Coral atolls face drowning threat from sea level rise

What The Science Says:
Thousands of coral atolls have "drowned" in the past when they were unable to grow fast enough to maintain a presence at sea level

Climate Myth: Coral atolls grow as sea levels rise

People living on coral atolls have long been the 'poster child' of global warming, and the threat posed by rising sea levels. Some emotive reporting in the media (and rightly so) tend to give the impression that the atolls should have been under water by now. Clearly this isn't the case, as Webb & Kench (2010) show, the sea level rises experienced in the South Pacific so far (2mm per year) have had little effect on the loss of land area on the atolls. Despite some people being confused regarding the timescale involved, the threat is still very real.

The ocean is, in fact, littered with thousands of former coral reefs and atolls which 'drowned' when they failed to grow fast enough to match sea level. Being generally less than 3 metres above sea level coral atolls are particularly vulnerable to rising seas. People living on coral atolls in the Pacific will be displaced from their homelands in the coming decades once sea level rises above the solid reef foundations which formed during a temporary regional sea level highstand 4000 to 2000 years ago. When this happens, the formerly stable atolls, will be subject to erosion by waves, long before the atolls are completely submerged.

Coral atoll formation

Coral reefs occupy tropical and sub-tropical waters and accumulate as generations of coral build upon the "bones of their ancestors". Given the right conditions coral are able grow fast enough to keep pace with moderate rates of sea level rise. So what appears to be solid rock formed by the Earth's geological processes, is in fact the result of biological activity over many years.

Figure 1 - coral formation on the uplifted atoll of Niue. Photo courtesy of Wikimedia Commons.

In the mid 19th century, after voyaging throughout the Pacific, Charles Darwin demonstrated remarkable insight by putting forth the idea that coral atolls are the remnants of submerged ocean volcanoes (Darwin 1842). He envisioned that, as volcanic activity ceased and the volcano slowly submerged beneath the sea, coral were able to grow on its shores, keeping pace with the subsidence rate and therefore able to maintain a presence at sea level. At the time however, Darwin was unaware of the huge changes in sea level which accompanied the Earths transition in and out of the Quaternary ice ages, so the process is more complex than he realized.

We now know that as the planet cooled at the onset of each ice age, more and more of the Earth's water became locked up in the growing ice sheets. At the last glacial maximum, sea level fell over 120 metres lower than modern sea level. This left coral high and dry and their remains were exposed to chemical weathering by carbonic acid in a process known as karstification. It is this weathering process which is responsible for the bowl-like shape, which many coral reefs take on (Purdy & Winterer 2001).

Core samples drilled deep from coral atolls (Royal Society of London 1904, Ladd et al. 1953) show that Darwin was correct. Atolls consist of old coral reef (limestone) sitting on top of a volcanic rock base. Often the reef limestone is hundreds of metres thick, consisting of layers of reef growth that have built up over many millions of years. During the ice age cycles the atoll tops have been repeatedly submerged and exposed as sea level fluctuated up and down (Purdy 1974). While exposed to the air the atoll tops have been eroded down, and when sea level rose again during the interglacials new coral reef has reclaimed the atoll summit. The top 10 -15 metres of many atolls represent the "recent" growth during the current interglacial, the Holocene. So rather than a continual process, as Darwin originally proposed, coral atoll formation has been a rather stop-start affair.

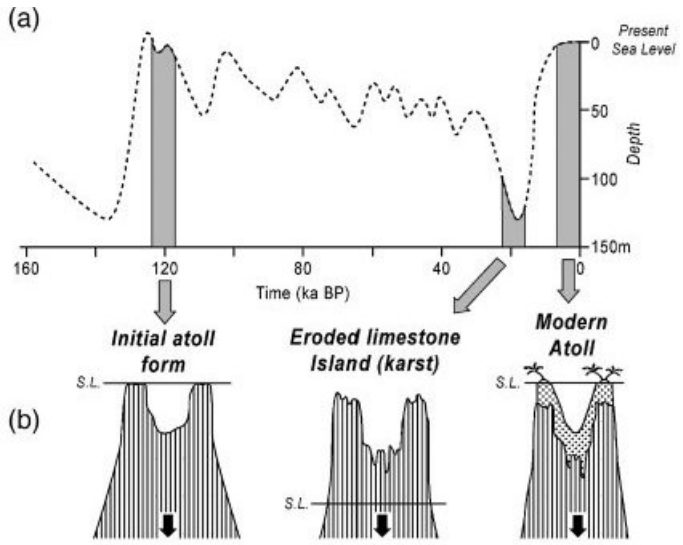

Figure 2. Schematic of atoll history through ice age sea level fluctuation. a) sea level thousands of years before & up to present. b) Atoll form relative to sea level. From Woodroffe 2008.

The Darwin Point and Guyots

A Darwin Point defines the threshold at which a coral reef "drowns". A point where, changing environmental conditions means the reef cannot grow fast enough to keep in touch with the sea surface and therefore receive enough sunlight to grow (Grigg 1982). It therefore effectively drowns and dies. Guyots are flat-topped seamounts deep below the sea surface. Thousands of guyots are spread throughout the Pacific. These were once coral atolls, but "drowned" when they passed the Darwin Point.

Because coral reefs flourish in a narrow range of environmental conditions, coral growth can slow down when waters become too hot, too cool or too acidified (Flood 2001, Scheibner & Speijer 2008). The Emperor seamounts in the Hawaiian Island chain are a case in point. These volcanic islands sit on a continental plate which has gradually drifted northwest into cooler waters over the timespan of tens of millions of years. As the northernmost atolls passed the Darwin Point they "drowned". This occurred in a sequential fashion as each atoll passed the threshold. Kure atoll, is the next in the chain destined for submersion, as its coral reef growth has almost dropped to zero (Grigg 2008).

There is also evidence that coral atolls drowned during the Cretaceous period (145-65 million years ago) from coral bleaching, (Wilson et al. 1997, Jenkyns & Wilson 1999) as the atolls migrated through the very warm water at the equator (Pearson et al. 2001). Ocean anoxia may have also played a part (Wilson & Norris 2001).

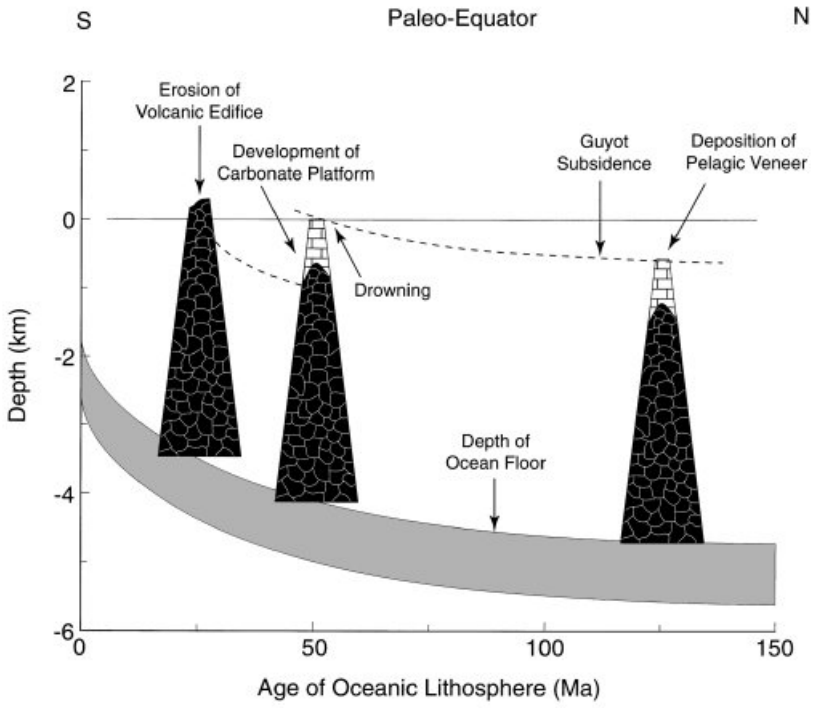

Figure 3. North Pacific guyot drowning sequence over 150 million year period. Volcanic eruption breaches the sea surface, followed by erosion and subsidence. If conditions permit, coral reef growth accumulates and matches rate of subsidence. Nearing the equatorial "hot zone" growth declines and the reef drowns. Ultimately debris builds up on the submerged atoll top. From Jenkyns & Wilson (1999).

Although the continued existence of some coral atolls in proximity to guyots implies some sort of paradox, it should be noted that many current atolls have not been drilled down the many hundreds of metres to the underlying volcanic base. One that has, Anewetak Atoll in the Marshall Islands, (formerly Enewetak) reveals it was still a volcano above the sea surface, at the time neighbouring atolls drowned (Wilson et al. 1997).

Perhaps one other point to address, is the difference in shape between guyots (flat-topped) versus coral atoll (bowl or saucer-like). They are the result of slightly different processes. The guyots are coral atolls which formed and submerged in Earth's warmer periods, prior to the beginning of the ice age sea level fluctuations. Therefore they were never exposed to chemical weathering and the forces causing the bowl-like formation. The ancient reef interior eventually became filled with debris as wave action eroded the outer reef. Modern coral atolls by comparison, have only emerged during the last few thousands years or so, and what we now see is a "snap-shot" in time of an ongoing process (Purdy & Gischler 2005).

Holocene Reef Growth

Coral reef growth during the Holocene, like that of ancient reefs, also has a complicated history. Many reefs around the world show evidence of back-stepping, a point where the reef is unable to keep up with sea level and drowns, but new coral is able to re-establish in shallower water closer to shore. Many regions also harbour relict reefs which have drowned during the Holocene. One vast relict complex exists in deeper water off the Great Barrier Reef. All of which is suggestive of rapid jumps in sea level rise, probably from the collapse of the large glacial lakes on the gigantic Northern Hemisphere ice sheets as they disintegrated (Blanchon & Shaw 1995). The full picture, yet to be fully resolved, may be more convoluted.

Pacific Sea level highstand in the Holocene

At around eight to nine thousand years ago, sea level caught up with the tops of the eroded atolls and new Holocene reef growth began to be cemented over the older reef foundations. Sea level reached a highstand in the Pacific between 4000-2000 years ago (Pirazzoli et al. 1987, Dickinson 2003, Woodroffe & McLean 1998). There is also evidence of a highstand in the Indian Ocean at the Maldives (Kench et al. 2008). Coral reef tops grew to this higher sea level but were exposed once local sea level fell again, through ocean siphoning (Mitrovica & Milne 2002).

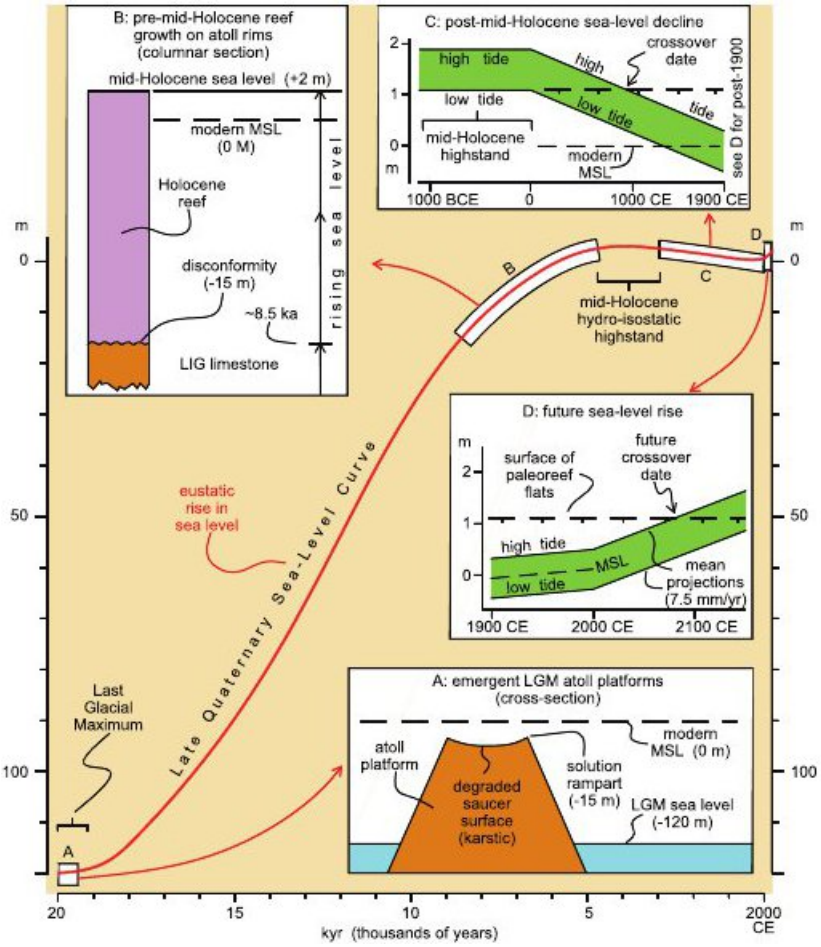

Figure 4. Pacific atoll formation during the Holocene. a) Old atoll form relative to sea level approx 20,000 years before present. b) Sea level rises above old reef and new growth begins reaching point above modern day sea level. c) Sea level declines, leaving reef flat exposed above sea level. d) Sea level begins rising. Reef flat will be over-topped mid to late 21st century

This process meant that, unlike sand cays where debris and sediment is constantly shifting (Flood 1986, Flood & Heatwole 1986) coral atolls had solid foundations above sea level upon which organic matter could accumulate. Excluding major storms these foundations made the atolls resistant to wave damage, and therefore stable over the last few thousand years.

Dating of human artifacts at archaeological sites shows Pacific atolls have not been inhabited for more than 1000 to 1500 years (Dickinson 2009), which is consistent with the history of Holocene atoll formation.

The end of atoll nations

Now that global sea level is rising once more the solid foundations (reef flats) which underpin the stable Pacific atolls, will be overtopped by the sea at some point. Many of these are 0.5 to 1 metre above local high tide. Submerging these solid foundations will lead to the atolls being vulnerable to wave damage. Erosion will begin to sweep away the rubble, sediment and thin soils, making them uninhabitable at some point in the future. Dickinson (2009) has constructed a table of estimated crossover dates for Pacific atolls. These are dates, based on projected rates of sea level rise, where the solid reef foundations are over-topped. Generally these cross-over dates occur mid 21st century at the earliest.

TABLE 1. INFERRED CROSSOVER DATES FOR PACIFIC ATOLL CLUSTERS*

Atoll cluster†	highstand magnitude‡ (m)	highstand termination# (BCE or CE)	tidal range (m)	past crossover date** (CE)	earliest future crossover date†† (CE)	latest future crossover date‡‡ (CE)
western Caroline Islands§§	1.6	100 CE	1.2	400	2050	2100
central Caroline Islands	1.2	100 BCE	0.6	500	2060	2120
eastern Caroline Islands	1.4	200 BCE	0.9	600	2050	2100
Marshall Islands	2.4	600 BCE	1.6	700	2080	2160
Kiribati-Tungaru chain	2.2	300 BCE	1.5	1000	2070	2140
Tuvalu	2.3	200 BCE	1.6	1100	2070	2140
Tokelau¶¶	1.8	100 BCE	1.0	1000	2080	2160
Phoenix Islands##	1.7	100 BCE	1.0	900	2070	2140
northern Cook Islands	1.1	400 CE	0.6	900	2050	2100
Line Islands (Kiritimati)	0.9	300 CE	0.4	800	2050	2100
northern Tuamotu Archipelago	1.0	500 CE	0.3	900	2070	2140
Society Islands (Tupai)	1.0	100 BCE	0.3	500	2070	2140
southern Tuamotu Archipelago	1.2	600 CE	0.4	900	2080	2160
Gambier Archipelago (Temoe)	1.5	300 CE	0.7	900	2070	2140
Cook-Austral chain (Aitutaki)	1.3	200 BCE	0.8	800	2050	2100

Figure 5 - Crossover dates for Pacific atoll clusters. BCE = BC on modern Christian calendar and CE=AD on Christian calendar. Columns from left-to-right show 1. height of sea level highstand, 2. century highstand ended, 3. tidal range, 4. date declining high tide fell below reef flat. 5. Estimated earliest date rising high tide over-tops reef flat. 6. Latest date rising high tide over-tops reef flat.

Homeless

As we've seen, coral reefs aren't always capable of keeping pace with sea level rise. To do so they need environmental conditions to be within their "goldilocks zone", move outside that and they are liable to drown. It just so happens that global warming is in the throes of doing that very thing, ocean acidification and coral bleaching will severely curtail or even stop reef growth completely (Silvermann et al. 2009).

But more significantly, a regional sea level highstand thousands of years ago formed the stable foundations upon which the soils and vegetation developed. Even if the Pacific atoll coral reefs were able to keep pace with future sea level rise, it won't stop the sea rising above the old reef flats and exposing the atolls to persistent wave attack.

So, although coral atolls may grow as sea level rises, this hasn't always been the case in the past, and won't be the case in the future. Atoll islanders may be hanging in there right now but eventually global warming, and the rising seas, will make them homeless.

This rebuttal was updated by Judith Matz in September 2021 to replace broken links. The updates are a result of our call for help published in May 2021.

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