were observed at 26 sites (Figure 25), including the two marine reserves at Blue Bay (south-east) and Balaclava (north-west). The most common form of human impact observed at the 34 sites was boat or anchor damage and this was noted at 21 sites in the lagoons at Le Marne (south-west), Trou aux Biches (north-west), Flat Island (north), Ile dArnbre (north-east), Trou dEau Douce (south-east), Blue Bay (south-east) and Flic en Flac (south-west) and on the Barrier Reef (south-east). Fishermen and tourist boars anchored their boats in the lagoonal parch reef: causing destruction of the corals. Trampling and snorkeller damage was also noted at 7 sites in the lagoons at Trou aux Biches 5 (north-west), Flat Island 11 (north), Balaclava 24 and 33 (north-west), Blue Bay 27 (south-east) and Flic en Flac 30 and 32 (south-west). At Flat Island 11 (north) and Balaclava 33 (north-west) the damage was observed to be caused by tourists snorkelling in shallow water; at Flic en Flac 30 (south-west) fishermen were observed walking across the reef towards the shore and in the lagoon at Ile d'Ambre (north-east) fishermen were observed standing on the reef searching for reef fish and octopus.

Another common impact to the reef observed was fish traps placed in coral beds. These were found at 14 sites in the lagoons at Le Morne (south-west), Trou aux Biches (north-west), Ile d'Ambre (north-east), Flic en Flac (south-west); on the fore reef at Trou aux Biches (north-west); on the Barrier Reef (south-east) and within the two marine reserves at Blue Bay (south-east) and Balaclava (north-west). The fish traps caused physical destruction to the corals. At Flic en Flac 32 (south-west) a fish trap was observed to be supported by upturned *Porites* heads,

other human impacts to the reefs included sand mining at Ile d'Ambre 16 and 17 (north-east) and possible nutrient enrichment in the lagoon at Trou aux Biches 6 and 7 (north-west) and on the fore reef at Grand Baie 25 (north). Trou aux Biches 6 and 7 (north-west) had a high abundance ot macro-algae and it is possible that the nutrient enrichment was due to sewage released into the lagoon from nearby hotels. At Grand Baie 25 (north) the percent cover of hard corals was low and soft corals were in high abundance. Live coral cover was observed to have decreased dramatically in the past 10 years (Turner, pers. comm.). It is likely that nutrient enrichment at this site came from Grand Baie. Damage from tourist developments included a bulldozed section of reef at Balaclava 24 (north-west) opposite the construction site of a new hotel; a concrete mooring near a hotel jetty, located on top of coral heads at Perybere 34 (north); litter, including plastic bottles and at Blue Bay 27 (south-east) coral heads arranged in a circle, possibly for dive training.

Natural impacts were also observed at many of the reefs studied (Figure 26). Possible storm/cyclone physical damage was observed at 15 sites visited. Tabular Acropora colonies were overturned and there was a high percent cover of rubble (>30%) at on the reef crest at Flat Island 12 (north) and in the lagoon at Blue Bay 27 (south-east). Cyclone Davina passed iauritius just one month before the survey on 4th March 1999. It produced gusts of up to 173 .m/hr and it is likely that the damage observed at these sites could be attributed to this factor. :rown-of-thorns Starfish *(Acanthaster planci)* were observed at 12 sites and were in jarticularly high abundance in the lagoon at Trou d'Eau Douce 22 (south-east). The sea urchin *chinometra mathaei* was in very high abundance in the lagoon at Ile d'Ambre 15 (north-east) ind on the reef crest at Ile d'Ambre 17 (north-east).

3.4 Meteorological Data

3.41 Climate during the 1998 sea warming event

3.411 Sea Surface Temperature

Sea Surface Temperature (SST) data for March to July 1997 and February to July 1998 obtained from a Waverider Buoy indicate that the mean SST reached its highest values during February (28.5°C) and March (28.1°C) 1998 (Figure 27). The mean temperature at this time of year is 27°C, thus temperatures were 1-1.5°C higher than normal. SST was higher in 1998 than in 1997 in both March (1998: 28.1°C; 1997: 27.5°C) and April (1998: 27.4°C; 1997: 26.8°C). No data were available for February 1997. A student's t-test indicates that SSTs were significantly higher in February and March 1998 than in April-July 1998 ($T = 5.19$, $df = 7$, $p<0.05$). A paired t-test indicates that SSTs were significantly higher in 1998 than in 1997 ($T = -3.47$, $p<0.05$). These data are confirmed by the SST anomaly charts produced by NOAA,

which indicate that SST in Mauritius was raised 1-1.25°C above the climatological maximum for this region on 31st January 1998. SST rose to 1.25-1.5°C above normal between 10th and 14th February 1998 and remained 1-1.25°C above normal until 28th February 1998.

3.412 General Climate

During the time of high sea surface temperature, Mauritius experienced very moist and unstable weather conditions. During 6th to 10th February a trough crossed the region producing thundery showers over the whole island. The tropical depression was named Anacelle by the Mauritius Meteorological Services on 8th February 1998 when it was located at 13.2°S, 61.0°E. It intensified as it moved south south west and became a tropical cyclone while passing off the west coast of St. Brandon. The cyclone passed approximately 60km off Belle Mare at its nearest point on 11th February 1998.

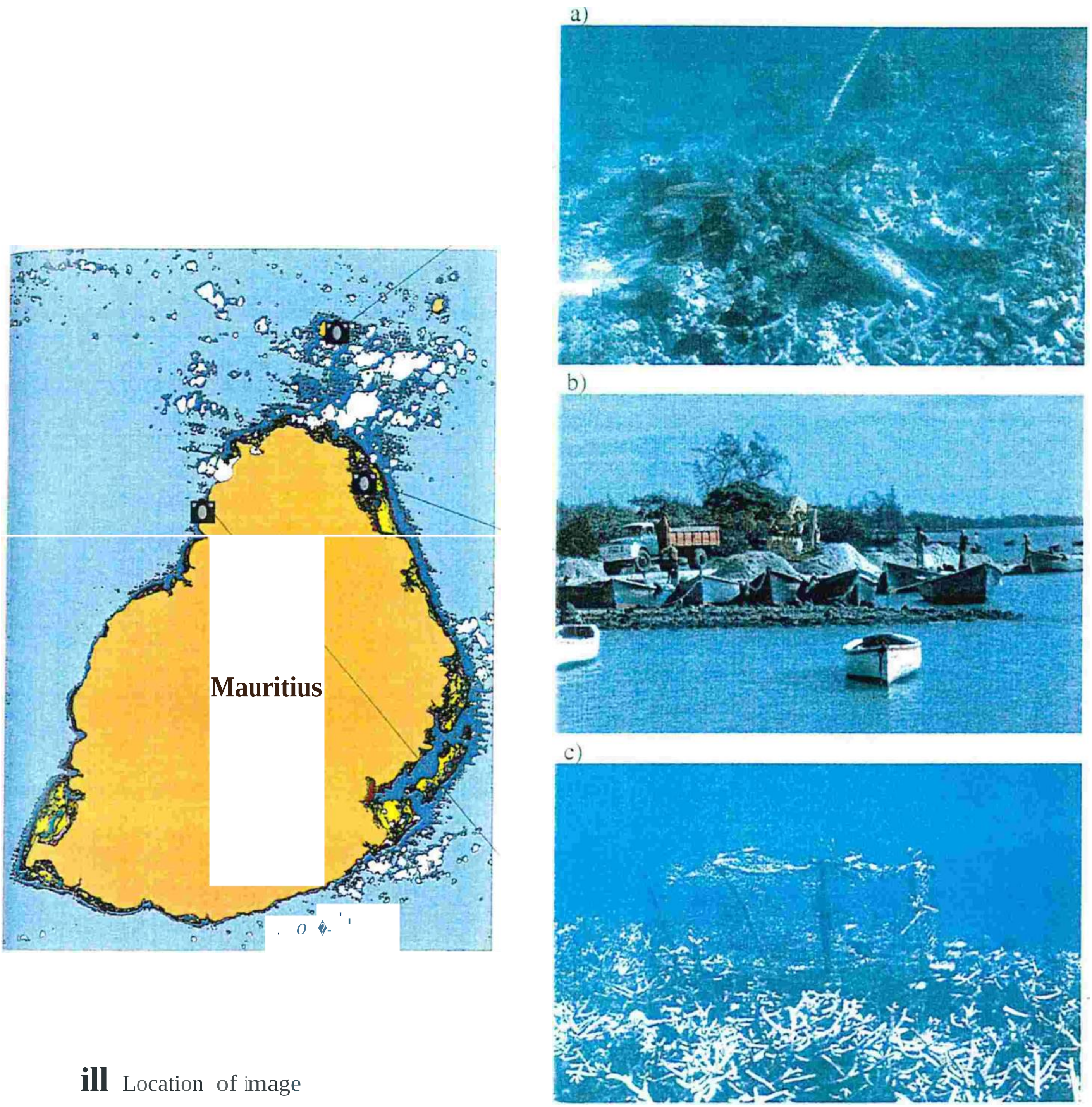


Figure 25. Three examples of human impacts to the reefs. a) anchor damage (Flat Island 11). b) represents potential damage caused by sand mining at Ile d'Ambre. c) fish traps (Balaclava 2J).

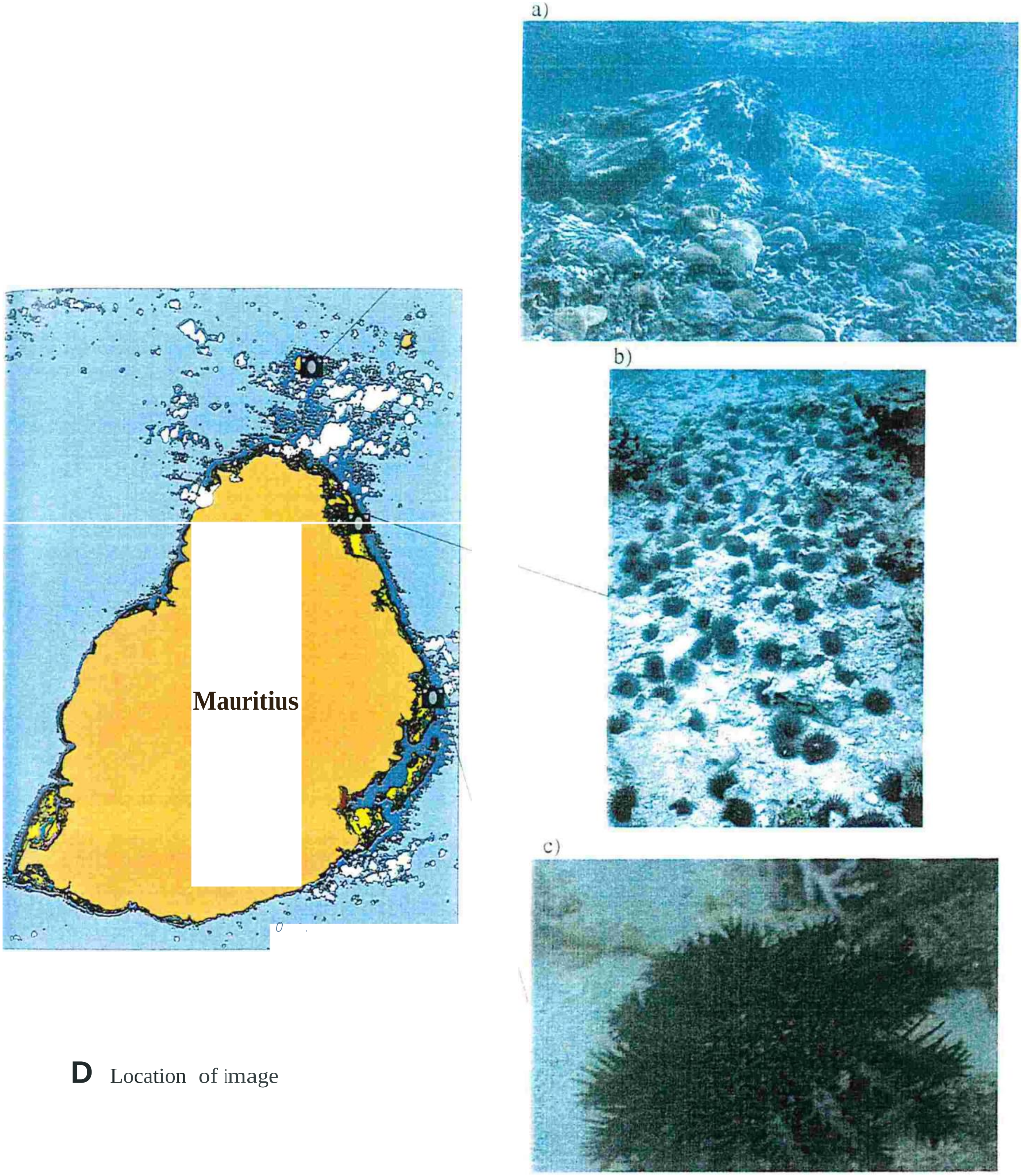


Figure 26. Three examples of natural impact: to the reefs. a) an overturned tabular Acropora colony. probably due to cyclone darnge (Flat Island 11).
b) a high abundance of Echinomerra mathaei (Ile d'Arnbre 16).
c) Acanthaster planci (Trou d'Euu Douce 22).

After the passage of cyclone Anacelle the airmass remained moist and unstable until 15th February 1998. During the second half of February moist and unstable weather persisted due to a marked low-pressure system located off the east coast of Madagascar. Clouds associated with this low continued to influence the weather until 24th February 1998 when it started to move east south eastward.

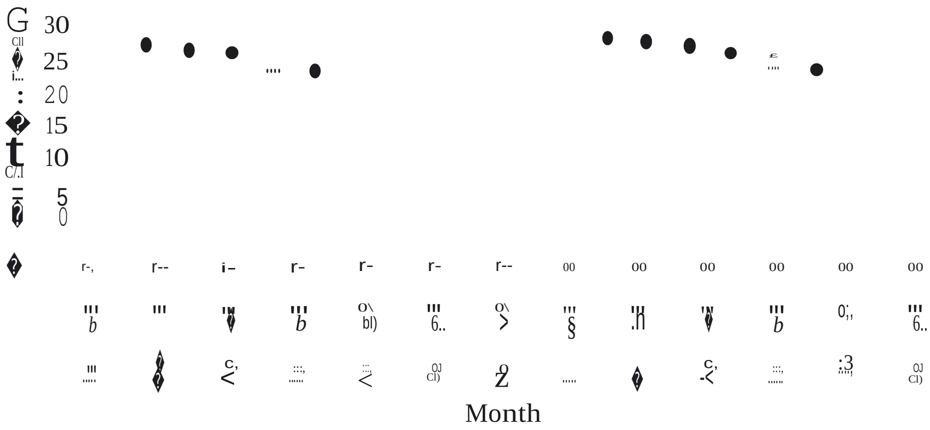
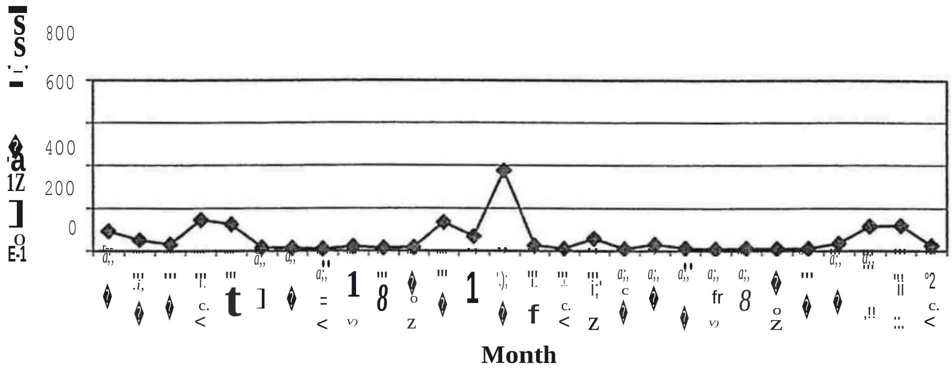


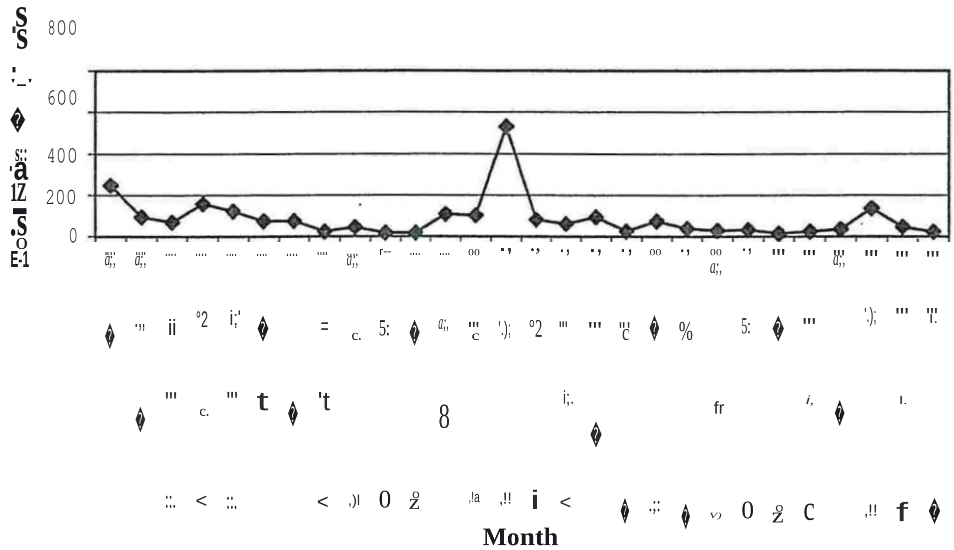
Figure 21. Mean Sea Surface Temperarure(°C) in Mauritius between March 1997 and July 1998. Data were obtained from the Waverider Buoy, located off Blue Bay, courtesy of the Meteorological Office, Mauritius.

3.413 Rainfall

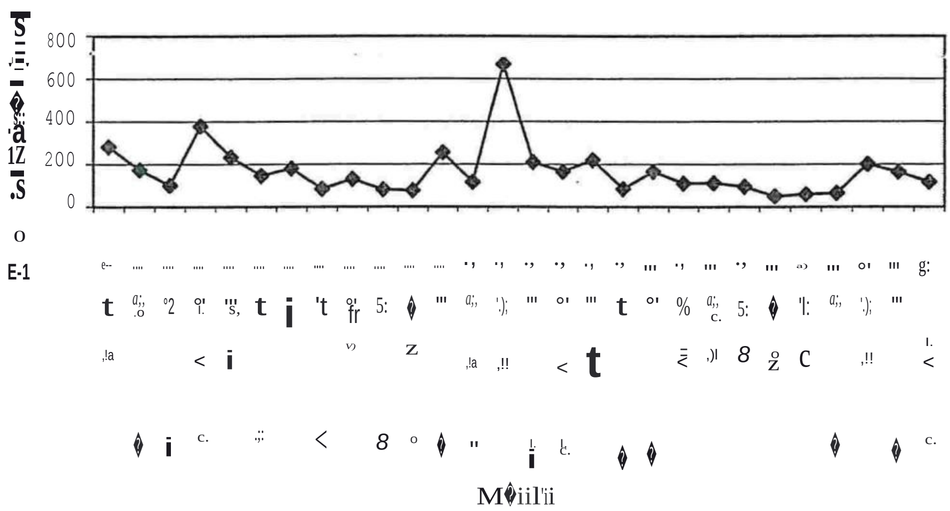
Rainfall was high during February 1998 due to cyclone Anacelle and the subsequent low-pressure system. Rainfall was above average during the first half of February and during the second half the west received 422% of the long-term mean rainfall, the north 395%, the east 328% and the south 345% (Figure 28). At Medine in the west 315mm of rain fell during February compared to 43mm in 1997 and 75mm in 1999. At Mont Choisy 546mm of rain fell during February 1998 compared to 95mm in 1997 and 111mm in 1999. Significantly more rain fell in February 1998 than in February 1997 and February 1999 in the north (Wilcoxon: $H = 6.3$, $df = 2$, $p<0.05$) and in the east (Wilcoxon: $H = 6.27$, $df = 2$, $p<0.005$).


800
600
400
200
0
Month

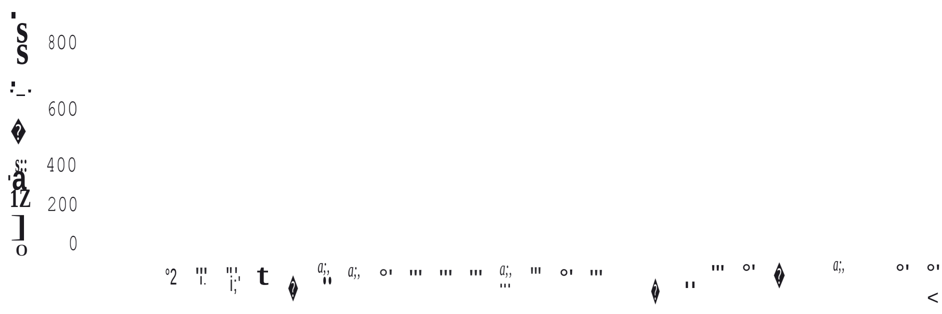
a)

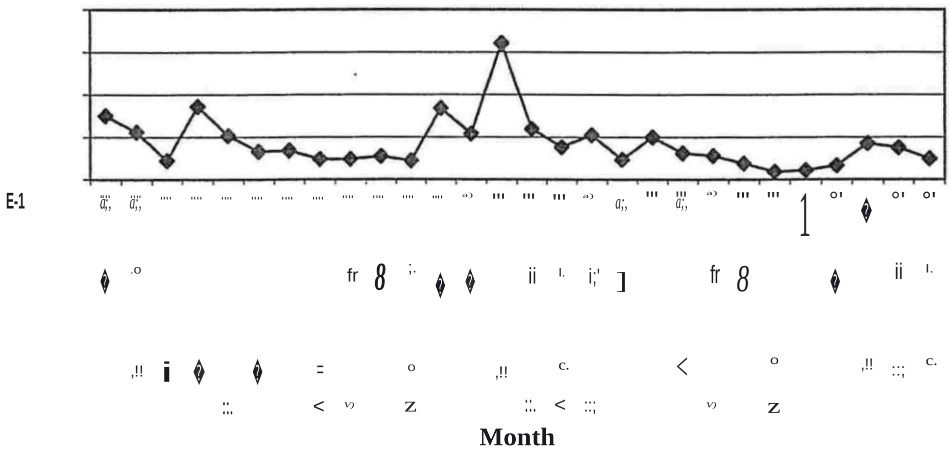

800
600
400
200
0
Month

b)


800
600
400
200
0

c)


800
600
400
200
0



d)

Figure 28. Total rainfall (mm) per month between January 1997 and April 1999 for sites in the a) west, b) north, c) east and d)south of Mauritius. Data were provided by the Mauritius Meteorological Office.

3.414 Cloud Cover and Sunshine

Cloud cover was high in February 1998 associated with cyclone Anacelle and the subsequent low-pressure system. February 1998 had the highest daily mean cloud coverage (6.7 hours, recorded at Vacoas) during the whole period of January 1997 to March 1999 (Figure 29). Cloud cover was higher in February 1998 than in either February 1997 or February 1999 however, due to lack of data this could not be proved statistically.

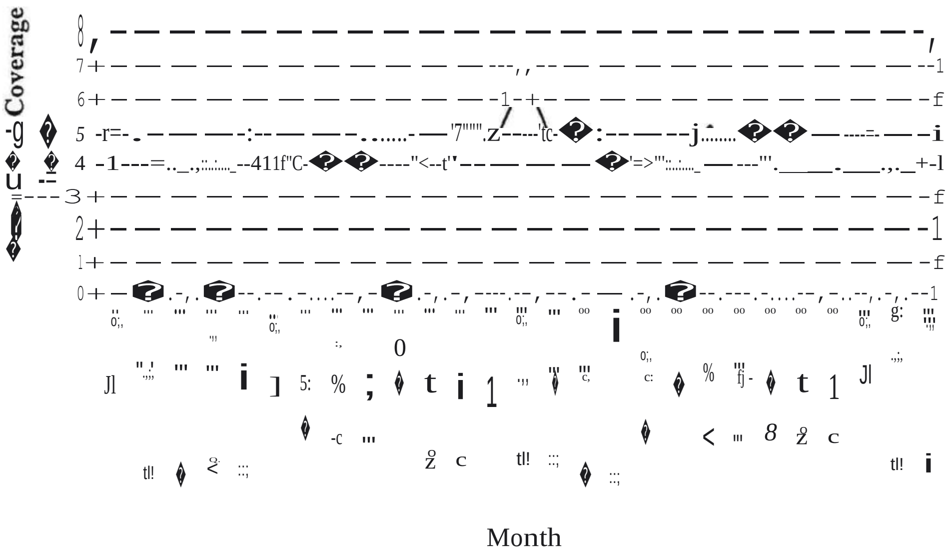
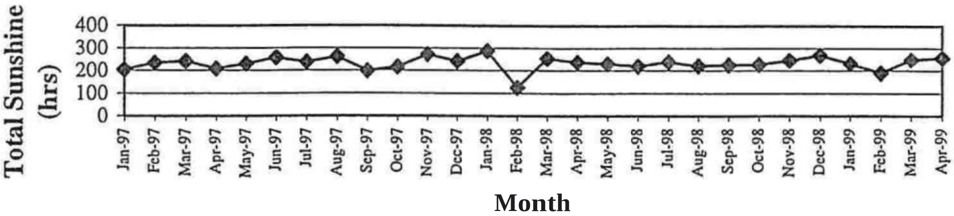


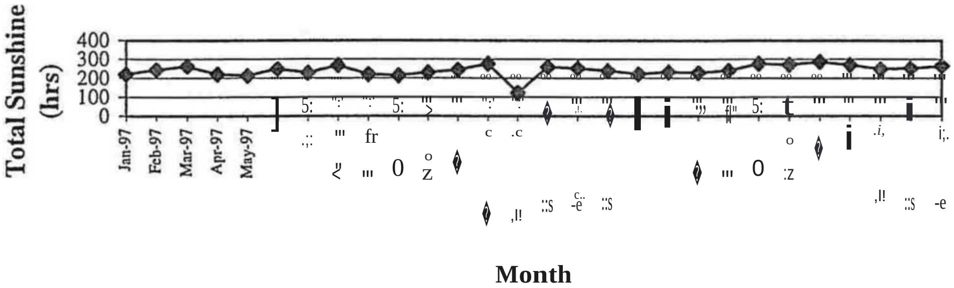
Figure 29. Mean cloud coverage per month between January 1997 and March 1999. Data were provided by the Mauritius Meteorological Office.

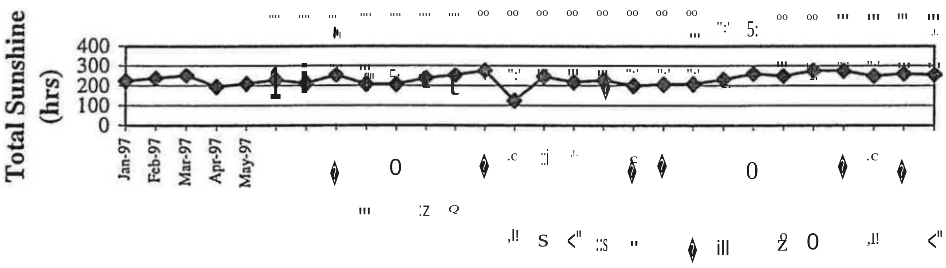
The total number of hours of sunshine in February 1998 were the lowest recorded during the period of January 1997-April 1999, due to the high cloud coverage (Figure 30). At Medine (west) there were only 126 hours of sunshine in February 1998 compared with 235 hours in February 1997 and 190 hours in February 1999. At Pamplemousses (north) there were 122 hours of sunshine in February 1998 compared with 244 hours in February 1997 and 248 hours in February 1999. An analysis of variance indicated that there were significantly lower hours of sunshine in February 1998 than in February 1997 at Medine (west) ($F = 4.68$, $df = 17$, $p<0.05$), February 1999 at Sans Souci (east) ($F = 6.85$, $df = 17$, $p<0.05$) and Plaisance (south) ($F = 6.29$, $df = 17$, $p<0.05$) and February 1997 and 1999 at Pamplemousses (north) ($F = 7.57$, $df = 17$, $p<0.05$), Digue Seche (north) ($F = 6.62$, $df = 17$, $p<0.05$) and Flacq (east) ($F = 6.25$, $df = 17$, $p<0.05$).

6
7


Total Sunshine (hrs)
400
300
200
100
0
Jan-97 Feb-97 Mar-97 Apr-97 May-97 Jun-97 Jul-97 Aug-97 Sep-97 Oct-97 Nov-97 Dec-97 Jan-98 Feb-98 Mar-98 Apr-98 May-98 Jun-98 Jul-98 Aug-98 Sep-98 Oct-98 Nov-98 Dec-98 Jan-99 Feb-99 Mar-99 Apr-99
Month

a)


Total Sunshine (hrs)
400
300
200
100
0
Jan-97 Feb-97 Mar-97 Apr-97 May-97
Month


Total Sunshine (hrs)
400
300
200
100
0
Jan-97 Feb-97 Mar-97 Apr-97 May-97

c) f)

d)

e)

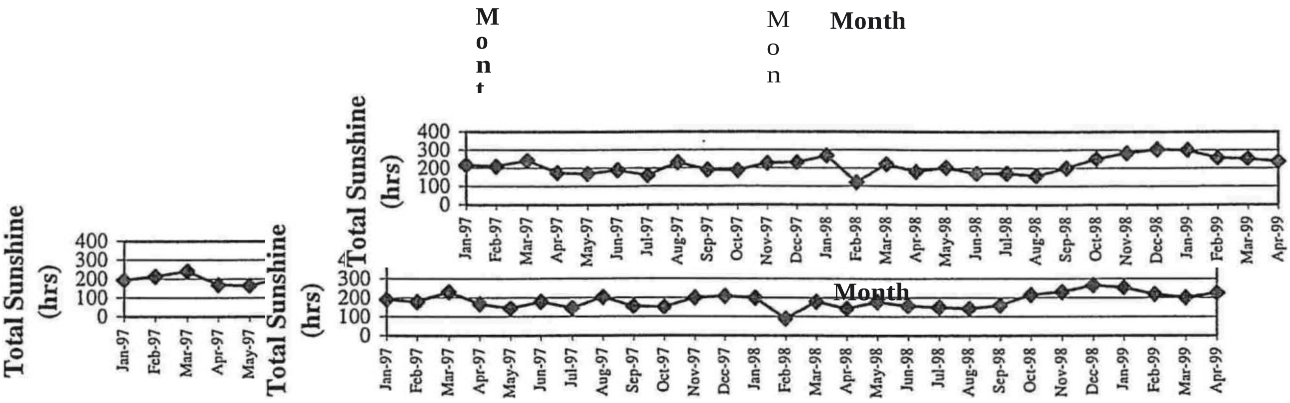


Figure 30. Total sunshine (hrs) per month between January 1997 and April 1999 for a) Medine (west), b) Pamplemousses (north), c) Digue Seche (north), d) Flacq (east), e) Sans Souci (east) and f) Plaisance (south). Data were provided by the Mauritius Meteorological Office.

3.415 Wind Speed

When cyclone Anacelle passed its nearest point to Mauritius it produced winds of up to 14kmlhr at Fort William and 77krn/hr at Plaisance. February 1998 did not however, have a Lgnificantly higher mean or absolute windspeed than February 1997 or February 1999 (Figures 31 and 32). During February 1998 the mean windspeed was significantly higher in the west then in the east (ANOVA: F = 4.72, df = 23, p<0.05).

3.416 Tidal Regime

Neap tides occurred during the first and third weeks of February. Low tide occurred in the middle of the day between lOam and 4pm, however, the tidal range was small (approximately 0cm) and low tide was still fairly high (approximately 170cm above Chart Datum). Spring tides occurred during the second and final weeks of February. The tidal range was much greater (40-50cm) and the lowest low tide during the day ranged from 150-160 cm above Chart Datum. Low tide, however, occurred between 0600 and 0800 and between 1800 and rvoGhrs (Figure 33).

3.42 Climate during the 1999 survey

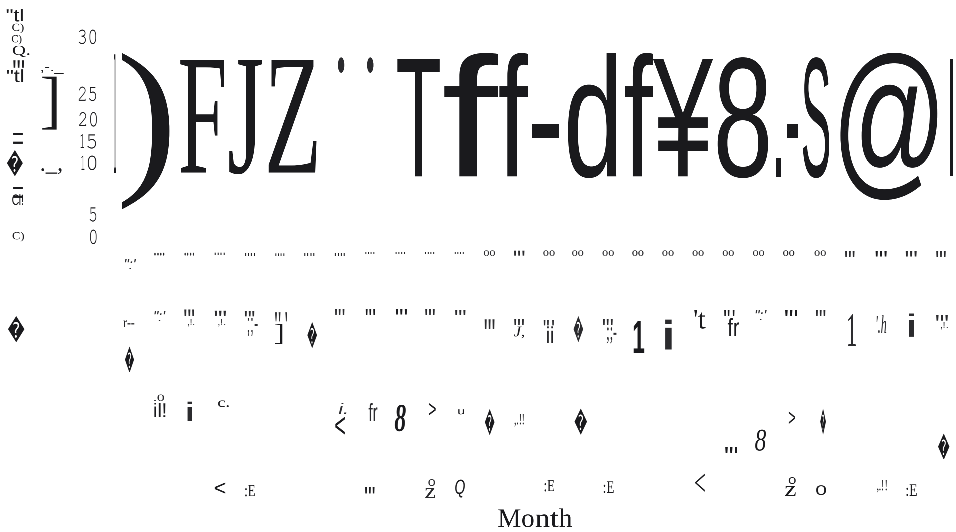
Sea Surface Temperature (SST) charts produced by NOAA indicate that SST did not exceed its normal monthly maximum during the 1999 survey (April). SST was normal throughout January 1999, rose to 0.5-0.75°C above normal during February and March and returned to normal at the end of March.

The 3 months preceding the 1999 survey were unsettled. On the 28th January Mauritius was affected by the tropical depression Birenda and on the 31st January the tropical depression Chikita. Between the 4th and io" March, Mauritius was hit by the tropical cyclone Davina, which passed at approximately 25km to the south east of Plaisance. Mauritius suffered cyclonic winds for 11 hours, especially in the eastern and southern parts of the island. The highest gust was 173krn/hr, recorded at Port Louis.

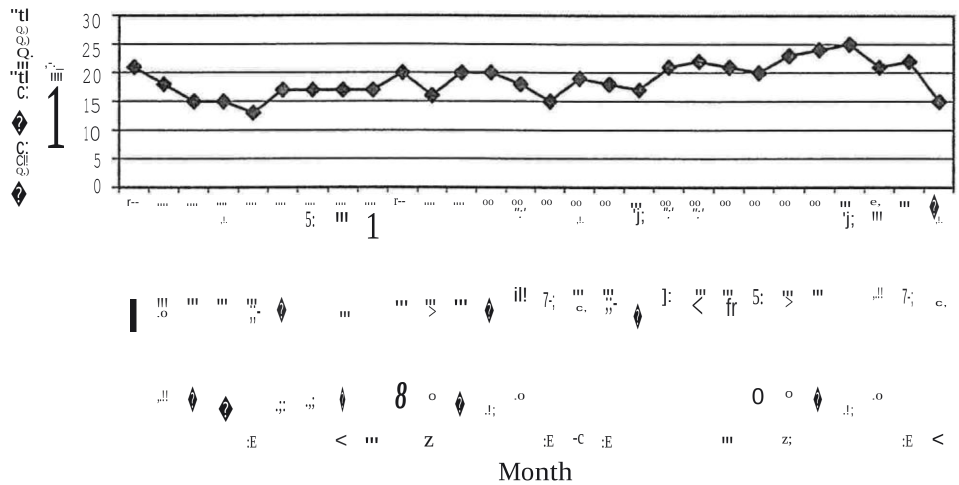
Very little rain was associated with these tropical depressions. The first 4 months of 1999 were very dry and in all parts of Mauritius the rainfall was below the mean rainfall value. During the first half of January 1999 as little as 1.4mm (2% of the normal rainfall) of rain fell

In the west and during the first half of April only 3.7mm (6% of the normal) of rain fell in the north. The total rainfall in the first 4 months of 1999 was significantly less than in the first 4 months of 1998 in the east (Kruskall Wallis: H = 11.30, df = 2, p<0.05) and was significantly less than in the first 4 months of both 1997 and 1998 in the north (Kruskall Wallis: H = 10.97, df= 2, p<0.05) and in the south (Kruskall Wallis: H = 11.47, df = 2, p<0.05).

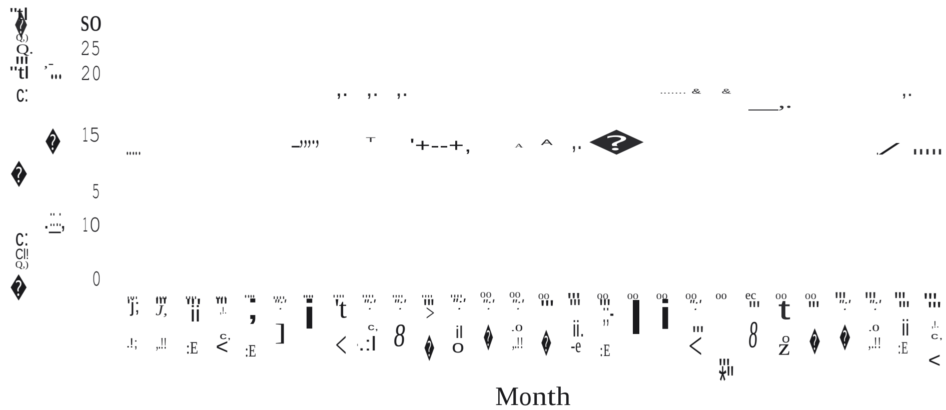
Sunshine levels during the first 4 months of 1999 were normal or above normal in all parts of Mauritius. During April 1999 sunshine levels were well above the mean in all areas and were up to 152% of the mean in Sans Souci (east). There were significantly more hours of sunshine during the first 4 months of 1999 than during the first 4 months of 1998 at Digue Seche (north) (ANOVA: F = 3.16, df = 71, p<0.05), Flacq (east) (Kruskall Wallis: H = 8.61, df = 2, p<0.05) and Sans Souci (east) (ANOVA: F = 6.65, df = 71, p<0.05) and the first 4 months of both 1997 and 1998 at Plaisance (south) (ANOVA: F - 6.65, df = 71, p<0.05). In addition, there were significantly more hours of sunshine during April 1999 than during April 1997 at Digue Seche (north) (ANOVA: F = 4.87, df = 17, p<0.05), April 1998 at Sans Souci (west) (ANOVA: F = 4.40, df = 17, p<0.05) and April 1997 and 1998 at Flacq (west) (ANOVA: F = 5.96, df = 17, p<0.05).


30
25
20
15
10
5
0
Month

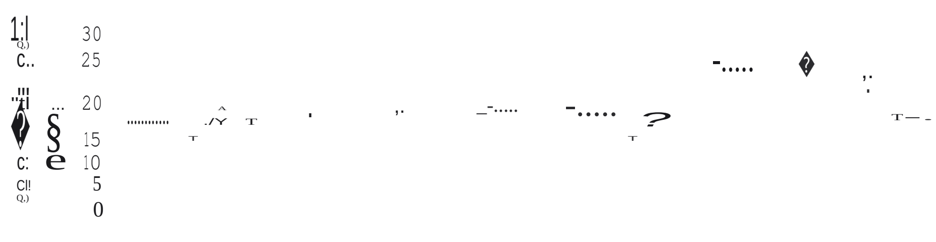
a)

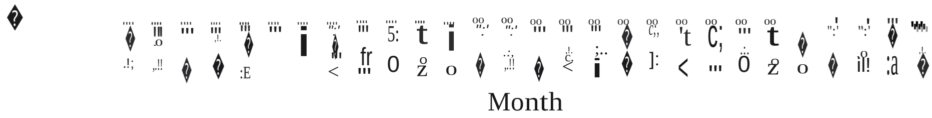

30
25
20
15
10
5
0
Month

b)


25
20
15
10
5
0
Month

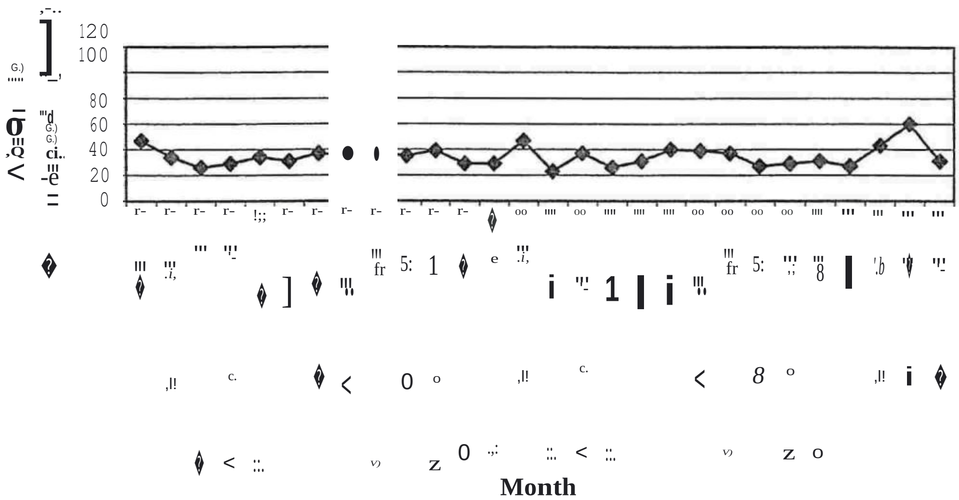
c)


30
25
20
15
10
5
0

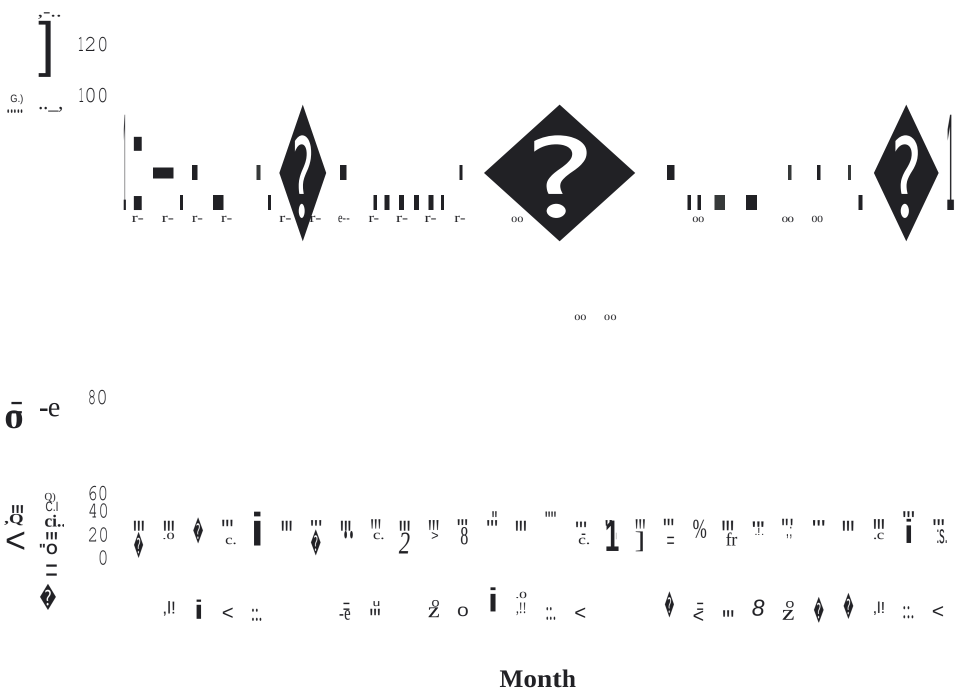


d)

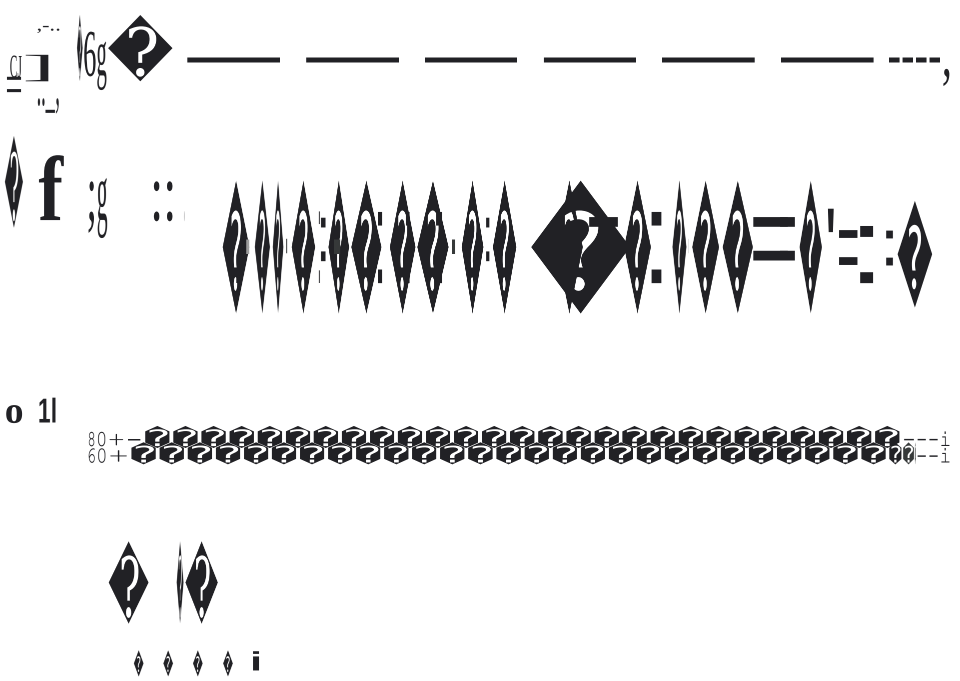
Figure 31. Mean windspeed (km/hr) for each month between January 1997 and April 1999 for a) Medine (west), b) Pamplemousses (north), c) Flacq (east), d) Plaisance (south). Data were provided by the Mauritius Meteorological Office.

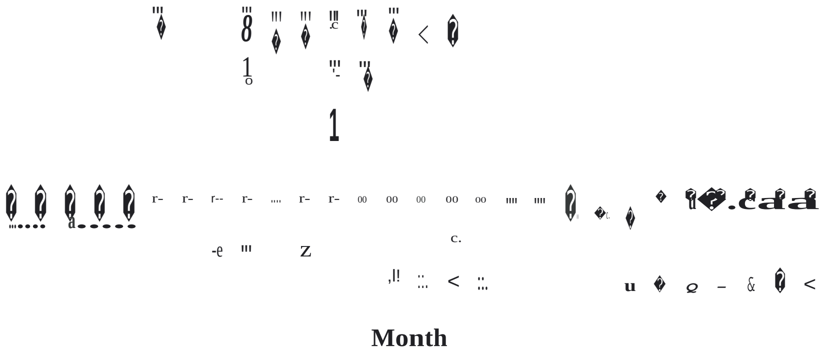


a)

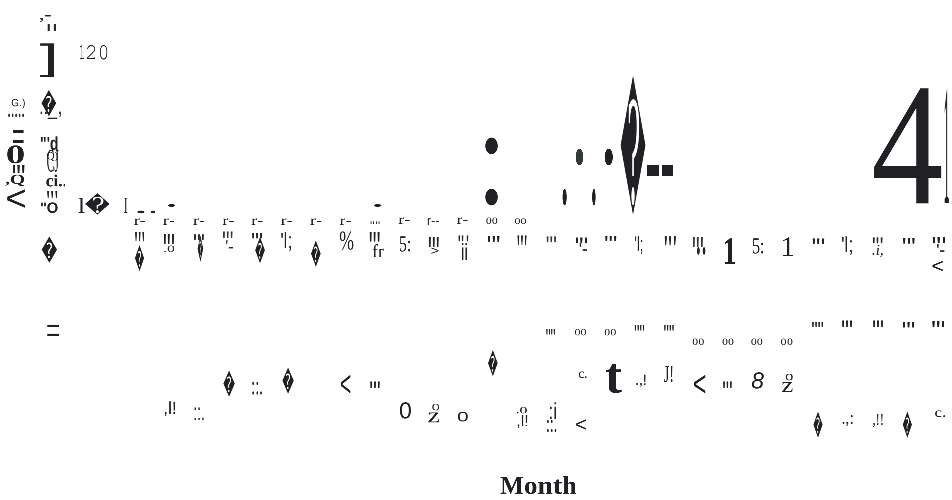


b)





e)



d)

Figure 32. Absolute windspeed (km/hr) for each month between January 1997 and April 1999 for a) Medine (west), b) Pamplemousses (north), c) Flacq (east), d) Plaisance (south). Data were provided by the Mauritius Meteorological Office.

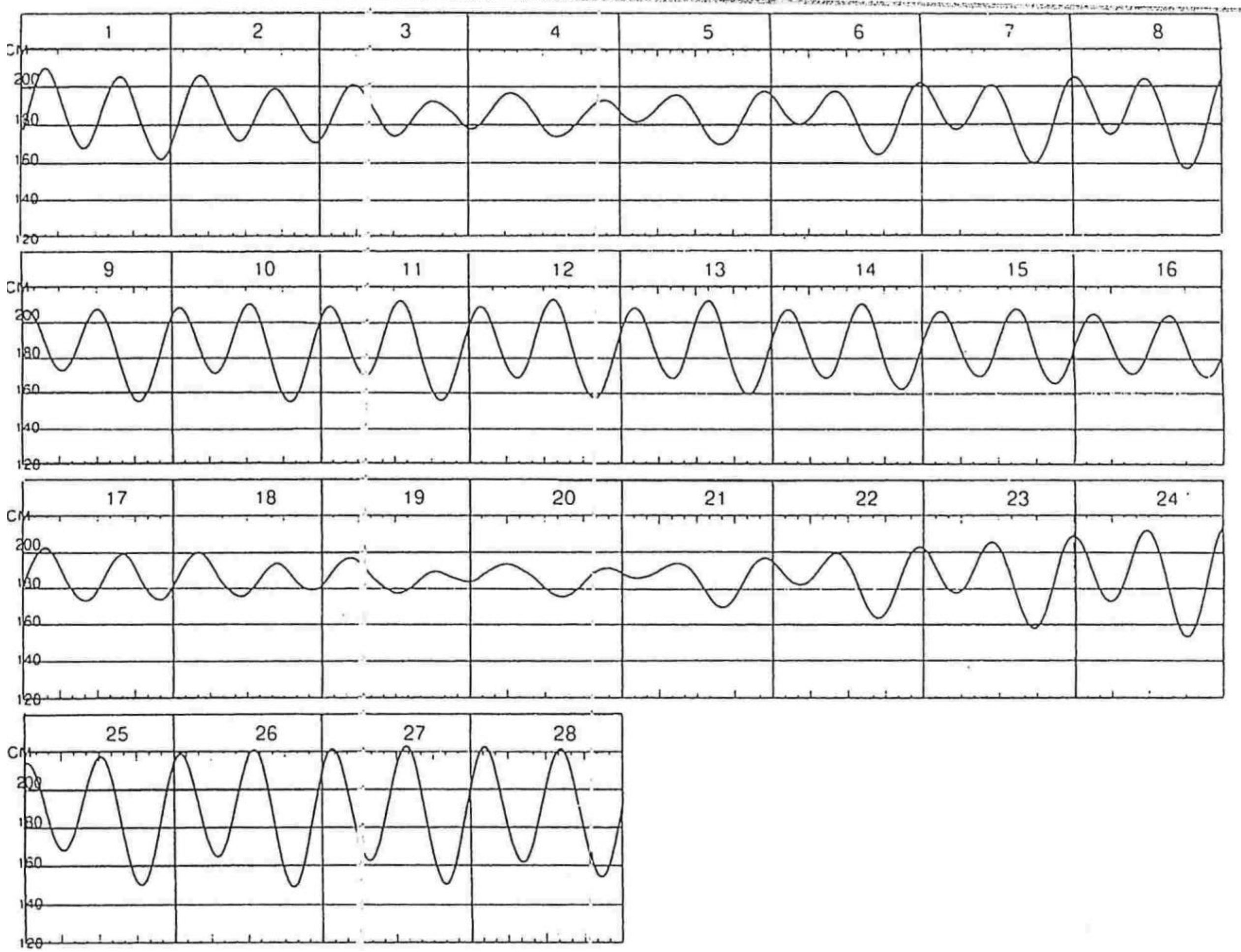


Figure 33. The tidal regime in Mauritius during the period of seawater warming (February 1998) recorded at Port Louis. The x-axis is time in hours, where each scale bar represents 2 hours. The y-axis is tidal height above Chart Datum in centimetres. Data were provided by the Mauritius Meteorological Office.

4.0 Discussion

The results show that the coral reefs of Mauritius escaped the mass bleaching event, which severely affected other areas of the Indian Ocean in 1998. Sea Surface Temperature (SST) anomaly charts produced by NOAA indicate that SST in Mauritius was raised 1-1.25°C above the climatological maximum for the region for over one month. This is supported by *in situ* data from the Waverider Buoy, which shows that sea surface temperatures offshore from Blue Bay were 1-1.5°C higher than normal. This temperature rise was not as high as in other regions such as the Maldives, where 4°-6°C increases were recorded. A rise of 1-2°C above normal has, however, been shown to induce bleaching in corals in both the laboratory (Jokiel and Coles, 1978) and the field (Glynn, 1984). We would expect therefore a mass bleaching event to have occurred in Mauritius during 1998.

One year later there were no indications that Mauritius had suffered a mass bleaching event. 47% of the sites studied were healthy with >50% coral cover. Reef Check surveys in 1997 found that the mean percentage cf living coral on-reefs Wa5 33% globally-and 37% 011 .reets in the Inda-Pacific (Hodgson, 1999). The reefs surveyed in Mauritius did not, therefore, have an unusually low percentage cover of hard coral species. Indeed, using the ASEAN-Australia Living Resources criteria (Chou, 1998) 47% of the sites surveyed can be described as 'Excellent' and 12% can be described as 'Good'. Sites with low hard coral cover tended to be the reef crest and fore reef sites, which have a naturally low cover of hard coral colonies due to environmental conditions. These sites, however, all showed a high species diversity and/or low dominance. Indicator species of reef crest sites were identified as *Porites sp.*, *Pavona cactus*, *Platygyra sp.*, *Favia sp.* and *Goniastrea sp.* Fore reef sites showed a high similarity (70.24%) and indicator species were identified as *Porites sp.*, *Lobophyllia sp.*, *Platygyra sp.*, *Pocillopora damicornis* and *Favites sp.* In contrast, 57% of lagoonal patch reefs had a coral cover >50%, however, these sites tended to have a low species diversity and be dominated by large colonies of one or two species. Indicator species of lagoonal patch reefs were identified as *Acropora formosa* and *Acropora cytherea*. The lagoonal patch reef Blue Bay 26 (south-east) was highlighted as a particularly healthy site with high coral cover, low dead coral cover, macroalgal and turf algal cover and a high species diversity and low dominance.

The coral reefs in Mauritius would not have recovered from a mass bleaching event within one year. In the Thousand Islands recovery from the 1983 mass bleaching event was not fully complete after 5 years (Brown and Suharsono, 1990) and in other regions affected by the 1998 mass bleaching event, few reefs showed any sign of recovery by 1999. In Kenya and Sri Lanka coral reefs were covered in thick algal turf and in Chagos and Socotra dead reefs had been eroded to rubble (Linden and Sporrong, 1999). In Mauritius, however, there were no large areas of dead standing coral, covered in macro- and filamentous algae that could be attributed to the bleaching event, other than at site 29 on the Barrier Reef.

The high SSTs experienced during 1998 are considered to be the cause of the mass bleaching event, however, the actual cause of bleaching at a particular reef may be a combination of other factors (Wilkinson *et al.*, 1999). Factors such as the level of storm activity, the number of days of cloud cover and the strength and direction of winds all affect whether the warm water is dissipated or builds up to lethal levels. Many workers have reported that mass coral bleaching followed extended periods of high temperatures, low wind velocity, clear skies, calm seas and low rainfall when conditions favoured localised heating and high penetration of Uv radiation (e.g. Glynn, 1991; Brown and Suharsono, 1990; Williams and Bunkley-Wiilliams, 1990; Gareau and Hayes, 1994).

In Mauritius, however, meteorological data indicates that during the period of elevated SST, Mauritius experienced very moist and unstable weather. Cyclone Anacelle passed Mauritius during the first half of February, resulting in very high cloud coverage (mean of 6.7 hours per day) and lower hours of sunshine than normally experienced at this time of year. At Medine there were only 126 hours of sunshine in February 1998 compared with 235 hours in February 1997 and 190 hours in February 1999, and at Pamplemousses there were 122 hours of sunshine in February 1998 compared with 244 in February 1997 and 248 hours in February 1999. During the second half of February a marked low pressure system produced very high rainfall, particularly in the north and east of the island. The north received 395% of the long-term mean rainfall and the east received 328%. The tidal cycle meant that during spring tides low tide occurred during the early morning and evening and the coral reefs were not therefore exposed during the hottest part of the day. In addition, the Waverider Buoy was located offshore from Blue Bay outside of the lagoon. The lagoons in Mauritius receive much freshwater run-off and are often cooler than the sea outside (Daby, 1994).

The Waverider buoy and sea surface anomaly charts confirm that seawater warming around Mauritius did occur. It seems however, that despite the high SST recorded the combination of climatological factors in Mauritius at the time of the warming were not conducive to cause bleaching. In contrast, conditions were very unstable and solar irradiance was low. High rainfall has been shown to produce coral bleaching at a local level (Goreau, 1964), however, in this case it is possible that the weather conditions at the time of the sea water warming prevented mass bleaching in Mauritius.

Site 29 on the Barrier Reef did, however, show signs of possible mass bleaching. The site was dominated by dead standing coral (>50%), covered in turf algae and consisted of small colonies of regenerating corals with healthy tips. The Barrier Reef is situated 3-5 km off the east coast and thus may be subjected to different climatic and oceanographic conditions than the inshore sites surveyed. The meteorological data do not, however, give any indications as to why this site may have bleached when the other sites did not. There was no significant difference in climatic conditions on a geographical basis, except that significantly more rain fell in February 1998 than in February 1997 or 1999 in the east. It is possible, therefore that the bleaching could have been caused by the high levels of rain as shown by Goreau (1964). Another possible explanation is that unlike mainland Mauritius, high cloud cover did not protect the Barrier Reef. This would have allowed high levels of UV radiation to penetrate the shallow waters and would have increased the likelihood of localised warming. This theory could be proved using Landsat TM satellite imagery, which illustrates cloud cover, taken during the period of sea warming. Unfortunately, no satellite image was available for Mauritius during this time period. A further possible explanation is that localised oceanographic features may have caused the water around the Barrier Reef to heat up more than at the inshore sites. Furthermore, being offshore could have meant that the reef was not affected by freshwater run-off, which tends to cool down the lagoons (Daby, 1994).

During the 1999 survey, bleaching was observed at 85% of the sites visited, however, in all cases it was only minor (<10%) and was only partial bleaching, rather than total bleaching. It has been suggested that coral bleaching is a seasonal phenomenon occurring at certain times of the year when seawater temperatures are either minimal or maximal (Oliver, 1985). Fagoonne *et al.* (1999) showed that in a lagoon in Mauritius there is a large variability in the zooxanthellae population of *Acropora formosa* with regular episodes of low densities occurring in the spring and summer. They suggest that minor bleaching episodes such as that observed during this survey may be a frequent and normal event relating to large environmental fluctuations experienced within the lagoon.

The minor bleaching observed during the 1999 survey was not caused by widespread sea warming, and SST anomaly charts produced by NOAA indicate that SSTs during the first 4 months of 1999 were normal. The fact that there was no geographical pattern in the bleaching, however, suggests that the cause of bleaching works on a large enough scale as to affect the whole coast of Mauritius. Localised bleaching events have been found to be caused by increased solar radiation (e.g. Brown *et al.*, 1994; Gleason and Wellington, 1993); low tidal exposure (Glynn, 1984); lowered salinity (Goreau, 1964) and increased turbidity (Bland, in Williams and Bunkley-Williams, 1990).

Partial bleaching of *Acropora formosa* occurred only on the upper surfaces of horizontal branches. *Galaxea fascicularis* and *Platygyra sp.* bleached mostly in shallow water (<10m) and only bleached on their upper surfaces. Other workers have reported greater bleaching on the upper or more light exposed surfaces and that portions of upper surfaces that fell in shadows of fixed objects were often not bleached (e.g. Williams and Bunkley-Williams, 1990). Harriott (1985) suggested that bleaching on the upper and unshaded surfaces of corals on the Great Barrier Reef indicated that the cause of the bleaching was high levels of solar irradiance, In Thailand, localised, naturally occurring bleaching at intertidal sites was also attributed to solar irradiance (Brown *et al.*, 1994). It is therefore, possible that the bleaching observed during this survey was a normal minor event caused by UV radiation. Sunshine levels in Mauritius during the first 4 months of 1999 were significantly higher than in 1998 in the north (Digue Seche) and the east (Flacq and Sans Souci) and 1998 and 1997 in the south (Plaisance), supporting this theory. Measurements of UV irradiance levels would however need to be made in order for this to be conclusive. In contrast, Fagoonee *et al.* (1999) suggest that zooxanthellae densities are positively correlated with nitrate concentration and therefore, this minor bleaching may be caused by nitrogen limitation within the lagoons.

At the sites surveyed, the number of coral species bleached varied from 0 to 6 and bleached colonies were often observed adjacent to unbleached colonies of the same species. Other workers have commented on the patchy spatial distribution of bleaching in coral colonies (e.g.

Oliver, 1985; Glynn, 1990; Jokiel and Coles 1990; Lang *et al.*, 1992). Edmunds (1994) suggests that this intraspecific variation in coral bleaching is due to the distribution of bleaching-susceptible genotypes. Rowan *et al.* (1997), however explain the patchy distribution of bleaching by the preferential expulsion of symbionts associated with low irradiance. They suggest that some colonies are protected from bleaching by hosting an additional symbiont that is more tolerant of high irradiance and temperature. Fitt and Warner (1995) also explain interspecific variation in bleaching by different physiological tolerances of the specific symbiotic algae of the different coral species.

For many of the species observed to be bleached and in particular *Platygyra sp., Galaxea fasicularis, Favia sp., Favites sp.* and *Porites sp.* the colonies appeared pale rather than fully bleached. This can cause confusion as to whether the colony is actually bleached and some corals that appear to have bleached may have, in fact, been light-adapted (Falkowski *et al.*, 1990). Brown and Ogden (1993) state that some intertidal coral species have an adaptive behavioural response to reduce desiccation, known as blanching, in which they pull back their external tissues, leaving their skeletons exposed. The mis-identification of bleached colonies could cause an over-estimation of the extent of bleaching and may help to explain the recent increase in coral bleaching events. It has therefore, been suggested that a standardised method js needed to assess the degree of coral bleaching (Glynn, 1993). There are a number of difficulties with standardising the degree of bleaching, such as the assessment of bleaching in colonies of the same species with different patterns of tissue coloration (Knowlton *et al.*, 1992); and the presence of genetically different zooxanthellae with different environmental tolerances (Rowan and Powers, 1991). In order to predict the future of coral reefs it is, however, important that bleaching events around the world are reported in a comparable manner.

Mauritius was not severely affected by the bleaching event of 1998, however, computer models predict an increase in the severity and scale of coral reef bleaching around the world (Glynn, 1993). The coral reefs around the whole coast of Mauritius are degraded by human and natural impacts. Stressed corals succumb more readily to bleaching stress and are more likely to die. Those that do survive will produce fewer larvae to repopulate damaged areas (Wilkinson *et al.*, 1999). It is therefore, important that reef management acts to reduce anthropogenic impacts on the coral reefs. At present most reefs in Mauritius are affected by trampling and anchor damage; overfishing; pollution and eutrophication. Even in the two Marine Parks fishing traps and boat damage were observed. If greater protection is not given to the coral reefs of Mauritius they may not survive the next bleaching event.

In addition, Mauritius is one of the few areas in the Indian Ocean not affected by the bleaching event. Coral reefs in the Maldives suffered up to 90% mortality and in the Seychelles mortality was close to 100% (Linden and Sporrong, 1999). In both areas diving and coastal tourism are a major source of income and it has been predicted that if recovery is slow there may be a loss in tourism as tourists go elsewhere (Linden and Sporrong, 1999). As information is spread throughout the diving community the number of tourists visiting Mauritius may increase, resulting in increased pressure on the reefs. Furthermore, reefs in the western Indian Ocean are closely linked by ocean currents of the sub-tropical anti-cyclonic gyre and the seasonally reversing monsoon gyres (Rao and Griifiths, 1998). The coral reefs in Mauritius, may therefore, act as a source of larvae for those coral reefs that suffered severe damage during the bleaching event. Little is known about the source-sink relationships in the Indian Ocean, however, the destruction of this source of larvae could prevent the recovery of coral reefs in other parts of the Indian Ocean (Salm *et al.*, 1998).

Despite the fact that Mauritius appeared to have escaped the mass bleaching event of 1998, its coral reefs are not yet safe. There has been significant progress in the management of reef resources in Mauritius in recent years (Wilkinson, 1998), however greater protection still needs to be given to the coral reefs. Stricter regulations and surveillance need to be introduced within the two marine parks to prevent boat damage and illegal fishing. In addition, an Integrated Coastal Zone Management (ICZM) plan needs to be implemented and further designations need to be made to limit human activities to certain areas of reef. In 1994 the Mauritian Wildlife Fund proposed that an area of lagoon around Ile aux Aigrettes should be declared a marine reserve (Bhuiyan, 1994), however, this recommendation has not yet been implemented. With the potential threat of increasing mass coral bleaching events Mauritius needs to act quickly to protect its coral reefs and its source of larvae from further degradation.

Geographical Information Systems (GIS) are a very important tool in the management of coastal resources. They allow data from a variety of different features to be integrated into a single database and provide an excellent medium for the visual presentation of data. This provides non-specialists with greater access to scientific information. There are few examples of GIS applications in the management of marine resources, although GIS has been used to produce a coastal zone management plan for the Barrier Reef in Belize (Mumby *et al.*, 1995). A GIS for the Trou d'Eau Douce lagoon in Mauritius has already been produced by Eastwood (1998). It is hoped that these two databases will be used in combination with other information to produce an effective coastal zone management plan for Mauritius.

6.0 References

Berkelmans, R. and Oliver, J. K. (1999). Large-scale bleaching of corals on the Great Barrier Reef. *Coral Reefs* **18:** 55-60.

Bhuiyan, J. (1994). Ile aux Aigrettes Marine Nature Reserve proposal in the Mahebourg lagoon. Winston Churchill Memorial Trust.

Bhuiyan, J. and Bell, M. (1995). A report on Ile Plate, Ilot Gabriel and the adjoining lagoon. Winston Churchill Memorial Trust.

Brown, B. E. (1987). Worldwide death of corals – natural cyclical events or man-made pollution? *Marine Pollution Bulletin* **18:** 8-13.

Brown, B. E. (1997). Coral bleaching: causes and consequences. *Coral Reefs* 16, Suppl.: S129-S138.

Brown, B. E. and Suharsono (1990). Damage and recovery of coral reefs affected by El Nino related seawater warming in the Thousand Islands, Indonesia. *Coral Reefs* 8: 163-170.

Brown, B. E. and Ogden, J.C. (1993). Coral Bleaching. *Scientific American*: 268: 64-70.

Brown, B. E., Dunne, R. P., Scoffin, T. P. and Le Tissier, M. D. A. (1994). Solar damage in intertidal corals. *Marine Ecology Progress Series* **105:** 219-230.

Brown, B. E., Le Tissier, M. D. A. and Bythell, J. C. (1 995). Mechanisms of bleaching deduced from histological studies of reef corals sampled during a natural bleaching event. *Marine Biology* **122:** 655-663.

Brown. B. E., Dunne, R. P. and Chansang, H. (1996). Coral bleaching relative to elevated seawater temperature in the Andaman Sea (Indian Ocean) over the last 50 years. *Coral Reefs* **15:** 151-152.

CARICOMP (1997). Studies on Caribbean coral bleaching, 1995-96. *Proceedings of the 8th International Coral Reef Symposium* **1:** 673-678.

CIA (1998). Mauritius. <http://www.odci.gov/cia/publications/factbook/mp.html>.

Clarke, K. R. and Warwick, R. M. (1994). Change in marine communities: an approach to statistical analysis and interpretation. Plymouth Marine Laboratory. pp 144.

Coles, S. L. and Jokiel, P. L. (1977). Effects of temperature on photosynthesis and respiration in hermatypic corals. *Marine Biology* **43:** 209-216.

Coles, S. L. and Jokiel, P. L. (1978). Synergistic effects of temperature, salinity and light on the hermatypic coral *Montipora verrucosa*. *Marine Biology* **49:** 187-195.

Chou, L. M. (1998). Status of Southeast Asian coral reefs. In: Wilkinson, C.R. (ed). Status of coral reefs of the world: 1998. Australian Institute of Marine Science and Global Coral Reef Monitoring Network, Townsville, Australia, pp 184.

Daby, D. (1990). Coastal zone inventory of Mauritius by remote sensing. MSc. Thesis, University of Wales, Bangor. pp 105.

Daby, D. (1994). Possible implications of the oceanographic thermal effects in a Landsat infrared image of Mauritius. *Hydrobiologia* **277:** 41-48.

Daby, D. (1999). Structure and function of two lagoon ecosystems of Mauritius. Ph.D. Thesis, University of Mauritius.

Davies, J.M., Dunne, R. P and Brown, B. E. (1997). Coral bleaching and elevated sea-water temperature in Milne Bay Province, Papua New Guinea, 1996. *Marine and Freshwater Research* 48: 513-516.