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PACIFIC MARINE CLIMATE CHANGE REPORT CARD
Science Review 2018: *pp* 31-42

Effects of Climate Change on Ocean Acidification Relevant to the Pacific Islands

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EXECUTIVE SUMMARY

Ocean acidification has the potential to significantly impact Pacific Island ecosystems and the ecosystem services they provide. There is compelling evidence that the ocean has become more acidic in response to rising atmospheric CO_2 levels. As atmospheric CO_2 levels continue to rise the ocean will increasingly become more acidic, and these changes are likely to persist for hundreds to thousands of years. The rate and magnitude of these changes will be directly proportional to the future carbon emission pathway followed. While a low carbon emissions pathway will clearly limit the impacts of ocean acidification, a high carbon emission pathway will lead to conditions that will threaten the long-term viability of important marine ecosystems, such as coral reefs. In the future, increased confidence in projected changes will come through a better understanding of how the large-scale changes are modulated by processes at the island scale. This will be achieved through a combination of sustained long-term measurements and higher-resolution modelling. There is also critical need to understand the impact of multiple environmental stressors, as future ocean acidification will be accompanied by ocean warming and other environmental consequences (e.g. invasive species). Finally, implementation of a viable emission pathway is urgently needed to underpin the development of sustainable adaption and resilience options, and to explore potential engineering and adaptation solutions that may be required to offset long-term ocean acidification changes.

Introduction

Atmospheric carbon dioxide (CO_2) concentrations continue to rise as a result of human activities such as fossil fuel usage and land use change. The ocean plays a critical role in slowing the rate of climate change taking up about 30% of the annual anthropogenic emissions (Le Quere *et al*. 2016). This in turn leads to changes in ocean chemistry (Box 1) that have the potential to significantly impact the marine ecosystem including calcification, fecundity, growth and physiology, species composition and distributions, food web structure and nutrient availability (Doney *et al*. 2012, Dore *et al*. 2009, Fabry *et al*. 2008, Iglesias-Rodriguez *et al*. 2008, Munday *et al*. 2010, Munday *et al*. 2009).

This poses significant threats to the diversity, productivity and overall health of marine environment, and the ecosystem services it provides such as food security, coastal protection and economic development (Johnson, Bell and Sen Gupta 2016).

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What is Already Happening?

Globally since the pre-industrial era (~1850) there has been a minimum 26% increase in acidity in the global ocean (Doney *et al*. 2009, Cao and Caldeira 2008, Raven *et al*. 2005). Over the same period, the Equatorial Pacific surface ocean aragonite saturation state is estimated to have fallen from about 4.5 to 3.8 (Feely, Doney and Cooley 2009), and on the Great Barrier Reef it is estimated that this increase has led to a 7% decrease in coral calcification rate (Albright *et al*. 2016).

Box 1: Carbonate Chemistry and Ocean Acidification

As carbon dioxide (CO_2) enters the ocean, it reacts with water to form carbonic acid, which subsequently dissociates, leading to an increase in Hydrogen ion concentration [H^+] causing an increase in acidity and a corresponding decrease in pH (the negative logarithm of [H^+]). This in turn leads to a shift in the forms in which dissolved inorganic carbon is stored in the ocean (see below). As atmospheric carbon dioxide levels increase, carbonate ions and their corresponding saturation decrease whereas increases occur in bicarbonate and aqueous CO_2. These changes in dissolved inorganic carbon are collectively known as ocean acidification (Caldeira and Wickett 2003).

$$CO_{2atm} + H_2O <-> CO_{2aq} + HCO_3- + CO_3^{2-}$$

Ocean acidification is the unavoidable consequence of rising atmospheric CO_2 levels, and even if emissions were to cease, the changes in the ocean chemistry that have occurred would take hundreds to thousands of years to be reversed (Frolicher and Joos 2010). For a more comprehensive description of seawater carbonate chemistry and the changes that have occurred see Zeebe (2012).

These large-scale changes are consistent with time-series observations collected over recent decades (Bates *et al*. 2014). While there are no well-established long-term ocean acidification time-series in the Equatorial Pacific, these do exist at Station ALOHA near Hawaii (Figure 1; (Dore *et al*. 2009)) and in can significantly modulate ocean acidification (Shaw *et al*. 2013). Future measurements at the local scale within the Pacific Islands are urgently needed to translate how the large-scale projected changes will be expressed within Pacific Islands and inform local adaption and resilience planning.Southern New Zealand (Munida; Bates *et al*. 2014). These observations show the increasing atmospheric CO_2 concentration, and the concomitant increase in ocean carbon. Associated with these changes is a monotonic decrease in pH and aragonite saturation state. More recent analysis of these observations confirms that these changes lay well outside the range of natural variability (Sutton *et al*. 2016). Similar decreases in pH and aragonite saturation state changes have been observed by repeat research voyages in all ocean basins (Feely *et al*. 2012). Synthesis of these observations highlights that these changes did not just occur in the surface ocean, but through the entire upper ocean.

Current estimates of the mean value of pH and aragonite saturation state from oceanographic measurements are shown in Figure 2 based on the recent compilation of global observations (GLODAP_V2, Lauvset *et al*. 2016). The values of aragonite saturation state and pH increase across the tropical Pacific from west to east consistent with higher CO_2 waters being upwelling in the eastern equatorial Pacific (Feely *et al*. 1999). At present, we see that most of the Equatorial Pacific experiences conditions that are marginal-to-good for coral reef health (Box 2). As the pH and aragonite saturation state continue to fall, in response to rising atmospheric CO_2 the reefs in Central Equatorial Pacific will be impacted more severely.

The long-term changes in ocean acidification in the Equatorial Pacific are also associated with large interannual variability. This variability is driven by changes in atmospheric CO_2 growth rate, and ocean uptake of CO_2, and the El Niño-Southern Oscillation (ENSO) (Sutton *et al*. 2014, McPhaden, Zebiak and Glantz 2006). ENSO influences the strength of upwelling in the Eastern and Central Pacific thereby impacting the ocean carbon content of the upper ocean. Ocean acidification appears to increase more rapidly under El Niño than La Niña conditions (Sutton *et al*. 2014). However, there is little consensus on the projected response of ENSO with climate change (Guilyardi *et al*. 2009), and so how this may influence future rates of ocean acidification remains unknown.

While there have been significant efforts to increase observational efforts in the Pacific Islands e.g. through the Global Ocean Acidification Observing Network (GOA-ON; http://goa-on.org), at present there are very few ongoing measurements at the local scale to document how ocean pH and aragonite saturation state are changing at the island scale. Studies at the island scale from other regions show local processes

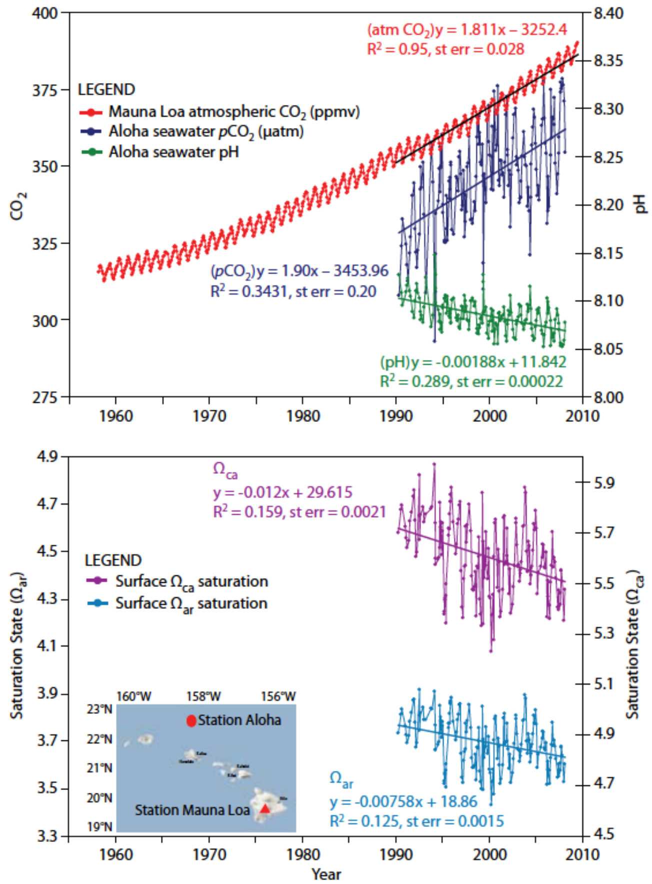


Figure 1. (Top) Time series of atmospheric CO_2 at Mauna Loa (ppmv) and surface ocean pH and pCO_2 (µatm) at Ocean Station Aloha in the subtropical North Pacific (see inset map). (Bottom) Calcite and aragonite saturation state data for surface waters. Reproduced with permission from Feely, Doney and Cooley (2009)

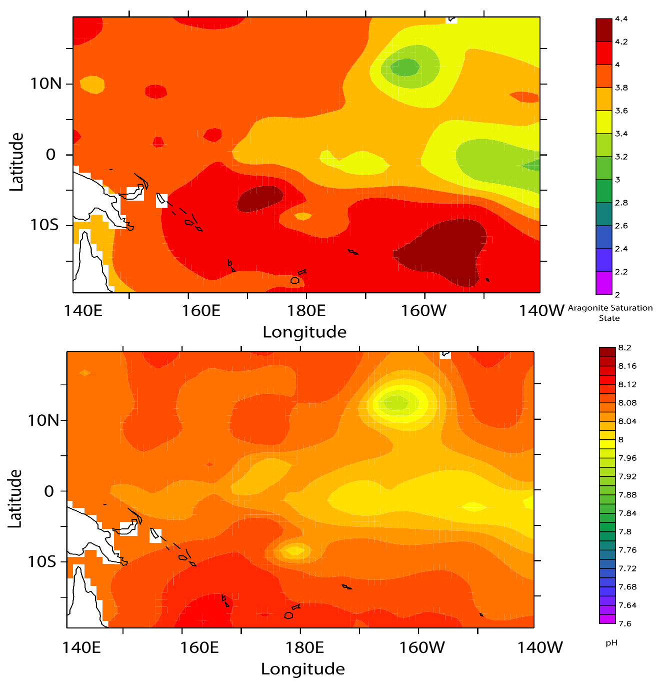


Figure 2. Maps of aragonite saturation state and pH for the Equatorial Pacific based on repeat hydrographic sections, referenced to the year 2002 (from GLODAP_V2).

What Could Happen?

Projections show that the changes in ocean pH and aragonite saturation state are proportional to the change in atmospheric CO_2 and the higher our

Box 2: Thresholds for coral reefs

Many thresholds for coral reef health have been proposed. In reality, these thresholds represent the relationship between calcification rate and dissolution rate. While aragonite saturation state strongly influences calcification, it is also a function of a number of environmental factors, such as freshwater input, ocean temperature, salinity, pressure e.g. (Mongin *et al*. 2016b) as well as individual coral species (Kuffner *et al*. 2008). Dissolution rates are dependent on a number of poorly quantified dissolution processes (Eyre, Andersson and Cyronak 2014, Silverman *et al*. 2009, Andersson and Gledhill 2013). When the dissolution rate exceeds the coral calcification rate, the long term viability of the coral and the ecosystems they support start to decline (Silverman *et al*. 2009). The projected values when this occurs are well above aragonite saturation states of 1, the level at which aragonite becomes chemically unstable in seawater (Orr *et al*. 2005).

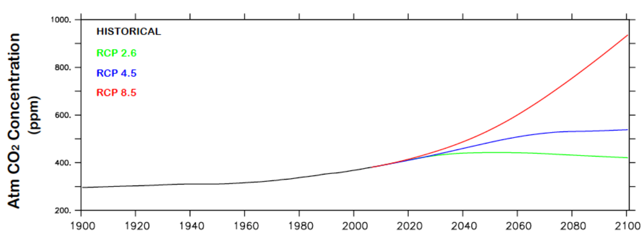
Many studies have also highlighted the sensitivity of magnesium calcite to ocean acidification e.g. (Andersson *et al*. 2008) and suggest that stability of magnesium calcite may be much more vulnerable than aragonitic corals. However, at present no explicit thresholds for magnesium calcite are currently available. Fabricius *et al*. (2011) report significant decreases in coral reef richness and complexity as pH declined in the vicinity of high CO_2 vents. They reported that in areas of pH 7.6 or lower, corals were not found.

At present, one of the key question is the ability of corals to adapt and evolve to the changing environmental conditions. Coles and Brown (2003) provide a comprehensive review of the possible routes of adaption. Given the complexity of estimating thresholds for entire coral reefs, a number of simplified metrics have been proposed. For example, (Guinotte *et al*. 2003) proposed that values of aragonite saturation state above 3.5 were considered as healthy, between 3-3.5 marginal, below 3 very marginal and below 2.5 corals are not historically found. While clearly this is only indicative, it provides a useful tool for assessing future environmental impacts.

emissions the higher atmospheric CO_2 and the greater the ocean acidification (Figure 4 and 5). For 2030, all pathways show a similar decrease in pH and aragonite saturation state, consistent with all of the emissions pathways showing similar atmospheric CO_2 concentrations (Box 3). By 2030, the median value of aragonite saturation state in the Central Equatorial Pacific areas has already started to shift from good to marginal conditions for corals (Box 2). By 2050 as atmospheric CO_2 concentrations start to stabilize under the low emissions pathway (RCP2.6) the ocean acidification also starts to stabilize. In contrast under medium (RCP4.5) and high (RCP8.5) emissions, atmospheric concentrations continue to increase (Figure 1) and the rate and magnitude of ocean acidification continues to increase. While the conditions for coral remain marginal, some areas in the Central Pacific have started to transition to values of aragonite saturation of less than 3, a value considered to be very marginal for long-term coral viability.

Box 3 Projected Changes

To project how ocean acidification may change in the future we use a suite of 6 Earth System Models from the Coupled Model Intercomparison Project 5 (CMIP 5) under 3 different pathways low (RCP2.6), medium (RCP4.5) and high (RCP8.5). These pathways are derived from different emissions scenarios known as Representative Concentration Pathways (RCPs) (Taylor, Stouffer and Meehl 2012). The emissions scenarios considered here are representative of high (RCP 8.5 or 'business–as-usual'), intermediate (RCP 4.5) and low (RCP2.6) emissions, corresponding to atmospheric CO_2 concentrations 936, 538, and 421 ppm respectively, by the end of century. While the simulation used prescribed atmospheric CO_2 concentrations, they do not consider all the potential carbon-climate feedbacks (Jones *et al*. 2016), which may significantly alter the future atmospheric CO_2 concentrations (Matear and Lenton 2018).



Historical and projected atmospheric CO_2 concentrations. The 3 different representative concentration pathways (RCPs) (van Vuuren *et al*. 2011) considered in this report are shown till the end of the century.

By 2100, atmospheric CO_2 concentrations have stabilized under low and medium emission pathways (RCPs 2.6 and 4.5 respectively). In the low emission scenario (RCP2.6), the surface pH and aragonite saturation state in 2100 are similar to the values projected for 2030. Under RCP4.5 scenario, pH and aragonite state values stabilized to values that are marginal for most corals across the Pacific, with very marginal conditions in the Central Pacific (where present-day values are low, Figure 2). In contrast, under the high emission scenario (RCP8.5) the entire Equatorial Pacific will experience conditions that are very marginal for coral and it is likely coral reefs will disappear from most of the Equatorial Pacific region. This is likely to have profound impacts on the marine ecosystem. Equally the changes in pH are very large and reach levels that are likely to have large impacts on the abundance and diversity of marine ecosystems (Fabricius *et al*. 2011). These projections represent only the median values (50th percentile), if the 90th percentile were to be considered (not shown) the values of aragonite saturation state would be well below the values at which corals are normally found (2.5), and the pH values close to 7.6, considered the threshold to support marine ecosystems (Fabricius *et al*. 2011). Such changes combined with ocean warming and other stressors are likely to be catastrophic.

Response of Individual Islands

To explore how ocean acidification may impacts individual islands, the projected changes in aragonite saturation state at a number Pacific Islands are examined. The same emissions pathways: low (RCP2.6), medium (RCP4.5) and high (RCP 8.5) are considered here, and the values calculated over the Exclusive Economic Zone for each nation (Figures 6 to 14).

For all Pacific Islands considered here the median of the models capture well the mean state over the historical period. Under low emissions (RCP2.6) in terms of aragonite saturation state, the conditions for coral remain favourable i.e. good (Box 2) for corals within this century, the exception being those located in the Central Equatorial Pacific that at present have the lowest mean values in the region. In this region, such as the Line Islands in the Kiribati Group, they transition to marginal conditions even under the low emission scenario. Under medium emissions (RCP4.5) and high emissions (RCP8.5) the projections all Pacific Islands transition from good to marginal conditions in the 2030s period. Those regions with larger mean present-day values e.g. Fiji (Figure 6) are the last to make this transition. As atmospheric CO_2 concentrations start to stabilize under RCP4.5 (Box 3) the conditions for corals remain marginal. However, under high emissions (RCP8.5), ocean acidification continues to increase and conditions transition from marginal to very marginal conditions by 2060s, to levels at which corals are not present by the end of this century.

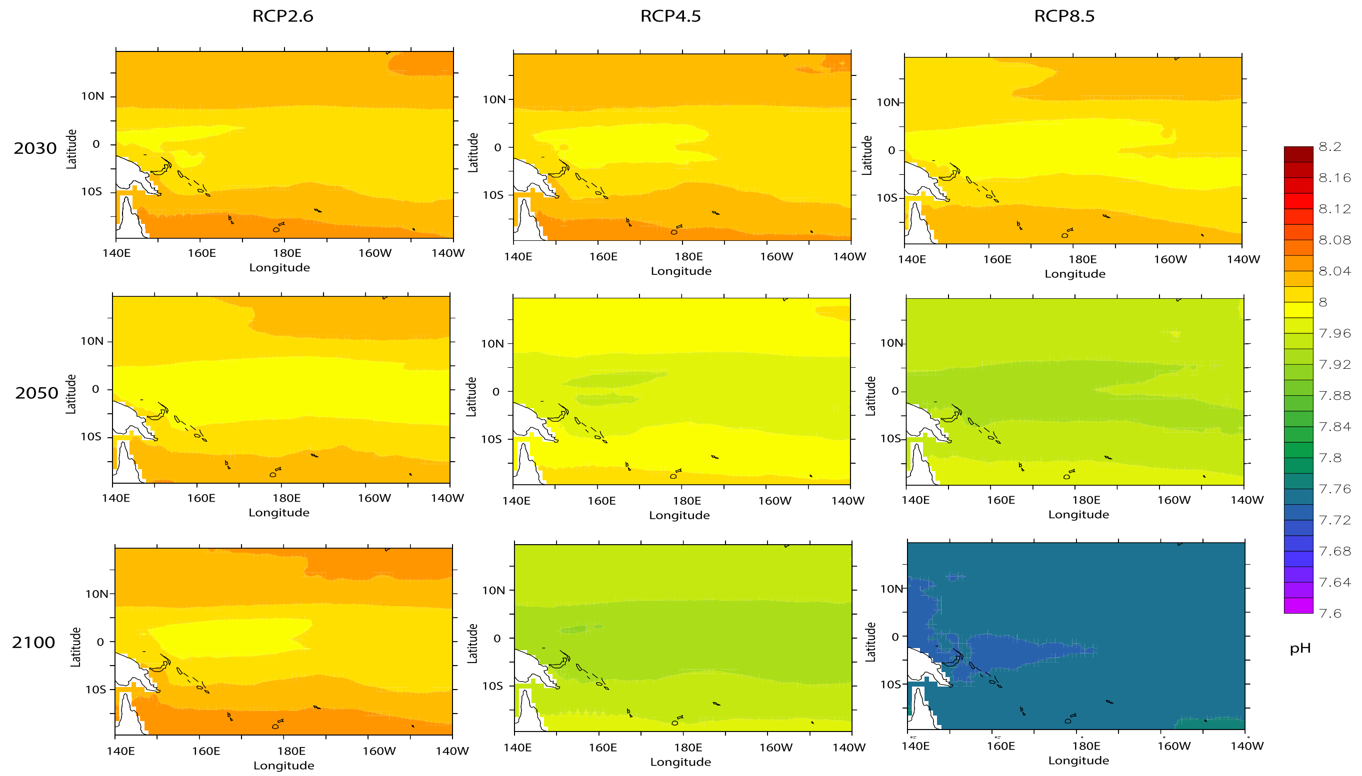


Figure 4. The median surface pH in the Equatorial Pacific in the periods 2030, 2050 and 2100, under low (RCP2.6), medium (RCP4.5) and high (RCP8.5) emissions pathways, as simulated from a suite of Earth System Models (see Box 3).

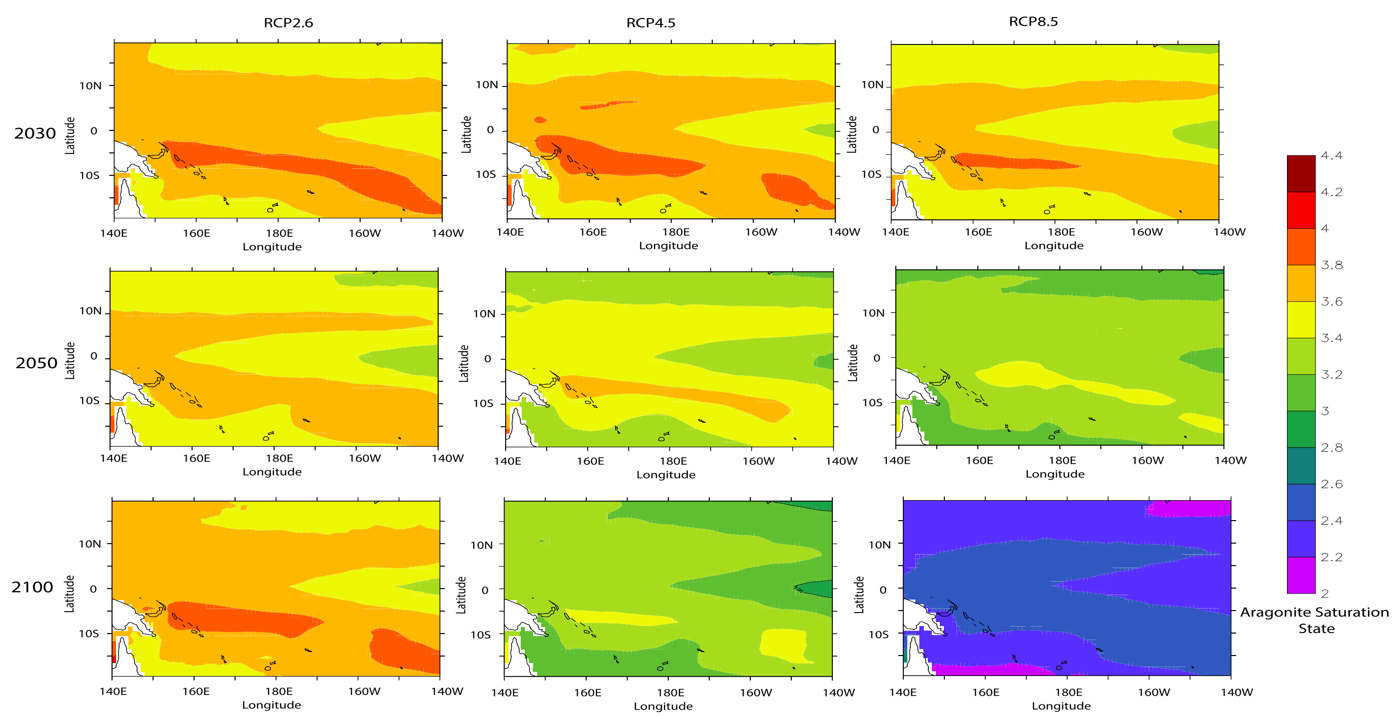


Figure 5. The median surface aragonite saturation state in the Equatorial Pacific in the periods 2030, 2050 and 2100, under low (RCP2.6), medium (RCP4.5) and high (RCP8.5) emissions pathways, as simulated from a suite of Earth System Models (see Box 3).

Box 4 Aragonite Saturation State

The decrease in carbonate ion concentration and saturation impacts the ability of important marine organisms such as tropical corals to calcify (Hoegh-Guldberg 2011, Hoegh-Guldberg *et al*. 2007, Langdon and Atkinson 2005). These organisms use carbonate $[CO_3^{2-}]$ and calcium ion $[Ca^+]$ dissolved in the seawater to construct their hard calcium carbonate structures ($CaCO_3$). It is these structures that form the cornerstone, and glue of the coral reef ecosystem. There are three primary forms of calcium carbonate produced by marine biota - aragonite, calcite and magnesium-calcite. Calcite is produced by coccolithophores, a common marine phytoplankton in the subtropical ocean, and some molluscs. Magnesium-calcite plays a critical role in supporting and building reef frameworks (Andersson, Mackenzie and Bates 2008). Aragonite is the primary form of calcium carbonate used by calcifiers in coral reef ecosystems, and the predominate biogenic carbonate mineral in the warm and shallow waters of the tropical ocean (Stanley and Hardie 1998). Consequently, changes in aragonite saturation state are considered a proxy for calcification rate (Langdon and Atkinson 2005). Aragonite saturation state (Ω_{AR}) is calculated following Mucci (1983), and is dependent on both the concentration of calcium and carbonate ions, as well as ocean temperature and salinity.

$$\Omega_{AR} = [Ca^+][CO_3^{2-}]/ K_{sp}$$

The calcite saturation state (Ω_C) is calculated using the same equation, but with a different value of K_{sp}, and is always higher than aragonite relative to calcite.

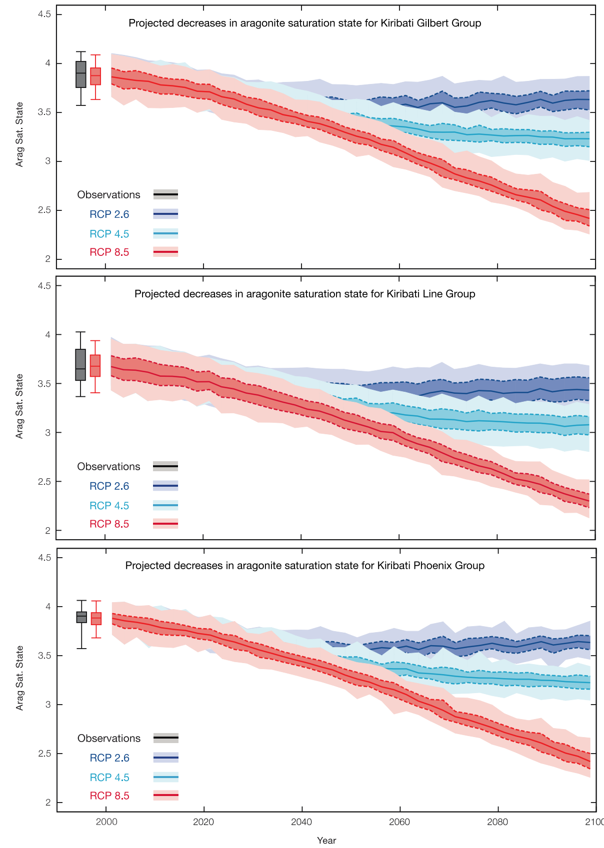


Figure 7. Projected changes in aragonite saturation state for the 3 island groups of Kiribati Gilbert Group (upper), Line Group (medium) and Phoenix Group (lower) under low (RCP2.6), medium (RCP4.5) and high emissions pathways (RCP8.5). Shown are the median values the (solid line), the interquartile values (dashed line) and the 10% and 90% percentiles (light shading). Shown on the plot is a comparison of observations with models over the historical period. Reproduced from CSIRO and BOM (2014).

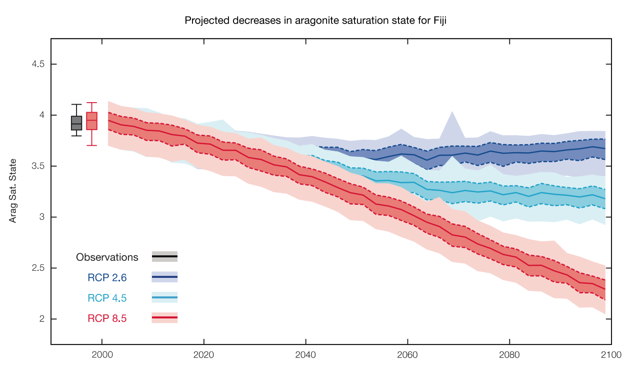


Figure 6. Projected changes in aragonite saturation state for Fiji under low (RCP2.6), medium (RCP4.5) and high emissions pathways (RCP8.5). Shown are the median values the (solid line), the interquartile values (dashed line) and the 10% and 90% percentiles (light shading). Shown on the plot is a comparison of observations with models over the historical period. Reproduced from CSIRO and BOM (2014).

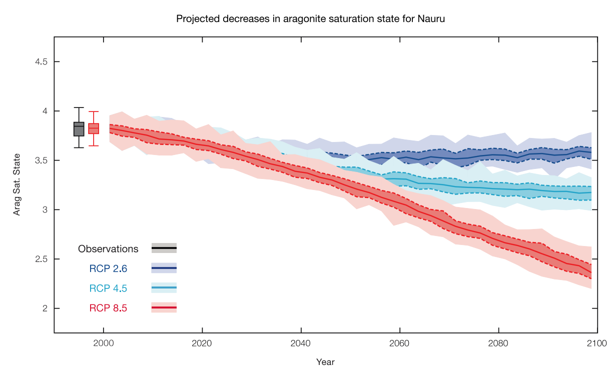


Figure 8. Projected changes in aragonite saturation state for Nauru under low (RCP2.6), medium (RCP4.5) and high emissions pathways (RCP8.5). Shown are the median values the (solid line), the interquartile values (dashed line) and the 10% and 90% percentiles (light shading). Shown on the plot is a comparison of observations with models over the historical period. Reproduced from CSIRO and BOM (2014).

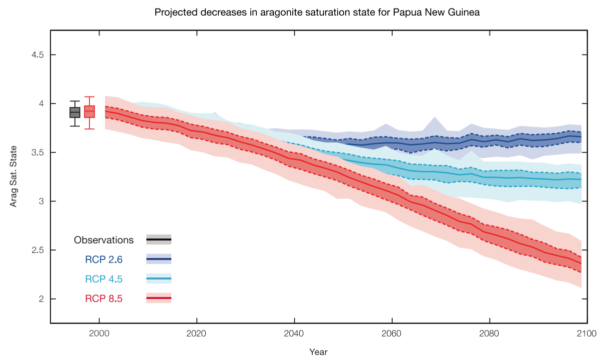


Figure 9. Projected changes in aragonite saturation state for Papua New Guinea under low (RCP2.6), medium (RCP4.5) and high emissions pathways (RCP8.5). Shown are the median values the (solid line), the interquartile values (dashed line) and the 10% and 90% percentiles (light shading). Shown on the plot is a comparison of observations with models over the historical period. Reproduced from CSIRO and BOM (2014).

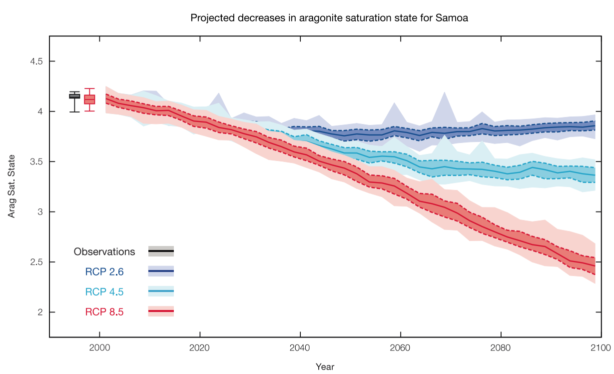


Figure 10. Projected changes in aragonite saturation state for Samoa under low (RCP2.6), medium (RCP4.5) and high emissions pathways (RCP8.5). Shown are the median values the (solid line), the interquartile values (dashed line) and the 10% and 90% percentiles (light shading). Shown on the plot is a comparison of observations with models over the historical period. Reproduced from CSIRO and BOM (2014).

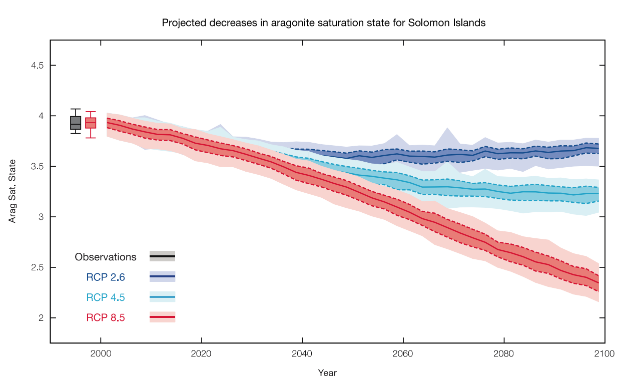


Figure 11. Projected changes in aragonite saturation state for the Solomon Islands under low (RCP2.6), medium (RCP4.5) and high emissions pathways (RCP8.5). Shown are the median values the (solid line), the interquartile values (dashed line) and the 10% and 90% percentiles (light shading). Shown on the plot is a comparison of observations with models over the historical period. Reproduced from CSIRO and BOM (2014).

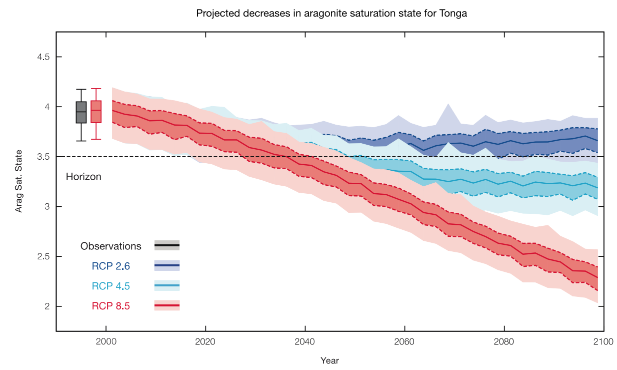


Figure 12. Projected changes in aragonite saturation state for Tonga under low (RCP2.6), medium (RCP4.5) and high emissions pathways (RCP8.5). Shown are the median values the (solid line), the interquartile values (dashed line) and the 10% and 90% percentiles (light shading). Shown on the plot is a comparison of observations with models over the historical period. Reproduced from CSIRO and BOM (2014).

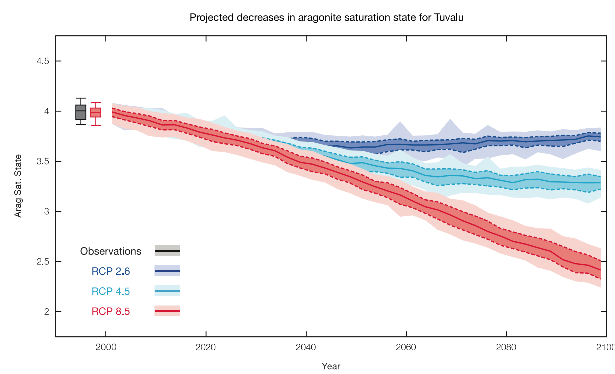


Figure 13. Projected changes in aragonite saturation state for Tuvalu under low (RCP2.6), medium (RCP4.5) and high emissions pathways (RCP8.5). Shown are the median values the (solid line), the interquartile values (dashed line) and the 10% and 90% percentiles (light shading). Shown on the plot is a comparison of observations with models over the historical period. Reproduced from CSIRO and BOM (2014).

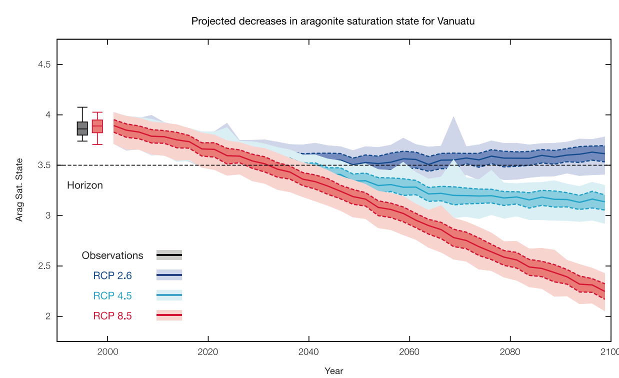
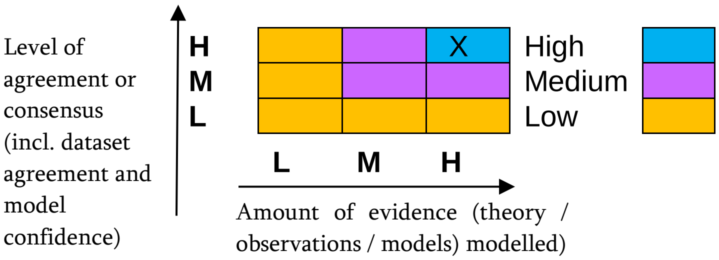


Figure 14. Projected changes in aragonite saturation state for Vanatu under low (RCP2.6), medium (RCP4.5) and high emissions pathways (RCP8.5). Shown are the median values the (solid line), the interquartile values (dashed line) and the 10% and 90% percentiles (light shading). Shown on the plot is a comparison of observations with models over the historical period. Reproduced from CSIRO and BOM (2014).

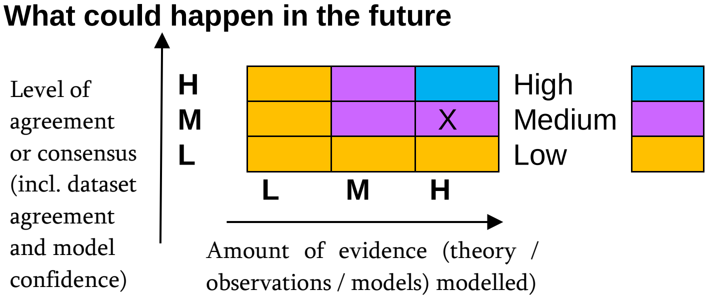
Confidence Assessment

What is already happening



There is very high confidence that the chemistry of the ocean is changing, and the seawater is becoming more acidic. This is occurring as the oceans continue to take up carbon in response to rising atmospheric CO_2 levels. Furthermore, the chemistry of these changes is well understood and well supported by observations. In the future, there is no doubt that as atmospheric CO_2 concentration continues to rise the ocean will become increasingly more acidic, and that these changes will be very long lasting, even if atmospheric CO_2 emissions were ceased today. It is less clear what the magnitude of these changes will be, i.e. which emissions pathway will be followed, although there is good agreement within each emissions scenario amongst the models used to project future changes. What is less clear is how these large-scale changes, including ENSO, will be modulated at the reef scale. At these scales, local processes are likely to play an important role, and it is unclear whether these will act as negative or positive feedbacks on ocean pH. At the same time the integrated impacts of these changes on the marine environment remain considerably less understood (Gattuso *et al*. 2015).

What could happen in the future



For the tropical Pacific, the most significant impacts of ocean acidification will be on coral reefs and the ecosystem services that they support, as a result of changes in carbonate availability (Box 3). Many coral reefs and associated aquatic ecosystems in the western tropical Pacific are important with high value marine areas. Any reduction in their health could have serious impacts on public amenity, tourism and economic development (Johnson, Bell and Sen Gupta 2016). At present, it is estimated that about 70% of protein in the diet of Pacific Islanders is derived from near-shore pelagic and inshore reef and lagoon fisheries (Bell, Johnson and Hobday 2011). Any decline in productivity or biodiversity of these fisheries may have serious impacts on food security, which in turn will impact the economic and social wellbeing of coastal communities. Furthermore, corals also play a critical role in protecting coastal resources and infrastructure by buffering coastlines from wave damage. Recent vulnerability assessments have highlighted the socio-economic and culture risks of ocean acidification to vulnerable Pacific island countries and territories and developed specific recommendations to help guide future planning and adaptation e.g. Johnson *et al*. (2016).

Knowledge Gaps

1. Local Processes

Very significant changes in ocean acidification are projected for the Pacific Islands. Typically, the models used to make projections are nominally 1°x1° resolution, and although some have enhanced resolution in the tropics, they do not resolve most Pacific islands. Consequently, most projections are based on the larger-scale open ocean conditions and ignore the local hydrodynamics, freshwater inputs etc. which can play a critical role at the local-scale (Mongin and Baird 2014, Mongin *et al*. 2016b). This may also explain why these models tend to also underestimate the magnitude of observed variability in ocean acidification (Sutton *et al*. 2016).

These projections ignore potential biological feedbacks on ocean chemistry such as through dissolution, which have the potential to impact ocean chemistry through raising ocean alkalinity. They do not include the role of other parts of the ecosystem such as mangroves (Donato *et al*. 2011) and seagrass (Fourqurean *et al*. 2012) which take up CO_2, and may play an increasingly important role in the future (Fabricius *et al*. 2011), thereby offsetting the impact of ocean acidification. All this means that at present how the large-scale changes are modulated at the local scale remains unknown and is an important knowledge gap. These gaps can be addressed in the future by a combination of high-resolution model development – which would resolve the biogeochemical and physical processes at the island scale - and sustained high resolution observations.

2. Multiple environmental drivers

Rising atmospheric CO_2 levels drive ocean acidification but also drive a number of other indirect effects and feedbacks such as sea-level rise, ocean warming, altered nutrient supply and hypoxia due to changes in mixing and stratification (Barros and Field 2014). At the local scale there are additional challenges such riverine input, changes in storm frequency and human pressures (Burke *et al*. 2011). The interaction between these changes is complex and will likely result in a cascade of physical and chemical changes (Harley *et al*. 2006). This means that no change can be considered individually as the impact on the marine ecosystem will be the integration of all the changes, and larger those based on ocean acidification alone e.g. Kroeker *et al*. (2013).

This will be addressed through ongoing studies integrating different environmental drivers at the coastal scale, thereby allowing us to provide more coherent projections. The impacts of these changes on the environment will be tackled through the development of mechanistic, and energetic models that account for these processes and as well as their potential synergistic and antagonistic effects (Hewitt, Ellis and Thrush 2016).

3. Emissions Pathways and Options

The magnitude and speed of ocean acidification will be determined by future atmospheric CO_2 concentrations. The recent Paris Agreement agreed to limit warming to well below 2°C with an aspirational goal of 1.5°C, which requires following the low emission pathway presented here. If this were to be achieved, the most severe impacts of ocean acidification may well be avoided in the Pacific Islands. However, at present emissions are well above the level needed to achieve these goals (Le Quere *et al*. 2016). In response to this a number of geoengineering schemes have been proposed to arrest or even reverse ocean acidification locally and globally through techniques that artificially change the seawater chemistry e.g. by altering alkalinity (Feng *et al*. 2016, Lenton *et al*. 2018) and removing CO_2 from the seawater through seaweed farms (Mongin *et al*. 2016a). The lack of certainty over what the future trajectory of atmospheric CO_2 remains a major impediment in developing successful adaptation and natural resource management plans in the Pacific Islands (Rogers *et al*. 2015). This knowledge gap will be addressed through stronger global commitment to mitigation, through the transition to lower carbon economies, the advancement of local ecosystem understanding, and by exploring engineering and adaptation approaches to mitigate impacts.

Citation

Please cite this document as:

Lenton, A., Matear, R.J., Mongin, M. (2018) Impacts of Climate Change on Ocean Acidification Relevant to the Pacific Islands. Pacific Marine Climate Change Report Card: Science Review 2018, pp 31-42.

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