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Effects of Climate Change Relevant to the Pacific Islands

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EXECUTIVE SUMMARY

Small Island Developing States in the South Pacific are particularly vulnerable to the effects of marine climate change due to their proximity to the ocean and their reliance on it for resources and transportation.

Changes to the physical environment (e.g. temperature, pH, sea level rise and storms and waves) are already being detected and are affecting biodiversity via shifts in distribution, the timing of natural events (phenology), increased energetic costs of physiological processes, mechanical damage and loss/fragmentation of habitats.

Much of the Pacific islands' population and infrastructure (including fresh water resources) are situated on the coast and thus, vulnerable to erosion, inundation and damage from cyclones. Food supplies are also at risk due to the heavy reliance on coastal fisheries.

The dispersed nature and heterogeneity of the SIDS presents a challenge for localised climate projections and adaptation strategies.

The South Pacific region is bringing SIDS together in partnership working on climate change, however, continued funding is needed to realise adaptation options and to link the physical science with societal and economic impacts. Engaging women and remote populations in climate talks will improve long term resilience.

Introduction

The oceans and the atmosphere are closely linked. The oceans have absorbed approximately 93% of the excess heat caused by global warming and around two thirds of anthropogenic CO_2 (Rhein *et al*., 2013). These changes are predicted to have profound effects on atmospheric, physical and biological processes, affecting ocean ecosystems and the services they provide to society and the ocean's capacity for further climate mitigation (Pörtner *et al*., 2014). Small Island Developing States (SIDS) are particularly vulnerable to these changes due to their reliance on marine resources and the concentration of settlements in coastal regions (Nurse *et al*., 2014).

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In the following report, we summarise key findings on the effects of climate change on the physical ocean processes, biodiversity and socio-economics of the Pacific, with a specific focus on the commonwealth SIDS of Fiji, Kiribati, Nauru, Papua New Guinea, Samoa, the Solomon Islands, Tonga, Vanuatu and Tuvalu (Figure 1). Further details on these topics can be found in the topic papers of the Science Review 2018. The impact of the ocean on SIDS is reflected in international climate politics; the Pacific island countries were instrumental in promoting formal ocean governance and successfully campaigned for an ocean Sustainable Development Goal (SDG) (Quirk & Hanich, 2016). Ocean issues were also reflected in the SIDS negotiating group's nationally determined contributions (NDCs) for the Paris Agreement, having a significantly higher percentage of marine keywords and categories in their than other groups (Gallo *et al*., 2017). Indeed, two of the SIDS that will be the subject of this report card, Kiribati and Nauru, had some of the most marine focused NDCs, citing ocean warming, ocean acidification, mangroves, coral reefs and Blue Carbon as areas of concern (Gallo *et al*., 2017).

Several different emissions scenarios have been devised for use in model simulations to project environmental conditions over this century. These scenarios are referred to as representative concentration pathways (RCPs) (see Stocker *et al*., 2015) and are used by scientists as a standardised set of scenarios to allow a robust comparison of results from model simulations; they will be the basis of the projections used in this report.

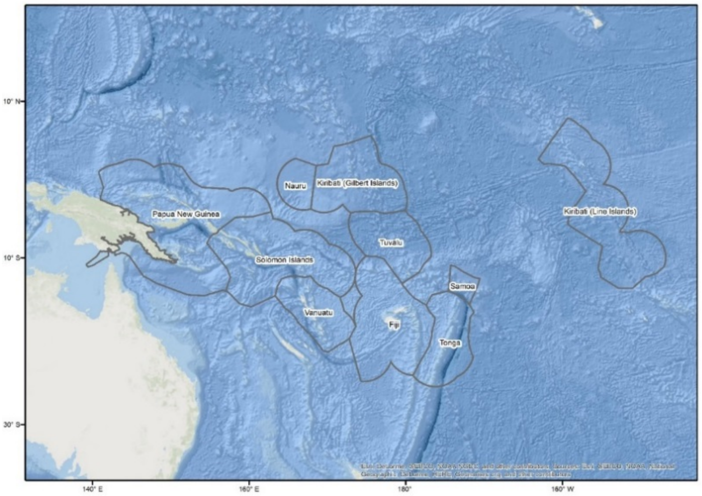

Figure 1. South Pacific SIDS included in this report, grey lines denote exclusive economic zones (EEZs).

Physical

Temperature

Sea surface temperatures (SSTs) in the South Pacific are strongly influenced by the position of the Intertropical Convergence Zone (ICZ), which is affected by large scale climatic drivers. Much of the year-on-year variability is driven by the El Niño Southern Oscillation (ENSO), whilst longer term (decadal) variability is governed by the Interdecadal Pacific Oscillation (IPO) (Hoegh-Guldberg *et al*., 2014). Generally, sea surface temperature (SST) decreases with distance from the equator; however, there are significant regional variations in SST (Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2011). The trade winds and resultant westward ocean currents push warm equatorial water into the western tropical Pacific, maintaining a warm volume of water called the 'Warm Pool' with surface temperatures nearing 30°C (Figure 2). The prevailing winds also cause equatorial upwelling and coastal upwelling along the coast of South America, both of which bring relatively cool, nutrient-rich water to the surface. This results in a tongue of relatively cool water extending along the equator from the South American coast to the central Pacific, where it meets the eastern limit of the Warm Pool at around 180-220°E.

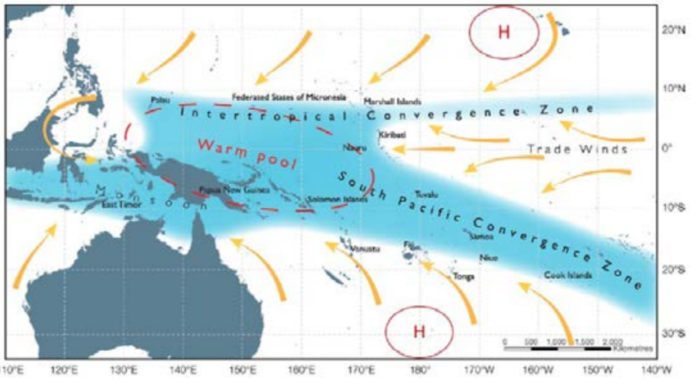

Figure 2. The average positions of the major climate features of the region in November to April. The yellow arrows show near surface winds, the blue shading represents the bands of rainfall (convergence zones with relatively low pressure), and the red dashed oval indicates the West Pacific Warm Pool. H represents the typical positions of moving high pressure systems (CSIRO, 2011).

The wider Pacific Ocean experienced a rapid shift to warmer sea temperatures in the mid-1970s, warming by 0.288°C between 1950-2009 due to both natural (e.g., IPO) and anthropogenic climate forcing. In the western South Pacific, temperatures have increased by 0.456°C between 1950-2009 (Hoegh-Guldberg *et al*., 2014). Models (CMIP5) were used to calculate average SST for the period between 1956 and 2005 (Figure 3). In the Exclusive Economic Zones (EEZs) of the southern SIDS such as Tonga, Fiji and the Cook Islands, average annual SSTs were between 24-27 °C, for the more northerly SIDS, such as The Marshall

Islands, Nauru and Kiribati, average annual SSTs were between 27-30 °C.

Over the course of the 21st century, global SST will increase under all RCPs and the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) predicts that tropical and subtropical regions will experience the strongest warming trends (Hoegh-Guldberg *et al*., 2014). Projections of future increases in SST have been calculated for the region using the CMIP5 model; over the next 50 years, SST around the South Pacific Islands is projected to increase by 0.7 to 1.1 °C under the highest IPCC emissions scenario (RCP 8.5) with temperature rises reaching 1.8 – 2.8 °C by 2100 (Figure 3). The ICZ influences the spatial variability of warming, warming is more intense within the ICZ, affecting Kiribati and Nauru. There is also east-west variability with less warming experienced in more easterly SIDS, such as Samoa and the Cook Islands than in the more westerly SIDS, such as Papua New Guinea and the Solomon Islands.

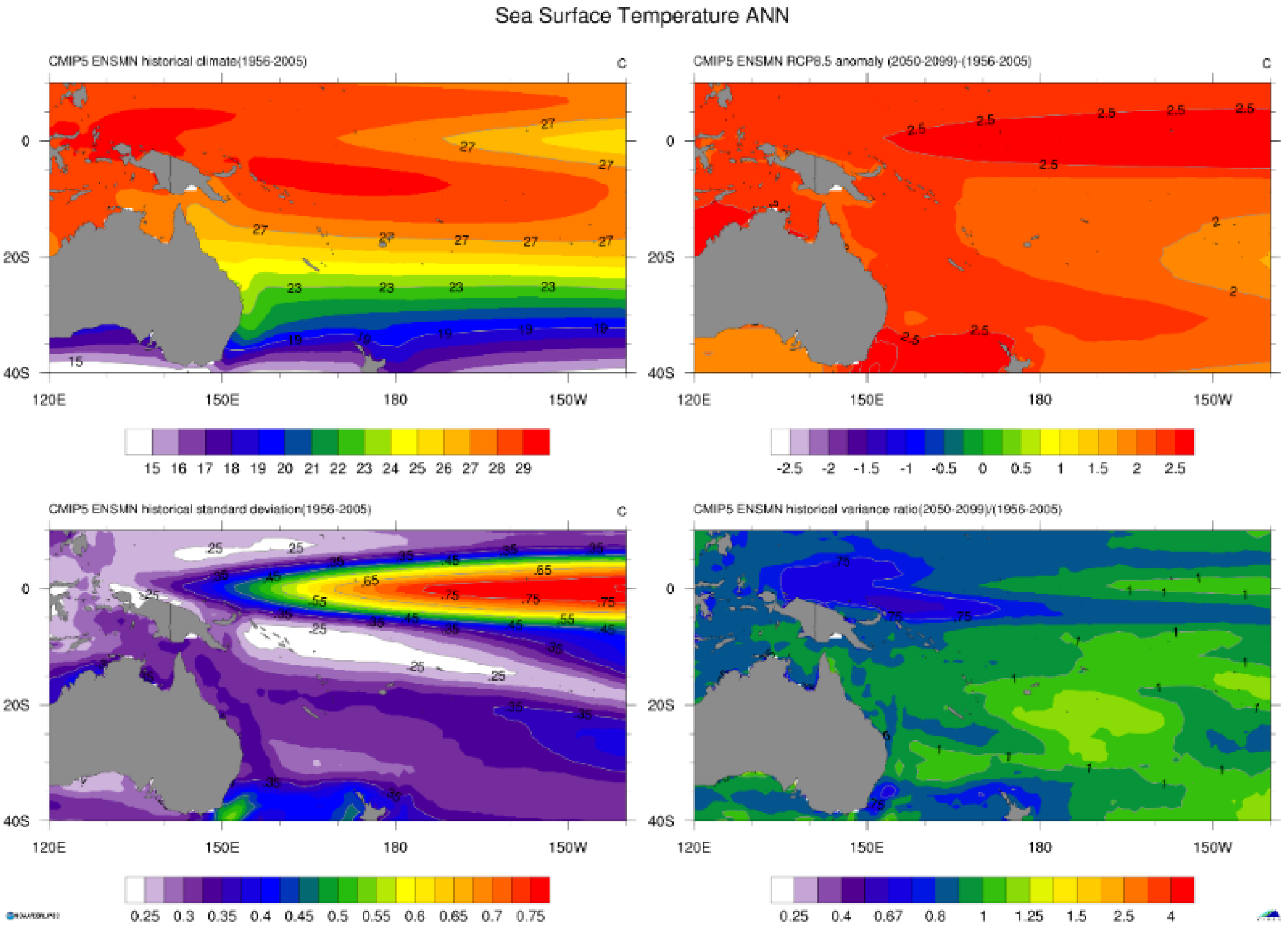

Figure 3. Annual sea surface temperature under a high emissions scenario RCP8.5, modelled using the CMIP5 model. Left panels: the CMIP5 representation of historical conditions (1956-2005 – upper panel: mean lower panel: standard deviation [de-trended]). Right panels: the comparison between the historical period and the subsequent 5 decades (2006-2100 – upper panel: different in the mean; lower panel: ratio of the de-trended variance).

Tropical cyclones and storm surge

Studies have shown that the total number of tropical cyclones in the south west Pacific has decreased (CSIRO, Australian Bureau of Meteorology, & SPREP, 2015). Some suggest that there has been an increase in the number of intense tropical cyclones (CSIRO *et al*., 2015; Holland & Bruyère, 2014), whilst Hoarau *et al.* (2017) found the opposite trend for the South Pacific after re-analysing and assessing the historical severity of cyclones and upgrading several storms that occurred between 1980 and 2016 as severe.

The IPCC AR5 states that, it is likely that the global frequency of occurrence of tropical cyclones will either decrease or remain essentially unchanged; however, it is likely that the intensity of tropical cyclones will increase with increases in wind speed and precipitation (Christensen *et al*., 2013; CSIRO *et al*., 2015). The future influence of climate change on tropical cyclones is likely to vary by region, but the specific characteristics of the changes are not yet well quantified and there is low confidence in region-specific projections of frequency and intensity (Christensen *et al*., 2013).

Modelling work suggests that the severity of storm surge experienced by Pacific SIDS is more strongly linked to extreme El Niño events with an eastward propagation than to intensity of storm (Santoso *et al*., 2013; Stephens & Ramsay, 2014) and a projected 10-20% increase in the intensity of cyclone made little difference to the severity of surge (Stephens & Ramsay, 2014).

Ocean acidification

Since the beginning of the Industrial Era, anthropogenic CO_2 has caused a decrease of 0.06 pH units in the tropical Pacific. The current rate of decrease is approximately 0.02 units per decade and with the pH of the tropical Pacific Ocean is projected to decrease by 0.15 units relative to averages in 1986–2005 period by 2050 (Hoegh-Guldberg *et al*., 2014). By the end of the century, the CMIP5 ensemble predicts a further decrease of 0.23-0.28 pH units relative to averages in 1956-2005; the model also predicts lower variance in pH, particularly in the waters to the north east of Papua New Guinea, Nauru, Kiribati (Gilbert and Phoenix Islands) and the Marshall Islands (Figure 4).

A decrease in seawater pH corresponds to a decrease in the concentration of dissolved carbonate ions (CO_3^{2-}), lowering the potential for $CaCO_3$ to precipitate (termed saturation sate or Ω). When Ω is greater than 1, precipitation is favoured, conversely, if Ω is less than 1, dissolution will occur**.** Pre-industrial saturation state in the waters surrounding the SIDS was between 4 to 4.5. By the mid-1990s, the aragonite saturation state had declined across the region and with values only slightly above 4 (Australian Bureau of Meteorology and CSIRO, 2011). The saturation state of aragonite and calcite has continued to decline across the region at a rate of approximately 0.4 per year (CSIRO *et al*., 2015). The IPCC AR5 states that under RCP 8.5, aragonite saturation states in subtropical gyre regions will continue to decrease to around 1.6 by then end of the century, this will make calcification significantly more difficult for organisms (Hoegh-Guldberg *et al*., 2014).

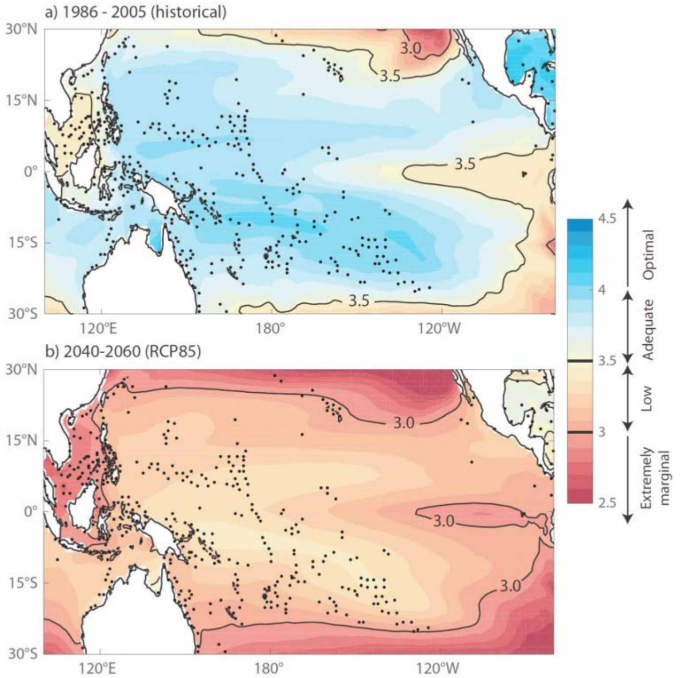

Figure 4. Aragonite saturation state for the periods (a) 1986–2005 (based on a multi-model median from the CMIP5 historical simulations) and (b) 2040–2060 (based on RCP8.5 simulations). Contour lines of 3 and 3.5 are superimposed. Black dots indicate location of coral reefs. Taken from Johnson *et al*. (2015).

Sea level rise

The IPCC AR5 states that there is high confidence, robust evidence and high agreement that sea level rise (SLR) is one of the most recognised climate change threats to low-lying land on islands and atolls (Nurse *et al*., 2014). Global mean sea level has been steadily rising at a rate of approximately 3.2 ± 0.4 mm per year over the last two decades (CSIRO *et al*., 2015; Fasullo & Nerem, 2016). However, data from satellites and tide gauges indicate that the rate of SLR since 1993 in the western Pacific has been up to about three times faster than the global average, such as around the Solomon Islands, Papua New Guinea and the Marshall Islands (Figure 5). This high rate is partially due to decadal climate variability with the IPO shifting from a positive to a negative phase over this period (CSIRO *et al*., 2015).

The IPCC AR5, projected global mean SLR by 2100 under the highest scenario, RCP 8.5, would be 0.45 (5th percentile) to 0.82 m (95th percentile). Regionally, there is greater variation in the extent of SLR for the Pacific SIDS under RCP 4.5 than the other scenarios; sea level is predicted to increase by up to 0.5 m (relative to averages during 1986-2005) for some of the more northern and eastern SIDS, while western SIDS will experience an increase of up to 0.6 m (Figure 5). Under RCPs 6.0 and 8.5, the region is projected to experience an increase of up to 0.6 m and 0.7 m, respectively, relative to averages during 1986-2005 (Church *et al*., 2013). Recent research suggests that the western Pacific may be one of the regions most affected by sea level rise being exacerbated by gravitational changes from loss of land ice and terrestrially stored ground water (Carson *et al*., 2016).

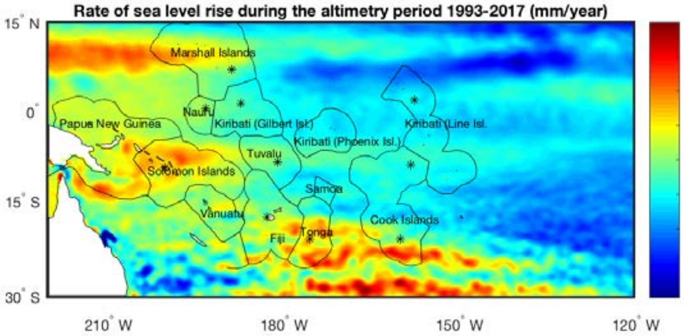

Figure 5. Rate of sea level rise from satellite altimetry (Aucan, 2018).

Extreme sea level, inundation, erosion

Coastal regions experience elevated water levels on an episodic basis due to wave setup and runup, tides, storm surge driven by wind stress and atmospheric pressure, contributions from seasonal and climatic cycles, e.g. El Niño/Southern Oscillation and Pacific Decadal Oscillation, and oceanic eddies (Vitousek *et al*., 2017). These extreme sea level events are exacerbated by global sea level rise, leading to an increased risk of inundation and coastal erosion and more severe storm surges.

Recent modelling studies indicate that rising sea level also increases the risk of inundation from storm surges associated with tropical cyclones; however, the risk is often modified by other factors or activities (Walsh *et al*., 2016). Documented cases of coastal inundation and erosion often cite additional circumstances such as vertical subsidence, engineering works, development activities, or beach mining as the causal process. On the Torres Islands, Vanuatu communities have been displaced as a result of increasing inundation of low-lying settlement areas owing to a combination of tectonic subsidence and SLR (Nurse *et al*., 2014). Recent research linked coastal erosion in the Pacific with ENSO action with increased wave action during La Niña events, causing higher levels of coastal erosion in the southern Pacific (Barnard *et al*., 2015); thus, alterations to large scale climate drivers may exacerbate the impacts of SLR.

Observations of shoreline change on reef islands conclude that rates of change experienced over recent decades, normal seasonal erosion and accretion processes appear to be the dominant drivers, as opposed to climate change drivers (Nurse *et al*., 2014). Several studies, including the IPCC AR5, predict an increase in extreme sea level events, mainly caused by the rise in mean sea level (Figure 6); a recent study showed that a 10 to 20 cm rise in sea level could more than double the frequency of flooding (Church *et al*., 2013; Vitousek *et al*., 2017; Wahl *et al*., 2017).

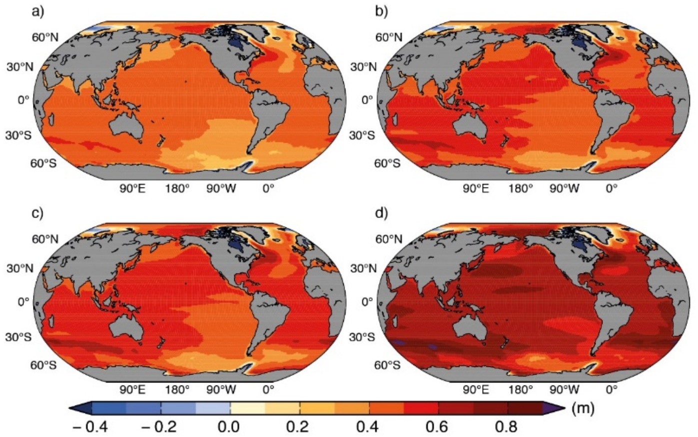

Figure 6. Ensemble mean regional relative sea level change (metres) evaluated from 21 CMIP5 models for the RCP scenarios (a) 2.6, (b) 4.5, (c) 6.0 and (d) 8.5 between 1986–2005 and 2081–2100. Each map includes effects of atmospheric loading, plus land ice, glacial isostatic adjustment (GIA) and terrestrial water sources (from Figure 13:20 (Church *et al*., 2013) IPCC AR5 WGI).

Wave climate

Typically, wind waves experienced by the South Pacific SIDS are not large but, in many places, are subject to natural variation in trade winds that is moderated by large scale climate drivers, such as ENSO. There has been no significant change in waves climate in the South Pacific (Aucan, 2018). Projections of extra-tropical storms, which generate waves in the tropics, are inconclusive. Astronomical tides, which are not related to earth climate, are not expected to change (Aucan, 2018).

Precipitation, droughts and floods

Since 1981, there has been a significant increase in rainfall across most of the western pacific monsoon region, south and west of the SPCZ from Vanuatu to the southern Cooks. Rainfall has decreased north and east of the SPCZ at Nauru, Tarawa, Funafuti (Taylor *et al*., 2016) and there has been an observed increase in heat waves (Lefale *et al*., 2018).

During El Niño events, southwest Pacific island nations experience an increased occurrence of forest fires, heat waves and droughts (Kumar *et al*., 2006; Salinger, 2001), and an increased probability of tropical cyclone damage, as tropical cyclogenesis tends to reside within 6° to 10° south of the SPCZ

(Vincent *et al*., 2011). Nauru experiences drought during La Niña as the SPCZ and ICZ move to the west (Brown *et al*., 2013; Christensen *et al*., 2013).

There is medium confidence that, as temperatures increase, there will be an intensification of SPCZ events which will lead to an increase in average rainfall during the wet season, for the southern group of the Cook Islands, the Solomon Islands, and Tuvalu, and an intensified seasonal cycle for Vanuatu, Tonga, Samoa, Niue, Fiji, where an decrease in dry season rainfall is accompanied by an increase in the wet season (Christensen *et al*., 2013). Kiribati, Nauru, Papua New Guinea are projected to have an increase in rainfall with an increase in extreme precipitation events (Lefale *et al*., 2018). There is low confidence in the predictions of how climate change will affect the frequency of droughts; the proportion of time in drought is projected to decrease slightly, decline or remain the same in all Pacific SIDS (Lefale *et al*., 2018). Extreme heat waves are likely to be regular and of unprecedented magnitude and duration (The World Bank, 2017).

ENSO / large scale ocean processes

El Niño events have marked effects on the South Pacific SIDS; impacting rainfall and drought, wind speeds and SSTs (CSIRO *et al*., 2015). El Niño events shift the position of the Intertropical Convergence Zone (ICZ) and South Pacific Convergence Zone (SPCZ) and hence, increased probability of tropical cyclone damage, as tropical cyclogenesis tends to reside within 6° to 10° south of the SPCZ (Vincent *et al*., 2011).

El Niño and La Niña events will continue to occur in the future, but there is low agreement as to whether these events will change in intensity or frequency (Christensen *et al*., 2013). There is high confidence, however, that ENSO will remain the dominant mode of natural climate variability in the 21st Century (Christensen *et al*., 2013 and references therein). There is low confidence in the intensity and spatial pattern of El Niño in a warmer climate (Christensen *et al*., 2013).

Biodiversity

Due to the magnitude and rate of the predicted changes to the physical environment, significant impacts on species and habitats are likely. Indeed, evidence of climate change stressors can already be observed, for example in the widespread coral bleaching in 2015/16 (Dutra *et al*., 2018). The effects of climate change on biodiversity can be synergistic or antagonistic and are often different in different species or geographic locations. Climate change is just one amongst a suite of other anthropogenic stressors which may have compound effects, e.g. loss of coral reefs due to warming may increase habitat loss caused by mechanical damage from shipping, tourism and fishery activities. Any significant loss or fragmentation of habitats will impact, not only upon the populations directly using that habitat, but also diminish connectivity between populations.

Connectivity of populations and climate change can also interact directly. Larval dispersal pathways can be altered via changes in hydrodynamics, but might also cause a changes in timing the timing of spawning, duration of larval transport, larval mortality, and behaviour (increased larval swimming speed) (Magris *et al*., 2014). Simultaneously, connectivity can influence post-disturbance recovery and the ability of organisms to adapt to rapid climate change (Munday *et al*., 2008). Altered species distributions might also limit or expand the connectivity of sites in the future (Magris *et al*., 2014).

Seagrass

Coastal and vegetated habitats, such as seagrass, are at risk from SLR. In the Pacific region, there is evidence that changes in sea level have resulted in global declines of these habitats and shifted their distributions (Pörtner *et al*., 2014). High temperatures can cause burn-off (blackened dying leaves), eventually leading to high levels of mortality. Instances of burn-off have been observed in Fiji, although sufficient data are lacking to link these events to warming trends (Waycott *et al*., 2011).

Under future climate change effects, seagrass populations in the Pacific are anticipated to be vulnerable to changes in SST, with acute heat stress decreasing biomass via causing burn-off events and chronic heat stress altering species composition and distribution of seagrass communities. Increases in rainfall projected for some southern SIDS (see earlier section on precipitation) may have indirect impacts on seagrass growth by increasing turbidity and limiting light availability (Waycott *et al*., 2011).

Seagrass will be highly vulnerable to damage from the predicted increased intensity of cyclones, causing physical damage to seagrass beds from the increased wave surge and scour from suspended sediment. However, seagrasses have been shown to be quick to recover, providing propagules are available to re-establish the community (Waycott *et al*., 2011).

Mangroves

Mangroves have a limited tolerance for submersion in seawater and need to migrate landwards to cope with rising sea levels (Pörtner *et al*., 2014). In southern Papua New Guinea, mangroves have been gradually retreating inland in response to SLR and in American Samoa, seaward margins of mangroves moved inland by up to 72 mm per year in response to SLR of approximately 2 mm per year (Waycott *et al*., 2011). Unfortunately, many of the SIDS that support mangrove systems have steep topography that will hinder distribution shifts inland (Bell *et al*., 2013) and this is exacerbated by human coastal development (Ellison, 2018). Mangroves have also been shown to be sensitive to changes in temperature, which can change the species composition and the timing of flowering and fruiting (Gilman *et al*., 2008); in Fiji, there is higher seagrass flowering and seed set success during years with normal rainfall, compared to drought years, and on the wetter west side of the island, relative to the drier coast in the east (Waycott *et al*., 2011).

There is high agreement that mangroves on Pacific islands will be particularly vulnerable to potential impacts of projected sea level rise. Mangroves in areas with low tidal range and low sediment supply could be submerged as early as 2070, including northern Papua New Guinea, which has a microtidal range of approximately 1 m, and the Solomon Islands (Lovelock *et al*., 2015). Mangroves that are squeezed by coastal developments and steep terrain will be at higher risk than those with the space to migrate inland (Waycott *et al*., 2011). Drier, warmer weather may also increase mortality and reduce reproductive success (Ellison, 2018).

Sandflats

There has been little research on the impacts of climate change on intertidal sandflats and their associated floral and faunal communities; due to natural variability and the gradual rates of change there is no established baseline against which to measure change resulting from climate change drivers. The limited evidence suggests that SLR will be the main threat to intertidal sandflats, this will be exacerbated in areas that are already degraded by human activities, such as pollution and aggregate extraction and where coastal development prevents the habitat from moving inland (Waycott *et al*., 2011).

Fish and shellfish

Naturally occurring extremes in SSTs, exacerbated by climate change, have already been observed to have indirect and direct impacts on demersal fish and invertebrates in the Pacific islands region. In 2015-2016, high SSTs resulted in mass fish mortality on the Coral Coast of Fiji and Vanuatu, likely due to the lowered oxygen concentration at higher sea temperatures. At the same time, there was mass bleaching of giant clams and coral, causing a loss of habitat for demersal fish (Johnson *et al*., 2018).

Continued impacts on fish and invertebrate fitness are predicted under increasing SSTs; it is likely that ocean acidification will act as an additional stressor (Hoegh-Guldberg *et al*., 2014). Ocean acidification has been shown to cause behavioural changes in the predator/prey interactions of demersal fish; however, the strongest effects are likely to be on calcifying invertebrates, causing shell dissolution and increased metabolic costs associated with calcification as well as behavioural changes (Pörtner *et al*., 2014). Changes in the quantity and quality of coastal habitats projected under climate change are also likely to have deleterious effects on invertebrate populations.

Pelagic species will also be affected by increasing SST, modelling results suggest that distributions albacore, skipjack tuna, bigeye tuna and yellowfin tuna will shift eastwards in response to changes in ocean currents and increased stratification limiting food supplies (Bell *et al*., 2011).

Corals

The combined drivers associated with climate change are currently the strongest driver affecting coral dynamics, globally (Aronson & Precht, 2016), exacerbating other non-climate pressures. Increasing SSTs cause corals to lose their symbiotic algae (zooxanthellae), which reduces calcification and increases mortality rates (Nurse *et al*., 2014). In the Pacific islands region, anthropogenic-induced ocean warming is already impacting on coral reefs through thermal coral bleaching (Dutra *et al*., 2018 and references therein). The Gilbert Islands of Kiribati have experienced the highest levels of thermal stress relative to other areas and global bleaching databases show that here has been a significant increase reports of coral bleaching events from SIDS, including Kiribati and Fiji (Donner *et al*., 2017). Ocean acidification is also affecting calcification rates (Johnson *et al*., 2015), while more intense tropical cyclones are becoming more frequent, causing widespread coral damage (Dutra *et al*., 2018).

Under a high emissions scenario (RCP8.5) changes to reefs are expected to become substantial from 2050 (or earlier) (Van Hooidonk *et al*., 2016). Higher SST will potentially lead to declines in coral populations which could cause unprecedented changes in coral reefs and associated habitats (Hoegh-Guldberg *et al*., 2014). Corals are adapted to calcifying in supersaturated waters with Ω_{arg} between 3-4, increasing levels of acidification will impact on coral physiology (calcification rates, ability to repair tissues and growth), behaviour (feeding rate), reproduction (early life-stage survival, timing of spawning), weaken calcified structures, and alter coral stress-response mechanisms (Fabricius *et al*., 2015; Fabricius *et al*., 2017). The IPCC AR5 has medium confidence that coral reef growth rate will be able to keep pace with SLR, however, a rise of >0.82 m by 2100 would cause coastal erosion which would increase turbidity and is likely to cause degradation of reefs (Dutra *et al*., 2018; Pörtner *et al*., 2014), and an increase in the intensity of tropical cyclones would increase damage and fragmentation of reefs (Dutra *et al*., 2018).

Invasive species

Introduced invasive species pose a serious threat to Pacific island ecosystems, especially given the high value and significance of coastal and marine resources to the people of the Pacific. Climatic driven changes may affect both local dispersal mechanisms, due to the alteration of current patterns, and competitive interactions between invasive non-native species (INNS) and native species, as marine conditions shift, they may begin to become more suitable for INNS and less suitable for some native species. There is little information relating to the impacts of climate change drivers on species that are invasive to the South Pacific SIDS.

Uthicke *et al*. (2015) found that temperature had an indirect effect on the larval development of the native crown of thorns starfish (*Acanthaster planci*). Experiments that incubated larvae with high food concentrations saw increased growth and faster development, but the effect was modulated by temperature, with higher temperatures interacting with high food concentrations to further speed up development. The authors suggest that increasing temperatures, combined with high food supply, could increase the probability of larval survival by 240%, which may mean that climate change drivers could increase crown of thorns outbreaks.

Birds

The IPCC has high confidence that the impacts on seabirds will be mostly indirect via effects of warming on their prey. Globally, shifts in distributions and phenologies in relation to temperature have already been observed (Pörtner *et al*., 2014). The physiological boundaries in tropical birds are much narrower than in temperate species, limiting their ability to cope with changing climate (Mack, 2009). The Pacific SIDS are home to many restricted range species from a variety of families such as Drepanididae (Hawaiian honeycreepers), Zosteropidae (White-eyes) and Paradisaeidae (birds of paradise) (S. Taylor, Kumar, & Taylor, 2016). Changing temperature may affect the flowering and fruiting cycle of trees which could have deleterious effects for frugivorous and nectivorous birds in the Pacific (Taylor *et al*., 2016).

Inundation and flooding of low-lying forested islets will diminish the available habitat for many species such as the Manus fantail (*Rhipidura semirubra*). Many of the atolls provide nesting and stopover sites for breeding and migratory species and species that over-winter on the islands could be severely impacted under increased storm surge and rising sea levels. However, there is evidence that some of the islands with more than 3 m elevation may provide refuges for some bird species under rising sea levels, as they did during SLR events in geologic history (Cibois *et al*., 2010). Most threatened bird species on the islands are found in forested habitats (Satterfield *et al*., 1998). Impacts of climate change on these species likely would be from physiological stress and loss or change of habitat, especially from fires and cyclones. For example, 30% of the forested area on the Santa Cruz islands (Solomon Islands) was lost in one cyclone in 1993 (McCarthy, 2001). Some vulnerable species and areas include the Samoan white-eye (*Zosterops samoensis*) and critically endangered Samoan moorhen (*Gallinula pacifica*) on Savai'i (Samoa), and the Santo Mountain starling (*Aplonis santovestris*) on Espiritu Santo (Satterfield *et al*., 1998).

Turtles

Turtles tend to nest just above the high-water mark but cyclones, storm surges and heavy rainfall can inundate nests or erode sand dunes resulting in significant damage to nests and eggs. Rising sea levels, increases in wave heights, coastal erosion and increased storm intensities may all act to increase the risk of tidal inundation of nests at higher beach levels (Poloczanska *et al*., 2010).

A major concern for marine turtles with respect to the effects of global warming is the impact on hatchling sex ratios, size and quality, and therefore on population dynamics. The temperature range over which sex ratios shift from 100% male to 100% female varies between marine turtle species and populations, but in general the range lies between 1 and 4°C (Wibbels, 2002). Small changes in temperature close to the pivotal temperature (~29°C) can result in large changes in the sex ratio of hatchlings (Poloczanska *et al*., 2016). Heavy rainfalls, such as those caused by storms and cyclones, may act to re-dress the balance in sex ratios through a cooling effect on sand temperature (Poloczanska *et al*., 2010).

Mammals

Globally, the impact of climate change on marine mammals remains poorly understood, this is mainly due to the difficulty of observing species. Direct effects of climate change on marine mammals are predicted to be similar to other species, likely causing shifts in distribution and phenology (Evans & Bjørge, 2013); although many marine mammals have limited geographic distributions so range shifts may be constrained (Learmonth *et al*., 2006). Indirect effects of climate change include changes in prey availability affecting distribution, abundance and migration patterns, community structure, susceptibility to disease and contaminants. Ultimately, these will impact on the reproductive success and survival of marine mammals and, hence, have consequences for populations (Learmonth *et al*., 2006).

People and livelihoods

Coastal fisheries

Due to their proximity to the ocean and limited agricultural land of some SIDS, there is a heavy reliance on marine fisheries. Fish supplies 50–90% of dietary animal protein in rural areas (Bell *et al*., 2009). Most of the fish eaten in the region comes from subsistence fishing in coastal waters particularly around coral reefs (Bell *et al*., 2011) and the degradation of coral reefs under climate change is thought to be the greatest threat to coastal fisheries (Hoegh-Guldberg *et al*., 2014). Approximately 47% of households in the region earn a first or second income from selling fish or shellfish (Bell *et al*., 2011).

The degradation and fragmentation of reefs is likely to impact on the survival of fish that depend on coral reefs and their associated communities for food and shelter. Degraded coral reefs and populations of associated fish and invertebrates are also expected to provide fewer opportunities for aquaculture of wild-caught juveniles. Rising sea surface temperatures and more acidic oceans are projected to have direct impacts on coral reefs and the habitats and food webs they provide for reef fish and invertebrates (Hoegh-Guldberg *et al*., 2014). Degraded coral reefs are likely to support different types of fish and lower yields of some species, reducing the value of local fishing knowledge (Bell *et al*., 2011).

Oceanic fisheries

Projections continue to suggest that declines in oceanic fisheries' catch potential are likely to occur in tropical regions (Barange *et al*., 2014). Climate change drivers could impact fisheries by causing shifts in latitudinal and depth ranges, contracting and expanding distributions, changing phenology, increasing local species diversity and expansion of nutrient poor areas (Bell *et al*., 2011). Shifts in the geographic distribution of fish stocks will create fisheries winners and losers (Hoegh-Guldberg *et al*., 2014); in Fiji, a potential increase in the abundance of skipjack tuna in their EEZ could lead to an 33% increase in catch under the IPCC AR4 high emissions scenario (Bell *et al*., 2011).

Settlements and infrastructure

Almost all major services, settlement and tourism infrastructure in the Pacific islands are coastal, with only Papua New Guinea having significant infrastructure, mines and plantations and population concentrations located away from coasts (Connell, 2018). This focus on the coastal zone makes the populations extremely vulnerable to sea level rise, erosion and inundation. The effects of increased inundation can already be seen; in 2005, Vanuatu communities became the world's first "climate refugees" after being displaced due to increasing rates of inundation in low-lying areas due to a combination of tectonic subsidence and SLR (Ballu *et al*., 2011). Water resources on small islands are vulnerable to salt water intrusion due to storm surges. Erosion can also cause a reduction in the size and water quality of the freshwater aquifers, or its complete disappearance from smaller islands (Connell, 2015). Loss of naturally occurring potable freshwater may be a significant factor forcing migration of populations away from smaller islands.

Increased intensity of cyclones will increase the likelihood of damage to infrastructure and the severity of associated flooding, both coastal and riverine. Fiji, Solomon Islands and Samoa already experience severe floods after intense storms, aggravated by steep topography and land clearance, causing increased run-off and faster rainfall accumulation (Connell, 2018). In flash floods after heavy rains in Honiara (Solomon Islands) in 2014, more than 20 people lost their lives, thousands were displaced, infrastructure was compromised, and hundreds of homes were damaged or destroyed. The total cost of the damage was estimated at US$107 million (Connell, 2018).

Cultural and gender aspects
The effects of climate change are gender and culture specific, meaning that the way each gender experiences the effects of climate change depends on local customs, traditions and gender roles (Global Gender and Climate Alliance (GGCA), 2016); in many of the Pacific countries, there is an additional component of age and status-segregated roles (Straza *et al*., 2018). In many developing countries, there is a lower level of literacy amongst women, compared to men, with women making up a large percentage of agricultural workers whilst owning a relatively small percentage of the land. This is an issue in South Pacific SIDS, where the vast majority of the land is under customary tenure, meaning that custom can affect women's inheritance rights to land (Farran, 2005).

Women tend to engage more in aquaculture and gleaning fisheries as these are low skilled, require little capital and can be conducted close to home, thus women may be more affected by a decline in the coral reef that supports many of the invertebrate fishery species they depend on. In contrast, men may be disproportionately affected by shifts in the ranges of pelagic fish (Global Gender and Climate Alliance (GGCA), 2016).

Globally, women have a higher probability than men to die in natural disasters, although, for flood and storm events, specific data for women's mortality risk versus men's is lacking (Global Gender and Climate Alliance (GGCA), 2016). In Fiji, women are less likely to work outside the home than men, which can sometimes constrain the information they receive on disasters; however, they were instrumental in communicating during a 2012 flood, as many women were awake preparing food the morning of the event (Global Gender and Climate Alliance (GGCA), 2016). Women can also suffer the after effects of disasters more than men, for example, the rural practice of women eating after men in Fiji means that they can be harmed during periods of food scarcity (Charan *et al*., 2017).

Women are underrepresented at all levels of climate talks, including international negotiations. In 2015, women from Africa and the Asia-Pacific region accounted for ~35% of all national Party delegates and ~26% of the Heads of Delegations (Straza *et al*., 2018).

Tourism
Climate change can affect the tourism sector by changing the attractiveness of the climate of tourism destinations, by reducing the value of attractions at destinations, and by altering the relative climate of the home countries of tourists. (Asian Development Bank, 2013). Climate can also impact directly on environmental resources that are major tourism attractions in small islands. Widespread resource degradation challenges such as beach erosion and coral bleaching have been found to negatively impact the perception of destination attractiveness (Nurse *et al*., 2014). The AR5 has high confidence that "Developing countries and small islands within the tropics dependent on coastal tourism will be impacted directly, not only by future sea level rise and associated extremes but also by coral bleaching and ocean acidification and associated reductions in tourist arrivals" (Wong *et al*., 2014).

Tourism is a major contributor to the economy of the region. The net contribution of the tourism industry to SIDS' GDPs in 2016 ranged from 1.9% for Papua New Guinea to 44.5% for Vanuatu (See Table 1) and is projected to rise up to 2027 for all countries where data are available (World Travel and Tourism Council, 2017b, 2017c, 2017d, 2017e, 2017f). However, as evidenced by the increasing value of the tourism industry to the Pacific SIDS, there is currently no evidence that observed climatic changes in small island destinations or source markets have permanently altered patterns of demand for tourism to small islands (Nurse *et al*., 2014). As the effects of climate change become more pronounced, this may no longer be the case. A modelling study for the region has projected climate change to have a negative impact on tourism revenue for the assessed South Pacific SIDS (Figure 7) (Asian Development Bank, 2013). Rainfall levels are projected to change as the SPCZ shifts, it may be that the climate of some SIDS become less appealing to tourists (Bigano *et al*., 2007).

Table 1. The total contribution of the tourism industry to the GDP of some Pacific SIDS (World Travel and Tourism Council, 2017a, 2017b, 2017c, 2017d, 2017e, 2017f, 2018). Data not available for Tuvalu and Nauru.

Country	Tourism (total contribution) (%)
Tuvalu	*N/A*
Kiribati	*21.8*
Solomon Islands	*9*
Vanuatu	*44.5*
Samoa	*25*
Papua New Guinea	*1.9*
Nauru	*N/A*
Fiji	*40.4%*
Tonga	*18.2%*

Tourism infrastructure and development is located on along the coastal fringe of many of the SIDS, making the sector particularly vulnerable to extreme tides, wave and surge events, and SLR (Weatherdon *et al*., 2015). Sea level rise and erosion may also reduce the recreational value of beaches as they get narrower (Nurse *et al*., 2014). Loss of coral due to acidification and bleaching is likely to devalue destinations for scuba divers and snorkelers and damage from increased intensity of extreme events can further degrade the environment as well as short term visitor perception following the occurrence of extreme events (Wong *et al*., 2014).

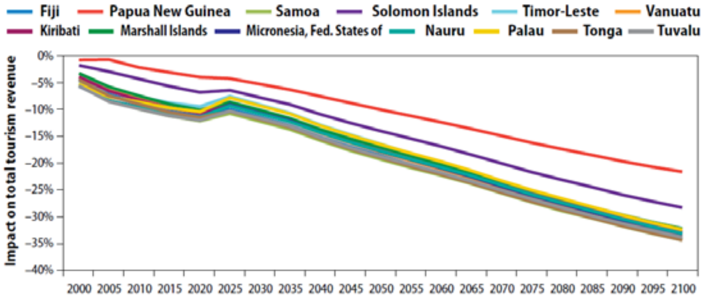

Figure 7. Tourism revenue under the IPCC A1 scenario (Asian Development Bank, 2013)

Port facilities

Seaports are vital for SIDS, facilitating inter-island travel as well as global transport for vital imports and exports, which many SIDS rely on as their main supplier of food and fuel (United Nations, 2014). Ports and associated infrastructure are located on coastal areas and vulnerable to coastal flooding caused by sea level rise, increased erosion and storm surges (Becker *et al*., 2013). The likelihood of damage to infrastructure during storms and cyclones will increase as the intensity of storms increases, exacerbated by the decreasing coastal protection offered by declines of mangroves, seagrass and coral reefs. Increased intensity of winds may also increase periods of downtime when it is not safe to carry out operations and increased rainfall may also impede associated activities such as road transport to and from ports during periods of flooding (United Nations, 2014). Higher rates of coastal erosion may also cause increase sedimentation of shipping channels, requiring more frequent maintenance dredging to admit larger vessels (Becker *et al*., 2013).

Human health (ciguatera, harmful algae):

As well as the direct health impacts caused by climate change drivers, such as risk of injury or death due to increased intensity of extreme weather events, there are also indirect effects. Increased levels of flooding from SLR and inundation will increase the risks associated with food and water security and vector borne diseases (McIver *et al*., 2016). During 2002–03 when Vanuatu experienced five cyclones, the incidence of malaria doubled that of the preceding year (Lal *et al*., 2009). The limited documentation on water-borne or vector-borne (e.g. typhoid fever, malaria and dengue) disease information from the Pacific islands indicates the high health risk created by cyclones persists long after the cyclone has passed. Low-lying islands and atolls are the most seriously affected as they rely on water from shallow and fragile ground-water lenses (Mosley *et al*., 2004). Increasing SST alters host/pathogen interactions, increasing infectious disease outbreaks, this may increase the outbreaks of diseases like Ciguatera; Funuafuti, Tuvalu experienced an outbreak of Ciguatera in 2012 (McCubbin *et al*., 2015).

The associated stresses of adapting to climate change may also have impacts on mental health in response to the detrimental effects of social disruption related to enforced migrations, loss of livelihoods, injuries, disease or death (McIver *et al*., 2016). McIver *et al.* (2016) suggest that there could be a significant effect of climate change on non-communicable diseases (NDCs), such as heart disease and cancer, via interaction between climate change phenomena and other factors driving the burden of NCDs, such as physical inactivity, food insecurity, and poor nutrition (Figure 8).

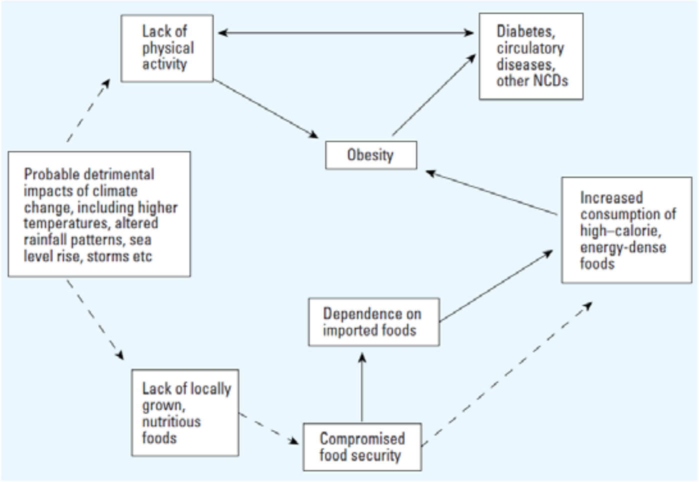

Figure 8. Conceptual model summarizing the pathways between climate change and NCDs (broken arrows represent hypothetical links), taken from McIver *et al.* (2016).

Adaptation options

The Pacific SIDS have been restively well studied in terms of vulnerability, risk and adaptation assessment methods, compared to other SIDS (Hay & Mimura, 2013; Nurse *et al*., 2014). However, the Pacific has been identified as one of the World's most at risk regions (Woodward *et al*., 2000), so adapting to climate change requires the SIDS to build resilience across the various sectors discussed above.

Physical:

Effective adaptation must be informed by a sound understanding of the risks. For this reason, it is vital that the physical parameters are monitored to create long term timeseries, provide a baseline for modelling and to better disentangle short term, e.g. daily and seasonal variance from long term change in climate. This knowledge will inform the basis of all other adaptation.

The Australian Government facilitated the Pacific Climate Change Science Program (PCCSP) and Pacific-Australia Climate Change Science Adaptation Planning (PACCSAP) programmes which have been extremely active in making data available via databases, and science tools web portals (summarised in CSIRO *et al*., 2015). The Secretariat of the Pacific Regional Environment Programme (SPREP) and many other agencies have been instrumental in supporting the projects to summarise the effects of climate change in the Pacific region and its future consequences (e.g., Lal *et al*., 2009, CSIRO *et al*., 2015) and this information is vital for the region to adapt to its changing climate. It is important that these projects continue to be supported to provide the long data series which will allow users to better constrain the differences between signals of natural variability and long term climatic changes.

Many of the more robust projections of future climate change effects are a Pacific-wide or even global scale. Downscaling modelling so that it focuses on a more local scale would allow predictions that take into account local factors that may improve the accuracy of predictions, providing a quantification of the probability, speed, scale, or distribution of future climate risks. This would be a powerful adaptation tool for managers who would have better information about high-risk areas to inform the implementation of targeted solutions. This approach has been demonstrated to be effective in disaster risk management in Vanuatu and Samoa with good results to assess seasonal variability in the likelihood of climate related hazards, such as droughts and floods (CSIRO *et al*., 2015).

Biological:

Coastal and marine ecosystems, such as seagrasses, coral reefs and mangroves can provide natural adaptation to erosion, inundation from storm surges and damage from storm waves (Spalding *et al*., 2014). They can also promote accretion and create conditions that are conducive to wetland reproduction (Guannel *et al*., 2016 and references therein). Recent research has shown that, while mangroves are the best single habitat for protection from storm and non-storm conditions, a combination of live coral reefs, mangroves and seagrasses are the most effective form of coastal protection, compared to any single habitat or combination of two habitats (Guannel *et al*., 2016).

Blue Carbon is the carbon stored in vegetated marine ecosystems, i.e. mangroves, seagrasses and saltmarshes. The carbon is stored in both the living plants (their leaves and root structures) and the organic matter in the soils, thus, the whole habitat is important for carbon sequestration (Sifleet *et al*., 2011). Coastal habitats store a disproportionate amount of carbon per square metre compared to tropical forests (McLeod *et al*., 2011) (Figure 9) and so, their conservation is vital for climate change adaptation as removal or destruction of the habitat will cause a large amount of carbon to be released. These are important ecosystems distributed in the Pacific – mangroves in the Federated States of Micronesia equate to 12% of its land area, and 10% in Papua New Guinea and Palau (“Pacific Blue Carbon Initiative: Promoting Coastal Blue Carbon Ecosystems at COP23 - Cop23,” 2017). The protection and regeneration of the SIDS’ mangrove and seagrass habitats are an important climate change adaptation mechanism as they will provide coastal protection from increasing intensity of storms, habitat for fish, invertebrates and mammals as well as sequestering large amounts of CO_2.

The Pacific islands are global leaders in bringing Blue Carbon conservation into future actions under the Paris Agreement via inclusion in countries’ Nationally Determined Contributions (including Fiji, Marshall Islands and Vanuatu). The Pacific governments participate in the International Partnership for Blue Carbon which plans to map these ecosystems, promote the importance of bringing Blue Carbon into future actions under the Paris Agreement, and explore action required to strengthen protection and restoration efforts including private sector investment. These types of initiatives could be achieved through high-level events such as the COP co-hosted by Fiji and Australia (“Pacific Blue Carbon Initiative: Promoting Coastal Blue Carbon Ecosystems at COP23 - Cop23,” 2017).

A recent study has shown that seagrass beds can help to combat ocean acidification at local scales as they remove CO_2 from seawater when they photosynthesise. The effect varies on a daily scale (as plants respire during the night which releases CO_2) and over seasonal scales (as during winter photosynthesis is lower). Nevertheless, over long timescales, it is thought that seagrasses increase local pH (Nielsen *et al*., 2018). This suggests that cultivation of seagrass beds near reefs and shellfish fisheries may be a good adaptation response to ocean acidification.

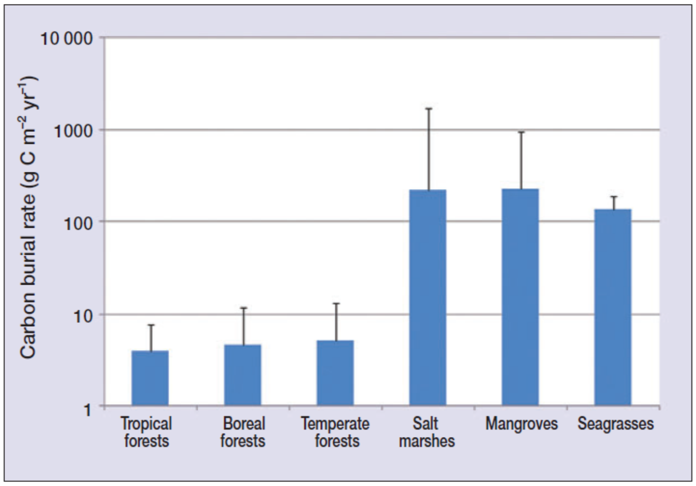

Figure 9. Mean long-term rates of carbon storage in grams carbon per metre squared per year (g C m^{-2} yr^{-1}) in soils in terrestrial forests and sediments in vegetated coastal ecosystems. Error bars indicate maximum rates of accumulation. Note the logarithmic scale of the y axis (McLeod *et al*., 2011).

Consideration of all aspects of climate change in marine spatial management is important to ensure long term resilience under a changing climate. Marine Protected Areas (MPAs) and Locally Managed Marine Areas (LMMAs) are important for creating refuges from other stressors, such as overfishing, that will build resilience in ecosystems to be able to cope with climate change impacts. Strictly protected MPA networks in coastal Blue Carbon habitats can ensure that no new emissions arise from the loss and degradation of these areas. At the same time, they stimulate new carbon sequestration through the restoration of degraded coastal habitats. improving the ability of marine organisms to adapt to climate change. A well connected network of MPAs can improve connectivity of species populations and provides areas for them to migrate into in response to local stressors (IUCN, 2017). Conservation planners should consider all possible interactions between connectivity and climate change that might act on species occurrences and abundances and influence the future efficacy of MPAs (Magris *et al*., 2014). In Fiji, connectivity studies have already been used to prioritise protection and spatial management of reef fishery species (Eastwood *et al*., 2016).

The region already has a very well-established network of LMMAs, mainly engaged in the management of small scale, local fisheries. Locally managed marine areas have the advantage of flexibility in their management strategy, providing greater resilience in changing conditions as they are able to switch fisheries as a risk aversion strategy (Conservation International, 2013). To provide increased adaptive capacity, it is important that climate change is factored into management plans of existing LMMAs and the design of new areas. Management portfolios should be strengthened in the climate change strategies to ensure that the correct adaptive management can continue to be applied (Le Cornu *et al*., 2017).

People:

To be truly robust and sustainable, adaptation to climate change in the SIDS should consider the needs of all its members. Over the past decade, the South Pacific has designated a wide range of Marine Managed Areas (MMAs). These initiatives have combined local knowledge and governance, combined with a strong understanding of fisheries and community types. These designations have often been successful as these recognize the need to maintain or improve livelihoods, often in connection to minimize threats to food security and overall revenues (e.g. Hamilton *et al*., 2011). Despite the increasing inclusion of local knowledge in adaptation planning, Pacific island women are underrepresented, both globally and locally. This can often be detrimental to the outcome as, when traditional roles are highly gendered, information is lacking on certain sectors when women are excluded from talks (Habtezion, 2012).

Awareness raising, education and improved communication across islands are important tools for building resilience. Communities' level risk associated with climate change is also linked to awareness and information sharing. The remote nature of communities in rural areas and outer islands ("periphery") of archipelagic countries such as Fiji, Kiribati, and Vanuatu, means that their climate change knowledge often suffers in comparison with communities in the major centres ("core"). In the core, communities tend to be better informed and have higher levels of awareness about the complex issues associated with climate change than in the periphery (Nurse *et al*., 2014).

Due to the SIDS' proximity with the marine environment, it is essential that resilience to the effects of marine climate change is built into various economic sectors. Sectors such as fisheries, which directly rely on natural recourses, could benefit from an ecosystem-based management to minimise other stressors that may interact with climate change drivers. All sectors should develop climate change risk management plans that are specific to the sector (Welch and Johnson, 2017).

Knowledge Gaps

Contemporary models are not sufficiently downscaled to produce useful projections that support local adaptation. For example, typical global climate model grid cell size is 50-100 km^2, and the total land area of Nauru and Tuvalu is 21 and 26 km^2, respectively. Even for SIDS with larger total land area, this is usually composed of many small islands and granularity in model outputs prevents any localised predictions to be made.

There is low agreement on how large scale climate drivers, such as ENSO, will be affected by climate change (Hoegh-Guldberg *et al*., 2014), this is particularly pertinent for the Pacific SIDS as this will limit the capacity to predict changes to the position of the SPCZ, and the impact that this will have on rainfall, droughts, wave climate and cyclogenesis.

Some SIDS, such as Kiribati, are spread over large distances, meaning that there is great heterogeneity of habitat and pressure on one country. It is important to address this complexity in projections and adaptation methods as local factors may affect the efficacy of measures that have successfully applied elsewhere (Nurse *et al*., 2014).

A recent review on the topic of tropical cyclone formation and climate change, published since the production of the IPCC AR5, highlights that there is still little agreement between different models on how regional cyclogenesis will be affected (Walsh *et al*., 2016).

Potential impacts of climate change on Blue Carbon habitats in the Pacific islands region have been extensively reviewed, but there are still limited available data on the current location, health and status of Pacific island Blue Carbon habitats (Ellison, 2018). These habitats are vital to the overall health of the ecosystem and present significant opportunities for adaptation and mitigation strategies (Nielsen *et al*., 2018; Sifleet *et al*., 2011; Temmerman *et al*., 2013); a better basic understanding would facilitate future work.

The physical science and effects of climate change on biodiversity are not well linked to the real social and economic costs. A better understanding of these costs will help to identify appropriate adaptation strategies to minimise these costs (Nurse *et al*., 2014).

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