

Status and Recovery of the Coral Reefs of the Chagos Archipelago, British Indian Ocean Territory

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ABSTRACT

Surveys of reef benthos and hard coral recruits were carried out between February and March 2006 at 19 reef sites in 5 atolls of the archipelago. Results showed that all atolls appear to have shown strong recovery in terms of benthic cover after the 1998 bleaching and mortality event. Reef benthos composition varied greatly between survey sites, and highly significant differences in reef composition were recorded between different atolls, and between different depths at all atolls, showing considerable unevenness in recovery.

New coral recruitment is also strong, such that even the lowest of the Chagos recruit densities are an order of magnitude higher than the rates of recruitment of new corals documented at reefs in South Asia, the central Indian Ocean, and the East African Coast. Chagos recruitment is 6 m⁻² to 28 m⁻² compared to other reported values of 0.4-0.6 recruits m⁻² elsewhere.

Despite observations of several subsequent shallow water bleaching events including a substantial, recent localised coral mortality at Egmont atoll within the previous year, evidence of archipelago-wide recovery of reef habitats as notable as this remains unrecorded elsewhere in the Indian Ocean. Significant gaps

remain in current understanding of the number and scale of bleaching episodes that have taken place since the 1998 mass mortality event. Given the critical biogeographical role of Chagos in the Indian Ocean marine ecosystem, and the importance of the archipelago as a reference site for studying environmental change in the absence of direct anthropogenic interference, greater levels of long-term monitoring and ecological research are needed to better understand the responses and trajectory of recovery of the region's coral reef communities.

INTRODUCTION

Situated in the central Indian Ocean the Chagos archipelago has been largely uninhabited for approximately 35 years; four of its five islanded atolls remain uninhabited, while a military base exists on the southern atoll of Diego Garcia. The archipelago comprises a further 10 submerged atolls and banks, which together make up a network of reefs across 500 km x 200 km of ocean. Chagos reefs suffered very heavy mortality of corals and soft corals to at least 30m depth following the severe coral bleaching event of 1998, related to anomalously high sea surface temperatures caused by the El Niño Southern

Obura, D.O., Tamelander, J., & Linden, O. (Eds) (2008). Ten years after bleaching - facing the consequences of climate change in the Indian Ocean. CORDIO Status Report 2008. Coastal Oceans Research and Development in the Indian Ocean/Sida-SAREC. Mombasa. <http://www.cordioea.org>

Oscillation (ENSO) event (Sheppard 1999, Sheppard *et al.* 2002). Subsequent surveys showed that up to 100% of hard corals died at reef sites in all atolls studied, with shallow reefs particularly heavily impacted.

Whilst most other reef sites in the central and western Indian Ocean also experienced widespread bleaching as a result of this ENSO episode, the maximum depth of reef mortality in parts of the Chagos archipelago, particularly in central and southern atolls, extended deeper than most other locations in the region (Sheppard and Obura 2005). Heavy mortality which reduced previously thriving reef habitats to vast expanses of bare limestone extended to at least 30 m depth in the southern atolls. This may have been a result of the exceptionally clear oceanic water in the isolated archipelago, which enabled greater penetration of incident light. This was exacerbated by a prolonged period of calm seas throughout the 1998 bleaching episode, which led to less surface reflection of light and is likely to have enhanced warming of surface water (Sheppard 2006).

Fast growing corals, in particular *Acropora*, the most diverse and once often the most common genus on Indo-Pacific reefs, were particularly heavily impacted by the 1998 bleaching event, becoming a rare genus in many areas after the mass mortality. Populations of *A. palifera* were almost entirely eliminated from shallow reef areas in Chagos. This species was formerly the dominant shallow water coral in Chagos (Sheppard 1999), commonly forming widespread dense thickets between the surface and 4m depth. The expansive monospecific structures created in shallow reef areas by this species, once the central feature of shallow reef architecture, were almost entirely lost as a result of erosion in the aftermath of the mortality, lowering the height of some shallow reef surfaces by up to 1.5m (Sheppard 2002).

We have observed repeated, though mostly less severe, bleaching events throughout the archipelago in the intervening years. This is in common with many parts of the Indian Ocean where repeated bleaching and some further degree of mortality has been seen,

for example in the Seychelles (Sheppard *et al.* 2005), central Maldives (C. Anderson pers. com.), in both Oman and Straits of Hormuz in both 2002 and 2004 (Wilson *et al.* 2002), Rodrigues in 2002 and later (Hardman *et al.* 2004), Mauritius in 2003 (Turner and Klaus 2005) to name some examples. Several further instances of moderate bleaching are reported in Wilkinson (2004) who notes varying degrees of severity from India to Africa, with some island groups being apparently more affected than some mainland areas. Some of the most severe subsequent events appear to have been in the granitic Seychelles where mortality of most juvenile corals has been recorded, in contrast to Chagos where corals appear to have recovered much better (Sheppard 2006). In view of the temperature patterns of the Indian Ocean (see later), further bleaching events are unsurprising. Recovery of the corals must therefore be viewed in the context of repeated setbacks, especially in shallow water, rather than being progressive or as a smooth succession from the very depleted state following 1998.

Chagos reefs, amongst the remotest in the Indo-Pacific, are almost entirely free of direct anthropogenic impacts. With the exception of low levels of illegal fishing on outer atolls and the effects of terrestrial military development on Diego Garcia whose impacts are very localized (Guitart *et al.* 2007 and citations therein), climatic change and broad scale oceanic and meteorological disturbances currently represent the only serious threats to its coral reef health and ecosystem function. Global climate change models predict that the frequency and severity of anomalous ocean surface heating events will increase significantly over coming decades.

Understanding how coral reefs respond to thermal and natural stress in the absence of human disturbance is critical to advising coral reef management, which often focuses on minimising or removing direct human interference at a local level. Opportunities to record responses of coral reefs to climatic change in the absence of direct human pressures are, by comparison, rare. Owing to its geographical isolation

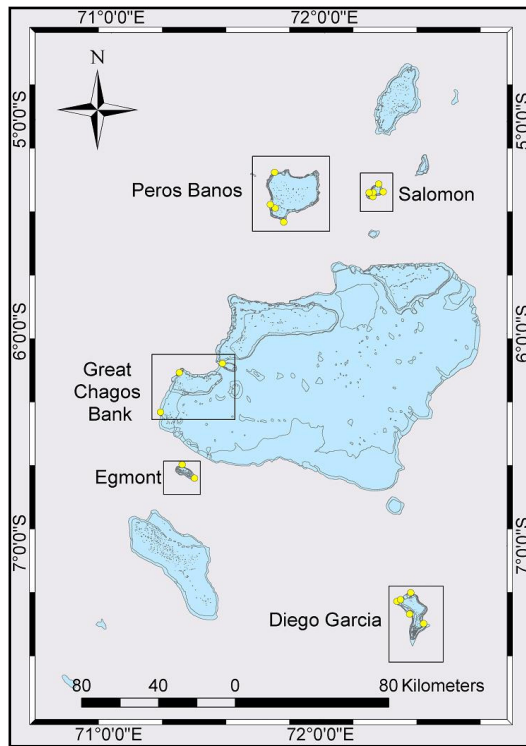


Figure 1. Location of atolls visited in this study, survey sites marked. In addition, lagoon sites were surveyed in the two northern atolls Peros Banhos and Salomon.

and current political status the Chagos archipelago provides an effective natural marine reserve and a natural ‘control’ site for monitoring specific responses and recoveries of coral reefs to natural disturbances and climate-related mass mortality events in the absence of local human impacts.

METHODS

All islanded atolls in the Chagos archipelago were surveyed for coral reef recovery. Surveys of reef benthos composition and hard coral recruit generic diversity and abundance were carried out by SCUBA diving between January and March 2006. Surveys were carried out at 19 reef sites visited in 5 atolls of the archipelago. From north to south the atolls visited were (with numbers of survey sites in brackets): Peros

Banhos (4), Salomon (5), Great Chagos Bank (3), Egmont (2) and Diego Garcia (5)

Surveys were carried out at up to three depths (5m, 15m and 25m) at each of these reef sites, which comprised 17 outer reef slopes and 2 lagoonal patch reefs. Survey sites included reefs studied by previous research expeditions to enable temporal comparisons of results, as well as previously unvisited sites, notably in Diego Garcia atoll. At each depth at each survey site up to 6 replicate 10m point intercept transects (PIT) were deployed to record biotic cover on the substrate.

Surveying of recruits was carried out by recording size and genus *in situ* of all hard coral recruits found within randomly placed 0.11m² (33cm x 33cm) quadrats. Sampling was replicated up to 46 times at each of the three survey depths at each of the 19 sites across all the atolls. Recruit sizes were recorded in 10mm categories from 0-100mm, measured as total distance across the surface of each colony along the longest axis of the colony.

Analyses of benthic community composition matrices were carried out using non-metric Multi-Dimensional Scaling (MDS) ordinations based on Bray-Curtis dissimilarities of root transformed multivariate sample data. Transformation was used as a means of down-weighting the importance of highly abundant benthos and substrate types (such as scleractinia), so that community similarities depended not only on their values but also those of less common (‘mid-range’) categories (such as alcyonidae). ANOSIM was used to identify significant differences between groups of samples defined by factors *a priori*, including depth, atoll and geomorphological class of reef. The same analytical procedure and factors were used to identify differences in hard coral recruit density and diversity (recruits per genus m⁻²) between samples.

The SST monthly data used is HadISST1, from 1871 to 2006 inclusive (<http://hadobs.metoffice.com/hadisst/>). Nine cells cover Chagos, which are averaged here. The SST trend is shown as differences from the 1960-1989 mean value.

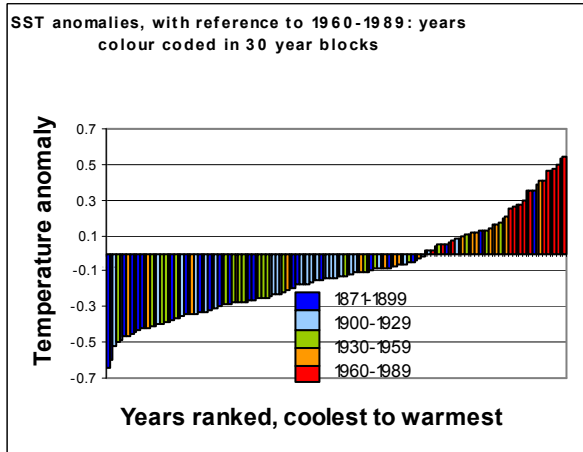


Figure 2. Chagos annual average sea temperature, shown as difference in °C from average 1960-1989 (following Hadley convention). Years are ranked, coolest to warmest. Colours code for 30 year block as shown in the key, except for the most recent block which is 1990 onwards (red bars) which has 17 bars. Data is HadISST1 monthly data from 1871-2006 inclusive, average of the 9 cells which cover Chagos archipelago.

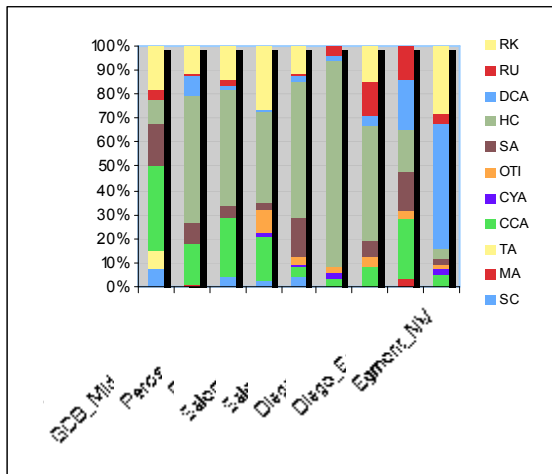


Figure 3. Mean average benthos composition values derived from PIT surveys at 5m depth. Survey codes used in results are as follows: RK (coral rock); RU (unconsolidated rubble); DCA (uncolonised dead coral); HC (hard coral); SA (sand); OTI (other acroinvertebrate); CYA (cyanobacteria); CCA (calcareous encrusting algae); TA (turf algae); MA (macroalgae); and SC (soft coral).

RESULTS

Sea Surface Temperature

Figure 2 presents the rising trend in annual average SST for this archipelago, over the past 135 years, showing that the six warmest years have all occurred during the last 10 years. No sub-surface temperature

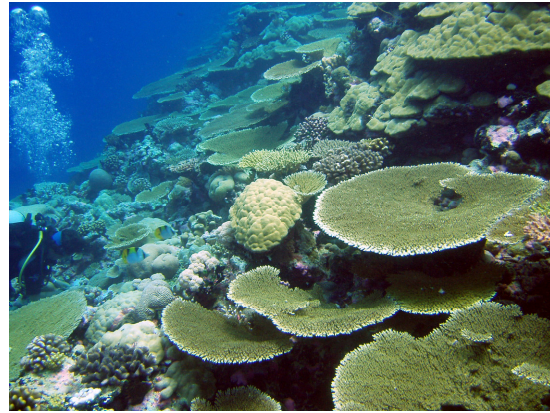


Figure 4. Thriving *Acropora cytherea* table corals at Ile Anglais, Salomon atoll, 8m depth.

recorders were in place over that time, so details of the critical warm periods at different depths are not available, but from the HadISST1 data (in prep), the years 2003 and 2005 both showed warm peaks extending above 29.5°C, which are the second and third warmest values after the 1998 value of 29.9°C.

Benthic Composition

With very few exceptions (most notably Egmont atoll), at all sites and depths living substrate far outweighed non-living substrate, and hard coral was the most dominant form of living benthos. Figure 3 shows, as an example, sites from 5 m depth,

Reef sites at Peros Banos, Salomon and Great Chagos Bank atolls had greater cover than Egmont or Diego Garcia atolls, with significantly higher levels of hard coral cover, as well as greater prevalence of larger, older corals. In many sites, coral cover appears to have recovered almost completely (Fig. 4).

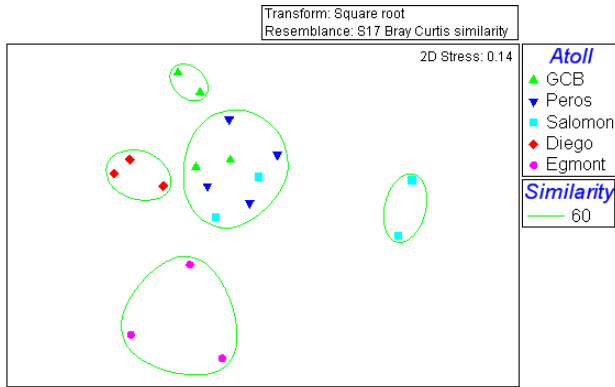


Figure 5. MDS ordination of samples (all atolls) based on benthic community data from 5m survey sites. Index is Bray-Curtis, grouping boundaries are 60% similarity (GCB = Great Chagos Bank).

Average hard coral cover at survey sites ranged from values as low as 6% at Egmont to 87% at Diego Garcia. Soft coral ranged from being entirely absent at several sites to 30% cover at Peros Banos.

Benthic cover varied among atolls for all depth



Figure 6: Widespread mortality of *Acropora cytherea*. at Egmont atoll, 8m depth. Living sections of some tables are a green-brown, while the dead tables are grey.

samples, illustrated for 5 m samples in an MDS ordination plot of benthic composition, showing Bray-Curtis similarity clusters at a 60% level (Fig. 5). Egmont sites were most dissimilar from other sites,

Diego Garcia sites clustered closely together, while sites from the other islands were mixed amongst each other. Two-way crossed ANOSIM testing for differences between depths and atolls confirms separation of samples between depths also (global $R = 0.48$, $p < 0.1\%$) and atolls (global $R = 0.42$, $p < 0.1\%$). This result suggests that different characteristic patterns of benthic composition are found consistently within the different groups. Egmont sites had been affected by a severe mortality event which appeared to have taken place in the 12 months prior to surveying. This event killed over 95% of hard coral on shallow reefs as well as dramatically reducing hard coral

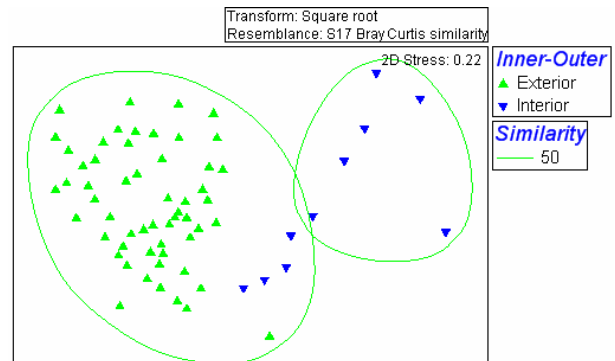


Figure 7. MDS ordination of samples (all atolls) based on coral cover from 15m sites showing disimilarities of lagoonal patch and outer reefs with Bray-Curtis grouping of samples at 50% resemblance (lagoonal patch = interior; outer reef = exterior).

recruitment. The substrate was covered almost entirely of large dead *Acropora cytherea* and some *A. clathrata* table corals up to 3.75m in diameter (Fig. 6). The collapse and erosion of these tables was also observed to cause further mortality by scouring of other corals on the outer reef slope down to 15m depth. Diego Garcia's reef communities showed higher levels of soft corals and sponges, and generally lower coral cover except at one deep site where *Pachyseris* provided over 75% cover. The eastern side of Salomon atoll showed less recovery than the west side; this site was previously dominated by soft corals which appear in

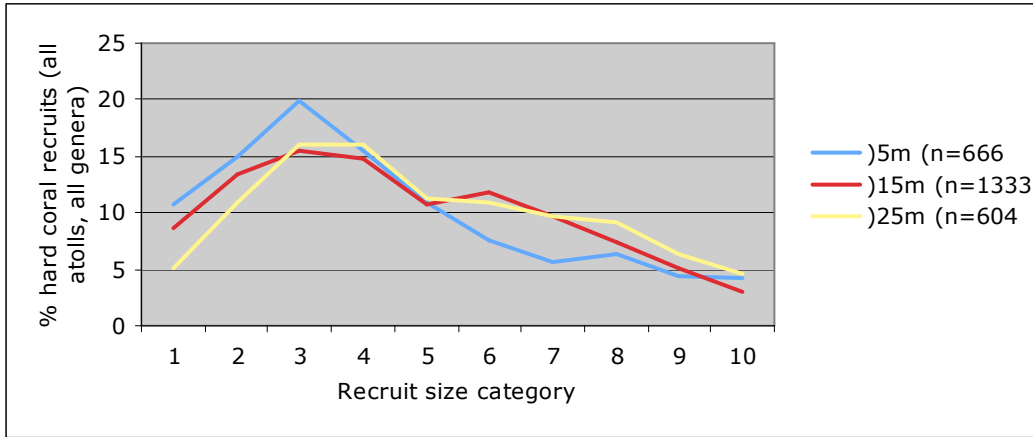


Figure 8. Size class frequency distributions of hard coral recruit genera at 5, 15 and 25m depths (pooled data from all genera at all atolls). Size categories in incremental 10mm intervals from category 1 (0-10mm).

all sites to have recovered much less successfully to date than have the stony corals. Such patchiness could be due to effects of localised environmental conditions such as cool upwellings (which are observed off Diego Garcia and which have led to some *Caulerpa* dominated sites), and localised current patterns.

Lagoonal patch reefs and the peripheral reefs fringing islands had also recovered well, and all those observed were dominated by tabular or staghorn forms of *Acropora*, in shallow water. Broad differences

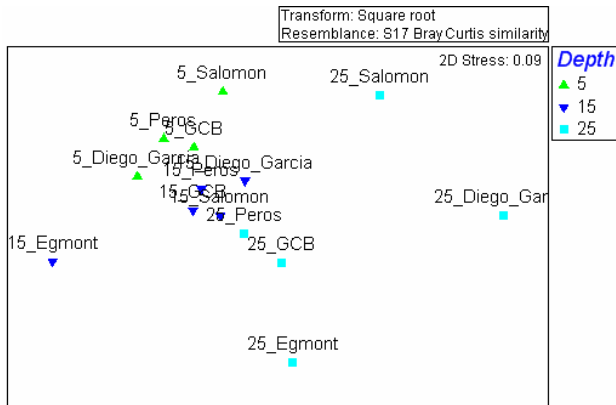


Figure 9. Non-metric MDS ordination of samples (all atolls, all depths) based on hard coral recruit community data (number of recruits per m² per genus) (GCB = Great Chagos Bank).

between lagoonal patch and outer reef slope communities were observed during the study (two-way crossed ANOSIM, global R = 0.72, p < 0.1%), as shown for 15m survey sites by the MDS ordination in Figure 7. In addition, lagoonal patch reefs showed generally higher hard coral cover at 25m than did outer reef slopes.

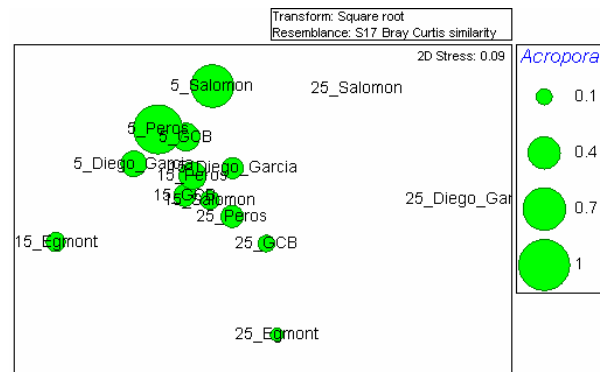


Figure 10. Bubble plot showing variation in relative density (recruits per m²) of *Acropora* recruits within MDS ordination of Figure 8 (GCB = Great Chagos Bank).

Recruitment

Two thousand six hundred and three hard coral recruits and juveniles from 35 genera were surveyed within 1,159 quadrats of 0.11m² sampled at three

survey depths within the 19 reef sites, equivalent to sampling a total reef area across the three depths of 129m². Recruit density varied from 6 m⁻² at Egmont atoll (5m) to 28 m⁻² at Salomon atoll (15m). Across all genera the frequency of hard coral recruits increased from size category 1 to 3 (0-10mm and 20-30mm respectively, then decreased with increasing size (Fig. 8). However the shape and nature of this decrease varies widely between different genera and between groups of genera. Shannon Wiener diversity (H') of recruits at genus level was lowest for Egmont and Diego Garcia sites at all depths (with the exception of Diego Garcia at 15m). Analysis of hard coral recruit density and diversity (recruits per genus m⁻²) by depth and atoll shows significant differences between depths (ANOSIM, Rho = 0.75, p < 0.05, Fig. 9), however there was no differentiation between atolls (Rho = 0.122, p < 0.3). Superimposing univariate genus-specific hard coral recruit density values on the multivariate MDS plot shown in Figure 9 provides a means of identifying variations in the density of recruits of individual genera across all of the samples. Common genera segregated into four groups according to recruitment by depth (e.g. Figs. 10, 11):

- Those favouring shallow depths (5m)– *Acropora*, *Porites*, *Acanthastrea* and *Hydnophora*;
- Those favouring medium depths (15m)– *Galaxea*, *Physogyra*, *Oxypora*, *Platygyra* and *Mycedium*;
- Those favouring deep depths (25m) – *Pachyseris*, *Podabacia*, *Seriatorpora*, *Leptoseris*, *Gardineroceras* & *Stylocoeniella*;
- No clear depth preference – *Pavona*, *Favia*, *Favites*, *Psammocora*, *Fungia*, *Montipora*, *Pocillopora*, *Goniastrea*, *Leptastrea*, *Lobophyllia*.

DISCUSSION

Recovery

All atolls have shown strong, vigorous recovery after the 1998 bleaching and mortality event. However the extent of this recovery, and the composition of reef

benthic communities around the archipelago, varied enormously between survey sites. Highly significant differences in reef composition were recorded between different atolls, and between different depths at all atolls. The higher coral cover observed at all depths at lagoonal reefs than at outer slope reefs in Chagos may be due to adaptation of corals to higher sea temperatures in these environments. Lagoonal reefs are more sheltered than outer reef sites, with more restricted water exchange, and are likely to experience warmer water conditions during calm conditions than the more exposed seaward slopes (Pugh and Rayner 1981).

The ability of Chagos reefs to 'bounce back' to rich reef communities after experiencing severe bleaching-related mortality in recent years has not been recorded in other reef environments in the Indian Ocean. Generally in the Indo-Pacific, recovery has been much poorer: Bruno and Selig (2007) assess 6000 surveys carried out over the past 40 years, finding that average decline both continues and varies on average from 1-2% per year, with average cover 5 years after the 1998 event being just 22%. This is similar to findings in the Caribbean (Gardner et al 2005). In contrast, many Chagos reefs have recovered to benthic cover values similar to that of 25 years ago (Sheppard 1980) with substantial recruitment, indicating a resilient system with unusually high recovery potential.

The recent mortality event documented at Egmont atoll killed almost all hard coral on shallow reefs, and has greatly reduced coral recruitment rates. This event is likely to have occurred in March-April 2005, when a sustained period of abnormally warm sea surface temperature impacted the central Indian Ocean region (in prep and see Fig. 2), and may have caused significant bleaching and the observed mortality. It is currently unknown why Egmont's reefs were more susceptible to bleaching and mortality in 2005 than any of the other atolls, but it could be due to the unusually shallow lagoon at Egmont, which may have acted as a basin for heating lagoonal water.

Recruitment

There is a general paucity of published data on temporal changes in coral recruit densities in the Indian Ocean post 1998. Data from Kiunga in northern Kenya show negligible recruitment in 1999 immediately following the widespread mortality event, increasing to 2 recruits m^{-2} in 2000/01 and 1-1.5 recruits m^{-2} in 2003/04 (Obura, 2002). These results are similar to the low recruitment measured on shallow sites in Egmont. Even the lowest of the Chagos recruit densities are an order of magnitude higher than the rates of recruitment of new corals documented at reefs in South Asia, the central Indian Ocean, and the East African coast, where 'substantial' rates of coral recruitment of 0.4-0.6 recruits m^{-2} have been recorded in recent years (Souter and Linden 2005). Other sites, such as marginal reefs in South Africa, have shown years where no recruitment of new corals was recorded at all.

The lack of between-atoll difference in recruitment may be explained in two ways. Firstly, within atoll differences are substantial, and may simply mask any between-atoll differences. But equally, present-day benthic cover values depend largely on recruitment that took place several years previously, when recruitment is likely to have been much more patchy from the very sparse adults which survived the 1998 event. While a certain degree of patchiness is always inevitable, greater evenness is likely to emerge as succession continues. Reproduction of survivors leads to broad-scale dispersal and settlement of new planulae enabling recruitment and recolonisation of reef areas affected by mortality. This pattern is only broken if, as is seen in Egmont at present, further intervening mortality takes place.

The abundance of juvenile corals in Chagos observed during this study indicates that recruitment is not currently a limiting factor for recovery of Chagos reefs. Recruitment, notably of previously dominant *Acropora*, has been identified as a limiting factor preventing reef recovery at marginal reef sites in East Africa, and at reefs influenced by cool currents in northern Kenya (Souter and Linden 2005). However

the observed high levels of recruitment of *Acropora* spp. in Chagos do not rule out the ability of *Acropora* species, including the decimated population of *A. palifera*, to regain their original dominant shallow water coverage in this group of atolls.

Differential Responses of Species

A number of authors have discussed recent evidence of differential susceptibility of coral genera to warming since the 1998 bleaching and mortality episode (Obura, 2001, Grimsditch and Salm, 2005, Sheppard, 2006).

Relative increases in the abundance of faviids and massive *Porites* species following the 1998 bleaching event have been recorded at other sites in the Indian Ocean, and especially in the Persian Gulf, to the extent that faviids, as enduring survivors, are now the most common family on many reefs, often occupying reef space created by mortality and subsequent disappearance of *Acropora* (Obura 2001, Riegl 2002, Sheppard 2006). This is not the case in Chagos, where despite experiencing repeated bleaching events, *Acropora* has recolonised most reef sites, both lagoonal and seaward. Given the extent of mortality recorded in the aftermath of 1998, most colonies are likely to be less than 8 years in age. Studies undertaken after the 1998 mortality at numerous other heavily impacted Indian Ocean reef sites have led to predictions that repeated exposure to lethal sea surface temperatures may alter reef succession towards a permanent alternative stable state. These concerns do not currently appear to apply for Chagos reefs, where stable *Acropora* dominated communities appear to have 'bounced back' within a matter of 4-6 years.

Sheppard (2006) noted that members of the genus *Montipora*, commonly smaller and more encrusting members of the acroporidae than are most *Acropora*, were not disturbed to the same degree and survived better than *Acropora*. This conclusion was not supported by observations during this study, where *Montipora* remained extremely uncommon on all reef sites. It is possible therefore that this genus has suffered significant disturbance in the 2 years since the

last detailed marine surveys were undertaken in Chagos.

One additional striking absence was of the faviid *Diploastrea heliophora*. Once noted as common in Chagos lagoons, this massive faviid was entirely absent in all surveys undertaken in this research. It is indeed possible that this monospecific genus may be one of the first candidate species for local extinction.

Recommendations for Future Research

Data recorded in this study suggest that Chagos reefs have followed a different trajectory to many other reef communities in the Indian Ocean following 1998. The high resilience and re-seeding capacity of Chagos reef systems may be a result of their undisturbed nature, although additional factors should also be considered. These include the complex geomorphology of this oceanic archipelago as well as its proximity to the south equatorial current, downstream from the outflow of coral larvae emanating from the highly biodiverse reef ecosystems of the south east Asian archipelagos.

Understanding ecological change in the marine environment of Chagos is severely restricted by limited opportunities for sampling in the archipelago. The irregular monitoring of Chagos reefs has prevented more detailed study of the successive phases of reef recovery, prohibiting sufficient understanding of the processes of regrowth of coral communities. It is likely also that there is an insufficient picture of the scale and number of bleaching-related stress and mortality events that have impacted the archipelago's reefs in recent years. Following observations of recent localised mortality episodes at Egmont atoll, future analyses of archipelago-wide recovery therefore must not assume recovery from a more or less 'clean slate' following 1998, but must take into account the further smaller but important episodes of warming since then. As a result of the importance of Chagos' marine systems, both as a stepping stone for regional marine biodiversity and especially as a globally important reference site for monitoring responses of

undisturbed reef systems to climate-related stress, it is important that long-term monitoring of both biophysical variables and reef community is increased to track and quantify temporal changes in reef health. Given that sub-lethal warming is likely also to severely reduce reproductive output of coral populations, better knowledge of the size frequency abundance of juvenile scleractinia would provide better insight into possible lethal and sub-lethal stresses to reefs too. Greater monitoring becomes increasingly important given the most recent predictions of SST rise in tropical locations (<http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>, Sheppard 2003). It is most important that future bleaching events in this area are not overlooked.

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