ADB

# Technical Assistance Consultant's Report

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# Regional: Strengthening Climate and Disaster Resilience of Investments in the Pacific

## Sea Level Change in the Pacific Islands Region

## - A Literature Review to Inform Asian Development Guidance on What Projections to Use in Climate Risk and Adaptation Assessments

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For Asian Development Bank



Asian Development Bank

## ABBREVIATIONS

| | | |
|---|---|---|
| ADB | – | Asian Development Bank |
| AEP | – | Annual Exceedance Probability |
| AR4 | – | Fourth Assessment Report from the IPCC |
| AR5 | – | Fifth Assessment Report from the IPCC |
| ARI | – | Average Recurrence Interval (years) |
| CMIP | – | Coupled Model Intercomparison Project |
| CSIRO | – | Commonwealth Scientific and Industrial Research Organisation |
| ENSO | – | El Niño/Southern Oscillation |
| GCM | – | General Circulation Model (or Global Climate Model) |
| IOD | – | Indian Ocean Dipole |
| IPCC | – | Intergovernmental Panel on Climate Change |
| IPO | – | Interdecadal Pacific Oscillation |
| ITCZ | – | Intertropical Convergence Zone |
| MJO | – | Madden Julian Oscillation |
| PARD | | ADB Pacific Regional Department |
| PCCSP | – | Pacific Climate Change Science Program |
| PIR | – | Pacific islands region |
| PDO | – | Pacific Decadal Oscillation |
| RCP | – | Representative Concentration Pathway |
| SAM | – | Southern Annular Mode |
| SPCZ | – | South Pacific Convergence Zone |
| SRES | – | Special Report on Emission Scenarios |
| SST | – | Sea Surface Temperature |
| TC | – | Tropical Cyclone |
| UNFCCC | – | United Nations Framework Convention on Climate Change |
| WMO | – | World Meteorological Organization |
| WPM | – | West Pacific Monsoon |

## NOTES

(i) In this report, $ refers to US dollars.

## CONTENTS

## EXECUTIVE SUMMARY

1. The Asian Development Bank (ADB) Pacific Regional Department (PARD) supports developing countries in the Pacific islands region (PIR) via activities including: (i) regional development forums and infrastructure finance; (ii) regional projects focused on renewable energy, marine and coastal management; and (iii) strengthening disaster preparedness. PARD's regional technical assistance also contributes to developing capacity for public financial management, statistics, and data collection.

2. The PIR, especially the western tropical Pacific, is particularly vulnerable to sea level rise (SLR) because of: (i) high shoreline to land area ratios; (ii) high sensitivity to changes in coastal sea level, waves and currents; combined with (iii) low-lying coral atolls, reef or volcanically composed islands.

3. Given this vulnerability of the PIR to SLR, how precautionary should PARD be when dealing with SLR in the Pacific? Which source, or combination of sources, for SLR projections should PARD use in climate risk and adaptation assessments (CRAs) and what should be considered when ADB is investing in the PIR? To address these questions, a literature review was undertaken to establish which source(s) of SLR projections are credible for the PIR, as well as the strengths, weaknesses and uncertainties associated with various sources of information on SLR in the PIR.

4. Projections from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) suggest that it is unlikely that SLR in the PIR will exceed one meter by 2100. This information is widely used (by ADB and others) to assess and manage SLR related risks in the PIR – with allowance and adaptation for SLR of up to one meter considered sufficiently precautionary for projects with operational life-times of less than 100 years. However, the key finding from this review is that there are several reasons why such an approach may not always be adequate:

(i) Although there is very high confidence in the direction of change for all PIR locations (i.e. a decrease in sea level is not projected anywhere in the PIR), there is only medium confidence in the magnitude of change. Nevertheless, for most locations in the PIR where location-specific analysis has been conducted and when the impacts of natural climate variability are considered, SLR by the end of the 21st century is projected to be greater than one meter.

(ii) Recent work, that has emerged since the IPCC AR5 was published, demonstrates that not only is SLR greater than one meter likely by the end of the 21st century but it is conceivable that SLR could exceed two meters by 2100. It is also important to note that SLR will not stop at 2100.

(iii) Some paleoclimate records suggest that SLR of 5 meters in a century has occurred before and that SLR of 6-9 meters is possible if temperatures become 1 °C warmer than they are now (which they are projected to do before 2100). However, the consensus view is that such extreme SLR would happen over very long periods (centuries to millennia) and is unlikely to occur before 2100.

(iv) Short-term variability in sea level caused by storm surge, wave climate and/or wave power has the potential to significantly increase local coastal water heights above what is expected as a result of changes to absolute sea level (i.e. changes to long-term average sea level). The reverse is also true – higher baseline sea levels increases impacts and damages associated with short-term sea level variations. This is especially true in the PIR, particularly the western tropical Pacific, because of the high exposure to tropical cyclones (TCs) and other tropical storms, high shoreline to land area ratio, high exposure to waves and currents, combined with low-lying coral atolls, reefs or volcanically composed islands.

(v) Based on observed data collected over the last ~20 years, most islands in the PIR are subsiding (i.e. have negative vertical land movements). Therefore, irrespective

of any other influence, the effect of SLR will be magnified where the land is falling and this appears to be the case for much of the PIR.

5. The findings of this review highlight the need for a more precautionary approach when considering SLR impacts in CRAs for the PIR – that is, there is a need to consider higher-end scenarios as the latest science suggests that SLR greater than one meter is likely at some point in the 21st century and SLR of two meters by 2100 is plausible (noting also that SLR will not stop at 2100). Therefore, it is advised that a precautionary approach for ADB CRAs in the PIR requires that a 2 meter SLR by 2100 scenario be used. Scenarios greater than 2 meters should be considered for projects with expected life-time beyond 2100. These SLR scenarios should feed into sensitivity analyses of the costs and benefits of additional climate proofing. Adaptive management approaches could also address higher SLR, noting this needs to consider the lifetime, risk of lock-in, and level of precaution associated with investments. Where warranted (i.e. at sites with high exposure and/or vulnerability), extra allowance should also be made for the influence of natural climate variability, tropical cyclones, storm surge, wave climate and wave power. Exactly what that allowance should be will depend on the type of project and the location within the PIR, as well as the appetite for risk and expected life-time of the project.

6. Options are provided for future phases of work required to develop and implement the recommendations on incorporating credible SLR projection information into ADB CRAs in the PIR. These include defining the objectives of each phase, tasks within each phase, estimated time for each task, and skills/personnel required. The approach for assessing and dealing with SLR in the PIR could be linked to the SLR calculator, and associated Knowledge Product, that ADB has already developed for Vietnam – so there is transparency and consistency in the approach across ADB.

# I. INTRODUCTION

## A. Brief project description

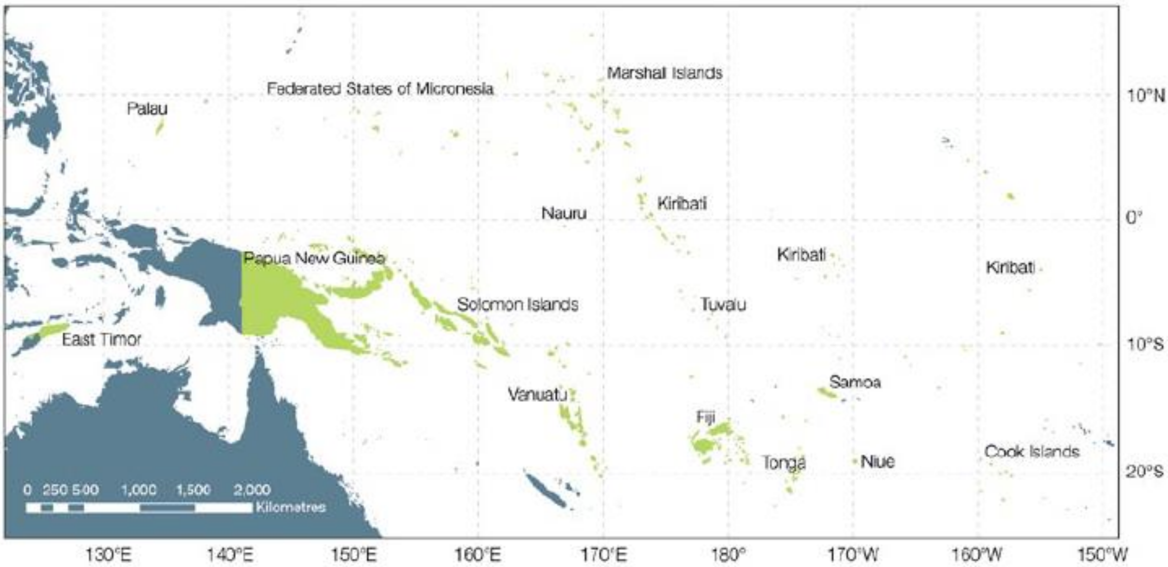
7. The Asian Development Bank (ADB) Pacific Regional Department (PARD) supports developing countries in the Pacific islands region (PIR) (Figure 1) via activities including: (i) regional development forums and infrastructure finance; (ii) regional projects focused on renewable energy, marine and coastal management; and by (iii) strengthening disaster preparedness. PARD's regional technical assistance also contributes to developing capacity for public financial management, statistics, and data collection.

8. The PIR (Figure 1), especially the western tropical Pacific, is particularly vulnerable to sea level rise (SLR) (Church et al., 2006) because of: (i) high shoreline to land area ratios (Barnett, 2001); (ii) high sensitivity to changes in coastal sea level, waves and currents (Becker et al., 2012); combined with (iii) low-lying coral atolls, reefs or volcanically composed islands (Connell, 2013).

9. Given this vulnerability of the PIR to SLR, how precautionary should PARD be when dealing with SLR in the Pacific? Which source, or combination of sources, for SLR projections should PARD use in climate risk and adaptation assessments (CRAs) and what should be considered when ADB is investing in the PIR? To address these questions, a literature review was undertaken to establish which source(s) of SLR projections are credible for the PIR, as well as the strengths, weaknesses and uncertainties associated with various sources of information on SLR in the PIR.

10. Once credible sources for SLR projection information are identified, PARD requires advice based on review of the latest science and good practice, to assist with the development of PIR specific guidance on how SLR projection information should be incorporated at the ADB project level (e.g. at the Project Feasibility and CRA stages). Note that this has been done for other regions within the ADB portfolio (e.g. Vietnam) and the approach for assessing and dealing with SLR in the PIR should be linked to this existing work so there is consistency in approach across ADB.

**Figure 1: Pacific Ocean island nations and territories (shaded green) considered in this review (Source: Australian Bureau of Meteorology and CSIRO, 2011).**



## B. Objectives and scope of this report

11. The objectives of this report are to:

- Summarize the state of understanding about the causes and impacts of SLR across the PIR, how sea levels across the PIR have changed in the past, and how sea levels across the PIR are projected to change in the future;
- Identify what sea level change data (historical) and projections (future) exist for the PIR and evaluate their relative strengths and weaknesses;
- Document the major uncertainties and science challenges that exist in relation to understanding and quantifying past and future sea level change in the PIR;
- Provide advice, based on the latest science and good practice, to assist PARD in developing PIR specific guidance on how to incorporate credible SLR projection information at the ADB project level (e.g. at the Project Feasibility and CRA stages);
- Offer recommendations on phases of work required to develop and implement the guidance on incorporating credible SLR projection information at the ADB project level. This includes the objectives of each phase, along with associated tasks, their estimated time and skills/personnel required to implement.[1]

[1] This includes recommendations on what tasks should be done as desktop studies, which should be tackled via meetings/workshops involving relevant experts (key people that should be invited will be identified), and which require field work or data collection activities.

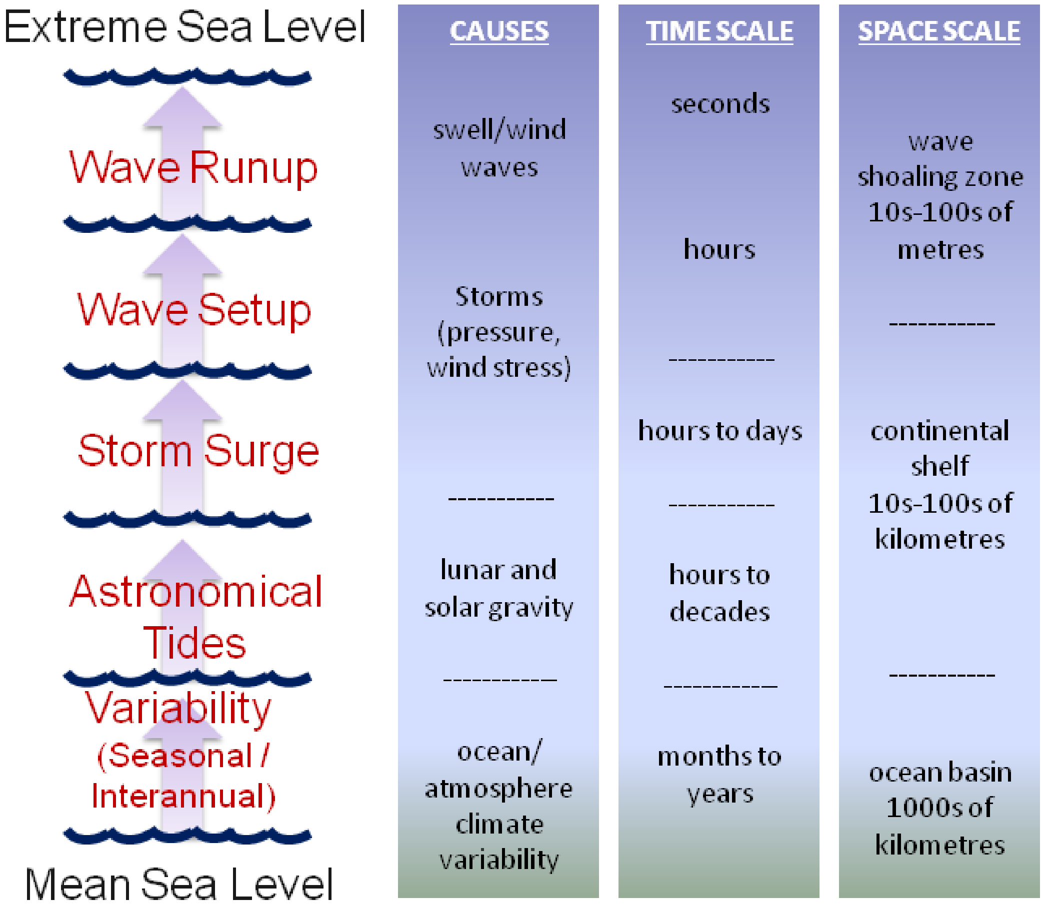
# II. UNDERSTANDING SEA LEVEL CHANGE IN THE PACIFIC ISLANDS REGION

## A. Causes of sea level change in the Pacific islands region (PIR)

12. Sea level changes can occur because of individual factors (e.g. storm surge), but more commonly arise from a combination of natural phenomena that individually may not be extreme (McInnes et al., 2016). These natural phenomena occur on a range of time and space scales (Figure 2) in any given PIR coastal location, and thus the contribution of each phenomenon to extreme sea levels varies. For example:

- Sea level variability is high over the PIR, where monthly, seasonal and interannual sea level anomalies are highly correlated with ocean-atmospheric modes like the El Niño/Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (e.g. Oliver and Thompson, 2010; Becker et al., 2012; Zhang and Church, 2012, White et al., 2014). See Section B for further details.
- Astronomical tides vary over multiple timescales (e.g. diurnal and semi-diurnal, fortnightly with spring and neap tides, and on seasonal to interannual timescales) and are often the largest contributor to both sea level variability and annual maximum sea level elevation (relative to mean sea level) in the PIR (Stephens et al., 2014), especially for PIR locations that are not influenced by tropical cyclone (TC) activity (Merrifield et al., 2007). Astronomical tides also vary in space with the highest spring tides across the PIR ranging from 0.6 m in French Polynesia and the Cook Islands to ~2 m in eastern Micronesia (Ramsay, 2011).
- Storm surges are gravity waves arising from the inverse barometric effect and wind stress (Walsh et al., 2012; McInnes et al., 2016). The former elevates sea levels by approximately 1 cm for every 1 hPa drop in atmospheric pressure relative to surrounding conditions. Wind stress refers to winds blowing from the ocean to the land and this causes an increase in sea levels (i.e. wind setup), particularly within semi-enclosed bays and/or under severe wind such as that produced by TCs. The magnitude of storm surge is also determined by storm track, storm intensity, bathymetry and the shape of the coastline.
- Wave setup is the increase in water level landward of the breaking point of waves (Hoeke et al., 2013; McInnes et al., 2016). The magnitude of wave setup increases with the breaking height of the wave. Because wave setup is caused by breaking waves, sheltered coastal areas such as harbors and lagoons, generally do not experience these effects. This is worth noting because sheltered coastal areas are the typical location for tide gauges meaning the impacts of wave setup on sea level changes are typically not captured in tide gauge data.
- Wave runup is the additional height reached by a wave on a beach before its energy is dissipated due to gravity and friction (Hoeke et al., 2013; McInnes et al., 2016). The magnitude of wave runup increases with the breaking height of the wave and is exacerbated when sea level is already elevated due to the factors mentioned in previous points (i.e. seasonal to interannual variability, tides, and/or storm surge). As with wave setup, wave runup is only relevant for locations where waves break and the impacts of wave runup are also typically not captured in tide gauge data.

**Figure 2: From McInnes et al. (2016). Oceanic phenomena that contribute to the total water levels at the coast during an extreme sea level event, their causes and the time and space scales over which they operate.**



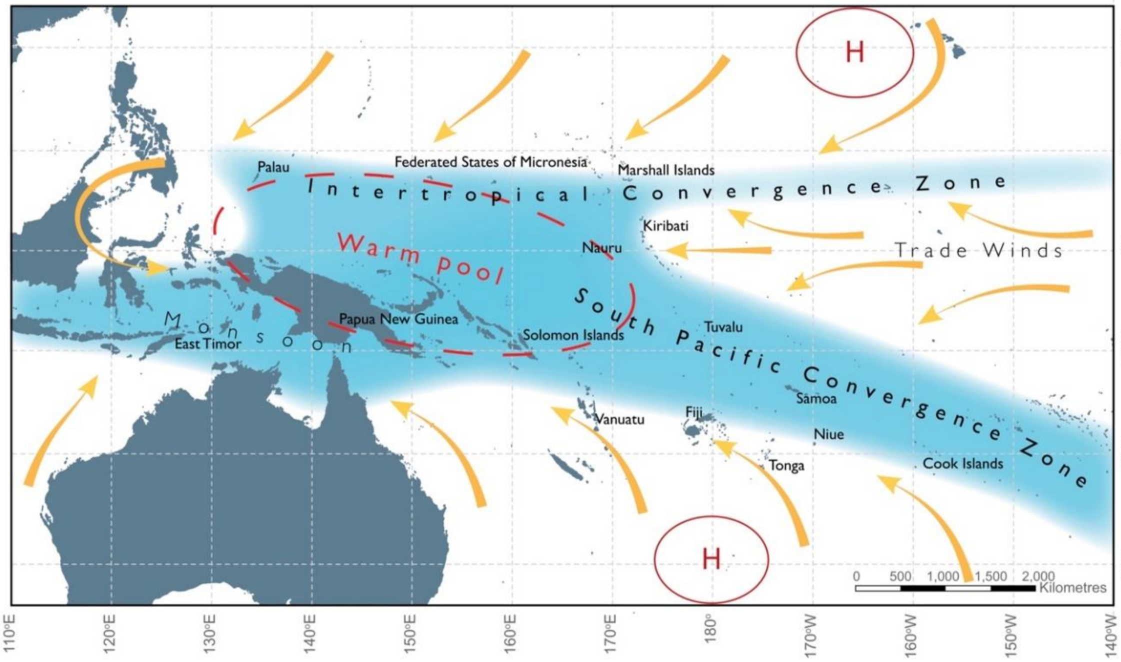

**B. Weather and climate influences on sea level change in the Pacific islands region (PIR)**

13. The PIR has numerous weather and climate processes driving sea level variability and change. Complex interactions between the ocean and atmosphere result in the continual exchange of heat and water, driven by prevailing winds to achieve dynamic/thermodynamic equilibrium. Figure 3 summarizes the weather and climate processes that influence the PIR between November and April (i.e. the TC season where storm surge and other short-term SLR events are most common). These climate influences operate over different temporal and spatial scales, from intra-seasonal to interdecadal. Also, given the spatial extent of the PIR, various climate phenomenon can influence different locations within the PIR in various ways.

14. TCs account for 76% of disasters within the PIR and bring extreme winds, intense storm surge, and prolonged rainfall with fluvial, pluvial and coastal flooding (Terry et al., 2004; McInnes et al., 2011; Brown et al., 2016). The highest observed coastal water levels in the PIR typically range between 4-6 m. However, TC Tomas (March 2010) generated a storm surge of 7 m around the Lau Island Group in Fiji (Needham et al., 2015). TC induced storm surges can be observed at vast distances from a TC system. For example, TC Pam produced significant storm surge that impacted Tuvalu, approximately 1100 km to the northeast of the storm system. TCs also produce significant wave heights which lead to extreme coastal water levels as a result of wave setup and runup for locations that are not sheltered from waves. For instance, TC Ofa (February 1990) generated a storm surge of 1.6 meters with significant wave

heights of 8.1 meters south of Samoa and up to 18 meters on the island of Niue (Solomon and Forbes, 1999).

**Figure 3: Weather and climate processes that influence the PIR between November and April. Yellow arrows indicate near-surface winds. Red dashed region indicates the typical location of the Pacific Warm Pool (i.e. during years classed as the Neutral phase of the El Niño/Southern Oscillation (ENSO)). High-pressure systems are indicated by H.**[2]




15. Coupled ocean-atmospheric modes such as ENSO cause substantial seasonal to interannual sea level variations across the PIR region (e.g. Church et al., 2006). During La Niña events, strengthened westerly winds and intensification of the Walker Circulation result in the displacement of the Pacific Warm Pool towards the west, resulting in sea levels that are up to 20-30 cm higher than normal in the western PIR (e.g. Becker et al., 2012). Since 1970, there is evidence of a potential intensification of La Niña related sea level anomalies (Becker et al., 2012). Conversely, El Niño results in the displacement of the Pacific Warm Pool towards the east, resulting in sea levels that are up to 20-30 cm lower than normal in the western PIR. During El Niño events, increased wave heights and an anticlockwise rotation of wave direction is typically observed in the eastern equatorial Pacific (Hemer et al., 2011).

16. Other aspects of ENSO also influence sea levels in the PIR. ENSO is typically characterized by anomalously warm sea surface temperature (SST) (for El Niño) or cool SST (for La Niña) in the eastern equatorial Pacific. El Niño Modoki (also known as the Central Pacific El Niño or the Dateline El Niño) (e.g. Ashok et al., 2007) is associated with anomalous SST warming and associated SLR in the central tropical Pacific and anomalous SST cooling in the eastern and western tropical Pacific. Conversely, La Niña Modoki is associated with anomalous SST cooling in the central tropical Pacific and anomalous SST warming and associated SLR in the eastern and western tropical Pacific. El Niño Modoki conditions have become more frequent since 2002 resulting in increased sea levels in the central PIR (e.g. Becker et al., 2012).

17. Interdecadal climate variability also influences sea levels across the PIR, particularly via the modulation of the frequency of El Niño and La Niña impacts during the different IPO

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[2] Source: https://www.pacificclimatechangescience.org/wp-content/uploads/2013/06/Climate-in-the-Pacific-summary-48pp_WEB.pdf.

phases (e.g. Kiem et al., 2003; Magee et al., 2017). Since negative IPO phases are associated with more La Niña events than positive IPO phases, negative IPO epochs (e.g. ~1945-76, ~1999-present) are associated with an intensification and expansion of the elevated sea levels in the western PIR that are typical under La Niña events (e.g. Becker et al., 2012). This is supported by reports of increases in non-TC related coastal inundation events in the western Pacific (e.g. Kiribati, Tuvalu and the Marshall Islands) since 1998 (e.g. Ramsay, 2011).

## C. Terrestrial factors that influence relative sea level change in the Pacific islands region (PIR)

18. The impacts of SLR (e.g. coastal flooding, inundation, erosion, salinization), are influenced by terrestrial factors such as vertical land movements and geomorphology (e.g. McInnes et al., 2016). In addition to long-term vertical land movement from Glacial Isostatic Adjustment (GIA), local vertical land movements due to tectonic movement and volcanism have been found to produce larger vertical movements than decadal changes in absolute sea level. This is particularly the case for Vanuatu and Tonga which are situated close to active plate boundaries (Ballu et al., 2011). In April 1997, a magnitude 7.8 earthquake occurred near the Torres Islands, Vanuatu, and resulted in subsidence of between 0.5-1 m. This contributed to a significant rise in relative sea level, and an increase in coastal inundation and flooding extent over subsequent years (Ballu et al., 2011; Ramsay, 2011).

19. Vertical land movements also occur due to human activities such as gas and groundwater extraction, urbanization and sediment consolidation (Becker et al., 2012; McInnes et al., 2016). Vertical movements in the PIR are monitored using tide gauge records and Global Positioning System (GPS) technologies. However, less than 20 inhabited islands in the PIR have such systems in place to monitor land movement.

20. Analysis of land-based Global Navigation Satellite System (GNSS) stations provides insights into vertical land movement in the PIR (Table 1). These records are typically short (ranging between 4.5 years for French Polynesia (Tubuai) up to 17 years for New Caledonia (Lifou)) and many are not continuous. Most stations listed in Table 1 are subsiding and this amplifies the impact of increases in relative sea levels. This is particularly the case for the Torres Islands (Vanuatu), where absolute sea level rose by 150 ± 20 mm between 1997 and 2009. However, GPS data reveal that some sites in the Torres Islands (Vanuatu) subsided by up to 117 ± 30 mm over the same period, almost doubling the effective SLR (see also Ballu et al. (2011) for further information).

**Table 1: Vertical land movements in the PIR as measured by Global Navigation Satellite System (GNSS) stations[3].**

| Station | Period of data (month/year) | Time span (years) | Data availability (% complete) | Total vertical land movement (mm) | Vertical land movement (mm/year) |
|---|---|---|---|---|---|
| Cook Islands (Rarotonga) | 9/2001-6/2019 | 12.30 | 75.02 | -6.15 ± 4.43 | -0.50 ± 0.36 |
| Fiji (Lautoka) | 11/2001-9/2019 | 12.10 | 85.00 | -13.92 ± 3.15 | -1.15 ± 0.26 |
| French Polynesia (Tubuai) | 5/2009-10/2017 | 4.53 | 84.52 | -1.49 ± 2.36 | -0.33 ± 0.52 |

[3] https://www.sonel.org/-Vertical-land-movement-estimate-.html?lang=en.

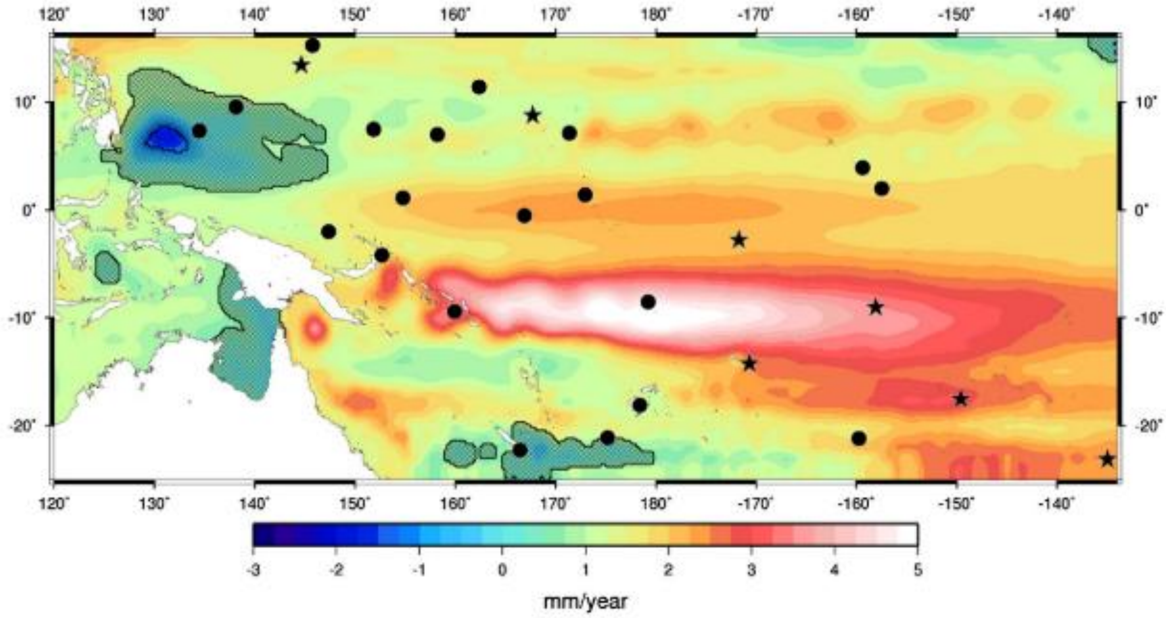
| | | | | | |
|---|---|---|---|---|---|
| French Polynesia (Papeete) | 12/2003-9/2019 | 9.96 | 83.24 | -19.32 ± 2.29 | -1.94 ± 0.23 |
| French Polynesia (Tahiti-Faaa) | 10/2006-9/2019 | 7.20 | 71.05 | -12.96 ± 3.24 | -1.80 ± 0.45 |
| French Polynesia (Rikitea) | 4/2000-9/2019 | 10.49 | 45.97 | -10.8 ± 4.20 | -1.03 ± 0.40 |
| Futuna | 9/1998-9/2019 | 15.26 | 57.78 | -4.27 ± 3.97 | -0.28 ± 0.26 |
| Kiribati (Betio Island) | 7/2002-9/2019 | 11.41 | 85.72 | -2.51 ± 2.74 | -0.22 ± 0.24 |
| Nauru | 6/2003-9/2019 | 10.50 | 76.18 | -10.08 ± 2.63 | -0.96 ± 0.25 |
| New Caledonia (Noumea) | 7/1997-3/2007 | 9.28 | 96.31 | -12.99 ± 2.60 | -1.40 ± 0.28 |
| New Caledonia (Noumea) | 5/2006-9/2019 | 7.62 | 92.02 | -14.17 ± 1.75 | -1.86 ± 0.23 |
| New Caledonia (Lifou) | 3/1996-9/2019 | 17.40 | 91.12 | 2.96 ± 7.66 | 0.17 ± 0.44 |
| New Caledonia (Koumac) | 4/1996-9/2019 | 17.69 | 88.86 | -2.83 ± 3.18 | -0.16 ± 0.18 |
| Papua New Guinea (Lae) | 1/2001-8/2019 | 11.30 | 56.13 | -57.44 ± 3.06 | -5.07 ± 0.27 |
| Papua New Guinea (Manus Island) | 5/2002-9/2019 | 11.66 | 80.83 | -31.37 ± 5.25 | -2.69 ± 0.45 |
| Samoa | | | | Unreliable because of station problems | |
| Solomon Islands (Honiara) | | | | Variable/unreliable because of common occurrence of earthquakes | |
| Tonga (Nukualofa) | 2/2002-9/2019 | 11.86 | 80.90 | 35.7 ± 4.86 | 3.01 ± 0.41 |
| Tuvalu (Funafuti) | 11/2001-2/2019 | 12.05 | 70.28 | -20.61 ± 2.05 | -1.71 ± 0.17 |
| Vanuatu (Torres Islands) | 1/1997-12/2009 | 13.00 | 94.00 | -117 ± 30 | -9.00 ± 3.33 |

# III. HISTORICAL SEA LEVEL CHANGE IN THE PACIFIC ISLANDS REGION

## A. Instrumental period (~1950 to present)

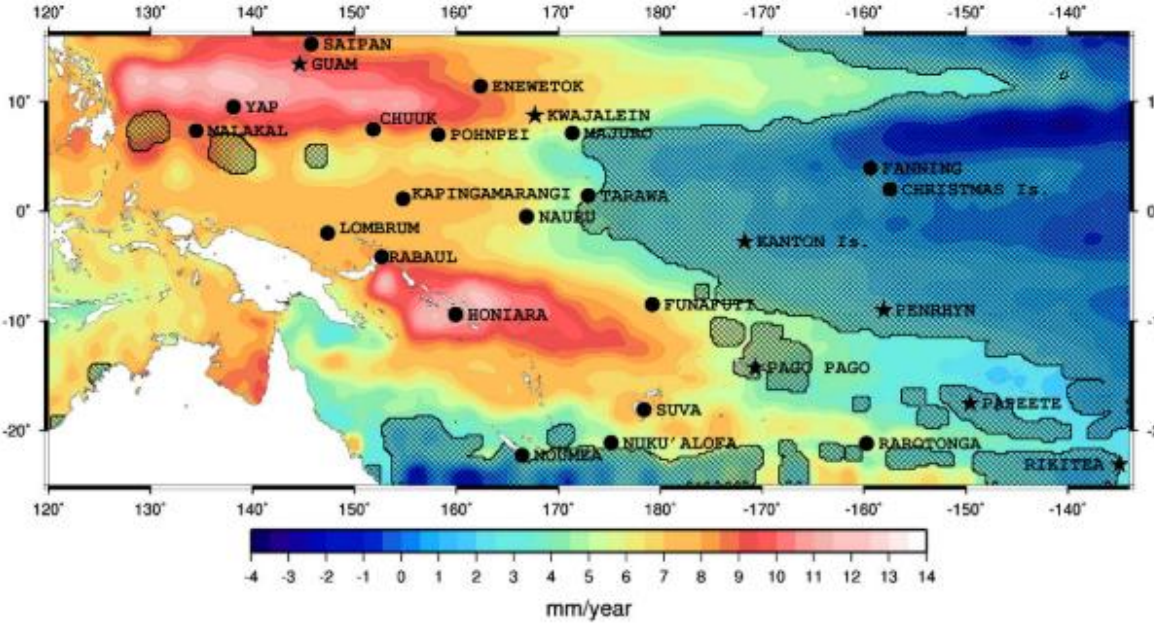
21. Since 1950, tide gauge observations indicate that global mean sea level rose by an average rate of ~1.7 mm/year (Church and White, 2006; Jevrejava et al., 2008). However, SLR is not spatially uniform, and sea level in the PIR is reported to have risen at a rate 3-4 times greater than the global mean (Cazenave and Llovel, 2009; Nerem et al., 2010) (Figure 4). At Nauru, Funafuti, Pago Pago, Papeete, Noumea and Tarawa, the SLR trend is significantly greater than the global average trend in SLR (e.g. at Funafuti, sea level trends over the last 60 years have been ~5 mm/year, accumulating to a total sea rise of ~30 cm since 1950 (Becker et al., 2012).

**Figure 4: From Becker et al. (2012). Interannual sea level trends 1950 to 2009 for the PIR. Black circles and stars indicate the locations of the 27 tide gauges used in the study (stars correspond to the 7 tide gauges used to reconstruct global sea level trends from 1950 to 2009). Hatched areas have non-significant trends (p-value > 0.1).**




22. Since 1990, accelerating global SLR has been attributed to increased rates of ocean warming/expansion and terrestrial ice melt (Nurse et al., 2014; Bindoff et al., 2007; IPCC, 2019). Nerem et al., (2010) reported that the average rate of global mean SLR since 1990 is 3.4 ± 0.4 mm/year which is double the rate reported since 1950 (Church and White, 2006). The spatial variability of this acceleration is summarized in Figure 5, including sea level trends exceeding 9 mm/year around the Solomon Islands. As previously discussed (Section II.B), these particularly high sea level increase are likely a combination of an underlying rising trend that is magnified in some locations by the impacts of natural climate variability (e.g. La Niña dominated IPO negative phase since ~1999 (as per paragraph 17) and other local/regional influences (as summarized in Section II.B and Section II.C).

**Figure 5: From Becker et al. (2012). Altimetry based sea level trends in the PIR from 1993 to 2009. Black circles and stars indicate the locations of the 27 tide gauges used (stars correspond to the 7 tide gauges used to reconstruct global sea level trends from 1950 to 2009). Hatched areas have insignificant trends (p-value > 0.1).**




**B. Pre-instrumental period (prior to ~1950)**

23. Although there is a tendency to focus on future sea level change (i.e. 21st century) it is important to recognize that sea levels (and rates of change) higher than those observed in the instrumental period (~1950 to present) have occurred in the pre-instrumental period. For example, SLR of 5 meters per century is evident in some paleoclimate records (e.g. Fairbanks, 1989; Deschamps et al., 2012). Hansen et al. (2016) also claim that during the last interglacial (~130,000-116,000 years before present, where present is 1950), when temperatures were less than 1 °C warmer than they are now, sea levels were 6-9 meters higher than they are now. This implies that by the end of the 21st century when temperatures are projected to be more than 1 °C warmer than now, there is the potential for sea levels to rise by several meters. However, it is important to emphasize that the Hansen et al. (2016) assessment is associated with major caveats and has certainly not been accepted unquestionably. For example, the pace at which such extreme SLR (i.e. several meters) might occur depends on the relative configuration of ice sheets and the extent to which they have reached critical tipping points (amongst other factors). Hence, the current consensus in the literature is that such extreme SLR would happen over very long periods (centuries to millennia) and is unlikely to occur before 2100 (IPCC, 2019).

# IV. FUTURE SEA LEVEL CHANGE PROJECTIONS FOR THE PACIFIC ISLANDS REGION

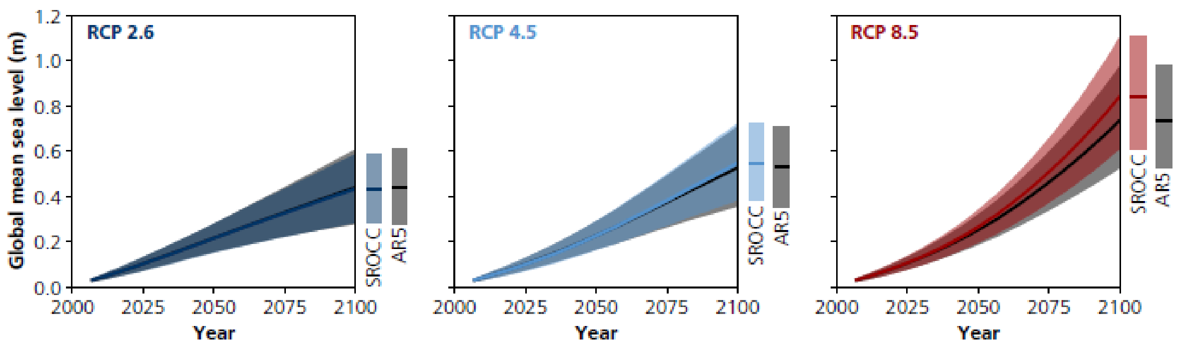
## A. Mean sea level change projections for the Pacific islands region (PIR)

24. Global mean SLR projections from the IPCC AR5 are summarized in Table 2 (Church et al., 2013). These findings were recently updated in Chapter 4 of IPCC (2019) to include research that has emerged since IPCC AR5 on the role and contribution of ice sheet melt. The IPCC (2019) results for global mean SLR, along with a comparison with the IPCC AR5 results, are shown in Figure 6. The updated results in IPCC (2019) indicate an increase in the median and upper bound of the likely range of global mean SLR for the second half of the 21st century, especially for RCP8.5.

**Table 2: From Church et al. (2013). Median values [and likely ranges] for projections of global mean sea level change in 2081-2100 relative to 1986-2005 for four Representative Concentration Pathways (RCPs)[4].**

| | RCP2.6 | RCP4.5 | RCP6.0 | RCP8.5 |
|---|---|---|---|---|
| **Global mean SLR (meters)** | 0.40 [0.26-0.55] | 0.47 [0.32-0.63] | 0.48 [0.33-0.63] | 0.63 [0.45-0.82] |
| **Rate of global mean SLR (mm/yr)** | 4.4 [2.0-6.8] | 6.1 [3.5-8.8] | 7.4 [4.7-10.3] | 11.2 [7.5-15.7] |

**Figure 6: From Figure 4.9 in Chapter 4 of IPCC (2019). Time series of global mean sea level for RCP2.6, RCP4.5 and RCP8.5 and, for reference, the IPCC AR5 results (Church et al., 2013). The shaded region should be considered as the likely range for global mean SLR.**




25. As per historical trends (Section III), Figure 7 shows that IPCC AR5 SLR projections for the PIR are at (or above) the upper bound of the projections for global mean SLR and that a decrease in sea level is very unlikely for the PIR. These findings are further confirmed in Figure 8. IPCC (2019) updates IPCC AR5 regional SLR estimates by including more recent research on the role and contribution of ice sheet melt to SLR. Again, as with the global SLR results (Figure 6), the IPCC (2019) regional SLR patterns in Figure 8 show higher SLR for PIR when compared to the IPCC AR5 results (Figure 7).

4 https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html

**Figure 7: From Figure 13.20 in Church et al. (2013). Ensemble mean regional sea level change (meters) evaluated from 21 CMIP5 models for the RCP[4] 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.**

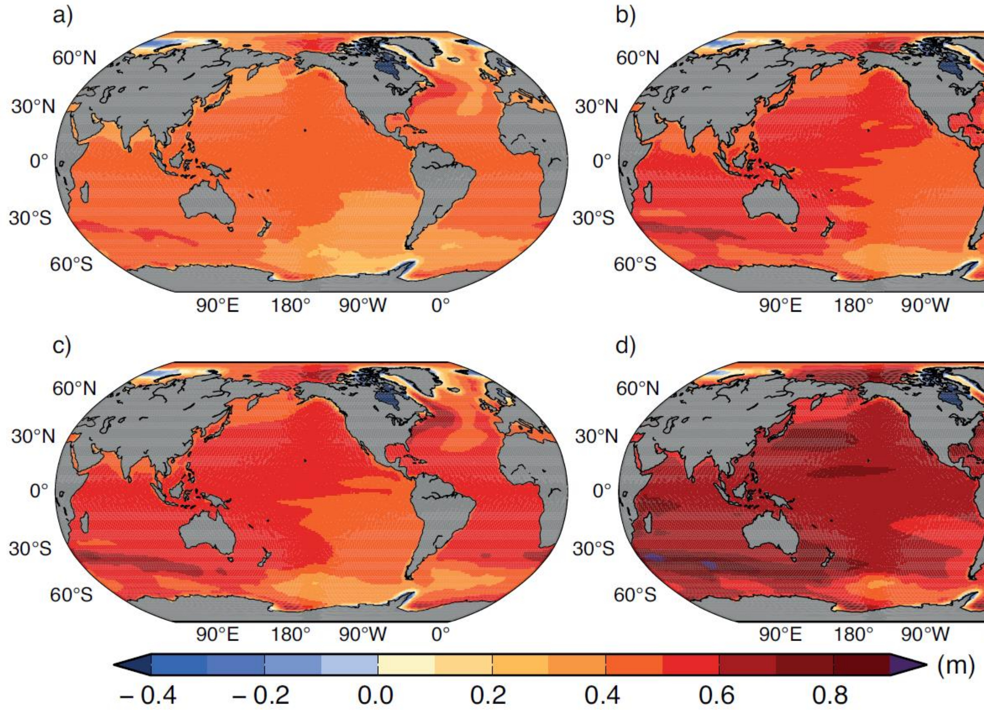
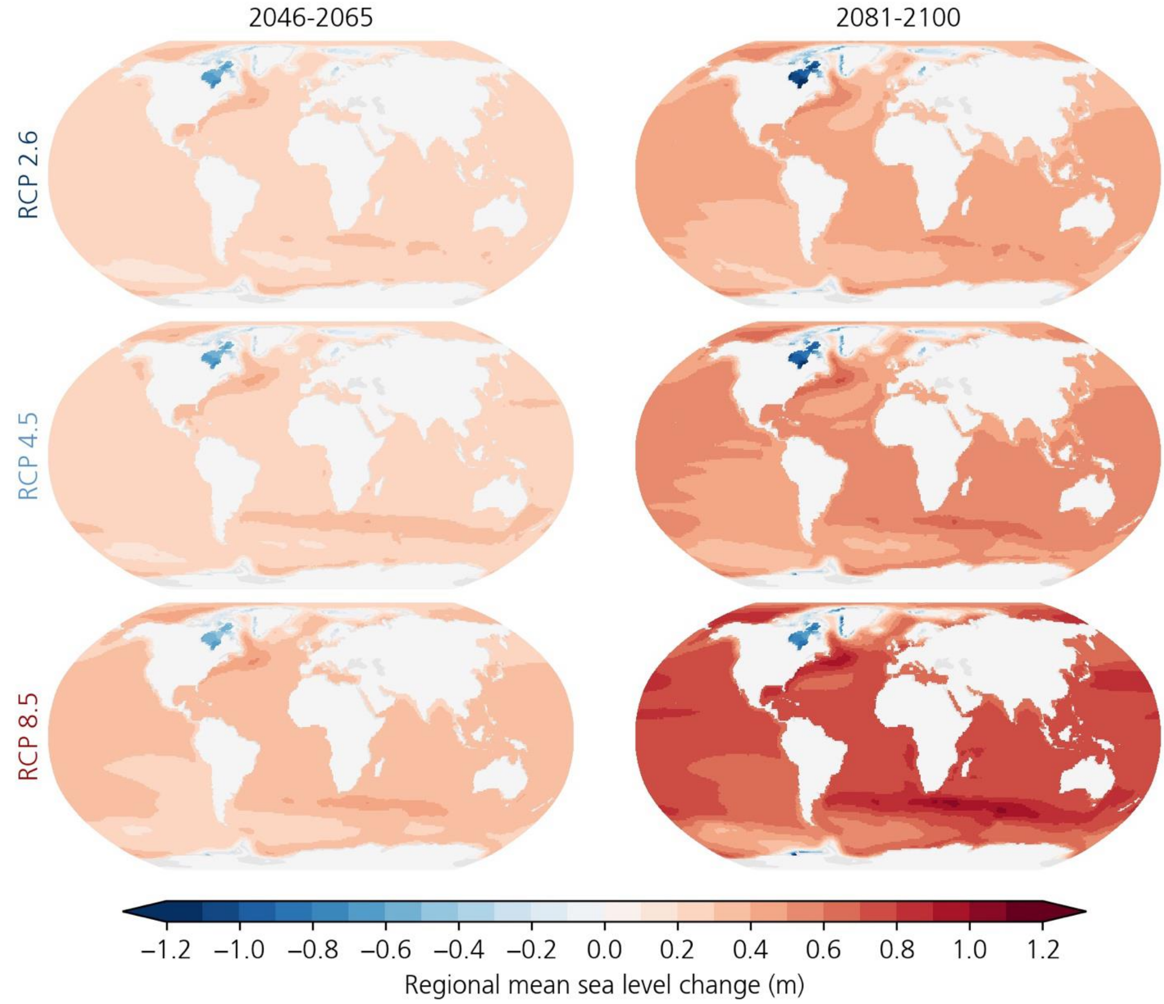


**Figure 8: From Figure 4.10 in Chapter 4 of IPCC (2019). Regional sea level change for RCP2.6, RCP4.5 and RCP8.5 in meters (includes glacial isostatic adjustment (GIA) and gravitational and rotational effects).**




26. As part of the Pacific-Australia Climate Change Science and Adaptation Planning Program (PACCSAP, https://www.pacificclimatechangescience.org/), regionally specific SLR projections were calculated for 15 island nations and territories across the PIR (Australian Bureau of Meteorology and CSIRO, 2014). This information is shown in Figure 9 and Figure 10 and represents the most up to date, location-specific analysis of future SLR projections for the PIR. Further information on location-specific changes in SLR within the PIR for four RCPs (RCP2.6, RCP4.5, RCP6.0, RCP8.5) and for four time periods (twenty years centered on 2030, 2050, 2070 and 2090) is included in Appendix I.

27. Figure 9, Figure 10 and Appendix I demonstrate that although there is very high confidence in the direction of change for all PIR locations (i.e. decrease in sea level is not projected anywhere in the PIR), there is only medium confidence in the magnitude of change. This is due to uncertainties associated with (i) projections of Antarctic ice sheet contributions; (ii) the influence of natural interannual to decadal variability which could lead to conditions where sea levels are further elevated (e.g. due to increased TCs (paragraph 14) or increased La Niña (paragraph 17)) - an indication of how natural climate variability could amplify SLR in the PIR is provided in Table 3; and (iii) the gravitational fingerprint associated with global redistribution of water from Greenland and Antarctic ice melt. Nevertheless, despite these (and other) uncertainties, comparing the information in Appendix I with the global IPCC projections

(Table 2) it is clear that the SLR projections for all PIR islands are at (or above) the upper range of the IPCC global SLR projections.

28. Note also that the SLR projections shown in Figure 9, Figure 10 and Appendix I do not consider the influence of changes in storm surge and/or wave climate (power and direction). The potential influence of changes to storm surge, wave climate and/or wave power are discussed in Section C, Section D and Section E respectively.

29. The SLR projections shown in Figure 9, Figure 10 and Appendix I also do not consider the impact of vertical land movements, which (as per Section II.C) can amplify (or reduce) the impacts of SLR.

**Figure 9: From Australian Bureau of Meteorology and CSIRO (2014). Observed and projected relative sea level change for eight PIR locations. The observed tide-gauge records of relative sea level (since the late 1970s) are indicated in purple and the satellite record (since 1993) in green. Reconstructed sea level since 1950 is shown in black. Multi-modal mean projections from 1995-2100 are given for RCP8.5 (red solid line) and RCP2.6 (blue solid line), with the 5-95% uncertainty range shown by the red and blue shaded regions. The ranges of projections for four emission scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5) by 2100 are also shown by the bars on the right. The dashed lines are an estimate of interannual variability in sea level (5-95% uncertainty range about the projections) and indicate that individual monthly averages of sea level can be above or below longer-term averages.**

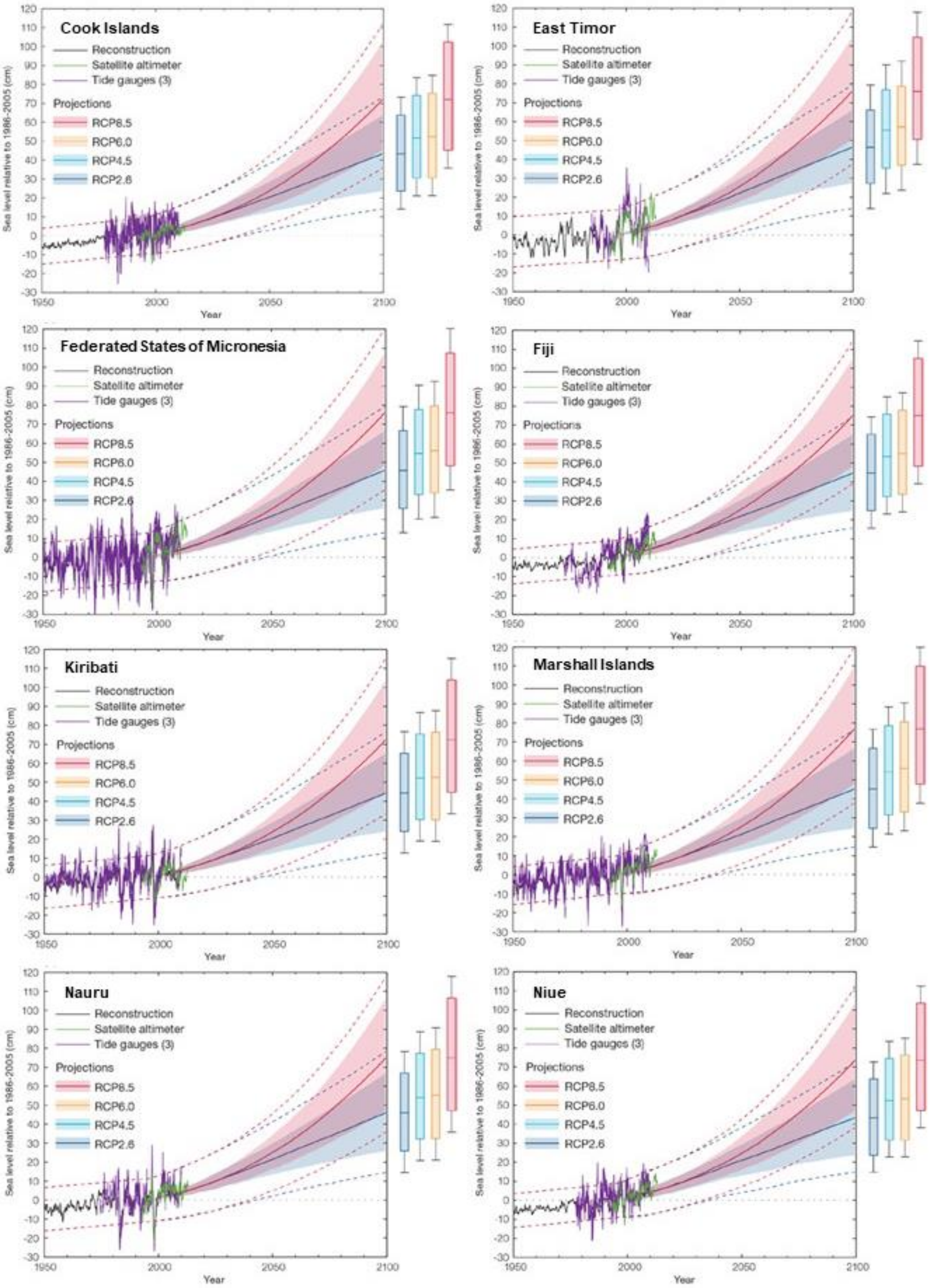


**Figure 10: From Australian Bureau of Meteorology and CSIRO (2014). As per Figure 9 but for seven other PIR locations.**

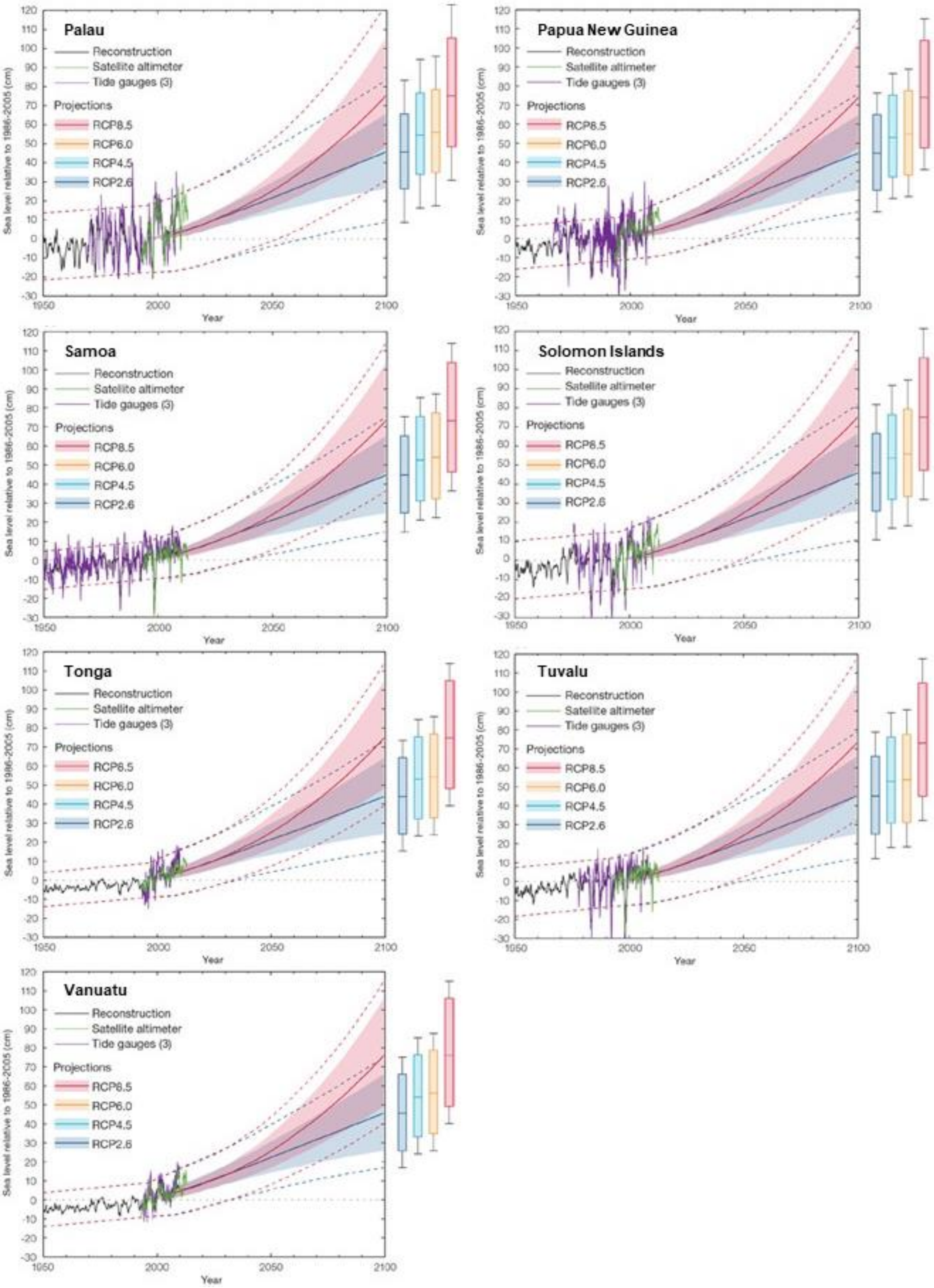


**Table 3: From Australian Bureau of Meteorology and CSIRO (2014). Projected changes, under RCP8.5 by 2090, in SLR plus the influence of historical interannual variability for 15 locations within the PIR. Historical interannual variability (cm) is taken from dashed lines in Figure 9 and Figure 10 (5-95% range, after removal of the seasonal signal).**

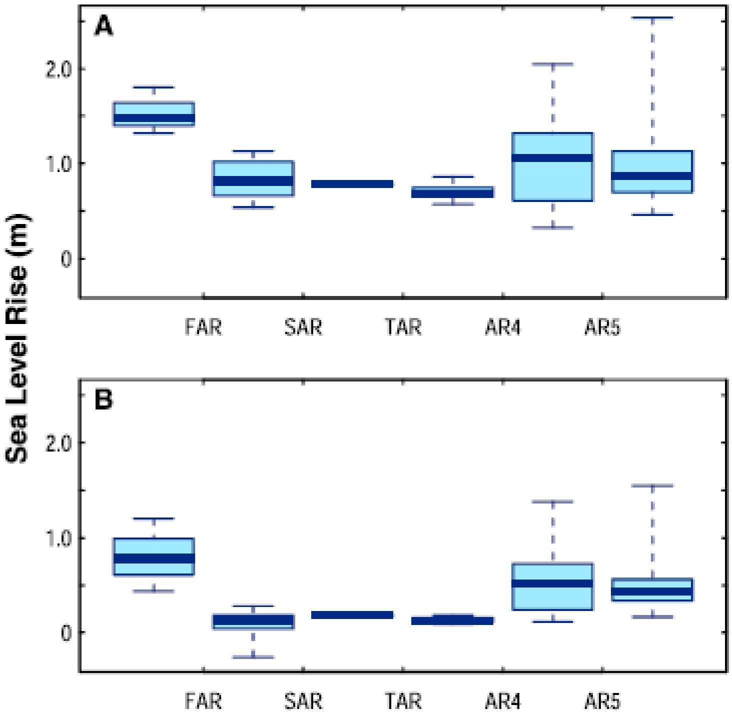
| | Projected SLR (cm) under RCP8.5 by 2090 (from Appendix 1) | Historical interannual variability (cm) | Upper bound of projected SLR (RCP8.5 by 2090) plus interannual variability (cm) |
|---|---|---|---|
| **Cook Islands** | 39-86 | 19 | **105** |
| **East Timor** | 43-88 | 24 | **112** |
| **Federated States of Micronesia** | 41-90 | 26 | **116** |
| **Fiji** | 41-88 | 18 | **106** |
| **Kiribati** | 38-87 | 23 | **110** |
| **Marshall Islands** | 41-92 | 20 | **112** |
| **Nauru** | 41-89 | 23 | **112** |
| **Niue** | 41-87 | 17 | **104** |
| **Palau** | 41-88 | 36 | **124** |
| **Papua New Guinea** | 47-87 | 23 | **110** |
| **Samoa** | 40-87 | 20 | **107** |
| **Solomon Islands** | 40-89 | 31 | **120** |
| **Tonga** | 41-88 | 18 | **106** |
| **Tuvalu** | 39-87 | 26 | **113** |
| **Vanuatu** | 42-89 | 18 | **107** |

## B. Extreme global sea level projections and their relevance to the Pacific islands region (PIR)

30. The previous section summarized what recent science says about the projected impacts of anthropogenic climate change on sea levels with a key finding being that there is very high confidence in the direction of change but large uncertainty associated with the projected magnitude of SLR. As discussed in Kopp et al. (2017), upper bounds of future SLR projections remain deeply uncertain. Garner et al. (2018) suggest that "the deeply uncertain nature of SLR projections is evident by the fact that there is no unique probability distribution of future sea level; thus, it is unlikely that there will be any particular method that is found to be best for estimating future sea level change anytime in the near future". Therefore, Garner et al. (2018) compared more than 70 individual SLR studies (conducted during 1983-2018) to evaluate the range of SLR that is plausible over the 21st century (Figure 11).

31. Figure 11 shows that recent research (particularly over the last five years) tends to expand the upper uncertainty bound as more is learned about specific mechanisms that contribute to SLR (and their relative likelihood) as well as improved insights from paleoclimate studies (see Section III.B). In summary, for the end of the 21st century, the most recent projections (i.e. those that incorporate ice sheet dynamics) indicate that sea levels may rise 0.7-1.0 m under RCP4.5 and 1.0-1.8 m under RCP8.5, and could even exceed 2 m or more (e.g. Kopp et al., 2017; Bakker et al., 2017; Wong et al., 2017; Le Bars et al., 2017; IPCC, 2019).

**Figure 11: Projections for (a) upper SLR projections for 2100 and (b) lower SLR projections for 2100 obtained from the 70 individual studies reviewed by Garner et al. (2018). Box edges are the interquartile (25th to 75th percentile) range; solid lines are the 50th percentile. Whiskers extend to data extremes (0 to 100th percentiles) to show the full range of SLR projections in each case. The horizontal axis uses the Intergovernmental Panel on Climate Change (IPCC) assessment reports to divide the literature based on publication date (FAR = first assessment report; SAR = second assessment report; TAR = third assessment report; AR4 = fourth assessment report; AR5 = fifth assessment report). Source: Garner et al. (2018).**




32. Subsequent research by Bamber et al. (2019) supports the Garner et al. (2018) findings by reiterating that "despite considerable advances in process understanding, numerical modeling, and the observational record of ice sheet contributions to global mean SLR since IPCC AR5, severe limitations remain in the predictive capability of ice sheet models. Consequently, the potential contributions of ice sheets remain the largest source of uncertainty in projecting future SLR". Bamber et al. (2019) report that, based on expert opinion, when inter- and intra-ice sheet processes and their tail dependences are accounted for, and thermal expansion and glacier contributions are included, global SLR projections for 2100 that exceed 2 m at the 95th percentile are plausible (Table 4). This is consistent with NOAA (2017) guidelines which (i) suggest that high levels of SLR (2.0-2.5 m) by 2100 must be considered plausible and (ii) emphasize that SLR will not stop at 2100, so SLR scenarios greater than 2.0-2.5 m should be considered for projects with expected life-time beyond 2100. Note, however, that NOAA (2017) assigned 0.3% probability to SLR greater than 2.0 m by 2100 whereas Bamber et al. (2019) assess this probability to be greater than 5%.

**Table 4: Total global-mean sea-level rise projections. Source: Table 2 in Bamber et al. (2019).**

| Centimeters above 2000 CE | 50% | 17–83% | 5–95% | 1–99% |
|---|---|---|---|---|
| 2050 L | 30 | 22–40 | 16–49 | 10–61 |
| 2050 H | 34 | 26–47 | 21–61 | 16–77 |
| 2100 L | 69 | 49–98 | 36–126 | 21–163 |
| 2100 H | 111 | 79–174 | 62–238 | 43–329 |

33. The conclusions of Garner et al. (2018) and Bamber et al. (2019) about the likelihood of significantly elevated global sea level projections have not yet been assessed for the PIR. Nevertheless, both studies, highlight the need for a more precautionary approach when considering SLR impacts in the PIR – that is, there is a need to consider higher-end scenarios as the latest science suggests that SLR greater than one meter is likely at some point in the 21st century and SLR of two meters by 2100 is plausible (noting also that SLR will not stop at 2100).

## C. Storm surge projections for the Pacific islands region (PIR)

34. There is limited research available for the PIR on future changes in storm surge – most existing literature focuses on how the impacts of storm surge could be magnified in the future by superposition upon rising sea levels. Storms surges could change in frequency and/or intensity, but this mostly depends on if, how, where and when the frequency or storms change. There is also the possibility of changes to the interactions between storm surges, tides and waves. Given that storm surges are also determined by bathymetry and the shape of the coastline (in addition to the frequency, intensity and track of storms), how storm surges in the PIR change in the future is very site specific.

35. For example, modelling of tropical cyclone storm surges for Apia (Samoa) suggest that where a 1-in-50 year storm surge under baseline (1990) conditions would have caused only partial inundation of the western side of Mulinu'u Peninsula, a 1-in-100 year storm surge would completely inundate the peninsula (Hoeke et al., 2014). However, by 2055, increases in sea level could result in a 1-in-50 year storm surge completely inundating the peninsula as well. Model results indicate that for a 1-in-100 year storm surge on top of future (2055) projected SLR, maximum sea levels on Mulinu'u Peninsula could be 2.6 m (mid-range estimate) to 3.2 m (upper estimate) above current sea level.

36. Given the high degree of local variation in storm surge heights (and associated inundation), a more concerted effort is required to comprehensively quantify existing and future risks associated with storm surge in the PIR. A fundamental first step in this effort involves collating existing sources of bathymetry and topography, identifying where such data are absent or insufficient, and prioritizing efforts to collect data in missing areas. Water level data across the PIR are also required to enable modelled storm surge heights to be validated (which in turn will improve model accuracy and increase confidence in what the storm surge models say about the future).

## D. Wave climate projections for the Pacific islands region (PIR)

37. Wave climate is the description of wave characteristics (i.e. wave height, wave period and wave direction) over time. Wave climate contributes to variability and change in sea levels via wave setup and wave runup (as explained in Section II.A). The PIR has been reported to be at least as vulnerable to variability and changes in wave climate as it is to increases in absolute sea level (Hemer et al., 2011).

38. Wave climate is influenced by variability and/or changes in wind, particularly in regions like the PIR that are affected by TCs (Church et al., 2013). Hence, any variability or change in the intensity, frequency, duration and/or path of TCs could alter the wave climate across the PIR, thereby modifying local sea levels. However, there is large uncertainty about whether, how, when and where TC behavior in the PIR could change in the future (e.g. Elsner et al., 2008; Knutson et al., 2010; Walsh et al., 2012; Emanuel, 2013; Sugi and Yoshida, 2015; Walsh et al., 2016). Obstacles such as the brevity of a reliable TC record (Magee and Verdon-Kidd, 2019), inhomogeneous environmental reanalysis data (Sterl, 2004), interannual variability of TC activity (Kuleshov et al., 2008; Magee et al., 2017), relatively coarse resolution of climate models (Henderson-Sellers et al., 1998; Walsh et al. 2016), and a lack of knowledge surrounding TC formation, organization and intensification (Walsh et al., 2016), all make it difficult to understand and model the impacts of future climate change on TC activity in the PIR. These science gaps and challenges contribute to uncertainty about SLR for the PIR, since TCs strongly influence wave climate and wave climate is strongly associated with sea level changes. Walsh (2015) projects a decrease in the number of TCs in the western (22%) and eastern (14%) South Pacific region by 2100. This is in line with a projection of 17% decrease in the number of TCs (under RCP8.5 by 2100) by Bell et al. (2019). However, while the number of TCs in the PIR are projected to decrease, the intensity of the TCs that do occur could increase by 10-20% (Parker et al., 2018; Patricola and Wehner, 2018). A poleward shift in global TC activity has also been observed (Sharmila and Walsh, 2018). While each of these projected changes could vary or change sea level in the PIR it is important to note again that there is no consensus yet on (a) whether anthropogenic climate change has affected TC behavior or (b) how continued warming, as a result of anthropogenic climate change or otherwise, might influence TC behavior in the future (Patricola and Wehner, 2018; Walsh et al., 2012). This again emphasizes the need for a more precautionary approach when considering SLR impacts in the PIR.

39. Dynamical wave climate projections suggest that significant wave height may increase (decrease) up to 0.2 m for the eastern (western) equatorial Pacific region during austral winter (Hemer et al., 2011), with greater decreases to the north of the equator (Trenham et al., 2013). Increases in annual mean wave periods by the end of the 21$^{st}$ century are also suggested by Hemer et al. (2011) but Trenham et al. (2013) found no statistically significant change in the mean wave period. Trenham et al. (2013) project changes in wave direction in the austral winter, namely, an increased southerly component due to projected increases in Southern Ocean storminess and an enhanced easterly component associated with projected increased strength of the easterly trade winds.

40. PACCSAP (https://www.pacificclimatechangescience.org/) produced regionally specific projections for changes to wave height, wave period and wave direction for 15 island nations and territories across the PIR (Australian Bureau of Meteorology and CSIRO, 2014). Appendix II shows the location-specific changes in wave height, wave period and wave direction within the PIR for four RCP4.5 and RCP8.5 for the twenty years centered on 2035 and 2090). It is important to note that, consistent with other literature, for all PIR locations covered in Australian Bureau of Meteorology and CSIRO (2014) there is only low confidence associated with the projected changes in wave height, wave period and wave direction. This uncertainty again highlights the need for a more precautionary approach when considering SLR impacts in the PIR.

## E. Wave power projections for the Pacific islands region (PIR)

41. Until recently, most analyses of wave climate focused on historical trends and future projections of mean and extreme values of wave parameters such as wave height, wave period and wave direction (as covered in Section D). However, Reguero et al. (2019) showed that global wave power, which is the transport of the energy transferred from the wind into sea-surface motion, increased globally by 0.47% per year between 1948 and 2008, and by

2.3% per year since 1994. Wave power in the Southern Ocean (defined by the 40ºS latitudinal limit) has increased by 0.58% per year, while wave power in the Pacific increased by 0.35% compared with 0.4% increases in the Atlantic Ocean and Indian Ocean (see Figure 12 and Figure 13). These trends are statistically significant and are due to upper-ocean warming and the resulting influence of SST on wind patterns (Reguero et al., 2019). As such, further research is required to better understand the past, present and future impact of wave power on wave setup and wave runup (Section II.A) and the resulting impact on sea level changes in the PIR.

**Figure 12: Spatial trend (% change per year) in mean wave power from 1985 to 2008 (the period with satellite-derived wave data). Hatched areas represent points that are statistically significant at the 95% confidence level according to the Mann–Kendall test. Source: Figure 6 in Reguero et al. (2019).**

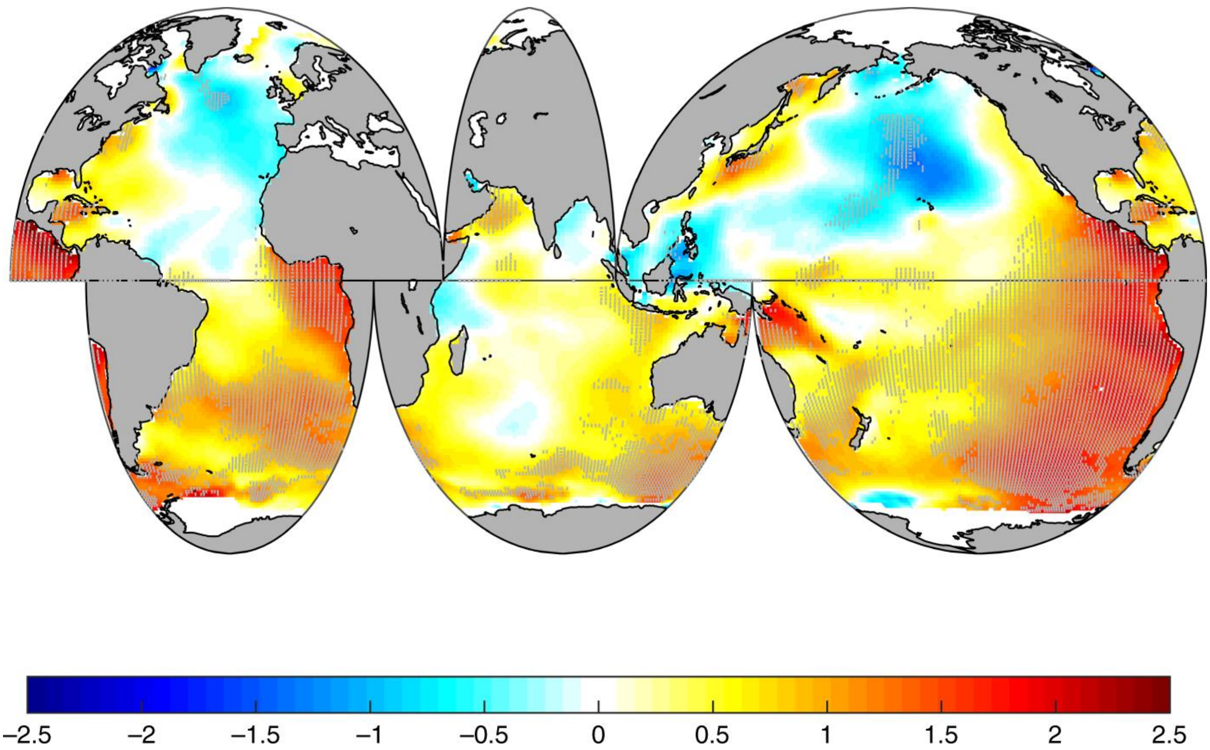
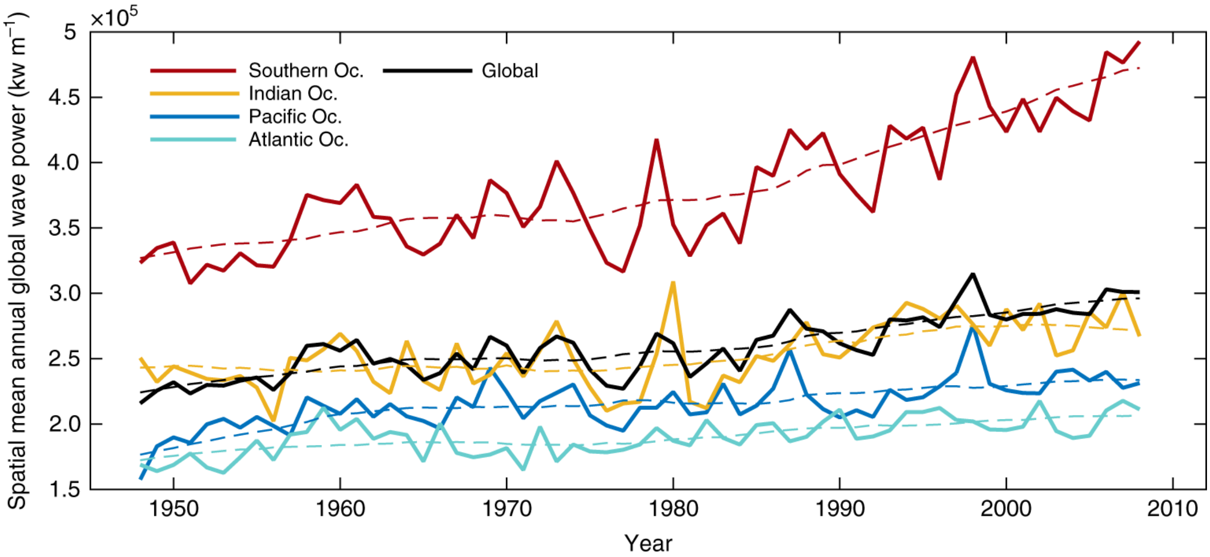


**Figure 13: Spatial mean annual wave power calculated globally and by ocean basin. The Southern Ocean is defined between latitudes of 40°S and 80°S. The solid lines indicate each time series. The dashed lines correspond to the 10-year moving averages. Source: Figure 1 in Reguero et al. (2019).**



## V. UNCERTAINTIES AND LIMITATIONS ASSOCIATED WITH THE SCIENCE ON SEA LEVEL RISE IN THE PACIFIC ISLANDS REGION

42. This review of literature on sea levels across the PIR reveals that substantial changes have occurred in the past and more changes are expected in the future. Although most studies agree that sea levels in the PIR are rising and will continue to do so, there is large uncertainty about the magnitude, timing and location of the projected changes. Even larger uncertainties exist around how the rises in sea levels could be influenced (i.e. amplified or moderated) by natural climate variability, storm surges, and changes to wave climate and wave power.

43. The most important uncertainties and knowledge gaps identified by this review include:

- **Limited historical data and inadequate reporting networks:** To realistically investigate the future, we must understand the past. Across the PIR region, limited observational hydrometeorological and coastal water level datasets are available. The lack of systematic and low density of in-situ wave and water level measurements in wave-exposed regions means studies are reliant on tide gauge data. This does not provide a comprehensive understanding of risk caused by remotely generated swell because tide-gauges are typically placed in sheltered locations (Hoeke, et al., 2013; McInnes et al., 2016). Although a few wave buoys exist, records are typically intermittent and short (Trenham et al., 2013). A long-term wave monitoring and observation program would enable enhanced coastal hazard assessments (Hemer et al., 2011).
- **SLR projections:** Variations between model outputs suggest that some aspects of sea level (both globally and regionally) remain poorly understood. Church et al. (2013) call for improved parameterizations of unresolved physical processes, improved numerical algorithms and a refined grid resolution to better capture features such as boundary currents and mesoscale eddies. In addition, changes in future greenhouse gas emissions are uncertain. Further uncertainties surround the magnitude and rate of the ice-sheet contribution to SLR and the regional distribution of SLR (Church et al., 2013). The IPCC (2019) report addresses some of these issues, however, more work is needed to better resolve uncertainties surrounding SLR, especially upper bound projections and abrupt change scenarios. In the meantime, a more precautionary approach is recommended when considering SLR impacts in the PIR – that is, there is a need to consider the more recent science which suggests that SLR greater than one metre is likely at some point in the 21st century and SLR of two metres by 2100 is plausible (noting also that SLR will not stop at 2100).
- **Relative contribution of tides, waves, storm surge (and their interactions) to sea levels across the PIR:** Understanding of the relative contribution of tides, storm surge, wave climate and wave power in amplifying in sea levels across the PIR is limited. Without a regionally specific understanding of the role these processes play in different parts of the PIR, it is difficult to understand how future climate change could affect sea levels at specific locations within the PIR (e.g. Walsh et al., 2012; Hoeke et al., 2013).
- **Regionality:** Small islands do not have uniform climate change risk profiles (Nurse et al., 2014). Island nations are composed of different geomorphological units and their locations determine the relative influence of climate variability and change. This includes impacts associated with, for example, intraseasonal/interannual/ interdecadal variability and TCs. More work is needed to produce location-specific projections for absolute SLR, storm surge, wave climate and wave power across the PIR. Regionally specific projections could assist decision makers, environmental agencies and PIR governments to make more informed decisions about climate adaptation and disaster risk reduction (Aucan, 2018).

- **Changes to future TC behavior:** Changes in the frequency, location and duration of future TC events could have significant implications for sea levels across the PIR. More work is needed to (i) quantify whether, how, where and when future TC activity could change and (ii) evaluate the impact projected changes in TC behavior could have on storm surge, wave climate and wave power and how, where and when that amplifies rises in absolute sea levels.
- **Future of interannual/interdecadal modes of variability:** The ENSO and IPO are known to drive significant changes in sea levels across the PIR. Although future extreme sea level 'seesaws' in the tropical Pacific are expected to persist, it is unclear if or how ENSO/IPO variability might change and what this could mean for PIR nations and territories.
- **Vertical land movement:** Relative to SLR, vertical land movement is an important consideration which can amplify or offset absolute SLR (e.g. Becker et al., 2012; Ballu et al., 2011; Aucan, 2018). As noted in Section II.C, records of vertical land movement in different locations across the PIR are typically short and many are not continuous. Given the importance of vertical land movement, more effort is needed to install and maintain monitors of vertical land movement to compile reliable, detailed, long-term records of vertical land movement. This would support more robust risk assessment and management.
- **Compound extreme events:** Potential changes to the frequency, location, or sequencing of extreme rainfall events was not considered herein nor were the impacts associated with compound extreme events (e.g. SLR in addition to increased rainfall frequency or intensity) – see, for example, Moftakhari et al. (2017) for further details.
- **Errors/bias in digital elevation models (DEMs):** Land topography and elevation, as represented by DEMs, is used to translate SLR observations and projections into socioeconomic and environmental impacts (e.g. by coastal inundation mapping, population exposure assessments, etc). The standard choice for assessing exposure to SLR is the United States National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) (https://www2.jpl.nasa.gov/srtm/). Kulp and Strauss (2019) recently showed that SRTM has a global mean positive vertical bias of ~2 m. This is comparable to global mean SLR estimates for 2100 and suggests that vulnerability to SLR is significantly underestimated where SRTM is used as the DEM. Other DEMs are also associated with bias and uncertainties. To address these DEM-related uncertainties, Kulp and Strauss (2019) call for "development and public release of improved coastal area elevation datasets building directly off of new high-resolution observations increasingly collected by satellites today".
- **Implications of the "gravitational fingerprint" for PIR:** Ice sheets and glaciers have a gravitational pull on the water that surrounds them, making sea level a little higher at their edges. When a glacier or ice sheet melts, it loses mass; therefore, the gravitational pull exerted on nearby ocean water weakens and the sea level falls. At the same time, the land rises up because the ice is no longer weighing it down, which causes a further drop in sea level. The loss of mass changes Earth's gravitational field causing the fresh meltwater and ocean water to move away towards faraway coastlines; the resulting pattern of SLR is the fingerprint of melting from that particular ice sheet or glacier (Hsu and Velicogna, 2017). Hence, the "gravitational fingerprint" for the PIR will depend on the combined patterns of future melt of the Greenland and Antarctic ice-sheets.
- **Changes in tidal range/position of the amphidromic points with SLR:** An amphidromic point, also called a tidal node, is a geographical location which has zero tidal amplitude for one harmonic constituent of the tide. The tidal range (the peak-to-peak amplitude, or height difference between high tide and low tide) for

that harmonic constituent increases with distance from this point. If/how amphidromic points could change with SLR is uncertain.

## VI. ADVICE ON DEVELOPING GUIDANCE ON HOW TO INCORPORATE CREDIBLE SEA LEVEL RISE PROJECT INFORMATION AT THE ADB PROJECT LEVEL

44. SLR projections from the IPCC AR5 suggested that it was unlikely that SLR in the PIR would exceed one meter in the 21st century (i.e. by 2100). This information is widely used (by ADB and others) to assess and manage SLR related risks in the PIR – with allowance and adaptation for SLR of one meter considered sufficiently precautionary. However, the key finding from this review is that there are several reasons why such an approach is no longer tenable in some situations:

(i) Figure 9 and Figure 10 (in Section IV.A) and Appendix I indicate that although there is very high confidence in the direction of change for all PIR locations (i.e. decrease in sea level is not projected anywhere in the PIR), there is only medium confidence in the magnitude of change. This is due to uncertainties associated with (i) projections of the Antarctic ice sheet contributions; (ii) the influence of natural interannual to decadal variability which could lead to conditions where sea levels are further elevated (e.g. due to increased TCs (paragraph 14) or increased La Niña (paragraph 17)); and (iii) the gravitational fingerprint associated with redistribution of water from Greenland and Antarctic ice melt.

(ii) Work that has emerged since IPCC AR5 demonstrates that global SLR greater than one meter by the end of the 21st century is conceivable. One expert elicitation suggests that there could be greater than 5% probability that SLR exceeds two meters by 2100 (Bamber et al., 2019), although other literature (NOAA, 2017; IPCC, 2019) assigns a lower probability (0.3%) to the two meters SLR by 2100 scenario.

(iii) Some paleoclimate records suggest that global SLR of 5 meters in a century has occurred before and that SLR of 6-9 meters is possible if temperatures become 1 °C warmer than now (which they are projected to do before 2100). However, the current consensus is that such extreme SLR would happen over very long periods (centuries to millennia) and is unlikely to occur before 2100.

(iv) Short-term variability in sea level caused by storm surge, wave climate and/or wave power has the potential to significantly increase local coastal water heights above what is expected as a result of changes to absolute sea level (i.e. changes to long-term average sea level). The reverse is also true – higher baseline sea levels increases impacts and damages associated with short-term sea level rise. This is especially true in the PIR, particularly the western tropical Pacific, because of the high exposure to tropical cyclones (TCs) and other tropical storms, high shoreline to land area ratio, high exposure to waves and currents, combined with low-lying coral atolls, reefs or volcanically composed islands.

(v) Based on observed data collected over the last ~20 years, it is evident that most islands in the PIR are subsiding (i.e. have negative vertical land movements). Therefore, irrespective of any other influence, the effect of SLR will be magnified where the land is falling and this appears to be the case for much of the PIR.

45. The implications of the potential for significantly elevated global SLR projections for the PIR have not yet been assessed and it is unlikely that it is feasible to do the detailed modelling work required to rigorously quantify location-specific SLR related risks for every ADB project in the region. However, the findings of this review clearly highlight the need for a more precautionary approach when considering SLR impacts in CRAs for the PIR. There is a need to consider the more recent science which suggests that SLR greater than one meter is likely at some point in the 21st century and SLR of two meters by 2100 is plausible (noting also that SLR will not stop at 2100).

46. Therefore, it is advised that a precautionary approach for ADB CRAs in the PIR requires that a 2 meter SLR by 2100 scenario be used. Scenarios greater than 2 meters should be considered for projects with expected life-time beyond 2100. These SLR scenario(s)

should feed into sensitivity analyses of the costs and benefits of additional climate proofing. Adaptive management approaches could also incorporate higher SLR, noting that this needs to consider the lifetime, risk of lock-in, and level of precaution associated with investments. Where warranted (i.e. at sites with high exposure and/or vulnerability) extra allowance should also be made for the influence of natural climate variability, tropical cyclones, storm surge, wave climate and wave power. Exactly what that allowance should be will depend on the type of project and the location in within the PIR, as well as the appetite for risk and expected life-time of the project (see Section VII for further details on the future work required to produce the information need to provide further guidance on this point). Guidance on addressing uncertainty in ADB investments is included in existing reports (e.g. Asian Development Bank, 2015) but further work to explore the consideration of extreme SLR, including in economic and financial analysis, is recommended.

## VII. RECOMMENDATIONS FOR FUTURE WORK

47. **Recommendation for future work #1**: Conduct a workshop involving relevant experts to (a) discuss this report (as well as the SLR calculator, and associated Knowledge Product, that ADB has already developed for Vietnam) to assist PARD in developing supplementary guidance on incorporating credible SLR projection information in climate risk management at the ADB project level; (b) prioritize the recommendations and tasks emerging from this workshop to develop supplementary guidance on assessing SLR in the PIR; and (c) plan the projects and terms of reference needed to address the specific technical recommendations and tasks emerging from this report and the workshop – this includes identifying skills and personnel required as well as providing realistic estimates of the budget and timeline required for each piece of work.

48. **Recommendation for future work #2**: For existing, long-lived ADB projects in the PIR that require guidance on the implications of SLR, sensitivity analysis is required to assess the impacts of allowing for two meters of SLR in the 21st century compared with the current practice of allowing for one meter of SLR. This due diligence should be incorporated within CRAs as another plausible scenario with which to inform existing and/or proposed adaptation measures. A first step in this due diligence exercise is to determine how many existing, long-lived ADB projects in the PIR need to be revisited.

49. **Recommendation for future work #3**: As per Section IV.C, to obtain better understanding of the impacts of storm surge, and how it exacerbates the impacts of SLR, an intensive effort should be made to collate existing sources of bathymetry and topography, identify where such data are absent or insufficient, and prioritize efforts to collect data in missing areas. Water level data across the PIR are also required to enable modelled storm surge heights to be validated (which in turn could improve model accuracy and increase confidence in what the storm surge models say about the future).

50. **Recommendation for future work #4**: As per Section IV.D and Section IV.E, changes in wave climate and wave power are anticipated but there is scarce information available for whether, how, and where within the PIR could be affected. Work is needed, mostly desktop, to establish what data exist (either observed or modelled) for wave climate and wave power in the PIR. Where enough data exist, work should be done to analyze whether, how, and where wave climate and wave power has changed or is projected to change for those specific locations. Where data gaps exist, work should be undertaken to implement monitoring of wave climate and wave power. Insights emerging from this work could provide information about the impact of wave power on wave setup and wave runup and the resulting impact on sea level changes in the PIR.

51. **Recommendation for future work #5**: The impacts of natural climate variability (e.g. ENSO, IPO) and TCs on historical sea levels at specific project sites needs to be better understood. This is essential for establishing reliable estimates of baseline SLR to which SLR projections and vertical land movements are applied. If the baseline SLR (and associated risk) estimates do not properly account for the impacts of natural climate variability then the feasibility, sensitivity and cost-benefit assessments may be flawed even if precautionary SLR scenarios of greater than two meters are used.

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## APPENDIX I – LOCATION-SPECIFIC CHANGES IN SEA LEVEL WITHIN THE PIR[5]

| | | 2030 | 2050 | 2070 | 2090 | Confidence in projected magnitude of change |
|---|---|---|---|---|---|---|
| **Cook Islands (Northern)** | RCP2.6 | 12 (7-17) | 21 (13-29) | 30 (18-43) | 39 (22-57) | Medium |
| | RCP4.5 | 12 (7-17) | 22 (14-30) | 33 (21-47) | 46 (28-65) | |
| | RCP6 | 11 (7-16) | 21 (13-29) | 33 (20-46) | 46 (28-66) | |
| | RCP8.5 | 12 (8-17) | 24 (16-33) | 40 (26-56) | 61 (39-86) | |
| **Cook Islands (Southern)** | RCP2.6 | 12 (7-17) | 21 (13-29) | 30 (18-43) | 39 (22-57) | Medium |
| | RCP4.5 | 12 (7-17) | 22 (14-30) | 33 (21-47) | 46 (28-65) | |
| | RCP6 | 11 (7-16) | 21 (13-29) | 33 (20-46) | 46 (28-66) | |
| | RCP8.5 | 12 (8-17) | 24 (16-33) | 40 (26-56) | 61 (39-86) | |
| **East Timor (Timor-Leste)** | RCP2.6 | 13 (8-17) | 22 (15-30) | 32 (21-45) | 42 (26-59) | Medium |
| | RCP4.5 | 13 (9-17) | 23 (16-31) | 36 (24-48) | 49 (32-67) | |
| | RCP6 | 12 (8-17) | 23 (15-30) | 35 (23-47) | 50 (33-68) | |
| | RCP8.5 | 13 (9-18) | 26 (18-34) | 43 (30-58) | 64 (43-88) | |
| **Federated States of Micronesia (east)** | RCP2.6 | 13 (8-18) | 22 (14-30) | 32 (20-45) | 42 (24-60) | Medium |
| | RCP4.5 | 12 (8-17) | 22 (14-31) | 35 (22-49) | 48 (30-68) | |
| | RCP6 | 12 (7-17) | 22 (14-30) | 34 (22-48) | 49 (31-69) | |
| | RCP8.5 | 13 (8-18) | 26 (17-35) | 43 (28-59) | 64 (41-90) | |
| **Federated States of Micronesia (west)** | RCP2.6 | 13 (8-18) | 22 (14-30) | 32 (20-45) | 42 (24-60) | Medium |
| | RCP4.5 | 12 (8-17) | 22 (14-31) | 35 (22-49) | 48 (30-68) | |
| | RCP6 | 12 (7-17) | 22 (14-30) | 34 (22-48) | 49 (31-69) | |
| | RCP8.5 | 13 (8-18) | 26 (17-35) | 43 (28-59) | 64 (41-90) | |
| **Fiji** | RCP2.6 | 13 (8-18) | 22 (14-31) | 31 (19-44) | 41 (24-58) | Medium |
| | RCP4.5 | 13 (8-18) | 23 (14-31) | 35 (22-48) | 47 (29-67) | |
| | RCP6 | 13 (8-17) | 22 (14-31) | 34 (22-47) | 49 (30-68) | |
| | RCP8.5 | 13 (8-18) | 25 (17-35) | 42 (28-58) | 64 (41-88) | |
| **Kiribati (Phoenix Group)** | RCP2.6 | 12 (7-17) | 21 (13-29) | 31 (18-44) | 40 (23-59) | Medium |
| | RCP4.5 | 12 (7-16) | 22 (13-30) | 33 (20-47) | 46 (27-66) | |
| | RCP6 | 11 (7-16) | 21 (13-29) | 33 (19-46) | 47 (28-67) | |
| | RCP8.5 | 12 (7-17) | 24 (16-33) | 40 (26-56) | 61 (38-87) | |
| **Kiribati (Line Group)** | RCP2.6 | 12 (7-17) | 21 (13-29) | 31 (18-44) | 40 (23-59) | Medium |
| | RCP4.5 | 12 (7-16) | 22 (13-30) | 33 (20-47) | 46 (27-66) | |
| | RCP6 | 11 (7-16) | 21 (13-29) | 33 (19-46) | 47 (28-67) | |
| | RCP8.5 | 12 (7-17) | 24 (16-33) | 40 (26-56) | 61 (38-87) | |
| **Marshall Islands (northern)** | RCP2.6 | 13 (7-18) | 22 (13-30) | 31 (19-45) | 41 (23-60) | Medium |
| | RCP4.5 | 12 (7-18) | 23 (14-32) | 35 (21-49) | 48 (28-69) | |
| | RCP6 | 12 (7-17) | 22 (14-31) | 35 (21-49) | 49 (30-70) | |
| | RCP8.5 | 13 (8-19) | 26 (16-35) | 43 (27-60) | 65 (41-92) | |
| **Marshall Islands (southern)** | RCP2.6 | 13 (7-18) | 22 (13-30) | 31 (19-45) | 41 (23-60) | Medium |
| | RCP4.5 | 12 (7-18) | 23 (14-32) | 35 (21-49) | 48 (28-69) | |
| | RCP6 | 12 (7-17) | 22 (14-31) | 35 (21-49) | 49 (30-70) | |
| | RCP8.5 | 13 (8-19) | 26 (16-35) | 43 (27-60) | 65 (41-92) | |
| **Nauru** | RCP2.6 | 12 (8-17) | 22 (14-30) | 32 (19-45) | 42 (24-60) | Medium |
| | RCP4.5 | 12 (7-17) | 22 (14-31) | 35 (22-48) | 48 (29-68) | |
| | RCP6 | 12 (7-16) | 22 (14-30) | 34 (21-48) | 49 (30-69) | |
| | RCP8.5 | 13 (8-18) | 25 (17-34) | 42 (28-58) | 63 (41-89) | |
| **Niue** | RCP2.6 | 12 (7-17) | 21 (13-30) | 30 (18-43) | 40 (23-57) | Medium |
| | RCP4.5 | 12 (8-17) | 22 (14-31) | 34 (22-47) | 47 (29-66) | |
| | RCP6 | 12 (7-17) | 22 (13-30) | 34 (21-47) | 47 (29-67) | |
| | RCP8.5 | 13 (8-18) | 25 (16-34) | 42 (27-57) | 62 (41-87) | |
| **Palau** | RCP2.6 | 13 (8-17) | 22 (14-30) | 32 (20-44) | 42 (25-59) | Medium |
| | RCP4.5 | 12 (8-17) | 23 (15-31) | 35 (23-48) | 48 (30-67) | |
| | RCP6 | 12 (8-17) | 22 (14-30) | 34 (22-47) | 49 (31-68) | |
| | RCP8.5 | 13 (8-18) | 26 (17-35) | 43 (28-58) | 64 (41-88) | |
| | RCP2.6 | 12 (8-17) | 22 (14-30) | 31 (19-44) | 41 (24-58) | Medium |

[5] Information obtained from Australian Bureau of Meteorology and CSIRO (2014), https://www.pacificclimatechangescience.org/. Table shows projected changes in annual mean sea level for 15 island nations and territories across the PIR under four emissions scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5). Projected changes are given for four 20-year periods centred on 2030, 2050, 2070 and 2090, relative to a 20-year period centred on 1995. Values represent the multi-modal mean change, with the 5-95% range of uncertainty in brackets. Confidence in magnitude of change is expressed as high, medium or low.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Papua New Guinea** | RCP4.5 | 12 (7-17) | 22 (14-31) | 34 (22-47) | 47 (29-66) | |
| | RCP6 | 12 (7-16) | 22 (14-29) | 34 (21-46) | 48 (30-67) | |
| | RCP8.5 | 13 (8-17) | 25 (17-34) | 42 (28-57) | 63 (47-87) | |
| **Samoa** | RCP2.6 | 12 (8-17) | 21 (13-30) | 31 (18-44) | 41 (23-59) | Medium |
| | RCP4.5 | 12 (7-17) | 22 (13-30) | 34 (21-47) | 46 (28-66) | |
| | RCP6 | 12 (7-17) | 21 (13-29) | 33 (21-46) | 48 (29-67) | |
| | RCP8.5 | 12 (7-17) | 24 (16-33) | 41 (27-56) | 62 (40-87) | |
| **Solomon Islands** | RCP2.6 | 13 (8-18) | 22 (14-31) | 32 (19-45) | 42 (24-60) | Medium |
| | RCP4.5 | 12 (7-17) | 22 (14-31) | 35 (21-48) | 47 (29-67) | |
| | RCP6 | 12 (7-17) | 22 (14-30) | 34 (21-47) | 49 (30-69) | |
| | RCP8.5 | 13 (8-18) | 25 (16-35) | 42 (28-58) | 63 (40-89) | |
| **Tonga** | RCP2.6 | 13 (8-18) | 22 (14-30) | 31 (19-43) | 40 (23-58) | Medium |
| | RCP4.5 | 13 (8-18) | 23 (15-31) | 35 (22-48) | 47 (29-66) | |
| | RCP6 | 12 (7-17) | 22 (14-31) | 34 (21-47) | 48 (30-67) | |
| | RCP8.5 | 13 (8-18) | 25 (17-35) | 42 (28-58) | 63 (41-88) | |
| **Tuvalu** | RCP2.6 | 12 (7-17) | 21 (13-30) | 31 (19-44) | 41 (23-59) | Medium |
| | RCP4.5 | 12 (7-17) | 22 (13-31) | 34 (20-48) | 47 (28-67) | |
| | RCP6 | 12 (7-16) | 21 (13-29) | 33 (20-47) | 48 (28-67) | |
| | RCP8.5 | 12 (7-18) | 24 (16-34) | 41 (26-57) | 62 (39-87) | |
| **Vanuatu** | RCP2.6 | 13 (8-19) | 23 (15-31) | 32 (20-45) | 42 (25-59) | Medium |
| | RCP4.5 | 13 (8-18) | 23 (15-32) | 36 (23-49) | 48 (30-67) | |
| | RCP6 | 13 (8-18) | 23 (15-31) | 35 (23-48) | 50 (32-69) | |
| | RCP8.5 | 13 (8-18) | 26 (17-35) | 43 (29-59) | 64 (42-89) | |

## APPENDIX II – LOCATION-SPECIFIC CHANGES IN WAVE HEIGHT, WAVE PERIOD AND WAVE DIRECTION WITHIN THE PIR[6]

| | Variable | Season | 2035 | 2090 | Confidence in projected changes |
|---|---|---|---|---|---|
| **Cook Islands (Northern)** | Wave height change (m) | December – March | -0.0 (-0.3–0.2)<br>-0.0 (-0.3–0.2) | -0.1 (-0.3–0.2)<br>-0.1 (-0.3–0.2) | Low |
| | | June - September | 0.0 (-0.2–0.2)<br>+0.0 (-0.1–0.2) | 0.0 (-0.1–0.2)<br>+0.0 (-0.2–0.3) | |
| | Wave period change (s) | December – March | +0.0 (-1.7–1.8)<br>-0.0 (-1.7–1.6) | -0.1 (-2.0–1.9)<br>-0.1 (-2.2–2.0) | |
| | | June - September | +0.0 (-1.1–1.2)<br>+0.0 (-1.1 to1.1) | -0.0 (-1.3–1.2)<br>-0.0 (-1.4–1.3) | |
| | Wave direction change (° clockwise) | December – March | +0 (-30–40)<br>0 (-30–30) | 0 (-30–30)<br>0 (-40–40) | |
| | | June - September | 0 (-10–10)<br>0 (-10–10) | -0 (-20–10)<br>-0 (-20–10) | |
| **Cook Islands (Southern)** | Wave height change (m) | December – March | 0.0 (-0.3–0.2)<br>-0.0 (-0.3–0.2) | -0.0 (-0.3–0.2)<br>-0.1 (-0.3–0.2) | Low |
| | | June - September | +0.0 (-0.3–0.4)<br>0.0 (-0.3–0.3) | 0.0 (-0.4–0.4)<br>0.0 (-0.4–0.4) | |
| | Wave period change (s) | December – March | -0.0 (-1.5–1.4)<br>-0.0 (-1.4—1.3) | -0.1 (-1.7–1.5)<br>-0.1 (-1.9–1.6) | |
| | | June - September | 0.0 (-0.9–0.9)<br>0.0 (-0.9–0.9) | 0.0 (-1.1–1.1)<br>-0.0 (-1.2–1.1) | |
| | Wave direction change (° clockwise) | December – March | 0 (-70–70)<br>0 (-60–60) | -0 (-60–60)<br>-10 (-70–60) | |
| | | June - September | -0 (-20–10)<br>-0 (-20–10) | -0 (-20–10)<br>-10 (-20–5) | |
| **East Timor (Timor-Leste)** | Wave height change (m) | December – March | 0.0 (-0.2–0.2)<br>0.0 (-0.2–0.2) | 0.0 (-0.2–0.2)<br>-0.0 (-0.2–0.2) | Low |

[6] Information obtained from Australian Bureau of Meteorology and CSIRO (2014), https://www.pacificclimatechangescience.org/. Projected average changes in wave height, period and direction across PIR nations for December-March and June-September for RCP4.5 (top values) and RCP8.5 (bottom values), for two 20-year periods (2026-2045 and 2081-2100), relative to a 1986-2005 historical period. The values in brackets represent the 5th to 95th percentile range of uncertainty. Confidence in ranges are expressed as high, medium or low.

| | | | | | |
|---|---|---|---|---|---|
| | | June - September | 0.0 (-0.4–0.5)<br>0.0 (-0.4–0.4) | 0.0 (-0.4–0.5)<br>0.0 (-0.4–0.6) | |
| | Wave period change (s) | December – March | -0.1(-1.0–0.9)<br>-0.0 (-1.1–1.0) | -0.0 (-0.9–0.9)<br>-0.0 (-1.1–1.0) | |
| | | June - September | 0.0 (-0.5–0.5)<br>0.0 (-0.5–0.5) | +0.0 (-0.5–0.7)<br>+0.0 (-0.5–0.6) | |
| | Wave direction change (° clockwise) | December – March | +0 (-40–50)<br>0 (-50–50) | 0 (-40–40)<br>-0 (-50–40) | |
| | | June - September | 0 (-10–10)<br>0 (-20–10) | 0 (-20–20)<br>-0 (-20–10) | |
| **Federated States of Micronesia (East)** | Wave height change (m) | December – March | -0.0 (-0.2–0.2)<br>-0.1 (-0.3–0.2) | -0.1 (-0.3–0.1)<br>-0.2 (-0.4–-0.0) | Low |
| | | June - September | +0.0 (-0.2–0.2)<br>+0.0 (-0.1–0.2) | 0.0 (-0.2–0.2)<br>+0.0 (-0.1–0.2) | |
| | Wave period change (s) | December – March | -0.1 (-0.6–0.4)<br>-0.1 (-0.6–0.5) | -0.1 (-0.7–0.5)<br>-0.2 (-0.9–0.4) | |
| | | June - September | 0.0 (-0.6–0.6)<br>-0.0 (-0.6–0.5) | -0.0 (-0.7–0.6)<br>-0.1 (-0.7–0.5) | |
| | Wave direction change (° clockwise) | December – March | 0 (-10–10)<br>0 (-10–10) | 0 (-10–10)<br>0 (-10–10) | |
| | | June - September | +0 (-20–40)<br>0 (-20–40) | +0 (-20–30)<br>+10 (-20–60) | |
| **Federated States of Micronesia (West)** | Wave height change (m) | December – March | -0.0 (-0.3–0.2)<br>-0.0 (-0.3–0.2) | -0.1 (-0.3–0.1)<br>-0.2 (-0.4–0.0) | Low |
| | | June - September | 0.0 (-0.2–0.2)<br>0.0 (-0.2-0.2) | 0.0 (-0.2–0.2)<br>0.0 (-0.2–0.2) | |
| | Wave period change (s) | December – March | -0.1 (-0.4–0.3)<br>-0.1 (-0.5–0.3) | -0.1 (-0.5–0.3)<br>-0.3 (-0.7–0.2) | |
| | | June - September | 0.0 (-0.4–0.4)<br>0.0 (-0.4–0.4) | -0.0 (-0.5–0.4)<br>-0.1 (-0.6–0.4) | |
| | Wave direction change (° clockwise) | December – March | 0 (-5–5)<br>0 (-5–5) | 0 (-10–5)<br>-0 (-10–5) | |
| | | June - September | +0 (-40–40)<br>0 (-40–40) | +0 (-30–40)<br>+10 (-30–50) | |
| **Fiji** | Wave height change (m) | December – March | 0.0 (-0.2–0.2)<br>-0.0 (-0.2–0.2) | -0.0 (-0.3–0.2)<br>-0 1 (-0.3–0.1) | Low |
| | | June - September | +0.0 (-0.3–0.4)<br>+0.0 (-0.3–0.3) | +0.0 (-0.3–0.4)<br>+0.0 (-0.3–0.4) | |
| | Wave period change (s) | December – March | -0.1 (-0.9–0.7)<br>-0.0 (-0.9–0.8) | -0.1 (-1.0–0.8)<br>-0.1 (-1.1–0.9) | |
| | | June - September | +0.0 (-0.9–0.9)<br>+0.0 (-0.8–0.9) | +0.1 (-1.0–1.2)<br>+0.1 (-1.1–1.2) | |
| | Wave direction change (° clockwise) | December – March | 0 (-20–20)<br>0 (-20–20) | 0 (-20–20)<br>10 (-20–30) | |
| | | June - September | 0 (-10–10)<br>0 (-10–10) | 0 (-10–10)<br>-0 (-10–10) | |
| **Kiribati (Gilbert Islands)** | Wave height change (m) | December – March | -0.0 (-0.2–0.1)<br>-0.1 (-0.2–0.1) | -0.1 (-0.2–0.1)<br>-0.2 (-0.3–0.1) | Low |
| | | June - September | 0.0 (-0.1–0.1)<br>0.0 (-0.1–0.1) | 0.0 (-0.1–0.1)<br>0.0 (-0.1–0.1) | |
| | Wave period change (s) | December – March | -0.0 (-1.0–1.5)<br>-0.1 (-1.3–1.1) | -0.1 (-1.2–1.6)<br>-0.2 (-1.3–1.5) | |
| | | June - September | +0.1 (-0.5–0.7)<br>0.0 (-0.6–0.6) | +0.0 (-0.7–0.7)<br>-0.0 (-0.7–0.7) | |
| | Wave direction change (° clockwise) | December – March | 0 (-10–10)<br>0 (-10–10) | 0 (-10–10)<br>0 (-10–10) | |
| | | June - September | +0 (-10–10)<br>0 (-10–10) | +0 (-10–20)<br>+0 (-10–20) | |
| **Kiribati (Phoenix Islands)** | Wave height change (m) | December – March | -0.0 (-0.3–0.2)<br>-0.0 (-0.3–0.2) | -0.1 (-0.3–0.2)<br>-0.1 (-0.4–0.2) | Low |
| | | June - September | 0.0 (-0.1–0.2)<br>0.0 (-0.1–0.1) | 0.0 (-0.1–0.2)<br>+0.0 (-0.2–0.2) | |
| | Wave period change (s) | December – March | 0.0 (-1.5–1.8)<br>-0.1 (-1.4–1.6) | -0.1 (-1.8–2.0)<br>-0.1 (-1.9–1.9) | |
| | | June - September | +0.1 (-0.8–0.9)<br>+0.0 (-0.8–0.9) | 0.0 (-1.0–1.0)<br>-0.0 (-1.0–0.9) | |

| | | | | | |
|---|---|---|---|---|---|
| | Wave direction change (° clockwise) | December – March | 0 (-20–20)<br>0 (-20–20) | -0 (-20–20)<br>-0 (-20–20) | |
| | | June - September | +0 (-10–10)<br>0 (-10–10) | 0 (-10–10)<br>+0 (-10–10) | |
| **Kirbati (Line Islands)** | Wave height change (m) | December – March | -0.0 (-0.3–0.3)<br>-0.0 (-0.3–0.2) | -0.1 (-0.4–0.2)<br>-0.1 (-0.4–0.2) | Low |
| | | June - September | 0.0 (-0.2–0.2)<br>+0.0 (-0.1–0.2) | 0.0 (-0.2–0.2)<br>+0.0 (-0.2–0.3) | |
| | Wave period change (s) | December – March | 0.0 (-1.5–1.8)<br>-0.1 (-1.4–1.7) | -0.1 (-1.7–1.9)<br>-0.1 (-1.8–2.0) | |
| | | June - September | +0.0 (-0.9–1.0)<br>0.0 (-0.9–0.9) | 0.0 (-1.0–1.0)<br>+0.0 (-1.2–1.0) | |
| | Wave direction change (° clockwise) | December – March | 0 (-30–30)<br>0 (-20–20) | 0 (-30–20)<br>0 (-30–30) | |
| | | June - September | 0 (-10–10)<br>0 (-10–10) | 0 (-10–10)<br>+0 (-10–10) | |
| **Marshall Islands (Northern)** | Wave height change (m) | December – March | -0.0 (-0.2 to 0.2)<br>-0.1 (-0.3 to 0.1) | -0.1 (-0.3 to 0.1)<br>-0.2 (-0.5 to 0.0) | Low |
| | | June - September | +0.0 (-0.2 to 0.2)<br>+0.0 (-0.2 to 0.2) | 0.0 (-0.2 to 0.2)<br>0.0 (-0.2 to 0.2) | |
| | Wave period change (s) | December – March | -0.1 (-0.6 to 0.5)<br>-0.1 (-0.6 to 0.5) | -0.1 (-0.8 to 0.5)<br>-0.2 (-1.0 to 0.5) | |
| | | June - September | -0.0 (-0.9 to 0.8)<br>-0.1 (-0.9 to 0.7) | -0.0 (-0.9 to 0.9)<br>-0.0 (-0.9 to 0.8) | |
| | Wave direction change (° clockwise) | December – March | 0 (-10 to 10)<br>0 (-10 to 10) | 0 (-10 to 10)<br>-0 (-10 to 10) | |
| | | June - September | 0 (-10 to 10)<br>+0 (-10 to 20) | +0 (-10 to 20)<br>+10 (-10 to 30) | |
| **Marshall Islands (Southern)** | Wave height change (m) | December – March | -0.0 (-0.3 to 0.2)<br>-0.1 (-0.3 to 0.2) | -0.1 (-0.3 to 0.1)<br>-0.2 (-0.4 to 0.0) | Low |
| | | June - September | 0.0 (-0.2 to 0.2)<br>+0.0 (-0.2 to 0.2) | 0.0 (-0.2 to 0.2)<br>0.0 (-0.1 to 0.1) | |
| | Wave period change (s) | December – March | -0.1 (-0.7 to 0.7)<br>-0.1 (-0.7 to 0.8) | -0.1 (-0.8 to 0.8)<br>-0.2 (-1.0 to 0.8) | |
| | | June - September | 0.0 (-0.9 to 0.9)<br>-0.1 (-0.9 to 0.8) | 0.0 (-0.9 to 0.9)<br>-0.0 (-0.8 to 0.8) | |
| | Wave direction change (° clockwise) | December – March | 0 (-10 to 10)<br>0 (-10 to 10) | 0 (-10 to 10)<br>-0 (-10 to 10) | |
| | | June - September | 0 (-20 to 20)<br>0 (-20 to 20) | +0 (-20 to 30)<br>+10 (-20 to 40) | |
| **Nauru** | Wave height change (m) | December – March | -0.0 (-0.2 to 0.2)<br>-0.1 (-0.3 to 0.1) | -0.1 (-0.2 to 0.1)<br>-0.2 (-0.3 to -0.1) | Low |
| | | June - September | +0.0 (-0.1 to 0.1)<br>+0.0 (-0.1 to 0.1) | 0.0 (-0.1 to 0.1)<br>+0.0 (-0.1 to 0.1) | |
| | Wave period change (s) | December – March | -0.0(-1.1 to 1.0)<br>-0.1 (-1.1 to 1.0) | -0.1 (-1.2 to 1.1)<br>-0.2 (-1.3 to 1.0) | |
| | | June - September | +0.0 (-0.6 to 0.7)<br>0.0 (-0.6 to 0.6) | 0.0 (-0.7 to 0.7)<br>-0.1 (-0.8 to 0.6) | |
| | Wave direction change (° clockwise) | December – March | 0 (-10 to 10)<br>0 (-10 to 10) | 0 (-10 to 10)<br>0 (-10 to 10) | |
| | | June - September | +0 (-10 to 20)<br>+0 (-10 to 20) | +0 (-10 to 20)<br>+10 (-10 to 30) | |
| **Niue** | Wave height change (m) | December – March | 0.0 (-0.2 to 0.2)<br>-0.0 (-0.2 to 0.2) | -0.0 (-0.3 to 0.2)<br>-0.1 (-0.3 to 0.1) | Low |
| | | June - September | +0.0 (-0.3 to 0.4)<br>+0.0 (-0.3 to 0.4) | 0.0 (-0.4 to 0.4)<br>0.0 (-0.4 to 0.4) | |
| | Wave period change (s) | December – March | -0.1 (-1.1 to 1.0)<br>-0.1 (-1.1 to 0.9) | -0.1 (-1.2 to 1.1)<br>-0.2 (-1.4 to 1.2) | |
| | | June - September | 0.0 (-0.9 to 0.9)<br>0.0 (-0.9 to 0.9) | 0.0 (-1.0 to 1.0)<br>-0.0 (-1.1 to 1.1) | |
| | Wave direction change (° clockwise) | December – March | 0 (-30 to 30)<br>0 (-30 to 30) | -0 (-30 to 30)<br>-0 (-40 to 30) | |
| | | June - September | -0 (-10 to 10)<br>-0 (-10 to 10) | -0 (-10 to 10)<br>-5 (-10 to 5) | |
| **Palau** | Wave height change (m) | December – March | -0.0 (-0.3–0.3)<br>-0.0 (-0.4–0.3) | -0.1 (-0.4–0.2)<br>-0.2 (-0.4–0.1) | Low |

| | | | | | |
|---|---|---|---|---|---|
| | | June - September | 0.0 (-0.2–0.2)<br>0.0 (-0.2–0.2) | 0.0 (-0.2–0.2)<br>0.0 (-0.2–0.2) | |
| | Wave period change (s) | December – March | -0.1(-0.4–0.3)<br>-0.1 (-0.6–0.6) | -0.1 (-0.6–0.4)<br>-0.2 (-0.8–0.4) | |
| | | June - September | -0.0 (-0.6–0.5)<br>-0.0 (-0.6–0.6) | -0.1 (-0.7–0.6)<br>-0.1 (-0.8–0.5) | |
| | Wave direction change (° clockwise) | December – March | 0 (-5–5)<br>0 (-10–5) | -0 (-10–5)<br>-5 (-10–5) | |
| | | June - September | +0 (-30 to 80)<br>0 (-0–60) | +0 (-30–80)<br>+10 (-30–70) | |
| **Papua New Guinea** | Wave height change (m) | December – March | -0.0 (-0.2–0.1)<br>-0.0 (-0.2–0.1) | -0.1 (-0.2–0.1)<br>-0.1 (-0.2–0.0) | Low |
| | | June - September | 0.0 (-0.3–0.3)<br>+0.0 (-0.3–0.3) | +0.0 (-0.2–0.3)<br>+0.0 (-0.2 –0.3) | |
| | Wave period change (s) | December – March | -0.0(-0.9–0.8)<br>-0.1 (-1.0–0.8) | -0.1 (-1.0–0.8)<br>-0.2 (-1.2–0.7) | |
| | | June - September | -0.0 (-0.8–0.7)<br>-0.1 (-0.9–0.8) | -0.1 (-0.9–0.7)<br>-0.2 (-1.1–0.7) | |
| | Wave direction change (° clockwise) | December – March | 0 (-10–10)<br>0 (-10–10) | -0 (-10–10)<br>-0 (-10–10) | |
| | | June - September | +0 (-40–70)<br>0 (-40–70) | +0 (-30–60)<br>+10 (-50–70) | |
| **Samoa** | Wave height change (m) | December – March | -0.0 (-0.2–0.2)<br>-0.0 (-0.2–0.1) | -0.0 (-0.2–0.1)<br>-0.1 (-0.2–0.2) | Low |
| | | June - September | +0.0 (-0.2–0.3)<br>+0.0 (-0.2–0.2) | 0.0 (-0.2–0.2)<br>+0.0 (-0.2–0.3) | |
| | Wave period change (s) | December – March | -0.1(-1.3–1.2)<br>-0.1 (-1.2–1.2) | -0.1 (-1.3–1.5)<br>-0.2 (-1.6–1.6) | |
| | | June - September | 0.0 (-0.9–1.0)<br>+0.0 (-1.0–1.0) | +0.0 (-1.1–1.2)<br>0.0 (-1.3–1.3) | |
| | Wave direction change (° clockwise) | December – March | 0 (-40–40)<br>0 (-40–30) | 0 (-40–40)<br>0 (-50–50) | |
| | | June - September | 0 (-10–10)<br>0 (-10–10) | 0 (-10–10)<br>0 (-10–10) | |
| **Solomon Islands** | Wave height change (m) | December – March | -0.0 (-0.2–0.1)<br>-0.0 (-0.2–0.1) | -0.1 (-0.2–0.1)<br>-0 1 (-0.2–0.0) | Low |
| | | June - September | +0.0 (-0.3–0.3)<br>+0.0 (-0.3–0.3) | +0.0 (-0.3–0.3)<br>+0.0 (-0.3–0.3) | |
| | Wave period change (s) | December – March | -0.0 (-0.7–0.7)<br>-0.0 (-0.7–0.7) | -0.1 (-1.0–0.7)<br>-0.2 (-1.1–0.8) | |
| | | June - September | -0.0 (-0.6–0.5)<br>-0.0 (-0.6–0.5) | -0.1 (-0.7–0.6)<br>-0.1 (-0.7–0.7) | |
| | Wave direction change (° clockwise) | December – March | +0 (-30–30)<br>+0 (-30–30) | 0 (-30–30)<br>-0 (-30–30) | |
| | | June - September | 0 (-5–5)<br>0 (-5–5) | 0 (-5–10)<br>0 (-5–10) | |
| **Tonga** | Wave height change (m) | December – March | 0.0 (-0.2–0.2)<br>-0.0 (-0.2–0.2) | -0.0 (-0.3–0.2)<br>-0 1 (-0.3–0.1) | Low |
| | | June - September | +0.0 (-0.3–0.4)<br>+0.0 (-0.3–0.4) | 0.0 (-0.4–0.4)<br>+0.0 (-0.4–0.4) | |
| | Wave period change (s) | December – March | -0.1 (-1.0–0.9)<br>-0.1 (-1.0–0.8) | -0.1 (-1.2–0.9)<br>-0.1 (-1.3–1.1) | |
| | | June - September | +0.0 (-0.9–1.0)<br>+0.0 (-0.8–0.9) | +0.0 (-1.1–1.1)<br>0.0 (-1.2–1.1) | |
| | Wave direction change (° clockwise) | December – March | -0 (-30–20)<br>0 (-30–20) | -0 (-30–30)<br>0 (-30–30) | |
| | | June - September | 0 (-10–10)<br>-0 (-10–10) | 0 (-10–10)<br>-5 (-10–5) | |
| **Tuvalu** | Wave height change (m) | December – March | -0.0 (-0.1–0.1)<br>-0.0 (-0.2–0.1) | -0.1 (-0.2–0.0)<br>-0 1 (-0.2–-0.0) | Low |
| | | June - September | +0.0 (-0.2–0.2)<br>+0.0 (-0.2–0.2) | +0.0 (-0.2–0.3)<br>+0.1 (-0.2–0.3) | |
| | Wave period change (s) | December – March | -0.0 (-1.1–1.2)<br>-0.1 (-1.2–1.1) | -0.1 (-1.4–1.4)<br>-0.1 (-1.6–1.4) | |
| | | June - September | +0.0 (-1.1–1.1)<br>+0.0 (-1.1–1.4) | +0.0 (-1.3–1.4)<br>0.0 (-1.4–1.4) | |

| | | | | | |
|---|---|---|---|---|---|
| | Wave direction change (° clockwise) | December – March | +0 (-20–20)<br>0 (-20–20) | 0 (-20–20)<br>+0 (-20–20) | |
| | | June - September | +0 (-10–10)<br>0 (-10–10) | +0 (-10–10)<br>+0 (-10–10) | |
| **Vanuatu** | Wave height change (m) | December – March | -0.0 (-0.2–0.1)<br>-0.0 (-0.2–0.1) | -0.1 (-0.2–0.1)<br>-0 1 (-0.3–0.0) | Low |
| | | June - September | +0.0 (-0.2–0.3)<br>0.0 (-0.2–0.3) | 0.0 (-0.2–0.3)<br>+0.0 (-0.2–0.3) | |
| | Wave period change (s) | December – March | -0.1 (-0.6–0.4)<br>-0.1 (-0.6–0.5) | -0.1 (-0.7–0.5)<br>-0.2 (-0.8–0.5) | |
| | | June - September | 0.0 (-0.5–0.5)<br>0.0 (-0.5–0.5) | -0.0 (-0.6–0.6)<br>-0.1 (-0.6–0.5) | |
| | Wave direction change (° clockwise) | December – March | +0 (-10–10)<br>0 (-10–10) | +0 (-10–10)<br>+0 (-10–10) | |
| | | June - September | 0 (-5–5)<br>0 (-5–5) | 0 (-5–10)<br>-0 (-10–5) | |