Key climate change effects on the coastal and marine environment around the Indian Ocean UK Overseas Territories

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EXECUTIVE SUMMARY

- A climate-change baseline and climate-change impacts of the highest priority were identified for the British Indian Ocean Territory (BIOT) by scientists with relevant expertise along with managers responsible for the area.
- Four priority climate-change issues were identified for BIOT:

  1. Changes in coral species
  2. Changes in coral reefs (reef carbonate structure and the living reef ecosystem)
  3. Changes in reef islands and sandy beaches
  4. Impacts on the provision of natural coastal protection and and island resilience to sea-level rise.

- All projections of future climate change suggest that severity and frequency of destructive ocean heatwaves will increase. Eighteen years ago, the 'extinction point' for reefs in the Chagos Archipelago was predicted to be in the early 2020s, and evidence suggests that the likelihood is increasing, based on present observations and the implication of climate-change projections on coral reefs in the Indian Ocean region.
- As a fully protected Marine Protected Area (MPA) in a remote location, BIOT provides a globally important reference site for climate change impacts that can give insights into finer-scale vulnerability and resilience in the absence of other anthropogenic stressors. Research to date has demonstrated the value of BIOT as an ocean observatory.
- Restoration of island ecosystems through the eradication of invasive rats, and restoration of native vegetation, is the quickest and most

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effective way to restore seabird populations and the associated nutrient pathways that build resilience against climate-change impacts in the marine environment.

- At a local level, the BIOT administration should implement any possible greenhouse gas reduction measures on the inhabited island of Diego Garcia and minimise stressors to the BIOT MPA. At a global level, the UK government must continue to demonstrate leadership in the immediate reduction of greenhouse gas emissions and meet and then exceed targets set in the Paris Agreement. COP26 will be instrumental in defining the pathway for the planet and any future for coral reefs in BIOT and elsewhere.

DESCRIPTION OF OVERSEAS TERRITORIES IN THE REGION

The British Indian Ocean Territory (BIOT) is the only UK Overseas Territory in the Indian Ocean and it includes the Chagos Archipelago (Figure 1). The BIOT Marine Protected Area (MPA) was designated as an IUCN management category 1a strict nature reserve in 2010, with no permitted fishing or other extractive activities. The entire MPA encompasses 640,000 km2 of which 19,120 km2 is shallower than 100 m, with the remainder deep oceanic water to depths of >5000 m with an estimated 86 seamounts (Sheppard *et al.*, 2012; Hays *et al.*, 2020).

The archipelago includes >60,000 km2 of shallow limestone platform and reefs, including the Great Chagos Bank, described as the world’s largest atoll structure, covering an area of 12,000 km2 (Sheppard *et al.*, 2012). The archipelago is made up of 58 islands with a land area of only 56 km2 of which only the most southerly atoll, Diego Garcia, is inhabited as a military base. This atoll falls outside the MPA with a three nautical-mile buffer, although there are other environmental protection measures in place, including a RAMSAR site that covers most of the atoll (covering a total area of 350 km2).

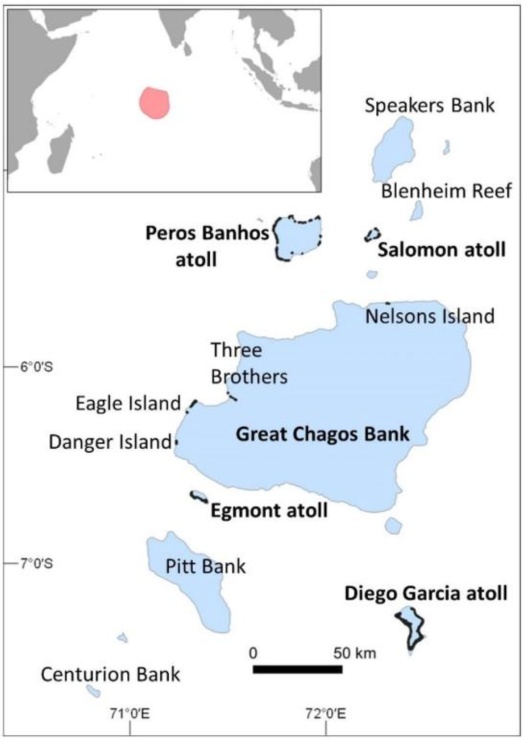


Figure 1. The Chagos Archipelago. Inset shows the general location within the Indian Ocean and the MPA boundary (red). Main map shows the archipelago which lies at the heart of the MPA. The five atolls with land are in bold type, whereas selected submerged reefs and atolls are not in bold. Islands on the Great Chagos Bank include Danger Island, Eagle Island, Three Brothers islands and Nelsons Island. Blue shading indicates water shallower than approximately 100 m. (From Hays et al., 2020.)

Research in BIOT began in the 1970s, but it was periodic and irregular until 2012 owing to the limitations of both access and resources required to work in such a remote location. Annual research expeditions have been running every year since 2012, with support from the Overseas Territories Environment Fund and Darwin Initiative to 2015. The data collected now form some of the World's longest time-series measurements on coral reefs. Over the last eight years, significant support from the Bertarelli Foundation (https://www.fondation-bertarelli.org/) has built a diverse and interdisciplinary programme of marine science that currently involves approximately 100 scientists from 24 institutions and seven countries. Research leading up to the MPA designation was consolidated in a review by Sheppard *et al.* (2012) with the next decade of research in the context of the MPA recently reviewed by Hays *et al.* (2020).

The uninhabited, remote, and protected 'no take' status of BIOT has meant it provides an invaluable reference site and ocean observatory to determine the interactions between global, regional, and local stressors in the context of climate change. This report highlights priority climate change issues to inform a report card on BIOT as part of a series for the UK Overseas

Territories following a standardised methodology (Frost *et al.*, 2017) used by the Marine Climate Change Impacts Partnership (MCCIP).

MAIN CLIMATE CHANGE DRIVERS

The tropical Indian Ocean has experienced rapid basin-wide sea surface temperature (SST) warming, with an average rise of 1.0 °C (0.15 °C/decade) during 1951–2015, faster than the global average.

Since 2006, direct sea temperature measurements have been taken in BIOT across atolls at depths of 5 m, 15 m, and 25 m, all of which show an overall rising trend of between 0.3–0.4 ˚C per decade (Figure 2).

Mass mortality of corals is often triggered when sea temperatures over 29.5˚C persist for 10 or more 'degree heating' weeks, as recorded across the archipelago in 1998 and in 2010, 2015, 2016, 2019 and 2020. Models project more frequent and severe marine heatwaves over the coming decades, with annual severe bleaching predicted by 2036 across the Chagos Archipelago under a business-as-usual emissions scenario.

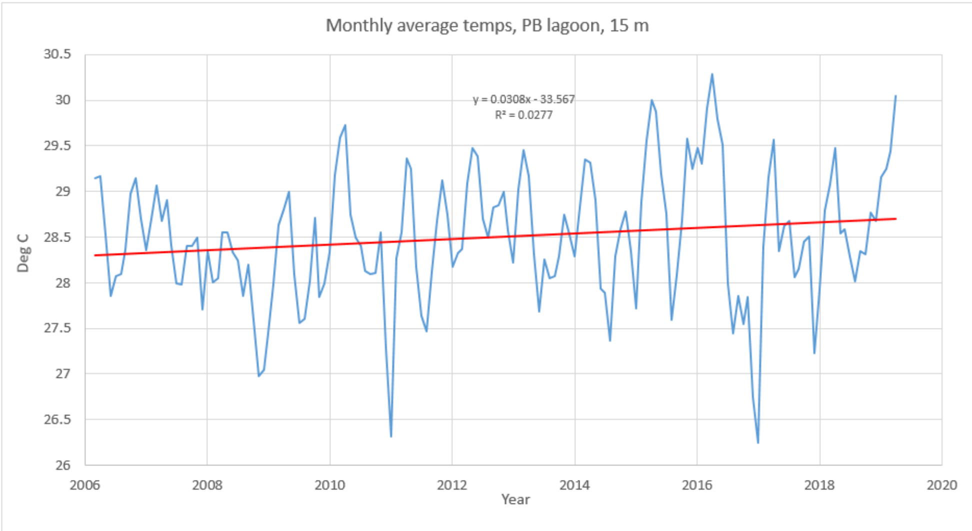


Figure 2. Temperature in Peros Banhos lagoon at 15 m depth (Sheppard et al., 2019).

Conditions in the region are strongly affected by the extreme positive Indian Ocean Dipole (IOD), an irregular east-west oscillation of SST across the Indian Ocean that in its positive phase can have effects that extend into BIOT waters. This could increase storm activity in the region and lead to more coral damage.

Rates of sea level rise in BIOT have tracked global averages for the region, with current rates of sea level rise reported to range between 3.3 mm and 6 mm per year (Dunne et al., 2012, Sheppard and Sheppard, 2019, Wu et al., 2021). Recent sea level rise in Diego Garcia, as recorded by the tide gauge, is shown in figure 3. Where higher rates than those that could be explained by sea level rise were documented, these were considered due to tectonic activity (Purkis et al., 2016), but this is now thought to be negligible (Wu et al., 2021). Instead, geodetic data suggest that the rate of sea-level rise the archipelago is presently subjected to is substantially swifter than the global eustatic average (Wu et al., 2021). There is emerging evidence that the islands in BIOT are experiencing morphological adjustment through both shoreline erosion and accretion, but that total island areas has been net static over recent decades in the uninhabited atolls despite the estimated rates of sea level rise in the range of 3.3 – 6 mm per year (Dunne et al., 2012, Wu et al., 2021).

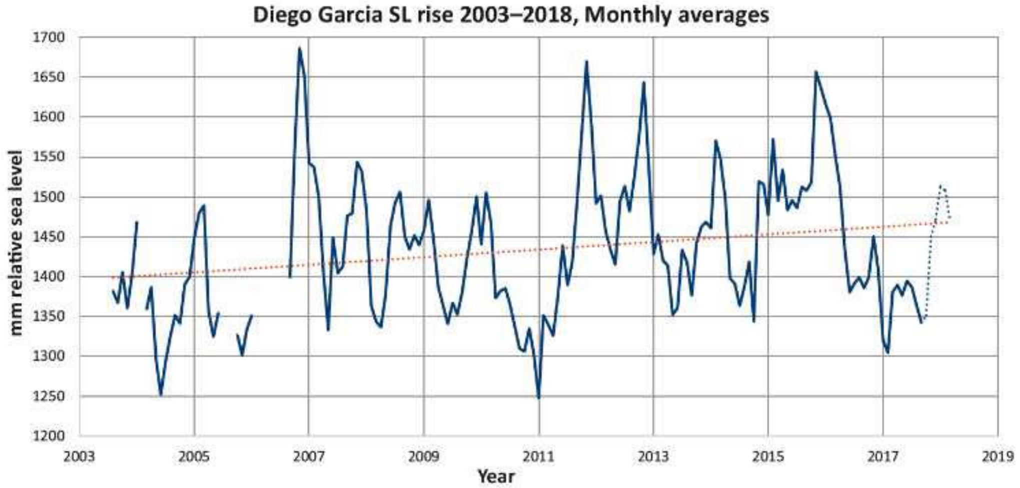


Figure 3: Recent sea level rise in Diego Garcia. A plot showing monthly means taken from the Diego Garcia tide gauge (Sheppard and Sheppard 2019).

A rise in annual average rainfall has been observed in Diego Garcia since 1950 from 2,500 mm in 1950 to over 3,100 mm at the end 2019 (figure 4)

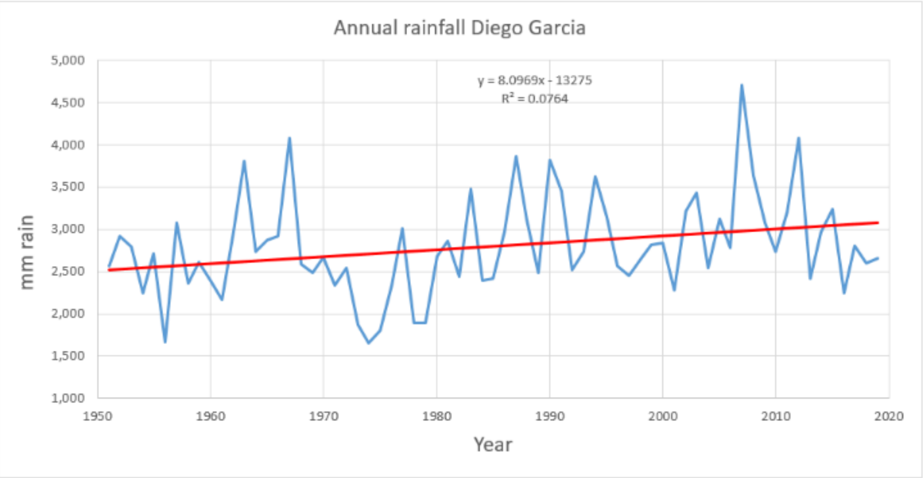


Figure 4. Annual rainfall based on data from the meteorological station at Diego Garcia airfield, between 1950 and 2019. (Sheppard and Sheppard, 2019.)

PRIORITY 1: CHANGES IN CORAL SPECIES

WHAT HAS HAPPENED

The Chagos Archipelago is one of very few sites in the world where long-term coral reef monitoring began in the 1970s and accounted for between 25–50% of the healthy reefs in the region (Sheppard *et al.*, 2012). However, BIOT has experienced two major recorded coral bleaching events in recent decades (in 1998, and 2015-2016), demonstrating that despite its geographically isolated position and fully protected status (since 2010), it is neverthless influenced by climate change. In the first major coral bleaching event of 1998, widespread coral mortality mainly affected reefs to a depth of 15 m but extended to depths of > 40 m in some locations (Sheppard *et al.*, 2012; Sheppard *et al.*, 2017). Average coral cover had decreased from 25 – 45% to around 10% in 1999 at all observed depths, but due to an absence of other pressures, most of the reefs recovered quickly and by 2012 coral cover on reefs in the BIOT MPA averaged 40–50%, with juvenile coral densities of 20–60 colonies m^{-2}, although species composition was not necessarily the same (Sheppard *et al.*, 2017).

Unfortunately, BIOT reefs suffered further severe bleaching and mortality because of more-recent back-to-back marine heatwaves. First, in 2015, a 7.5 maximum Degree Heating Weeks (DHW) thermal anomaly (where DHW is equivalent to one week of sea surface temperature one degree Celcius above the expected summertime maximum, or accumulated heat stress) similar to that in 1998 caused a 60% coral cover decrease from 30% cover in 2012 to 12% in April 2016 (Head *et al.*, 2019). Mortality was taxon-specific, with *Porites* becoming the dominant coral genus post-bleaching concomitant with an 86% decline in *Acropora*. Due to the similar levels of mortality after the 2015–2016 event, it was inferred that no coral acclimation had happened following the 1998 event. Then in 2016, a 17.6 DHW thermal anomaly caused further damage, with 68% of remaining corals bleaching in May 2016, and coral cover further declining by 29% at Peros Banhos Atoll (Head *et al.*, 2019). Although there is comparably limited information for habitats below 20 m deep, the largest losses were of foliacious forms (Hays *et al.*, 2020). Soft corals have also been lost, especially on shallow reefs and seaward-facing exposed reefs, and they now occupy less than 4% of coral cover in the 15–25 m depth range (Hays *et al.*, 2020). However, there was variation across the archipelago and some sites did escape mortality, including much of the shallow water lagoonal reefs of Salomon Atoll, and an area along the north-west reef-slope of Egmont.

The extensive damage to the reefs through these more-frequent and severe global-warming events is compromising coral recruitment (Sheppard *et al.*, 2020). Data from 2017 indicate that the density of newly settled coral recruits of less than one-year-old have reduced by approximately 90% since 2013 (Sheppard *et al.*, 2017). Larger young corals over one-year-old are present in greater numbers, though most are located on unstable dead table corals or mobile rubble and therefore are likely to experience high mortality rates

(Sheppard *et al.*, 2017). Measured growth rates for several coral species were also comparatively low in 2018–2019, potentially as a function of prolonged heat stress on coral physiology (Lange and Perry, 2020). Shallow reefs are increasingly covered by the bioeroding sponge *Cliona* spp., decreasing the area suitable for new coral settlement (Hays *et al.*, 2020).

Since the late 1970s, several coral species and key assemblages in the Chagos Archipelago have become regionally or functionally extinct. Although species diversity remains high at present, local extinctions may increase in the future, following the collective impact of low recruitment and lack of suitable substrate for young corals to settle (Sheppard *et al.*, 2020). Regional extinctions of at least three coral species were reported in BIOT (Sheppard *et al.*, 2020). These are:

1. *Diploastrea heliopora* – likely to be regionally extinct in the archipelago, common until 1996 then not seen since
2. *Seriatopora* sp. – abundant in BIOT until the 1998 marine heatwave after which it disappeared until 2014, became common again, but has not been reported since 2015
3. *Catalaphyllia jardinei* is also absent since the 1998 heatwave, although it has always been quite rare.

In addition, three formerly extensive coral assemblages in this archipelago were considered functionally extinct: the *Isopora palifera* assemblage; the deep foliaceous species assemblage; and the shallow 'finger coral' assemblage (Sheppard *et al.*, 2020). Finally, the endemic Chagos brain coral (*Ctenella chagius*) is near extinction, from being one of the 25 most common corals in BIOT in the 1970s (Sheppard *et al.*, 1984). No live colonies could be found following the 2015 warming until 2018, at which point a few remnant colonies were reported, and research is currently underway to establish if the species is still viable (Sheppard *et al.*, 2020). Although these species were not major reef-builders, their loss or reduced abundance is perhaps indicative of increasing climate stress on these remote ecosystems.

Changes in live coral cover and coral recruitment were accompanied by a major shift from competitive to stress-tolerant coral taxa. Magnitudes of decline were comparable to those reported elsewhere in the Indian Ocean, despite inter-site differences in dominant coral species. These trends differ from those on reefs dominated by stress-tolerant taxa, which experienced minor declines in production post-warming (Lange and Perry, 2019).

A very few BIOT reefs have also experienced localised outbreaks of crown-of-thorns starfish (*Acanthaster planci*) causing high mortality locally, notably eastern Eagle Island and Danger Island on the Great Chagos Bank of branching *Acropora* spp. in 2013 (Roche *et al.*, 2015). Coral diseases have been recorded more frequently, that may relate to warming events. White Syndrome disease was prevalent on many reefs in 2014 and 2015, causing widespread mortality of tabular *Acropora* colonies (Sheppard *et al.*, 2017). The first record of coralline fungal disease in the Indian Ocean was recorded in BIOT in 2018 at high densities which may also impact coral recruitment (Williams *et al.*, 2018).

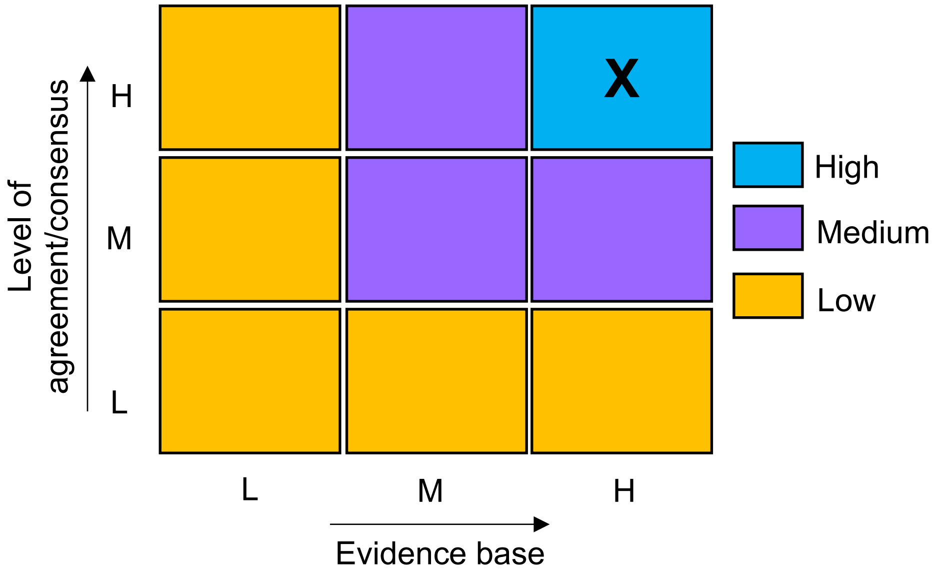
WHAT MIGHT HAPPEN

Reefs in the Chagos Archipelago have repeatedly been impacted by coral-bleaching events, and the current ecological condition of the reefs suggests they are at a critical recovery stage (Sheppard *et al.*, 2020). The third global coral bleaching event of 2015-2016 was the longest on record, but climate model projections suggest that the frequency and severity of such events may become the norm in the coming two decades (UNEP, 2020). However, models demonstrate considerable spatial variation in the projected timing of the onset of annual severe bleaching conditions which will be a major driver of differences in the relative vulnerability of coral reef ecosystems to climate change (UNEP, 2020). BIOT is predicted to see a large increase in the frequency of severe bleaching events in the coming decades, even under conservative emission scenarios (van Hooidonk *et al.*, 2016). In addition, atmospheric nitrogen deposition from anthropogenic sources is projected to increase in the future, negatively affecting even remote coral reefs by adding nutrients that increase macroalgae that can outcompete corals (Chen *et al.*, 2019).

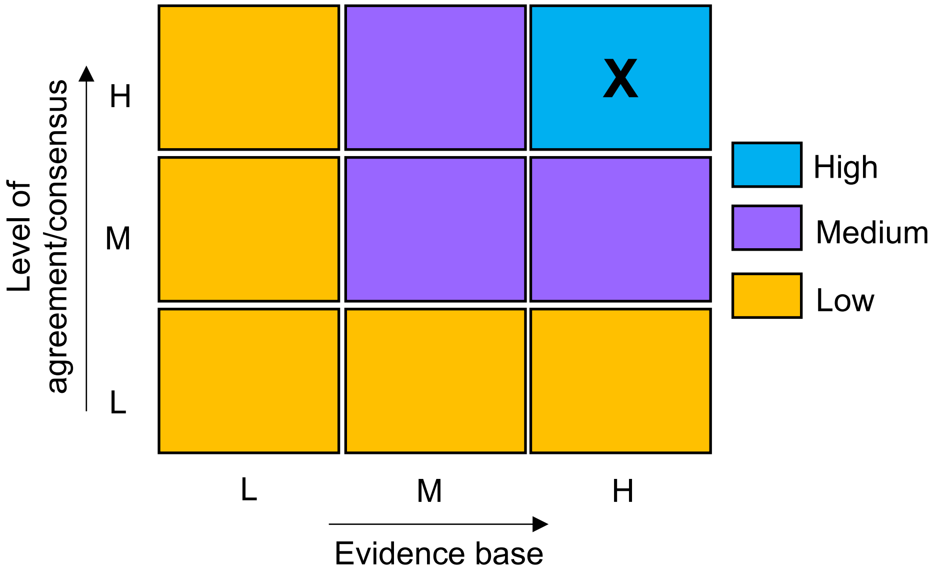
In BIOT, key questions are whether the reefs will either follow the same recovery trajectories as after 1998, or follow more-divergent trajectories at different sites and locations, or whether some sites may regime-shift to other states (Sheppard *et al.*, 2020). Ultimately, the primary control on coral-reef recovery will be the recurrence intervals and magnitudes of future heat-stress events. As BIOT is so remote and only inhabited on one island, recovery trajectories will not be impeded by local stressors such as anthropogenically derived nitrogen enrichment and altered nutrient ratios, which can exacerbate coral disease and bleaching, and has led to reef degradation in other protected areas (Hays *et al.*, 2020). Research is currently underway to conduct higher-resolution climate-model projections (from 20 km to 5 km) of future coral bleaching conditions for BIOT and the broader Indian Ocean that will increase our understanding of variation among reefs in vulnerability to climate change (G. Williams, pers. comm.). The results of these models will be available for COP26.

CONFIDENCE ASSESSMENT

WHAT HAS HAPPENED



WHAT MIGHT HAPPEN



Research has been focused on building a strong long-term baseline of coral data by gathering samples and observations from key reef areas over multiple years. Expert input from scientists who have worked on coral reefs in BIOT for up to 45 years, including as yet unpublished data.

IMPACTS ON BIODIVERSITY AND SOCIO-ECONOMICS

The evidence to date demonstrates a serious threat to coral reef biodiversity as a result of climate-change impacts, with impact on specific species, assemblages and reef community structure. Under this priority category, focusing on coral species, there are already several species that may be functionally extinct, including the only known endemic coral species in BIOT, the Chagos brain coral, *Ctenella chagius*. However, the major regionally important reef-building coral taxa, such as *Acropora*, have previously recovered well from bleaching events, and their recovery from recent disturbance events. In the future they will be more critical to the maintenance of the reef framework and its structural complexity on which most reef-associated species depend.

DRIVERS OF CHANGE

Climate-change driven increases in sea temperature are the major driver for changes in coral reefs, resulting in bleaching and mortality. Models indicate more-frequent and severe projected frequency of sea temperature increases (UNEP, 2020). Since 2006, direct sea temperature measurements have been encompassed BIOT across atolls at depths of 5 m, 15 m, and 25 m, all of which show an overall rising trend, with some evidence of larger annual variability (Figure 2, Sheppard *et al.*, 2017; Sheppard and Sheppard, 2019).

The rise in temperature in Perhos Banhos lagoon, shown by the line of best fit in Figure 2, is 0.4 ºC between 2006–2019, or just over 0.3 ºC per decade, and is significant ($p<0.05$) despite the annual variation. The rise is greater in Salomon lagoon (more than 0.45 ºC at 5 m depth) as it is smaller, and shallower with much more-restricted water flow (Sheppard *et al.*, 2017, 2019). The water temperature threshold for mass coral bleaching in this region is ~29.5ºC, as recorded in 1998, and this temperature was exceeded in 2010, 2015, 2016, 2019 and 2020 at all locations and depths to 25 m across the archipelago. The duration of these HW episodes was critical in determining the impact of them on corals. Some patchiness exists, for reasons that are likely to include localised cooler currents and upwellings that moderate the duration of the warm spike and the sharpness of the rise (Sheppard *et al.*, 2017).

Research on the super charging of the Eastern Indian Ocean dipole suggests potential for increased storm activity that may be a significant climate driver of changes in corals (Cai *et al.*, 2014), although how this will impact

BIOT is unknown. A rise in rainfall has occurred from 2500 mm in 1950 to over 3100 mm at the end 2019 (Figure 4), an increase of about a quarter in the overall trend. This is a significant increase ($p<0.05$) and is a clear signal of gross climate change, although this is likely to have positive effects on groundwater aquifers on the islands.

KEY EVIDENCE SOURCES

- The UNEP 2020 report of projections of the timing of severe coral-bleaching conditions using the new generation of climate models used by the IPCC – the Coupled Model Intercomparison Project Phase 6 (CMIP6) generation of models. These have >4 times the spatial resolution of previous iterations (UNEP, 2017) and are forced by the recently released Shared Socioeconomic Pathways (SSPs). These projections include the SSP5-8.5 and SSP2-4.5 pathways. SSP5-8.5 represents current rates of emissions and emissions growth; a 'worst-case scenario' that assumes there is no or ineffective climate policies. SSP2-4.5 represents a highly ambitious, but plausible, moderate (between extremes) scenario where there is a greater level of emissions reduction than would result from all Nationally Determined Contributions in the Paris Agreement combined (UNEP, 2020).
- Most recent climate-change projections for reefs using the Coupled Model Intercomparison Project Phase 6 (CMIP6) ensemble which is based on Shared Socioeconomic Pathways (SSEPs) as opposed to Representation Concentration Pathways (RCPs) (G. Williams, pers. comms).
- Peer-reviewed publications from research dating back to the 1970s – see references.
- Data from island-based research expedition visited the atolls in 1978–1979, followed by ship-based research visits to the area at irregular intervals from 1996 to 2012, and annual ship and island-based expeditions from 2012 to 2020.
- Data from BIOT stored on the Allen Coral Atlas https://allencoralatlas.org/atlas/#7.92/-5.8360/72.9118
- Expert input from scientists who have worked on coral reefs in BIOT for up to 45 years, including unpublished data.

KNOWLEDGE GAPS

- Research has been focused on building trends by visiting the same sites over several years. This means that there are very patchy geographical, demographic, and temporal data on most hard, soft and mesophotic coral species' in BIOT, making species' viability assessments and recovery plans more challenging.
- Available data are very limited on soft corals and corals distributed below 25 m (current diver limits), although estimates of soft coral cover at lifeform level are in progress (J. Sannassy Pilly, Bangor University).

PRIORITY 2: CHANGES IN CORAL REEFS

WHAT HAS HAPPENED

The tropical Indian Ocean has experienced rapid basin-wide sea surface temperature (SST) warming, with an average rise of 1.0 °C (0.15 °C/decade) during 1951–2015, compared to an average rise of 0.7 °C globally (0.11 °C/decade). The SST warming is spatially non-uniform and about 90% of the warming is attributed to anthropogenic emissions (Roxy *et al.*, 2020). The rate of warming in the tropical Indian Ocean is the fastest among tropical oceans and accounts for about one quarter of the increase in global oceanic heat content over the last two decades (Beal *et al.*, 20120 despite representing only 13% of the global ocean surface (Roxy *et al.*, 2020).

In BIOT, after the 1998 bleaching event, coral recruitment was prolific and the reefs largely regained coral cover levels consistent with those documented prior to 1998. This high degree of coral cover and return of dominant branching and tabular species on many forereef sites supported high net positive carbonate budgets, an important metric influencing reef growth potential and the maintenance of habitat complexity (Perry *et al.*, 2015). The carbonate budget of a reef describes the net rate of carbonate production resulting from various biologically-, physically- and chemically-driven production and erosion processes. By measuring the carbonate budget over time, insights can be gathered on a reef's growth potential and its capacity to sustain key geo-ecological services such as habitat provision and coastal protection (Lange *et al.*, 2020). Resultant estimates of average vertical reef accretion rates on *Acropora*-dominated reefs (4.4 ± 1.0 mm per year) in BIOT after the 1998 event were high in both a regional and global context, indicating that many of the reefs had the capacity to track projected future sea-level rise (Perry *et al.*, 2018). However, the 2015–2016 bleaching event had a major impact on community composition and reef carbonate production. The decline in coral cover was mostly driven by mortality of tabular *Acropora* spp. with an associated decline in mean reef rugosity (by 16%); rubble cover doubled between 2015 and 2018 (Lange and Perry, 2019). This resulted in an associated decline in coral carbonate production rates, which dropped by an average of 77% (Lange and Perry, 2019).

While coral cover is starting to increase, structural complexity changes are likely to continue for several years, as the remaining reef continues to degrade due to intense external and internal bio-physical erosion. Reef structural complexity is a useful indicator of the health and resilience of reefs, as well as providing important habitat for diverse reef species (Bayley *et al.*, 2019). Monitoring change is assisted by the greater use of 'structure from motion' photogrammetry techniques that accurately and repeatably capture the 3D reef structure in a way that is less biased by the observer and can be readily archived (Bayley *et al.*, 2019). This method can be applied from the species/colony level (Lange and Perry, 2020) to large scale analysis of reefs (Bayley and Mogg, 2020). Changes in large-scale structural complexity drive much of the associated changes in abundance and diversity of other organisms, such as fish (Graham and Nash, 2013).

It is important to consider all corals, including mesophotic coral ecosystems (MCEs) that are typically found at depths of 30 m to >150 m (Turner *et al.*, 2017) and are poorly studied in BIOT. Records date back to 1905, diver surveys to the 1970s (Sheppard, 1980) and a small number of brief ROV surveys were undertaken in 2016 (Andradi-Brown *et al.*, 2019). These studies were able to broadly document four reef habitat types that contain MCEs: seaward outer atoll reefs, lagoonal reef slopes, knolls within the lagoons (large pinnacles of reef reaching close to the surface from the lagoon floor), and submerged seamounts and banks (Andradi-Brown *et al.*, 2019). Coral and fish communities vary considerably with depth and among habitat types (Andradi-Brown *et al.*, 2019). In late 2019, multibeam tools and an ROV were deployed to conduct extensive surveys of both upper and lower mesophotic communities from 30 m to 150 m around Egmont Atoll and Sandes Seamount. Preliminary analysis has revealed diverse and abundant MCEs at all locations surveyed, hosting communities of zooxanthellate scleractinian corals, soft corals, sea fans and sponges (Hays *et al.*, 2020). Molecular analysis of sampled scleractinian coral specimens will identify the coral species and enable assessment of the genetic connectivity among shallow and mesophotic reefs (N. Foster and K. Howell, unpublished data).

WHAT MIGHT HAPPEN

As reported above, there is high confidence in the current projections that the SSTs in the tropical Indian Ocean will continue warming, with associated decreases in oxygen concentrations and pH (Roxy *et al.*, 2020). However, there is considerable local variation in the vulnerability of reefs to these changes, which may offer some resilience. Finer-resolution models under development (G. Williams, unpublished data) will identify the relative vulnerability of coral reefs across the Indian Ocean, which will need further research to understand the resilience of those reefs.

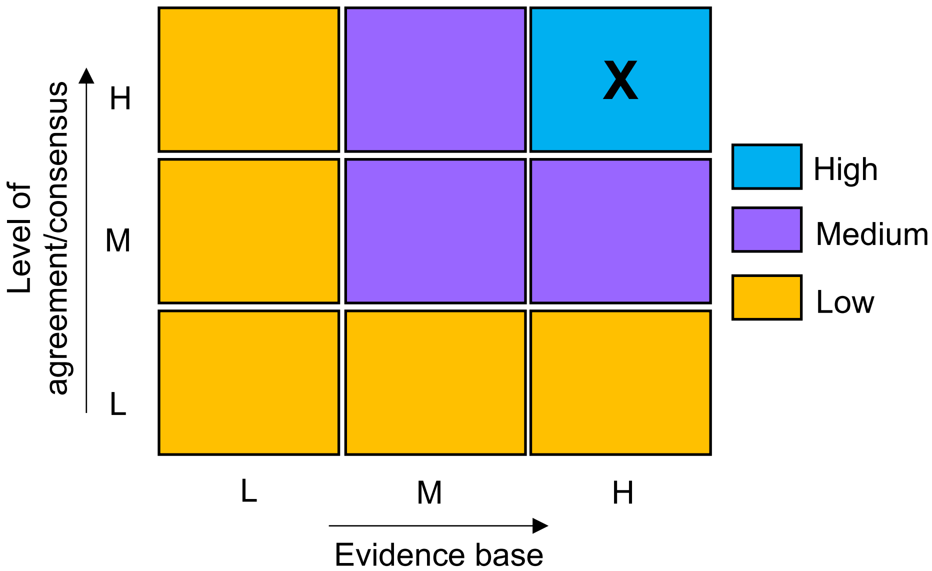
Resilience factors include heat selection, remote reefs, coral morphology, and *Symbiodinium* adaptation, but current understanding of coral reef recovery is based on decadal to sub-decadal impacts, so we do not yet know the adaptive capacity of corals to predicted annual frequencies of bleaching (Roche *et al.*, 2018). The return of *Acropora* spp. dominated communities will be crucial to restore the key geo-ecological functions of habitat complexity and carbonate production that local reefs delivered pre-bleaching (Lange and Perry, 2019).

The complex situation unfolding in the lagoons in BIOT is of interest. Shallow water reefs (less than 5 m) appeared to survive the 2015–2016 warming, while deeper reefs (20–25 m) are very badly affected. Degradation of lagoonal coral populations will impact regeneration potential of all coral populations due to their connectivity, decreasing reef resilience on the entire atoll (Riegl and Purkis, 2008). Modelling of pH and the aragonite saturation state suggests that conditions under continued high CO_2 emission scenarios may become unfavourable for corals by 2080 (Hofmann *et al.*, 2019). However, lagoons are projected to become 10% less saline and if this occurs the alkalinity of lagoon waters will decrease, causing a further decrease in saturation state (R. Dunbar, unpublished data).

Preliminary observations indicate that the MCEs of BIOT offer huge potential in the level of diversity they encompass and the extension of the shallow-water reefs into deeper waters. The BIOT MPA therefore has significant value in protecting extensive areas of diverse mesophotic coral ecosystems, which have the potential to support both local and regional shallow-water reefs if they act as refugia for some species, although the connectivity between shallow and deep reefs is still being established (Laverick *et al.*, 2016).

CONFIDENCE ASSESMENT

WHAT HAS HAPPENED



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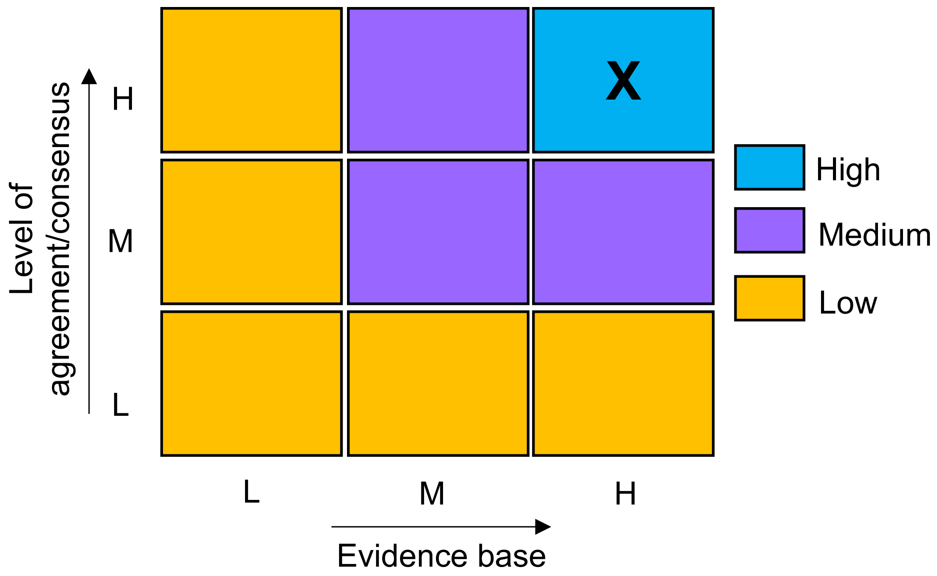


The negative effects of climate change on coral reefs, including in this region are well documented and there is high confidence that these environments will become increasingly stressed in the future.

IMPACTS ON BIODIVERSITY AND SOCIO-ECONOMICS

Pioneering research in BIOT demonstrates a strong link between rich biodiversity and a thriving ecosystem, with fish biodiversity vital to the health of tropical coral reef ecosystems, both reefs that are pristine and those that have been bleached (Benkwitt *et al.*, 2020). Fish assemblages vary in structure and density across atolls, for example parrotfishes varied in density over 40-fold between sites (Samoilys *et al.*, 2018).

Differences were explained by the amounts of live and recently dead coral, reflecting different recovery trajectories following coral-bleaching events (Samoilys *et al.*, 2018). Reef-dwelling parrotfish populations boom in the wake of severe coral bleaching (Taylor *et al.*, 2019a), while many other species of fish can decline in number, particularly if reef structural complexity is lost (Wilson *et al.*, 2006). Coral and parrotfish constitute a feedback loop, slowly bringing each other into balance: When reefs are damaged, parrotfish numbers swell and as the reef then returns to a healthy state, parrotfish numbers decline again (Taylor *et al.*, 2019a). The commercially important bluespine unicornfish, *Naso unicornis*, is significantly influenced by SST, with a shorter lifespan in warming waters (Taylor *et al.*, 2019b). There is considerable variation depending on energetic pathways, with some reef fish species fuelled by pelagic rather than reef plankton, meaning they are more resilient to coral mortality than might be expected (Morais and Bellwood, 2019).

Nutrients from seabirds nesting on BIOT islands enhance the productivity and functioning of adjacent coral reefs, dramatically increasing biomass across reef-fish trophic groups off islands where there are no invasive rats (Graham *et al.*, 2018). While relative declines in coral cover happened irrespective of the presence of seabirds, there was more calcareous algae, and all feeding groups of fishes were positively affected on reefs off seabird-colonised islands (compared to those with rat populations). Herbivorous and piscivorous fish were unaffected by the bleaching event, while coral-dependent corallivores and planktivores experienced the greatest losses after the bleaching (Benkwitt *et al.*, 2019). While seabird nutrients did not enhance resistance to bleaching, they may promote recovery due to their positive influence on calcareous algae and herbivorous fishes (Benkwitt *et al.*, 2019).

It is important that any possible greenhouse gas reduction measures be adopted on the inhabited island of Diego Garcia to reflect the local context and importance of the ecological importance of the BIOT MPA. However, given the fact that impacts are commonly synergistic in their effects, of key importance is the maintenance of existing restrictions on activities that would add to the stresses on the shallow reefs that already exist from climate change.

DRIVERS OF CHANGE

The drivers are the same as those outlined under Priority 1.

KEY EVIDENCE SOURCES

These include:

- The most-recent climate-change projections for reefs using the Coupled Model Intercomparison Project Phase 6 (CMIP6) ensemble which is based on Shared Socioeconomic Pathways (SSEPs) as opposed to Representation Concentration Pathways (RCPs) (UNEP, 2020).
- Peer reviewed publications from research dating back to the 1970s – see references.
- BIOT Biodiversity Action Plans produced by John Turner and Ronan Roche (Bangor University).
- Data from island-based research expedition visited the atolls in 1978–1979, followed by ship-based research visits to the area at irregular intervals from 1996–2012, and annual ship and island-based expeditions from 2012 to 2020.
- Data from BIOT stored on the Allen Coral Atlas https://allencoralatlas.org/atlas/#7.92/-5.8360/72.9118
- Expert input from scientists who have worked on coral reefs in BIOT for up to 45 years, including unpublished data.

KNOWLEDGE GAPS

Gaps include:

- A lack of more-detailed climate model projections of future coral bleaching conditions for BIOT and the broader Indian Ocean. However, these are currently being produced and are due for completion mid-2021, in work led by Gareth Williams (Bangor University). These will help guide local reef managers, governments and policy makers in what actions are required to increase the time reefs have to naturally adapt to warming temperatures. A key challenge for reef management lies in deciding where to target actions to reduce anthropogenic stress, ensuring efficacy, as well as cost effectiveness of actions taken.
- A lack of detailed and continuous monitoring of key environmental parameters to improve climate models as part of global ocean observing networks. These are largely absent in BIOT, though we are gaining valuable insights from the long-term temperature monitoring (since 2006) and more-recent logging of other parameters (oxygen, pH, salinity etc.) in lagoons across the archipelago.
- Little is known about important habitats in the BIOT MPA. While coral reefs have been a focal habitat for concerted research for some time, a depth limit of 25 m is placed on diving activities to minimise the risks in such a remote location. Yet most of the Great Chagos Bank, the world largest atoll structure, is between 25 m and 100 m deep. Studies of MCEs are at their early stages. Long-term monitoring of mesophotic reefs will help identify if they are more resilient than shallow reefs to global heatwaves and if these deep reefs help the recovery of bleached areas.
- The present paucity of supporting data on growth and erosion rates for most coral species and reef-associated taxa represent a constraint on the carbonate budget (and thus reef growth) estimates and limits between-site comparisons (Lange *et al.*, 2020).
- The recent insights into the connectedness between islands and reefs, driven by seabird nutrient transfer, demonstrate the highly connected nature of different species and habitats. In other reef locations, surface ‘bioslicks’ – narrow, meandering lines of ocean convergence – have been shown to represent important larval fish nurseries at ecosystem scales (Gove *et al.*, 2019) with different plankton pathways supporting both reef and pelagic productivity (Skinner *et al.*, 2021). Such studies show that the systems are connected and complex, meaning that not all consequences of the impacts of ocean warming are fully understood.
- Lack of quantification of blue carbon in BIOT and how that may contribute to NDCs.

PRIORITY 3: CHANGES TO REEF ISLANDS AND SANDY BEACHES

WHAT HAS HAPPENED

Analyses of large global data sets for multiple island atolls in both the Pacific and Indian Oceans have shown that while naturally dynamic, islands of more than 10 ha have been relatively net stable in terms of land area over recent decades (Duvat, 2018), with sea-level rise having no clear influence on island size or land-area loss (McLean and Kench, 2015; Kench *et al.*, 2018).

The patterns are complicated, but suggest that the smallest islands (<0.5 ha) are more vulnerable to shoreline migration on the reef-platform surfaces and to net erosion. Data from BIOT follow a similar pattern of high flux, with a very recent study looking at the dynamics of atoll-island coastlines for 20 islands in Peros Banhos Atoll and the island of Diego Garcia (Wu *et al.*, 2021) demonstrating that coastline expansion and retreat are in balance such that total land area of all the considered islands is virtually static over the last 50 years. In addition, and corresponding to global data sets, small islands (<20 ha) were found to substantially more dynamic than large ones (Wu *et al.*, 2021). Richly vegetated older and 'brown' soils are being lost, along with deposition of areas of soft sediments, without an overall change in area (Purkis *et al.*, 2016; Sheppard and Sheppard, 2019).

Some island erosion is observed across the atolls, particularly on ocean-facing shores, but it is unclear what the net changes in island areas have been on the northern atoll islands. Erosion occurs even when the adjacent coast is elevated, and this is clearly observed in north-west Diego Garcia where relatively high coastal dunes are being lost to the sea (Spalding, 2020) and on Middle Brother. Coastal structures, coastal engineering, and removal of coastal vegetation may be exacerbating this erosion (Spalding, 2020).

WHAT MIGHT HAPPEN

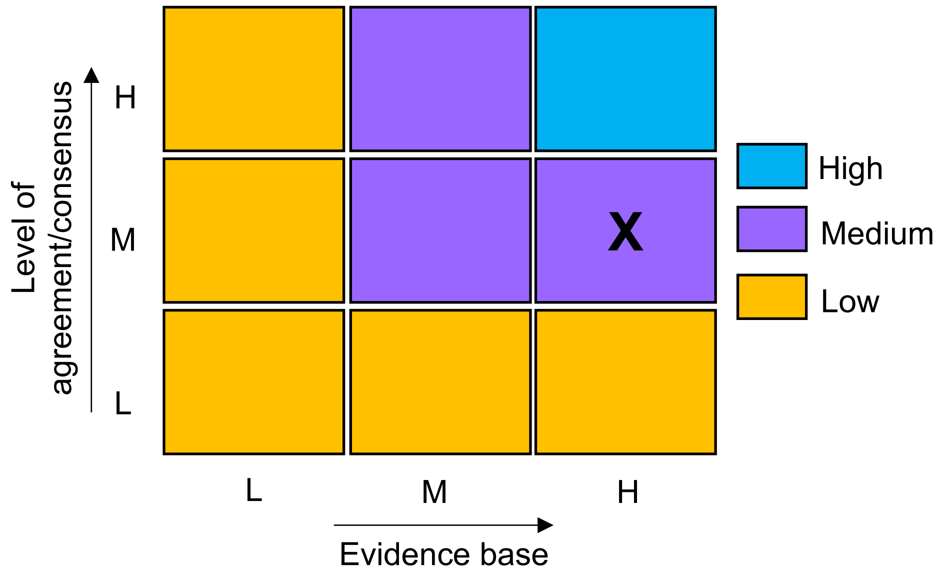
A new study (Wu *et al.*, 2021) found that islands in BIOT are likely to display multi-decadal stability based on island area. However, the coastlines are highly dynamic, undergoing erosion where they face prevailing wave energy and extending on the leeward sides. The human modifications on Diego Garcia appear to amplify these dynamics, increasing erosion under the contemporary conditions of sea-level rise, and substantially more likely to erode than those of the uninhabited islands of Peros Banhos (Wu *et al.*, 2021). Socio-economically, this is most likely to cause greatest concern on Diego Garcia where there is less tolerance to shifts in island margins, overtopping and inundation, due to it being an inhabited island and a military base (Spalding, 2020). However, the ecological consequences may be profound on the outer uninhabited islands, due to the multiple localised impacts on groundwater, vegetation and on important sea turtle and seabird nesting sites.

Studies of reef carbonate budgets in BIOT (described earlier) suggest a negative carbonate budget resulting from the 2015/2016 bleaching event and in the short-term at least, reef accretion potential may be insufficient to keep track with sea-level rise (Perry *et al.*, 2018, Lange and Perry 2019), potentially leading to periods of enhanced shoreline wave exposure. Set against this are likely short-term pulses of enhanced sediment supply caused by elevated rates of parrotfish substrate erosion (Perry *et al.*, 2020).

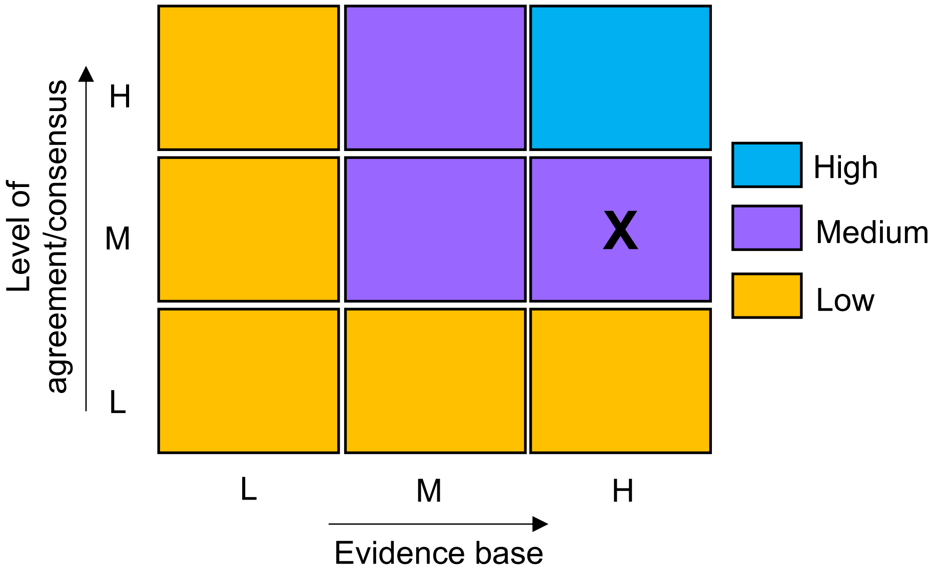
Ecological recovery trajectories will thus be key to determining the interplay between rates of change in reef growth and sediment supply, relative to changes in sea-level rise rates which almost all climate projections suggest will increase markedly through to 2100 (Duvat *et al.*, 2021). Indeed, the latest IPCC sea-level rise projections suggest rise rates of ~7.6 mm per year by 2050 mm and 15 mm per year by 2100 under RCP8.5 type scenarios (Duvat *et al.*, 2021), and these regardless of reef growth and sediment supply will almost inevitably increase island mobility/erosion rates and exacerbate existing observed recent rates of shoreline change (Purkis *et al.*, 2016; Spalding, 2020).

CONFIDENCE ASSESMENT

WHAT HAS HAPPENED



WHAT MIGHT HAPPEN



More regular monitoring of change in reef islands, particularly accurate shoreline monitoring is required to improve confidence. A greater understanding of BIOT island dynamics and changes in coral reef sediment supplies, including understanding how and when the islands were formed, would increase predictive capability of island mobility. New research on projected erosion and deposition patters on 10, 25 and 50 year timeframes will help inform long term planning.

IMPACTS ON BIODIVERSITY AND SOCIO-ECONOMICS

There are economic implications of breaches of land barriers by the sea into the lagoon in Diego Garcia, due to the infrastructure associated with the military base. Reports of such breaches have been reported as far back as 1883, with this being a regular occurrence even 50 years ago (Stoddart, 1971). There is a risk of a complete breach of the island north-west of Cust Point (Spalding, 2020), while near the south on most Spring high tides breaches permit fish including small sharks and rays to swim over the grass and a car park (Sheppard, 2012). On the northern atolls, there is a high risk of damage and loss of cultural heritage sites. The dynamic nature of the coastlines is likely to be the major determinant as to whether an atoll island is suitable for long-term human habitation, as radical shifts on sub-decadal timescales will impact infrastructure, such as roads and utilities, and exacerbate flooding (Wu *et al.*, 2021).

BIOT currently provides a climate-resilient nesting sanctuary for turtles from across the Western Indian Ocean, as it is one of the rare locations globally where hatchlings are 50:50 males to females (reviewed in Hays *et al.*, 2020). However, the combination of temperature changes and nesting beaches may skew sex ratios of regionally important turtle nesting sites. Temperature of nesting sites is also linked to sediment grain size which is partially determined by reef taxa and complicated by microplastics, with marine heatwaves shown to have a significant impact on the turtle hatching success rate (Hays *et al.*, 2021). There is also a more fundamental issue if entire nesting beaches are lost through erosion and beach mobility.

DRIVERS OF CHANGE

Sea surface temperature and changing weather have been reported earlier and apply here. Ocean acidification will decrease growth and structural integrity of the fringing reefs, increasing the probability of wave overtopping and damage to the islands from storms and waves.

KEY EVIDENCE SOURCES

These include:

- BIOT Biodiversity Action Plans produced by John Turner and Ronan Roche (Bangor University).
- Peer reviewed publications from research dating back to the 1970s – see references.
- Official public reports from the Dr Mark Spalding, Chief Science Advisor to BIOTA.
- Expert input from scientists who have worked in BIOT for up to 45 years, including unpublished data.

KNOWLEDGE GAPS

Gaps include:

- Chagos Archipelago island dynamics and changes in sediment supplies, including understanding how and when the islands were formed and how actively they are linked to the surrounding reef sediment supply sites.
- Monitoring of seagrass communities on the Great Chagos Bank, which may degrade in a warming ocean.
- Regular monitoring of change in reef islands, particularly accurate shoreline monitoring, combined with the development of physical models to project future changes in island area and position, including impacts on groundwater and vegetation.
- Appropriate and effective green or hybrid green-grey engineering approaches on Diego Garcia that would mitigate impact and move away from hard (usually concrete) engineering that can exacerbate erosion (or displace the erosion to other areas) and negatively impact flora and fauna. Several options that have been implemented successfully elsewhere have been proposed (Spalding, 2020). Options also need development for uninhabited islands to protect cultural heritage.

PRIORITY 4: IMPACTS ON THE PROVISION OF NATURAL COASTAL PROTECTION, RESILIENCE TO SEA LEVEL RISE AND ISLAND MAINTENANCE

WHAT HAS HAPPENED

Rates of sea level rise in BIOT have tracked global averages for the region, with current rates of sea level rise reported to range between 3.3 mm and 6 mm per year (Dunne et al., 2012, Sheppard and Sheppard, 2019, Wu et al., 2021). Recent sea level rise in Diego Garcia, as recorded by the tide gauge, is shown in figure 3. Where higher rates than those that could be explained by sea level rise were documented, these were considered due to tectonic activity (Purkis et al., 2016), but this is now thought to be negligible (Wu et al., 2021). Instead, geodetic data suggest that the rate of sea-level rise the archipelago is presently subjected to is substantially swifter than the global eustatic average (Wu et al., 2021). There is emerging evidence that the islands in BIOT are experiencing morphological adjustment through both shoreline erosion and accretion, but that total island areas has been net static over recent decades in the uninhabited atolls despite the estimated rates of sea level rise in the range of 3.3 – 6 mm per year (Dunne et al., 2012, Wu et al., 2021).

The extreme positive Indian Ocean Dipole (IOD) is an irregular perturbation across the Indian Ocean that in its positive phase can have effects that extend into the central Indian Ocean (Cai *et al.*, 2014). Extreme positive IOD events have also been clearly associated with large-scale perturbations in sea level, and a particular feature has been an upwelling or ridge of raised seawater in the region between 5°S–10°S and 50°E–80°E, known as the Seychelles Chagos Thermocline Ridge which may be giving a 10 cm additional lift to already high tides (Nyadjro *et al.*, 2017; Deepa *et al.*, 2018; Deepa *et al.*, 2019; Han *et al.*, 2019).

In October and November 2019, Diego Garcia, and to a slightly lesser extent, the northern atolls of BIOT, underwent dramatic physical impacts linked to extreme high sea levels (Spalding, 2020). This accelerated erosion, caused flooding and deposition of sand and rubble and were attributed to a combination of natural seasonal high tides, rising sea levels, and the positive IOD (Spalding, 2020). The impacts were exacerbated by the widespread deterioration of coastal vegetation, linked both to salinisation of the soil caused by tidal flooding and drought conditions (Spalding, 2020).

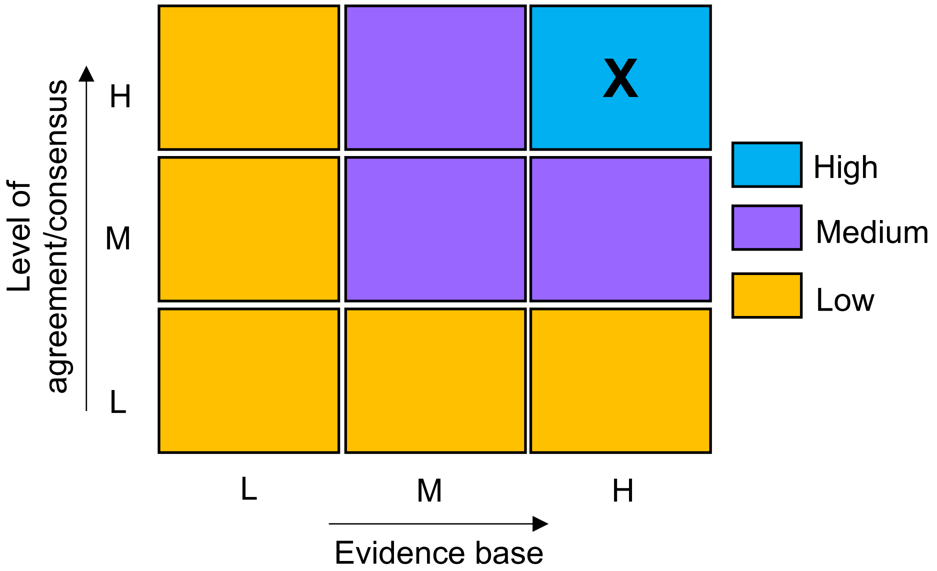
WHAT MIGHT HAPPEN

The frequency of extreme positive IOD events is projected to increase by almost a factor of three, with once-in-seventeen-year events in the 20th Century to once-in-six-yearly by the end of the 21st Century (Roxy *et al.*, 2020). Tectonic activity is inherently unpredictable but could exacerbate changes in island levels in conjunction with sea-level anomalies.

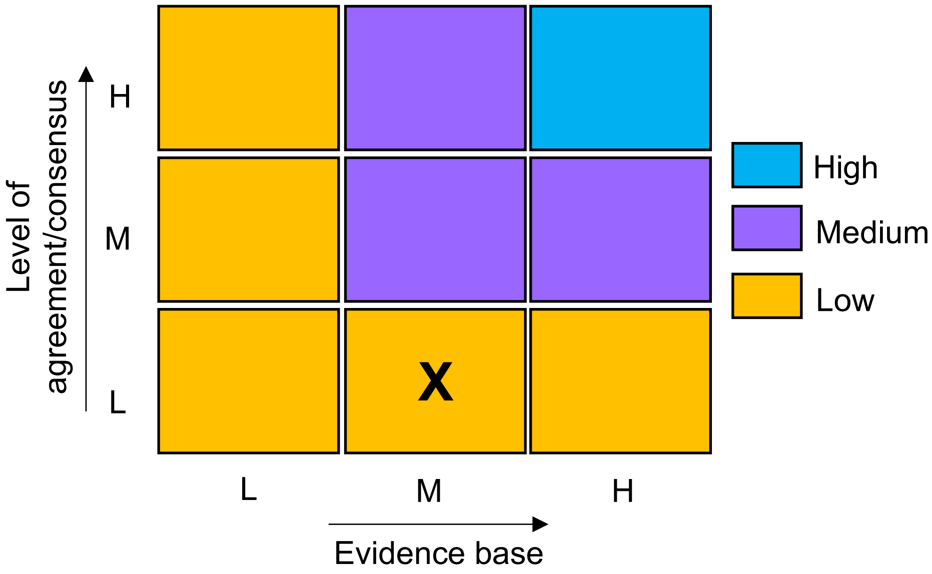
As reefs lose their structure associated with global bleaching events, they lose their ability to provide wave-attenuation benefits. This may start to impact on island shoreline stability and result in more frequent wave over-topping events. Whilst wave over-topping is critical (and indeed the only process) that sustains vertical island building this is also necessarily dependant on sufficient sediment being available to be supplied to the islands. Projected increases in bleaching and thus resultant loss of reef structure and thus of reef-associated sediment generating taxa are likely to have negative consequences of island stability. This may be exacerbated by storminess increases caused by more extreme projected IOD events (Roxy *et al.*, 2020). Both will have major consequences on island groundwater and vegetation, the latter being also important in island stability, as well as critical for nesting seabirds.

CONFIDENCE ASSESMENT

WHAT HAS HAPPENED



WHAT MIGHT HAPPEN



More regular monitoring of change in reef islands, particularly accurate shoreline monitoring is required to improve confidence. A greater understanding of BIOT island dynamics and changes in coral reef sediment supplies, including understanding how and when the islands were formed, would increase predictive capability of island mobility. New research on projected erosion and deposition patters on 10, 25 and 50 year timeframes will help inform long term planning.

IMPACTS ON BIODIVERSITY AND SOCIO-ECONOMICS

In Diego Garcia substantial and costly shoreline hardening takes place which negatively impacts biodiversity, although there is considerable economic pressure to maintain infrastructure.

The impact of recent climate-change driven events on native vegetation is concerning, as freshwater lenses may be compromised, and the soil becomes saline. Changes in rainfall patterns may impact the recovery of conditions suitable for vegetation, which in turn impacts both biodiversity and the role vegetation plays in stabilising soil and in wave attenuation.

DRIVERS OF CHANGE

Island dynamics are a natural process but are being changed by climate-change driven sea level rise and loss of reefs and associated sediment through ocean acidification and sea temperature rises. These climate drivers have been discussed in previous sections.

KEY EVIDENCE SOURCES

- BIOT Biodiversity Action Plans produced by John Turner and Ronan Roche (Bangor University).
- Peer reviewed publications from research dating back to the 1970s – see references.
- Official public reports from the Dr Mark Spalding, Chief Science Advisor to the BIOT Administration.
- Vegetation report from Royal Botanical Gardens, Kew with species data stored in UKOTs Online Herbarium (Barrios and Wilkinson, 2018).
- Expert input from scientists who have worked on coral reefs in BIOT for up to 45 years, including unpublished data.

KNOWLEDGE GAPS

Gaps include:

- Regular monitoring of change in reef islands, particularly accurate shoreline monitoring, combined with the development of models to project future change, including impacts on vegetation.
- Understanding of the age and composition of the islands to determine when they formed relative to past sea-level changes, which reef taxa have primarily driven island sediment supply, and how actively islands are connected to the surrounding reefs.
- Understanding of the role of parrotfish and other sand-grade generating organism abundance and size structure in sediment supply for island maintenance, and how seabird nutrient inputs may influence this supply. Current data show four times faster bioerosion adjacent to seabird islands (Graham *et al.*, 2018) but this will be investigated in more detail under a new four-year programme of research (N. Graham, pers. comm.).
- Further research is required to better understand the delicate ecosystems of the terrestrial environment**,** especially at the ecosystem level, to assist in countering future threats at the global (e.g. climate change) and local (e.g. invasive species management) scale. As priority, a systematic botanical survey of the northern atolls, focusing on the extent of non-native/invasive vascular plants is required.
- Tectonic activity in the northern atolls and the impact on island structure.

NOTE: In the online summary report card, priorities 3 and 4 are combined under ‘Changes to reef islands and sandy beaches’.

REGIONAL NATURE-BASED SOLUTIONS: CASE STUDY

The research and management priority within BIOT is the restoration of natural nutrient cycles by eradicating invasive rats and restoring seabird populations. Seabirds are key components of island ecosystems, transporting nutrients from the open ocean to islands, enhancing the productivity of island flora and fauna and surrounding marine ecosystems (Graham *et al.*, 2018). Seabird-derived nutrients enhance calcification rates (Benkwitt *et al.*, 2019), including growth rates of corals (Savage, 2019), and enhance processes that produce island building sediments (Graham *et al.*, 2018). New research shows that seabird-derived nutrients return to both tropical islands and nearby coral reefs within 16 years of rat eradication, although full recovery may take several decades (Benkwitt *et al.*, 2021). Seabird recovery can be dramatically enhanced through rehabilitating native vegetation for at least 55% of the habitat, once predators have been eradicated (Carr *et al.*, 2021).

NEXT STEPS

- As a fully protected MPA in a remote location, BIOT provides a globally important reference site for climate-change impacts that can give insights into finer-scale vulnerability and resilience in the absence of other anthropogenic stressors. Integration of data from BIOT into regional and global studies should therefore be encouraged.
- The restoration of island ecosystems through the eradication of invasive rats and restoration of native vegetation is the quickest and most effective way to restore seabird populations and the associated nutrient pathways that build resilience against climate change impacts. This should therefore be the priority conservation action for BIOT.
- Regular monitoring of key species and habitats and associated environmental parameters (e.g. temperature, rainfall) is required to understand factors relating to climate change, including vulnerability, resilience, and adaptation.
- Research to identify the remaining knowledge gaps identified in this report should be prioritised. While some of these will be achieved through Phase II of the Bertarelli Foundation's marine science programme, not all projects have been finalised, so gaps will subsequently need to be identified once this process is complete.
- A detailed assessment of erosion impacts is required to inform the potential cultural and economic impacts resulting from the dynamic nature of the islands. Any mitigation strategies should prioritise green-grey engineering options that protect and/or restore native vegetation.
- It is important that any possible greenhouse gas reduction measures be adopted on the inhabited island of Diego Garcia to reflect the local context and importance of the ecological importance of the BIOT

MPA. However, given the fact that impacts are commonly synergistic in their effects, of key importance is the maintenance of existing restrictions on activities that would add to the stresses on the shallow reefs that already exist from climate change.

- Through the UK's involvement in international treaties, there are opportunities for more-regional engagement to increase climate smart ocean protection that allows species range shifts along climate gradients, for example, exploring how MPAs in the region act synergistically.
- The only pathway to actually control climate change and limit its impacts, including to coral reefs, is through effective and immediate reduction of greenhouse gas emissions at a global scale and meet then exceed targets set in the Paris Agreement. COP26 will be instrumental in defining the pathway for the planet and any future for coral reefs.

LIMITATIONS OF THE STUDY

This report should be considered as complementary to the assessment of climate change impacts on corals in the UKOTs of BIOT and the Pitcairn Islands (Blue Belt Report Card, 2021, Lincoln *et al.*, 2021), although the processes were run in parallel.

By covering a wide scope of all species, habitats and systems, the methodology offers a relatively simple, but crude approach to assess low to high risk to climate change. As one example, research on climate change will impact sea turtles in BIOT and nesting success (Hays *et al.*, 2021), as well as the key knowledge gaps that need to be addressed (summarised in Hays *et al.*, 2020). However, this was represented as only a single question in the prioritisation exercise and therefore was not considered a priority issue.

There is inevitably a bias generated by (a) workshop participants, and (b) current knowledge. This tends to lead to a focus on assessing and ranking existing information rather than the gaps which are much harder to list and evaluate. As such, we know a lot about corals and fish on reefs in BIOT but know very little about many other areas of the entire ecosystem, e.g. microbes, plankton and the deep sea, and its functionality and connectedness.

ACKNOWLEDGEMENTS

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