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Effects of Climate Change on Sea Levels and Inundation Relevant to the Pacific Islands

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EXECUTIVE SUMMARY

Sea level rise is a major consequence of climate change. The global sea level rise is due to a combination of the thermal expansion of the oceans (because of their warming), and an increase in runoff from the melting of continental glaciers (which adds water to the oceans).

The rate of global mean sea level (GMSL) has likely accelerated during the last century, and projections predict that sea level will be 0.4 to 0.8 m higher at the end of this century around the Pacific islands.

Regional variations in sea level also exist and are due to large scale current or climate features. In addition, the sea level experienced on Pacific islands can also be affected by vertical land movements that can either increase or decrease the effects of the rise in GMSL.

Coastal inundations are caused by a combination of high waves, tides, storm surge, or ocean eddies. While future changes in the number and severity of high waves and storms are still difficult to assess, a rise in GMSL will cause an increase in the frequency and severity of inundation in coastal areas.

The island countries of the Pacific have, and will continue to experience, a positive rate of sea level rise. This sea level rise will cause a significant increase in the frequency and severity of coastal flooding in the near future.

What is Already Happening?

This report will focus on marine/coastal inundation and sea level and how they are affected by climate change. The region of interest is the Pacific Islands, with a focus on Commonwealth countries (Fiji, Kiribati, Nauru, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu).

The variations of sea level occur over a wide range of temporal scales, from seconds to decades. Extreme sea level events that lead to coastal inundations are episodic events that can last from hours to days and can be caused by a combination of waves, tides, and storm surges.

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The severity and frequency of these flooding events can be increased (or decreased) by an elevated (or lowered) mean sea level, which can fluctuate over months, years or decades.

To understand the evolution of extreme sea level events in the context of climate change, it is therefore necessary to consider first the changes and variability of the mean sea level, then consider the factors leading to extreme sea level events.

Mean sea level

Sea level can be accounted for in two different ways: "relative sea level", when it refers to the sea level relative to the coastal area of interest, or "absolute sea level" when it refers to the sea level as measured from the centre of the earth.

The difference between absolute and relative sea levels is the vertical movements of the coastal area relative to the centre of the earth. While a rising relative sea level will induce a shoreline retreat, shoreline changes such as beach erosion can also be related to other man-made or natural processes, independently of sea level rise (Albert et al., 2016).

Over the last 25 years, absolute sea level is monitored globally by a series of satellites (Figure 1). During this altimetry period (1993-2017), the latest calculations show a rise in sea level of 3-6 mm/year for the Pacific islands, with notable differences between islands (Figure 1).

Some islands in the Western Pacific (Solomon Islands, Papua New Guinea, Marshall Islands) have experienced a higher rate of sea level rise (up to 6 mm/year), compared to others islands further east (Samoa or Kiribati). This difference in sea level rise is attributed to large scale trends in trade winds (Merrifield, 2011).

Tide gauges installed throughout the Pacific can provide a longer record of relative sea level at a small number of islands, with some datasets starting in the 1960s (Figure 2). All tide gauges show a rise in relative sea level over the past 30-40 years, again with rates varying between islands.

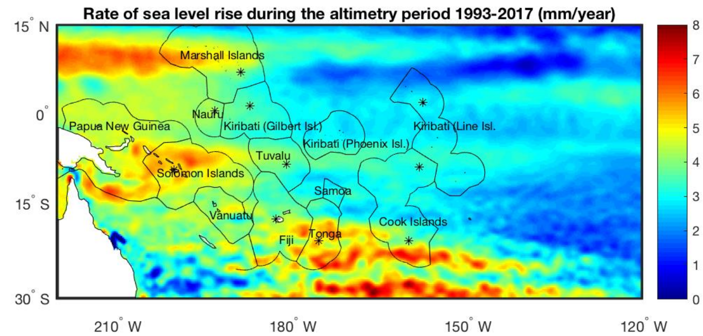


Figure 1. Rate of sea level rise from satellite altimetry (data source: Delayed Time, all-sat-merged Global Ocean Gridded SSALTO/DUACS Sea Surface Height L4 product, CLS,CNES).

Relative sea level data measured at island tide gauges combines the absolute sea level measured by satellite with the effect of the island vertical land movements. These vertical land movements include the effect of the last Glacial Isostatic Adjustment (Peltier, 2004), or tectonic effects, and are measured by land-based Global Navigation Satellite System (GNSS) stations. Some islands are very close to active plate boundaries (Vanuatu, Tonga), where vertical movements from earthquakes can be larger than decadal changes in absolute sea level (Ballu et al., 2011). Most other islands far from active plate boundaries exhibit land subsidence that will aggravate the effect of the rise in absolute sea level (see Table 1).

Individual tide gauge records also highlight the amount of inter-annual variability at the different islands (Figure 2). Most of this inter-annual variability is due to the different phases and types of the El-Niño Southern Oscillation, or ENSO for short (Nidheesh et al., 2017). Satellite altimetry during the past 25 years show that this inter-annual variability (Figure 3) is more pronounced in the central equatorial Pacific (Line Islands of the Kiribati) and in the Western Pacific (Solomon Islands). When the regional sea level is anomalously high, a given storm or wave event will create a more damaging inundation event. Conversely, when the regional sea level is anomalously low, damages from a given storm will be mitigated. Except near the location of tide gauges, reconstructing regional sea level variability remains an unsolved challenge for the period that pre-dates the satellite altimetry observations (Carson et al., 2017).

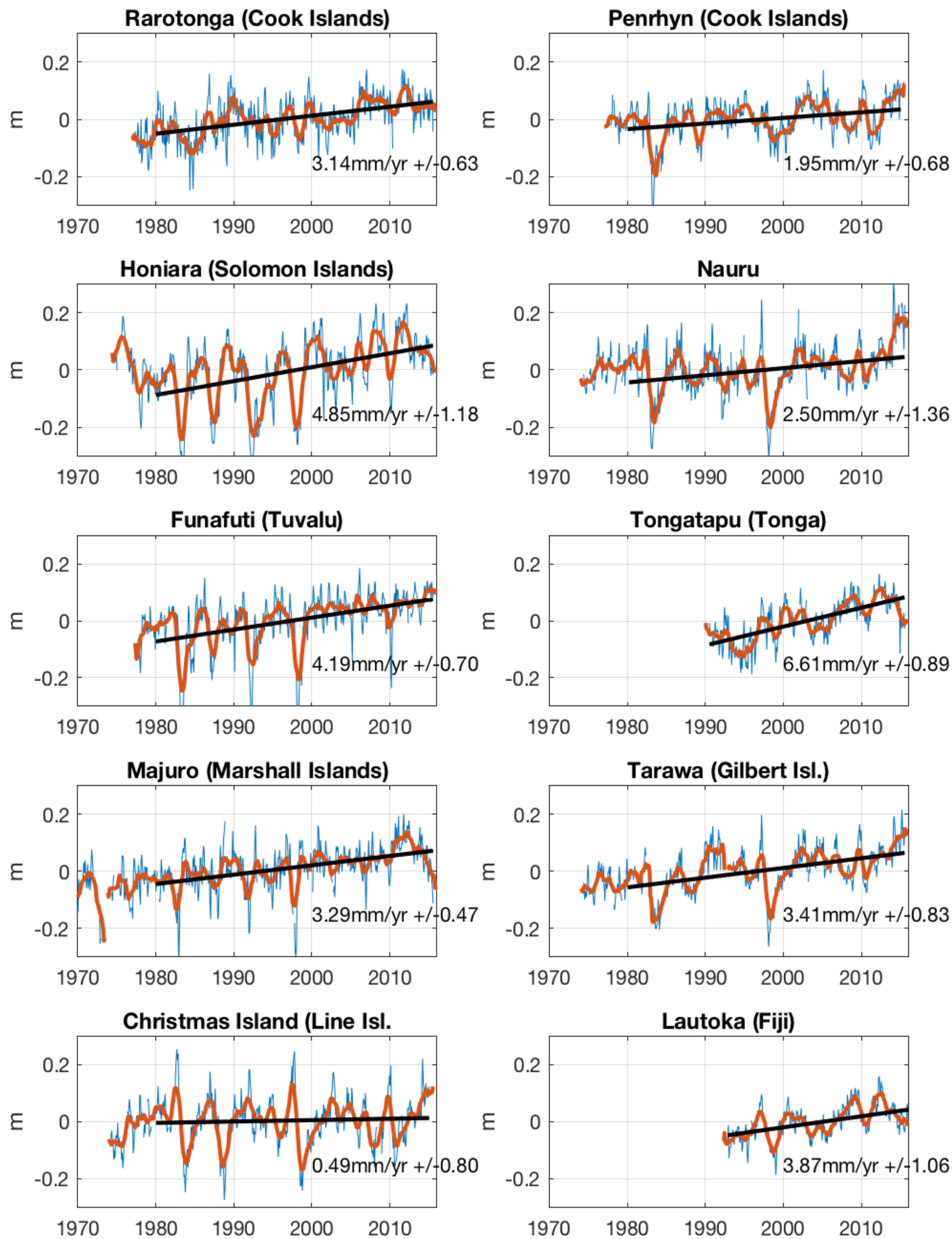


Figure 2. Monthly and yearly running averages of relative sea level measured at tide gauges. Trends are calculated over the period 1977-2017 except for Tonga and Fiji (data source: University of Hawaii Sea Level Center).

Table 1. Vertical land movements of Pacific Commonwealth islands

Vertical movements measured by GNSS stations (from www.sonel.org)	
Station	**mm/year**
Tonga	*3.01 +/- 0.41* Variable/unreliable because of common occurrence of earthquakes
Kiribati (Tarawa)	-0.22 +/- 0.24
Nauru	-0.96 +/- 0.25
Solomon Is. (Honiara)	Variable/unreliable because of common occurrence of earthquakes
Cook Is. (Rarotonga)	-0.50 +/- 0.36
Samoa	Unreliable because of station problems
Tuvalu (Funafuti)	-1.71 +/- 0.17
Vanuatu	Variable/unreliable because of common occurrence of earthquakes
Fiji (Lautoka)	-1.15 +/- 0.26

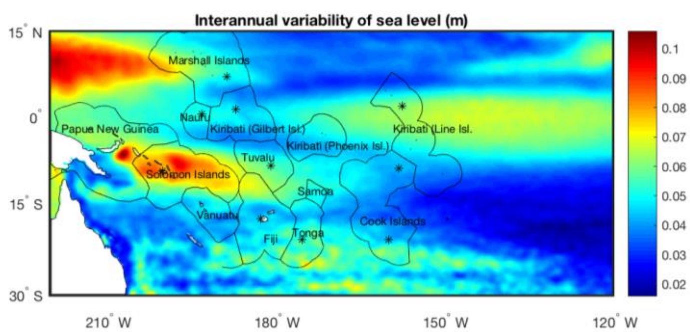


Figure 3. Inter-annual sea level variability from satellite altimetry (data source: Delayed-Time all-sat-merged Global Ocean Gridded SSALTO/DUACS Sea Surface Height L4 product, CLS,CNES).

Extreme sea level

Extreme sea level events are short duration (hours to days) coastal flooding events which can have devastating impacts on coastal infrastructure, freshwater resources and agricultural fields. If these events are too recurrent, they will render the coastal area inhabitable long before the area is permanently flooded (Storlazzi et al., 2015). Tide gauge data have been used to investigate the occurrences of these events. A Global Extreme Sea Level Analysis (GESLA, http://gesla.ordg) compiles all available high frequency tide gauge data necessary to analyse these events (Woodworth et al., 2017).

The most ubiquitous sea level variation is due to the astronomical tide, created by the gravitational effect of the moon and the sun. Most Pacific Commonwealth Islands experience a mixed semidiurnal tidal regime (2 high tides per day), with higher tidal amplitudes during New Moon and Full Moon (spring tides). A high astronomical tide can cause flooding on very low islands such as Tuvalu (Lin et al., 2014).

Breaking waves on a beach, or a reef, create an anomalous sea level called “wave setup”. This wave setup can cause inundation of the coastal area. As a result, waves from distant storms in the high latitudes can trigger inundation in the tropics on Pacific islands (Hoeke et al., 2013). Islands and islets that sit within a lagoon protected by a barrier reef can also be indirectly flooded by waves because the wave setup at the barrier reef can elevate the sea level throughout the entire lagoon (Aucan et al., 2012).

To investigate extreme sea level from distant waves, one must also investigate the trends and variability of the high latitude storms which generated these waves. For islands in the Pacific, coastlines can be exposed to waves from the northern or southern hemisphere, or both. During the past century, waves in the North Pacific have been increasing (IPPC AR5), while the trend in the Southern Ocean is either negative or insignificant (IPCC WG1AR5 ch.2).

During tropical cyclones, coastal flooding is caused by wave setup (as described above), combined with the “storm surge”. The storm surge is an anomalously elevated sea level due to the combined action of low atmospheric pressure, and the wind, which can push large amounts of water over shallow areas.

Current data sets indicate no significant observed trends in tropical cyclone frequency over the past century and it remains uncertain whether any reported long-term increases in tropical cyclone frequency are robust (WG1AR5 ch.2).

While the drivers of extreme sea levels may not have significantly changed over the past decades, extreme sea level events are nonetheless becoming more severe and frequent because of the decadal rise in sea level discussed above (Woodworth et al., 2011).

What Could Happen?

The Intergovernmental Panel for Climate Change (IPCC) provides in its assessment reports (AR) the scientific view of climate change. The AR provides the current knowledge of expected changes under the different possible future concentrations of greenhouse gases. These different Representative Concentration

Pathways (RCPs) describe four possible climate futures, depending on our emissions.

Mean sea level rise

Global mean sea level is expected to rise under all emission scenarios (figure 4). In the Pacific the rate of sea level rise is projected to be higher than the mean rate in all scenarios. The mean sea level for the Pacific Commonwealth islands for 2080-2100 is expected to be 0.4 to 0.8 m higher compared to 1986-2005. These projections are the result of large number of process-based models and are considered likely by the IPCC.

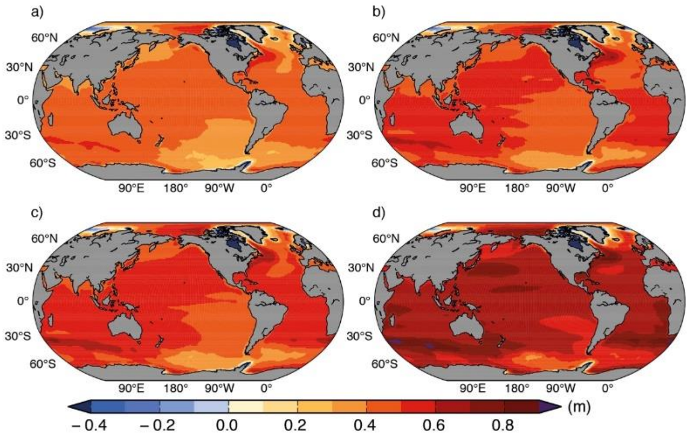


Figure 4. Ensemble mean regional relative sea level change (metres) evaluated from 21 CMIP5 models for the RCP scenarios (a) 2.6, (b) 4.5, (c) 6.0 and (d) 8.5 between 1986–2005 and 2081–2100. Each map includes effects of atmospheric loading, plus land ice, glacial isostatic adjustment (GIA) and terrestrial water sources (from figure 13:20, IPCC AR5 WGI).

Under all emission scenarios (except the most optimist RCP 2.6), the rate of sea level rise is expected to increase to reach values between 6 and 12 mm/yr by 2100 for RCP 8.5 (see Table 2).

Table 2. Expected rates of sea level rise in the Pacific and globally.

	Emissions scenarios			
	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Projected change in relative sea level between 1986-2005 and 2081-2100 for the Central Western Pacific (in m)	0.4-0.5	0.4-0.6	0.4-0.6	0.6-0.8
Range of projected rate of global sea level rise in 2100 (in mm/yr)	2-7	4-9	5-10	8-16

Given these amounts and rates of sea level rise, and considering the inter-annual variability observed in the Pacific, the anomalously low sea level periods of mid-century will be as high or higher than the anomalously high sea level periods of today (see example of American Samoa on Figure 5).

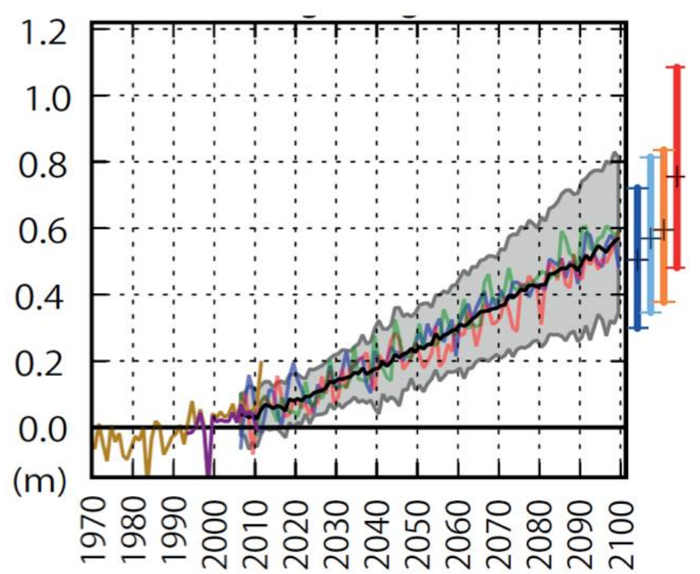


Figure 5. Observed and projected relative sea level change (from figure 13:23, IPCC AR5 WGI) at Pago Pago, American Samoa. The observed *in situ* relative sea level records from the tide gauge (since 1970) is plotted in yellow, and the satellite record (since 1993) is provided as purple lines. The projected range from 21 CMIP5 RCP4.5 scenario runs (90% uncertainty) is shown by the shaded region for the period 2006–2100, with the bold line showing the ensemble mean. Coloured lines represent three individual climate model realizations drawn randomly from three different climate models used in the ensemble. Vertical bars at the right sides of each panel represent the ensemble mean and ensemble spread (5 to 95%) of the *likely* (*medium confidence*) sea level change at each respective location at the year 2100 inferred from RCPs 2.6 (dark blue), 4.5 (light blue), 6.0 (yellow) and 8.5 (red).

Extreme sea level

Projections for tropical cyclones for the 21st century are currently inconclusive (IPCC WG1AR5 ch.14). Similarly, 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. Projections of the drivers of extreme events are therefore not available, but we can nonetheless generate projections of extreme sea level by using projections of mean sea level rise and assume a similar pattern of extreme event drivers (wave, storm surge and tides).

Global or regional projections of extreme sea level and associated flooding are complicated because the relationship between water level and flooding depends at each location on coastal topography, and coastal infrastructure. Most comprehensive projections of extreme sea level and flooding rely on statistical approaches. To further improve these projections, a more process-based modelling approach will be necessary for each site of interest (see paragraph 4: Knowledge Gaps). The statistical approach provides nonetheless a scenario for the future.

Wahl et al., 2017 quantified the uncertainties of extreme sea level estimations and established projections of changes in extreme level occurrences. Looking at the tropical Pacific, an event which currently happens once a century will become a yearly occurrence by 2050. While Wahl et al., 2017 considered storm surge as the main cause of extreme sea level, they do not consider wave setup. Yet, over Pacific Islands, waves can be the dominant cause of extreme sea level (Hoeke et al., 2013) and need to be taken into account in extreme level projections. Vitousek et al., 2017 combined sea level projections with the effects of wave and storm surge to statistically analyse the evolution of the flooding frequency, for which they use extreme water level as a proxy. They found that throughout the tropical Pacific, a 10 - 20 cm sea level rise would more than double the frequency of flooding.

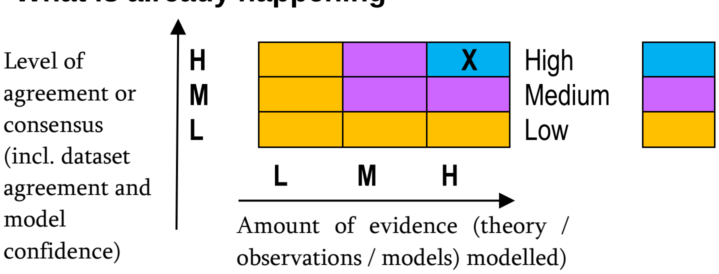
These recent studies (Vitousek et al., 2017; Wahl et al., 2017), together with the 2015 IPCC WG1AR5 report, all support a projected increase of extreme sea level events, mainly caused by the rise in mean sea level.

What is already happening?
The level of confidence for impacts of climate change of sea level and inundation needs to be considered in regard to the two main factors: the mean (and regional) sea level rise; and the storminess which causes the inundation (directly and or through long distance wave propagation).
The sea level rise over the past century is well established, and its continuous rise is also widely considered as very probable. There is therefore a high level of consensus, based on a large amount of evidence, that sea level has been rising for the last century, and will continue to do so at an accelerated pace.
Storms are at the origin of most extreme sea level events. Yet, the changes in storminess (i.e. the number and severity of tropical and extra-tropical storms), are hardly detectable, and future projections regarding the number and severity of storms vary too widely to be considered reliable.

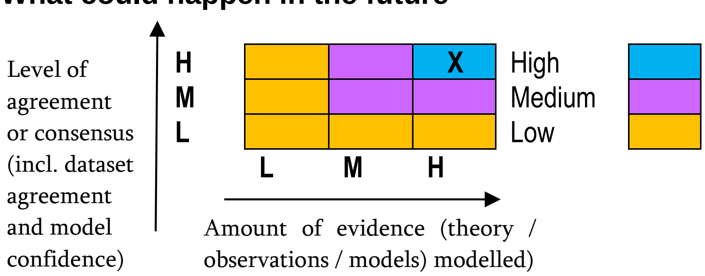
What could happen in the future?
Because the changes in extreme sea level are mainly dependent on the mean sea level, and given that there is a high level of confidence that the mean sea will continue to increase, we have a high level of confidence that the occurrence of extreme sea level events will increase.

Confidence Assessment

What is already happening



What could happen in the future



Knowledge Gaps

1) The overarching knowledge gap is the lack of systematic studies of localized wave and storm impacts to obtain flooding risk maps for coastal communities. Knowledge of potential inundation areas is necessary to create relevant evacuation zones to protect life ahead of extreme events. Potential inundation maps, coupled with statistics of inundation, are also crucial to help coastal communities develop mid- and long-term strategies for coastal developments.
This knowledge gap can be addressed with high resolution modelling of coastal areas, coupled with short-term in-situ data collection.

2) Regional sea level has a strong impact on flooding levels. To support the overarching knowledge gap above, a better knowledge of short to mid-term (months to years) regional sea-level variations is necessary. This knowledge can be addressed with the continuous improvement of coupled ocean-atmosphere models at the regional or basin scale.

3) Vertical land movement can be a determining factor of the relative sea level experienced by some Pacific Commonwealth Islands (Tonga and Vanuatu). Long term monitoring of vertical land movement is necessary to monitor co-seismic and tectonic land movement, and to allow a direct comparison between satellite and tide gauge measurements.

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