Section 4

Subchapter 5C

Atolls and their lagoons and islands

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Key points

- New antecedent karst theory for the origin of atolls and atoll islands as an alternative to Darwin's subsidence theory.
- New concepts on the hydrogeology of atolls and atoll islands.
- Updated perspective on atolls and lagoons and tourism.
- Production of carbonate sands and sediment transport during anomalous storm events and its role in maintaining the sediment supply to atoll islands.
- Increasing alteration of the functioning of critical ecological processes on atolls by global and local stressors.
- Need for conservation measures for atoll ecosystems to be focused on reducing carbon dioxide (CO_2) emissions, enforcing marine protected areas (MPAs), promoting sustainable use, engaging communities and supporting research.

1. Introduction

Atolls are ring-shaped coral reefs encircling lagoons, commonly found in tropical and subtropical seas (see figure I). Atoll islands are morphologically coherent wave-built accumulations of bioclastic sediment located on atoll rims or on patch reefs within atoll lagoons and emergent at all stages of the tide. Distant from continental influence, atolls are usually surrounded by abyssal depths, although their reef crests rise close to mean sea level and enclose lagoons that range from a few meters to 70 m deep (Purdy and Winterer, 2001). At a broader scale, the diameter of an atoll typically spans from a few kilometres to several dozen kilometres. Worldwide, there are some 268 atolls, with a further 171 subtidal atoll reefs with little or no island development (Goldberg, 2016). Lagoons are often euhaline, with ocean water being exchanged through reef passages or by means of indirect mechanisms, but many atolls in the Central Pacific have isolated lagoons that range from hypersaline to brackish or fresh. Atolls serve as habitats of global significance for tropical biodiversity, including seabirds, marine turtles and other keystone island species, while inhabited "atoll nations" serve as home to Indigenous Peoples and cultures (Steibl and others, 2024a,b).

2. Environmental changes since the second *World Ocean Assessment*

Further baseline information on atolls and their lagoons and islands can be found in the supplementary materials[1] and in chapter 7 of the first *World Ocean Assessment* and chapter 7C of the second *Assessment*. According to Darwin's "subsidence theory", atolls form as volcanic islands gradually sink, with coral growth keeping pace, creating a reef-ringed lagoon (Darwin, 1842; Davis, 1928). In contrast, according to the "antecedent karst theory" (Droxler and Jorry, 2021), atolls develop from pre-existing limestone karst topography, with dissolution and erosion shaping the reef structure before submersion. In essence, the emphasis of the former theory is vertical subsidence, while the emphasis of the latter theory is preformed karst landscapes serving as the foundation for atoll formation. "Antecedent karst theory" as an alternative to Darwin's "subsidence theory" is introduced as a new concept in the present *Assessment* that was absent from the previous *Assessments*. An updated perspective is also provided on the hydrogeology of atolls and atoll islands and the impact of tourism on atolls and lagoons. Further novel topics addressed in the present *Assessment* are the vulnerability of atolls and their fauna to sea level and climate change, along with response strategies and the role of ecosystem services, restoration, conservation, mitigation and adaptation.

Unique ecological functioning of atolls

Isolation from continental influence results in the reef ecosystems of atolls functioning differently from those of coastal reefs located on continental shelves. The absence of river discharges and the typical remoteness of atolls limit nutrient availability, making them highly oligotrophic (Hatcher, 1990; Ke and others, 2018). Primary production is thus more dependent on the photosynthesis performed by coral-associated Symbiodiniaceae dinoflagellates. Symbiodiniaceans are hosted intracellularly by corals and dependent primarily on nutrients provided by the host metabolism instead of the surrounding water (Davy and others, 2012). The remoteness of atolls also limits connectivity processes, as atolls have fewer nearby source populations than coastal reefs, making recruitment and population replenishment reliant on self-seeding and long-distance larval transport (Underwood and others, 2012). Likewise, isolation and the lower sediment input amplify the impact of bioerosive processes by such organisms as sponges, bivalves and urchins, which perforate the reef carbonate framework produced by hermatypic corals (Pari and others, 2002). As a result of these processes, the availability of sediment, nutrients and larval propagules on atolls is limited compared with that in coastal areas, making atolls more vulnerable to natural and anthropogenic disturbance.

Atoll vulnerability to anthropogenic stressors, including sea level rise and climate change

Habitability is dependent upon the availability of safe land freshwater and food, as well as access to safe settlements and infrastructure and to sustainable economic activities (Duvat and others, 2017, 2021; Duvat, 2020). Multiple anthropogenic stressors affect atolls as a result of human activities or environmental changes at both the local and the global scale. Local-scale stressors include overfishing, unregulated tourism and coastal development (Knowlton and Jackson, 2008; McMichael and others, 2023). Overfishing is common, as local populations rely heavily on fisheries resources and can quickly deplete fish stocks (Newton and others, 2007; Wolanski and others, 2020). Unregulated tourism often results in trampling and anchoring on the reef, which damages the carbonate reef framework, while

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[1] See https://zenodo.org/records/19262017.

coastal and infrastructure development often results in habitat destruction and reef pollution (Hawkins and Roberts, 1993; Allemand and Osborn, 2019; Ríos and others, 2021; United Nations Environment Programme (UNEP), 2022). Increased waste discharge from residential and industrial activities leads to organic and inorganic contamination, plastic pollution and nutrient enrichment, promoting algal overgrowth and coral mortality across the reef (Sheppard and others, 2020).

Besides local-scale stressors, atolls and reef ecosystems in general are highly vulnerable to the two major global-scale stressors affecting environments worldwide, namely, global warming and ocean acidification, both of which are a consequence of increased CO_2 concentrations in the atmosphere and ocean. Increasing sea surface temperatures and more frequent and intense marine heatwaves are by far the greatest threat to atolls and reef ecosystems. Corals under thermal stress undergo bleaching, which produces extensive coral mortality (Hughes and others, 2020), while ocean acidification greatly intensifies erosive processes in the atoll framework (Hoegh-Gudlberg and others, 2007). In addition, with an increasingly energetic atmosphere, atolls are subject to intense wave action that threatens their structural integrity (McLean and Kench, 2015; Hynes and others, 2025).

Impacts on organisms, functional roles and ecological processes

Global warming, the main threat to reef environments, disrupts coral-dinoflagellate symbiosis in a phenomenon called "bleaching" (Glynn, 1996). Thermal stress triggers the excessive production of reactive oxygen species by dinoflagellates (Lesser, 2006). As an accumulation of reactive oxygen species overwhelms the antioxidant defences of the coral, it leads to cellular damage. Corals eventually expel their symbiotic dinoflagellates and the white calcareous skeleton becomes visible under the translucent tissue. Consequently, the absence of the photosynthetically derived carbon provided by the dinoflagellates leads to an energetic deficit, causing coral mortality (Anthony and others, 2007). Once corals perish, their bare skeleton is subject to erosion, further undermining reef integrity (Braz and others, 2022). Since 2018, numerous atolls worldwide, including those in Hawaii, the Chagos Archipelago, French Polynesia and Maldives, have experienced severe coral cover declines of up to 76% due to bleaching (Sheppard and others, 2020; Speare and others, 2022; Winston and others, 2022). The most vulnerable species are branching corals, especially *Acropora* spp., which play a key role in supporting biodiversity by providing habitat complexity (Richardson and others, 2017).

Ocean acidification is slowly producing its first impacts on coral reefs. Its main consequence is the impairment of the calcification process in corals, giant clams and other calcifying reef organisms. The CO_2 absorbed by the ocean reacts with water to form carbonic acid (H_2CO_3), which dissociates and releases a proton (H^+), thus lowering the pH. This proton binds with carbonate ions (CO_3^{-2}) and reduces its availability, thus inhibiting the production of calcium carbonate ($CaCO_3$) skeletons (Hoegh-Guldberg and others, 2007). This makes corals more susceptible to erosion from waves and boring organisms, ultimately reducing habitat complexity. Recent projections have shown that atolls in the Western and Central Pacific are among the most vulnerable to this process (Duvat and others, 2021).

Overfishing has also had a major impact on the functioning of atolls. One of the main symptoms of overfishing is a reduction in catch per unit effort, which is declining globally in reef environments (Eddy and others, 2021). Keystone species, such as sharks, groupers and parrotfishes, have experienced a significant recent decline on atolls in Belize, Maldives, and Solomon Islands (Hughes and others, 2020; McClanahan and Muthiga, 2020; Skinner and others, 2020). Some of these species play critical roles in maintaining reef resilience; for example, herbivorous parrotfishes consume large amounts of turf algae, which are the main competitors of corals (Holbrook and others, 2016). Parrotfish removal contributes to the occurrence of phase shifts, where reefs transition from a coral-dominated to an algae-dominated state (Hughes and others, 2007). Likewise, the loss of higher trophic levels, such as predators, often leads to trophic cascades. Global and local stressors are thus altering the functioning of critical processes on atolls, including calcification, photosynthesis, competition and trophic interactions.

3. Region-specific changes

Arctic Ocean, North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean, North Sea and Southern Ocean

The Arctic Ocean, North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean, North Sea and Southern Ocean do not have atolls.

South Atlantic Ocean, wider Caribbean, Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden, Persian Gulf, North Pacific Ocean and South Pacific Ocean

Atolls are present across the world's ocean basins at low latitudes, but the vast majority (96%) of them lie in the Indian and Pacific Oceans, which have 56 and 367 atolls, respectively (Goldberg, 2016). Reef provinces are generally divided into three macroregions based on their biogeographical patterns: Indo-Pacific, Caribbean and South Atlantic. Exposure and vulnerability to global environmental change, however, are determined by a combination of biological factors, with contrasting atoll and island physical geomorphologies and degrees of socioeconomic development – from uninhabited and rural to urban islands (Duvat and others, 2017). All climate scenarios project a global increase in the intensity of cyclones and the frequency of intense El Niño/Southern Oscillation and Indian Ocean Dipole events (Intergovernmental Panel on Climate Change (IPCC), 2019) that will affect atolls in all ocean basins. There are important spatial variations in exposure to climate risk, however, with atolls in the Western Pacific subject to a more rapid increase in risk compared with those in the Central Pacific and Indian Oceans (Duvat and others, 2021).

The responses and resilience to these stressors vary significantly among reef provinces (Roff and Mumby, 2012; Duvat and others, 2021). Coral bleaching disparities have been observed, with South Atlantic reefs, which are typically dominated by massive, stress-tolerant corals, experiencing less bleaching than those in the Indo-Pacific and Caribbean (Mies and others, 2020). Rocas Atoll, the only atoll in the South Atlantic, experienced minimal coral mortality despite record-breaking thermal stress in 2019 (Gaspar and others, 2021). In the Indian Ocean, reefs on the remote atolls of the Chagos Archipelago recovered to net accretion within two to six years after mass bleaching episodes associated with El Niño/Southern Oscillation events (Lange and others, 2023). Conversely, the densely populated atolls of Maldives took approximately 15 years to reach a similar degree of recovery and accretion (Carruthers and others, 2024). This underlines the need for a holistic and spatial planning-based approach to improve coral reef recovery on atolls because each one will respond in a unique way.

Increasing seawater temperature and acidification, coupled with rapid rates of sea level rise, may alter the oceanographic dynamics and biological functioning of atolls. This may enhance erosive processes and lead to the inundation of low-lying islands, resulting in multiple territorial and social challenges for island nation communities. Atoll islands are subject to changes in their size and position due to both anthropogenic and natural causes, and one of the most pressing questions is whether they are currently gaining or losing land. A recent study of land area changes in 221 atolls in the Indo-Pacific between 2000 and 2017 showed a net land mass gain (Holdaway and others, 2021). It should be noted, however, that these increases, which are more common on atolls located in the South China Sea and Maldives, resulted mostly from land reclamation rather than natural processes. McLean and Kench (2015), Kench and others (2022) and Kench and others (2024) investigated shoreline change on 244 islands in the past 30 years, during which the sea level rose at an average rate of 3 mm year. Contrary to the prevailing narrative of inundation, erosion and outmigration (Dickinson, 2009; McMichael and others, 2023; Weatherill, 2023; Tierolf and others, 2023), the evidence shows that island area is generally expanding due to sediment accretion.

Critical to the future preservation of atoll islands is the maintenance of sediment supply (Tuck and others, 2021), both in situ through the production of carbonate sands and by sediment transport during anomalous storm events through reef crest-sediment apron pathways. Sediment consolidation and binding are regulated by vegetation and soil development, influenced by rainfall patterns, wind exposure (Steibl and others, 2024a,b) and the aeolian supply of non-carbonate material and guano, which enhance soil productivity (Browning and others, 2023; McTainsh and Strong, 2007; D'Amico and others, 2023) (see figure II).

Rising sea levels will also result in lateral intrusion of saltwater. On islands with a dense human population, this stress is superimposed on salinization from overabstraction of groundwater and aquifer contamination (Ferguson and Gleeson, 2012; Werner and others, 2013; Michael and others, 2017; Sawyer and others, 2016). In some areas, including the western part of the Micronesian group of islands, the effects of sea level rise may be mitigated in part by increased freshwater recharge due to higher rainfall in the coming decades, but islands in other areas will experience increasing drought influenced by natural climatic cycles, such as the El Niño and La Niña phases of the El Niño/Southern Oscillation phenomenon (Der Velde and others, 2006; Bailey and others, 2021). Changes in tidal and wave energy and morphological changes due to coastal erosion during storm surges will also negatively affect the volume of fresh groundwater (Briggs and others, 2021; Stanic and others, 2024).

In addition to a rise in mean sea level, the freshwater lens is vulnerable to salinization due to seawater inundation during extreme storms. Saltwater can infiltrate through the vadose zone, as well as through open boreholes, trenches and karst shafts, which provide direct access to the aquifer; saltwater can continue to infiltrate after the storm surge, sourced from seawater ponded in surface depressions (Holding and Allen, 2015). According to numerical simulations, the degree of aquifer salinization due to overwash is largely determined by vadose zone thickness, but it is the recharge rate that determines recovery times (Holding and Allen, 2015). These range from 1 year to 19 years after a single overwash event. The non-linear interactions between wave-driven flooding and sea level rise will lead, by the middle of the twenty-first century, to annual overwash of most atoll islands, causing widespread erosion and loss of potable water (Storlazzi and others, 2018). Combined with the effects of tidal fluctuations on the mixing of an increasingly thin freshwater lens with underlying seawater, inundation will detrimentally affect the ecological sustainability, agricultural productivity and human habitation of atoll islands.

Another critical issue is the appeal of atoll islands to tourists, which arises in part from the perception of lagoons as pristine and tranquil destinations. For instance, surveys conducted in Maldives revealed that 65% of tourists consider environmental quality a critical factor in their choice of lagoon destinations

(UNEP, 2022). Environmental degradation and overcrowding can tarnish this image, diminishing atoll islands' attractiveness to future visitors. Maintaining a positive destination image requires balancing the development of tourism with conservation efforts to ensure that lagoons retain their natural beauty and ecological health. Nonetheless, lagoons remain highly attractive destinations, often creating a trade-off between preservation and visitation.

Tourism-related activities commonly exert pressure on lagoon ecosystems. The development of infrastructure, such as hotels, restaurants and marinas, can lead to habitat destruction and fragmentation. For instance, the construction of coastal resorts often involves dredging and land reclamation, which disrupt lagoon hydrodynamics and sedimentation patterns (Pinto and others, 2020). Data indicate that over 50% of mangroves in some lagoon regions have been lost to tourism infrastructure (Gómez-Vega and Herrero-Prieto, 2018). Furthermore, direct tourism activities, such as diving and snorkelling, as well as boat anchoring and trampling, cause additional erosion and also interfere with trophic interactions from the lagoon to the reef (Diedrich, 2007; Renfro and Chadwick, 2017). Pollution is another critical concern. An influx of tourists can result in elevated levels of solid waste and wastewater, often exceeding the natural assimilative capacity of lagoons. This can lead to eutrophication, characterized by algal blooms, oxygen depletion and fish kills (Martínez and others, 2019).

While tourism can boost local economies by creating jobs and generating revenue, it can also lead to sociocultural changes (Everett and others, 2018). The commercialization of lagoon areas may marginalize local communities, who often depend on these ecosystems for traditional livelihoods, such as fishing and aquaculture. Furthermore, overcrowding during peak tourist seasons can strain local infrastructure and reduce quality of life for residents.

4. Key remaining knowledge and capacity gaps and new gaps

Response strategies and the role of ecosystem services

Although reducing greenhouse gas emissions is essential, the magnitude of physical and chemical changes already embedded in climate and ocean systems indicates that the proper implementation of adaptation strategies to enhance resilience is crucial to ensuring the survival of atoll islands. Anomalous storm events can have a positive effect on the sediment balance of an atoll island, where shoreward sediment transport leads to coastal accretion, and bleaching events can result in periods of enhanced sediment generation (Perry and others, 2020, 2023). It is more often the case, however, that storm-driven coastal erosion and sediment export have a negative (and potentially catastrophic) effect (Storlazzi and others, 2018; Georgiou and others, 2024). Superimposed on these effects are the negative environmental and social impacts of tourism, which must be balanced against the economic benefits that it can bring. Adaptation strategies, including the establishment of effective MPAs and no-take zones and the promotion of ecotourism practices that minimize environmental footprints (UNEP, 2022), should be adopted.

Efforts are under way to control seawater intrusion along some continental margins through the construction of engineered barriers, such as cut-off walls and subsurface dams, which physically limit the hydraulic connectivity between the aquifer beneath the island and the saline aquifer offshore (Chang and others, 2022; Zheng and others, 2022; Fang and others, 2023). This is likely an impractical solution for most low-lying atoll islands, but comparable impoundment of freshwater within a Pleistocene karstified island aquifer has been shown to result from a coastal mantle of lower-permeability Holocene grainstone (Whitaker and Smart, 2004). This highlights the risks of construction and dredging that threaten the integrity of such natural barriers, especially for islands growing by lateral accretion. The focus should be directed towards developing approaches to minimize the effects of washover on the freshwater lens.

The effectiveness of responses to climate-driven challenges on atoll water supply depends on abundance and demand. Traditional rainwater storage tanks can support low demand but quickly become depleted, especially during droughts (Wallace and Bailey, 2015). Enhanced aquifer recharge and underground storage schemes are generally preferable to more high-cost options, such as seawater desalination, especially for smaller communities, but remain vulnerable to seawater inundation and contamination. In contrast, atoll island cities and tourist developments can more readily benefit from technological advances allowing potable water to be supplied at an increasingly low cost (Shokri and Fard, 2023).

While climatic factors cannot be controlled locally, the retention of sediment on islands can be supported through ecological interventions, such as reforestation, forest diversification and the removal of invasive species, as well as appropriate management of agricultural activity and human infrastructure engineering (Duvat and others, 2017; Steibl and others, 2024a,b). Mangrove swamps, seagrass beds and other coastal ecosystems have high organic carbon storage capacity in biomass and soil (Macreadie and others, 2021). There is a need to preserve and to enhance this "blue carbon" storage, as well as to restore biodiversity and the other benefits of the services provided by coastal and shallow marine ecosystems (Twomey and others, 2024; Hagger and others, 2024). Nature-based solutions are more sustainable and widely applicable to the diverse range of challenges facing non-urbanized atolls. It has been strongly suggested that the key to unlocking these solutions is linking ecosystem-based interventions that span marine and terrestrial zones with processes of sediment production and accretion of atoll islands (Steibl and others, 2024a,b). The success of such a programme depends heavily on prior planning and design, effective monitoring, evaluation and reporting and post-implementation maintenance (Standards Reference Group (SERA), 2018). On urbanized atolls, such as Malé in Maldives and Majuro in the Marshall Islands, however, the timescales involved render nature-based solutions largely unviable. The raising of atolls and the construction of coastal defences are the types of intervention being implemented at present in such capitals as Funafuti and Majuro (Esteban and others, 2019). Moreover, adaptation by communities with limited means can be successful, using a combination of creativity, low-level construction techniques and some nature-based solutions (Jamero and others, 2017, 2018; Narayan and others, 2020).

One of the largest sources of uncertainty in monitoring, modelling and managing such low-lying islands is the limited availability of accurate high-resolution bathymetric and topography data (Pacheco and others, 2015) with which to examine changes in coastal morphology over a larger spatial scale and at higher temporal frequency (Hamylton 2017; Vitousek and others, 2023). Satellite remote sensing, airborne light detection and ranging, and drone photogrammetry should be employed to obtain high-resolution bathymetric and topographic data, assess vegetation cover and analyse recharge and evapotranspiration on atoll islands (Andréfouët and Paul, 2023; Hamylton and others, 2020; Casella and others, 2017; Collin and others, 2018).

More attention has recently been focused on the resilience of atoll freshwater lenses to natural and demographic changes (Ketabchi and others, 2016). Notwithstanding the resource-intensive nature of hydrogeological investigations of atoll islands, there are a few long-established monitoring networks, such as those on Bonriki in Kiribati and the Cocos (Keeling) Islands. More high-quality investigations that encompass the full range of island sizes and environmental conditions are needed for the purposes of improving groundwater management and mitigation strategies for individual atoll islands (Werner and others, 2017; Sengupta and others, 2022). Even in well-studied atoll islands, scientists' understanding of the flow paths within the lens and mixing zone is surprisingly poor. In addition, a better understanding of the effects of tides in karstified island aquifers is needed, not least to reconcile discrepancies between mixing zones simulated using numerical models and those measured in the field (Martin and others, 2012; Ghassemi and others, 2000; Collignon and others, 2019). Groundwater resources on atoll islands are particularly vulnerable due to a combination of high-permeability soils and a thin vadose zone, but relatively little attention has been paid to biological and chemical contamination aside from aquifer salinization.

Numerical models can be used to simulate a wide range of physical, chemical and biological processes, develop a quantitative understanding of the interactions between different processes and predict responses to changes in environmental conditions and management practices. Two challenges common to computer simulations of any system are difficulties in model parameterization and a paucity of field data for validation (Splinter and Coco, 2021; Twomey and others, 2024). Moreover, the quantification of model uncertainty requires a suite of simulations to be run (Liu and others, 2022; Herrera and others, 2022). The potential use of the output as training data sets for machine learning algorithms (Reichstein and others, 2019; Papacharalampous and Tyralis, 2022) could be a powerful tool with which to address these challenges. It is critical to match modelling methods to project objectives, budget and available data. Relatively simple algebraic models can be rapid to implement. For example, Bailey and others (2021, 2022) and Sengupta and others (2021) calculate the future groundwater resources of 91 atoll islands in the Federated States of Micronesia from mean annual recharge, island width, Holocene thickness and hydraulic conductivity. As a final point, it should be noted that, although quantitative models are essential to describe risks and reduce uncertainty in resource management and climate change response projects, conceptual models may suffice for project managers to make informed decisions (Larsen and others, 2016; Twomey and others, 2024).

Restoration, conservation, mitigation and adaptation

The health of active coral reefs along atoll rims is one of the key properties that may mitigate the adverse effects of sea level rise and increased tempestuousness. Reef crests act as natural breakwaters and dissipate incoming wave energy through wave breaking and bottom friction (Carlot and others, 2023; Huang and others, 2024), providing the ecosystem service of coastal protection. Rates of sea level rise exceeding those of coral growth and reef crest accretion have a negative effect on the wave dissipation exerted by coral reefs (Baldock and others, 2014; Quartaet and others, 2015; Toth, 2023). Rising sea levels may also increase seawater circulation across the reef, moderating diurnal temperature extremes (and thus coral bleaching), as well as affecting lagoon flushing times, calcification rates and many other physically linked biological processes that affect the health and resilience of coral reef communities and those within the lagoon (Gruber and others, 2019; Lowe and others, 2016).

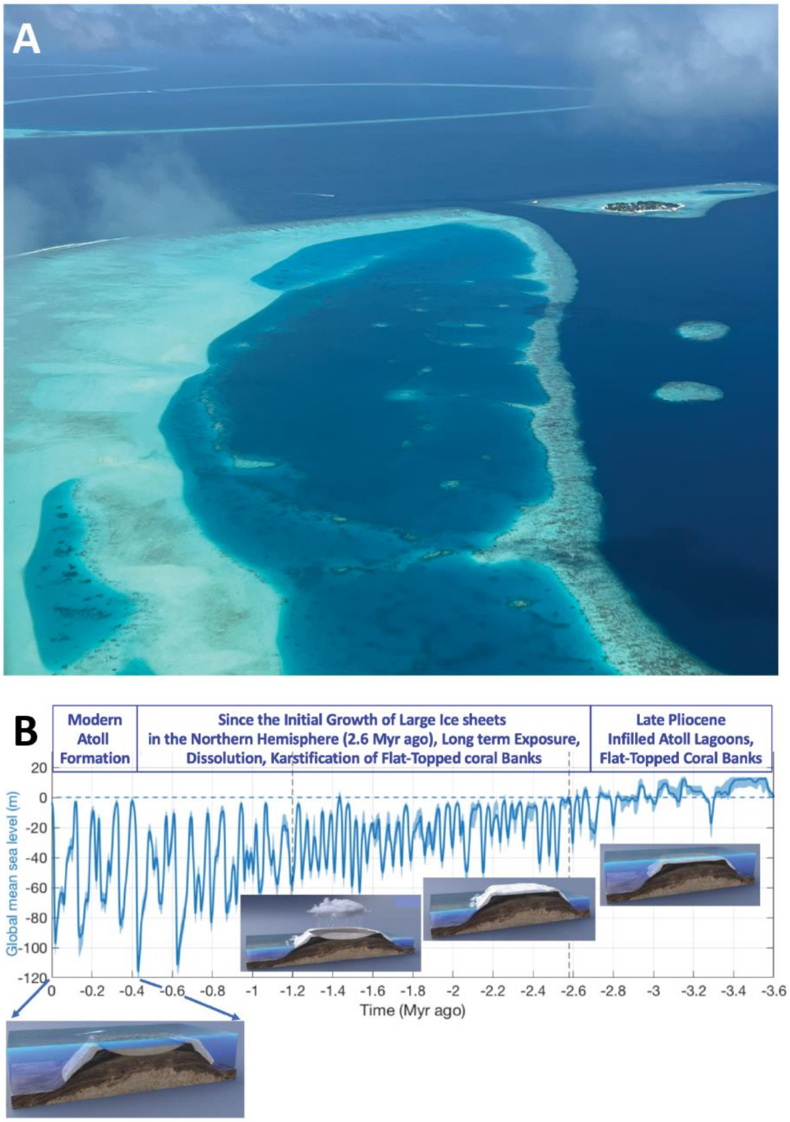
Many conservation measures have been proposed for the protection of atolls, ranging from passive to active initiatives. Active coral restoration projects have been developed around the world, but have so far failed to restore species or ecosystem functioning at a relevant scale. This is largely because the restoration performed is often undone by bleaching episodes associated with heatwaves and global warming (Hughes and Grumbine, 2023). This has caused some Governments to refrain from funding any further active restoration practices. It should be noted, however, that creating MPAs and neutralizing local-scale impacts (such as pollution, unregulated fisheries and tourism) have occasionally proved effective in reducing global-scale impacts (Graham and others, 2008). Nevertheless, MPAs must be adequately designed, anticipating local oceanographic and biological factors, such as larval and other types of connectivity, which is critical for sustaining genetic and species diversity on atolls, which are often remote.

As with all coastal communities, the adoption of hazard mitigation and adaptation strategies by atoll nations is critically contingent on the communication of impacts to policymakers and users. Communities are more receptive to such messaging when sea level and climate metrics are explained in terms of local-scale societal impacts, such as the risk to hospitals, airports and similar facilities posed by both more frequent and rarer extreme sea level events (Rasmussen and others, 2022). The survival of atoll nations, with the exception of urbanized atolls, depends on the development of cross-disciplinary collaboration to protect and restore exchanges of sediment, water and nutrients between atoll islands, lagoons and coral reefs. This does not apply to urbanized and densely populated atolls because several engineering solutions are available (Yamamoto and Esteban, 2017).

In this context, given the ecological uniqueness and vulnerability of atoll ecosystems, conservation measures must be tailored to their specific needs. Such measures include: (a) reducing CO_2 emissions to halt global warming and ocean acidification; (b) establishing and enforcing MPAs to limit local stressors; (c) implementing sustainable use programmes; (d) engaging local communities in conservation through education, awareness and sustainable livelihoods; and (e) supporting research and long-term monitoring programmes to address knowledge gaps and evaluate conservation efforts.

Figure I

Vattaru Atoll, Maldives (A) and improved antecedent karst theory for modern atoll origin (B)

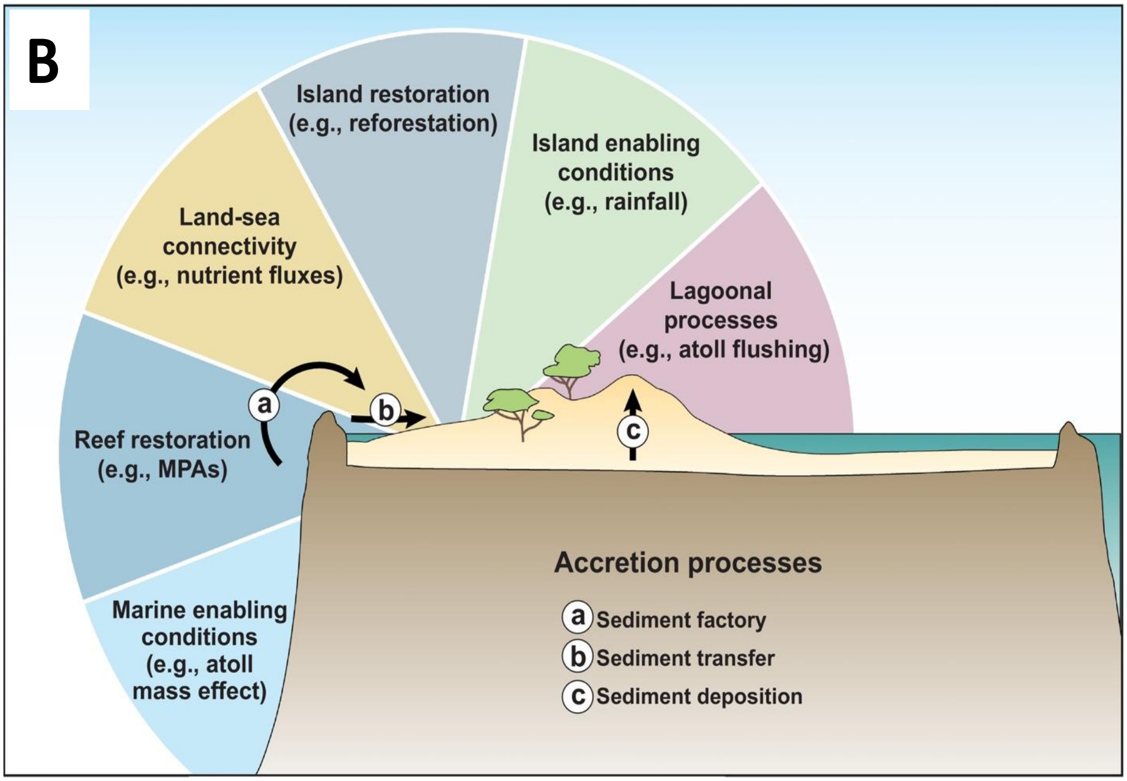


Source: André W. Droxler (A) and https://cp.copernicus.org/articles/17/361/2021 and www.youtube.com/watch?v=J950wu7tsmw (B).

Note: A. View towards the south-west, on a flight crossing the southern rim of Felidhe Atoll on 30 August 2023. Vattaru Atoll appears in the background (shown in light blue) with a coralgal rim fully enclosing its lagoon. In the foreground, the southern rim of Felidhe Atoll is displayed, consisting of a small atoll, referred to as Faro; Rakeedho Island formed behind the reef crest. B. The graph shows sea level fluctuations over the past 3.6 million years (modified from Berends and others, 2021); this framework can be used to explain the origin of modern atolls through the newly published improved antecedent karst theory (Droxler and Jorry, 2021). A series of schematic representations (from a video produced by IFREMER (the French Research Institute for Exploitation of the Sea) display the evolution of a Late Pliocene flat-topped bank, through long-term exposure during the Quaternary, forming a karstic morphology characterized by a central depression bounded by a raised rim, which becomes the templet preferentially colonized by coral reefs during successive deglacial and highstand refloodings in the past 450,000 years.

Figure II

Identification of biogeosphere links critical for atoll island protection and restoration



Source: Steibl and others, 2024b.

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