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Climate change impacts on corals in the UK Overseas Territories of British Indian Ocean Territory (BIOT) and the Pitcairn Islands

Blue Belt Programme

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1. Executive summary

British Indian Ocean Territory (BIOT)
BIOT will become less suitable for corals due to future ocean acidification and warming sea surface waters. By the end of the century and under high emissions scenario, pH will decrease by more than 0.2 units and saturation of calcium carbonate minerals will become suboptimal for coral calcification. These conditions will lead to mass coral bleaching and decalcification.
Past marine heatwaves and an increase in average sea surface temperature of more than 0.5°C since the 1980s have caused substantial coral bleaching and mortality across BIOT, particularly in shallow reefs.
Islands are suffering erosion due to an estimated sea level rise of more than 5 mm per year, combined with the degradation of protective fringing reefs due to coral bleaching and mortality.
Protection and management activities in the BIOT Marine Protected Area (MPA), particularly the limitation of direct human pressures such as fishing and anchoring and monitoring of specific environmental indicators, could contribute to making corals more resilient to future climate change impacts to an extent.
Pitcairn
Pitcairn Islands corals grow at unusual depths, below 30 m, where the water is cooler and they are sheltered from warming surface temperatures, but there is high risk that future ocean acidification conditions will prevent coral survival: by the end of the century and under high emissions scenario, pH will decrease by almost 0.3 units and saturation of calcium carbonate minerals will be too low to support calcification.
The remote location of Pitcairn corals, in terms of the long distance between the islands themselves and even longer distance from other reefs, is a further challenge as it suggests limited connectivity and low influx of coral larvae from other healthy reefs that could boost recolonisation and recovery. Recruitment of juvenile corals in these reefs has yet to be assessed but it is expected to be heavily reliant on self-seeding.
Sea level rise is projected to rise by 95 cm on average across the South Pacific by the end of the 21st Century. It is unclear whether the Pitcairn Islands will continue to adjust to this accelerating sea level rise, particularly the low elevation coral islands of Henderson, Ducie and Oeno.
Some ocean and atmospheric processes such as the South Pacific Circulation Gyre may slow down warming compared to the wider Pacific; however targeted research is needed to fully understand these future changes.

2. Introduction

2.1. Purpose of this document

This document aims to compile the latest scientific information available from observed and future climate change literature covering the marine and coastal environments of the UK Overseas Territories of the Pitcairn Islands and the British Indian Ocean Territory (BIOT). This report gathers current understanding of the expected impacts on the coral reefs, as well as other key marine species and habitats, and will help to inform potential management actions in support of the designated Marine Protected Areas of these territories. A summary report card is also available. The summary report card provides a synthesis of this document to inform policy, decision making and conservation activities. This work has been funded by the UK Blue Belt Programme[1].

2.2. Background to this document

Warm-water coral species are projected to decline and local extinctions are expected in the coming decades as climatic and non-climatic stressors are causing a rapid decline worldwide (IPCC 2014a). About one quarter of coral reefs have already died off with a further half impacted to varying degrees in terms of loss of structural complexity and changes in species composition, and only one quarter remain in reasonably good condition and retain optimal levels of ecosystem function and diversity (IPCC 2014a). The composition of coral reefs in the future is expected to be different to the present day (IPCC 2019), with loss of species from most sites globally by 2050 as a consequence of global warming (IPCC 2014a). Reef-building or stony corals are keystone species and have a disproportionately important role, because they are critical for the structure of the entire ecological reef community, affecting many other organisms and helping to determine the types and numbers of various other species in the reef. Therefore changes to the species composition of coral communities can affect the ecological functioning of the reef and all the derived goods and services that are vital to society and regional economies, such as fisheries, coastal protection and tourism, and impact the wider marine areas beyond the reef (Fisher et al. 2015; IPCC 2014a; Baker et al. 2008; Moberg and Folke 1999; Glynn 1993). Any detrimental impact to the corals could result in a much wider impact to approximately 500 million people and to the associated ecosystem services that depend on these habitats.

This report provides information on impacts of climate change on corals in BIOT and the Pitcairn Islands, as well as likely impacts that can be expected over the course of the 21st Century, based on most up-to-date Representative Concentration Pathways (RCP) climate model projections (Van Vuuren et al. 2011). Where possible, projections used were based on either of the main Representative Concentration Pathways (RCP): low (mitigation) emissions scenario (RCP2.6), medium (stabilization) scenarios (RCP4.5/RCP6) and high (baseline) emission scenarios (RCP8.5; Van Vuuren et al. 2011). RCP8.5 is also known as the ‘business-as-usual’ scenario as it assumes that no, or very limited, mitigation will be put in place, while RCP2.6 is more aligned with the mitigation commitments of the UNFCCC Paris Agreement. RCP2.6 and RCP8.5 are therefore extreme scenarios, and it is expected that future emission scenarios will likely fall in between these

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[1] www.gov.uk/government/publications/the-blue-belt-programme

projections. This report makes use of available information and focusses on key marine physico-chemical drivers of climate change in ocean conditions by which organisms are influenced: sea temperature, ocean acidification, sea level rise and extreme weather events, which provide context specific to the unique marine species and habitats across these territories. The final sections of this report discuss potential options in terms of management actions that could potentially enhance the resilience of the coral reef ecosystems in BIOT and the Pitcairn Islands.

2.3. British Indian Ocean Territory (BIOT)

The British Indian Ocean Territory (BIOT) is an archipelago of 58 islands. It lies between 4°–8°S and 70°–75°E, about 500 km south of the Maldives archipelago and about 1,800 km east of the Seychelles (Sheppard et al. 2012). BIOT consists of five atolls, including the largest atoll in the world: Great Chagos Bank, and many submerged atolls and banks. The islands cover an aggregated land area of about 60 km^2 (about half of which is the atoll Diego Garcia) with 698 km of coastline. The terrain is flat, and most areas do not exceed 2 m in elevation. The BIOT Marine Protected Area (MPA) covers the whole maritime zone and coastal waters (Figure 1) with an approximate area of 640,000 km^2 and was first proclaimed as a Fisheries Conservation and Management Zone (FCMZ) in 1991.

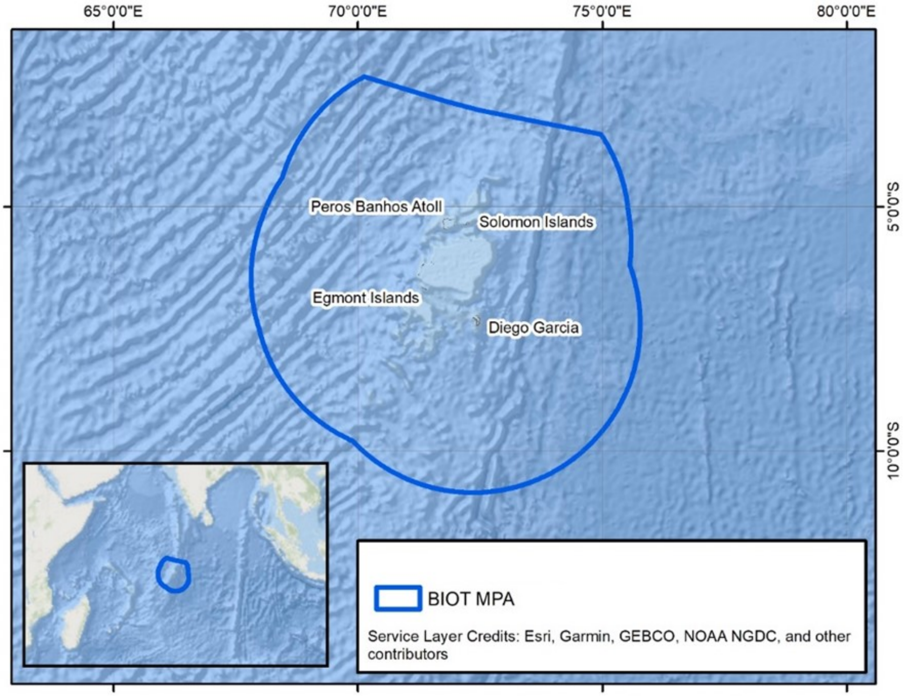

Figure 1. The British Indian Ocean Territory Maritime Boundary and designated Marine Protected Area, which occupies the entire Fisheries Conservation and Management Zone.

In 2003 this territory was further protected as an Environment Protection and Preservation Zone, until in 2010 the entire FCMZ was declared as the no-take BIOT MPA[2] with the only exclusion of the 3 nautical miles territorial waters around Diego Garcia. All commercial fishing and extractive

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[2] British Indian Ocean Territory (gov.io)

activities are prohibited within the MPA, but recreational fishing by residents is however allowed. Diego Garcia is the only inhabited island, and hosts a joint UK-US military base facility that includes military personnel, contractors and BIOT Administration staff.

BIOT is home to a rich and diverse marine environment that makes it a unique and a prime location for science and education programmes; scientific expeditions from a wide range of disciplines have established BIOT as an observatory for undisturbed ecosystems (BIOTA 2018). The BIOT MPA includes an unusually large expanse of sublittoral substrate in the photic zone, around 60,000 km², that consists of shallow limestone covered with live coral, rubble, and extensive seagrass beds (Sheppard et al. 2012). The archipelago is an important stepping-stone for many species (Sheppard and Sheppard 2019). It serves as an important breeding ground for sharks, dolphins, and sea turtles (Hays et al. 2020).

Coral cover measurements since the 1970s have shown some episodes of coral decline associated with several sea warming events. Some lagoon reefs in the atolls have been less affected than ocean facing reefs though this is patchy, with some areas appearing heavily bleached while others show high percentage of live coral cover (above 50%). Most of the shallow areas are dominated by communities of seagrass or sponges, or are covered by limestone rubble rather than coral (Sheppard and Sheppard 2019).

2.4. Pitcairn Islands

The Pitcairn Islands include Pitcairn, Oeno, Henderson, and Ducie Island, with an aggregated land area of only 49 km^2 (Irving and Dawson, 2012). They are part of an outcrop situated along the Foundation Seamount chain, running west northwest to east southeast through the Central South Pacific between 20°–30°S and 120°–135°W (Figure 2). Pitcairn Island is of volcanic origin, steep and rocky, and exposed to large ocean swells (Avagliano et al. 2016) and it is also the only inhabited island with 52 permanent residents as of January 2020[3]. Henderson Island is formed from a raised coral reef, and Oeno and Ducie are low coral atolls (Robinson et al. 2017; Spencer 1995). The Pitcairn Islands Marine Protected Area[4] established in September 2016, covers the entire Pitcairn Exclusive Economic Zone (EEZ), 841,910 km^2, and is a no-take MPA (Figure 2).

The Coastal Conservation Areas (CCAs) consist of the territorial waters around Pitcairn, Henderson, Ducie and Oeno; the CCA around Pitcairn Island also includes the 2 nautical miles of the area known as “40-mile reef” on the edge of Adam’s Seamount, and the transit zone between the island and 40-mile reef, which explains the different elongated shape of the CCA around Pitcairn compared to the other islands (Figure 2). Subsistence fishing is allowed within these areas[5]. The Pitcairn Islands are considered to be one of the tropical reef regions least impacted by human activity in the Pacific, but diversity of benthic communities and fish around these islands is not as high as expected due to their isolation – with Oeno Island scoring the highest amongst them in terms of fish assemblages diversity index (Shannon-Weaver Diversity Index 2.3; Friedlander et al. 2014).

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[3] Pitcairn Miscellany, January 2020 [www.miscellany.pn/]

[4] http://www.mpatlas.org/mpa/sites/9178/

[5] Revised Laws of Pitcairn, Henderson, Ducie and Oeno Islands, 2017 Rev. Ed. - Volume 2 (government.pn)

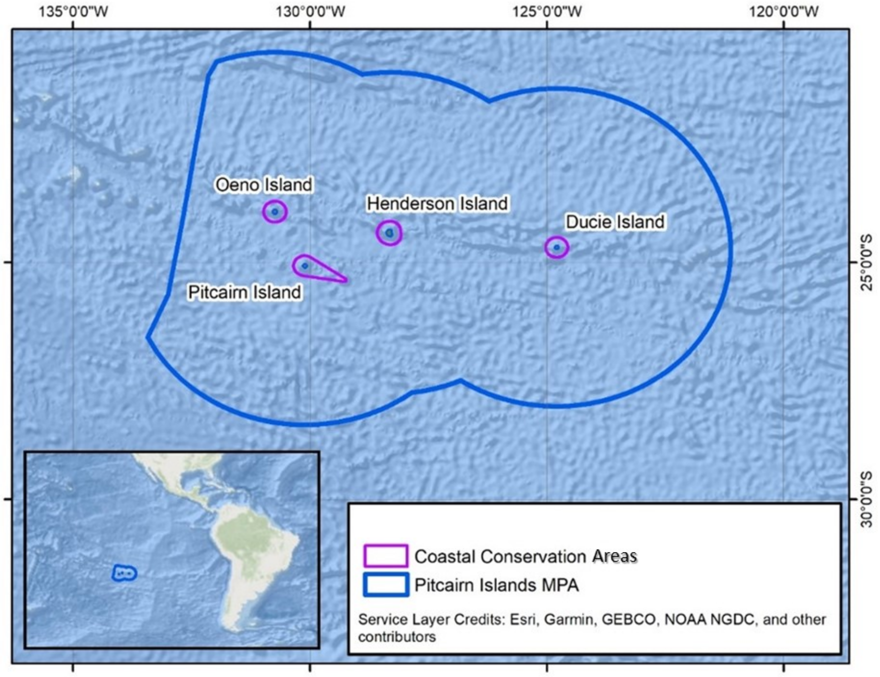

Figure 2. The Pitcairn Maritime Boundary and designated Marine Protected Area, which occupies the entire Exclusive Economic Zone. The Marine Protected Area is a no-take area, but subsistence fishing is allowed within the Coastal Conservation Areas.

Coral reefs are present around all the Pitcairn Islands, with Ducie having the highest coral cover, 56%, and Pitcairn the lowest, 5% (Friedlander et al. 2014). Unique fish assemblages are found in these islands due to their isolation (Friedlander et al. 2014). Macroalgae are abundant around Pitcairn Island, and corals are predominantly absent above 10 m water depth, possibly due to the combined impact of wave action and sediment run off (Duffy 2014; Friedlander et al. 2014). Below 10 m coral reefs are present and occur deeper than usual (below 30 m depth), due to exceptional water clarity (Duffy 2014; Friedlander et al. 2014; Irving and Dawson 2013).

2.5. Overview of marine climate change in the Indian and Pacific Ocean regions

2.5.1.Sea surface temperature change

To understand the potential impact of future climate changes, it is necessary to consider natural climate variability driven by the interaction of atmospheric and oceanic systems, as sea surface temperature (SST) conditions in the Pacific and Indian Oceans are strongly affected by natural interannual variation which drives warmer and cooler conditions in these areas. The El Niño/Southern Oscillation (ENSO) is defined by a bimodal fluctuation in SST and air pressure across the eastern equatorial Pacific (NOAA, 2020), typically with a 2- to 7-year cycle. El Niño events are characterized by positive SST anomalies, and La Niña events exhibit negative SST anomalies (Figure 3; Santoso and National Center for Atmospheric Research Staff 2020; Stuecker et al. 2017).

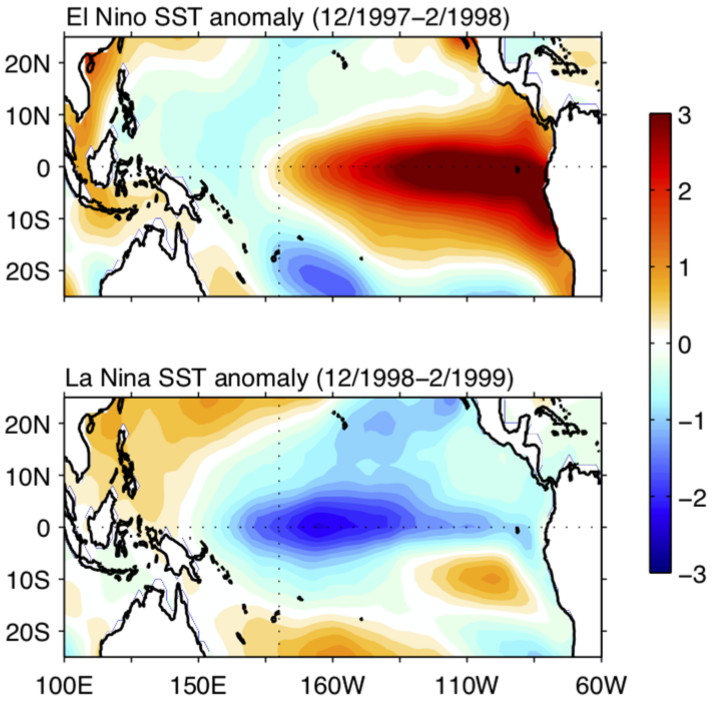

Figure 3. SST anomalies during example years of El Niño (top) and La Niña events (bottom). Figure copied with permission from Santoso and National Center for Atmospheric Research Staff (2020).

During La Niña conditions, changes in air pressure encourage circulation of air across the Pacific that draws cooler waters towards the surface in the east of the Pacific (Stuecker et al. 2017). During El Niño conditions, this pressure difference weakens, and warm surface water builds to the east of the Pacific. As well as SST, ENSO also influences cyclonic activity, waves, and ocean acidification in the Pacific (Stuecker et al. 2017). It is unclear how the strength and frequency of El Niño and La Niña will change in the future with climate change, but ENSO is expected to remain the dominant mode of interannual climate variation in the region (Stuecker et al. 2017; IPCC 2013).

Interannual variation in the SST of the Indian Ocean is driven by the Indian Ocean Dipole (IOD). Positive IOD conditions tend to coincide with a warmer than normal western tropical Indian Ocean, while a negative IOD phase coincides with a cooler than normal western tropical Indian Ocean (Johnson 2020). The IOD is partially linked to the ENSO system. El Niño conditions initiate a positive IOD phase, associated with warm waters in the western tropical Indian Ocean (Johnson 2020). However, the exact amount that the ENSO system drives IOD is unknown, as the phases do not always occur at the same time. As with ENSO, it is unclear exactly how climate change will affect the IOD (Johnson 2020), but there is evidence that extreme positive events (and so warmer western tropical Indian Ocean waters) may occur more frequently in the future (Cai et al. 2014).

From the 1850–1900 period until 1986–2005, SST has risen by 0.63°C on average, with marine heatwaves increasing in frequency and intensity since the 1980s (IPCC 2019). Marine heatwaves have been defined as warm events that last for five or more days, during which mean or maximum temperature anomalies are at least 3–5°C above normal and warmer than the 90th percentile based on a 30-year historical baseline period (Hobday et al. 2016). The oceans are expected to continue to warm throughout the 21st Century with more heatwaves that are more intense, last longer and cover larger areas (Benthuysen et al. 2020; Jacox et al. 2020; Laufkötter et al. 2020; Oliver et al. 2020; IPCC 2019). By the end of the 21st Century, SST is projected to rise by a further

4°C on average under a high greenhouse gas emissions scenario (IPCC 2019). By the end of century, marine heatwaves will increase in frequency, duration, spatial extent and intensity throughout the ocean under future global warming, and on average the probability of marine heatwave occurring each year will be 20 times or higher than currently (Collins 2019). Some authors are even pointing to a further acceleration of these changes already taking place (Hu et al. 2020; Shepherd et al. 2020; Cheng et al. 2019; WMO 2019).

Reef recovery relies on new recruitment as well as growth and propagation of surviving colonies, and full recovery of mature coral assemblages can take 10–15 years for the fastest growing species and even longer for slower-growing species; therefore, if marine heatwave events intense enough to trigger mass coral bleaching begin to reoccur with greater frequency it could be catastrophic for many reefs and prompt an irreversible collapse of the world's tropical reefs as we know them (Sheppard 2003), even if some thermal tolerant species or colonies are able to adapt.

2.5.2. Ocean acidification and carbon chemistry

Since pre-industrial times atmospheric CO_2 has increased from approximately 277 parts per million (ppm) to 409.8 ± 0.1 ppm in 2018 (Blunden and Arndt 2020), with oceans acting as sinks for atmospheric CO_2 and absorbing 20–30% of global emissions (Bindoff et al. 2019; Friedlingstein et al. 2019; Gruber et al. 2019). Absorbed CO_2 reacts with seawater and causes a decrease in pH, referred to as ocean acidification. Organism responses to ocean acidification vary depending on their life history traits with heavily calcified organisms such as corals, molluscs and echinoderms being most negatively impacted (Birchenough et al. 2015). This is because besides calcification, many physiological processes require pH to be tightly controlled including photosynthesis, neuronal processes, growth, reproduction, and survival (Turk et al. 2019; Henson et al. 2017; Marshall et al. 2017; Sutton et al. 2016, 2017; Keller et al. 2014; Pörtner et al. 2014; Kroeker et al. 2013; Wittman and Pörtner 2013; Honisch et al. 2012), but there are still gaps in our current understanding of the impacts of acidification on marine systems (Doo et al. 2020).

Calcifying organisms secrete calcium carbonate-based ($CaCO_3$) minerals, which include calcite and aragonite. Shells and skeletons of unprotected $CaCO_3$ minerals begin to dissolve when the saturation level (denoted as Ω) of aragonite (Ω_{ar}) or calcite (Ω_{ca}) drops below $\Omega = 1$, noting that the locations of this saturation horizon where $\Omega = 1$ in the water column differ for these two carbonate minerals (Birchenough et al. 2017; Feely et al. 2009). Thus, the $\Omega = 1$ horizon is a useful indicator but not a strict criterion for biomineralization and dissolution (Feely et al. 2009). The saturation states of carbonate minerals naturally decrease with depth as total dissolved CO_2 increases because of biological respiration and cold temperatures in deep seawater (Feely et al. 2009). In addition, and while perhaps less relevant at large scales, Ω and pH can also vary at local scales depending on the habitat mosaic present (Liu et al. 2020; Bergstrom et al. 2019; Cyronak et al. 2018a; Pacella et al. 2018) and it can be affected by biological processes like photosynthesis (Fabricius et al. 2020; Hurd et al. 2018).

The trend of global decline in ocean pH has been estimated to be between 0.017–0.027 pH units per decade, with variability between ocean basins as well as seasonal changes in seawater pH (Bindoff et al. 2019; Landschützer et al. 2018; Wu et al. 2018; Lauvset et al. 2015). Ocean pH and aragonite saturation state are expected to continue decreasing globally (Bindoff et al. 2019) with a likely significant lag between emissions and oceanic uptake of CO_2 (Laruelle et al. 2018). By the end of the 21st Century, surface ocean pH will decrease by 0.036–0.042 pH units under a low emissions scenario or 0.287–0.291 pH units under a high emissions scenario (Kwiatkowski et al. 2020; Bindoff et al. 2019).

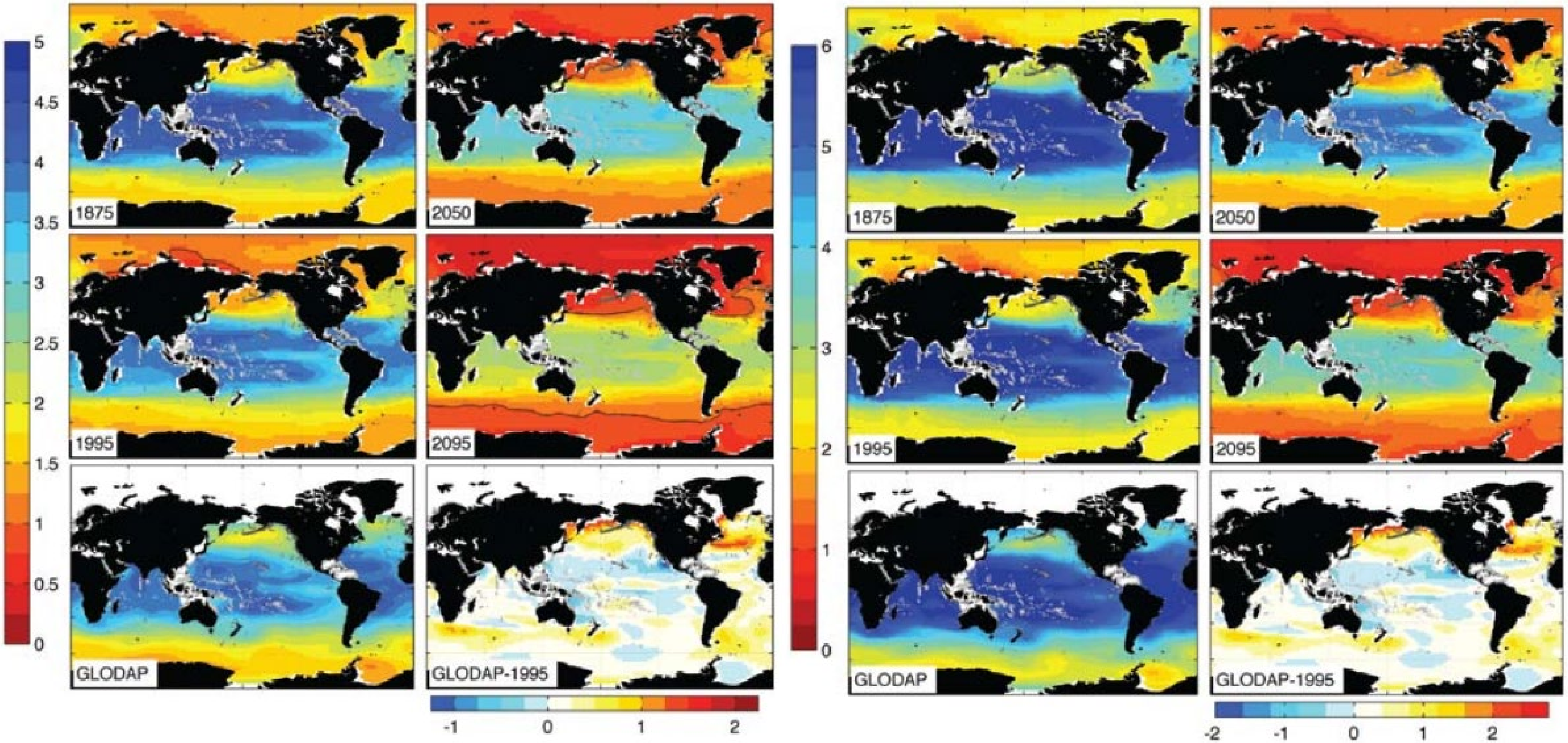

Figure 4. (Top and middle rows) CCSM3-modelled decadal mean Ω_{ar} (left) and Ω_{ca} (right) at the sea surface, centred around the years 1875, 1995, 2050, and 2095 (bottom row) GLODAP-based Ω_{ar}/Ω_{ca} at the sea surface, nominally for 1995; the GLODAP-1995 plot shows the difference between the GLODAP-based and CCSM-based 1995 fields. Note the different range of the difference plots. Deep coral reefs are indicated by darker grey dots; shallow-water coral reefs are indicated with lighter grey dots. White areas indicate regions with no data. GLODAP denotes carbon system measurements collected from 1990 through 1998, during CO2 survey oceanic cruises. Figure copied with permission from Feely et al. (2009).

For most open-ocean surface waters, model projections suggest that by 2050 aragonite undersaturation will intensify and spread from the poles, with all of the Southern Ocean and North Pacific expected to be undersaturated by the end of the century (Figure 4; see also Feely et al. 2009). With respect to calcite, most surface waters across the globe will see a substantial decline compared to present levels albeit still at a saturated state with the exception of the Arctic, by the end of the century (Figure 4; see also Feely et al. 2009).

On the other hand, increased levels of dissolved CO_2 can also benefit certain photosynthesising organisms, including macroalgae, seagrasses and diatoms (Brodie and De Ramon N'Yeurt 2018; Brodie et al. 2014; Kroeker et al. 2013).

2.5.3. Sea level rise

The dominant drivers of sea level rise are thermal expansion of the ocean, and meltwater loss from land-based ice sheets and glaciers, but regional differences in the relative contribution of each component of sea level change introduce considerable variability and uncertainty particularly in the case of long-term estimations (Nauels et al. 2019; Vitousek et al. 2017; Church et al. 2013).

Since the Intergovernmental Panel for Climate Change Fifth Assessment Report (IPCC AR5), recent studies have attributed chronic coastal flooding to higher mean sea levels and extreme weather events (Oppenheimer et al. 2019; IPCC 2013). Latest IPCC projections are robust up to 2050 and indicate that global mean sea level will raise 0.24 m (0.17–0.32 m, likely range) under RCP2.6 and 0.32 m (0.23–0.40 m, likely range) under RCP8.5 (medium confidence; Oppenheimer et al. 2019). The combined effect of mean and extreme sea levels results in events which are rare in the historical context (return period of 100 years or larger; probability <0.01 per year) occurring annually at some locations by 2050 under all emission scenarios (high confidence; Oppenheimer et al. 2019). Extreme weather contributes to extreme sea levels through wind-waves and storm surges, which threaten coastal areas particularly when those events also coincide with high tides (Vousdoukas et al. 2018; Vitousek et al. 2017; Wahl et al. 2017; Muis et al. 2016).

Beyond 2050, uncertainty in climate change induced sea level rise increases substantially due to uncertainties in emission scenarios and the associated climate changes (Oppenheimer et al. 2019). Global mean sea level is projected to rise between 0.43 m (0.29–0.59 m, likely range) under RCP 2.6 and 0.84 m (0.61–1.10 m, likely range) under RCP 8.5 by 2100 (Oppenheimer et al. 2019). Another study of a global set of local sea level projections suggests a *likely* range of mean global sea level rise of 0.6–1.0 m, with a *very likely* range of 0.5–1.2 m and a *virtually certain* range of 0.4–1.8 m by the end of the 21st Century under RCP8.5 (Kopp et al. 2014; Figure 5). Those projections may be relatively conservative, compared to other more recent projections that estimate global sea level is likely to raise above 1.1 m on average by 2100, on the basis that the relationship between warming and sea level rate may not be linear (Grinsted and Christensen 2021).

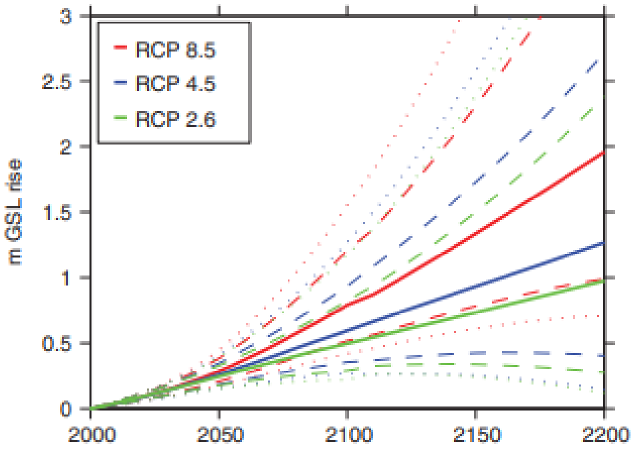

Figure 5. Projections of global sea level rise for the three RCPs, calculated based on a global set of local sea level projections. Solid line = median, dashed = 5th–95th percentile, dotted = 0.5th–99.5th percentiles. Copied with permission from Kopp et al. (2014).

Long-term sea level and tidal gauge records are still very limited in either the Indian Ocean and the South Pacific, making it challenging to estimate trends of sea level change with confidence (Chambers et al. 2012).

2.5.4. Extreme weather events

Changes in ocean wave conditions are governed by changes in the major wind systems, especially in the main areas affected by tropical and extra-tropical storms (Church et al. 2013). Unusually large deep ocean swells, generated by extratropical cyclones in the mid and high latitudes, can also cause considerable damage to small islands thousands of kilometres away in the tropics (Nurse et al. 2014). Impacts include coastal flooding, damage to coral reefs and severe beach erosion. As well as the impacts from the direct landfall of severe storms or cyclones, the potential importance of inter-regional transboundary processes like swells to distant, low-lying coasts warrants further research, particularly if the climatology of swells is modified under future climate change (Shope et al. 2016; Nurse et al. 2014; Vassie et al. 2004).

Tropical cyclones exacerbate extreme sea levels by intensifying wind-waves and storm surges (Church et al. 2013). However, the influence of observed climate change on past tropical cyclone frequency and intensity is still uncertain. An increase in tropical cyclone activity has been detected in recent years, but this apparent trend could be the result of changes in observation methods over time (IPCC 2012; Peduzzi et al. 2012; Knutson et al. 2010).

The Fifth Assessment Report (AR5) of the IPCC concluded that whilst long-term increases in tropical cyclone activity have been found globally, there was low confidence in any attribution to particular causes, as natural variability prevented the detection of clear climate change signals (Collins et al. 2019; IPCC 2013). Since the AR5, there have been further downscaling studies of tropical cyclones and higher resolution ocean circulation experiments, and the latest findings generally support those from previous AR5 projections: a general increase in intensity of the most intense tropical cyclones and a decline in tropical cyclone frequency overall (Collins et al. 2019).

The future influence of climate change on the frequency and intensity of tropical cyclones is not yet fully understood (Chand et al. 2020; Howes et al. 2018; CSIRO et al. 2015; Christensen et al.

2013). Global 21st Century climate projections indicate that the frequency of tropical cyclones is likely to either remain roughly constant or decrease, whilst their mean intensity is likely to increase, together with cyclone-related rainfall (Walsh et al. 2019; Peduzzi et al. 2012). There is limited confidence however in the geographical details of regional projections of future tropical cyclone track and occurrence (Knutson et al. 2019; Walsh et al. 2019; Ramsay et al. 2018; Nakamura et al. 2017). Global climate models are unable to realistically simulate maximum wind speeds and other key tropical cyclone features even after downscaling (Strazzo et al. 2015). Further research is needed to improve the resolution of meteorological data to better model the contribution of tropical cyclones to extreme sea level events, to better understand these events, validate and ground-truth computer models and provide robust, regional projections (Wahl et al. 2017; Muis et al. 2016).

Modelling studies of global wave height under future emission scenarios for the end of the 21st Century suggests increased probability of extreme waves in the Southern and Indian Ocean, and to a lesser extent the Pacific (Church et al. 2013; Dobrynin et al. 2012). These projections of global wind-wave climate carry low confidence due to their considerable regional and seasonal variability (Nurse et al. 2014; Wang et al. 2014). However the projected increase of extreme wave activity in the Southern Ocean could be of concern for both BIOT and Pitcairn due to their exposure to open ocean conditions; for example evidence of damage by cold intrusion and waves has been found in Ducie Island (Dawson and Zhang, 2020; Irving and Dawson 2013; Rehder and Randall 1975), which could have been caused by long distance waves originated in southern latitudes. Such waves are known to propagate as deep-ocean swells and northwards into adjoining basins (Hemer et al. 2013) and can have devastating impacts on coastal margins and shallow coral reefs, for example causing displacement of sediments and boulders, coastal flooding and damage to infrastructure and buildings, with implications for biodiversity as well as communities and livelihoods (Nurse et al. 2014).

2.6. Overview of climate change impacts on corals

2.6.1.Impacts from bleaching

According to the UNEP coral bleaching futures report (2017), in the central Indian Ocean Reef Area, the average projected timing of the onset of annual severe bleaching events under a high emissions scenario is 2046, with the earliest projected timing taking place in BIOT by 2041. This implies that severe bleaching events are expected to occur on an annual basis in that region by 2041 (Van Hooidonk et al. 2016). BIOT corals are already at the upper limits of their thermal tolerance, and it is doubtful they will persist under projected future SST conditions. Based on present-day tolerance limits and unless these corals are able to adapt physiologically, the BIOT region will become largely unsuitable for corals before the end of the 21st Century (Couce et al. 2013). In contrast, the onset of regular severe bleaching in the Pitcairn Islands is projected to be delayed until the second half of the 21st Century, due to their southerly latitude and an expected slower SST warming rate in that region of the Pacific Ocean implying that future SST conditions will likely remain optimal for coral growth for longer compared to other tropical reef areas exposed to higher SST and faster warming rates (Jones et al. 2019; Van Hooidonk et al. 2016; Couce et al. 2013; Irving and Dawson 2013).

Bleaching is the outcome of a complex biological and ecological response of corals designed to protect the coral animal against harmful products, such as reactive oxygen and or nitrogen

(Suggett and Smith, 2020; Obura 2009; Coles and Jokiel 1978). A large body of evidence has demonstrated that perturbations to environmental factors underpinning optimum metabolic functioning can result in bleaching; notably, temperature, light, salinity as well as inorganic nutrients (see Suggett and Smith, 2020; and references therein). The rate of photosynthesis increases with temperature and light, hence the corals expel excess zooxanthellae to reduce the overall rate of photosynthesis during warmer conditions (Baker 2001). Seasonal paling of corals can occur naturally during summer months with no obvious harm to coral colonies (Obura 2009; Baker et al. 2008). However, during extreme temperatures corals lose too many of their zooxanthellae and can no longer obtain food from photosynthesis and eventually die. Without their symbiotic algae, the tissue becomes transparent, and colonies appear white, or bleached, due to their white skeletons made of calcium carbonate.

Bleaching of coral reefs is becoming more frequent and severe across the world due to climate change (Hughes et al. 2017; Heron et al. 2016). However, it is also known that not all corals will necessarily die during a bleaching event, as some will have lower exposure to the thermal stress and others may be less sensitive to these events (Obura 2005; West and Salm 2003). Factors such as location of reef, cloud cover, ocean-facing versus lagoonal (Cowburn et al. 2019; Muir et al. 2017; Pandolfi 2015; Ateweberhan et al. 2013; Obura and Mangubhai 2011), coral morphology (Ateweberhan et al. 2013; McClanahan et al. 2007; Loya et al. 2001), previous bleaching experience and zooxanthellae type (Baker et al. 2004; Brown et al. 2002), as well as the degree of autotrophy versus heterotrophy – with branching corals tending to be more autotrophic than massive corals – (Conti-Jerpe et al. 2020; Ferrier-Pagès et al. 2011), appear to determine the coral's sensitivity to thermal stress. For example, autotrophic corals appear to have an advantage in ambient temperature and high irradiance environments, whereas heterotrophic corals appear more tolerant of increasing temperatures; and similarly, branching corals with thinner tissues bleach earlier and more extensively compared to massive or encrusting coral species with thicker tissues (Conti-Jerpe et al. 2020; Hughes et al. 2018; Woolridge 2014; Hughes and Grottoli 2013; Anthony et al. 2009; Grottoli et al. 2006; Obura 2001). The most likely scenario is that tropical coral reefs will continue to degrade globally over the 21st Century until climate change stabilizes and surviving populations reorganize into heat-tolerant reef assemblages, as the effect of the 2016 global bleaching event demonstrated by triggering an initial transition in many reef regions (Hughes et al. 2018).

There is an extensive body of knowledge about coral bleaching and potential intervention and management options (Mcleod et al. 2019; Van Oppen et al. 2017) although some of those options are better explored than others. Some interventions such as selective breeding or genetic engineering require the use of complex technologies, and further research and understanding of the genetic, physiological, and ecological processes involved are needed, and therefore need to go hand in hand with continuing and potentially increasing efforts in conventional management (Anthony et al. 2017; Anthony et al. 2015).

2.6.2. Impacts from changes in carbon chemistry and ocean acidification

As aragonite depositing organisms, corals are more vulnerable to the effects of ocean acidification (Pandolfi et al. 2011; Anthony et al. 2008) than calcite depositing organisms and non-calcifying forms (Kroeker et al. 2013). Aragonite is more soluble than calcite, however recent studies suggest that this does not necessarily determine an organism's vulnerability to ocean acidification (Doney et al. 2020).

Evidence from experimental studies simulating a range of pH levels suggests that corals are highly sensitive to ocean acidification, with decreasing saturation state resulting in impaired calcification (Langdon and Atkinson 2005; Langdon et al. 2000) and increased dissolution (Andersson et al. 2007). In turn, these effects trigger stress-response mechanisms that affect the rates of tissue repair, feeding rate, reproduction, and early life-stage survival (Enochs et al. 2015a; D'Angelo et al. 2012; Kroeker et al. 2010; Fabry 2008). Field studies using pH gradients that mimic future conditions have largely supported these assumptions, finding declines in coral skeletal density, species composition, colony size, and net calcification, and increases in bioerosion and dissolution (Dove et al. 2020; Eyre et al. 2018; Mollica et al. 2018; Enochs et al. 2015b; Fabricius et al. 2011; Shamberger et al. 2011; Silverman et al. 2007).

Many knowledge gaps still remain but as our understanding of the subject progresses, it is clear that the impacts are less straightforward than first thought and it is clear that they vary geographically as well as between species (Cyronak et al. 2018b; Shaw et al. 2013; Fabricius et al. 2011). Research is attempting to disentangle the impacts of ocean acidification on coral calcification as it is a complex process that occurs in several stages over which the organism maintains a degree of control (Mollica et al. 2018). Like many calcifying organisms, corals can modulate the pH of fluids during calcification (Venn et al. 2011). This may confound observation of ocean acidification effects *in situ* and it has been suggested that corals could buffer some of the impacts of decreased pH, but at an energetic cost. Despite their ability to elevate the pH of calcifying fluids, results from experimental observations demonstrate that seawater pH still affects the corals (Comeau et al. 2017). There is also evidence that ocean acidification induces a loss of skeletal density rather than slowing down growth (Guo et al. 2020; Mollica et al. 2018), explaining how some corals have been observed to sustain growth rate under acidic conditions. Some observations of manipulation experiments and of corals in naturally low pH reefs appear counterintuitive, but consistent with a two-phase model of coral growth that involves two fundamentally different processes: extension or upward growth and densification or lateral thickening (Mollica et al. 2018). Skeletal density is directly sensitive to changes in seawater carbonate ion concentration and thus, to ocean acidification, whereas extension is not (Mollica et al. 2018).

There is high confidence that ocean acidification will continue to progress to the end of the century and beyond, with potential severe effects for corals. Globally, the species composition of coral reefs and their associated communities are projected to change as a result of future interactions of multiple climatic and non-climatic hazards (Bindoff et al. 2019), with ocean acidification very likely exacerbating the effects of warming sea temperatures (Hoegh-Guldberg et al. 2017). The response of corals to ocean acidification will be species-specific: some warm water corals can continue to calcify at saturation states below one, though at an energetic cost (Pörtner et al. 2014). Despite species-specific responses, there is high confidence that, globally, reefs will experience reduced rates of calcification (Albright et al. 2018), increased dissolution (Andersson et al. 2007); shifts in species composition, competition and functioning (Johnston et al. 2020; Edmunds et al. 2019; Agostini et al. 2018; Enochs et al. 2015b; Fabricius et al. 2011), increased erosion (Enochs et al. 2016; Enochs et al. 2015a), reduced recruitment (Fabricius et al. 2017), and loss of skeletal density (Mollica et al. 2018). In spite of the evidence of the relative adaptive capacity of corals, their ability to overcome ocean acidification remains uncertain (Langdon et al. 2000).

It is difficult to isolate and identify ocean acidification effects on corals and coral reefs as seawater pH and net reef calcification are highly variable. Observed changes in seawater pH are still within the ranges of natural variability: the climatological mean of seawater pH vary from 8.00 to 8.21, and the seasonal amplitude of seawater pH vary from 0.01 to 0.14 (calculated from data from various oceanic, coastal, and coral reef locations, according to Sutton et al. 2019). A lack of long-time data prevents the attribution of observed changes to the effect of ocean acidification: for example, it is estimated that the length of time for an anthropogenic trend in the partial pressure of CO_2 in seawater to emerge from natural variability varies from 8 to 41 years (Sutton et al. 2019). In addition, the dominant driver of reef health is sea temperature and extreme declines due to bleaching may mask the negative effects of ocean acidification (Doo et al. 2020). Despite these caveats, Albright et al. (2016) demonstrated that coral reef net community calcification rates increase when saturation states are increased to preindustrial levels, suggesting that coral reefs may have already suffered declines in net calcification that were not obviously apparent (Doney et al. 2020).

Most ocean acidification research on corals focuses on single species responses to decreased pH, however, ocean acidification is just one of a multitude of climate and non-climate anthropogenic stressors acting on a complex reef ecosystem. It is increasingly ‘the norm’ to conduct experiments using multiple stressors on single species, to reveal how the effects of other climate stressors interact with ocean acidification. However, it is still not clear to what extent the reef environment can acclimatise and adapt to ocean acidification. *In situ* studies are therefore important to transpose the understanding of single species effects of ocean acidification over to the effect on the functioning of whole reef ecosystems. It is possible that ocean acidification will be less harmful or even beneficial to some reef organisms and it is unclear how the ensuing changes in food webs and competition will affect reefs.

In spite of current international efforts, greenhouse gas emissions continue to increase (Hausfather and Peters 2020; UNEP 2019). However, although the majority of studies focus on RCP8.5 as the ‘worst case scenario’ of continuing with fossil-fuel intensive activities globally and excluding any significant climate mitigation policies, leading to nearly 5°C of warming by the end of the 21st Century (Hausfather and Peters 2020) research should also consider a more nuanced approach to end of century projections and investigate biological and ecological responses to mid-range emissions scenario conditions.

Coral reefs in the Indian and Pacific Oceans are already in decline due to a variety of human induced stressors including pollution, sedimentation, overfishing and habitat destruction by coral mining and destructive fishing practices (Burke et al. 2011). In addition, climate change is increasing SST and decreasing pH (Bindoff et al. 2019). Therefore, it is expected that the combination of these multiple stressors will continue to impose pressure on these coral reefs systems resulting in a much rapid degradation rate.

2.6.3. Impacts from sea level rise and extreme weather events

Severe storms can cause extensive damage to coral reefs (Cinner et al. 2016; De’ath et al. 2012). Wave action during intense storms fractures carbonate reef foundations (McAdoo et al. 2011; Nott and Hayne 2001). Extreme surface waves of up to 10–15 m produced by cyclones have been known to propel large boulders of carbonate reef of more than 200 tonnes (Goto et al. 2011) reducing live coral cover and structural complexity by 80–100% (Harmelin-Vivien 1994). The redistribution of sediment and rubble, heavy rainfall, flooding, surface currents and augmented coastal erosion can result in water turbidity, coral smothering and declining coral and fish health

(Goatley and Bellwood 2012; McAdoo et al. 2011; Mallela et al. 2007; Fabricius and Wolanski 2000; Scoffin 1993; Van Woesik et al. 1991; Woodley 1980), as well as habitat loss (Cinner et al. 2016). The elevated catchment runoff due to heavy rainfall causes nearshore accumulation of freshwater, sediment, nutrients, fertilisers and pollutants, lowering salinity and stimulating growth of algae and microbes, which can stress corals (Witt et al. 2012; Heron et al. 2008).

Storm events can also facilitate windows of opportunity for renewal, for example by scouring algal-covered reefs and exposing the solid limestone structure of the reef, which provides new foundations on which corals can recruit, settle and grow (Graham and Nash 2013; Heron et al. 2008). Storms can also provide fast relief from warming stress (Heron et al. 2008).

Relative sea levels are calculated based on tide gauge data and having removed regular seasonal fluctuations and reduced to a common datum[6], and main forces inducing variations of sea level include thermal expansion, meltwater from ice sheets and glaciers, and vertical movements of land masses (Nauels et al. 2019; Vitousek et al. 2017; Church et al. 2013). Relative sea level rise on its own is not expected to have profound direct negative effect on healthy coral reef environments because accretion rates of coral are generally sufficient to keep pace with sea level rise, and in some locations this might create increased habitat availability as reefs grow upwards and expand into new areas (Cinner et al. 2016). The species assemblage of the existing reef will determine the outcome of these responses, so degraded reefs with altered species composition and slower growth rates may be less able to respond and adapt (Saunders et al. 2016).

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[6] https://psmsl.org/data/obtaining/psmsl.hel

3. BIOT: drivers of marine climate change

3.1. Sea surface temperature change

3.1.1. Observed changes

The average SST of the Indian Ocean increased by more than 0.6°C between 1950 and 2009 (IPCC 2014a). Analysis of sea temperature records from monitoring sites in BIOT demonstrates four major thermal stress events, or marine heatwaves, between 1998 and 2016, the latest being the most pronounced (Figure 6). The measurements also show a gradual increase in SST of around 0.5°C over the same period. Degree Heating Weeks or Months (DHW or DHM) denote coral susceptibility to climate change, representing the number of weeks or months they are exposed to warming multiplied by temperature above expected.

Temperature loggers have been located in between 10–20 locations at depths of 5, 15 and 25 m depth on all atolls (Sheppard and Sheppard 2019). These have recorded water temperature at intervals of 2 hours since 2006 and over 11 years showing: a rise of 0.28°C on an ocean-facing reef in Diego Garcia, an increase of 0.4°C in a large and open lagoon of Peros Banhos, and the largest warming of 0.52°C, in a smaller, shallow lagoon of Salomon Atoll with a restricted water flow (Sheppard and Sheppard 2019). Most coral mortalities, both for hard and soft species, are usually caused when temperatures rise more than 2°C above the local seasonal average. The pattern is complicated by seasonal episodes caused by undulating thermoclines driven by subsurface waves, which cause plunging temperatures by almost 6°C with a periodicity of about 1–4 days during the warm season (Sheppard 2009). These cooling events ameliorate harmful effects of warming, but the upwelling does not enter lagoons, whose overall rise best reflects background warming trends in BIOT. An analysis of the loggers within these lagoon sites by calendar year has shown that 2012 was significantly warmer than preceding years (Sheppard and Sheppard 2019). This measure is roughly analogous to the widely used DHW but with important differences: the reference temperature is that which was known to cause coral mortality in 1998; the temperatures are those measured at 5 m and/or 15 m depth rather than surface measurements; and finally, the data set spans a daily cycle of observations, whilst satellite measurements for computing DHW are acquired at night (Sheppard and Sheppard 2019).

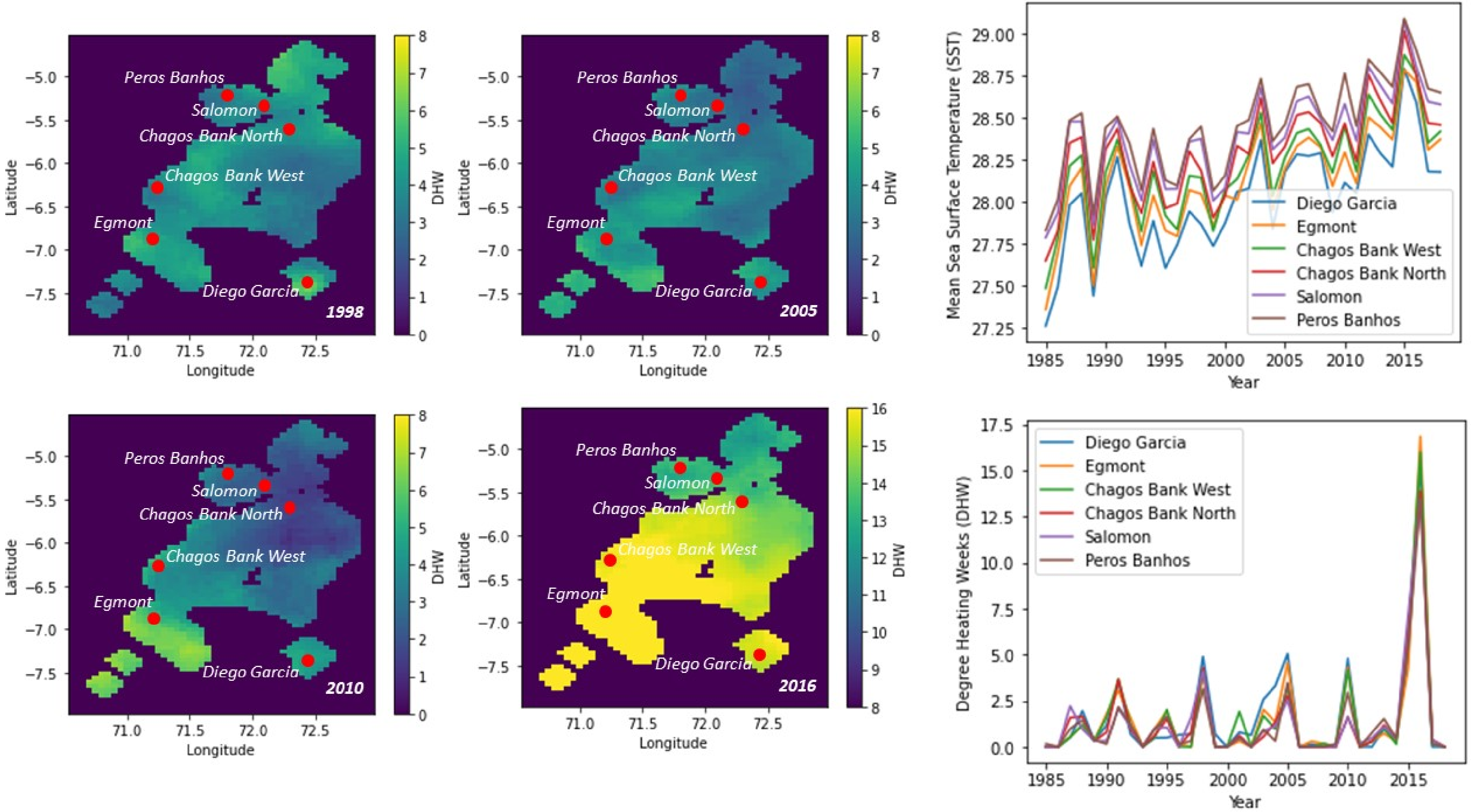

Figure 6. Past thermal stress in British Indian Ocean Territory (BIOT) showing: time series of mean annual sea surface temperature (SST) (top right) and total Degree Heating Weeks (DHWs) (bottom right) from six monitoring sites; and maps of DHWs during strong thermal stress years 1998, 2005, 2010 and 2016, showing the position of the monitoring sites. The dark blue areas denote no data. Data obtained from NOAA Coral Reef Watch (2018).

3.1.2. Projected future changes

In the Indian Ocean, SST is projected to continue rising into this century (Figure 7, taken from IPCC 2014a). The surface layers of the three ocean basins have warmed (very likely), with the Indian Ocean (0.11°C per decade) warming faster than the Atlantic (0.07°C per decade) and Pacific (0.05°C per decade; IPCC 2014a). It is important to note that projections for BIOT regarding mass coral mortality events recurring every 5 years or less, appear to be already underway (Sheppard 2003).

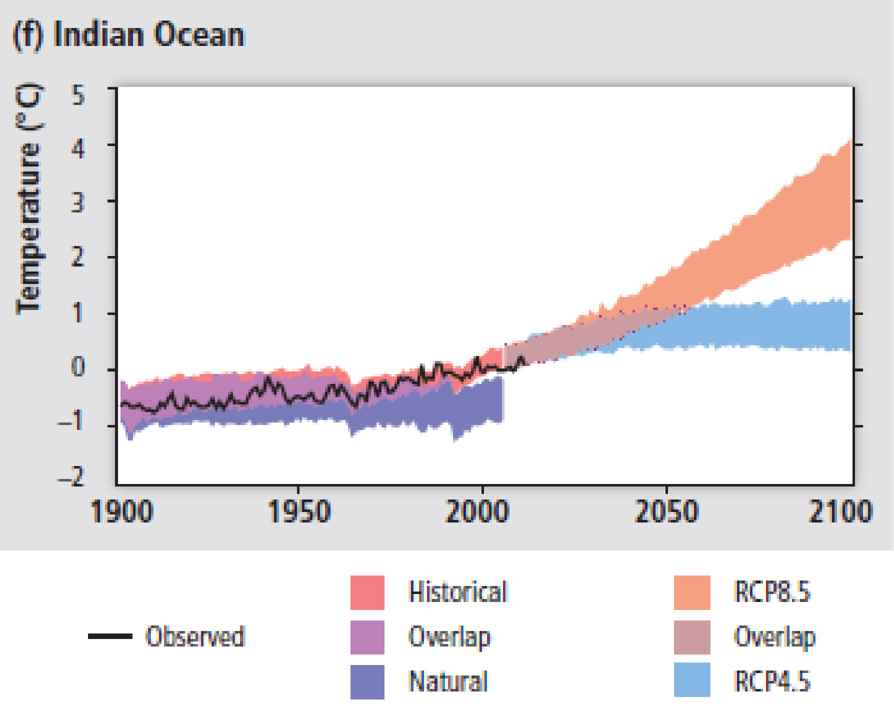

Figure 7. Historical and projected SST in the Indian Ocean, under two climate change emissions scenarios. Original source: Figure 30.2 (Panel (f)) from Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry, and S. Jung, 2014: The Ocean. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731.

Under a medium emissions scenario, SST is projected to rise in BIOT by approximately 1°C by 2050, and by 1.5°C by the end of the century (NOAA Climate Change Portal 2020). Under a high emissions scenario, average SST in BIOT is expected to increase by 4–5°C by 2099 (Figure 8).

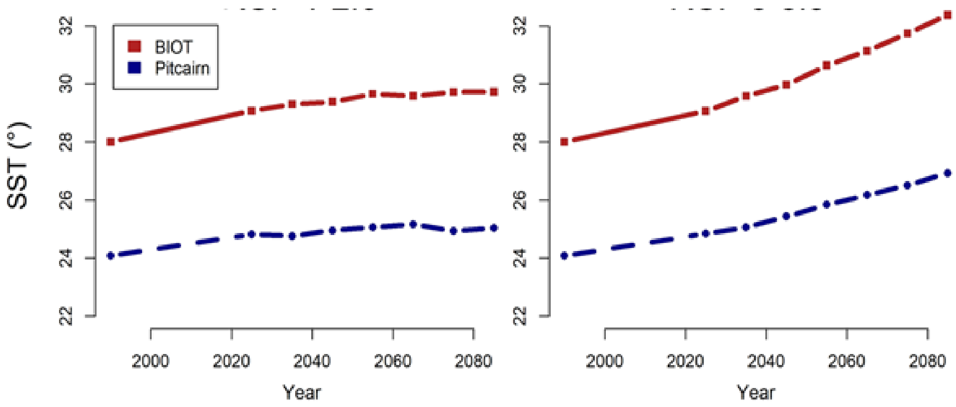

Figure 8. Future average SST for Pitcairn and BIOT, showing the predicted warming under Paris Agreement (RCP2.6, left) and worst-case scenario (RCP 8.5, right). Data were obtained from the UKESM1 forecast model, from Sellar et al. (2019).

Figure 9 shows the proportion of corals reefs in the western Indian Ocean projected to be exposed to DHM higher than 1 or 5 in the coming century (IPCC 2014a). A DHM equal to 1 is associated with bleaching, while DHM higher than 3 is associated with mortality. More than half of corals are projected to be exposed to bleaching by 2050, in all except the lowest emissions scenarios. A high emissions scenario causes more than half of corals being exposed to more than 5 months of DHM leading to mortality (IPCC 2014a).

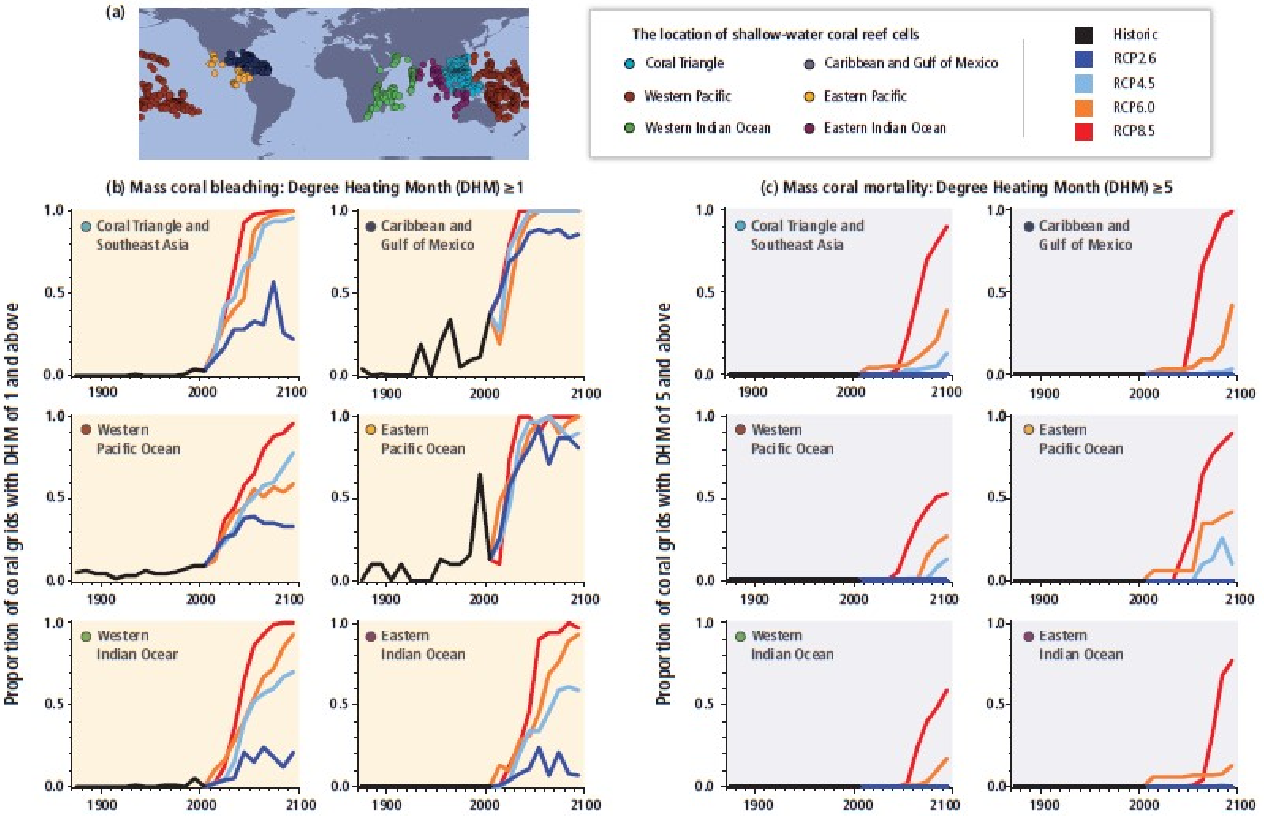

Figure 9. Left: mass coral bleaching in different oceans under different climate change scenarios, indicated by proportion of coral grids that are subject to at least Degree Heating Month (DHM) equal to 1 or higher. Right: mass coral mortality under different climate change scenarios, where mortality is indicated by the proportion of coral grids that are subject to DHM of 5 or higher. Original source: Figure 30.10 from Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry, and S. Jung, 2014: The Ocean. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655–1731.

3.2. Ocean acidification and carbon chemistry

3.2.1. Observed changes

The biogeochemistry of the Indian Ocean is highly variable and influenced by the seasonal monsoons and by oceanic circulation systems (Xue et al. 2014). Surface pH is relatively low, particularly in the northern Indian Ocean, compared to the subtropical North Pacific and North Atlantic, especially during the northern winter months (Takahashi and Sutherland 2013) and appears to be declining more rapidly than the global average: -0.027 pH units per decade between 1991–2011 (Ishii et al. 2020; Lauvset et al. 2015). Using the same ensemble of global ocean-atmosphere general circulation models (CMIP5) as the IPCC 5th Annual Report (AR5), a mean surface water pH of around 8.09 for BIOT has been estimated between 1956–2005 (Figure 10).

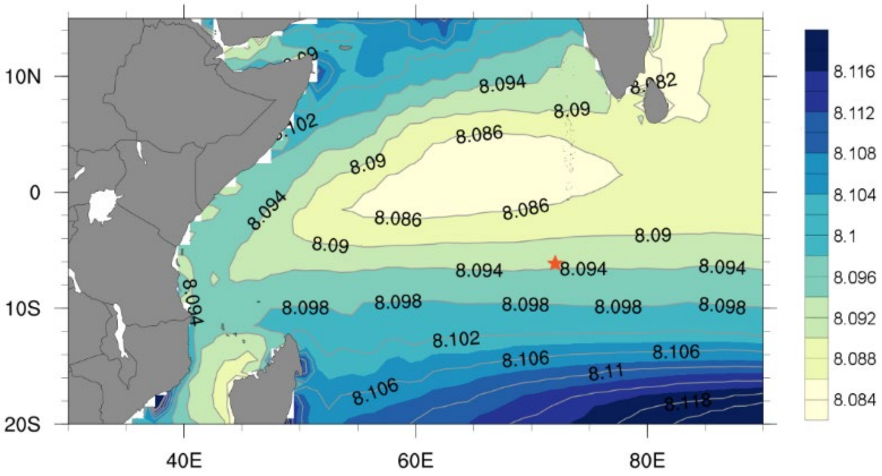

Figure 10. Outputs from the CMIP5 ensemble showing mean surface water pH in the western Indian Ocean for the period 1956–2005. The approximate location of BIOT is indicated by the orange star symbol (NOAA Climate Change Web Portal 2020).

Ocean acidification effects in the Indian Ocean remains largely understudied due to the challenges involved in collecting relevant biological and carbonate chemistry data to establish vulnerability status of ecosystems and species (UNEP 2018; Lam et al. 2019). The Global Ocean Acidification Observing Network (GOA-ON 2020) is working towards Improving our understanding of global ocean acidification conditions, of ecosystem response to those conditions, and to acquiring and exchanging data and knowledge necessary to optimize modelling for ocean acidification and its impacts (GOA-ON 2019), but as yet there is a lack of direct spatially and temporally resolved chemical and biological data enough to support modelling of ocean acidification conditions and impacts for the BIOT region.

3.2.2. Projected future changes

Projections of aragonite saturation state, which is critical for coral calcification, suggest a likely decrease to 2.5 in BIOT under an RCP8.5 emissions scenario by the end of the 21st Century (Figure 11).

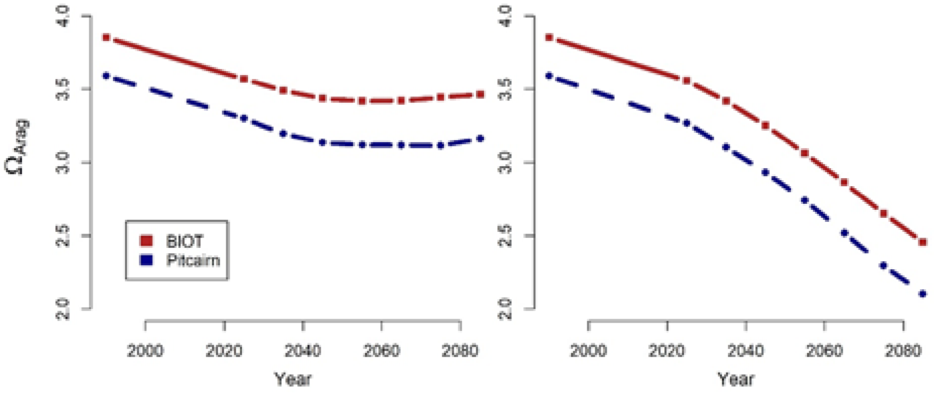

Figure 11. Current and future average sea surface aragonite saturation state (Ω_{ar}) for Pitcairn (Blue) and BIOT (Red), showing the predicted decline in saturation under Paris Agreement (RCP2.6, left) and worst-case scenario (RCP8.5, right). Data were obtained from the UKESM1 forecast model, from Sellar et al. (2019).

Global models project that, under RCP8.5 and by the end of the century, the average surface pH around BIOT will decrease by 0.27 pH units (Figure 12; NOAA Climate Change Portal 2020). This projection is slightly lower than global estimates (Bindoff et al. 2019). Under RCP2.6, the average annual pH would decrease by 0.08 units by the end of the century (NOAA Climate Change Portal 2020). Interestingly, this projection is nearly twice as high as the range estimated by Bindoff et al. (2019) under the same scenario.

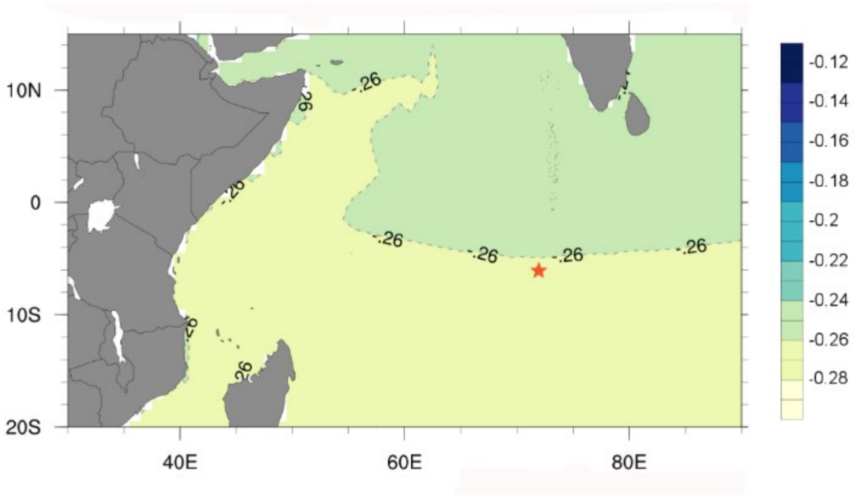

Figure 12. Outputs from the CMIP5 ensemble showing mean surface water pH anomaly under high emissions scenarios (RCP8.5) in the western Indian Ocean for the period 2050-2099 compared to averages in 1956-2005. The approximate location of BIOT is indicated by the orange star symbol (NOAA Climate Change Web Portal 2020).

3.3. Sea level rise

3.3.1. Observed changes

Sea level measurements in Diego Garcia, as measured by buoys, radar and pressure[7], indicate that the rate of rise is faster than the oceanic average. The 5.5 mm per year of recorded sea level rise according to Sheppard (2002) is higher than the estimated mean reef growth rate by Perry et al. (2018) for northern atolls before the massive coral mortality in many Indian Ocean archipelagos in 1998; since then the situation has reverted to net erosion with many shallow reef surfaces having lost up to 1.5 m in height of previously dense *Acropora* thickets (Sheppard 2002). The gap between coral vertical growth and sea level rise is expected to be increasing (Sheppard 2002). In the BIOT atolls, dune and berm systems may extend a few meters above high tide level, but the rest of the atoll area including Diego Garcia lies within 1 m of the high tide mark. Most of the BIOT atolls are just above or even below sea level (cross section profiles of Diego Garcia are available from Purkis et al. 2016; cross section of islands from Egmont atoll and Great Chagos Bank are available from Sheppard, 2002). It is important for the persistence of the islands that the fringing reefs are able to grow upwards. Healthy reefs can keep up with current rates of sea level rise, but currently reef attrition is overtaking reef growth, adding to the widening gap between the surface of reef breakwaters and the sea. There is evidence that smaller islands are losing considerable areas of mature soil and land, while in horseshoe-shaped Diego Garcia the accumulation of soft

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[7] http://www.ioc-sealevelmonitoring.org/station.php?code=garc

sediments in the lagoon has replaced, in terms of area, some of the erosion, although this is soft mud rather than soil (Perry et al. 2018; C.R.C. Sheppard, *Pers. comm.*).

3.3.2. Projected future changes

Observed changes in the pattern of Indian Ocean Hadley and Walker atmospheric overturning circulation cells suggest that if anthropogenic warming continues to dominate natural variability, the rate of sea level rise is likely to augment environmental stress on coasts and islands of the Indian Ocean, according to a study combining in situ and satellite observations of Indian Ocean sea level with climate-model simulations by Han et al. (2010). This increase in basin-mean sea level comes from a combination of wind-driven mass redistribution of ocean water, and global thermal expansion and salinity effects (Han et al. 2010). There is considerable geographical as well as seasonal variability in these projections, however. For example, while mid-ocean regions (such as the Mascarene Islands), coastal regions off Indonesia, and the North Indian Ocean, may experience significantly (data model correlations above 95% significance) sea level rise higher than the global mean, other areas such as the Seychelles, east coasts of Kenya and Tanzania, and Maldives may see little or no sea level rise (Han et al. 2010). Furthermore, in the case of the Maldives (1025 km north from BIOT), whilst no significant sea-level rise appears on the basis of all-season records, statistically significant (data model correlations above 95% significance) sea-level rise is shown during winter (Han et al. 2010).

No projections exist for the BIOT region specifically, so it is difficult to be confident in terms of future sea level rise and its potential impact on the corals, particularly on fringing reefs. Observed coastal erosion and repeated flooding of roads and infrastructure – in spite of costly shoreline defences being reinforced every year, particularly in Diego Garcia and around military structures – are indications of ongoing sea level rise (C.R.C. Sheppard, *Pers. comm.*).

3.4. Extreme weather events

3.4.1. Observed changes

In the Indian Ocean, while fewer storms appear to be making landfall in south-east Africa, an increasing number of tropical cyclones are tracking south of Madagascar (Walsh et al. 2019; Leroux et al. 2018; Nash et al. 2015; Fitchett and Grab 2014). Due to its proximity to the equator however, BIOT is outside of the Indian Ocean cyclone belt. The last known cyclone to pass over the islands was in 1891 (Dunne et al. 2012). There are no routine measurements of waves near BIOT, but insights have been obtained from measurements taken by passing ships, satellites and numerical wave models, showing no evidence of long-term changes in the wave and wind fields in this area (Dunne et al. 2012). According to NOAA's Historical Hurricane Tracks records, the last two tropical storms to pass close to BIOT (within 60 nautical miles) were storms Nano and Saba in January and March 1983 respectively (NOAA Hurricane Tracks 2020).

Although BIOT experiences few direct storm hits, this region is still exposed to the impact from deep ocean swells that may originate from storms or cyclones at considerable distances away. Such long-distance swells are known to reach islands such as the Maldives, which have been subject to coastal flooding and damages from large waves originated by extra-tropical cyclonic events, for example those that occur in the Southern Ocean (Meucci et al. 2020; Kamranzad and

Mori 2019; IPCC 2014b; Maldives Department of Meteorology 2007). Indeed, there is evidence of significant storm damage to reefs in BIOT damage (C.R.C. Sheppard, *Pers. comm.*).

3.4.2. Projected future changes

A wave climate study by Semedo et al. (2013), using atmospheric forcing and based on the A1B medium-high emissions IPCC scenario (Nakicenovic et al. 2000), reported a global, poleward shift in wave activity, and for the Indian Ocean an increase in mean wave height of more than 0.5 m, particularly during the June to August season. Nevertheless, most modelling studies of wave conditions in the Indian Ocean appear to indicate negligible changes or even a decrease in mean significant wave height in regions dominated by trade and monsoon winds (Church et al. 2013).

Projected changes in tropical cyclone climatology with increasing temperatures (based on a low mitigation scenario for 1.5°, 2° and 3°C change relative to the 1971–2000 baseline climate) show a likely general downward trend in tropical cyclone frequencies for the Indian Ocean (Muthige et al. 2018). Associated with a lower frequency of tropical cyclones, there is also a 25–50% decrease in cyclone landfalls (Muthige et al. 2018). The lower tropical cyclone frequency over much of the South West Indian Ocean is related to changes in large-scale circulation, with consequential changes in vorticity and wind shear, as well as changes in stability in the troposphere (Muthige et al. 2018).

4. BIOT corals: climate change impacts

4.1. Impacts from bleaching

4.1.1. Observed impacts

BIOT has one of the longest coral monitoring time-series of any location in the Indian Ocean, with coral and other benthic data extending back to the 1970s (Sheppard et al. 2020). From 1970 and until 1997, coral cover was high (50–70%) around the archipelago, with diverse coral communities found in the lagoons, reef crests and reef slopes. It is thought that a major thermal stress event took place in 1983, with varying bleaching and mortality effects across the area, but by 1997 the coral cover had recovered to pre-1983 levels (Sheppard 1999). In 1998, a mass bleaching event of global scale was observed, when DHW close to 4 were recorded across BIOT (see Figure 6, Table 1) and extensive coral bleaching and mortality occurred, with just 12% coral cover remaining in 1999 (Sheppard 1999). Post-1998, coral cover was mostly reduced to thermally resistant *Porites* species, and significant declines were observed in *Acropora,* Pocilloporidae and Mussidae corals. There were also significant declines of non-scleractinian corals including soft corals (Octocorallia), blue coral (*Heliopora coerulea*) and fire corals (*Millepora* spp.; Sheppard 1999). Over the years following the 1998 bleaching, communities recovered and were eventually dominated by thermally sensitive *Acropora* (Sheppard et al. 2008).

Table 1. Past thermal stress in British Indian Ocean Territory (BIOT), showing the mean SST at the start and end of a time-series spanning 1985–2018 and the difference in mean SST, along with Degree Heating Weeks (DHWs) levels in potential bleaching years, the cumulative DHW, and the number or Alert Level 1 and 2 thermal stress events. Data from NOAA Coral Reef Watch (2018).

	Diego Garcia Island	Egmont Islands	Chagos Bank West	Chagos Bank North	Salomon Islands	Peros Banhos Atoll
Mean SST (1985-89)	27.7	27.84	27.94	28.05	28.17	28.21
Mean SST (2013-18)	28.41	28.52	28.59	28.66	28.75	28.82
Difference in mean SST	0.71	0.68	0.65	0.61	0.58	0.61
DHW 1995	4.9	4	4.2	4.3	4.1	3.1
DHW 2006	5	4.6	3.2	2.8	2.5	3.5
DHW 2017	4.8	4.3	4.2	1.6	1.6	3
Cumulative DHW	15.5	16.8	16	13.9	13.4	13.5
Alert 1 (DHW 4-8) frequency	30.2	29.7	27.6	22.6	21.6	23.1
Alert 2 (DHW >8) frequency	3	3	2	1	1	0

By 2006, coral cover in most sites was 30–50%, with deeper reefs showing slower recovery (Sheppard et al. 2008). Minor thermal stresses were recorded in 2005 and 2010, reaching bleaching Alert Level 1 in Diego Garcia and Egmont (see Figure 6, Table 1), but these events did not appear to cause extensive mortality except around Egmont, where cover remained at only 10–20% (Sheppard et al. 2008). Rapid recovery of cover and composition to pre-bleaching levels was aided by high recruitment in the archipelago (e.g., in 2001, densities of juvenile corals reaching 65.8 m^{-2}), as well as by the near-absence of other human impacts such as fishing, pollution and coastal development (Head et al. 2019; Sheppard et al. 2008).

During the next global bleaching registered between 2014–2017, BIOT experienced successive acute thermal stress events (Head et al. 2019). In 2015, thermal stress reached DHW 7.5, which is at the highest end of Alert Level 1, while in 2016 exceptionally high DHW were recorded in the range of 13–17. Average coral cover in BIOT declined from 30% in 2012 to 12% in April 2016, just prior to the second thermal stress event (Head et al. 2019). Peros Banhos showed a decline from 36% coral cover in 2012 to 14% in 2016, and then a further decline to 10% in 2017 (Head et al. 2019). This suggests that even though 2016 saw higher thermal stress than 2015, the impact on corals was disproportionally greater in 2015 because many of the thermally sensitive colonies were already lost by 2016, leaving only the more resistant ones to face the second stress event (Head et al. 2019). By 2019, average coral cover around BIOT remained at 10%, suggesting no further recovery (Sheppard et al. 2020). The density of coral recruits in 2017 at just 5 per m^2 was much lower than post-1998, which explains the slow regrowth of the reef (Sheppard et al. 2020). These repeated thermal stress events have also caused several important community shifts in the corals of BIOT, with *Diploastrea heliopora* and *Seriatopora hystrix* being completely extirpated from the archipelago, and a reduction in the presence of *Isopora palifera* and the endemic endangered *Ctenella chagius* corals (Sheppard et al. 2020). It is moreover worth noting that the rates of bleaching and mortality were very similar when compared between the 1998 and 2016 events in BIOT (and also in the Maldives), with no apparent increase in thermal resistance (Cowburn et al. 2019; Head et al. 2019). This may be in partly due to the fact that, after 1998, colonies had partially recovered to pre-bleaching communities still dominated by thermally-sensitive *Acropora* branching corals (Pisapia et al. 2016; Sheppard et al. 2008).

4.1.2. Projected future impacts

BIOT is expected to experience more thermal stress and bleaching in the near future, with no guarantee that corals might continue to recover (Sheppard 2003). Deep ocean-facing reefs are the least exposed to thermal stress and may become important refuges for corals, but the highly sensitive *Acropora* dominated communities in the shallower and more sheltered areas will likely continue to experience high levels of thermal stress, with a high risk of bleaching and mortality (Sheppard 2003). According to Sheppard (2003) we can expect local “extinctions” of reefs to take place if the frequency of thermal stress and bleaching events is 1 in 5 years or greater, since 5 years is the average age needed for coral polyps to mature and reproduce. In 1998, more than 90% of shallow corals were lost on Indian Ocean reefs primarily due to high SST (Sheppard 2003), and three major marine heatwaves have taken place since, the latest in 2016 being the most pronounced.

Situated near the equator, BIOT corals are already experiencing what are present-day upper limits of thermal tolerance, and it is doubtful they will persist under projected future SST conditions. Severe bleaching events are expected to occur on an annual basis by 2041 (Van Hooidonk et al. 2016). Based on present-day tolerance limits, the BIOT region will become largely unsuitable for corals by 2099 (Couce et al. 2013).

The presence and persistence of reefs in the area will depend on future sea temperature rise, and their location and exposure to open oceanic waters. As a result of high water clarity, there are diverse coral colonies growing on BIOT's fore-reef slopes down to 70 m deep, with high cover despite the impact of bleaching on the archipelago (Head et al. 2019). Subsurface waves reach the ocean-facing reef slopes periodically, bringing cooler deeper waters and offering relief during thermal stress events (Sheppard 2009). These deeper and ocean-facing reef slopes may be sheltered from future thermal stress events and therefore less affected by bleaching, whilst the extensive reef flats, and shallow back-reef colonies in the atolls, will continue to be exposed to high thermal stress and irradiation and will likely experience recurrent severe bleaching.

Some thermal resistance has already been seen in BIOT's corals, as discussed above. It is not clear what will happen in the future: if the coral community recovers rapidly again to an *Acropora* dominated state it may remain sensitive, however if a novel coral community of more resistant coral types emerges, this will reduce the reef's sensitivity.

BIOT's reefs are far from most human influence, other than the military base in the Diego Garcia atoll, and as a consequence the area is largely uninhabited with very little fishing, land-based pollution or coastal construction (Burke et al. 2011). Herbivorous fish communities appear to be relatively healthy, and the abundance of macroalgae is low (Head et al. 2019), all of which should be in favour of recovery potential for BIOT's reefs. However, there is concern that particular coral types may be permanently lost from BIOT's reefs as past marine heatwaves appear to have exceeded thermal thresholds for most species of corals, as shown by massive *Porites* corals accounting for most (80%) of the remaining live coral cover whilst *Acropora* table corals were nearly completely absent following the mass bleaching and mortality events of 1998 and 2015-2016 (Head et al. 2019).

4.1.3. Knowledge gaps and research needs

BIOT has a good historic data record, with baseline data starting from the near-pristine conditions of the 1970s, that allows confident conclusions about changes to the reef ecosystem as a result of bleaching (Sheppard et al. 2020). It is important to continue monitoring key indicators of reef resilience, including but not limited to coral cover and colony species composition, coral recruitment rate and changes in macroalgal cover and reef fish assemblages, in order to gather further evidence on the response of the reefs to future climate change, and to use that evidence to inform MPA management actions.

4.2. Impacts from changes in carbon chemistry and ocean acidification

4.2.1. Observed impacts

To date, there are few studies on the impacts of ocean acidification in Indian Ocean reefs. In this region, research has traditionally focussed on warming impacts (Sheppard et al. 2020; Lam et al. 2019) while ocean acidification studies have been more prevalent in the more diverse Indo-Pacific reefs. As a result, global models must be relied upon to provide an indication of ocean acidification effects. Modelling suggests global reefs are so far relatively unaffected by ocean acidification impacts where the saturation state of waters has remained above 3.8, as seawater saturation is rarely above 4 (Guan et al. 2020). Models used by Sellar et al. (2019) indicate that Ω_{ar} around the BIOT is roughly 3.8, suggesting that one would anticipate very little impact from ocean acidification alone, as healthy reefs in the region can function at Ω_{ar} of 3.6 (Guan et al. 2020).

4.2.2. Projected future impacts

Results from global modelling studies that have assessed the impacts of both warming sea temperatures and ocean acidification show that under high emissions scenarios the waters around BIOT are projected to become less suitable for corals (Guan et al. 2020; Couce et al. 2013). The combination of future ocean acidification and bleaching represents an increased risk of further loss of live coral (Lange and Perry 2019), which in turn represents a greater risk of erosion for BIOT coral reefs in the future.

Aragonite saturation states below 3 are considered extremely marginal for coral growth, with no major reef systems currently found at locations with those levels (Langdon and Atkinson 2005). Model projections suggest that by the end of this century and under an RCP2.6 scenario, the waters around BIOT would have a surface Ω_{ar} of 3.5 (Figure 11) suggesting conditions that would be marginal for corals, even though this may be one of the places less badly affected by ocean acidification. A modelling study of future global habitat suitability for corals, indicated that ocean acidification is not expected to have significant deleterious effects for the reefs in BIOT (Guan et al. 2020). Other studies, however, suggest that under high emissions scenarios, future declines in saturation state would lead to a 12% loss of skeletal density of *Porites* corals in BIOT (Mollica et al. 2018). These apparent discrepancies hint at a lack of understanding of the impacts of ocean acidification and of the response mechanisms in corals at present.

4.2.3. Knowledge gaps and research needs

Improved monitoring is needed to better understand the changes in carbonate chemistry and the potential for coral adaptation in BIOT reefs. Work is already underway as part of expanding the Global Ocean Acidification Observing Network monitoring (GOA-ON 2019). It is essential that any initiatives include capacity building and support of active monitoring efforts in these locations, as far as possible. Improvement of autonomous sensor technology could help improve the monitoring network, although this is a global issue and not unique to BIOT. Work is underway as part of the United Nations Decade of Ocean Science for Sustainable Development to provide further instrumentation in data-poor regions, through a commitment to enhance global ocean acidification monitoring and research and with involvement of regional hubs and members (GOA-ON 2019).

Contemporary models are not sufficiently powerful or accurate to produce useful downscaled projections to meaningfully support local adaptation for small islands such as BIOT. For example, typical global climate model grid cell size is 50–100 km^2, a coarse scale that inevitably masks localised variations that might be driving ecosystem change.

4.3. Impacts from sea level rise and extreme weather events

4.3.1. Observed impacts

The changes in sea level observed in the Indian Ocean are twice the global average, but not unprecedented over the past 2,000 years (Kench et al. 2020; Thompson et al. 2016). Coastal habitats including coral reefs have experienced sea level oscillations that are of lower frequency and greater magnitude than ENSO, which characterizes sea level variability in the Indo-Pacific, and evidence has been found in coral skeletons of the present acceleration in sea level in the Indian Ocean that began in the early 19th Century.

BIOT lies outside of the Indian Ocean cyclone belt and there is no evidence of significant changes in the wave and wind climate in the area (Dunne et al. 2012), however there is evidence of significant storm damage to reefs in BIOT damage (C.R.C. Sheppard, *Pers. comm.*). Extreme deep-ocean waves originated by distant extratropical cyclones, usually in the Southern Ocean, are also known to have reached other islands such as the Maldives and causing significant damage (IPCC 2014b; Maldives Department of Meteorology 2007). Distant extratropical cyclonic activity therefore represents a latent, if minor, threat to BIOT coral reefs.

4.3.2. Projected future impacts

Many reef areas in the Indian Ocean, including BIOT, were extensively affected by the 2016 bleaching event and suffered widespread coral mortality (Perry et al. 2018; Sheppard et al. 2017). The relatively high vertical reef accretion potential that has been reported for BIOT (2.94 ± 2.06 mm per year) far exceeds contemporary rates of sea level rise (Perry et al. 2018). Through to 2099 however, only a very small proportion of reefs (less than 3%) are likely to sustain vertical accretion potential to match the expected future sea level rise rates under an RCP4.5 scenario, and even less (below 1%) under the RCP8.5 scenario if recurrent bleaching persist (Perry et al. 2018). Sea level rise therefore remains a risk to coral reefs in the future (Sheppard et al. 2017). In Diego Garcia, the rate of sea level rise is higher than the global average (Sheppard et al. 2017). Most reef crests that provide breakwater effect are close to the islands, sometimes only 25 m from the shorelines, meaning that the breakwater effect of reef crests will be less effective in attenuating the waves (Sheppard et al. 2017; Storlazzi et al. 2015; Sheppard et al. 2005). Continued or prolonged erosion due to wave damage for example could therefore become severe and preclude the reef from keeping up with future accelerating rates of sea level rise (Sheppard et al. 2017; Purkis et al. 2016).

If reef crests are overtopped permanently, the immediate consideration is erosion of shores and inundation by the sea, and salination of water tables rather than the sea level rise per se, although coral atoll islands are known to have very dynamic shores that change shape in response to erosion and accretion processes (Purkis et al. 2016; Sheppard et al. 2012). BIOT has suffered considerable shoreline erosion, registering episodes of up to 1 m per year of horizontal attrition in parts of several atolls, and showing net erosion over the past 100–150 years in some of the islands (Sheppard et al. 2012). Bleaching and coral mortality are also likely to lead to changes in sand production, which would have marked consequences on shorelines across the wider Indian Ocean (Sheppard et al. 2005).

4.3.3. Knowledge gaps and research needs

There are considerable gaps in the understanding of geological sea level rise adjustments of small islands, particularly coral islands, thus creating a barrier to supporting adaptation and risk reduction strategies (Kench et al. 2015; Barnett and O'Neill 2012). From a geological perspective, rising sea levels are expected to erode island coastlines, remobilise sediments and destabilise islands. In extreme cases, major erosion of islands is projected but there are discrepancies and debate amongst latest studies about likely impacts to atoll islands (Ford et al. 2020; Kench et al. 2018b; Storlazzi et al. 2018; Kench et al. 2015).

Reconstruction of coral records suggests an increase in the strength and frequency of Indian Ocean Dipole events during the 20th Century; BIOT being the ideal reference site for climate variability research in the Indian Ocean region and beyond, emphasizing the importance for measuring high-quality *in situ* climatic parameters (Sheppard et al. 2012) particularly in relation to sea level changes, both average and extreme.

4.4. Other anthropogenic pressures

Climate change is only one of many pressures being exerted on corals, with many others causing stress and loss. Non-climatic pressures impacting corals globally include pollution, sedimentation, eutrophication, fishing, invasive species, coral diseases, and physical damage from anchors, mining, and other activities (Carlson et al. 2019; Dutra et al. 2018).

Although human pressures on BIOT are relatively low compared to other marine areas, some human activities are taking place that cause a degree of impact.

Since the designation of the BIOT MPA in 2010[8], commercial fishing and any other extracting activities have been prohibited although recreational fishing is allowed around Diego Garcia, only to residents and under strict conditions, targeting tuna and other scombrids; it is estimated that this fishery took between 8–13 tonnes of tuna and tuna-like species each year between 2013 and 2017 (Bell et al. 2018). The remainder of this fishery is mainly on reef fish, but catches are not usually recorded. In addition, there is illegal, unreported and unregulated (IUU) fishing for tuna and shark (Bell et al. 2018). Sharks have been depleted in BIOT due to poaching and bycatch, with numbers of reef sharks in the northern atolls declining by around 90% between the 1970s and 2006 (Graham et al. 2010; Koldewey et al. 2010). Shark populations appear to have recovered slightly since then (Graham et al. 2010; Koldewey et al. 2010). In the past, there has also been heavy sea cucumber poaching, with evidence of thousands being collected in each haul (Readman et al. 2013). Sea cucumbers play an important role in nutrient cycling on coral reefs and thus removal of large numbers can have a negative impact on corals (Readman et al. 2013).

The waters of BIOT are exposed to few pollutants and contaminants (Readman et al. 2013), but recent sampling found low traces of nutrients, chemicals and heavy metals, particularly around

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[8] British Indian Ocean Territory (gov.io)

Diego Garcia lagoon (Painting et al. 2020). Further sampling was recommended, and close monitoring is being carried out. Plastic pollution has not yet been confirmed as a threat to corals in BIOT (Sheppard et al. 2012). Elsewhere in the Indo-Pacific region however, marine plastics have been linked with an increase in the likelihood of coral diseases (Lamb et al. 2018).

There are largely unchecked populations of black rats on most islands of BIOT, which have caused population crashes to resident seabird colonies (Vogt et al. 2014; Carr et al. 2011). The loss of seabird numbers has in turn resulted in a deficit of supplementary nutrients from guano leaching, which is needed to support growth of reef fish, benthic algae, and sponges. The rats therefore have disrupted natural nutrient flows to the detriment to the reefs, affecting their resilience and recovery rate in the face of other stressors such as climate change (Benkwitt et al. 2021; Benkwitt et al. 2020; Graham et al. 2018; Graham et al. 2017). So far, no invasive marine species have been found in BIOT; strict environmental regulations are enforced owing to the combined existence of one designated Ramsar Wetlands Site of International Importance (JNCC: Ramsar Site UK61002), four IUCN Strict Nature Reserves and, principally, a no-take MPA that extends up to the 200 nautical mile boundary (Sheppard et al. 2012; Nelson and Bradner 2010).

There have been reports of anchor damage to corals in the lagoon of Diego Garcia caused by military ships, with an estimated two-thirds of corals in the lagoon suffering breakages (Sheppard and Turner 2008). In 2013, steps were taken to restrict anchoring to only a few sites within the lagoon to limit damage (The Chagos Archipelago 2018). Yachts occasionally moor off the outer islands, and may be granted a permit to moor in approved sites in Salomon Islands and Peros Banhos if essential for their safe passage across the Indian Ocean.

4.4.1. Knowledge gaps and research needs

There may be room to improve monitoring and management of the recreational fishery in BIOT. Regular water quality monitoring should be maintained, particularly around Diego Garcia, to detect any pollution, trace the source and avoid accumulation beyond trace levels (Painting et al. 2020). BIOT in particular, could be further promoted as a scientific reference site given its low level of human pressures, and monitoring of key ecological indicators could be developed and implemented to help provide early warning signals of ecological change (Lewis et al. 2017; Sheppard et al. 2013).

5. Pitcairn Islands: drivers of marine climate change

5.1. Sea surface temperature change

5.1.1. Observed changes

The average SST in the Pacific increased by 0.31°C between 1950 and 2009 (IPCC 2014a). Sea temperature records from monitoring sites in Pitcairn Islands show three relative heatwaves, with peaks in 1995, 2006 and 2017, principally in Oeno, Pitcairn and Henderson, but less noticeable in Ducie (Figure 13).

In the coral reef province of the western Pacific Ocean, SST has risen by 0.44°C in the warmest months over the period 1950–2009. There is also substantial natural variability in the temperatures of the Pacific Ocean, driven by the Pacific Decadal Oscillation and the ENSO system, which makes the climate change signal difficult to distinguish (IPCC 2014a).

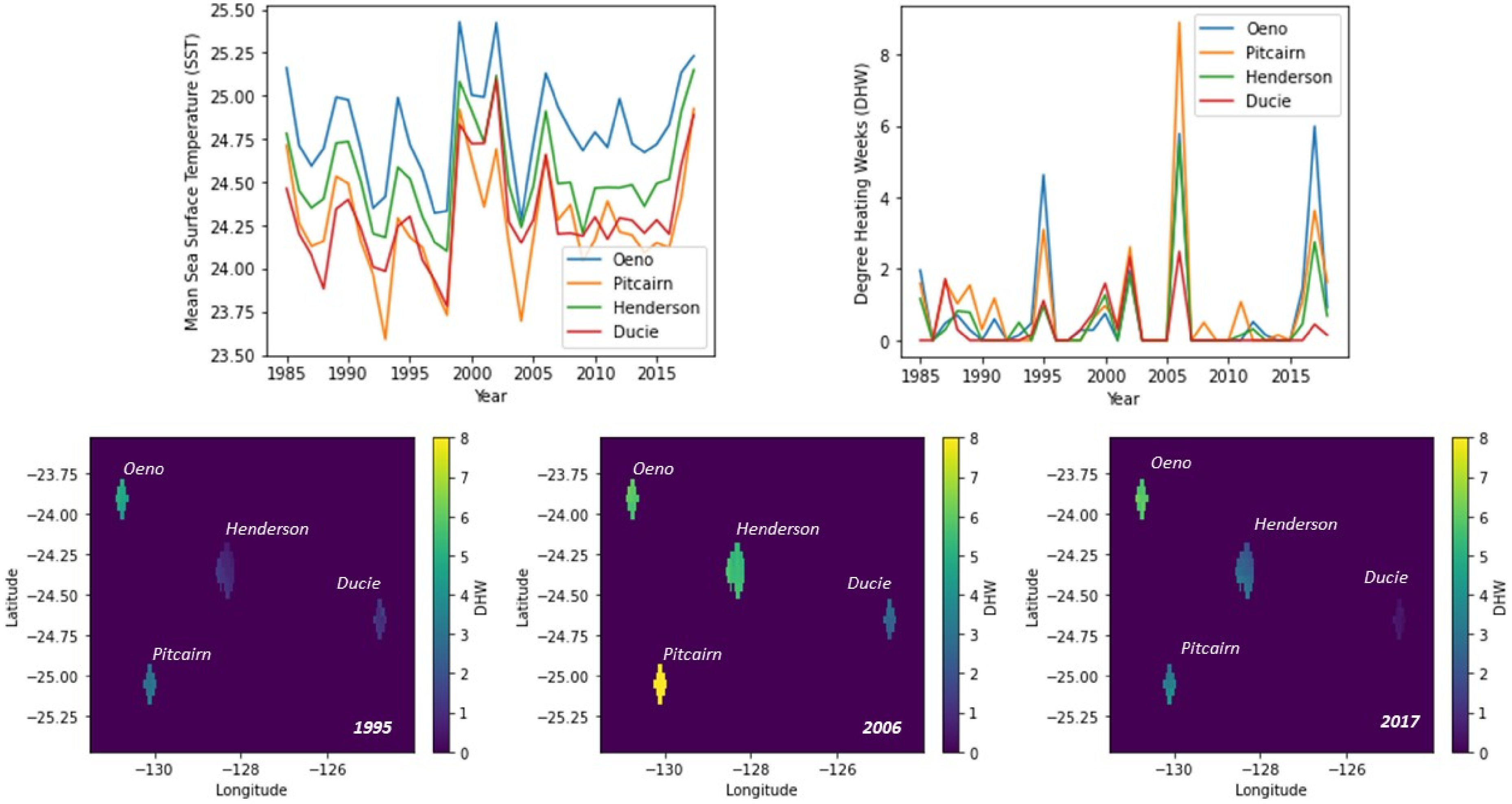

Figure 13. Past thermal stress in the Pitcairn Islands showing: time series of mean annual sea surface temperature (SST) (top left) and total Degree Heating Weeks (DHWs) (top right) from each of the islands; and maps of DHWs during strong thermal stress years 1995, 2006, and 2017, around the location of each of the islands. The dark blue areas denote no data. Data obtained from NOAA Coral Reef Watch (2018).

The Pitcairn Islands are situated in the central South Pacific Ocean region, where heat is absorbed near the equator and then cools towards the poles (Sutton 2018). Each year, trade winds and currents push warm water from the equator eastward, creating a 'warm pool' (Figure 14), also known as the equatorial Pacific warm water volume (Capotondi et al. 2020). This warm pool extends further east towards Pitcairn during El Niño years, and it has generally increased in area since the 1980s (Sutton 2018; Weller et al. 2016).

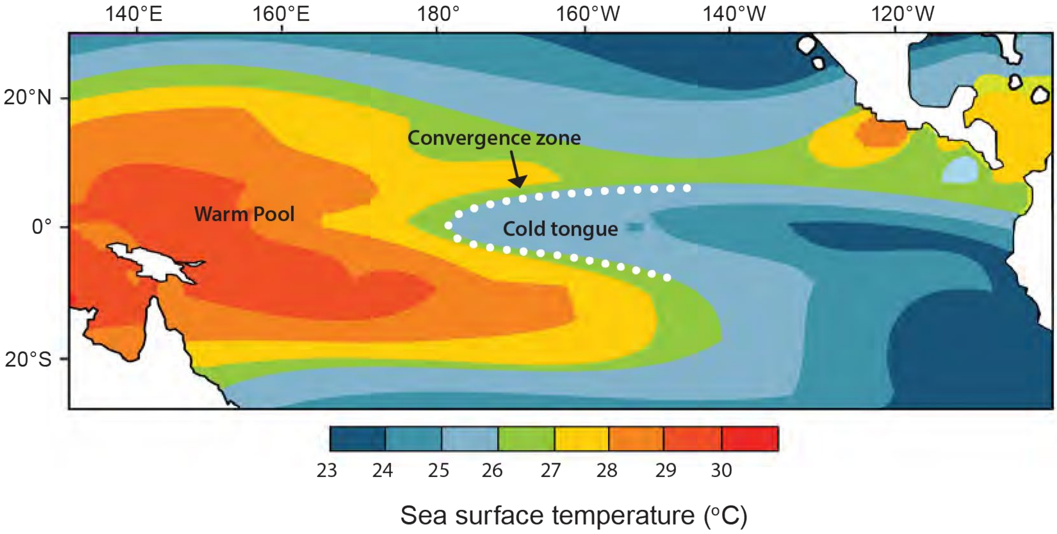

Figure 14. The position of the warm pool in the western Pacific (here shown under La Niña conditions), and the convergence zone where the warm pool meets nutrient-enriched waters of the eastern equatorial Pacific. In El Niño years, the warm pool extends further east, towards Pitcairn. The location of the Pitcairn Islands is shown by the black dot. Figure copied with permission from Bell et al. (2011a). Original source is the Met Office Hadley Centre sea-Ice concentration and Sea-Surface Temperature data set (HadISST), from Chagnaud (2008).

5.1.2. Projected future changes

By 2099 and under a worst-case emissions RCP8.5 scenario, Pitcairn's average SST is expected to warm by 2–2.5°C, resulting in conditions similar to many present-day tropical reefs (see Figure 8).

The equatorial Pacific warm pool or warm water volume (Figure 14) is expected to continue to expand, increasing the area of the western tropical Pacific experiencing higher than average temperatures each year (Sutton 2018). The warm pool is controlled by ENSO: equatorial wind patterns cause the thermocline to adjust, which in turns is reflected in the evolution of the warm water volume (Capotondi et al. 2020). But, the high complexity of the ENSO phenomenon, its cyclic variability and increasing amplitude, which could be attributable to anthropogenic influences and is now larger than in preindustrial simulations, hinder the ability of climate models to represent the diversity of El Niño events (Capotondi et al. 2020). However, it is not yet possible to consistently predict changes in ENSO events over the coming century (Cai et al. 2020; Capotondi et al. 2020; Fang and Yu 2020; IPCC 2013). Bearing in mind these caveats, SST around Pitcairn is, under a medium emissions scenario, projected to rise by approximately 0.5°C by the middle of this century and by 0.9°C by the end of the century (NOAA Climate Change Portal 2020).

Modelling studies indicate that in the Pitcairn region, half of corals are likely to be exposed to bleaching by 2050 under all emissions scenarios except RCP2.6, while under an RCP8.5 scenario, more than half of corals will be exposed to periods of increased temperature consistent with mortality by the end of the century (see Figure 9; IPCC 2014a).

5.2. Ocean acidification and carbon chemistry

5.2.1. Observed changes

There are no long-term ocean acidification data for the equatorial region of the Pacific, although there are plans to improve data resolution (GOA-ON 2020; Lenton et al. 2018). A range of surface pH between 7.91–8.12 has been previously estimated for the equatorial Pacific between 1997 and 2011 (Sutton et al. 2014). These values are lower, and appear to be declining faster, compared to surface pH from other open-ocean regions, and this agrees with findings from other studies (Wagener et al. 2018; Johnson et al. 2015; Lauvset et al. 2015). There are indications that surface ocean aragonite saturation state in the Pacific has declined from 4.5 to 3.8 (Feely et al. 2009). ENSO dominates ocean climate in the Pacific, including ocean acidification. During non-El Niño periods, ocean acidification has been observed to progress more rapidly due to the influx of upwelling deep, CO_2-rich water (Sutton et al. 2014; McPhaden et al. 2006; Fiedler and Lavín 2017).

Mean surface water pH around the Pitcairn Islands has been estimated to be near 8.12 (Figure 15; NOAA Climate Change Portal 2020).

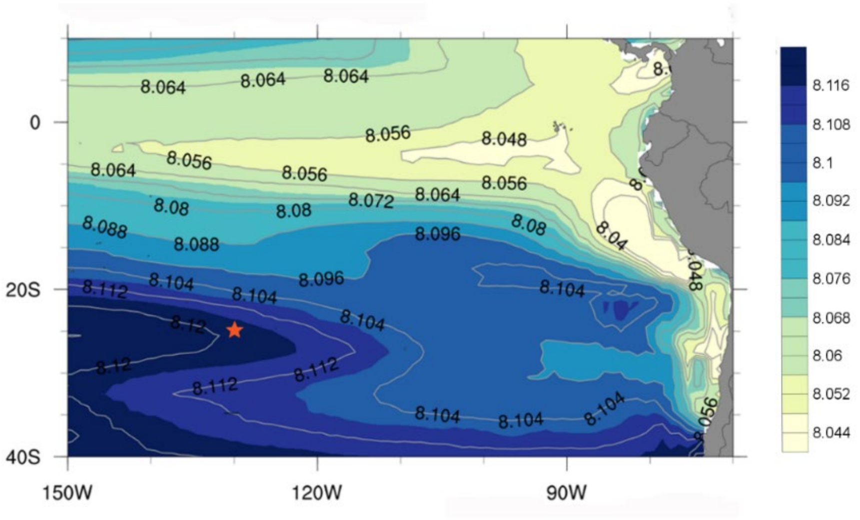

Figure 15. Outputs from the CMIP5 ensemble showing mean surface water pH in the central South Pacific Ocean for the period (1956-2005). The approximate location of the Pitcairn Islands is indicated by the orange star symbol. Figure reproduced from NOAA Climate Change Web Portal (2020).

5.2.2. Projected future changes

Projections of aragonite saturation state, which is critical for coral calcification, suggest that by the end of the 21st Century this is likely to decrease below 2.5 for Pitcairn under a high emissions scenario (see Figure 11).

End-of-century, global projections estimate the average pH of surface waters around the Pitcairn Islands will have decreased between 0.08–0.27 pH units, depending on the emissions scenario (low to high) (NOAA Climate Change Portal 2020). The pH of the wider tropical Pacific is projected to decrease 0.15 pH units by 2050 under a high emissions scenario (Johnson et al. 2015).

The confidence in these projections however is only relative, due to the variability of the ENSO and the associated upwelling forcing, and the influence that these processes have on future ocean pH levels in the Pacific Ocean (Christensen et al. 2013 and references therein).

5.3. Sea level rise

5.3.1. Observed changes

Sea levels have risen across the Pacific with varying ranges coupled to large-scale climate processes, and extreme sea levels have also been detected caused by a combination of long-term sea level rise from climate change and short-term factors such as extreme tides, storm surges and the associated wind-wave setup (Australian Bureau of Meteorology and CSIRO 2014).

Large regional differences have been detected in sea level rise across the tropical Pacific, with rates up to four times the global average (approximately 12 mm per year), reported in the western South Pacific between 1993 and 2009 (Nurse et al. 2014; Meyssignac et al. 2012). These high rates are thought to reflect short-term modulations by natural climate phenomena such as ENSO, with lower/higher-than-average sea level during El Niño/La Niña events of the order of ±20 to 30 cm (Becker et al. 2012; Cazenave and Remy 2011).

There are no tide gauge records available for the Pitcairn Islands, and therefore no sea level data, principally as a consequence of the lack of airfield and therefore difficulty of access for maintenance visits (Woodworth and Hibbert 2015). The closest station is at Rikitea, French Polynesia[9] (692 km west from Pitcairn) with records dating back to 1970 that indicate a long-term sea level rise (PSMSL 2020). Data from a Global Sea Level Observing System (GLOSS) station on Easter Island[10] (1,925 km east from Pitcairn) on the other hand, indicate high interannual to decadal variability with no sign of a long-term trend (PSMSL 2020). The Permanent Service for Mean Sea Level (PSMSL) responsible for the collection, publication, analysis, and interpretation of sea level data from the global network of tide gauges, including the GLOSS network, constructs time series of sea level measurements at each station using monthly and annual means and reducing to a common tide gauge datum[11]. The next nearest time series available from NOAA/CO-OPS[12] corresponds to Papeete, French Polynesia, 2,332 km west-northwest from Pitcairn, where observed relative sea level trend is estimated at 2.6 mm per year. NOAA/CO-OPS relative sea level trends are calculated based on tide gauge data and having removed regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. While these datasets may not be directly comparable, they demonstrate a high degree of regional variability in the sea level signal across the Pacific basin.

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[9] www.psmsl.org/data/obtaining/stations/1253.php

[10] www.psmsl.org/data/obtaining/stations/1272.php

[11] www.psmsl.org/products/trends/methods.php

[12] tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=780-011

5.3.2. Projected future changes

Future projections of sea level rise in the Pacific carry a very high confidence (Lafale et al. 2018; Nurse et al. 2014). In the Western Pacific, the rise will be larger than the global mean, which will have far-ranging adverse consequences for small islands especially when combined with the projected possible increased intensity of tropical cyclones, climate change-induced effects on oceanic ecosystems (e.g., loss of protective reefs due to temperature increases and ocean acidification), and other extreme events (Lafale et al. 2018; The World Bank 2016). In the South Pacific, sea level fluctuations driven by waves and storm surges have been shown to be linked to long-term trends of ENSO and the Antarctic Oscillation (Beetham and Kench 2018; Melet et al. 2018; Perry et al. 2018; Storlazzi et al. 2018; Vousdoukas et al. 2018; Mentaschi et al. 2017; Vitousek et al. 2017; Reguero et al. 2015).

According to Vousdoukas et al. (2018), the greatest sea level rise values toward the end of the century are projected in the South Pacific under a high emissions scenario, (median: 95 cm, [very likely range: 54–217]), and also under a medium scenario (median: 59 cm, [very likely range: 27–97]). By the end of the century and under a high emissions scenario, many South Pacific small islands are projected to experience more than 1 m sea level rise, which at present is considered to be equivalent to a one in 100-year extreme sea level event (Masselink et al. 2020; Tajima et al. 2020; Kench et al. 2018a; Vousdoukas et al. 2018).

Mid-range sea level projections based on multi-model ensembles of CMIP5 global climate models and the IPCC AR5 for the western tropical Pacific indicate that under a medium emissions scenario the estimated sea level rise for Pitcairn will be within the lower half of the range of values for the whole South Pacific (Zhang et al. 2014). The uncertainty of these projections for the region of Pitcairn, however, is of the same order of magnitude as the change itself (Zhang et al. 2014).

5.4. Extreme weather events

5.4.1. Observed changes

The trajectory and frequency of tropical cyclones in the South West Pacific typically varies with the ENSO phase: during El Niño the focus is in the eastern portion of the basin, but this reverses to an increase in frequency to the west during La Niña (Lafale et al. 2018). Most tropical cyclones in the South Pacific basin are formed in the Vanuatu archipelago region (Diamond et al. 2013). The most intense tropical cyclones, however, tend to strengthen as they move southwards, and so islands such as the Pitcairn Islands tend to miss the most severe events (Lafale et al. 2018). The intensity of tropical cyclones appears to have increased since 1990 (Diamond et al. 2013); however more work is required to fully validate these findings (Lafale et al. 2018).

The attribution of tropical cyclone events to climate change remains unclear, particularly in the tropical Pacific basin (Chand et al. 2020; Collins et al. 2019). Whilst patterns of storm activity across the Pacific basin appear strongly correlated with ENSO (Collins et al. 2019; Chand et al. 2017), after removing those effects, a reanalysis of historic and modern data indicates a decrease in the number of tropical cyclones making landfall over eastern Australia (Walsh et al. 2019; Dowdy 2014). Other studies show a similar decrease in the total number of tropical cyclones in the South West Pacific (Dutheil et al. 2020; Howes et al. 2018; CSIRO et al. 2015; Australian Bureau of Meteorology and CSIRO 2014). There is still great controversy in terms of changes in the number of very intense tropical cyclones across the Pacific basin, which some studies indicate has increased (CSIRO et al. 2015; Holland and Bruyère 2014), whilst others have found the opposite trend for the South Pacific (Hoarau et al. 2018; Australian Bureau of Meteorology and CSIRO 2014).

In the case of the Pitcairn Islands, the impact of long-distance ocean swells from remote low pressure systems such as the Southern Ocean, may be more significant than the effect of tropical cyclones (IPCC 2014b). These deep ocean swells generated by extratropical cyclones in mid and high latitudes frequently reach Pacific islands (IPCC 2014b). For example, there is evidence of damage to coral growth in Hawaii by oceanic swells that originated in the North Pacific, especially during years with a strong El Niño (Fletcher et al. 2008; Rooney et al. 2004).

5.4.2. Projected future changes

Models suggest that in the Pacific the severity of storm surges experienced by small islands is more likely linked to extreme El Niño events with an extensive eastward propagation, rather than being driven by the intensity of the storm (Howes et al. 2018; Stephens and Ramsay 2014; Santoso et al. 2013). The number of tropical cyclones is projected to decline in the Pacific basin (medium confidence; Dutheil et al. 2020; Australian Bureau of Meteorology and CSIRO 2014), while their average maximum intensity or wind speed is likely to increase (Lafale et al. 2018; The World Bank 2016). However, according to Stephens and Ramsay (2014), a projected 10–20% increase in the intensity of tropical cyclones will not necessarily translate into a significant increase in surge risk or severity.

Since the IPCC AR4 Climate Change report in 2007 (IPCC 2007), global wave-climate projections for the end of the 21st Century are based on downscaled models (Fan et al. 2013; Hemer et al. 2013; Semedo et al. 2013; Mori et al. 2010; Wang and Swail 2006). Over the past century, mean significant wave heights have increased in regions of the Pacific and Southern Oceans, but limited records make it difficult to separate long-term climate-related trends from multidecadal natural variability (Church et al. 2013; Seneviratne et al. 2012; Young et al. 2011; Wang and Swail 2006). This increase of wave height appears associated with a projected strengthening of austral winter easterly trade winds, but there is low confidence in these projections (Church et al. 2013).

6. Pitcairn Islands corals: climate change impacts

6.1. Impacts from bleaching

6.1.1. Observed impacts

There are few ecological datasets available for the Pitcairn Islands and no published observations of coral bleaching (Irving et al. 2019). The Global Coral Reef Monitoring Network only monitored one site at Pitcairn Island on a few occasions between 2009–2014, where coral cover was found to range between 10–20% (Moritz et al. 2018). Hence it is not possible to construct time-series of coral and benthic communities for these islands to understand past bleaching impacts. A comprehensive expedition to the islands in 2012 found high coral cover (56.3%) in Ducie, moderate cover for Oeno (27.8%) and Henderson (23.5%), and low cover around Pitcairn (5.2%; Irving et al. 2019; Friedlander et al. 2014). The most dominant coral types were thermally resistant *Porites* spp. and bleaching-sensitive *Pocillopora* and *Millepora* (Irving et al. 2019; Friedlander et al. 2014; Irving and Dawson 2013).

Based on satellite data, peaks of thermal stress expressed as DHWs occurred in 1995, 2006 and 2017 (see Figure 13 and Table 2), with Oeno reaching Bleaching Alert 1 (DHW 4–8) in all three years. Pitcairn was the only island to experience DHWs higher than 8 (Bleaching Alert 2) during 2006, while Ducie did not experience thermal stress enough to trigger a bleaching alert (DHW less than 4; see Figure 13 and Table 2). There has been no obvious change in average SST.

Table 2. Past thermal stress in the Pitcairn Islands showing mean SST at the start and end of a time series spanning 1985–2018 and the difference in mean SST, along with Degree Heating Weeks (DHWs) in potential bleaching years, the cumulative DHW, and the number or Alert Level 1 and 2 thermal stress events. Data obtained from NOAA Coral Reef Watch (2018).

	Oeno	Pitcairn	Henderson	Ducie
Mean SST (1985-89)	24.79	24.32	24.5	24.16
Mean SST (2013-18)	24.82	24.19	24.55	24.31
Difference in mean SST	0.03	-0.13	0.05	0.15
DHW 1995	4.6	3.1	1	1.1
DHW 2006	5.8	8.9	5.5	2.5
DHW 2017	6	3.6	2.8	0.5
Cumulative DHW	16.4	15.6	9.3	4.1
Alert 1 (DHW 4-8) frequency	3	2	1	0
Alert 2 (DHW >8) frequency	0	1	0	0

While no evidence of coral bleaching in the Pitcairn Islands has been found, in the Ducie atoll there are records of coral mortality due to cold-water stress caused by unusual oceanic cold intrusions in 1970 and again during the 2015-2016 El Niño (Dawson and Zhang, 2020; Irving and Dawson 2013). There is also evidence of transient conditions of coastal turbidity and sediment runoff in Pitcairn Island in 2012 following a very heavy rainfall event, although it is thought that prevailing strong currents surrounding the island were likely to disperse any suspended sediment in the water column and therefore mitigate against any likely impacts such as reduced light availability etc. (Irving et al. 2019; Irving and Dawson 2013). The low cover of coral in Pitcairn has been partially attributed to excess sediments and nutrient runoff entering nearshore waters, but the small, domestic scale of land use practices in the island suggests that it is more likely to be due to wave exposure and sand scouring preventing coral growth. However, without baseline data it is not possible to accurately assess the relative importance of these factors or their changes over time. Significant acute thermal stress (DHW 8.9) was experienced in Pitcairn in 2006, and in Oeno (DHW 6) in 2006 and 2017, that could have potentially caused localised bleaching, but otherwise the risk of acute thermal stress in the archipelago appears to remain low (Table 2). Undetected episodes of coral bleaching and mortality over the past 35 years in the Pitcairn Islands, however, remain a possibility.

6.1.2. Projected future impacts

Thermal stress for Pitcairn corals over the 21st Century is expected to remain low compared to other reefs globally, particularly in the deeper fore-reefs where most of the coral grows, although the (inferred) lack of previous bleaching experience may heighten their sensitivity to thermal stress should it occur. The geographical isolation of the Pitcairn Islands and lack of connectivity to other reef systems pose challenges to the supply of new coral larvae that could aid recovery (Romero-Torres et al. 2018; Robinson et al. 2017). On the other hand, the low level of human activity is an advantage for coral resilience in these islands.

Pitcairn is located near the southern limit for optimal reef growth, with Ducie being the most southerly atoll in the world. Under a high emissions scenario, Pitcairn's average SST is expected to increase 2–2.5°C by 2099 (see Figure 8), which is a relatively small change and similar to what many present-day reefs are already experiencing in the tropics. As a result of Pitcairn's cooler conditions and low rate of warming, future SST conditions will likely remain optimal for coral growth (Jones et al. 2019; Couce et al. 2013). Under a high emissions scenario, the onset of annual severe bleaching events is not expected until 2059, which is later than the average global onset threshold of 2043 (Van Hooidonk et al. 2016).

Based on these findings, the risk of bleaching in Pitcairn's reefs is expected to remain lower than in other areas of the world over the coming century, as most of the corals in the Pitcairn Islands appear to grow on reef slopes more than 10 m deep. While the corals in the shallow reef flats in Oeno and Henderson, and even in the as yet unexplored 15 m deep lagoon in Ducie, will be more exposed to high irradiance intensity and thermal stress and therefore to higher risk of bleaching, it is expected that the deeper fore-reefs will be sheltered from thermal stress because of decreasing irradiance with depth and the flushing and cooling effect of subsurface waves (Cowburn et al. 2019; Muir et al. 2017; Nakamura and Van Woesik 2001).

Coral colonies in Pitcairn have low species richness compared to reefs further west in the Pacific, and are dominated by thermally resistant *Porites* spp. and thermally sensitive *Pocillopora* and

Millepora spp. (Friedlander et al. 2014; Irving and Dawson 2013), the latter being a colonial hydrocoral, also known as fire coral, rather than a true coral. In similar communities in the Central and East Pacific, those same coral species were found to die in large numbers during bleaching events (Pratchett et al. 2013; Glynn 1984) indicating they are highly susceptible to thermal stress. This confirms the vulnerability of reefs to thermal stress in Pitcairn (Figure 13; Table 2). Ducie's reefs, in particular, owing to the dominance of *Acropora* and *Montipora* spp., are expected to be sensitive (Loya et al. 2001).

The reefs of the Pitcairn Islands are some of the most isolated in the world and have low exposure to human activities (Irving and Dawson 2013; Burke et al. 2011), which should bolster recovery should bleaching and mortality take place. Reef fish communities appear healthy, with high numbers of top predators like sharks and groupers (Dawson and Irving 2020; Coghlan et al. 2017; Friedlander et al. 2014). Herbivorous fish are numerous, preventing algal overgrowth and clearing space for coral larvae to settle. Around Pitcairn Island, macroalgae are more abundant than around other islands, potentially due to a combination of runoff nutrients from land use (Irving et al. 2017) and wave action, but the waters around the four islands are unusually clear generally suggesting very low levels of nutrients. These factors would play in favour of coral recovery following bleaching or mortality. However, even though recruitment of juvenile corals has yet to be assessed, the isolation of these islands, being further than 100 km away from each other and even further away from any other reefs, indicates limited connectivity and reliance on self-seeding (Wood et al. 2014; Swearer et al. 1999), which reduces recovery potential.

6.1.3. Knowledge gaps and research needs

Apart from surveys carried out as part of an expedition to the islands in 2012, there is limited data available on coral reef communities of the Pitcairn Islands (Friedlander et al. 2014) making it difficult to determine a pre-bleaching baseline conditions. Regular coral monitoring of key ecological indicators including but not limited to: coral cover, coral colony species composition, coral recruitment rate, and changes to macroalgal cover and fish species abundance, which would help understand the risk of bleaching, and the future vulnerability of the Pitcairn Islands' reefs.

6.2. Impacts from changes in carbon chemistry and ocean acidification

6.2.1. Observed impacts

Levels of aragonite saturation in the South Pacific are already thought to be close to the point where it can debilitate coral skeletons and slow coral growth (Dutra et al. 2018). However, direct field observations linking acidification to physiological impacts on corals are still rare (Doney et al. 2020, Doo et al. 2020). It is likely that the responses of corals to more acidified waters are still within the ranges of natural variability, also influenced by local conditions such as circulation patterns and pollution (Field et al. 2014).

Dutra et al. (2018) conducted a recent review of climate impacts of corals in Pacific islands and found no studies of ocean acidification effects *in situ*. Observations of acidification conditions from elsewhere have found changes in the species composition of coral communities, together with increased algal cover and increased bioerosion from boring organisms (Enochs et al. 2016; Enochs et al. 2015b; Fabricius et al. 2011). Those responses threaten the integrity and ecosystem functioning of coral reefs (Anthony et al. 2011; Mumby 2009). Studies in Japan offshore waters, where pH is naturally low, indicate that much less coastal carbonate reef habitat is formed once dissolved CO_2 levels rise beyond 300–400 parts per million (Agostini et al. 2018). A recent modelling study by Guo et al. (2020) that disentangled the effects of warming sea temperatures from those of ocean acidification on the Great Barrier Reef, estimated that decreasing pH has been responsible for a 13% decline in the skeletal density of massive *Porites* corals on the Great Barrier Reef since 1950.

A study on *Porites* corals across a gradient of saturation states in the Pacific, showed that skeletal density rather than skeleton extension was significantly affected by ocean acidification (Mollica et al. 2018). Separate measurements in *Porites* in the western North Pacific Subtropical Gyre support these findings, showing that ocean acidification is significantly decreasing the pH of coral calcifying fluid (Kubota et al. 2017).

6.2.2. Projected future impacts

By the end of the century under low emissions scenarios, surface Ω_{ar} in waters around the Pitcairn Islands are projected to decline to just over 3.1 (Figure 11). This is at the very limit for coral calcification, with no major reef systems currently known to persist at these levels (Lenton et al. 2018; Langdon and Atkinson 2005).

As Pitcairn is located near the centre of the South Pacific Circulation Gyre, changes in SST, carbonate saturation and pH are expected to evolve more slowly than in other global regions (Friedlander et al. 2014; Hoegh-Guldberg and Bruno 2010). However, by mid-century under a high emissions scenario, Ω_{ar} is projected to reach 3 meaning a shift to sub-optimal conditions for the entire tropical Pacific region (Johnson et al. 2015). This is likely to cause a decline in coral calcification rate of about 10% (Chan and Connolly 2013). By the end of the century, saturation states in waters around Pitcairn are expected to decrease to 2 (Figure 11), unlikely to support net coral calcification. The growth of calcified macroalgae and coralline algae would also be affected, and their decline will have further negative implications in substrate stability and coral recruitment.

6.2.3. Knowledge gaps and research needs

It is important to improve our understanding of carbonate chemistry and coral adaptation in the Pitcairn Islands, which could be integrated as part of the expansion of the water chemistry monitoring network, ideally by encouraging capacity in location. Given that this is a data-poor region, and added to the concerning projections of future ocean acidification in this region, this should be treated as a priority. The use of autonomous sensor technology could be a possibility.

Contemporary models are not sufficiently downscaled to produce useful projections that support adaptation for small islands such as Pitcairn as the coarse scale masks local changes.

Research of ocean acidification on corals mainly focuses on single-species responses. Increasingly, experiments are being conducted combining multiple climatic and non-climatic stressors on single species, which are revealing how other climate stressors interact with ocean acidification. It is not yet clear to what extent corals and other reef organisms can acclimatise and adapt to ocean acidification, however. It is possible that ocean acidification may be less harmful or even beneficial to certain reef organisms. *In situ* studies are required to build an understanding of effects in single species, and extrapolate these responses to impacts on whole reef systems and functions, including food webs and competition.

6.3. Impacts from sea level rise and extreme weather events

6.3.1. Observed impacts

In the Pitcairn Islands, sea level has risen 3–4 times the global average, but this has not resulted in widespread erosion or islands “drowning”. Instead, the islands have persisted and even increased in surface area and elevation by way of natural processes (McLean and Kench 2015). Island margins continue to adjust according to seasonal erosion and accretion processes, even after extreme events and changes in sediment supply – often supplied from the coral reefs themselves (McLean and Kench 2015).

There are signs of extreme weather impacts in the Pitcairn Islands. In Henderson, damage is evident in parts of the fore-reef where bedrock is visible or appears encrusted by coralline algae (*Litophyllum kotschyanum*). Extensive areas of coral rubble are also found below 30 m depth, likely to have been caused by strong wave action during storm events as coral debris from shallower areas of the reef is dragged into deeper waters (Irving and Dawson 2013). In Ducie, an expedition in 1975 found evidence of storm waves having deforested the island, and mass mortality of lagoon corals apparently due to the effect of a cold water intrusion (Rehder and Randall 1975). A later expedition found further evidence of coral bleaching in the Ducie atoll caused by such rare cold oceanic intrusions coinciding with the 2015–2016 El Niño (Dawson and Zhang, 2020). A major rainfall event on Pitcairn Island in 2012, the heaviest since records began, caused landslides across the island and high sediment loads entering the nearshore marine environment, and whilst prolonged suspended sediment in the water column is known to have a deleterious effect on coral reef health, the prevailing strong currents surrounding Pitcairn Island are likely to mitigate against these events (Irving and Dawson 2013).

6.3.2. Projected future impacts

No regional projections of future sea level rise for the Pitcairn have been found, however studies from other South Pacific small atoll islands such as the Funafuti Atoll in Tuvalu suggest a cautiously optimistic future despite a sea level rise of over 0.30 m in the past century. Sea level rise rates of 5 mm per year over the past 60 years appear to have caused neither widespread erosion nor overall loss of dry land area: whilst some of the islands have decreased in size, the aggregated land area of the atoll has actually increased over the past century (Kench et al. 2015). However, sea level rise is projected to accelerate and reach over 1 m by the end of this century, and thus it is unclear whether islands will continue to adjust (Kench et al. 2015), particularly when considering other climatic and human pressures that are likely to aggravate impacts on the health, species composition and structure of the protective reefs.

The extreme water clarity surrounding the Pitcairn Islands allows corals to grow at depths greater than usual for the Pacific (Friedlander et al. 2014; Kleypas et al. 2010), which may allow some refuge and resilience from climate change impacts (Carpenter et al. 2008).

6.3.3. Knowledge gaps and research needs

In order to support adaptation and resilience strategies, it is important to better understand the processes by which small coral islands adjust to sea level rise (Kench et al. 2015; Barnett and O'Neill 2012). Rising sea level is expected to cause coastal erosion, remobilise sediments and destabilise islands, but there are discrepancies and there is debate about the likely physical changes to atolls in the future (Ford et al. 2020; Kench et al. 2018b; Storlazzi et al. 2018; Kench et al. 2015).

6.4. Other anthropogenic pressures

In spite of their isolation and very small human population, there are a number of non-climatic human impacts – some transboundary – causing disturbances to the marine environment of the Pitcairn Islands. A number of pressures on the reef are identified in the Pitcairn MPA Management Plan, in addition to climate change: IUU fishing by foreign fishing vessels, pollution including oil spills and marine plastics, anchor damage, erosion and run-off from land, and invasive non-native species.

Fishing has been banned since the designation of the Pitcairn Islands MPA in 2016[13], although subsistence fishing by the local community is allowed in the 12 nm around Pitcairn Island. There is concern that some reefs fish and shellfish species are being overfished, with islanders selling fish and souvenirs to cruise ship passengers, including groupers, sharks, and lobsters (Coghlan et al. 2017; Irving and Dawson 2012). Sharks have an important role in the reef as apex predators; if their numbers decline their direct prey, the mesopredators that in turn consume herbivorous fish, increase in numbers, and cause the population of herbivores to collapse which allows more algae to grow and overtake the coral (Roff et al. 2016). A Fisheries Management Plan was introduced in 2017 for the management of fisheries within the coastal conservation areas, particularly around Pitcairn Island (Dawson and Irving 2020; Irving et al. 2019). The management plan brought in minimum catch sizes for a number of species of fish and shellfish and also banned the fishing of sharks within the CCA. Recording of catches is not mandatory, and there is only intermittent fisheries monitoring, therefore apart from some sampling between 2014 and 2015 and reconstructed catches combining official reports and estimates of unreported data, it is unclear how much fish is caught by this fishery (Coghlan et al. 2017).

There is concern that visiting yachts and cruise ships which anchor off Pitcairn are causing deterioration of the seabed and corals (Irving et al. 2019). Anchors and anchor warps can cause the destruction of large swathes of seabed as they settle and are then retrieved (Giglio et al. 2017). Hard corals are especially susceptible to the impacts of anchoring.

Henderson has some of the highest levels of ocean-borne plastic litter on the planet (Ryan 2020; Ryan and Schofield 2020; Irving et al. 2019; Forrest and Hindell 2018). The island is on the edge of

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[13] Revised Laws of Pitcairn, Henderson, Ducie and Oeno Islands, 2017 Rev. Ed. - Volume 2 (government.pn)

the South Pacific Gyre, which collects litter from distant Pacific shores and deposits them on the island[14,15]. As well as endangering other marine life, plastic is associated with increased risk of coral diseases (Lamb et al. 2018) and so could be causing effects in the corals around the island. Invasive black rats on Henderson Island have caused either extinctions or declines of a number of endemic or endangered bird species (BirdLife International 2020).

Finally, there remains a relative risk of runoff around Pitcairn Island, which could impact the water quality nearshore and therefore the corals, and corallivorous crown-of-thorns starfish may be present in the islands, which can have devastating impacts on reefs as outbreaks can alter the coral composition (Birkeland 1989).

6.4.1. Knowledge gaps and research needs

There is a need for improved monitoring programmes and in particular effective management of the subsistence fisheries (Dawson and Irving 2020; Bell et al. 2018; Coghlan et al. 2017; Bell et al. 2011b). The marine environment of the Pitcairn Islands is largely understudied, but the MPA management plan proposes to introduce habitat and biodiversity monitoring to improve the knowledge base. This would help to determine the extent of negative impacts from non-climatic stressors, so that cause-effect relationships of these stressors could be understood and managed accordingly. A regular and continuous water quality monitoring, coral integrity assessments (e.g., coral diseases) and presence of non-native species could be beneficial.

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[14] https://marinedevelopments.blog.gov.uk/2019/04/04/henderson-island-expedition/

[15] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/919540/Blue_Belt_Annual_Update_2018_2019_WEB.pdf

7. Other valuable marine habitats and communities

7.1. Macroalgae

In BIOT, some of the macroalgae communities, such as green algae of the *Halimeda* genus, were initially described as being richer than elsewhere in the Indian Ocean and more similar to those from the Pacific Ocean (Jollife and Basson 1999; Drew 1995). Calcareous coralline algae are an important and integral component of the reefs across BIOT, particularly at depth, where they cover a significant area of the benthos and play a key role in sediment production and also coral recruitment (Lange and Perry 2019; Samoilys et al. 2018; Sheppard et al. 2017; Sheppard 1980). Endemic species of algae are not common in BIOT (Procter and Fleming 1999).

There are differences in macroalgal communities between the four islands in the Pitcairn Islands group that appear related to their different geography, geomorphology and habitats (Friedlander et al. 2014). Several species of macroalgae occur in Pitcairn's nearshore waters, compared to near absence at Henderson, Oeno and Ducie. This may be due to Pitcairn's more southerly position, slightly cooler waters and nutrient-rich runoff (especially iron) that has accelerated with evolving land use and local weather patterns (Friedlander et al. 2014; Irving and Dawson 2012). Macroalgae communities in Pitcairn are dominated by bushy brown algae such as *Sargassum* and *Lobophora*, that cover bedrock outcrops between 14–22 m depth (Irving and Dawson 2012; Friedlander et al. 2014). In contrast, Henderson, Ducie and Oeno show very low algal cover apart from encrusting forms, denoting relatively healthy reefs with abundance of herbivorous fish (Friedlander et al. 2014; Irving and Dawson 2012).

7.2. Seagrass

Seagrasses provide important services by protecting coastlines from flooding and erosion and improving the water quality (Guannel et al. 2016). They usually do this in tandem with coral reefs and, where found, coastal mangroves; together these habitats substantially dissipate wave energy and moderate inundation levels and loss of muddy sediment (Paul 2018; Potouroglou et al. 2017; Guannel et al. 2016). Seagrasses provide nursery and feeding grounds to many marine animals including invertebrates, fish, turtles and mammals (Nordlund et al. 2016). They are also an important carbon sink ecosystem (Fourqurean et al. 2012).

In BIOT, seagrasses are common within the Great Chagos Bank (Sheppard et al. 2012). Meadows of *Thalassodendron ciliatum* are known to occur off island on shallow banks including the Great Chagos Bank: a study using a combination of marine turtle telemetry and SCUBA video surveys, confirmed the existence of extensive (more than 100 km long) monospecific seagrass meadows of *Thalassodendron ciliatum* at depths down to 29 m (Esteban et al. 2018). A small amount of *Halophila decipiens* has also been reported in even deeper waters (Drew 1980). Several fish species are known to favour these seagrass meadows (Procter and Fleming 1999). Fish assemblages are diverse and abundant and include, unusually, large predatory sharks (*Carcharhinus amblyrhynchos*; Esteban et al. 2018).

Based on the information available, no seagrass meadows have been found in the Pitcairn Islands (Irving and Dawson 2012).

Higher than average sea temperature is known to cause defoliation, seed abortion and loss of below-ground rhizomes (Arias-Ortiz et al. 2018; Thomson et al. 2014). Globally, future climate change is expected to further exacerbate other negative human impacts on seagrass systems, particularly poor water quality conditions (Waycott et al. 2011). At local scales however, seagrass may benefit from higher CO_2 levels and potentially buffer acidity (Koch et al. 2013; Repolho et al. 2017), even though the effects are likely to be minor and localised, and long-term effects are unknown.

7.3. Mangroves

Mangroves provide important services, including coastal protection, and form a vital link with coral reefs by providing nursery areas for many reef fish species, and by sheltering nearby reefs from the effects of warming and excess land sediment runoff following heavy precipitation (Guannel et al. 2016; Yates et al. 2014).

There are two stands of the mangrove *Lumnitzera racemosa* in BIOT. A stand on Eagle Island, with an associated peat bog, was described by Procter and Fleming (1999) as one of the most isolated mangrove communities in the world. The second stand, discovered in 2010 on the same atoll, is estimated to extend over 3 km^2 (Sheppard and Sheppard 2019; Sheppard et al. 2012).

Based on the information available, there are no coastal mangrove forests in the Pitcairn Islands (Irving and Dawson 2012).

Climate change is likely to have substantial negative impacts on mangrove habitats. Warming temperatures are likely to constrain their growth, changes in average precipitation and supply of runoff sediments can result in mangroves unable to maintain surface elevation to counteract sea level rise, and storms can cause significant damage and impact forest productivity (Sippo et al. 2018; Ward et al. 2016; Ellison 2015; Clough, 2013).

7.4. Reef fishes and sharks

In BIOT, reef shark abundance declined substantially after the 1970s, and the species composition also changed, largely due to illegal fishing activities (Graham et al. 2010; Koldewey et al. 2010). The relative abundance of reef sharks was stable at 4.2 per dive between 1975–1979 but was reduced to a mean of 0.7 sharks per dive by 1996 and to 0.4 sharks per dive by 2006, which represents a decline of over 90% in the number of sharks observed in BIOT between 1975 and 2006 (Graham et al. 2010). The composition of reef sharks also changed between 1996–2006: a greater proportion of the silvertip shark (*Carcharhinus albimarginatus*) was observed in 2001 and 2006, while the proportion and abundance of other sharks appeared to decline including the grey reef shark (*Carcharhinus amblyrhynchos*), tawny nurse shark (*Nebrius ferrugineus*) and blacktip reef sharks, (*Carcharhinus melanopterus*) (Graham et al. 2010). Some of these reef sharks are likely to be resident in BIOT, therefore the MPA offers an opportunity for their recovery (Koldewey et al. 2010), and there is the hope that shark numbers will increase with the designation of the no-take MPA (Graham et al. 2013). However, latest telemetry and tagging studies reveal that the

BIOT MPA, despite its extreme remoteness, remains subject to incursions of IUU fishing with a demonstrable impact on biodiversity, particularly sharks (Hays et al. 2020; Tickler et al. 2019).

A number of reef fish species have been found to be endemic to BIOT, some examples are the Chagos anemonefish or clownfish *Amphiprion chagosensis,* the goby *Trimmatom offucius*, the worm fish *Paragunellichthys fehlmani* and a razorfish *Xyrichtys* sp. (Koldewey et al. 2010; Procter and Fleming 1999; Winterbottom and Anderson 1997), highlighting the importance of the MPA as a means to protect these unique species. Until the early 2000s, the coral reefs of BIOT exhibited a relatively healthy community structure of reef fishes, showcasing a resilience that had been long lost in other regions due to chronic exposure to human pressures (Graham et al. 2013). Since the study by Graham et al. (2013) however, the effect of more recent warming events on the corals may have induced changes in the communities of reef fish in BIOT.

In the Pitcairn Islands, due to their isolation, the nearshore fish fauna is generally poorer in terms of richness of species compared to archipelagos further to the west, and the abundance of offshore fish also appears lower compared to other regions in the south-western and Central Pacific (Friedlander et al. 2014; Irving and Dawson 2012; Procter and Fleming 1999). The offshore waters within the Pitcairn Islands MPA include abyssal areas that are vastly under-explored (Irving and Dawson 2012) and fisheries information is mostly based on reconstructed catch data (Coghlan et al. 2017).

In the Pacific, there are examples of reefs where local disturbances have impaired the ability of reef fish communities to recover following severe heat stress, possibly because these sites have less structural complexity, which reef fishes rely on as habitat (Magel et al. 2020). Any impacts of climate change on the fish communities of Pitcairn, particularly SST warming, are as yet understudied. It has been suggested that tuna stocks may increase within Pitcairn's waters due to climate-driven shifts in their distributions (Bell et al. 2011b).

7.5. Seabirds

BIOT is home to 17 species of seabirds that range in size from large oceanic birds to small coastal species, of which 5 species occur in globally important numbers, resulting in 10 islands being classified as Important Bird Areas (Carr 2011; Koldewey et al. 2010; Carr et al. 2020; Perez-Correa et al. 2020). Diego Garcia also qualifies as an internationally important Ramsar site for birds (Carr 2011). Seabird populations are key to the health and resilience of the BIOT islands' ecosystems, including the reefs themselves, as seabird-derived nutrient subsidies leaching into coastal waters enhance their productivity and functioning (Benkwitt et al. 2021; Benkwitt et al. 2020; Benkwitt et al. 2019; Graham et al. 2018; Graham et al. 2017).

The Pitcairn Islands qualify as Important Bird Areas in account of their internationally important and endangered bird species, in particular Henderson for being the only location in the world where the Henderson petrel (*Pterodroma atrata*) is known to breed (BirdLife International 2020; Spatz et al. 2017; Irving and Dawson 2012). The Pitcairn Islands also have a number of endemic land birds: the Pitcairn reed warbler, the Henderson fruit dove, the Henderson lorikeet, the Henderson rail or crake and the Henderson reed warbler (Brooke, 2010).

Seabirds are a highly threatened group of birds and are hugely impacted directly or indirectly by human activities such the introduction of invasive species. This is illustrated by the collapse in seabird numbers across both BIOT and Pitcairn since the introduction of rats, and cats in the case of Pitcairn Island (Harper et al. 2019; Spatz et al. 2017; Irving and Dawson 2012). Other major sources of impact on seabirds are overfishing and climate change, in particular rising temperatures and the resulting changes in fish, as well as damage to breeding colonies caused by coastal erosion, flooding and storms (MCCIP 2020; Dias et al. 2019; Spatz et al. 2017).

7.6. Marine turtles

The BIOT archipelago is a globally significant breeding site for hawksbill (*Eretmochelys imbricata*) and green (*Chelonia mydas*) turtles (Hays et al. 2018; Esteban et al. 2016; Koldewey et al. 2010; Procter and Fleming 1999; Mortimer and Day 1999). The most important nesting rookeries of hawksbill turtle are found in Peros Banhos and Diego Garcia. Green turtles nest mainly in the Chagos Bank beaches, and it was the tracking studies of those green turtles that led to the discovery of the deep seagrass meadows in the archipelago (Esteban et al. 2018). Leatherback turtle *Dermochelys coriacea* is a vagrant in the area (Procter and Fleming 1999). Census data have shown recent increases in the overall abundance of sea turtles in BIOT, at least some of which is linked to the lack of recent harvesting, with annual numbers of green turtle clutches across the archipelago reaching 20,500 and increasing, highlighting the importance of BIOT for the future of both species in this region (Hays et al. 2020; Mortimer et al. 2020).

Both green and hawksbill turtles occur around the Pitcairn Islands (Irving et al. 2019). A small number of green turtle females used to nest on East Beach on Henderson Island (Irving and Dawson 2012; Procter and Fleming 1999; Brooke 1995). A more recent report from BirdLife International (2020) confirms that approximately 10 female green turtles lay annually on Henderson, which although a trivial number globally represents about one percent of the French Polynesian total.

The sex and fitness of sea turtle hatchlings is determined by the incubation temperature of the sand around the nest, with females produced at higher temperatures, and males at lower temperatures depending on species. Given the projected rise in global temperatures, the mass feminization of sea turtle hatchlings is a serious concern (Reneker and Kamel 2016; Fuller et al. 2013). Rising sea levels and storms can also cause severe damage and reduce availability of nesting areas for turtles, and degrade the seagrass and reefs where they feed undermining their fitness and resilience and ultimately survival (Stubbs et al. 2020; Fuentes et al. 2010). Studies in other regions have also indicated that future changes in SST may distort the migration behaviour and trajectories of sea turtles (Almpanidou et al. 2019; Wabnitz et al. 2018).

7.7. Cetaceans

Although BIOT is within the Indian Ocean Whale Sanctuary established in 1979, very little is known about the abundance of cetaceans in the area (Dunne et al. 2014). Sightings include short-finned pilot whales (*Globicephala macrorhynchus*) and dolphins (spinner dolphin *Stenella longirostris*, bottlenose dolphin *Tursiops* sp., striped dolphin *Stenella coeruleoalba*, spotted dolphin *Stenella attenuata*), and in addition acoustic monitoring demonstrates that blue whales (*Balaenoptera musculus*) and sperm whales (*Physeter macrocephalus*) also visit the waters of the archipelago (see Dunne et al. 2014 and references wherein).

Various species of dolphins and whales are found in EEZ waters of the Pitcairn Islands (Irving et al. 2019; Irving and Dawson 2012). Humpback whales (*Megaptera novaeangliae*) are common sightings between May and October as they use the local waters as wintering grounds (Irving et al. 2019; Horswill and Jackson 2014), and as recent evidence suggests, breeding grounds (Irving et al. 2020). Pilot whales (*Globicephala* sp.) have been sighted off Pitcairn Island and a male Cuvier's beaked whale (*Ziphius cavirostris*) was found washed ashore dead on Ducie Island in 1997[16]. A code of conduct for whale watching has been developed and published on the Pitcairn Islands Tourism website, and education and training is underway to support the local community to effectively implement the guidance[17] for providing whale watching trips for tourists.

There are considerable gaps in the knowledge of abundance and distribution of whales and dolphins in both territories. As endothermic animals, marine mammals generally have broader tolerance to changes in temperature compared to other marine species. Also, due to their long life span, long gestation times and low birth rates, their behaviour is fairly adaptable and therefore climate change impacts are most likely going to be relative to effects on their prey species – notably due to changes in temperature. This behavioural plasticity will be paramount to adapt to climate change (Albouy et al. 2020; Sanderson and Alexander 2020; Sousa et al. 2019; Avila et al. 2018; Silber et al. 2017). However, the compounding effect of other human stressors could undermine their resilience to future climate change (Evans et al. 2010).

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[16] https://www.visitpitcairn.pn/marine_reserve/whales/index.html

[17] https://marinedevelopments.blog.gov.uk/2019/08/09/whale-watching-training-in-the-pitcairn-islands/

8. Building resilience to climate change

There are two main approaches which can be employed to enhance resilience of ecosystems to a changing climate: by managing the pressures from local human activities and by implementing adaptation and resilience actions. Here we discuss a number of potential options, based on research studies and examples from other areas. Any intervention and management actions should be undertaken with full consultation and collaboration with residents, when present, so that they understand the long-term benefits and risks of interventions and so that they can be incorporate their valuable local and traditional knowledge. Decisions on actions should also be based on scientific evidence wherever possible and, ideally, long-term data and direct observations, and should ensure they include implementation of monitoring plans, review periods and adaptive management (Belokurov et al. 2015).

8.1. Limiting impact of human activities

Reducing pressures from human activities, other than climate change, while it does not prevent coral bleaching or mortality, it may help by improving coral resilience and therefore delaying the onset of mass mortalities allowing time for mitigation measures to reduce emissions, eventually limiting global warming (IPCC 2019; 2014). Evidence shows that corals with reduced exposure to, or absence of, other human pressures are more resilient to bleaching (IPCC 2014; Nyström et al. 2008). This can be achieved through management strategies that regulate the uses of the coastal and marine environment, thus alleviating pressures such as soil erosion, pollution, overfishing and coastal developments (UNEP 2017; IPCC 2014).

The marine environment of BIOT and the Pitcairn Islands, due to their remote location and small population, are exposed to lesser pressures from human activities compared to similar coral atoll islands in the Indian and Pacific Oceans. Nevertheless, as identified in the Pitcairn MPA Management Plan, there are concerns about a number of activities including fishing, marine plastic litter and anchoring, that could be having adverse impacts on the marine environment of the islands and their reefs. Other potential issues are the presence non-native invasive species, both on land and at sea, and excess runoff due to soil erosion.

Fisheries management and the protection of large marine areas such as the Pitcairn Islands MPA can help improve the resilience of coral and fish communities to climate change impacts (Hays et al. 2020; Coghlan et al. 2017; McClanahan et al. 2008; Hughes et al. 2003). Reducing fishing pressure should contributes to the resilience of corals, as it allows large enough populations of herbivorous fish to exist, which graze on the algae that otherwise could smother the coral and the same time free up substrate for coral recruitment (Steneck et al. 2019; Mumby et al. 2007). There are examples from Caribbean reefs having suffered significant losses from hurricane impacts and bleaching, whereby allowing herbivorous fish to proliferate and graze on the algae, coral recruitment increased, and corals recovered (Steneck et al. 2019). There are differences in the interaction between herbivores and reefs in different oceans, but the presence of herbivorous fish and certain other functional groups can indirectly support the recovery of coral reefs following impacts (Steneck et al. 2019; Mumby et al. 2016).

Improving water quality is also proven to increase coral resilience to climate change. The ridge-to-reef approach to coastal zone management emphasises the importance of reducing impacts from land and freshwater sources of pollution and disturbance (Carlson et al. 2019). Coral monitoring in the Great Barrier Reef has shown that improving water quality, whilst not preventing bleaching for the most sensitive species, helps corals to recover more quickly and it also reduces susceptibility to crown-of-thorns starfish outbreaks (MacNeil et al. 2019). In BIOT, low traces of contaminants have been found around Diego Garcia lagoon (Painting et al. 2020). On the other hand, changes in land use and soil erosion in Pitcairn island may have contributed to excess runoff input into coastal waters coinciding with a particularly heavy precipitation event, which was observed to cause excess sedimentation in the short-term (Friedlander et al. 2014). Ensuring the preservation of vegetation cover on the island and a sustainable management of agricultural activities would prevent soil erosion and contribute towards maintaining good water quality nearshore and minimise the risk to nearshore corals. Generally, it would be advisable to implement marine spill and pollution response plans to ensure that any incidents nearshore or offshore can be responded to quickly, and damages limited. Perhaps a more noticeable issue in terms of marine pollution in the case of the Pitcairn Island is plastic litter, with Henderson Island declared to have some of the highest levels of ocean-borne plastic litter on the planet (Ryan 2020; Ryan and Schofield 2020; Irving et al. 2019; Forrest and Hindell 2018). Marine plastics are known to endanger many marine animals and although a specific direct link to the corals themselves, other than by physical damage by large items such as entangled fishing nets etc. is not overly clear yet, it has been suggested that the proliferation of plastic litter increased the risk of coral diseases (Lamb et al. 2018).

Another important threat to corals are coral diseases and also the presence of invasive and non-native species, even on land. A clear example is the dramatic effect that the introduction of rats has had on bird populations of both Pitcairn and BIOT, which has been shown to impact the coastal coral reefs themselves as the nutrient subsidies to the reef from guano leaching, which are important for the ecological functioning of the reef, are lost (Benkwitt et al. 2021; Benkwitt et al. 2019; Graham et al. 2018; Graham et al. 2017). Eradication of rats should therefore be a conservation priority for the islands (BirdLife International 2020; Perez-Correa et al. 2020; Benkwitt et al. 2019; Graham et al. 2017). Corallivorous crown-of-thorns starfish may be present in the islands, (Birkeland 1989). Crown-of-thorns could be monitored in order to prevent potential outbreaks, as it would be important to screen for coral diseases, both of which can have equally devastating consequences.

There are concerns that anchoring yachts and cruise ships may be causing damage to the corals and other benthic communities, particularly concerning in the case of BIOT with military vessels using the lagoon area of Diego Garcia (Irving et al. 2019). Some measures have been taken towards limiting anchoring to certain areas, but the seabed around these locations should be monitored regularly, so that further measures can be put in place if necessary (Sheppard and Sheppard 2019; Lewis et al. 2017).

The MPAs of BIOT and the Pitcairn Islands have often been described as some of the most remote and better preserved oceanic island environments (Moritz et al. 2018; Readman et al. 2013), where corals may be able to survive longer into the future (Head et al. 2019). They may have a role to play as climate refuges for many forms of marine life, including corals, where the low level of other human pressures grants a greater resilience allowing them to persist longer into the future (UNEP 2017), even if as it is expected in the case of coral reefs, they are likely to experience changes and lose structural and functional complexity (Sheppard et al. 2020).

8.2. Active interventions

Reducing future global CO_2 emissions is, at present, the only feasible pathway to control future global warming and therefore effectively limit climate change impacts on coral reefs (Bruno et al. 2019), including those in BIOT and the Pitcairn Islands. To further promote the resilience and adaptation of the reefs in the MPAs of these territories, tangible and targeted management measures and regular monitoring can help in determining what, if any, active steps are required to promote resilience and limit impact. It will likely involve an array of conventional as well as novel interventions in order to improve their protection through MPA management, alleviate local pressures, and restore degraded and damaged reefs (Abelson 2020).

Recent coral planting and seeding initiatives to remediate coral loss have had some local success in coral reefs elsewhere (IPCC 2019). Planting or seeding of corals can draw on species or strains which are more resistant to climate change (Dance 2019), and so while this might change the species composition of the corals in an area, it can enhance the overall resilience of the reefs to climate change. Coral recruitment can also be enhanced by collecting gametes from the sea during spawning, and following fertilization returning settled larvae to the sea a few days later (Dance 2019). Research is underway in Australia to breed species and strains of heat tolerant corals (Cornwall 2019). Coral husbandry also allows testing if corals can adapt to warming temperatures, and genetic manipulation of the bacteria or zooxanthellae in the corals, or even the corals themselves, may allow the creation of new heat tolerant mixtures (Crabbe 2019).

Reducing bleaching during heatwaves in localised coastal areas by using artificial shading at times of high sea temperatures has been proposed (Belokurov et al. 2015), but this does not seem a practical intervention considering the large scale of the BIOT and Pitcairn Islands MPAs.

All these potential interventions often involve complex decisions (Abelson 2020; Anthony et al. 2020) and are not without controversy as to their efficacy. Their implementation across large and remote areas such as the BIOT and Pitcairn Islands MPAs presents big challenges.

8.3. Current management measures in place

There are strict no-take regulations as part of the MPA designation in both territories. Until 2016, non-commercial fishing was infrequent in the Pitcairn Islands, mostly by islanders visiting the site known as 40-mile reef to the east-southeast of Pitcairn (Irving and Dawson 2012). Under the Pitcairn MPA, only limited fishing is permitted to islanders within denominated coastal conservation areas[18]. A Fisheries Management Plan has been put in place that focuses on management measures for the inshore subsistence fishery including gear restrictions and minimum landing sizes (Dawson and Irving 2020; Irving et al. 2019). A separate Compliance and Enforcement Strategy covers the surveillance and prosecution of IUU fishing offences. In BIOT, commercial fishing is also forbidden and only rod/hand line fishing is allowed for own consumption, with Fisheries Officers having authority to inspect vessels and logs[19]. BIOT are currently implementing several

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[18] Revised Laws of Pitcairn, Henderson, Ducie and Oeno Islands, 2017 Rev. Ed. - Volume 2 (government.pn)

[19] British Indian Ocean Territory (gov.io)

management actions on reducing the impact of human activities on corals and investigating further work on the eradication of rats on some of the islands.

8.4. Further options to be considered

The management plans for the MPAs include a number of measures to reduce stress on the marine environment. In the Pitcairn MPA, monitoring of benthic habitats including coral reefs would help identify any impacts on corals and other vulnerable habitats around Pitcairn, Henderson, Oeno and Ducie Islands. It would be important to consider aligning the monitoring of benthos and coral reefs to any data gathering and recording of catches as part of the Fisheries Management Plan, to coordinate efforts and maximise coverage of the MPA. The eradication of rats on Henderson Island could have positive effects on the corals if seabird populations are able to re-establish their numbers to previous levels (BirdLife International 2020), and the subsidies of guano nutrients to the reef areas are restored (Benkwitt et al. 2021; Benkwitt et al. 2019; Graham et al. 2018).

These territories could be considered as nursery areas where corals and seed could be harvested for replanting in other areas. While in the case of Pitcairn current data suggest that those corals are likely to be more thermally “naïve”, BIOT corals appear as a stronger option. An expedition to BIOT found areas of resistant colonies with young corals settled only two years after a bleaching event (Koldeway et al. 2016). There were also deeper, twilight reefs with up to 100% coral cover in places which may be acting as refuge and seed sources from where areas of bleached coral can be replenished with new polyps.

8.5. Knowledge gaps and research needs

8.5.1. Habitat mapping and vulnerability assessments

Compared to the abundance of coral research in BIOT, there is a lack of data on coral reef communities of the Pitcairn Islands (Friedlander et al. 2014) making it difficult to determine a pre-bleaching baseline. One of the priorities should be to undertake a detailed habitat mapping of coral reefs and other benthic communities across these marine areas, particularly the Pitcairn Islands MPA. Regular coral monitoring of key ecological indicators should also be implemented, including but not limited to: coral cover, coral colony species composition, occurrence of coral diseases, occurrence and potential outbreaks of non-native invasive species such as crown-of-thorns, coral recruitment rate, water quality, changes to macroalgal cover and fish species abundance. Any data gathering as part of this monitoring will require careful consideration to provide maximum coverage with minimum effort, and to ensure that the information provided is ecologically relevant and provides the necessary evidence to detect early signs of potential changes so that adaptive management measures can be put in place.

A coral vulnerability assessment of the reefs in BIOT and the Pitcairn Islands (UNEP 2017; Belokurov et al. 2015) is recommended and is already underway, at least in BIOT, to determine and characterise the corals in terms of exposure and sensitivity to climate change or other risks across the MPAs. This will help inform what interventions should be most appropriate, beyond reducing other human pressures. Where it exists, information from local coral monitoring can be used to identify species or colonies that show higher resistance to bleaching (Belokurov et al.

2015), so they can be prioritised for further protection and research and the knowledge can be applied to improve the protection of reefs in other regions.

8.5.2. Coral interventions

Some of the emerging intervention techniques such as planting, seeding and genetic engineering of coral and zooxanthellae strains require further research and discussion. It has been proposed that some of the healthier reefs in BIOT and Pitcairn Islands have the potential to become coral seed banks for coral conservation and restoration, which again would require further research.

8.5.3. Ocean acidification and carbon chemistry

It is important to improve our understanding of the changes in ocean carbon chemistry and coral adaptation in these MPAs, which could be integrated as part of the GOA-ON[20] monitoring network expansion, ideally by encouraging capacity in location. Given that this is a data-poor region, and added to the concerning projections of future ocean acidification particularly in the case of the Pitcairn Islands, this should be treated as a priority. The use of autonomous sensor technology could be a feasible option.

Research of ocean acidification (including total alkalinity, dissolved organic carbon, pH, nutrients including phosphates and silicates) on corals mainly focuses on single-species responses. Increasingly, experiments are being conducted combining multiple climatic and non-climatic stressors on single species, which are revealing how other climate stressors interact with ocean acidification. It is not yet clear to what extent corals and other reef organisms can acclimatise and adapt to ocean acidification, however. It is possible that ocean acidification may be less harmful or even beneficial to certain reef organisms. *In situ* studies of baseline conditions are required to build an understanding of effects of ocean acidification on single species, and extrapolate these responses to impacts on whole reef systems and functions, including food webs and competition.

8.5.4. Sea level

In order to support adaptation and resilience strategies, it is important to better understand the processes by which coral islands adjust to sea level rise (Kench et al. 2015; Barnett and O’Neill 2012). Rising sea level is expected to cause coastal erosion, remobilise sediments and destabilise islands, but there are discrepancies and there is debate about the likely physical changes to atolls in the future (Ford et al. 2020; Kench et al. 2018b; Storlazzi et al. 2018; Kench et al. 2015). Further research into atoll coastal processes in response to sea level rise and reef erosion in BIOT and the Pitcairn Islands would be important.

8.5.5. Implementation of fisheries management and collection of catch records

There is a need for an effective management of the local subsistence and recreational fisheries (Dawson and Irving 2020; Bell et al. 2018; Coghlan et al. 2017; Bell et al. 2011b), which could have

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[20] www.goa-on.org

a positive effect on the resilience of the associated reefs. Data and information gathered as part of the fisheries management and catch recording should be integrated and coordinated with marine monitoring activities across the wider MPAs, including corals.

9. Summary and conclusions

	Impacts	BIOT	Pitcairn Islands
Bleaching	Current	Coral monitoring records show evidence of repeated ocean heat events since the 1970s that caused bleaching and mortality. The most severe bleaching event took place in 2016, from which the reefs have not yet recovered.	There are no observations of past coral bleaching, and no obvious change in average SST has been detected. Improved monitoring is needed to ensure that any future bleaching is recorded.
	Future	More bleaching events are expected over the coming years and decades. Deep reefs are less exposed to warming and may act as refuges, but those colonies are likely to be more sensitive to changes in temperature, which in turn may heighten other risks such as coral diseases. Low levels of other human pressures in BIOT are not sufficient to guarantee the resilience of reefs to future climate impacts.	Pitcairn is expected to have low levels of thermal stress over the rest of the century. However, corals may be more sensitive if thermal stress occurs, and the isolation of the Pitcairn reefs may be a challenge in terms of recovery potential.
Ocean acidification	Current	There is a lack of data on ocean acidification in Indian Ocean reefs, and in BIOT in particular. Some preliminary, coarse scale models suggest little impact on coral reefs from ocean acidification alone thus far.	Saturation levels are low and close to the point where it can weaken coral skeletons and slow coral growth. Direct observations of physiological impacts on corals are rare, but there is evidence that low pH is changing the composition of colonies, increasing algal cover, and encouraging bioerosion.
	Future	When combined with bleaching, ocean acidification places a greater risk of decalcification and erosion to reefs in the future. Over the coming century and under high emissions scenarios, BIOT is projected to become less suitable for corals due to changes in carbonate chemistry conditions.	By the end of the century under low emissions scenarios, projected ocean acidification levels in the Pitcairn Islands region are unlikely to support net coral calcification.
Sea level rise, storms, and waves	Current	Sea level change observations from the Indian Ocean and BIOT indicate it is rising twice as fast as the global average. Extreme values in relative sea level appear related to El Niño or La Niña events.	Sea level has risen faster than the global average, although island margins appear to have adjusted. There is evidence of strong wave damage around Henderson, and storm damage and mass coral mortality caused by cold water influx in Ducie. Heavy rainfall on Pitcairn has caused landslides and runoff, although strong prevailing

			currents seem to be able to mitigate the risk of sedimentation and turbidity to corals.
	Future	Sea level rise remains a future risk to BIOT reefs when combined with bleaching and acidification, which will reduce the effectiveness of reefs to perform as breakwaters. BIOT has suffered considerable shoreline erosion, which suggests loss of breakwater effects from protective fringing reefs.	The influence of the South Pacific Circulation Gyre may slow down the warming and acidification impacts in the Pitcairn Islands region. In addition, the deeper reefs found around these islands may be relatively sheltered from future climate change impacts. However, sea level rise is projected to accelerate by the end of the century, and it is unclear whether these islands will continue to adjust.
Other human pressures		Rats are a threat to coral reefs in BIOT. Recreational fishing is allowed to residents around Diego Garcia, including for tuna and scombrids. There is also IUU fishing of tuna and sharks, and sea cucumber poaching. Traces of pollution have been found around Diego Garcia which require further examination. Anchor damage has been observed in lagoon corals in Diego Garcia.	There is some concern of overfishing impacts. Henderson Island has some of the highest levels of plastic pollution on the planet. There is concern that cruise ships and sediment runoff are causing damage to the seabed and corals. Crown-of-thorns starfish may be present around Pitcairn. There are rats on Henderson Island, which reduce numbers of seabirds.

Future climate change is likely to bring about a host of combined pressures, feedbacks, and indirect impacts on coral reefs. The knowledge and appreciation of such cumulative impacts is growing rapidly (Bruno et al. 2019; Cinner et al. 2016; Ateweberhan et al. 2013). Even among the direct impacts, there are major differences in the understanding and confidence surrounding impact pathways, that are partly attributable to differences in the timing of impacts: for example while impacts from warming SST and storms are already being observed, those from sea level rise and ocean acidification will take time to emerge (Cinner et al. 2016). As research in these fields continues, it is expected that new impact pathways will be found (Cinner et al. 2016). For example, ocean acidification is likely to increase susceptibility of corals to the mechanical damage caused by storms because a lower seawater pH will weaken coral skeleton density and strength (Madin et al. 2008; Hoegh-Guldberg et al. 2007). Decreases in calcification rates may also be exacerbated by warming ocean temperature, as has already been observed for encrusting coralline algae (Martin and Gattuso 2009). To date, observational and experimental research on how synergies between key climate drivers affect coral reef systems is very limited (Ban et al. 2014) and therefore assessments of climate change impacts usually focus on individual drivers, rather than on cumulative effects (Cinner et al. 2016). Because of their isolation and low levels of human impacts, further studies of the corals in the BIOT and Pitcairn reefs can help disentangle these synergies and provide answers to many of these scientific questions, for the benefit of other reef areas around the world.

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