Stability of coral reef islands and associated legal maritime zones in a changing ocean

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Abstract

Coral reef islands can support large legal maritime zones (i.e. ocean spaces where States have rights and responsibilities) and are of international and geopolitical importance. This review focuses on low-lying coral reef islands supplied with sediments derived from skeletons and shells of calcifying organisms. For coral islands, the outer ‘low-water line’ of the reef can be used as the legal ‘baseline’ to establish maritime zones. Coral islands and the reefs that support them are experiencing the effects of rising and warming seas, increased storminess and ocean acidification. Coral reefs, their islands and associated maritime zones support millions of people, including those in Small Island Developing States (SIDS). SIDS communities are arguably the least responsible for climate change but are at the forefront of its impacts so ensuring their continued wellbeing is a global responsibility. Securing the future of coral reefs and islands is dependent on reducing global climate threats and emissions, improving local management, and investing in restoration and adaption research. It is uncertain if coral islands will persist into the future, and on what timelines. This raises questions such as, where coral islands support maritime zones, what are the legal implications of island instability or loss? This review focuses on the bio-physical interactions of coral islands and associated reefs in the face of changing climates, and implications for legal maritime zones and SIDS.

1. Introduction

Coral reef islands and associated reefs can support legal maritime zones (i.e. ocean spaces where States have rights and responsibilities) and so are of national and international geopolitical significance. However, they are already experiencing the negative impacts of changing oceans and climates. Coral reef islands (henceforth referring only to low-lying coral reef islands and excluding continental, volcanic and high reef islands) typically have elevations <10 m above sea level (Kench et al 2018, Nunn et al 2020). These islands are accumulations of calcium carbonate sediment derived from the skeletons and shells of reef calcifiers (Dawson and Smithers 2014). Coral reefs have a wide distribution (figure 1), and millions of people are reliant on them for food security and other reef-associated ecosystem services including fisheries, tourism, mineral exploration, and coastal hazard protection (Woodhead et al 2019). Worldwide, coral reefs provide an estimated US$2.4 trillion per year, equal to 2.2% of global ecosystem services (Spalding et al 2017). They are among the most productive and biodiverse marine ecosystems in the world, and thrive within a specific range of bio-physical, ocean and climate conditions (Hoegh-Guldberg et al 2007).

Coral reef islands and associated reefs are vulnerable to changing climates. Sea-level rise (SLR), warming oceans and coral bleaching (Putnam et al 2017, Sully et al 2019, Hughes et al 2021), ocean acidification (Hoegh-Guldberg et al 2007) and increased storminess (Chand et al 2020,
Tebaldi et al (2021) are increasing pressures on the bio-physical processes that govern the structural integrity of coral reefs and islands. Small Island Developing States (SIDS) are the least responsible for anthropogenic climate change but are at the forefront of its effects (Barnett and Adger 2003, Wolff et al 2015). To secure the long-term health and resilience of coral reefs there needs to be a reduction in climate threats and global emissions, improvement to local management and protection strategies (e.g. marine protection areas), and investment in restoration (e.g. coral farming) and active adaptation research (e.g. genetic diversity and resilience) (Knowlton et al 2021). The future persistence of coral islands is not clear. Some scientists contend that coral islands will be unstable and drowned by rising seas, eroded by storms and increased wave heights (Bramante et al 2020), and may shrink due to beaching and ocean acidification-driven reduced calcification and sediment supply (Dawson et al 2014). Others contend that, due to their morphodynamic nature, islands may be stable and grow with changes in sea level due to continued sediment supply (Masselink et al 2020, Tuck et al 2021).

For coral islands, the outer ‘low-water line’ of the reef as marked on official charts can be used as the legal ‘baseline’ from which maritime zones are established (Article 6, UNCLOS 1982). Maritime zones are the way which international law spatially organises States’ rights and responsibilities in the world’s oceans (Roach 2014, Crawford 2019). These rights and responsibilities differ depending on where in the ocean an activity or resource is located. For example, a State has the exclusive right to regulate fisheries in its own exclusive economic zone (EEZ; a maritime zone up to 200 nautical miles (NM) from its baseline) but may not do so on the high seas (beyond 200 NM). The dynamic and transient nature of coral reefs and islands influenced by natural processes and climate change has raised a key question: where coral reef islands support maritime zones, what are the legal implications of island instability or loss? Many legal scholars consider that baselines and maritime zones ‘ambulate’ with natural changes to coral reefs or islands (O’Connell 1984, Caron 1990, Soons 1990). This means that a flooded or receding low-water reef line, or the loss of a coral island, would result in a receding baseline and a potential loss of the corresponding maritime zone. This legal view, however, is not settled, and urgently needs to be informed by insights as to the likely future of coral reef islands in light of climate change.

Understanding the impact of climate change on coral reefs and islands is an urgent science and legal issue. This is highlighted by recent Intergovernmental Panel on Climate Change (IPCC) projections (Fox-Kemper et al 2021), the 2018 Pacific Islands Forum and SIDS statements at the 2021 United Nations Climate Change Conference of Parties (COP26) (Alliance of Small Island States 2021, Freestone and Schofield 2021, Pacific Islands Forum 2021, Rasheed and Athaulla 2021). This review considers the bio-physical processes controlling the structural integrity of coral reef islands and associate reefs, in the face of climate change, and implications for legal maritime zones and SIDS. We identify areas for further investigation that bring legal and scientific perspectives together as a coherent research enterprise, offering important insights for States that use coral islands to support maritime zones.

2. Biological processes in a changing ocean

The formation of coral reefs is based on the symbiosis between the coral polyp and their algal symbiont (zooxanthellae) (Hoegh-Guldberg et al 2007). The polyps, supported by the energetic resources provided
by the symbiont, secrete the calcium carbonate skeleton. Coral reefs require sunlight to support photosynthesis of the zooxanthellae and so are mostly restricted to shallow (<30 m) clear water. They also require low nutrient conditions, free flowing water and sea surface temperatures (SST) between 23 °C and 29 °C (Hoegh-Guldberg et al. 2007). Coral reefs are highly productive ecosystems that support a vast diversity of species, and many coral islands support human populations and are key habitats for threatened species (Waller et al. 2017).

Corals exhibit a range of colony growth forms (e.g. branching, encrusting and massive) with morphology influenced by environmental conditions (Todd 2008, Teixidó et al. 2020). In wave-exposed outer reef zones, corals have a more robust morphology (e.g. encrusting), than those in protected backreef zones (Todd 2008). Growth rates vary between coral species. On the Great Barrier Reef (GBR) branching corals (e.g. Acropora spp.) can grow up to 89 ± 6 mm yr\(^{-1}\), while massive corals (e.g. Porites spp.) grow more slowly, up to 9.6 ± 2 mm yr\(^{-1}\) (Roff 2020). Coral community growth rates are estimated to be 7–9 mm yr\(^{-1}\) in the GBR (Roff 2020) and 2–12 mm yr\(^{-1}\) in Japan (Hongo and Kayanne 2010).

Reefs grow vertically to sea level and then extend laterally into circular or elongate structures (Hopley 1982, Woodroffe and Webster 2014). Lateral reef growth is supported by sediment supply that can infill backreef environments creating sand aprons, shallow lagoons and coral islands (Mandlter and Kench 2012, Ortiz and Ashton 2019, Rankey 2021). The main reef calcifiers that supply sediments are corals, large benthic foraminifera, calcareous algae (e.g. Halimeda), echinoderms and molluscs (Dawson and Smithers 2014, Dee et al. 2020). Foraminifera tests (i.e. skeletal shell) constitute a large proportion of many reef sediment budgets. For example, they constitute <95% of sands in Nusa Dua (Bali, Indonesia) (Hohenegger 2006), <50% on Raine Island (northern GBR) (Dawson et al. 2014), <50% on the islands of Majuro Atoll (Marshall Islands) (Fujita et al. 2009), <42% on Fongafale Island (Tuvalu) (Collen and Garton 2004), <32% of sand aprons on One Tree Island (southern GBR) (Fellowes et al. 2017) and <25% at Sesoko Island (Ryukyus, Japan) (Hohenegger 2006).

Sediment composition is used as a proxy to determine present and past reef and coral island conditions (Yasukochi et al. 2014). For instance, foraminifera skeletal abundance, abrasion, geochemistry and age are used to determine sedimentation rates, wave and current conditions, sediment transport pathways and historical island dynamics (Dawson et al. 2014, Fellowes et al. 2017, Gacutan et al. 2017). Coral reefs are under rapid decline due to intensifying climate change with environmental warming and acidification of particular concern (Putnam et al. 2017, Dove et al. 2020) (figure 2).

Dire projections suggest that net carbonate production will be reduced by 76%–156% due to warming and acidification (Cornwall et al. 2021), and this may impact the structural integrity of coral reefs and islands.

2.1. Ocean warming and heatwaves
Water temperatures only 1 °C–2 °C above ambient mean maximum SST can result in mass bleaching (Dove et al. 2020, Ainsworth and Brown 2021). Increased temperatures result in expulsion of algal symbionts in corals and other invertebrates (e.g. foraminifera, giant clams) thereby causing a bleaching (figure 2(a)), a significant cause of mortality that can result in reef collapse (Hughes et al. 2017, 2021). Bleaching can sometimes be reversed if the water cools.

Predictions for the best (SSP1-2.6) and worst (SSP5-8.5) case scenarios indicate that mean SST will increase between 0.7 °C and 1.1 °C by 2050 and 0.8 °C and 2.7 °C by 2100, respectively (Fox-Kemper et al. 2021) (figures 3(a) and (b)). While projections for gradual warming are of concern, it is the marked increase in temperature that occurs in marine heatwaves that are most damaging. Exposure to bleaching is measured as degree heating weeks (DHW), the number of weeks temperatures are 1 °C above the mean temperature for that time of year (see Hughes et al. 2017, 2021). On the GBR after four DHW, 60% of corals bleached and after 12 DHW up to 100% bleach. Recovery after a major bleaching event takes 10–15 years (van Hooidonk et al. 2016). The frequency of bleaching events, as seen over the last 20 years for the GBR (1998, 2002, 2016, 2017, 2020), have weakened the capacity of reefs to recover and their ecological resilience (Hughes et al. 2021). It is predicted that 94% of the world’s coral reefs will be eroding by 2050 due to climate change (Cornwall et al. 2021).

Mass bleaching is associated with coral mortality and an increase in rubble and sediment production. This was seen in the Ryukyus (Japan) where a coral rubble island doubled in size following the 1998 marine heatwave (Kayanne et al. 2016). However, the island eroded back to the original size or smaller within 3 years. Over the medium to long-term, climate warming will reduce the supply of carbonate sediment required to maintain the structural integrity of coral islands.

2.2. Ocean acidification
The ability of reef calcifiers to build their skeletons and thereby contribute to sediment production for island building, depends on ocean chemistry which is changing due to ocean uptake of anthropogenic CO\(_2\) (Anthony et al. 2008, Putnam et al. 2017). This uptake has caused ocean acidification with the sea surface pH decreasing from 8.2 in pre-industrial times to a present-day average of 8.07 ± 0.02 (Jiang et al. 2019).
Figure 2. Coral responses to (a) marine heating, (b) ocean acidification and (c) both.

Figure 3. IPCC projections in 2081–2100 relative to 1995–2014 for SSP1-2.6 (left) and SSP2-8.5 (right). (a), (b) Sea surface temperature (SST), (c), (d) pH, and (e), (f) SLR. Black areas show coral reef locations.
Projections based on the best (SSP1-2.6) and worst (SSP5-8.5) emissions scenarios indicate a drop in sea surface pH to 7.6–7.7 by 2050 and 7.4–7.7 by 2100, respectively (Fox-Kemper et al 2021) (figures 3(c) and (d)).

Ocean acidification encompasses three stressors, reduced pH, increased organic CO₂ and reduced mineral saturation, all of which have negative impacts on reef biota (Cyronak et al 2018). The greatest peril for reef calcifiers is the reduced saturation state of aragonite and calcite challenging the calcification systems (Cyronak and Eyre 2016) (figure 2(b)). Coral reef species must work harder and expend more energy with decreasing raw materials and the corrosive effects of lower pH (Byrne and Fitzner 2020). When more energy is needed to make and maintain skeletons and shells, this reduces the energy available for other processes such as growth and reproduction. Only a few coral species (e.g. slow-growing Porites spp.) appear to be able to survive in near future ocean acidification conditions, as shown at CO₂ vent sites in Papua New Guinea and Japan (to pH 7.7) (Fabricius et al 2011).

Under ocean acidification conditions, Acropora spp. (key reef builders) change their skeletal structures to growth forms that require less carbonate mineral, impacting reef integrity (Putnam et al 2016). Calcareous coralline algae, that bind the reef framework, also have diminished productivity and calcification rates under ocean acidification conditions (Anthony et al 2008). Meanwhile, foraminifera are highly sensitive to reduced carbonate availability from ocean acidification and warming (Doo et al 2014, Kлиз et al 2021). The implications of losing these and other reef-building calcifiers, could have catastrophic effects on reef integrity (Teixidó et al 2020), sediment budgets and island structural stability (Dawson et al 2014, Kлиз et al 2021, Browne et al 2021).

3. Physical processes in a changing ocean

Coral reefs are physical barriers that dissipate wave energy in the forereef and outer reef zones (Harris et al 2018, Callaghan et al 2020, Pomeroy et al 2021). This dissipation is a function of the water level above the reef and forereef slope and seafloor rugosity (i.e. roughness), with the latter a proxy for reef heath (Harris et al 2018, Summers and Donner 2022). Waves and currents physically erode and transport reef framework, rubble and the skeletons of reef calcifiers towards backreef sand aprons, lagoons and islands (Vila-Concejo et al 2014, Pomeroy et al 2021) (figure 4).

Coral islands started to form ~6 ka, when sea level stabilised (Montaggioni et al 2019). These islands have a diverse array of physical attributes including sediment type (e.g. sand, rubble), the presence of vegetation, size, shape and maximum elevation (Hopley 1982, McLean and Kench 2015, Nunn et al 2016) (figure 4). They can exist on wave-exposed and protected reef margins and in central lagoons (Hopley 1982). Sand islands typically develop at convergence points where waves and currents deposit sediments, through a form of overwash driven transport (Ortiz and Ashton 2019, Bramante et al 2020, Rankey 2021). Rubble islands form when tropical storms/cyclones deposit larger rubble and framework into backreef zones (Ortiz and Ashton 2019), and subsequent storms then control rubble island morphology (Talavera et al 2021). Mixed sediment islands such as atoll Motu typically have rubble cores (formed by storms) and sandy shores (formed by waves and currents) (Ortiz and Ashton 2019). The sediment composition of many islands remains unknown, and a greater understanding of sediment types, calcifier contributions (e.g. large benthic foraminifera) and island structural integrity is needed, especially for SIDS.

Coral islands are morphologically active on storm to millennial timescales and can migrate, prograde, erode, rotate and merge with adjacent islands. Studies show that only 15% of islands in the Indo-Pacific are eroding on decadal scales, with most islands either stable or getting larger (Kench et al 2015, 2018, Albert et al 2016, Duvat 2019, Holdaway et al 2021, Sengupta et al 2021) (figure 5). These authors found that the shrinking islands are typically smaller than 10 Ha.

In the last 20 years one of the main mechanism driving increases in coral island area in the Indo-Pacific is land reclamation, primarily in the Maldives and South China Sea (Holdaway et al 2021). It remains unclear if coral islands will become structurally unstable in the future, or if they will be able to adapt to changing climates.

3.1. SLR

SLR is a significant threat to the survival of coral reefs and SIDS (Storlazzi et al 2018, Tebaldi et al 2021, Tuck et al 2021). Sea level is currently rising at 3.7 mm yr⁻¹ and is projected to increase for best (SSP1-2.6) and worst (SSP5-8.5) emissions scenarios by 0.2–0.3 m by 2050 and 0.4–0.7 m by 2100, at rates as high as 15 mm yr⁻¹ (Fox-Kemper et al 2021) (figures 3(e) and (f)). As seas rise, the future stability of coral island will depend on reef integrity, wave dissipation, carbonate productivity, and sediment supply. Studies using physical and numerical models show that some coral islands can withstand and adapt to rising seas if there is ample sediment (Masselink et al 2020, Tuck et al 2021). However, they also show that islands may destabilise or even drown when the sediment supply is scarce. Research shows the dissipative efficiency of coral reefs is drastically reduced with SLR (Harris et al 2018, Bramante et al 2020). This is of particularly concern in the west Pacific where SLR is currently 5.1 ± 0.7 mm yr⁻¹ (McLean and Kench 2015).

SLR can lead to increases in erosion (Bramante et al 2020), storm surge and flooding (Winter et al 2020), island overtopping (Beetham and Kench 2018) and...
Figure 4. Cross-section of coral reef geomorphic zones, showing wave energy gradients, sedimentary features (islands, sand aprons and lagoons) and UNCLOS baselines. Figure based on Vila-Concejo and Kench (2017) John Wiley & Sons. © 2017 John Wiley & Sons Ltd.

Figure 5. Decadal change in coral island area (Ha) across the Indo-Pacific. Data from Duvat (2019) from multiple sources, and Albert et al (2016).

3.2. Waves and increased storminess
Wave and storm climates in tropical regions are intensifying (Chand et al 2020, Meucci et al 2020). In the future, projected long-term increases in wave heights, storm surges, and storm frequency and intensity might outweigh short-term constructive effects for reefs and coral islands (Beetham and Kench 2018, Bramante et al 2020, Tebaldi et al 2021). This is especially true when sediment supply to islands is limited. The true impacts of future increases in storminess and wave heights are poorly understood (Hongo et al 2018). Modelling shows that wave heights compared to historical records will increase and decrease across the tropics (Meucci et al 2020). These authors state that the frequency of extreme 1 in 100 year storms will be lower for the southwest Pacific (5%–15%) but higher (5%) for the northeast Indian Ocean. These regions are home to SIDS and are already experiencing above average SLR (Fox-Kemper et al 2021). Even with reduced storm frequency, SLR will make even small storms or increases in wave height a major threat to the structural stability of coral islands. Modelling based on Japanese reefs, show that future wave heights in backreef zones will
almost double under SLR and increased storminess (Hongo and Kiguchi 2021). These authors also show that potential increases in backreef wave heights are reduced by 30% in scenarios where reef productivity and structural integrity are maintained.

4. Legal consequences in a changing ocean

4.1. The international legal framework for baselines and maritime zones

From a legal perspective, rights over ocean space are closely connected to rights to land; so, if there are changes to the land, the question arises whether there are consequent changes to maritime zones. The legal basis for the global system of maritime zones is reflected in the United Nations Convention on the Law of the Sea (UNCLOS). UNCLOS is a treaty with almost universal membership (167 States parties plus the European Union) and for non-States parties (e.g. USA) is generally applicable as customary international law (UNCLOS 1982). This treaty governs the rules relating to the different kinds of maritime zones: the territorial sea measured up to 12 NM from the baseline (e.g. along the outer low-water line of a reef), the contiguous zone up to 24 NM and EEZ up to 200 NM, and beyond 200 NM for some continental shelf claims (Roach 2014, Crawford 2019). If neighbouring States’ maritime zones overlap, a maritime boundary needs to be delimited between them, either through a separate treaty or through a decision by a court or tribunal. It is likely that the legal implications for a delimited maritime boundary will have a high degree of permanence because of treaty law (Liszwan 2012, Stoutenburg 2013). Here we focus on the scenario of a maritime zone, where coastal State maritime zones do not overlap with each other and are unilaterally established via domestic legislation. Importantly, UNCLOS permits a coastal State to use a variety of baseline types, the predominant one being the normal baseline which generally follows the shoreline (Schofield 2012). Baselines can be supported by both continental land and islands (Article 121, UNCLOS 1982). For coral reef islands, the reef crest (defined at the outer low-water reef line) is used as the baseline, rather than the shoreline of the coral island itself (figure 6). This moves the baseline seaward (of the island shoreline) and expands the size of maritime zones measured from the baseline, as well as enclosing the lagoon as internal waters over which the coastal State has complete sovereignty (Hodgson and Smith 1976). The geographic rationale for this special provision is that the reef and island are considered one system (Nandan et al 2013).

4.2. Ambulatory baselines?

Small coral islands (<10 Ha) are the most morphologically active (Kench et al 2018) and commonly support baselines under UNCLOS (figures 5 and 6). Potential loss of maritime zones due to changes in reef baselines and coral islands is a serious concern for SIDS (e.g. Kiribati, figure 6(b)) as well as for larger States that use coral reefs and islands to support their maritime zones (e.g. Australia, figures 6(a) and (c)). Previous studies have either surveyed legal issues relating to reef baselines (Beazley 1991, Kawaley 1992, Trümpler 2017), or considered the potential impacts of SLR on baselines generally (Caron 1990, Rayfuse 2011, Schofield and Freestone 2019). Further work is required to consider whether changes to the structural integrity of coral reef islands as a result of climate threats automatically lead to legal vulnerabilities. Three legal areas require further investigation and are considered here.

Firstly, does a change to the shape or location of the low-water line of a reef automatically result in a change in the reef baseline it supports? The reef edge may be impacted by SLR, acidification or degradation of reef structural integrity. If the outer low-water reef line is fully submerged or the reef does not have the capacity to ‘keep up’ with SLR, then the question arises as to whether the baseline would automatically shift to the island shoreline and shrink the respective maritime zones (Caron 2009). Studies have insufficiently examined the potential legal stabilising effect of designating a charted low-water line as the legal reef baseline (Anggadi 2021), as is permitted by UNCLOS (1982, Article 6). Further consideration is needed to assess whether current international law allows a State to retain a baseline on a chart even if there are some changes to the outer low-water line of the reef. Further, many States (including SIDS) which rely on coral reef baselines to support their maritime zones have described the location of the baselines and maritime zones by geographic coordinates. This practice is widespread in the Pacific (Trahanas 2013, Frost et al 2018), and is also seen elsewhere (e.g. Mauritius). The same question arises as to whether a reef baseline defined by coordinates might also be able to be maintained despite changes to the reef itself.

Secondly, does degradation of a coral reef island’s ‘habitability’ necessarily impact the island’s ability to support maritime zones? Habitability is a potential concern because some consider that continuing to ‘sustain human habitation and economic life’ (Article 121(3), UNCLOS 1982) is a necessary precondition for supporting key maritime zones such as the EEZ (South China Sea Arbitration 2016), although this view has been criticised by some legal scholars (Tanaka 2017). The question is whether loss of habitability due to reduced island stability from sediment supply and shoreline erosion or saltwater intrusion can legally remove entitlement to certain maritime zones (Rayfuse 2011). This issue is important to understand because the habitability of many coral reef islands is projected to diminish well before 2100 (Storlazzi et al 2018). But it is legally unclear whether the requirement to assess habitability based on the island’s ‘natural state’ (South China
Sea Arbitration (2016) might mean that any degradation in island habitability resulting from anthropogenic climate change may be disregarded (Kaye 2017, Aurescu and Oral 2020). If this were the case, this could mean that a coral island and associated reef could retain its maritime zones despite changes to their ability to ‘sustain human habitation and economic life’.

Thirdly, once a State has established its maritime zones, including those based on coral reef islands, do they have any obligation to revise those maritime zones because of changes to the reef or island? An increasing number of States, including many SIDS, have made clear their intention to maintain their baselines and maritime zones notwithstanding the effects of SLR (Micronesia 2019, Alliance of Small Island States 2021, Pacific Islands Forum 2021). Since UNCLOS does not contain any express obligation to update baselines and maritime zones once published (Aurescu and Oral 2020), the question is whether this approach to retain baselines and maritime zones will be internationally accepted (Anggadi 2022). If so, this would be a practical means of achieving jurisdictional stability despite changes to the structural integrity of coral islands or associated reef baselines.

5. The future of coral reef islands and associated maritime zones

This review considers the bio-physical processes controlling the structural integrity of coral reefs and associated coral islands in the face of climate change, and implications for legal maritime zones and SIDS. This is relevant as millions of people rely on them for their livelihoods and in the case of SIDS, their Statehood. Securing the long-term health and resilience of coral reefs that support islands is conditional on reducing global climate threats and emissions, improving local management, and investing in restoration and adaption research. The continuing persistence of
coral islands that support maritime zones is not clear, and their status under legal maritime frameworks (i.e. UNCLOS) needs to further consider climate induced changes. Here we identify areas that require urgent attention and further investigation.

The first area relates to defining baseline locations at the outer low-water reef line by geographic coordinates. States should continue to support each other to establish reef baselines, including through collaborative efforts such as the Pacific Maritime Boundaries Project (see, Frost et al 2018, Anggadi 2021). Such projects could use remote sensing approaches (e.g. satellite derived bathymetry) to provide coordinates. Because baselines defined by geographic coordinates give the baseline a precise location, as a practical matter it is possible to maintain those baselines irrespective of changes to the location of the coral island or outer low-water reef line. While early indications are positive, further research is required to fully assess whether States’ increasing legal claims to maintain their established baselines are acceptable to the international community.

The second area deals with issues of island habitability (i.e. sustaining ‘human habitation or economic life’). Research must conduct assessments (e.g. through numerical modelling and eco-morphological approaches) to determine which coral islands may not satisfy this requirement in the future. It is urgent that we understand reef sediment budgets and the contributions from sensitive calcifiers (e.g. foraminifera) so we can understand island stability and habitability to determine the timelines of island evolution with climate change. Since the legal effect of impacts on habitability are still unclear, research on the bio-physical processes that control the structural stability of coral reefs and islands can assist in the pursuit of further clarity in the law.

Further investigation is required to address other scientific knowledge gaps. Greater investment in needed in restoration efforts (e.g. coral farming) and active adaptation research (e.g. ensuring genetic diversity and reef resilience). A comprehensive coral island classification based on remote sensing data (e.g. satellite imagery), geomorphology, calcifying community and global climate models (e.g. SST, SLR, pH, storms) is needed. There is also a need to improve our knowledge of reef-wave interactions (e.g. through field and modelling studies) to better quantify the impacts of future emission scenarios on coral reef and island structural integrity.

We show that understanding the future stability and integrity of coral reefs and their associated islands is important from a scientific, social (e.g. habitability) and legal perspective. Because the legal regime of maritime zones is established on the basis of natural features such as these, their futures are intertwined.

Data availability statement
No new data were created or analysed in this study.

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