Assessment of Sea Level Rise and Associated Impacts for Tuvalu

NASA Sea Level Change Team[1]
Technical Report, N-SLCT-2023-01
June 2023

Credit: UN Development Programme, Fiji Office

Overview

For low-lying island nations in the Pacific Ocean, increasing sea levels pose an existential threat. One of these nations, Tuvalu, has already begun experiencing impacts driven by the combined effects of the rising ocean, storms, naturally-occurring ocean variability, and changes in other physical processes. These impacts are expected to worsen in the future, and planning and adaptation is underway in Tuvalu. In this technical report, the NASA Sea Level Change Team (N-SLCT) assesses the available observations and latest scientific understanding to provide information on future sea level rise and associated impacts for Tuvalu. This report is written in support of the objectives of the Rising Nations Initiative (RNI), enabled by the UN Global Center for Climate Mobility, and serves as a scientific foundation upon which activities and plans can be based.

Key Messages

1. Sea level in Tuvalu has risen by 0.15 m over the past 30 years, at an average rate of 5 mm/year since 1993, and this rate will increase in the future, potentially more than doubling by 2100.
2. Relative sea level is projected to increase by 0.2-0.3 m by 2050 relative to 2005 and 0.5-1.0 m by 2100, with an upper-end worst-case estimate approaching 2 m.
3. The majority of Tuvalu sits at low elevation, and much of the land plus critical infrastructure will sit below the level of the current high tide by 2050.
4. Future sea level rise will cause a large increase in the frequency and severity of episodic flooding within the 21st century for Tuvalu. Across all future scenarios and under the assumption of no additional protections, Tuvalu will experience more than 100 days of flooding every year by the end of the century.
5. Sea level impacts beyond flooding - like saltwater intrusion - will become more frequent and continue to worsen in severity in the coming decades.

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[1] *See Acknowledgement Section for full list of authors.*

1. Introduction

Sea level rise is a direct consequence of our warming climate. On a global scale, the combination of warming ocean waters and melting ice located on land is leading to sea level rise that is occurring at an ever-increasing rate (e.g. Dangendorf et al., 2019; Nerem et al., 2018; 2022; Willis, Hamlington, Fournier, 2023). Observations of sea level made from satellite altimeters show an acceleration in the rate of global sea level rise of almost 1 mm/year every decade, leading to a present rate of more than 4 mm/year. This seemingly small rate and year-over-year increase in that rate already hold great significance for coastal communities that have seen more than a century of persistent sea level rise (e.g. Frederikse et al., 2020). The gap between the average high tide and flooding conditions has narrowed, and coastal impacts driven by sea level rise have increased in frequency and severity in recent years.

This is particularly true for low-lying island nations in the Pacific Ocean. Sea level rise does not occur at the same rate everywhere across the globe and can be exacerbated by natural ocean fluctuations that occur over time periods from years to decades. In the western tropical Pacific, the amount of sea level rise has been substantially higher than the global average over the past three decades (Figure 1). It is an active research question as to whether these higher-than-average trends will persist into the future, but projections of future sea level rise encompass a range of possibilities - all indicating accelerating sea level rise - in the years to come. In the near-term, the ongoing sea level rise will combine with naturally occurring ocean variability and storms to drive worsening impacts.

In this report, the focus is specifically on the island nation of Tuvalu (Figure 1; star marker). Tuvalu is located about midway between Hawaii and Australia in the South Pacific Ocean, and is home to a population of approximately 11,000 people. It consists of nine inhabited islands, with approximately half the population living on the atoll of Funafuti. Given its low elevation and increasing sea levels, Tuvalu has been a recent focal point for academic research and has become a case study for island nations attempting to adapt to the changes that are occurring along its coastlines. Working alongside partners including the United Nations Development Programme (UNDP)

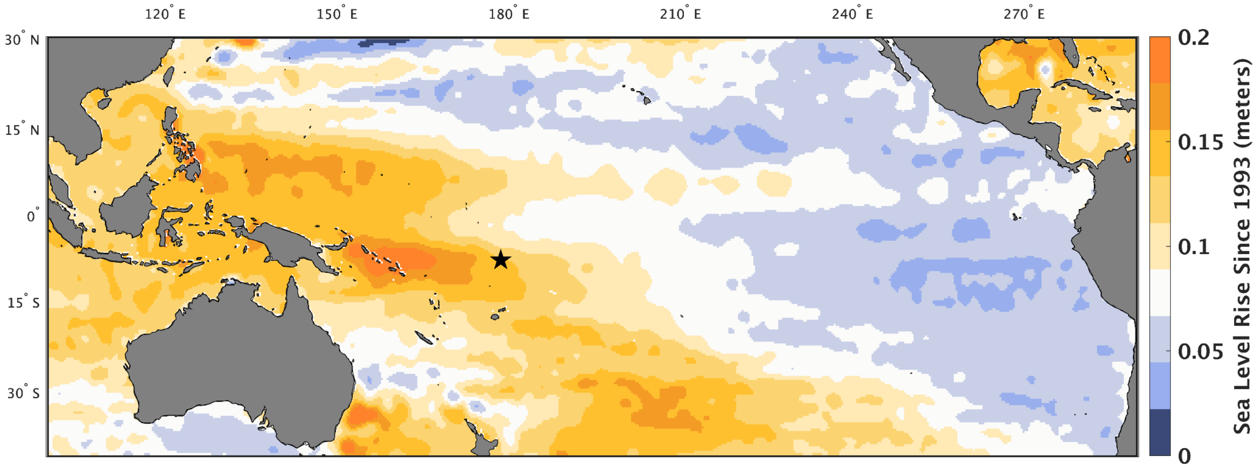

Figure 1. Amount of sea level rise (meters) from 1993 to 2022 estimated from satellite altimetry data. The star marker indicates the location of Tuvalu.

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and the Green Climate Fund, Tuvalu has developed and has started implementing the Tuvalu Coastal Adaptation Project (TCAP; https://www.adaptation-undp.org/projects/tuvalu-coastal-adaptation-project). TCAP considers a wide range of coastal protection measures and seeks to build capacity for resilient coastal management. An important step in this effort is collecting needed data that sits at the foundation of the project. As an example, UNDP initiated the collection of a high-resolution, high accuracy Digital Elevation Model (DEM) for Tuvalu. Leveraging this data, technical partners including The Pacific Community (spc.int) are producing high-resolution, at-the-coast assessments of the impact of the combination of physical processes affecting the coastlines of Tuvalu.

This report represents a complementary component to this ongoing work by providing information on the latest understanding of sea level rise in the past, present and future, and assessing future impacts associated with this sea level rise. In August 2021, the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6; Fox-Kemper et al., 2021) was released, documenting the latest understanding of sea level change and providing authoritative projections of future sea level rise on a global scale. The information relevant to Tuvalu from the IPCC AR6 is presented here and supported by observations of sea level change and the processes that drive it. Additionally, the projections from the report are used to assess some of the future impacts along the coastlines of Tuvalu. Finally, the role that the current observational network can play in monitoring the ongoing changes that are occurring in Tuvalu is discussed.

2. Past and Present Sea Level Change in Tuvalu

a. Observations of Sea Level in Tuvalu

The tide gauge record in Funafuti (Funafuti B; https://psmsl.org/data/obtaining/stations/1839.php) and modern satellite altimeter record both cover the time period from 1993 to present. Satellite altimetry provides continuous and ongoing near-global measurements of sea level. Comparing the tide gauge data and the nearest data point from the satellite altimetry, one sees that the two sets of observations agree closely (Figure 2). The rate of sea level rise estimated from the tide gauge data is 5.0 +/- 1.1 mm/year and the rate from the satellite altimeter data is 4.7 mm/year +/- 0.7 mm/year. These two rates are not statistically different, although the tide gauge measures relative sea level that incorporates the movement of the land and the satellite measures geocentric (or absolute) sea level. There is a positive acceleration of 0.12 mm/year^2, but this is not statistically different from zero and is heavily influenced by the presence of substantial sea level variations occurring around the long-term trend.

The year-to-year variations in sea level are closely associated with the El Niño-Southern Oscillation (ENSO). For the positive phase of ENSO (El Niño), sea level around Tuvalu typically drops in January-February-March following the onset of the event in the previous year. Within the observational record, these drops can exceed 20 cm, although there is substantial variability from year-to-year. For negative phase ENSO events (La Niñas), sea level in Tuvalu does not exhibit a substantial response. Tuvalu also experiences a regular annual cycle, with peak-to-trough amplitude

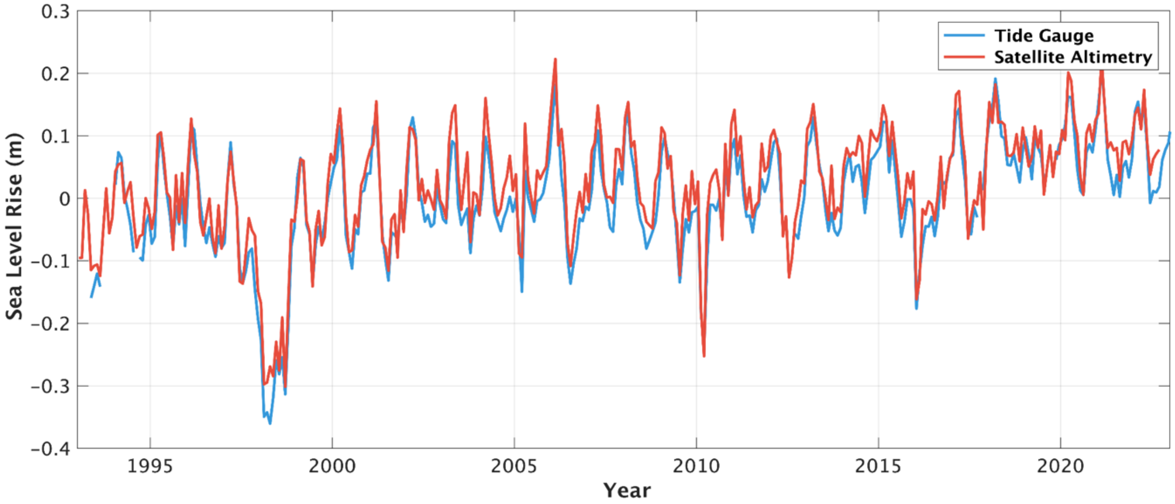


Figure 2. Comparison of monthly data from the Funafuti B tide gauge (blue) and nearest satellite altimetry data point (red). The rate from 1993 to 2023 at the tide gauge is 5.0 mm/year while the rate from the satellite altimetry over the same time period is 4.7 mm/year.

approaching 10 cm. This annual cycle results from a combination of seasonally varying winds and the seasonality of solar heating.

b. Processes Contributing to Sea Level Rise in Tuvalu

Understanding the individual physical processes that are causing sea level to rise can lead to improved interpretation of future projections and help prioritize ongoing monitoring in Tuvalu. By using a combination of satellites, on-the-ground measurements, and other data products, the processes that are contributing to increasing sea level in Tuvalu can be estimated. Table 1 shows the contributions to the rate of sea level rise from the most dominant physical processes that drive relative sea level over the time period from 1993 to 2023 (updated from Harvey et al., 2020). The sum of the individual process contributions is 6.1 mm/year compared to the 5.0 mm/year measured directly at the tide gauge. The error estimates on the two rates overlap, and it cannot be concluded that these two rates are statistically different.

Although the uncertainties in the rates are relatively large and error estimates overlap, the comparison between data sources does provide additional information about the relative sea level change in Tuvalu. At the tide gauge location, the absolute sea level measured by the satellites and the relative sea level measured by the tide gauge closely agree (4.7 mm/year vs. 5.0 mm/year). Additionally, the combination of sterodynamic change (global ocean thermal

Table 1. Approximate contribution from individual physical processes to the rate of sea level rise in Tuvalu from 1993 to 2023, in mm/year. Sterodynamic change refers to the combined contribution from global ocean thermal expansion and ocean dynamics. Ocean mass change refers to the addition of water into the ocean from sources on land (e.g. melting ice).

Physical Process	**Rate Contribution**
Sterodynamic Change	3.0 +/- 1.4 mm/year
Ocean Mass Change	1.7 +/- 0.2 mm/year
Subsidence	1.4 + 0.7 mm/year
Sum of Contributions	6.1 +/- 1.6 mm/year
Tide Gauge Rate	5.0 +/- 1.1 mm/year
Difference	1.1+/- 1.9 mm/year

expansion + changes in ocean dynamics) and ocean mass change (4.7 mm/year) agree with the absolute sea level rise measured by the satellite altimetry (4.7 mm/year). This leads to the conclusion of very limited land motion impacting Tuvalu. At the nearby GPS station, however, the land is subsiding at a rate of 1.4 +/- 0.7 mm/year from 2002 to present (http://geodesy.unr.edu/NGLStationPages/stations/TUVA.sta). The GPS and tide gauge are not collocated (separated by approximately 2-3 km), suggesting that there could be spatial differences in the vertical land motion impacting both the atoll of Funafuti and Tuvalu more broadly. Further investigation is needed to determine the extent of spatial differences in vertical land motion across all islands of Tuvalu. Substantial differences in land motion could mean that future sea level rates and coastal impacts vary strongly over short distances across the islands of Tuvalu.

Two of the contributors in Table 1 can be further decomposed. For changes in ocean mass in the area surrounding Tuvalu, about 50% of the changes are associated with ice mass loss from the Greenland Ice Sheet, 25% is associated with ice mass loss from the Antarctic Ice Sheet, and the rest coming from mountain glaciers. The contribution from sterodynamic change is more complicated. Analysis of a NASA ocean state model (Estimating the Circulation and Climate of the Ocean; ECCO) suggests that the sterodynamic contribution to Tuvalu since 1993 is due in large part to the convergence of warm waters within the upper layers of the ocean. This warm water convergence is strongly related to shifts in the tropical Pacific wind field over the past few decades. Determining how much these changes can be attributed to human activity is an area of ongoing research. Tuvalu is situated within the western Pacific warm pool, where the local sea level is part of a basinwide east-west gradient that is strongly coupled to the easterly trade winds (part of the Walker cell). The easterly trade winds have been strengthening in recent decades, steepening the slope of the thermocline, which raises sea level in western tropical Pacific region (and lowers it in the eastern tropical Pacific). This is a major factor in why sea level rise to date has been relatively high in Tuvalu compared to locations outside of the western tropical Pacific.

The physical description of the sterodynamic change is a topic of ongoing research and will continue to evolve in the coming years. As with further investigation into the vertical land motion, this research is critical for understanding future sea level rise and variability in Tuvalu. Subtle shifts in the sterodynamic sea level change will increasingly drive impacts for Tuvalu as sea level continues to rise. Better understanding the physical processes that are important will also lead to refinement in projections of future, long-term sea level rise.

c. Short-Term Sea Level Variability in Tuvalu

The long-term sea level rise and annual to decadal sea level variations discussed in sections 2a and 2b combine with shorter-term sea level variability to drive impacts along the coasts of Tuvalu. Whereas the processes discussed above provide a similar signature for all islands in Tuvalu, these shorter-term signals can lead to differences along the coastlines of Tuvalu. In terms of assessing impacts occurring at the shoreline, it is the total water level that is of the greatest consequence. Total water level encompasses contributions from all processes across the spatial and temporal scales - both local and global, long and short term - that result in sea level change at the shore. Total water level at any time can be assessed as the combination of changes in mean sea level (as discussed in sections 2a and 2b), tides, surge and wave runup.

Storm events and waves play important roles in total water level changes on shorter timescales (minutes to days) in Tuvalu. Storms both in the vicinity of Tuvalu or more remote to Tuvalu can lead to significant impacts for the coastlines of Tuvalu. Substantial wave runup can be generated either by nearby tropical storms and cyclones or from wind-waves triggered from distant sources (known as "blue sky events"; Hoeke et al., 2013). Sea level rise enhances the impact of wave runup on Tuvalu by increasing the water level over the coral reefs, allowing larger waves to reach the shoreline (Hoeke et al., 2013; Merrifield et al., 2014; Storlazzi et al., 2018). Recent studies have demonstrated that wave runup and thus total water level associated with these events can vary depending on the approach of a storm or direction of waves generated remotely (Hoeke et al., 2021).

On slightly longer time scales, another short-term variation of interest is the 30-60 day intraseasonal or Madden-Julian Oscillation (MJO). The MJO is manifest as an eastward propagating wave of deep atmospheric convection that is more active in the austral summer (Chand et al., 2023). Significant sea level variations result from wind-stress anomalies propagating with the MJO in the western tropical Pacific, with a larger response found along western coastlines (Oliver and Thompson, 2010). In addition, the MJO influences both rainfall and the frequency and intensity of tropical cyclones, which will enhance short-term sea level variations.

Combining the sea level variability across all timescales, there is an average annual sea level maxima of 125 cm at the Funafuti B tide gauge that is dominantly driven by tidal variability (updated from Merrifield et al., 2013). The actual maximum experienced for a given year will vary, but this average value does provide an indication of the upper edge of the envelope of naturally occurring sea level variability in Tuvalu. This envelope will sit on top of the long-term increase in sea level associated with ongoing and future warming and lead to flooding when sea level sits near the upper end of this envelope. This is shown in Figure 3 for the Funafuti B tide gauge and instances where sea level exceeded the 2-year flood threshold (0.56 m over mean higher high water, MHHW). Typically, flooding has occurred in the past during exceptionally high spring tides in January-February-March combined with natural ocean variability that pushes mean sea level higher (AusAID, 2007; e.g. 1996, 1997, 2001, 2002, 2006). In recent years, flooding in Tuvalu has been associated with runup generated from distant source swell waves or locally generated waves from cyclones (e.g. 2015, Cyclone Pam; 2020, Cyclone Tino). This is consistent with the studies mentioned above indicating that wave runup will become a significant driver of flooding as sea level continues to increase.

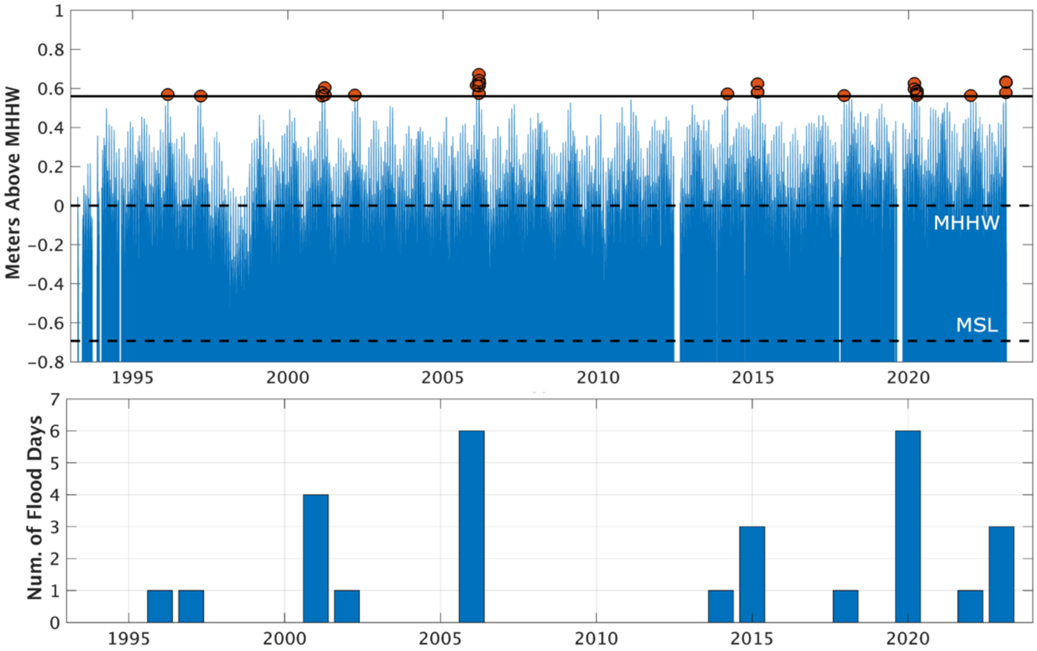


Figure 3. The occurrence of individual flooding days (top) for the 2-year flood threshold (solid black line; 0.56 m above MHHW) and the number of flooding days in each meteorological year (May–April, bottom) for the combined record of Funafuti B tide gauge. The flooding days are not distributed evenly throughout the year and tend to occur in January, February and March, coinciding with the highest tides of the year (adapted from source: https://pacificislandsflooding.org/projected-flooding?station-id=025).

3. Sea Level Rise Projections for Tuvalu

The updated sea-level projections from the Intergovernmental Panel on Climate Change 6th Assessment Report (IPCC AR6) are formed by integrating different projections of the individual processes that cause sea-level change (see section 2b for description of these processes) with a consistent framework (see Fox-Kemper et al., 2021). The latest generation of global climate models are used to account for the global-mean thermosteric and ocean dynamic regional sea-level rise and similar methods are used for assessing vertical land motion contributions as in past reports. The IPCC AR6 incorporates multiple methods of projecting future ice-sheet changes, which are the major sources of future sea level rise and pose the biggest source of uncertainty in projecting the timing and magnitude of future possible rise amounts.

These multiple methods for accounting for the future ice sheet contributions, when combined with the other processes causing future sea-level rise, led to a set of five shared socioeconomic pathways (SSP)-based projections that included only physical processes in which there is at least medium confidence in the current scientific understanding, and two additional scenarios (one high emissions and one low emissions) that included ice sheet processes in which there is currently low confidence among scientists. Low confidence as applied to these processes means limited agreement between scientists and models on if and when they could come into play. There is also low confidence in the ability to quantify the sea-level rise that will result once triggered. These low confidence processes include earlier-than-projected ice-shelf disintegration in Antarctica, abrupt, widespread onset of marine ice-sheet instability and/or marine ice-cliff instability in Antarctica, and faster-than-projected changes in surface-mass balance on Greenland. As a result of the low confidence in these processes, the two scenarios in which they appear are considered of unknown likelihood.

The sea level projections from the IPCC AR6 for Tuvalu are shown in Table 2. In 2050, there is a relatively narrow range across all scenarios, both medium and low confidence (Figure 4). The difference between the median values for the lowest scenario (SSP1-1.9) and the highest scenario (SSP5-8.5 Low Confidence) is 6 cm. The upper end of the likely range across all medium confidence scenarios is 0.35 meters. For comparison, the trajectory of near-term sea level rise inferred from the observations at the Funafuti B tide gauge can be assessed. This is done by first removing the influence of ENSO from the time series and then extrapolating the rate and acceleration estimated over the record from 1993 to 2023 out to 2050 (Figure 4, solid blue line). This leads to an observation-based estimate of near-term sea level rise of 0.25 m from 2005 to 2050. This is within the narrow range of the model-based projections, and the 17th-83rd percentile range of the observation extrapolation encompasses the ranges of all medium confidence scenarios. The rate of sea level rise in 2050 implied by this extrapolation is 8.1 mm/year, a substantial increase from the 5.0 mm/year currently being experienced in Funafuti.

After 2050, the range across the different sea level projections expands to 0.38 m for the medium confidence scenarios (Figure 5). The median values for the medium confidence scenarios range from 0.45 m for the lowest scenario to 0.83 m for the highest scenario. In addition, the SSP5-8.5 Low Confidence starts to diverge from the other scenarios. The 83rd percentile of this scenario is 1.84 m (Figure 5, dashed red line) and represents a plausible upper-end estimate of sea level rise in 2100. The rate of sea level rise by 2100 could also be more than double the current rate, adding over 1 cm every year to the foundation of sea level rise on top of which other ocean variability sits.

Table 2. Projected values (first two rows), in meters, and rates (last two rows), in mm/year, for different SSP scenarios in 2050 and 2100 for Tuvalu, relative to the year 2005. The 17th-83rd ranges are shown in parentheses for each scenario. The first five columns for the SSP scenarios include processes in which scientists have at least medium confidence. The two scenarios marked LC refers to scenarios with unknown likelihood that include some processes in which scientists have low confidence. The observational trajectory is created by extrapolating the ENSO-corrected tide gauge time series using a quadratic fit out to 2050.

	SSP1-1.9	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**	**SSP5-8.5**	**SSP1-2.6 LC**	**SSP5-8.5, LC**	**Obs. Trajectory**
2050	0.20 (0.14-0.28)	0.21 (0.15-0.30)	0.23 (0.16-0.32)	0.24 (0.17-0.33)	0.25 (0.18-0.35)	0.22 (0.15–0.37)	0.26 (0.17-0.46)	0.25 (0.10-0.40)
2100	0.45 (0.26-0.69)	0.53 (0.31-0.79)	0.65 (0.47-0.91)	0.73 (0.51-1.03)	0.83 (0.58-1.18)	0.55 (0.31–0.98)	0.97 (0.58-1.84)	-
2050 Rate	4.2 (2.3–6.8)	5.4 (3.8–8.0)	6.4 (4.4–9.1)	7.0 (4.6–9.8)	8.0 (5.6–11)	5.8 (3.8–11)	8.9 (5.6–19)	8.1 (4.0-12)
2100 Rate	5.0 (1.0–9.6)	7.0 (1.2–13)	9.8 (6.2–15)	10.9 (6.2–17)	13.4 (7.2–21)	7.2 (1.2–16)	18.0 (7.2–35)	-

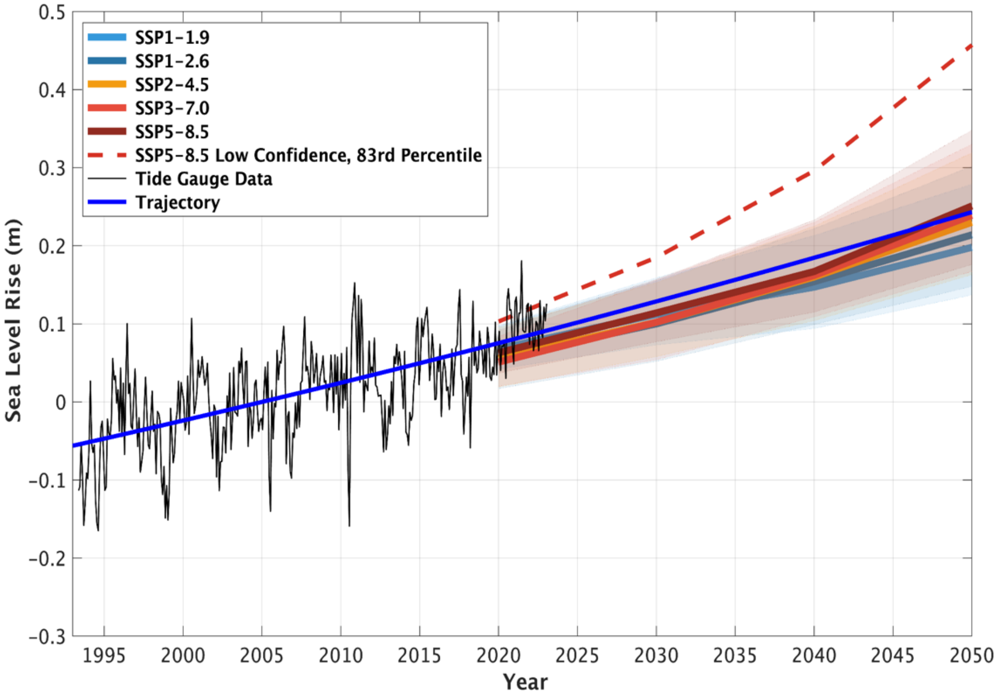


Figure 4. Projections of future sea level rise from 2020 to 2050 for Tuvalu, in meters. For comparison, the tide gauge observations from the Funafuti B tide gauge (black) are shown along with the extrapolated trajectory from these measurements (blue). The shaded regions represent the likely range for each projection, and the red dashed line represents a plausible upper end estimate for sea level rise in 2050.

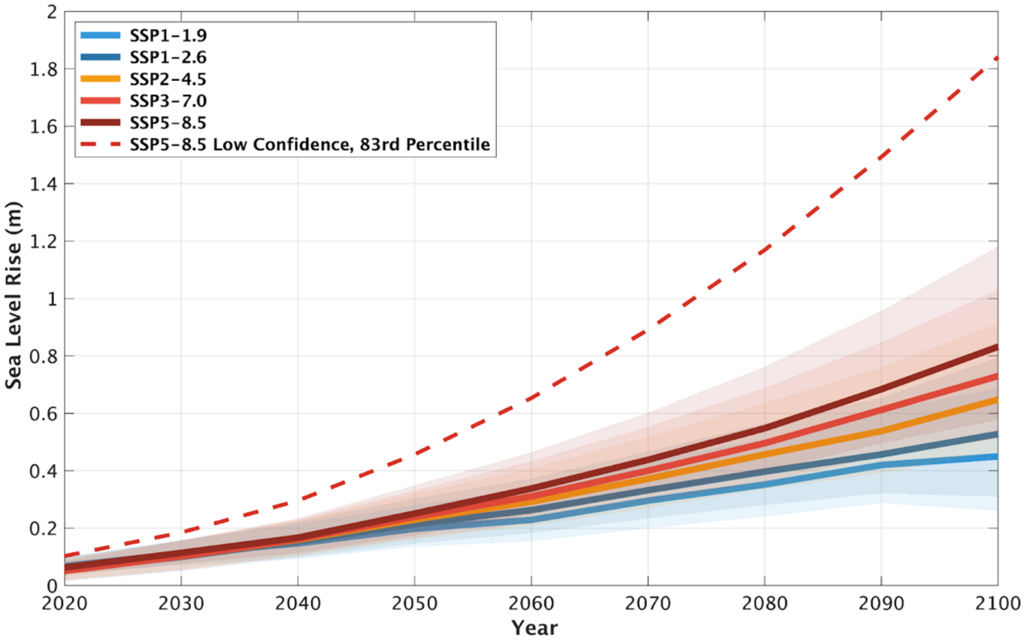


Figure 5. Projections of future sea level rise from 2020 to 2100 for Tuvalu in meters. The shaded regions represent the likely range for each projection, and the red dashed line represents a plausible upper end estimate for sea level rise.

Table 3. Exceedance probabilities for specific amounts of future sea-level rise based on IPCC warming level–based global mean sea level projections. Global mean surface air temperature anomalies are projected for years 2081–2100 relative to the 1850–1900 climatology. The solid blue line indicates shift in exceedance probabilities evaluated in 2050 vs. 2100. As an example of how this table can be read, the third row could be used to produce the following two sentences: “Assuming 3°C of warming in 2100, there is a 5% chance of exceeding the 1 meter in 2100” and “Assuming high levels of warming in 2100 and contributions from the low confidence processes, there is a 49% chance of exceeding the 1 meter in 2100.

Global Mean Surface Air Temperature 2081-2100	1.5°C	2.0°C	3.0°C	4.0°C	5.0°C	Low Confidence Process, Low Emissions	Low Confidence Processes Very High Emissions
Probability of > 0.1 m in 2050	>99%	>99%	>99%	>99%	>99%	98%	>99%
Probability of > 0.2 m in 2050	40%	49%	54%	72%	94%	49%	77%
Probability of > 0.3 m in 2050	3%	7%	8%	10%	20%	19%	39%
Probability of > 0.4 m in 2100	58%	81%	97%	>99%	>99%	49%	98%
Probability of > 0.5 m in 2100	36%	50%	82%	96%	>99%	49%	96%
Probability of > 0.6 m in 2100	15%	32%	50%	76%	97%	36%	88%
Probability of > 0.7 m in 2100	6%	15%	35%	49%	78%	24%	59%
Probability of > 1 m in 2100	<1%	2%	5%	9%	22%	7%	49%

To further assist in interpretation and understanding of the sea level projections, the probability of exceeding specific amounts of sea-level rise in the future for different levels of warming is estimated and shown in Table 3. For 2050, Table 3 shows the probabilities for exceeding 0.1 m, 0.2 m and 0.3 m in Tuvalu. There is a greater than 98% chance across all scenarios of exceeding 0.1 m by 2050, while there is between 3-39% chance of exceeding 0.3 m. For 2100, the probability of exceeding 0.5 m is between 36-99%, while the probability of exceeding 0.7 m is between 6 and 78%. Table 3 highlights the importance of limiting future warming. For low levels of future warming (< 3.0°C), it is very unlikely that 1 m of sea-level rise will be surpassed. Higher levels of warming increase the possibility that the low confidence processes will become a factor, and the potential to exceed 1 m by 2100 increases significantly. The information in Table 3 can also be reframed to estimate the timing of exceeding the specific thresholds of sea level rise (Figure 6). Across all future warming levels, 10 cm of sea level rise in Tuvalu is expected to be surpassed by 2050. At higher warming levels, 0.30 cm may also be surpassed by 2050.

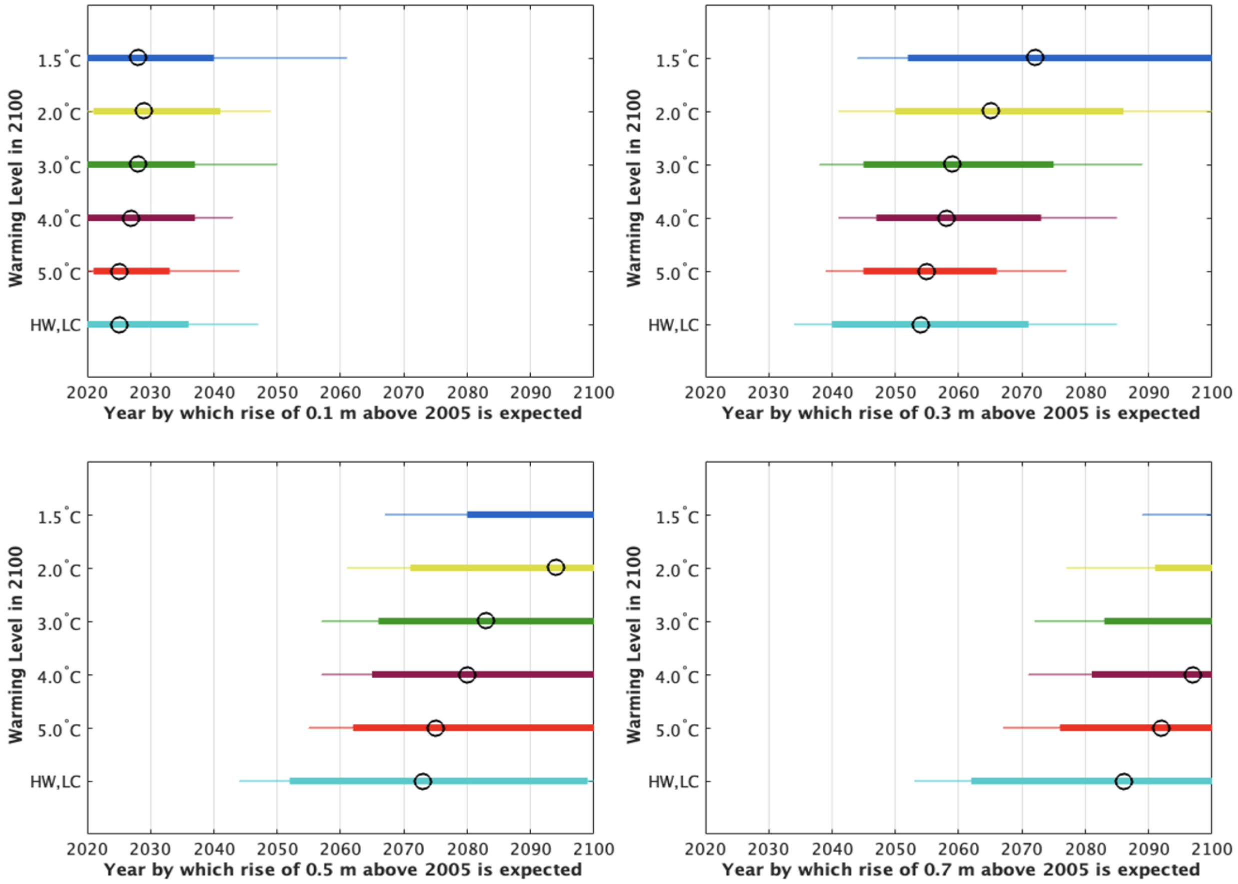


Figure 6. Timing of exceedance of different thresholds of 0.1 m (top left), 0.3 m (top right), 0.5 m (bottom left) and 0.7 m (bottom right) under different warming levels. Thick bars show 17th-83rd percentile ranges, and black circles show median value. Thin bars also show 5th–95th percentile ranges are also shown.

4. Projections of Sea Level-Driven Impacts for Tuvalu

Future sea level rise in Tuvalu will not lead to permanent inundation in the near-term. Instead, it will manifest as more frequent and more severe episodic flooding. It will also lead to a range of additional sea level-driven impacts. In this section, an assessment is made of 1) the areas most threatened by flooding driven by future sea level rise, 2) the change in the occurrence of saltwater intrusion driven by future sea level rise. flooding as a result of future sea level rise, and 3) the potential for the occurrence level rise.

a. Areas of Tuvalu Threatened by Future Flooding

To assess areas of Tuvalu that are most threatened by future sea level rise, the elevation of Tuvalu is estimated and then linked to specific thresholds to assess when flooding begins to occur. To estimate the elevation, a digital surface model (DSM) is constructed using satellite images from WorldView-2. A 50 cm horizontal-resolution DSM is created and to ensure vertical accuracy, the DSM is co-registered to ICESat-2 satellite laser altimetry. Once the DSM is produced, a satellite-based gridded mean sea surface model (DTU21, Anderson et al., 2023) is tied to the Funafuti B tide gauge to compute the spatially varying local mean sea level. Onto this new baseline, MHHW is added. This then represents the best available estimate of current MHHW in Tuvalu. To assess the areas of Tuvalu that will be flooded in the future, thresholds of 0.5, 0.7 and 1.0 m above MHHW are used. These are referred to below as thresholds of Low Flooding Extent, Medium Flooding Extent and High Flooding Extent, respectively.

The areas in the DSM below the level of current MHHW (Figure 7a), 50 cm (Figure 7b), 70 cm (Figure 7c), and 100 cm (Figure 7d) are computed. These values are determined to be thresholds at which flooding may begin occurring in Funafuti and are referred to here as thresholds for Low Flooding Extent (50 cm over MHHW), Medium Flooding Extent (70 cm above MHHW) and High Flooding Extent (100 cm over MHHW). Note, the Low Flooding Extent threshold is close to the 2-year flooding threshold used in Figure 3. Areas that are

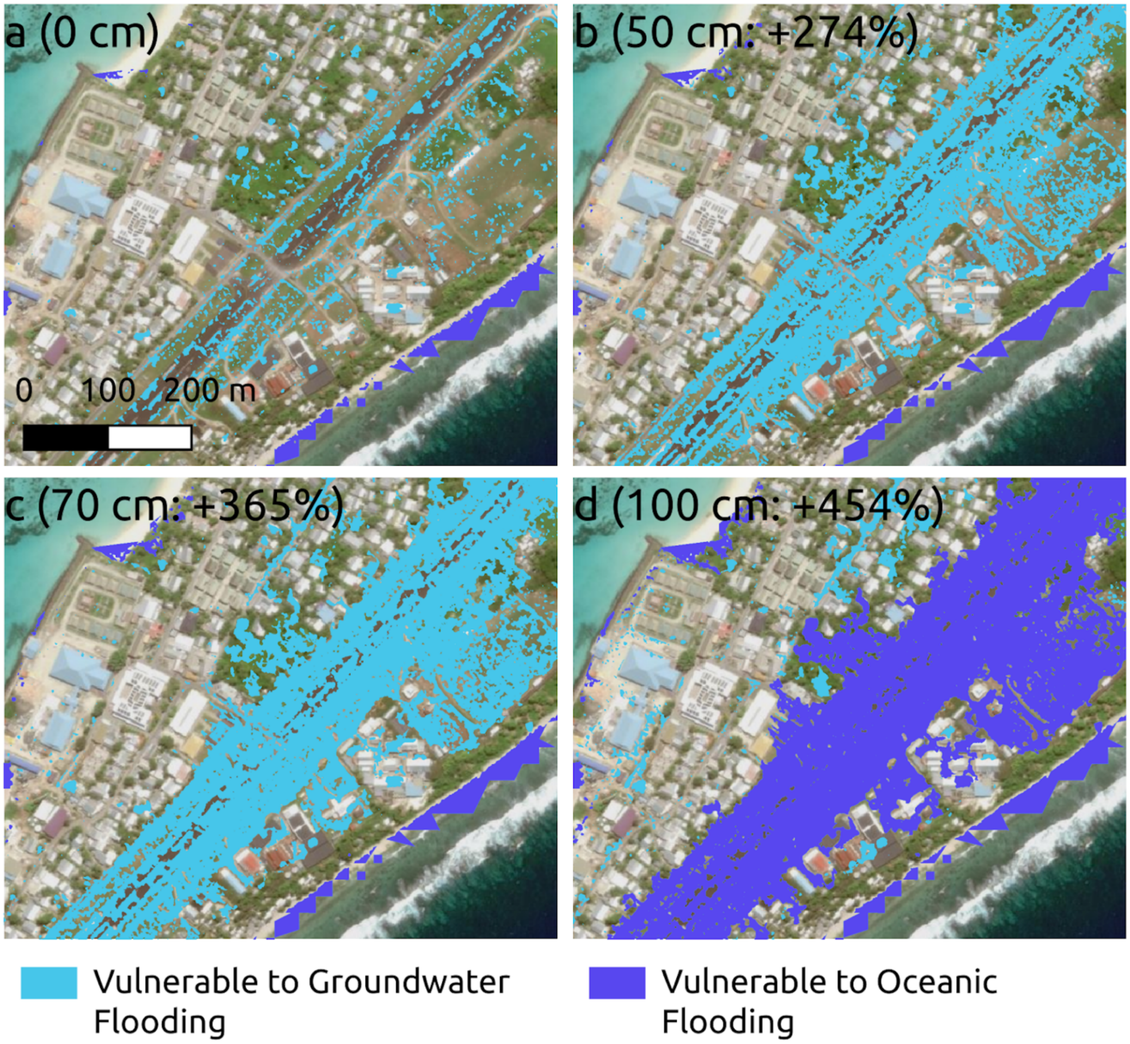


Figure 7. Projected inundation for 0 (a), 50 (b), 70 (c) and 100 cm (d) of sea level rise. Light blue denotes areas below future MHHW, but not necessarily connected to the sea, while dark blue areas are projected to be directly inundated from the sea. Note, this assumes no additional protection or adaptation beyond what is currently implemented.

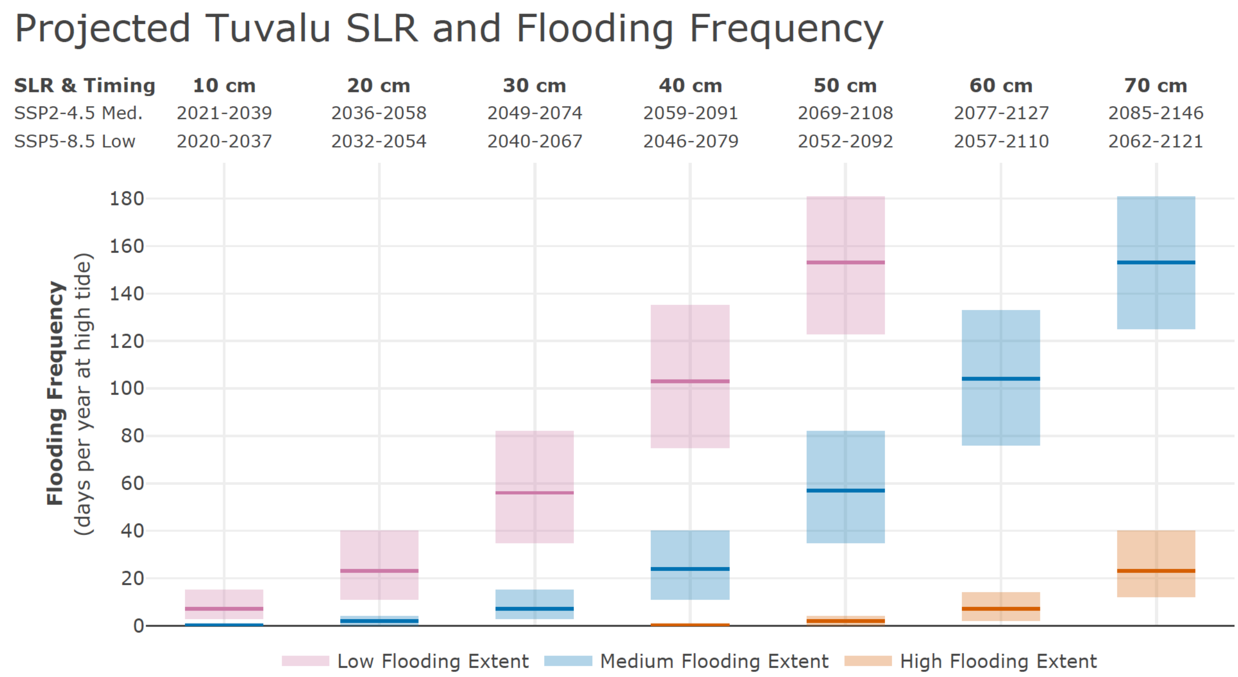
connected to the coast are considered directly vulnerable to flooding from the sea and are shown as dark blue. Areas that are below the targeted value and thus susceptible to groundwater flooding but disconnected from the sea are shown in light blue. The focus area for Figure 7 is central Funafuti in the area surrounding the airport. The assessment here is also made for the entirety of Tuvalu including the remote islands, but shown only for Funafuti in this report. The airport runway and surrounding areas are among the lowest in Tuvalu and thus prone to flooding with only 10 cm of future sea level rise or additional sea level change. This area, however, remains disconnected from the sea at this threshold and it is not until more than 50 cm of additional sea level occurs that this area becomes directly vulnerable to flooding.

To understand the results in Figure 7, it is important to consider how and when the different thresholds can be reached. As Figure 6 shows, these thresholds will be permanently reached in the coming decades. In other words, by 2050, 10 cm of sea level rise is expected to have occurred and 30 cm could occur, meaning Figures 7a and 7b will be the permanent situation in Tuvalu. Additionally, with 1 m of sea level rise, the airport and surrounding areas will be permanently flooded towards the end of this century without additional protections. Of more immediate concern, however, is episodic flooding driven by shorter-term ocean variability that pushes sea level above the combined level of MHHW and these thresholds, which can and will occur in the years to come. The likelihood of exceeding these thresholds will increase as sea level continues to rise. Connected to this, the frequency with which these thresholds are exceeded will also increase.

b. High-Tide Flooding

The change in the occurrence of episodic flooding as sea level rises discussed above can be assessed for Tuvalu. High-tide flooding is—as the name suggests—flooding that occurs at high tide, but it is not necessarily due to the tidal forces alone. There are a variety of factors that contribute to any given high sea-level event. For example, some high tides are higher than others. The spring-neap cycle, for example, is related to the alignment of the earth, moon, and sun, and causes the height of high tides to get higher and lower roughly twice per month. Tidal amplitude also does not just vary on a quasi-monthly basis due to the spring-neap cycle—it also varies from season to season and year to year. More specifically, there are substantial 4.4- and 18.6-year cycles (Haigh et al., 2011) in the tides with important implications for the frequency of coastal flooding (Thompson et al., 2021). As discussed in section 2, there are also other factors across time and space scales that affect how often sea level will exceed a given threshold. For example, changes in ocean circulation and year-to-year variations in climate cause average sea level to rise and fall over periods of months or years (see section 2a,b). Finally, changes in storminess or short-term chaotic ocean variability (ocean "weather") can lead to differences in flooding frequency from one month or year to the next (see section 2c).

At any given time, these factors will combine to drive sea level higher or lower. Combining these factors with increasing sea level in Tuvalu allows for an assessment of changes in the occurrence of high-tide flooding in the future. To do



Projected Tuvalu SLR and Flooding Frequency

SLR & Timing	10 cm	20 cm	30 cm	40 cm	50 cm	60 cm	70 cm
SSP2-4.5 Med.	2021-2039	2036-2058	2049-2074	2059-2091	2069-2108	2077-2127	2085-2146
SSP5-8.5 Low	2020-2037	2032-2054	2040-2067	2046-2079	2052-2092	2057-2110	2062-2121

Figure 8. Flooding frequency in Funafuti for different amounts of future sea level rise (10-70 cm) above current MHHW. The timing of the indicated amount of sea level rise is shown for the SSP2-4.5 scenario and the SSP5-8.5 Low Confidence Scenario. Flooding frequency is computed using thresholds indicating Low Flooding Extent (red; 50 cm over MHHW), Medium Flooding Extent (blue; 70 cm above MHHW) and High Flooding Extent (orange; 100 cm over MHHW).

this, the predictability of the different drivers of sea level change needs to be considered. The tidal variability in Tuvalu can be predicted far into the future using models that are based on the understanding of the tidal cycles that impact the coastlines. The other ocean signals from short-term to interannual-to-decadal cannot be similarly predicted, but the possible sea level contribution from these signals and their timing can be simulated using the past historical record from the Funafuti tide gauge. Combining all of these factors along with a scenario for future sea level rise allows for an assessment of the likely number of times to exceed a particular threshold in the future.

The projected number of flooding days per year at high tide in Funafuti is shown for the three different flood thresholds described in section 4a. Future sea level rise amounts between 10 and 70 cm are considered, and the timing for reaching those values for the SSP2-4.5 and SSP5-8.5 Low Confidence scenarios is indicated. Information on the potential timing of reaching these amounts of sea-level rise for other scenarios can be seen in Figure 6. The flooding analysis shows that flooding frequency will increase rapidly as sea level rises in Funafuti. More specifically, the analysis conducted here supports the following statements:

- With 30 cm of sea level rise, a plausible projection for 2050, the Low Flooding Extent threshold will likely be exceeded between 35 and 80 days each year.
- With 50 cm of sea level rise, a plausible projection to occur prior to 2100, the Low Flooding Extent threshold will likely be exceeded

between 120 and 180 days per year, while the Medium Flooding Extent threshold will likely be exceeded between 35 and 80 days per year.

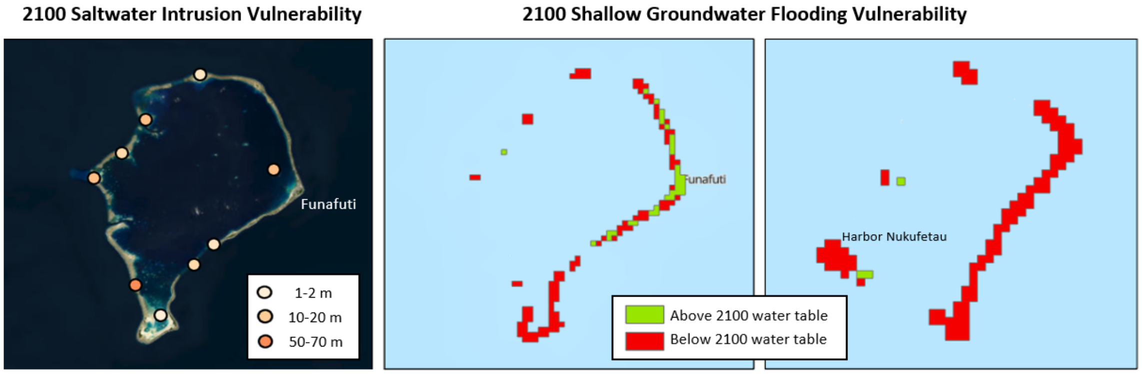
- Under all future sea level scenarios, it is likely that the Low Flooding Extent threshold will be exceeded more than 100 times a year by 2100, and the Moderate Flooding Extent threshold will be exceeded more than 40 times a year by 2100.
- Exceedance of the High Flooding Extent threshold of up to 40 times a year is possible with 70 cm of sea level rise, which is a plausible amount under all future sea level scenarios by 2100.

c. Saltwater Intrusion and Shallow Groundwater Flooding

As sea level rises, saltwater can be driven into fresh groundwater, in a process called saltwater intrusion. Atoll systems with soils derived from reef-borne carbonates often have poor water holding capacity (Barr, 1992; Webb, 2007), and freshwater tends to occur perched on top of saline water as lenses (Werner et al., 2017). A 2007 report from Tuvalu has already documented elevated salinity conditions in groundwater pools in Funafuti and other parts of the island (Webb, 2007).

Future vulnerability to saltwater intrusion in Tuvalu can be calculated in a 1-D screening-level model using 2100 projections of sea level rise and on-land recharge. Groundwater recharge is obtained from ISIMIP Protocol 2b and sea level from IPCC AR6 projections. Using a mean of SSP2-4.5 and SSP5-8.5 for both recharge and sea level, it is estimated that regions in Tuvalu will experience up to ~70 m of saltwater intrusion at depth. Such estimates rely on published numbers of hydrogeologic parameters (hydraulic conductivity, coastal watershed delineations, aquifer thickness) and can be updated as more detailed in-situ data are provided.

An associated impact of sea level rise is shallow groundwater flooding. As sea level rises, the groundwater table also rises in return to accommodate the changes in pressure. However, in low-lying areas such as Tuvalu, the lack of unsaturated space may


2100 Saltwater Intrusion Vulnerability

2100 Shallow Groundwater Flooding Vulnerability

Figure 9. 2100 saltwater intrusion and shallow groundwater flooding vulnerability for Tuvalu. Note for saltwater intrusion, calculations are done at the centroid of different watersheds, leading to circles in the nearshore ocean for curved watersheds (e.g. near Funafuti). There is more risk of saltwater intrusion near the southwest part of the island, near Tefonufala Beach. Higher parts of the island near Funafuti display less vulnerability to shallow groundwater flooding.

drive the groundwater table to instead "shoal" inland to other discharge pathways or cause local flooding. The 2100 projected groundwater head is calculated at centroid locations for coastal watersheds and compared to the elevation of the watershed. Elevation is obtained from HydroSHEDS, based on NASA's Shuttle Radar Topography Mission. While this model is still under development and the above calculation used HydroSHEDS as a first estimate, the model will be retrofitted to the aforementioned DSM as development progresses. Regions below the head and therefore have shallow groundwater flooding risk are highlighted in red, while regions above the head are colored in green. As the calculated groundwater head used against elevation is a point measurement and not a planar surface, it likely overestimates vulnerable regions. It also is unable to resolve flood risk at finer resolutions due to microtopography and local hydrogeology. Nonetheless, it is able to provide a screening-level view of where detailed groundwater monitoring in conjunction with tide data may be useful.

5. Areas of Informational Need and Data Gaps

Linking past and present observations of sea level change in Tuvalu to projections of future sea level rise provides a pathway for comprehensively assessing future sea level-driven impacts in and around the island nation. In doing so, areas of remaining uncertainty and observational needs are also identified. For example, based on the analysis of available observations of the processes causing relative sea level change in Tuvalu, there is the possibility of spatial variations in the rate of vertical land motion across the different islands that make up Tuvalu. Additional GPS stations - even on a temporary basis - could help determine if this is indeed the case.

Furthermore, the at-the-coast sea level change that is most closely linked to impacts is largely unknown away from the Funafuti tide gauge. This could lead to particular challenges for parts of the islands with coastlines facing different directions for the Funafuti atoll or for the more remote islands that make up Tuvalu. Additional tide gauges could improve the understanding of local sea-level variability, and satellites could provide further coverage. In particular, the Surface Water and Ocean Topography (SWOT) mission is currently measuring sea level at higher resolutions and closer to the coast than any of its predecessors and could support insight into sea level change occurring around Tuvalu.

6. Summary

The assessment made here details worsening impacts associated with sea level rise for Tuvalu in the years to come. Episodic flooding will increase in severity and frequency as temporary fluctuations of sea level resulting from natural ocean and tidal variability will be pushed higher and higher by long-term sea level rise. Moderate scenarios of future sea level rise will still be problematic in terms of increasing flooding, but higher-end sea level rise scenarios will lead to frequent and potentially catastrophic flooding prior to the end of the century. Efforts to adapt to these potential impacts are necessarily underway in Tuvalu, including through the implementation of the TCAP. Regular assessments like the one produced here coupled with ongoing monitoring of sea level rise, the processes causing the sea level rise, and sea level-driven impacts will be critical to support these efforts. Such monitoring will be achievable through the combination of in situ, on-the-ground measurements made in Tuvalu and satellite-based observations that connect global-scale processes to local sea level change. This framework of assessment and monitoring can provide the decision-makers working in Tuvalu the information needed to support planning for and adapting to sea level rise.

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8. List of Authors (Alphabetical Order) and Recommended Citation

Kyra Adams, NASA Jet Propulsion Laboratory
Carmen Blackwood, NASA Jet Propulsion Laboratory
Richard Cullather, NASA Goddard Space Flight Center
Benjamin Hamlington, NASA Jet Propulsion Laboratory
Eduard Heijkoop, University of Colorado at Boulder
Kristopher Karnauskas, University of Colorado at Boulder
Robert Kopp, Rutgers University
Eric Larour, NASA Jet Propulsion Laboratory
Tong Lee, NASA Jet Propulsion Laboratory

R. Steven Nerem, University of Colorado
Sophie Nowicki, University of Buffalo
Christopher G. Piecuch, Woods Hole Oceanographic Institution
Richard Ray, NASA Goddard Space Flight Center
David Rounce, Carnegie Mellon University
Philip Thompson, University of Hawai'i at Mānoa
Nadya Vinogradova, NASA Headquarters
Ou Wang, NASA Jet Propulsion Laboratory
Michael Willis, Virginia Tech University

NASA Sea Level Change Team, K. Adams, C. Blackwood, R. Cullather, E. Heijkoop, B. Hamlington, K. Karnauskas, R. Kopp, E. Larour, T. Lee, R. Nerem, S. Nowicki, C. Piecuch, R. Ray, D. Rounce, P. Thompson, N. Vinogradova, O. Wang, M. Willis, (2023) Assessment of Sea Level Rise and Associated Impacts for Tuvalu, N-SLCT-2023-01 Technical Report, pp 18. Doi: 10.5281/zenodo.8069320.

9. Acknowledgements

The research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). The authors acknowledge support from the NASA Sea Level Change Science Team.