Assessment of Timelines for Future Sea Level Rise and Associated Impacts for Kiribati

NASA Sea Level Change Team[1]

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Overview

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 Kiribati. An objective of the analysis is to provide context for future scenarios of sea level rise by assessing the rate and drivers of ongoing sea level rise. The focus of the report is on providing updated timelines for increasing sea level and coastal flooding, following the scientific consensus of the IPCC 6th Assessment Report. This report is non-prescriptive and is not intended to be directive. It is intended as a foundational document that contains the latest scientific understanding of sea level and impacts for Kiribati.

Key Messages

1. Sea level in Kiribati has risen between 5 cm (Line Islands) and 11 cm (Gilbert Islands) over the past 30 years.
2. Between now and 2050, Kiribati can expect to see between 15 and 30 cm of additional sea level rise across all islands regardless of changes in emissions.
3. Beyond 2050, future emissions and warming are directly related to the future sea level rise that will be experienced. Sea level projections for Kiribati range from 50 to 100 cm by 2100, with an upper-end, worst-case estimate that depends on the evolution of the ice sheets approaching 2 m.
4. The impact on the islands of Kiribati will vary due to the geographical extent of Kiribati. In the near-term (prior to 2050), the Gilbert Islands will see worsening of some of the impacts that are already underway. The Phoenix and Line Islands will potentially see a very rapid increase in frequency and severity of impacts shortly thereafter.
5. Future sea level rise will cause a large increase in the frequency and severity of episodic flooding in Kiribati within the 21st century. Across all future scenarios and under the assumption of no additional protections, all island chains in Kiribati will likely experience more than 100 days of flooding every year by the end of the century.
6. Analysis to include additional processes that cause impacts along the coastlines of Kiribati is needed to fully assess the threat of future sea-level rise. The analysis done here provides a screening level assessment of the potential impacts on Kiribati.

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 countries in the Pacific Ocean. Kiribati, an island nation in the central Pacific Ocean, is acutely threatened by increasing sea level rise and coastal flooding, which are being exacerbated by climate change. Kiribati is composed of 33 coral atolls and reef islands, spanning three main island groups: the Gilbert Islands, the Phoenix Islands, and the Line Islands. Each of these groups faces unique challenges related to sea level rise:

- **The Gilbert Islands:** This is the most populous group, including the capital, Tarawa. The low-lying nature of these atolls makes them particularly vulnerable to rising sea levels (Sabuñas et al., 2021). Tarawa, where a significant portion of the population resides, is experiencing erosion and inundation – driven both by high tides and storms - threatening both residential areas and essential infrastructure (Biribo and Woodroffe, 2013; Duvat et al., 2013). Past and ongoing shoreline modification has led to a complicated amalgam of localized erosion, accretion and inundation (e.g. Webb, 2005; Webb and Kench, 2010; Donner, 2012). The situation in Tarawa is emblematic of the challenges faced throughout the Gilbert Islands, where land is scarce and elevation is minimal.
- **The Phoenix Islands:** These islands are largely uninhabited, primarily due to their remote location and lack of sustainable freshwater sources. However, the Phoenix Islands are ecologically and culturally significant, hosting a UNESCO World Heritage Site (Claudino-Sales, 2019). Sea level rise poses a threat to the unique ecosystems and biodiversity found here (Obura et al., 2016).
- **The Line Islands:** This chain includes both inhabited and uninhabited islands, with Kiritimati (Christmas Island) being the most notable. Kiritimati is one of the largest coral atolls in the world and faces its own unique challenges with sea level rise. Flooding and saltwater intrusion into freshwater lenses pose significant risks to the communities and ecosystems. The Line Islands, due to their geographical spread, exhibit a range of impacts from sea level rise including erosion and habitat loss.

Across all these island groups, the threat of climate change, sea level rise, coastal flooding, and other deleterious impacts is multifaceted, localized, and can be complicated to assess. The threat includes the direct loss of land due to inundation, increased salinity of freshwater resources, and damage to coral reefs and coastal habitats which act as natural buffers to coastal flooding. Furthermore, the social and cultural fabric of Kiribati is intrinsically linked to the coast and sea, meaning that these environmental changes have profound implications for local lifestyles and traditions. The geographical expanse of Kiribati also prohibits a “one size fits all” approach to describing the changes in sea level taking place both now and in the future. For example, the distance between the Gilbert and Line Islands is greater than the width of the contiguous United

States. As a result, the relative contribution of physical processes on each island group is different on different timescales.

Over the past two decades, significant work has been done to investigate these topics, as reflected by summary reports and scientific literature (e.g., Republic of Kiribati, 2016; WBG, 2021). The purpose of this particular report is narrower, with an objective of providing updated timelines for increasing sea level rise and associated flooding necessitated by the release of the IPCC 6th Assessment Report (AR6) in 2021. The scientific understanding of future sea level rise continues to advance at a rapid pace, and maintaining and updating the state of knowledge in line with assessment reports like the AR6 is both cumbersome and necessary. We also investigate and present results of the localization of these timelines and projections. Coupling these projections to higher-resolution data products where possible provides additional information and insight into the potential future challenges facing the islands in Kiribati. Producing the datasets that support localized assessments can be difficult in remote parts of the world, particularly when relying on in situ or airborne platforms for data collection. We rely on satellite observations of the ocean and land to fill gaps and provide screening level assessments of future flooding for the islands of Kiribati. This report is intended to complement the efforts being made in the region to understand and address climate change and sea level, and presents a framework that can be used to provide future updates as conditions and scientific understanding change in Kiribati.

The structure of this report is as follows:

1. **Past and Present Sea Level Change:** Using available in situ and satellite observations, the change in sea level across a range of timescales is discussed. The rate of current sea level rise and processes contributing to this rate are also outlined.
2. **Future Sea Level Rise:** Based on the IPCC AR6, projected sea level rise and associated timelines for reaching different thresholds of sea level rise are presented. The current trajectory of sea level rise inferred from the observations is compared to these projections.
3. **Evolution of Impacts:** The occurrence and severity of future flooding in Kiribati is assessed by tying the sea level projections to estimates of sea level change occurring on other timescales. These flooding projections are localized by analyzing what parts of Kiribati will be most impacted.

Sections 2 and 4 address the three island chains separately, while section 3 provides projections of future sea level rise that are applicable to the entirety of Kiribati. The justification for this will be discussed in the section below.

2. Past and Present Sea Level Change in Kiribati

The distance between the Gilbert Islands to the west and Line Islands to the east is almost 4000 km, spanning over 30 degrees of longitude. This geographical extent has important implications for the sea level change observed across the islands of Kiribati. In particular, on interannual timescales, the sea level response to the El Niño Southern Oscillation (ENSO) varies significantly. Additionally, the impact of remote storms is different on each island chain, resulting in differences in the occurrence of flooding. An assessment of sea level change in Kiribati necessitates consideration of the three main island chains separately. There are three tide gauges in Kiribati that are located in Tarawa (Gilbert Islands), Kanton Island (Phoenix Islands) and Kiritimati (Line Islands). In this section, we provide a summary of past and recent sea level change as measured by each of these tide gauges, in addition to a broader, regional look using measurements from satellite altimeters.

a. Observations of Sea Level in Kiribati

The three primary tide gauges in Kiribati span the time periods from 1993 to 2024, 1973 to 2024, and 1974 to 2024 for the Tarawa, Kanton Island and Kiritimati gauges, respectively. The modern satellite altimeter record covers 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 1). During the overlapping time period, the rates of sea level rise from satellite altimetry and tide gauges are similar for Tarawa and Kanton Island. From 1993 to present, the tide gauge record in Kiritimati has a trend (1.7 mm/year) lower than that of the satellite altimeter data. The tide gauge measures relative sea level that incorporates the movement of the land and the satellite measures geocentric (or absolute) sea level, which suggests a contribution from vertical land motion at Kiritimati. The main cause of the apparent discrepancy, however, is the gap in the tide gauge record around 2015/2016, when there was a significant increase in sea level due to an El Niño. If removed from the satellite altimeter record, the difference between the rates is not significantly different from zero. The acceleration computed at all three locations – using either the full available record or satellite altimeter period – is not statistically different from zero and is heavily influenced by the presence of substantial sea level variations occurring about the long-term trend.

The west-to-east decrease in sea level trends exhibited by the tide gauges (Figure 1) is confirmed by the regional map of sea level trends computed from the satellite altimetry data (Figure 2). The Gilbert Islands sit on the edge of a region with persistent sea level rise in the western tropical Pacific observed by satellite altimeters. The rate of 3.7 mm/year from 1993 to present is higher than the rate of change in global sea level over the same time period. Both the Phoenix and Line Islands have trends lower than the global average. This west-to-east difference in observed sea level rise in Kiribati is associated with the effect of the strengthening trade winds in the past few decades that enhanced the sea level rise in the west, superimposing on the effect of global mean sea level rise, e.g., due to ice melt and ocean warming.

The year-to-year variations in sea level are closely associated with the El Niño-Southern Oscillation (ENSO). However, the effect of ENSO varies greatly across Kiribati, reflecting the geographical extent and changing relative influence of different physical processes. For the positive phase of ENSO (El Niño), sea level in the Gilbert Islands decreases while sea level in the Line Islands shows a substantial increase. Within the observational record, these drops can exceed 20 cm, although there is substantial variability from year-to-year. Similarly, for negative phase ENSO events (La Niña), sea level in the Gilbert Islands increases, with the opposite occurring in the Line Islands. The Phoenix Islands sit between the dominant areas of sea level response associated with ENSO, so year-to-year sea level variations are less associated with the phases of ENSO. Nevertheless, there is still interannual variability found in the record on the order of 10-20 cm relative to the mean.

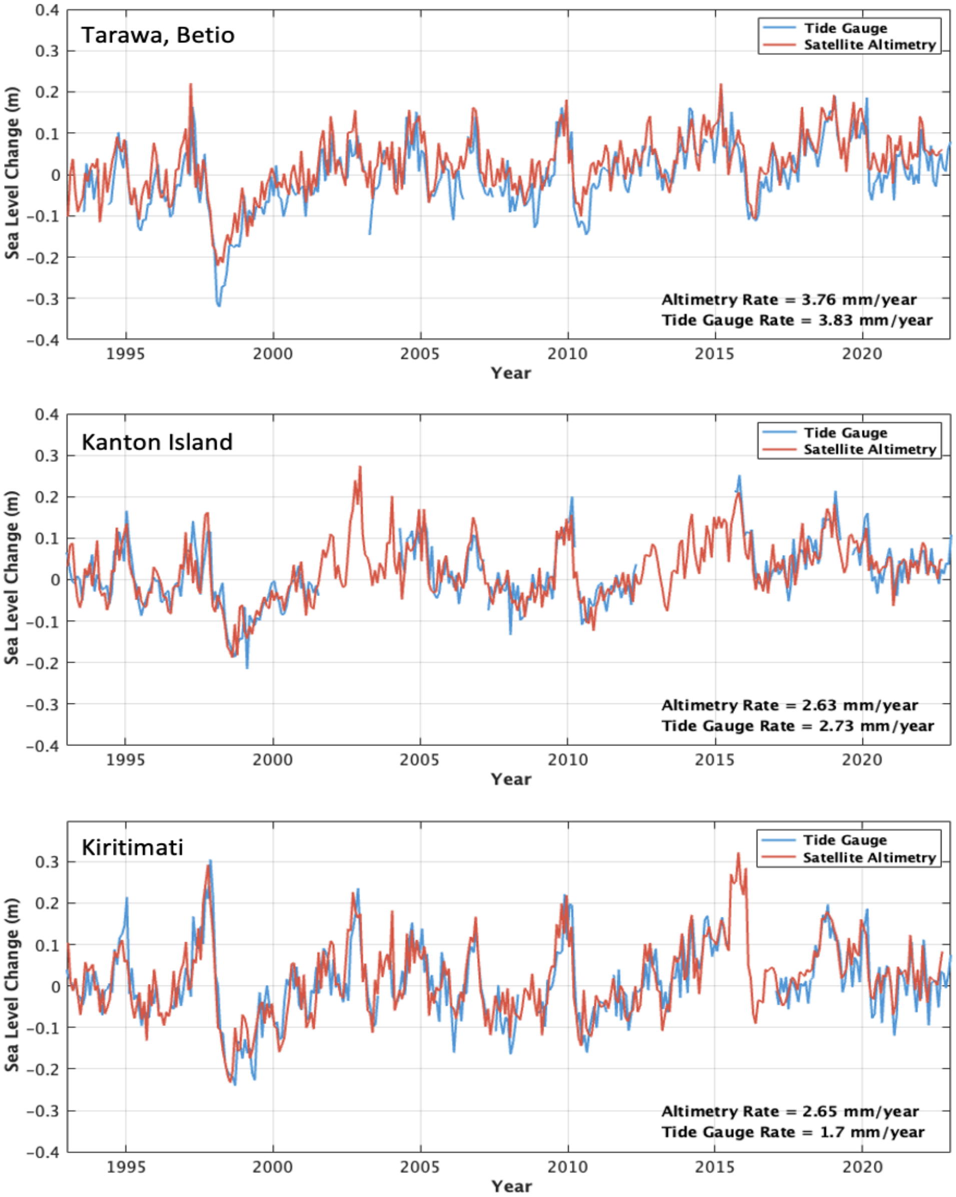

Figure 1. Comparison of monthly data from the three tide gauges in Kiribati (blue) and nearest satellite altimetry data point (red). The three tide gauges located in the Gilbert (Tarawa), Phoenix (Kanton Island) and Line (Kiritimati) Islands, from west to east, are shown from top to bottom. Rates are provided for only the time period of overlap between the tide gauge and satellite altimetry data, from 1993 to present. The Kanton Island and Kiritimati gauges cover longer time periods not shown here.

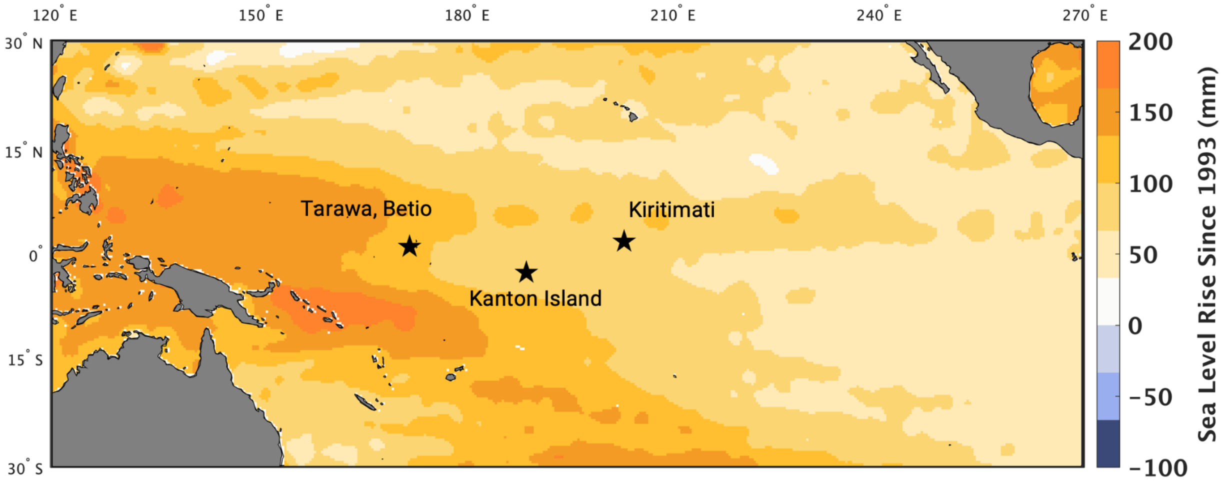

Figure 2. Amount of sea level rise (mm) from 1993 to 2022 estimated from satellite altimetry data. The star markers indicate the locations of the three tide gauges located in the Gilbert (Tarawa), Phoenix (Kanton Island) and Line (Kiritimati) Islands, from west to east, shown in Figure 1.

b. Processes Contributing to Sea Level Rise in Kiribati

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 Kiribati. By using a combination of satellites, on-the-ground measurements, and other data products, the processes that are contributing to increasing sea level in Kiribati 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., 2021). Similar to the results shown above, the process breakdown is shown for each tide gauge (island chain) separately.

The sum of the individual process contributions agrees with tide gauge observations within uncertainty estimates in Tarawa, Kanton Island, and Kiritimati. There is no available direct observation of vertical land motion (subsidence) in Kanton Island, and GPS records found on Tarawa and Kiritimati are not suitable for measuring a long-term rate that is applicable over the three-decade long record considered here. There is a GPS station on Kiritimati with a record length approaching two decades and measuring around 1.3 mm/year of subsidence. However, the tide gauge and GPS are not collocated (separated by approximately 7 km). For this reason, the difference between the tide gauge-measured rate and satellite altimeter-measured rate is used as an estimate of vertical land motion for all three tide gauges. Beyond the land-driven changes, changes in ocean mass in the area surrounding Kiribati ae associated with ice mass loss from the Greenland Ice Sheet (50%), ice mass loss from the Antarctic Ice Sheet (25%), and mountain glaciers across the globe (25%).

Table 1. Approximate contribution from individual physical processes to the rate of sea level rise in Kiribati from 1993 to 2023, in mm/year. Sterodynamic change refers to the combined contribution from global ocean thermal expansion and ocean dynamics [Gregory et al., 2019]. Ocean mass change refers to the addition of water into the ocean from sources on land (e.g., melting ice). Due to data deficiencies, gaps in the record, and a lack of adequate vertical land motion estimates, the tide gauge rates, sum of contributions and differences for Kanton Island and Kiritimati are noted in red and should be interpreted with caution.

Physical Process	**Betio, Tarawa**	**Kanton Island**	**Kiritimati**
Sterodynamic Change	1.8 +/- 2.3	0.7 +/- 3.0	0.7 +/- 3.5
Ocean Mass Change	1.9 +/- 0.3	1.9 +/-0.3	1.9 +/- 0.3
Subsidence	0.1 +/- 0.1	0.3 +/- 0.1	-0.1 +/- 0.2
Sum of Contributions	3.8 +/- 2.4	2.9 +/- 3.1	2.5 +/- 3.9
Satellite Altimetry Rate	3.8 +/- 2.8	2.6 +/- 3.2	2.7 +/- 3.8
Tide Gauge Rate	3.9 +/- 2.9	2.7 +/- 4.0	1.7 +/- 4.0
Difference (Sum - Tide Gauge Rate)	-0.1 +/- 1.1	0.2 +/- 1.2	0.8 +/- 1.2

c. Short-Term Sea Level Variability in Kiribati

The long-term sea level rise and annual and longer sea level variations discussed in sections 2a and 2b combine with shorter-term sea level variability to drive impacts along the coasts of Kiribati. These shorter-term processes can lead to differences in sea level along the coastlines of Kiribati, particularly given their geographical extent. In terms of assessing impacts occurring at the shoreline, the total water level has the greatest importance. 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 the mean sea level (as discussed in sections 2a and 2b), short-lived sea level anomalies, tidal amplitude, sea level setup from storm surge, and water level fluctuations due to wave processes.

Storm events and waves play important roles in total water level changes on shorter timescales (minutes to days), although this is most relevant for the Gilbert Islands. Storms both in the vicinity of the Kiribati Islands or more remote can lead to significant impacts for the coastlines. 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). Seasonal north-easterly and south-easterly trade winds during winter months bring larger waves with longer wave periods and hence more wave energy to Tarawa and Kiritimati in particular. Along reef-fringed coastlines and dissipative beaches, such as the western and northern coasts of Tarawa in the Gilbert Islands, infragravity waves (which have periods of 80-300 s and are generated by long period ocean swell) can lead to the propagation of destructive bores with wave set-up 15-30% of the breaking wave height (Espejo et al., 2023; Hoeke et al., 2013). Sea level rise enhances the impact of wave runup on Kiribati 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 swell direction (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 manifests 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. Future work to document past total water level variations due to atmospheric processes and future conditions in a warmer climate are necessary to determine the relative role of these processes on future flooding across the Kiribati islands.

Figure 3 shows the total water level at hourly increments for Tarawa, Kanton Island and Kiritimati. Instances where sea level exceeds 50 cm over mean higher high water (MHHW) for each gauge are shown. This 50 cm above MHHW threshold is to indicate time periods when flooding may have occurred. It should be noted that without on-the-ground confirmation of appropriate thresholds, this 50 cm is somewhat arbitrary when looking only at the tide gauge data. However, as will be discussed in section 4, higher resolution inundation mapping suggests 50 cm above MHHW is a reasonable estimate of when flooding might start to occur. This 50 cm threshold has been exceeded many times for Tarawa, but has been reached only a few times in Kanton Island and never in Kiritimati within the tide gauge record. In recent years, flooding in Tarawa has been associated with runup generated from distant source swell waves or locally generated waves from cyclones (e.g., 2015, Cyclone Pam). This is consistent with the studies mentioned above indicating that wave energy will become a significant driver of flooding as sea level continues to increase.

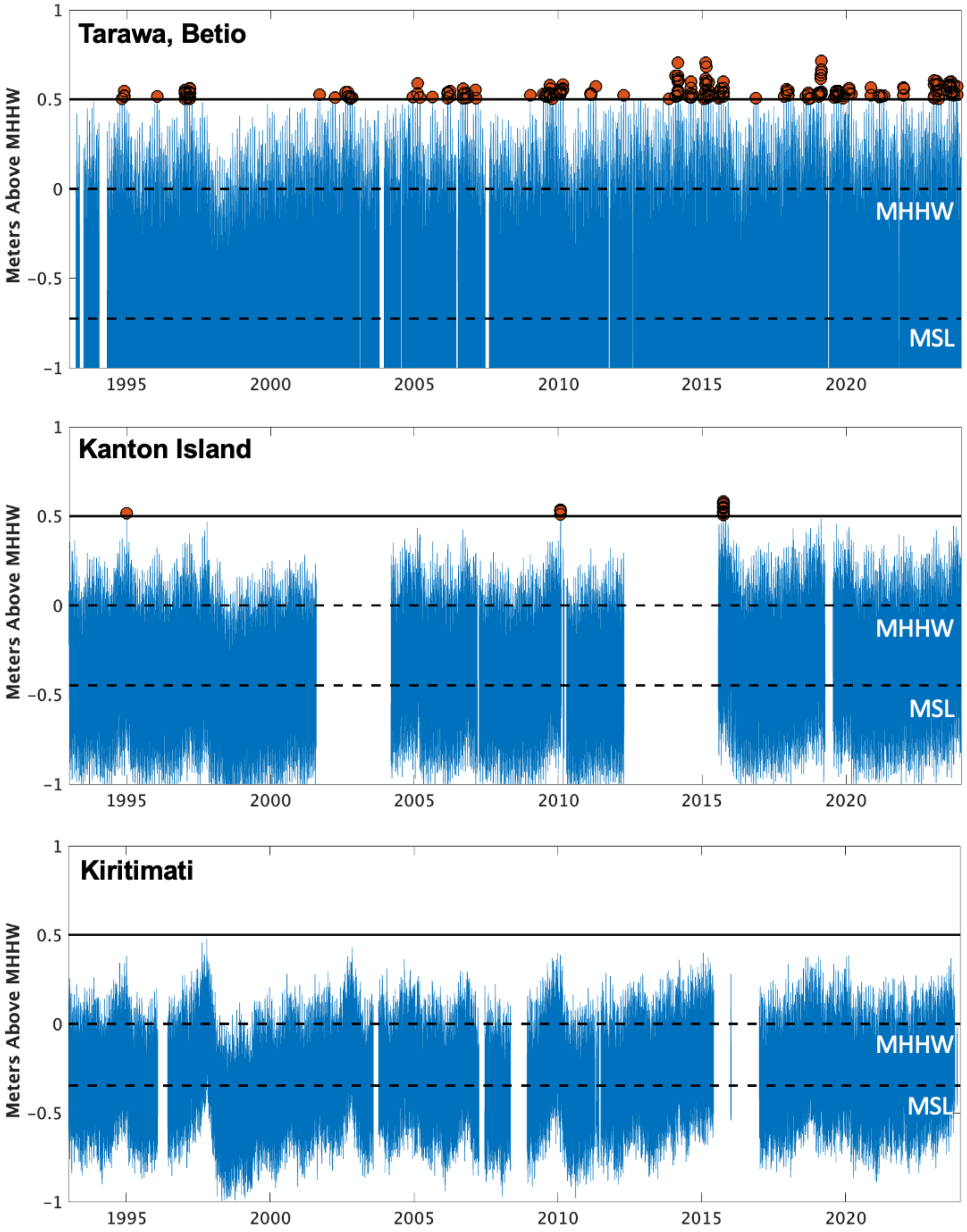

Figure 3. The occurrence of individual flooding days (top) for the 50 cm above MHHW threshold (solid black line) for the tide gauge records in Kiribati. The flooding days are not distributed evenly throughout the year and tend to occur in January, February and March, coinciding with the highest tides of the year. (adapted from source: https://pacificislandsflooding.org/projected-flooding).

3. Sea Level Rise Projections for Kiribati

The updated sea-level projections from the Intergovernmental Panel on Climate Change Sixth 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 IPCC 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 for which there is currently low confidence among scientists. Low confidence, as applied to these processes, means limited agreement among 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 (i) earlier-than-projected ice-shelf disintegration in Antarctica; (ii) abrupt, widespread onset of marine ice-sheet instability and/or marine ice-cliff instability in Antarctica; and (iii) 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 the three tide gauges in Kiribati are shown in Figure 4 across each SSP in 2100. The difference in projection across all SSPs is less than 3 cm for the islands of Kiribati. As a result, the presentation of projections is collapsed to a single set of values, and only the projections in Tarawa are provided for the rest of this section. The projected values and rates of sea level rise are given for both 2050 and 2100 in Table 2. In 2050, there is a relatively narrow range across all scenarios, both medium and low confidence.

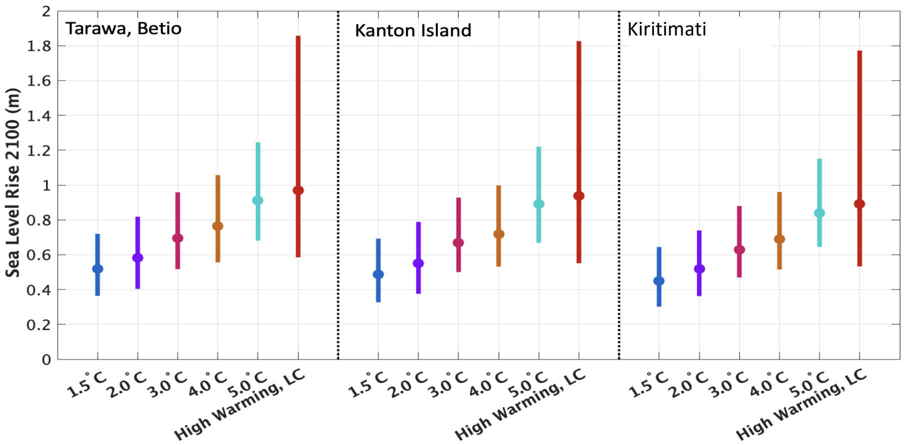

Figure 4. IPCC AR6 Projections in 2100 for three locations across Kiribati, relative to 2005. Projections are shown for each AR6 scenario. Circle markers indicate the median projection, while the bars represent the 17th-83rd percentile confidence interval.

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 Kiribati, relative to 2005. The 17th-83rd percentile confidence intervals 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.

Warming in 2100	1.5°C	2.0°C	3.0°C	4.0°C	5.0°C	High Warming, LC
2050	0.20 (0.15-0.28)	0.21 (0.16-0.30)	0.24 (0.17-0.33)	0.24 (0.19-0.32)	0.27 (0.22-0.36)	0.26 (0.19-0.45)
2100	0.52 (0.36-0.72)	0.58 (0.40-0.82)	0.70 (0.52-0.96)	0.76 (0.56-1.06)	0.91 (0.68-1.25)	0.97 (0.58-1.86)
2050 Rate	4.8 (3.2-7.1)	5.7 (4.0-8.3)	6.4 (4.5-9.3)	7.0 (4.8-9.8)	8.1 (5.9-11)	8.7 (5.6-19)
2100 Rate	5.4 (2.9-8.2)	6.4 (2.6-11)	8.9 (3.8-15)	10 (4.4-17)	13 (6.2-21)	18 (5.9-35)

The difference between the median values for the lowest scenario (SSP1-1.9) and the highest scenario (SSP5-8.5 Low Confidence) in 2050 is 6 cm. The upper end of the likely range across all medium confidence scenarios is 0.35 meters. 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 in 2100 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.

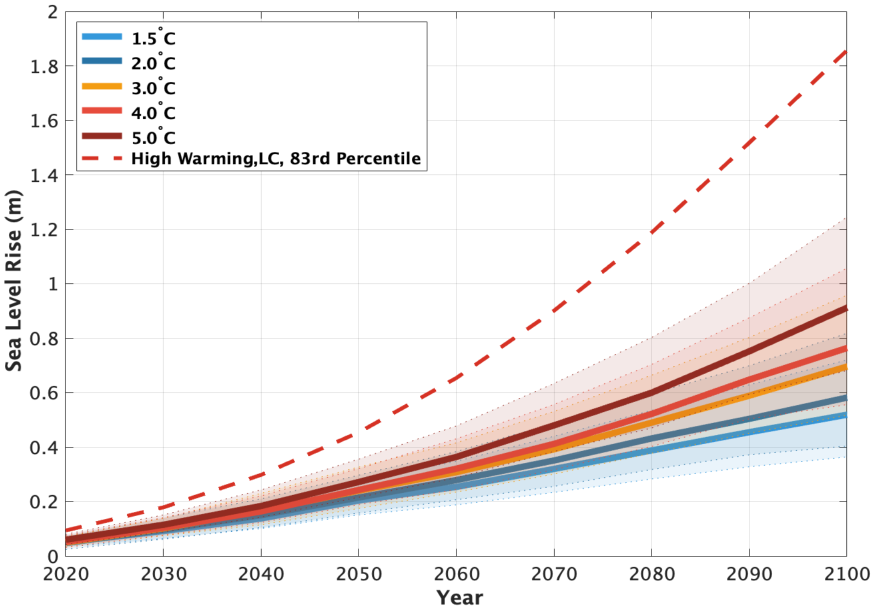

Figure 5. Projections of future sea level rise from 2020 to 2100 for Kiribati in meters, relative to 2005. The shaded regions represent the likely range for each projection, and the red dashed line represents a plausible upper end estimate for sea level rise.

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 Kiribati. 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 6-78%. Table 3 highlights the importance of limiting future warming. For low levels of future warming (< 2.0°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, 0.1 cm of sea level rise in Kiribati is expected to be surpassed by 2050. At higher warming levels, 0.30 m may also be surpassed by 2050.

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%

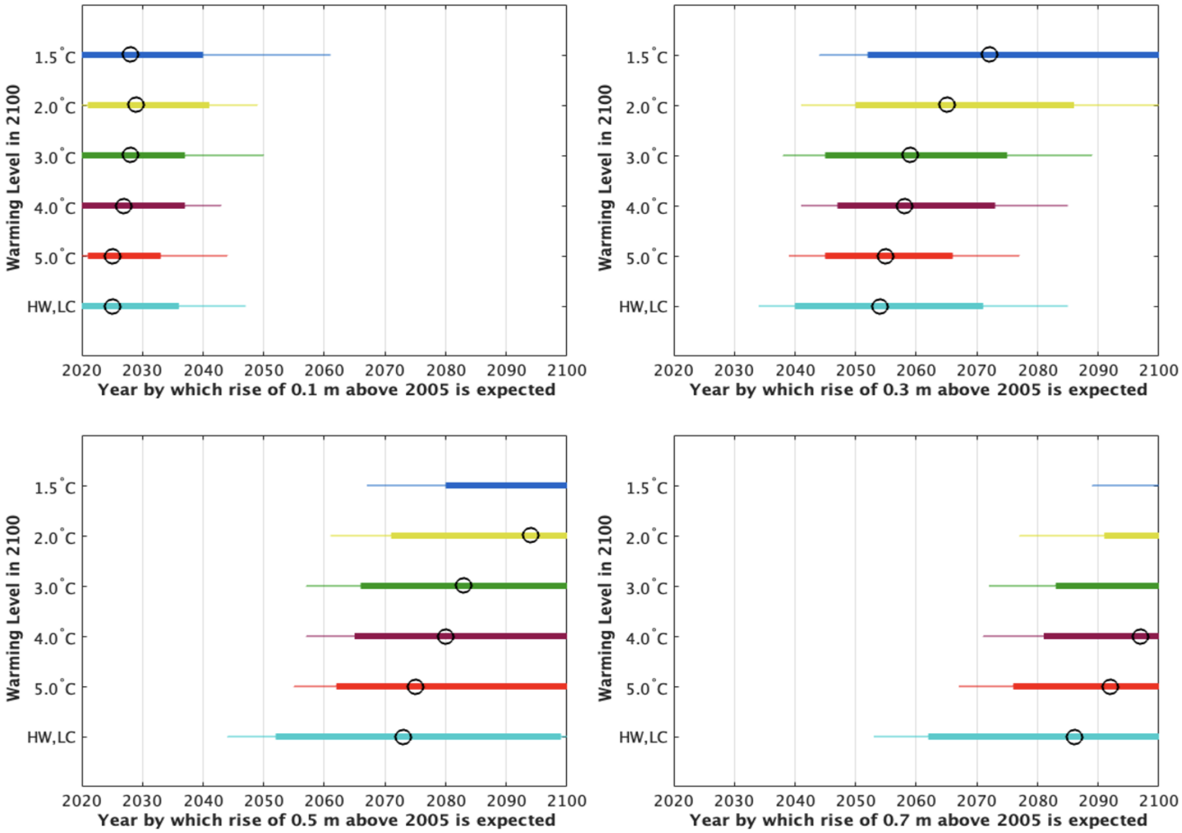

Figure 6. Timing of exceedance of different thresholds of 0.1 m (top left), 0.3 m (top right), 0.5 m (bottom left) and 0.7 m (bottom right) under different warming levels. Thick bars show 17th-83rd percentile ranges, and black circles show median value. Thin bars also show 5th–95th percentile ranges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

4. Projections of Future Flooding for Kiribati

Future sea level rise in Kiribati 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, a screening-level assessment is made of the areas most threatened by flooding driven by future sea level rise.

a. Approach to Assessing Areas of Kiribati Threatened by Future Flooding

To assess areas of Kiribati that are most threatened by future sea level rise, the elevation of Kiribati is estimated and then linked to specific thresholds to assess when flooding begins to occur. To estimate the elevation, a 50 cm horizontal-resolution digital surface model (DSM) is constructed using satellite images from WorldView-2 and, to ensure vertical accuracy, 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 tide gauges in each island chain in Kiribati to compute the spatially varying local mean sea level baseline. Assuming a uniform water level encroachment over land, and adding this to baseline to the tide gauge MHHW datum represents the best available estimate of the current, spatially-varying MHHW in Kiribati.

The areas in the DSM below the level of current MHHW, and MHHW +50 cm, +70 cm, and +100 cm are computed. These values are determined to be thresholds at which flooding may begin occurring in Kiribati 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). Areas that are connected to the coast are considered directly vulnerable to flooding from the sea and are shown as dark blue (Figures 7, 9, and 11). Areas that are below the targeted value and thus susceptible to groundwater flooding but disconnected from the sea are shown in light blue (Figure 7, 9, and 11).

To understand the results of such mapping, 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, 20 cm of sea level rise is expected to have occurred and 30 cm could occur. 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.

The change in the occurrence of episodic flooding as sea level rises, discussed above, can be assessed for Kiribati. 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 Kiribati allows for an assessment of changes in the occurrence of high-tide flooding in the future. To do this, the predictability of the different drivers of sea level change needs to be considered. The tidal variability in Kiribati 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 Kiribati tide gauges. 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.

b. Future Flooding Projections for Kiribati

The results for the combined inundation mapping and flood frequency analysis are shown for the Gilbert, Phoenix and Line Islands. The projected number of flooding days per year is shown for the three different flood thresholds described in section 4a (Figures 7-12). An example of how to read the figures below is provided in the appendix. Future sea level rise amounts between 10 and 70 cm are considered, and the timing for reaching those values for the ~3.0°C Warming and High Warming, 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 Kiribati. More specifically, the analysis conducted here supports the following statements:

Gilbert Islands (Figures 7 and 8):

- With 30 cm of sea level rise, a plausible projection for 2050, the Low Flooding Extent threshold will likely be exceeded between 50 and 90 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 145 and 185 days per year, while the Medium Flooding Extent threshold will likely be exceeded 50 to 90 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 over 40 times a year is possible with 70 cm of sea level rise, which is a plausible amount under all future scenarios by 2100.

Phoenix Islands (Figures 9 and 10):

- With 30 cm of sea level rise, the Low Flooding Extent threshold will likely be exceeded between 5 and 25 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 110 and 185 days per year, while the Medium Flooding Extent threshold will likely be exceeded between 5 and 25 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 20 times a year by 2100.
- Exceedance of the High Flooding Extent threshold is possible with 70 cm of sea level rise, which is a plausible amount under all future sea level scenarios by 2100.

Line Islands (Figures 11 and 12):

- With 30 cm of sea level rise, a plausible projection for 2050, the Low Flooding Extent threshold will likely be exceeded between 0 and 25 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 more than 180 times per year while the Medium Flooding Extent threshold will likely be exceeded between 0 and 25 days per year.
- Under all future sea level scenarios, it is likely that the Low Flooding Extent threshold will be exceeded more than 180 times a year by 2100, and the Moderate Flooding Extent threshold will be exceeded more than 60 times a year by 2100.
- Exceedance of the High Flooding Extent threshold is possible with 70 cm of sea level rise, which is a plausible amount under all future sea level scenarios by 2100.

The rapid shift in flooding days seen in both the Kanton Island and Kiritimati analysis is reflective of the confluence of a number of factors including very low elevations, relatively small differences in annual maximum sea level, and potentially lack of adequate information on tidal datums and flooding thresholds in these particular locations. Indeed, the extent of area that will be impacted at the Low Flood Extent threshold in Kanton Island is relatively small, for example. Nevertheless, the analysis conducted here does underscore the potential increase in flooding that will occur across Kiribati as sea level continues to rise. This increase will be substantially greater and more rapid if higher scenarios of future sea level rise are realized.

Tarawa, Gilbert Islands: Inundation Mapping

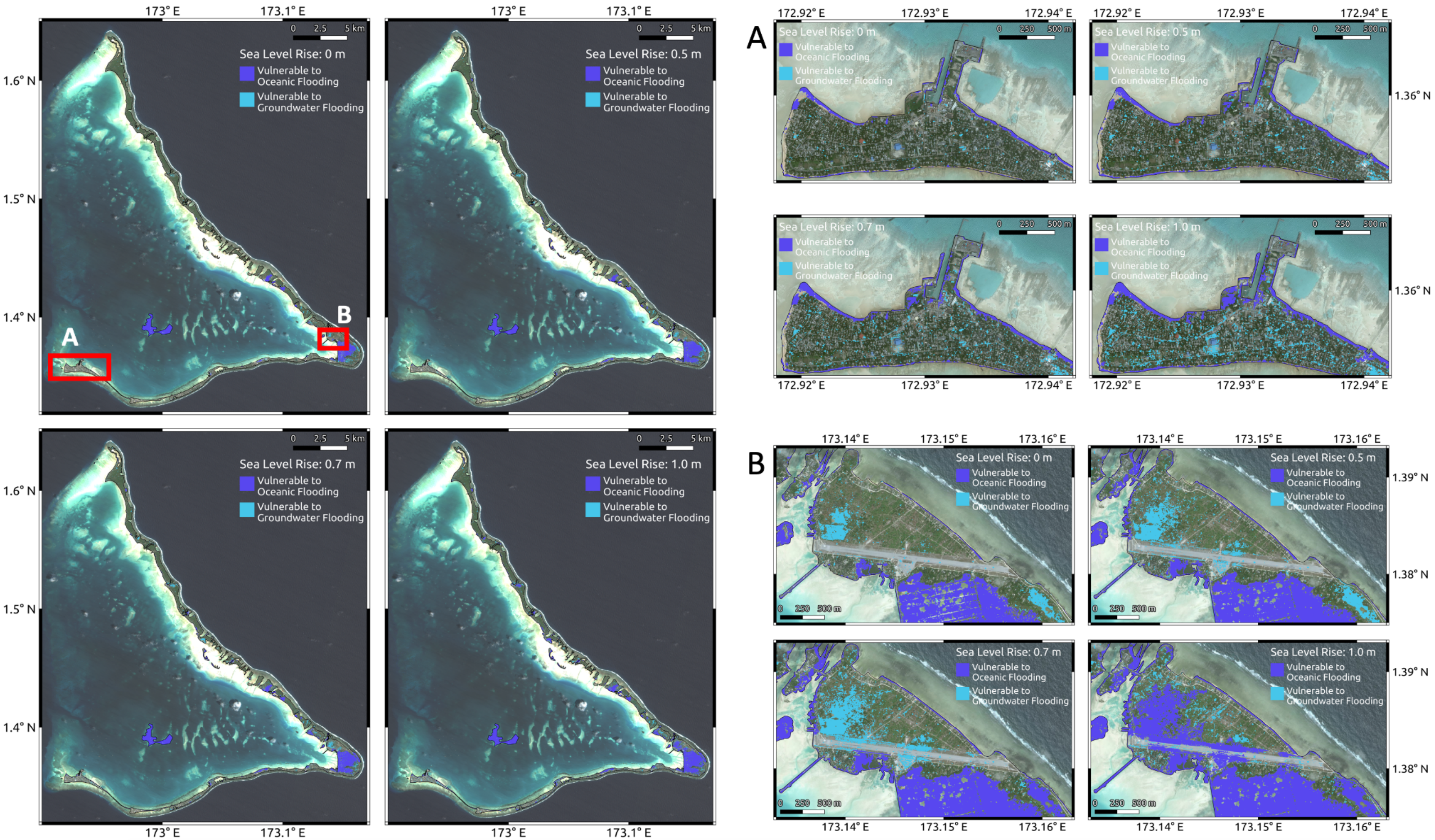

Figure 7. Projected inundation for 0 cm, 50 cm (Low), 70 cm (Moderate) and 100 cm (High) of sea level rise over current MHHW for Tarawa. Light blue denotes areas below future MHHW, but not necessarily connected to the sea, while dark blue areas are projected to be directly inundated from the sea. Note,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

Tarawa, Gilbert Islands: Flood Frequency Analysis

SLR & Timing	**10 cm**	**20 cm**	**30 cm**	**40 cm**	**50 cm**	**60 cm**	**70 cm**
~3.0°C Warming	2021-2039	2036-2058	2049-2074	2059-2091	2069-2108	2077-2127	2085-2146
High Warming, LC	2020-2037	2032-2054	2040-2067	2046-2079	2052-2092	2057-2110	2062-2121

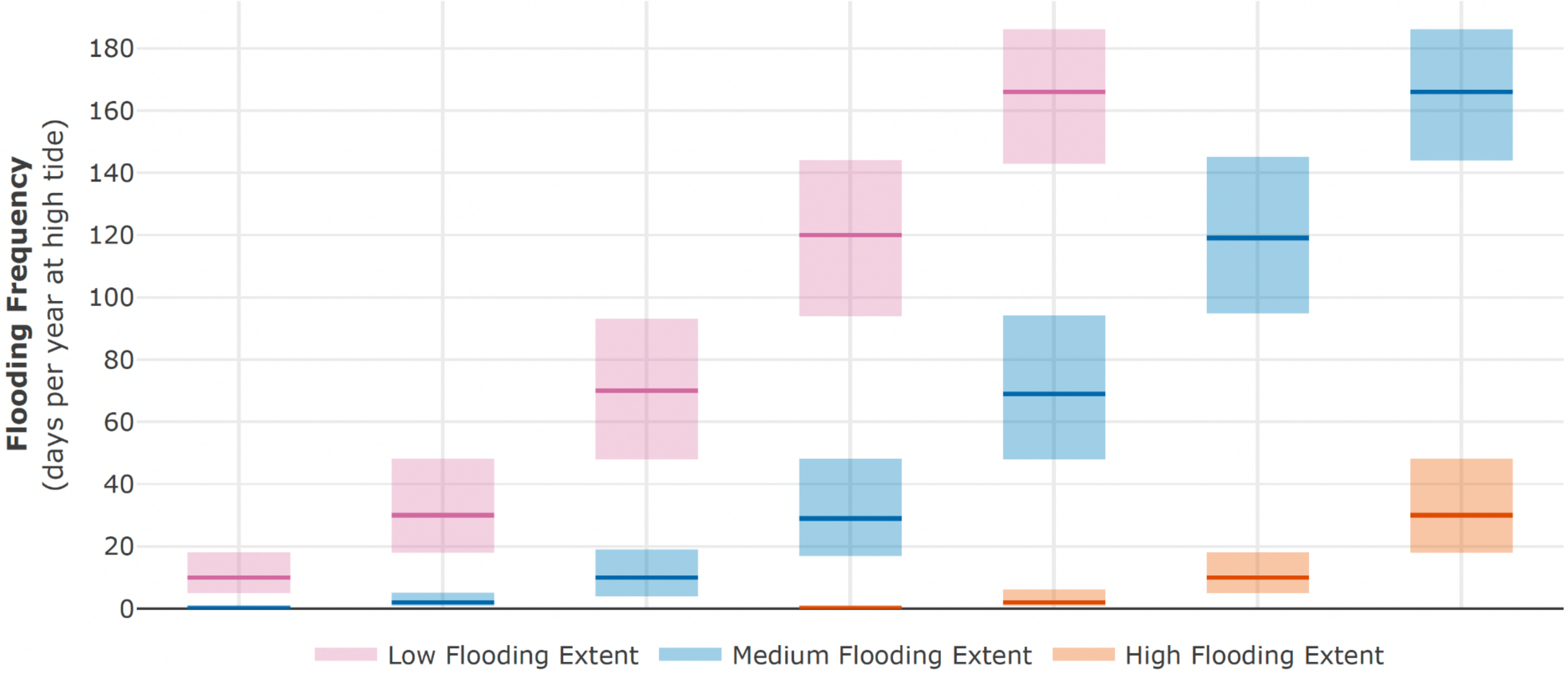

Figure 8. Flooding frequency in Tarawa for different amounts of future sea level rise (10-70 cm) above current MHHW. The timing of the indicated amount of sea level rise is shown for the ~3.0°C Warming and High Warming, Low Confidence Scenarios. Flooding frequency is computed using thresholds indicating 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).

Kanton Island, Phoenix Islands: Inundation Mapping

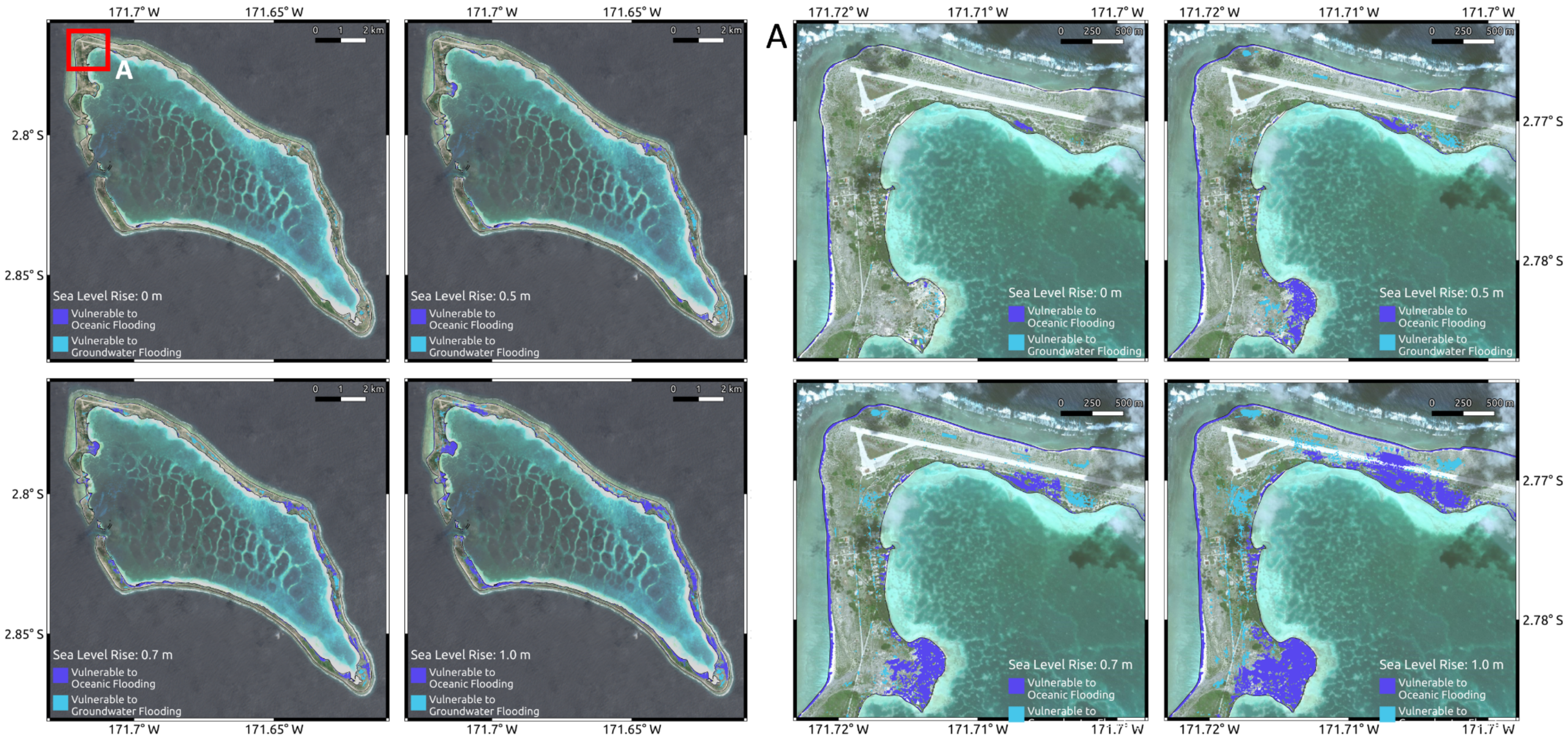

Figure 9. Projected inundation for 0 cm, 50 cm (Low), 70 cm (Moderate) and 100 cm (High) of sea level rise over current MHHW for Kanton Island. Light blue denotes areas below future MHHW, but not necessarily connected to the sea, while dark blue areas are projected to be directly inundated from the sea. Note, this assumes no additional protection or adaptation beyond what is currently implemented.

Kanton Island, Phoenix Islands: Flood Frequency Analysis

SLR & Timing	10 cm	20 cm	30 cm	40 cm	50 cm	60 cm	70 cm
~3.0°C Warming	2021-2039	2036-2058	2049-2074	2059-2091	2069-2108	2077-2127	2085-2146
High Warming, LC	2020-2037	2032-2054	2040-2067	2046-2079	2052-2092	2057-2110	2062-2121

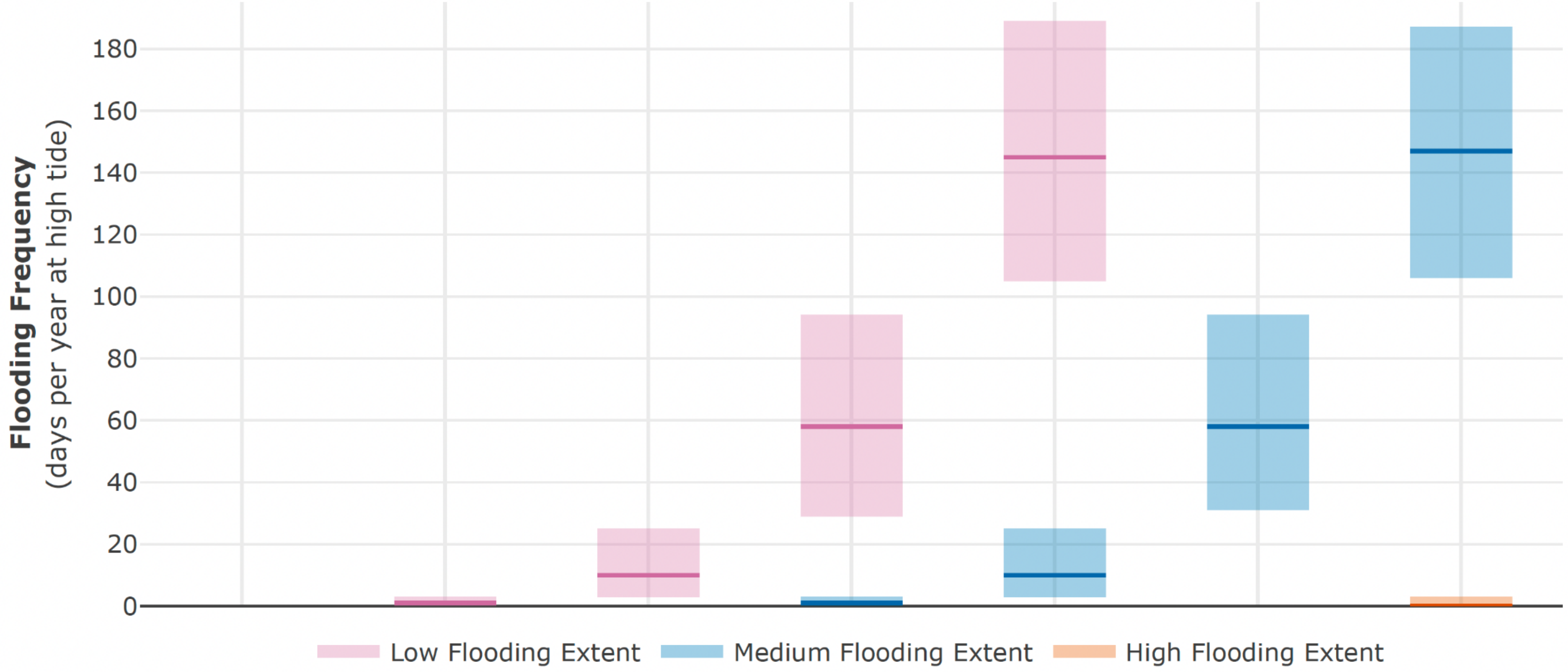

Figure 10. Flooding frequency in Kanton Island for different amounts of future sea level rise (10-70 cm) above current MHHW. The timing of the indicated amount of sea level rise is shown for the ~3.0°C Warming and High Warming, Low Confidence Scenarios. Flooding frequency is computed using thresholds 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).

Kiritimati, Line Islands: Inundation Mapping

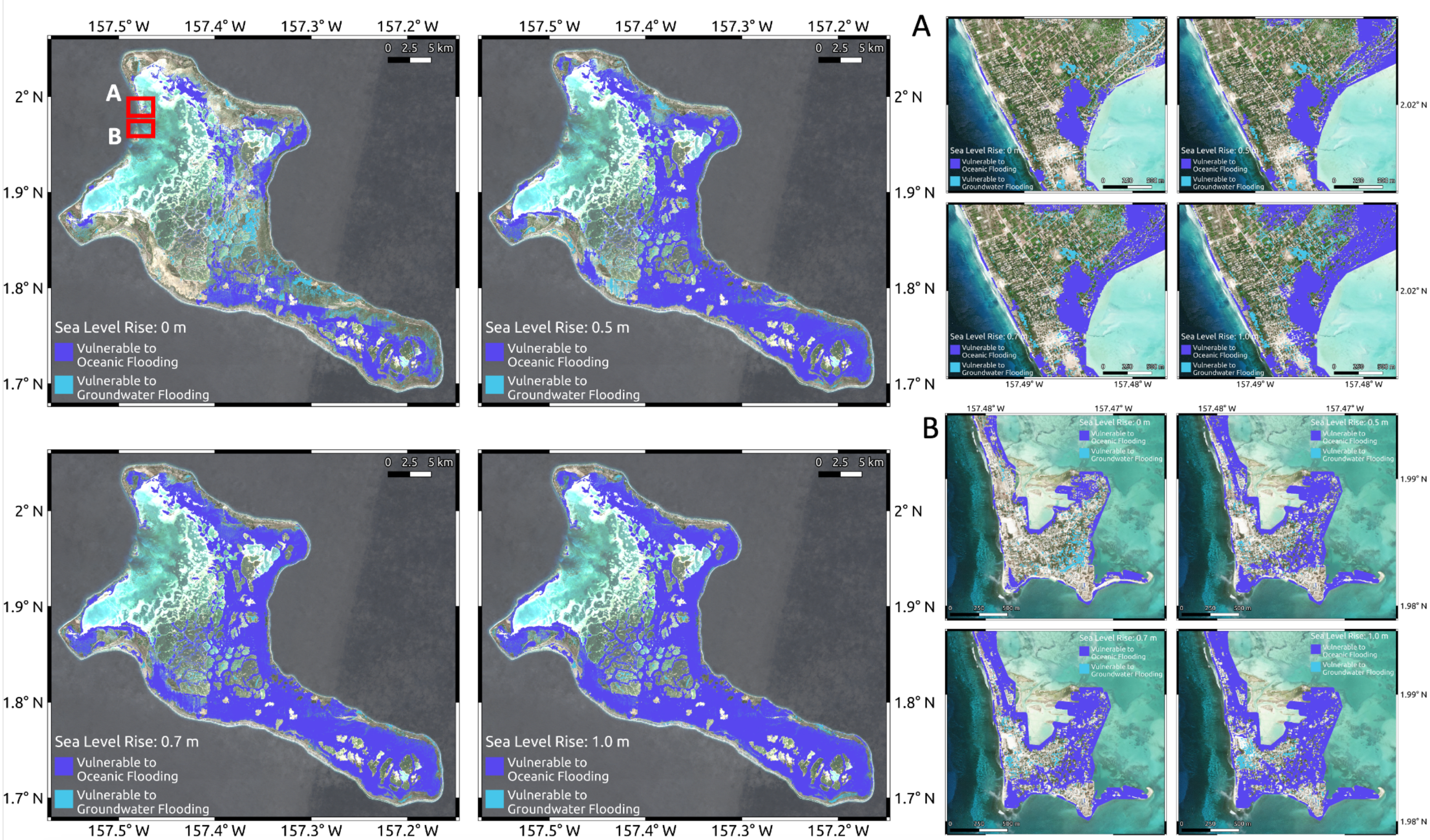

Figure 11. Projected inundation for 0 cm, 50 cm (Low), 70 cm (Moderate) and 100 cm (High) of sea level rise over current MHHW for Kiritmati. Light blue denotes areas below future MHHW, but not necessarily connected to the sea, while dark blue areas are projected to be directly inundated from the sea. Note, this assumes no additional protection or adaptation beyond what is currently implemented.

Kiritimati, Line Islands: Flood Frequency Analysis

SLR & Timing	10 cm	20 cm	30 cm	40 cm	50 cm	60 cm	70 cm
~3.0°C Warming	2021-2039	2036-2058	2049-2074	2059-2091	2069-2108	2077-2127	2085-2146
High Warming, LC	2020-2037	2032-2054	2040-2067	2046-2079	2052-2092	2057-2110	2062-2121

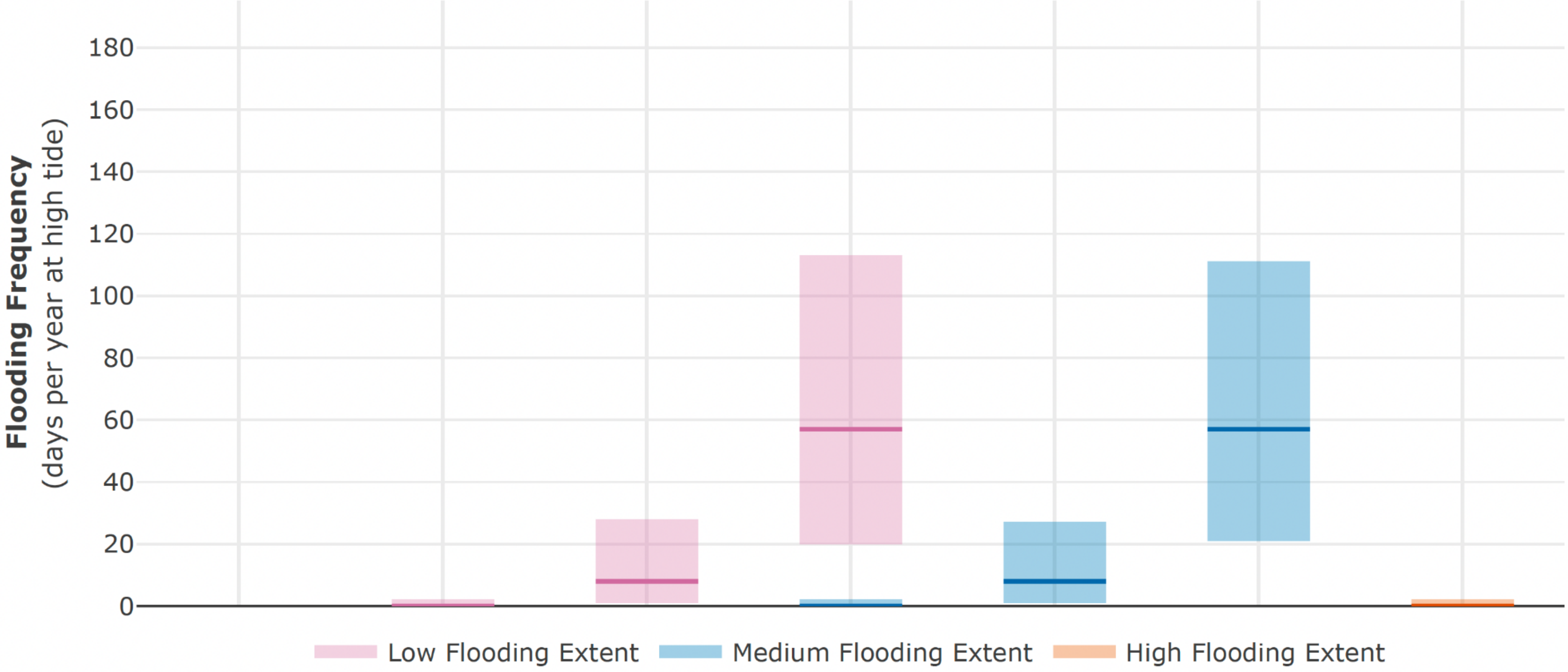

Figure 12. Flooding frequency in Kiritimati for different amounts of future sea level rise (10-70 cm) above current MHHW. The timing of the indicated amount of sea level rise is shown for the ~3.0°C Warming and High Warming, Low Confidence Scenarios. Flooding frequency is computed using thresholds indicating 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).

5. Areas of Informational Need and Data Gaps

Linking past and present observations of sea level change in Kiribati 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 Kiribati there is the possibility of spatial variations in the rate of vertical land motion across the different islands that make up Kiribati. Additional GPS stations - even on a temporary basis - could help determine if this is indeed the case. Interferometric synthetic aperture radar analysis (InSAR) analysis also provides a path forward, leveraging satellite observations to observe subsidence in Kiribati. An example of this is shown below in Figure 13. The high-resolution map of 30-m spatial resolution shows broadscale subsidence in Kiritimati from 2014-2023. The rates vary across the island, ranging from greater than 4 mm/year of subsidence to almost stable land movement. Further work is needed to understand how to integrate such estimates into the analysis conducted here.

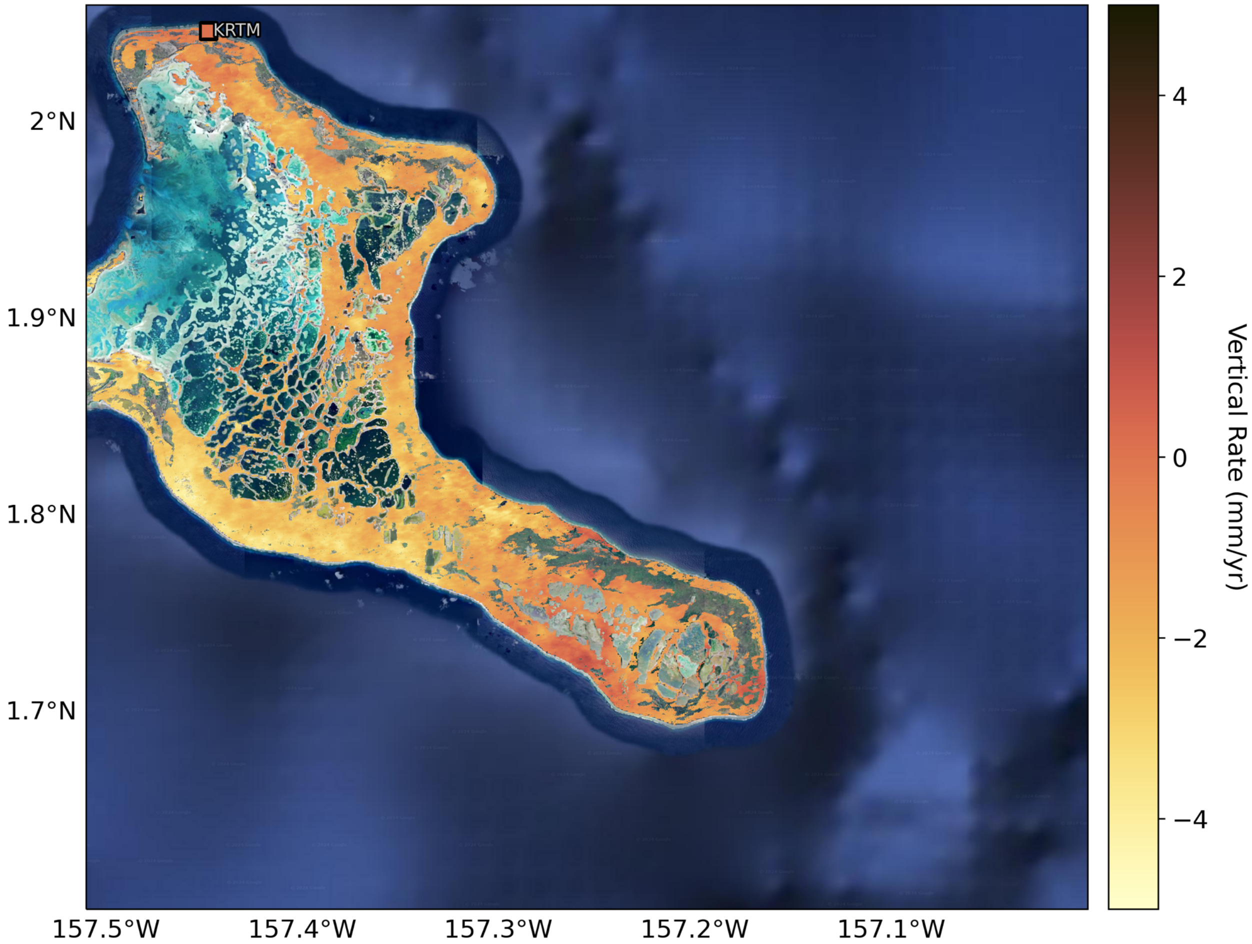

Figure 13. InSAR-estimated map of vertical land motion for Kiritimati from Sentinel-1 observations over the period from 2014 to 2023. The map indicated broadscale subsidence with some spatial variability in the rate of subsidence across the island.

As an additional limitation, the at-the-coast sea level change that is most closely linked to impacts is largely unknown away from the available tide gauges in Kiribati. This could lead to challenges in parts of the islands not directly observed by tide gauges. In particular, wave, tidal, and short-lived sea level anomaly propagation around the islands will manifest as signals with altered timing and amplitude at different places along the coast. 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 Kiribati, particularly illuminating the role of chaotic ocean variability and storm surge in flood threshold exceedances.

Indeed, assessing impacts occurring in Kiribati is limited by the availability of localized, high-resolution information. In particular, and relevant to the analysis conducted here, flooding thresholds – essentially at what height flooding begins to occur - are challenging to assess. A common threshold range of 50 cm, 70 cm and 100 cm is used here, although the results show that the actual extent of flooding varies from one location to the next. This indicates that thresholds specific to each location need to be defined. One way to do this is through inundation mapping by coupling land elevations to information on tidal datums. The land elevations used here were generated from satellites, and can vary in terms of vertical accuracy. In some Pacific Islands, airborne campaigns have led to high-resolution land elevation data with excellent vertical accuracies (e.g., Tuvalu). This is not currently available for the islands of Kiribati, which ultimately limits the conclusions that can be made. Likewise, in order to account for wave transformation processes between offshore wave buoys/models and the shoreline, where runup-driven inundation may occur continuous bathymetric detail offshore and elevation over periodically inundated regions is required, but not currently not available.

Finally, the assessment made here is limited in scope, covering only occurrences and severity of future flooding. It is well documented that the impacts associated with sea level rise in Kiribati will extend beyond flooding and inundation and will provide multiple stressors to the populations and habitats of Kiribati. Further study is needed to extend the analysis here into those areas. Additionally, a detailed assessment that includes the influence of all of the sources of short-term total water level variability, and their potential for changes in the future, is required for a more thorough view of future flooding and coastal impacts.

6. Summary

The assessment made in this report details worsening impacts associated with sea level rise for Kiribati 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. The specific goal of this analysis is to link present sea level rise to future projections of sea level rise before extending to what that will mean for impacts seen at the coast. A summary of this information is shown in Figure 14, detailing how sea level rise will change in the future. It is plausible that current rates of sea level rise in Kiribati will more than double by 2050 when compared to their current rate. Additionally, the range across all possible scenarios for future sea level rise is small in 2050, indicating increased certainty in an additional 20 cm or more sea level rise across all islands in Kiribati. This increased foundation of sea level will result in increased episodic flooding, although the potential impact across the three island chains varies substantially. The analysis suggests that the Phoenix and Line Islands will be less impacted in the near-term before a rapid shift occurs towards the end of the century. By 2100, all islands are projected to have substantially more than 100 days exceeding what is defined as the Low Flood Extent threshold (50 cm above MHHW) used here.

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 Kiribati 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 Kiribati the information needed to support planning for and adapting to sea level rise.

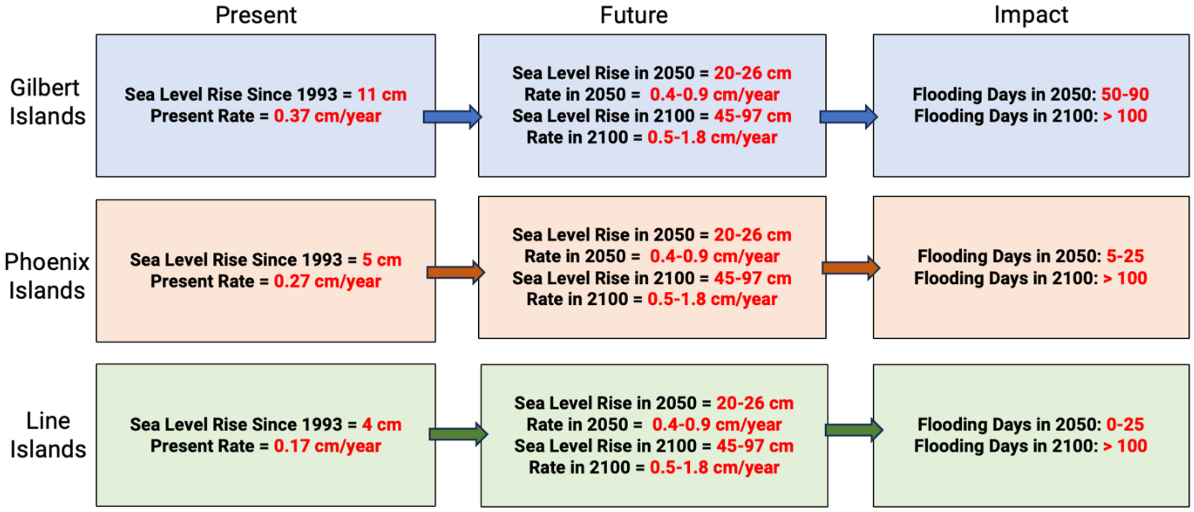

Figure 14. Summary of connection made in this report between present and future sea level rise, and associated impacts for the three island chains of Kiribati.

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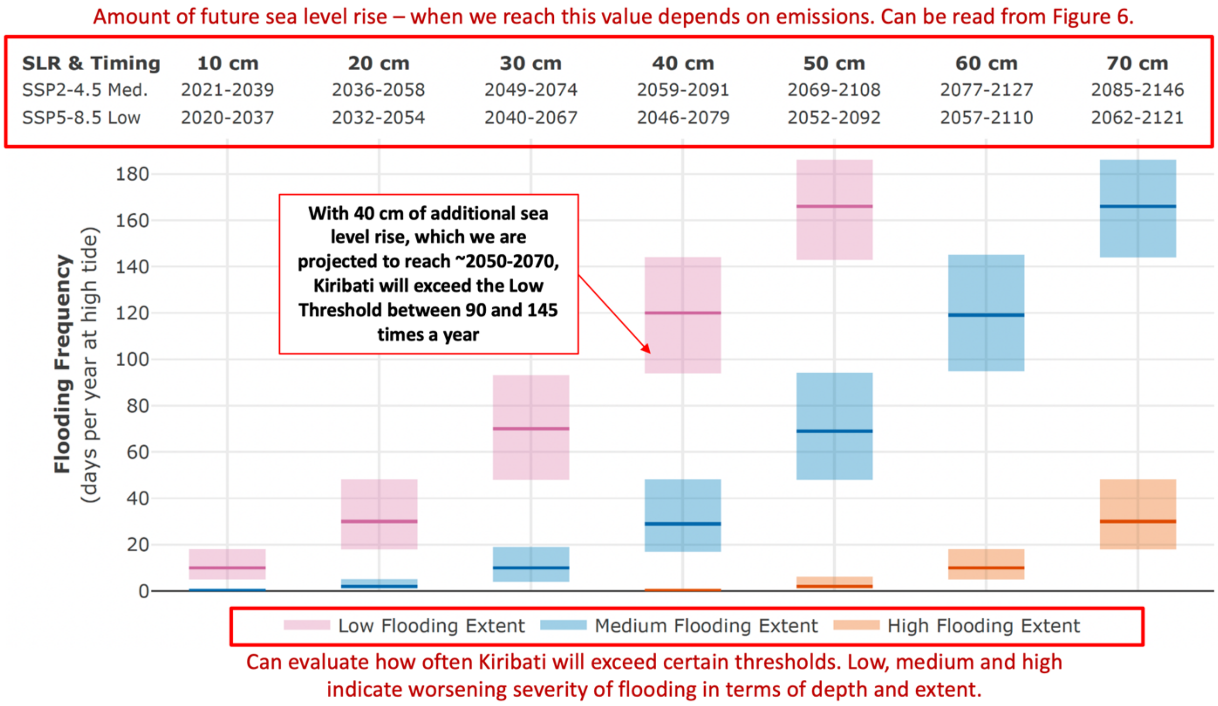
10. Appendix

To assist in understanding the flood frequency figures and information contained therein, Figure A1 provides an annotated example of the different components of the figures shown in section 4.


Amount of future sea level rise – when we reach this value depends on emissions. Can be read from Figure 6.

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

With 40 cm of additional sea level rise, which we are projected to reach ~2050-2070, Kiribati will exceed the Low Threshold between 90 and 145 times a year

Can evaluate how often Kiribati will exceed certain thresholds. Low, medium and high indicate worsening severity of flooding in terms of depth and extent.

Figure A1. Annotated example of flood frequency figure. Shown here is the figure for Tarawa, corresponding to Figure 9 in the report above. The red box on the graph itself provides an example of the type of statement that can be generated using this analysis.