THE PENNSYLVANIA STATE UNIVERSITY
COLLEGE OF EARTH AND MINERAL SCIENCES

DEPARTMENT OF GEOSCIENCES

Contrasting Inundation Patterns of Two Pacific Islands under Sea-Level Rise

A Senior Thesis in Earth Sciences
by

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Submitted in partial fulfillment
of the requirements
for the degree of

Bachelor of Science

Spring 2015

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[redacted] May 1st 2015

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Acknowledgements

I would like to thank Dr. Klaus Keller and Dr. Patrick Applegate for advising me this year and for discussions that shaped my senior thesis. I am grateful for Dr. Keller agreeing to take me on even when I had no modeling experience and for teaching me how to become a better writer and scientist; and also for always having chocolate nearby. I would like to acknowledge Dr. Applegate for introducing me into the world of R and for his attention to the smallest details. Because of Dr. Keller and Dr. Applegate, I was able to accomplish my goal for this year: to learn something new. This seems like an obvious statement but an important one.

I would also like to thank the Keller lab group for being a great support system throughout the year. While I was giving updates and occasionally presenting at the weekly meetings I was provided with great feedback and food for thought. Special shout-out goes to Dr. Greg Garner who helped me finally smooth out a piece a code I was struggling with. I wish everyone the best of luck in wherever their future leads them.

Finally I would like to thank The College of Earth and Mineral Sciences and The Pennsylvania State University for providing me with the resources and the ability to conduct research as an undergraduate student. This work was partially supported by the National Science Foundation through the Network for Sustainable Climate Risk Management (SCRiM) under NSF cooperative agreement GEO-1240507.

Introduction

Significance

Coral Atolls are coral reef islands that are found mostly in the Pacific and Indian Oceans and are vulnerable to rising sea levels due to their low elevation. By 2100, it is possible that sea level may rise 0.5-2 meters, which could cause partial or complete submergence of atoll islands[1]. Atolls support diverse ecosystems, including endangered species, as well as human populations. The loss of these islands would lead to the displacement of these populations.

It is unclear whether or not these dynamic landforms will persist under sea-level rise, and two competing hypotheses regarding the survival of atoll islands have emerged. One hypothesis is that as sea level rises and atolls are exposed to increased wave action, the islands will erode and eventually disappear. Wave-energy dissipation could be a major factor as distance between the surface water and reef flat grows leading to larger waves[2]. Alternatively, enhanced coral growth and sediment transport on reef flats may lead to shoreline accretion and islands increasing in area.[3] The rate of future sea-level rise may be a fundamental control on the survival; average coral growth is about 1-4 mm/yr and rates of sea-level rise that greatly exceed this growth rate could lead to the drowning of atoll islands[2].

Atoll island nations are particularly vulnerable to sea-level rise because they are densely populated islands with a large fraction of each island in the coastal zone[4]. This vulnerability has led nations like Kiribati to discuss relocation and possible abandonment[5]. Some coral atolls may become unable to sustain human population before land loss from sea-level rise becomes a major issue. Atoll nations are typically densely populated, have poor infrastructure, and are among the world's lowest-income populations[4]. Low income and highly dense areas are at high risk of climate impacts. Coral atoll islands also have limited water resources because their water supply comes from shallow freshwater lenses that are easily contaminated by salt water.

Sea-Level Rise

Recent observations have shown that global mean sea level is rising due to the effects of climate change. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report shows that over the 20th century, global average sea level rose about 1.9mmm yr^{-1}, due mostly to thermal expansion and the melting of glaciers[6]. The IPCC report also predicts a future increase in the rate of sea-level rise relative to the observed a rate of about 3.2 mm yr^{-1} since 1993. Church et al. (2006) has shown significant sea-level rise acceleration from 1870-2004 of 0.013 +/- 0.006 mm/yr, consistent with climate model simulations that show accelerating sea-level rise through the 21st century[7].

Future projections of sea-level rise range from about 0.5 m to 2.0 m by 2100[7].A number of studies have used semi-empirical models for sea-level rise projections. Semi-empirical models are used when the exact relationship between the forcing (in this case, temperature increase) and the response to that forcing is not yet clear. For example, Rahmstorf (2007) used a semi-empirical approach to project a future sea-level rise by 2100 of 0.5 to 1.4 m above the 1990 level by linking global sea-level rise to global mean surface temperature[8]. Similarly, Vermeer (2009) estimated a sea-level rise of 0.75-1.9 m from 1990-2100[9]. A sea-level rise of 0.5-2 m would likely increase flooding and cause land loss in low-lying islands.

Atoll Formation

Charles Darwin described the origin of coral atolls in *The Structure and Distribution of Coral Reefs*[10]. Atoll formation begins with the growth of coral reefs on the side of a volcano. As the volcano cools and drifts from its hotspot due to plate tectonics, it begins to sink, and the reef grows upwards to stay in the photic zone. The photic zone is the upper layer of the ocean where sunlight penetrates the water. This is important for the corals symbiotic algae, which provides food for the coral animal through photosynthesis. A narrow, shallow lagoon separates the fringing reef from the island coast. As the island sinks, the fringing reefs become barrier reefs and become separated from the coast by lagoons that increase in depth and width. Eventually the volcano becomes completely submerged leaving a ring of corals and islets surrounding a lagoon. Figure 1 shows the evolution from a volcanic island with a fringing reef, to a barrier reef, and finally to a coral atoll.

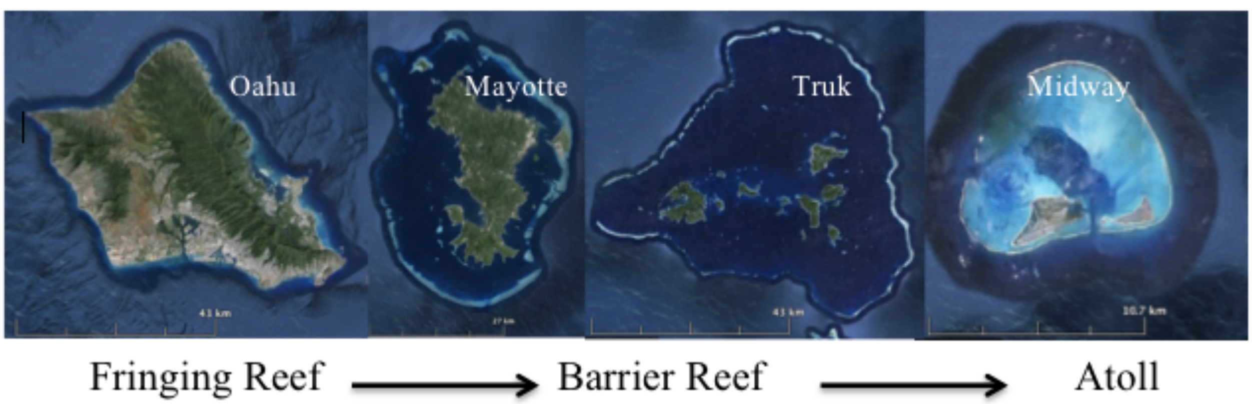


Figure 1 Coral Atoll Subsidence Theory, images from Google Earth. Note that the scales differ from island to island. The tick marks for the scales are 43 km, 27 km, 43 km, and 10.7 for islands Oahu, Mayotte, Truk, and Midway respectively. Note how as the island progress from a fringing reef, to barrier reef, and finally to atoll, the lagoon gets wider as the volcanic island subsides.

Sediment accumulation leads to island forming alongside lagoon channels or on the protruding sides of the coral reefs[10]. Islets often have smaller dimensions on the windward side. Typically, an atoll has two to three channels, often with one leading into the lagoon on the side of the atoll not fully exposed to the prevailing wind. The islands are typically 2-3 meters in elevation, and are restricted by the ability of waves to pile up reef sediment.

Compared to larger islands and continents, atolls are relatively short-lived landforms. Modern atoll islands formed during the late Holocene and are composed mostly of unconsolidated Holocene carbonate sands and gravels[11]. While a long time from human perspectives, most current atolls only formed within the past few thousand years and have been inhabited by an even shorter amount of time. Therefore, human presence on atoll islands is short compared to the long history of humans on the continents.

Recent Studies

One way of studying past changes in atoll island area uses historical aerial images. For example, Yamano et al. (2007) applied this approach to Fongafale Islet on Funafuti Atoll and argued that studies of atoll islands should focus on characteristics particular to that area of study[12]. In particular, historical reconstruction can be used to study island-specific vulnerabilities. Webb et al. (2010) studied 27 Pacific atoll islands over 42 years to analyze changes in island area[13]. These results showed that 86% of islands did not grow or shrink, whereas 14% of islands decreased in area. Thus, atoll islands are dynamic landforms, which respond to sea-level rise.

A similar study using aerial images conducted by Biribo et al. (2013) analyzes historical area and shoreline change of Tarawa Atoll over the past 30 years[14]. They found that these reef islands had grown by about 450 ha. Natural factors mostly influenced shoreline changes in North Tarawa. However, South Tarawa, was mostly influenced by human activities and the El Nino-Southern Oscillation (ENSO). These influences have led to more stability in North Tarawa, but widespread erosion along both ocean- and lagoon-facing shorelines in South Tarawa.

Numerous studies have created models to study island geomorphology and the potential effects of sea-level rise. Kench et al. (2001) presents a model that dismisses some common misconceptions about atoll islands and sea-level rise, and shows that atoll island response varies depending on island physical characteristics, conglomerate platforms do not guarantee island stability, and total atoll island loss is unlikely due to their dynamic nature[15]. Kench et al. (2005) presents a model for reef-island evolution that suggests that seal level rise will not hinder vertical reef growth or make islands less stable[16]. Storlazzi et al. (2013) compares passive inundation models to dynamic models that includes the effects of waves on water levels[2]. Dynamic models results show that island inundation increased substantially with the inclusion of wave-driven effects compared to passive inundation models. The model also suggests that classic atolls with islands on shallow rims were more vulnerable to sea-level rise combined with wave-driven inundation than those with a deep atoll rim.

In this study, we investigated the impact of sea-level rise scenarios on Midway Atoll and compare it to the Hawaiian island of Oahu. Midway Atoll is a United States territory in the North Pacific Ocean, and Oahu is part of the Main Hawaiian Islands. We used digital elevation models from NOAA to map how various levels of sea-level rise change the topography of these islands, assuming no change in island topography due to coral growth or sediment movement[17, 18]. We hypothesize that the passive bathtub inundation model will show increasing levels of island inundation as sea-level rises with

Midway having more inundation due to its lower average elevation. This study provides tools to assess the effects of sea-level rise on coral atolls and my results can be used to inform risk assessments.

Methods

Study Area

The Hawaiian archipelago spans thousands of miles from Hawaii to Kure Atoll, and arcing towards Alaska with the Aleutian Islands[19]. This study is focuses on the Main Hawaiian Islands and the Northwestern Hawaiian Islands. The main Hawaiian Islands include the islands of Hawaii, Oahu, and the Northwestern Hawaiian Islands is chain of small islands, atolls, and shoals including Midway Atoll[20]. Figure 2 shows a map of the Archipelago[19]. The islands of the Archipelago were formed by an active volcanic hotspot on the middle of the Pacific plate.[20] The hotspot is fixed, however, the Pacific Plate is moving. This allowed a chain of islands to form as the plate moved over the hotspot. The youngest seamount is Loihi, which is currently erupting 1000 m below sea level from its summit.[19] As you go northwest from the main island of Hawaii, the islands get progressively older; for example, Midway Atoll is older than Oahu.

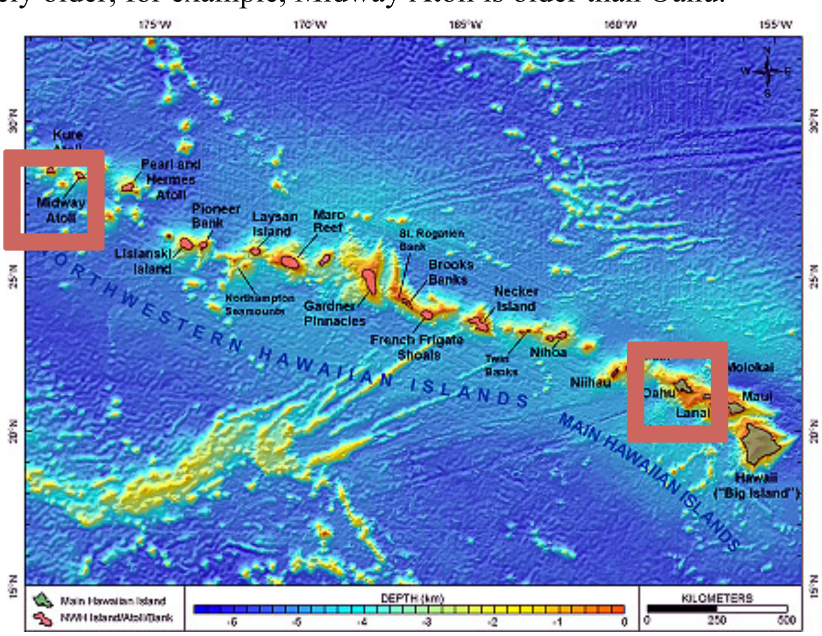


Figure 2 Map of the Hawaiian Archipelago including the Main Hawaiian Islands and the Northwestern Hawaiian Islands. Note Oahu on the Southeastern end of the Main Hawaiian Islands Midway Atoll in the Northwestern part of the chain. As the chain goes from southeast to northwest, the islands typically get older and lower in elevation as the volcanoes cool and subside[19].

Midway atoll (28 11 N, 117 18 W) is a circular-shaped coral atoll located in the North Pacific Ocean. It is a part of the Northwestern Hawaiian Islands between Kure Atoll and Pearl and Hermes Atoll. Midway is comprised of three islands on the southern end of a shallow white sand lagoon. The three islands of Midway are Sand, Spit, and Eastern Island, each having maximum elevation of 11.7m, 2.4m, and 7.4m respectively, and a mean elevation of 3.2m, 1.5m, and 7.5m respectively[2]. Figure 3 is an aerial satellite image of Midway Atoll. The aqua blue water seen inside the atoll illustrates the shallower water inside the lagoon compared to the dark navy blue of the deep ocean.

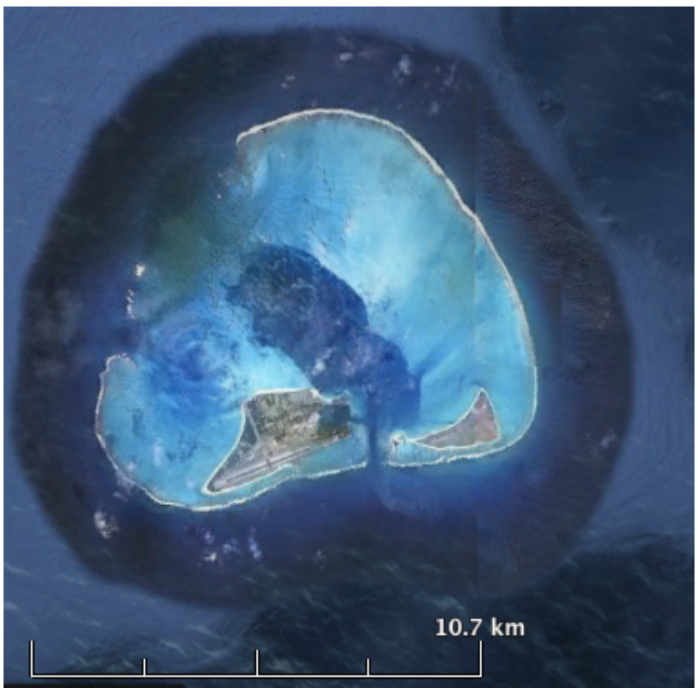


Figure 3 Aerial Satellite Imagery of Midway Atoll from Google Earth. Note Sand, the largest island, on the left, Spit in the middle, and Eastern Island on the right. The light aqua water indicates shallower water verses the darker and deeper water in the center of the lagoon and immediately surrounding the atoll ring.

Midway is part of the Papahānaumokuākea Marine National Monument, which is the United State's largest conservation area, incorporating small islands, atolls, submerged banks, and reefs.[21] In 2010, Midway was listed as a mixed World Heritage

Site. The Northwestern Hawaiian Islands is a diverse ecosystem with many species listed as endangered, threatened, or species of concern and currently managed by the U.S. Fish and Wildlife Service. The ex-naval base was once home to about 5,000 people; however, the current population is about 40 individuals with much of the original infrastructure still in place.

Data

In this study, we created a bathtub inundation model using a digital elevation model (DEM) from the US National Oceanic and Atmospheric Administration (NOAA). A bathtub inundation model infers that as modeled sea-level rises, any land area that becomes below sea level becomes inundated regardless of whether it is coastal or inland. For Midway, the DEM version used was the Midway Atoll v2, PI 1/3 arc-second MHW DEM[17]. This DEM covers the area surrounding the atoll including, Sand Island, Spit Island, and Eastern Island, and extending onto the volcanic base. Figure 4 shows the topography and bathymetry of the area covered by the Midway DEM. The DEM was updated in 2012 from the original 2009 DEM to include new topographic lidar data gathered by the U.S. Geological Survey. The DEM has a resolution, or cells size, of 1/3,

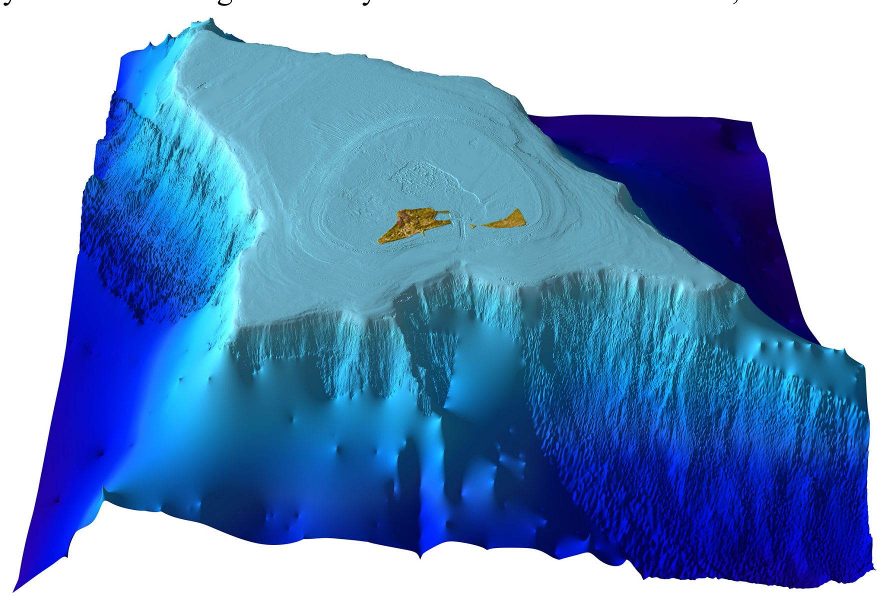


Figure 4 Range of Midway DEM[17] The top of the image reflects the atoll itself with a faint outline of the ring-like structure and the islands represented in brown. The DEM then drops down to the base of the volcano, turning a darker blue with increasing depth.

which equates to a resolution, or cell size, 1/3 of an arc-second, or about 10 meters at the equator. Mean high water datum serves as a reference for the DEM.

The DEM used for the Oahu was the Oahu, HI 1/3 arc-second MHW DEM[18]. This model was built in 2011 and covers the island of Oahu, Hawaii that includes Honolulu, the largest settlement in the state of Hawaii. This geologically younger island is different than Midway due to its much higher elevation and also high permanent population. The study of Oahu could be important for the islands many inhabitants. It is expected that Oahu will experience less flooding under sea-level rise scenarios.

Experimental Method

I downloaded the DEMs from the NOAA website and datum analyzed them using the graphics and statistical tool R, which is a computing environment for data analysis and graphical display. The DEMs were originally referenced to mean high water. To change the DEMs reference elevations from mean high water to mean sea level, each islands station datum was looked up via NOAA's Tides and Currents website[23,24]. The mean high water value was subtracted by the mean sea level to get a new reference value. Figure 5 shows how the different datums relate to one another on Midway Island.[21]

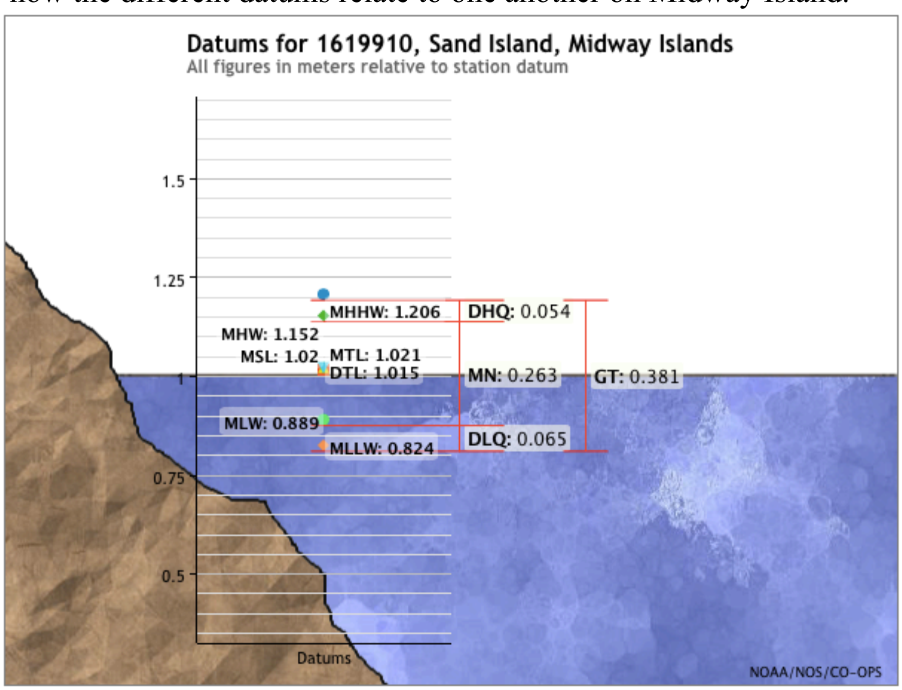


Figure 5 Station elevation datum for Midway Atoll. In particular, note the difference in mean sea level and mean high water[23].

I examined amounts of sea level rise from 0.5 to 2.0 m, consistent with studies that make projections of future sea-level rise[7]. I took the grid of topographic data represented by the DEM and subtracted spatially constant amounts to model changes in sea level. This method assumes that the islands' shape is static; thus, natural and anthropogenic processes that change the islands' topography are omitted.

To show hypothetical sea-level rise projections, a sequence of figures were created to model island inundation as sea levels rose. Another script was created to show a cumulative density function, which represents the percentage of island area that is covered by sea-level rise, more specifically, the area that was once above 0 m that becomes inundated by the sea level scenarios. Appendix 1 provides the script that produces Figures 6 and 7. Appendix 2 provides the script that produces Figures 8 and 9.

Results

Figures 6 and 7 show the effects of varying amounts of sea level rise on Midway Island and Oahu respectively from no sea-level rise to 1.5 meters of sea level rise. Any elevation below 0 (blue) represents elevation below sea level with the color shifting as island elevation becomes lower with respect to sea level. As sea level rises, more of the three islands become inundated with a shift from predominantly above 1 meters of elevation to most of the islands below 1 meter above sea level with Spit Island disappearing completely with 1.5 meters of rising sea levels.

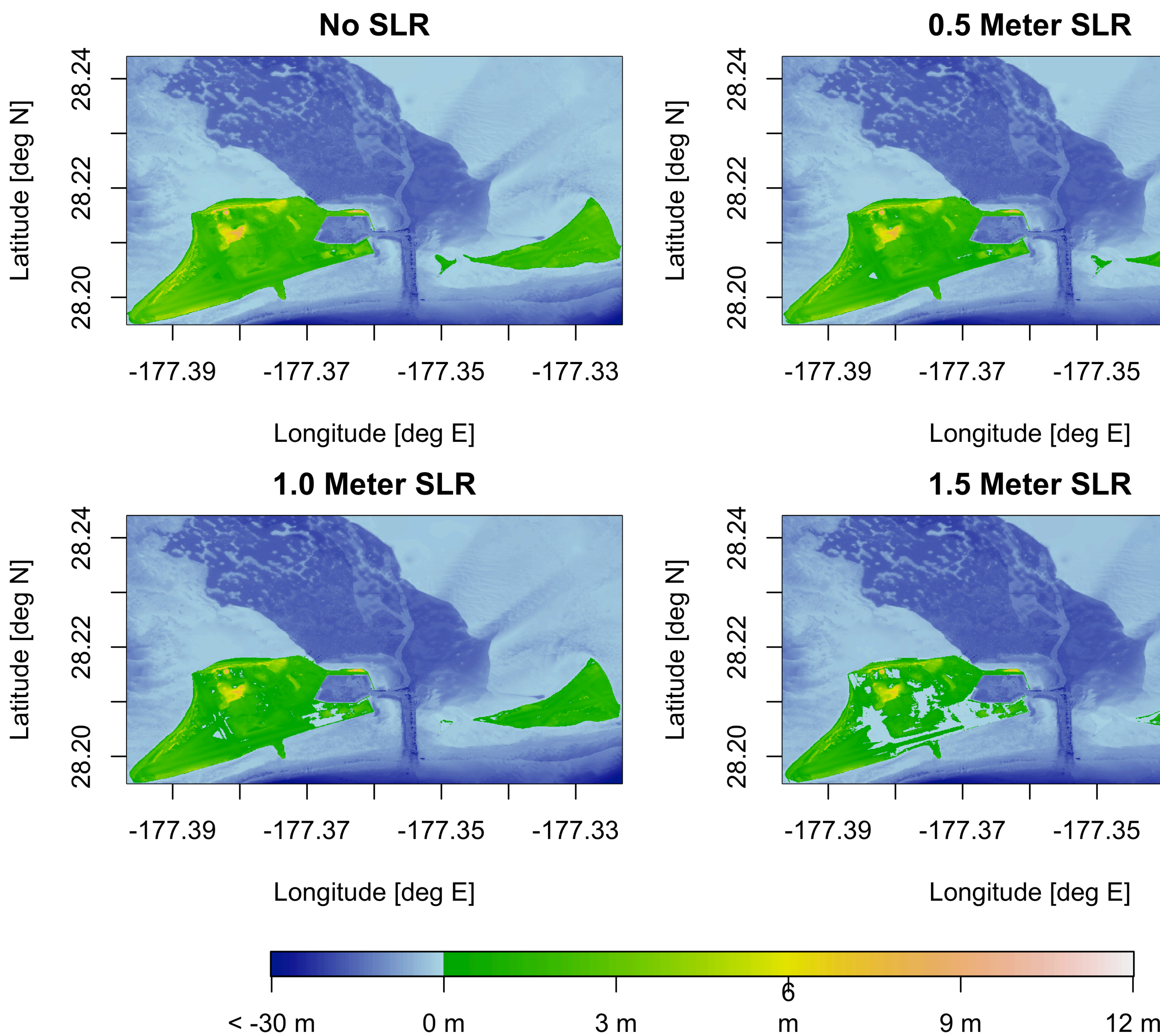


Figure 6. Hypothetical sea-level rise progressions for Midway Atoll. As sea-level rises from 0-1.5 meters, more island area becomes inundated.

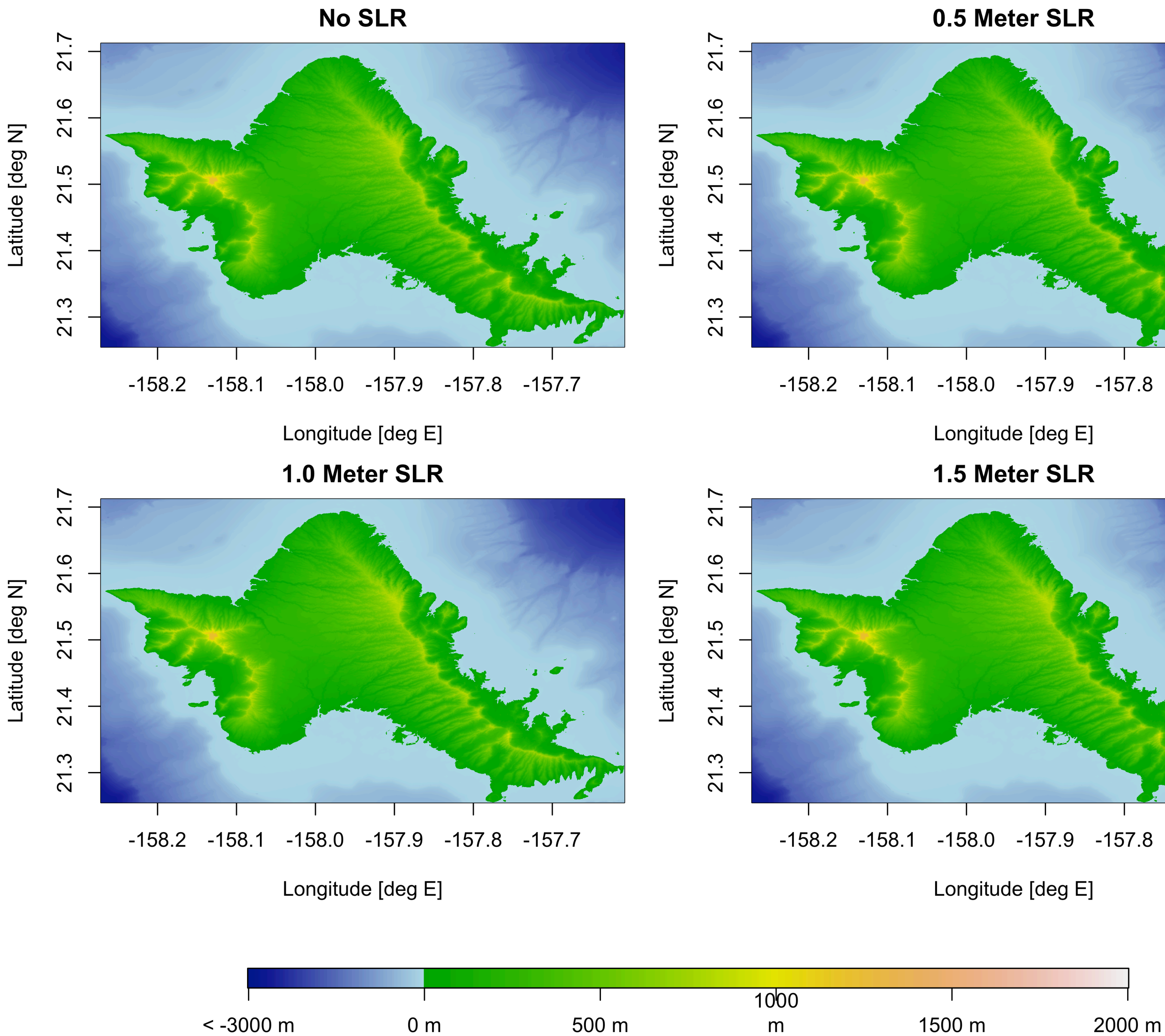


Figure 7 Hypothetical sea-level rise progressions for Oahu. Inundation occurs mostly on the Northern Coast and the Southern coast especially around the area of Honolulu.

Figures 8 and 9 show cumulative density functions for sea-level rise scenarios plus an additional 0.5 meter for scenarios of 0.5-2 meters. Because the Midway Islands have generally lower elevations than Oahu, a given amount of sea level rise covers a larger fraction of Midway than Oahu. Table 1 summarizes the fractional area and total area covered for both islands given differing amounts of sea level rise.

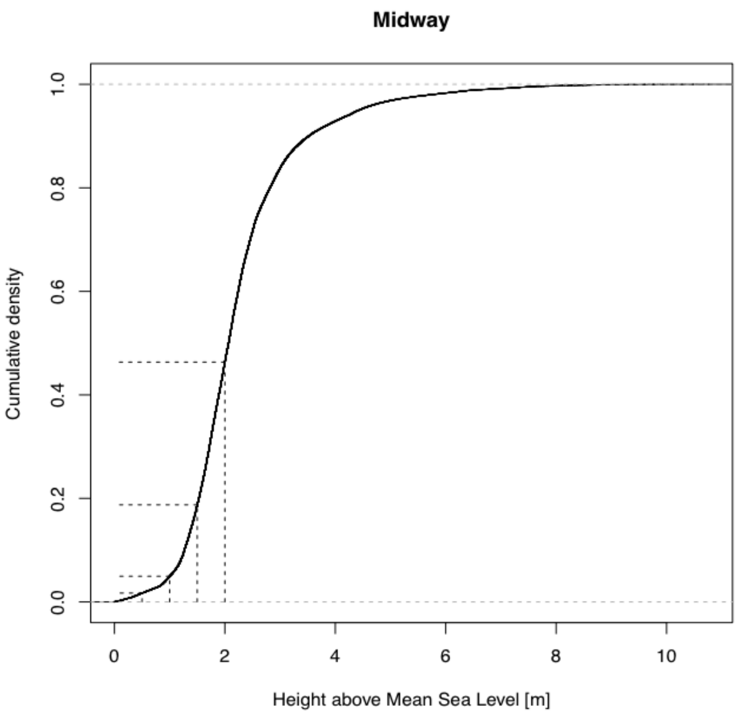


Figure 8 Cumulative density function for 0.5-2 meters of sea-level rise on the islands of Midway Atoll

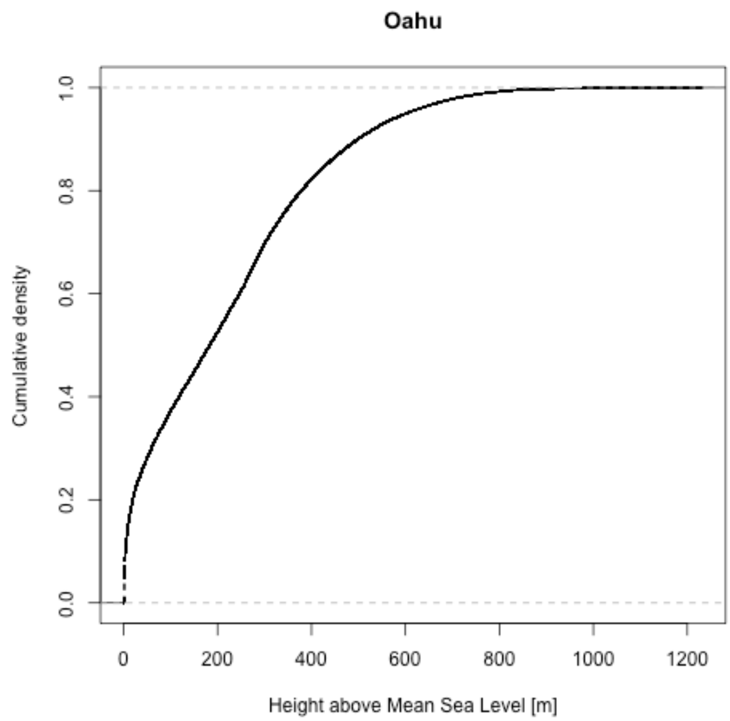


Figure 9 Cumulative density function for 0.5-2 meters of sea-level rise on Oahu. The dashed lines representing the levels of sea-level rise are hidden in the lower left-hand corner of the figure as they represent very small levels of inundation.

Table 1 This table summarizes the fraction of island area covered and total area covered by sea-level rise scenarios for Midway Atoll and Oahu

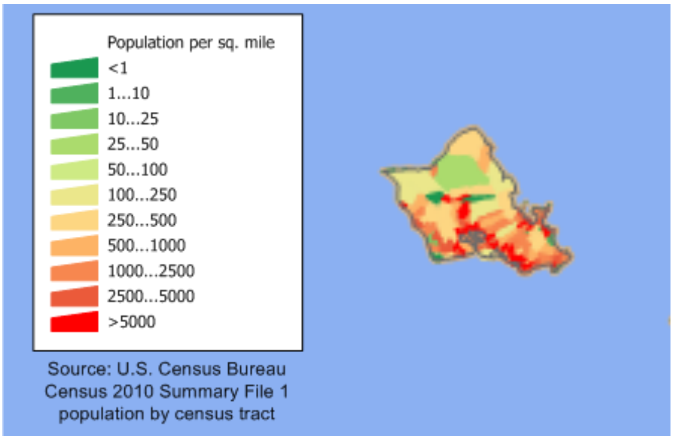
Sea level rise [m]	Area covered [%]	Area covered [km^2]
Midway		
0.5	1.70%	108.90
1	4.95%	316.80
1.5	18.76%	1200.20
2	46.34%	2964.60
Oahu		
0.5	0.34%	5312.40
1	5.31%	83030.70
1.5	5.58%	87302.20
2	6.78%	106013.40

Discussion

In this study, I used digital elevation models (DEMs) of Midway Island and Oahu in the Hawaiian chain to examine how these islands might change in response to different amounts of sea level rise. My results represent possible outcomes depending on amounts of future sea-level rise. It is not certain whether, or at what time in the future, these amounts of sea level rise will be reached.

Midway Atoll is an important U.S. National Marine Monument. Midway was an American marine base during World War II, and holds historical value. Midway also serves as a safe haven for a large host of wildlife including the world's largest colony of albatross.[25] The loss of inundation on Midway would mean the loss of habitat for many native and endangered species. Oahu was inundated to a lesser extent than Midway. However, of particular interest is inundation in Honolulu. Honolulu is Hawaii's capital and largest city. Figure 10 shows the population density of the Hawaiian Islands from the 2010 U.S. Census Bureau. Honolulu is on the southern end of Oahu and Figure 7 shows inundation on the densest part of the island.

Figure 10 Population density map of the Main Hawaiian Islands adapted from the U.S. Census Bureau in 2010.[26] Most of the population on Oahu lives on the Southern end of the island in the city of Honolulu. Compare the population to the sea-level rise projections in the figures above.



Storlazzi et al. (2013) compares passive and dynamic inundation models on Midway Atoll[2]. The inclusion of wave-driven dynamics in projected sea-level rise led to an increase of 0.4-0.5 meters of wave height with 1.0 meters of sea-level rise, and 0.9-1.0 meters of wave height with 2.0 meters of sea-level rise. As sea-level rises, water depth increases leading to larger waves forming on reefs and impacting coastlines. Overall, it was found that models including wave-driven dynamics projected more island area becoming inundated under sea-level rise scenarios. Increasing wave heights as sea-level rises, and its impact on coastal erosion and inundation, will important factors to study for future management of low-lying islands.

Besides long-term sea-level rise and wave dynamics, the addition of flooding due to storm surges also has the potential to increase flooding on these low-lying islands. The maps in Figure 3 and 4 represent changes in mean sea level; thus, the areas shown in blue on these figures would be covered by water about half the time. Flooding due to storm surges is temporary; however, it would still be risky to build a house on an area that typically floods once or more a year. When looking at adaptation strategies for Pacific islands, it may be important to look at events such as a 10-year storm to further protect low-lying areas from flooding.

A 10-year storm is a storm that statistically has a 10% chance of happening in any year. This could mean that there are two 10-year storm events in a year or even no 10-year storm events that year. These storm events e.g. hurricanes, are often the cause of heavy flooding and inundation of low-lying areas. These storm events are based on past data and can change with the extent of the past record and frequency of these events. One way to calculate these storm frequencies is through tide gauge data. Tidal records give a glimpse in to the past. Coastal areas have a typical daily average high and low tide that is predominantly caused by the gravitational pull of the moon on the world's oceans. During a large storm event such as a hurricane, the storm generates a higher than average rise in water levels called a storm surge. Looking at tidal gauge data, the top few percentiles of tidal elevation data is usually a good representation of storm events.

Figure 11 shows the monthly tidal gauge data for a station on Sand Island on Midway Atoll[27]. However, typically daily or hourly tidal gauge data is used because it is more indicative of extreme tidal events vs. and averaged out monthly data set. Looking at this graph, the line of best fit represents the average increase in sea-level rise from 1947-2010 for Sand Island. A simple way to generate a cumulative density function (Figure 12) from this tidal gauge data is to calculate the residuals, or distance from the mean (the line of best fit). These residuals can then be plotted on a cumulative density function with the top percentile representing the highest tidal events often indicative of major storm events.

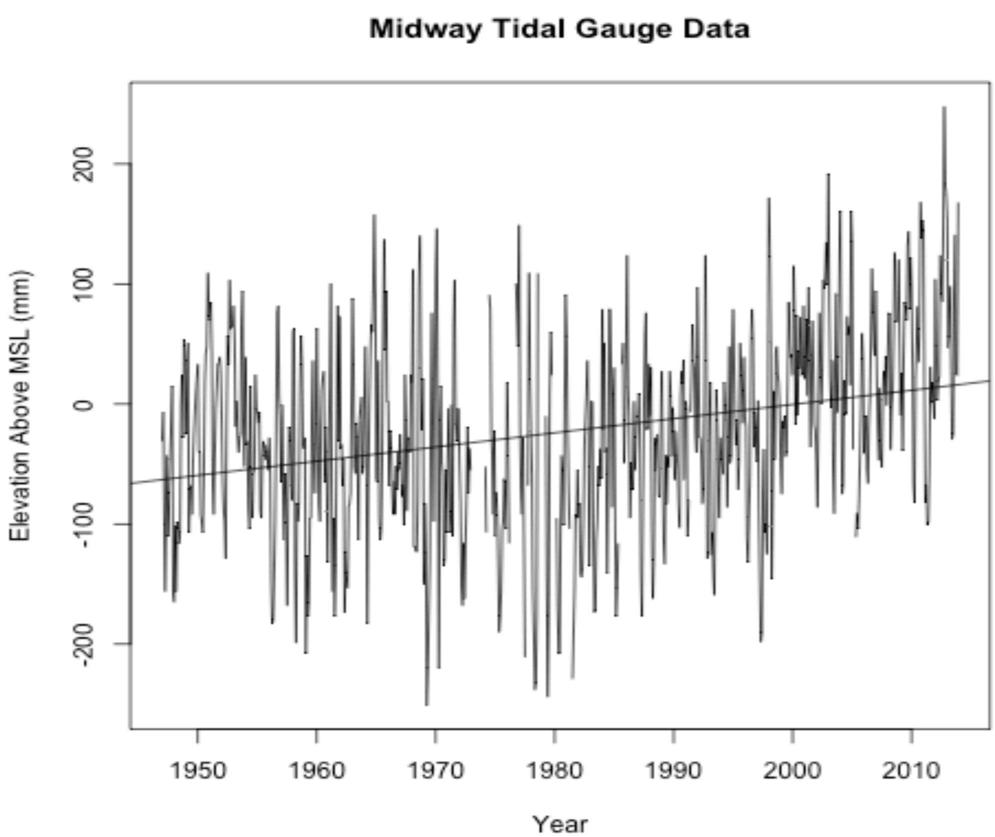


Figure 11 Monthly tidal gauge data from a station on Sand Island, Midway. The line represents the line of best fit, or the average of the data points. As shown by the line of best fit, sea level has risen 1.18 mm y^{-1} from 1947-2013[27].

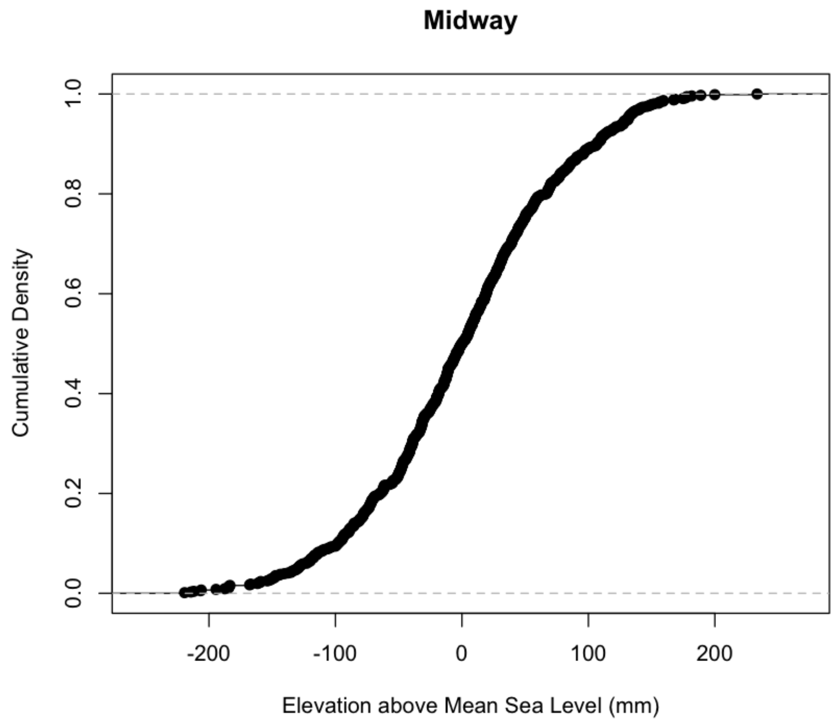


Figure 12 Cumulative density function plotting the residuals from the monthly tidal gauge data.

Management and adaption strategies are going to be important for the future of atoll islands and many other Pacific Islands. It is quite possible that other effects will render the islands uninhabitable before the direct impacts of sea-level rise itself. The issue of fresh drinking water is likely to become a major due to salt-water intrusion, which could be due to major flooding from a storm. Another area of concern is the coral reefs themselves. Corals are very sensitive to slight changes in sea surface temperature[28]. When the water becomes too warm, the coral animal expels its zooxanthellae which provides food for the coral. For short warm spells, it is possible for the coral to recover and reclaim the zooxanthellae back into its tissues. However, with projected risings ocean temperatures, the coral will likely become too stressed, expel its zooxanthellae, and become bleached. This eventually leads to the death of the animal, leaving behind a white skeleton. Once the reef dies, it will no longer grow. This will lead to increasing water depths and potentially larger waves. As previous studies have shown, this has the potential to further increase coastal erosion and inundation[2].

A lot of research is being conducted on corals that are more resistant to coral bleaching and rises in ocean temperatures and there is debate among coral biologists about whether these ecosystems will be able to survive in a changing climate and ultimately how much stress they can take. Besides providing being an important marine ecosystem, coral reefs are important in the formation of atolls. They provide important sediments that waves pile up to form islands inside the shallow lagoon. Without the effects of bleaching and coral disease, reefs could potentially keep pace with rising sea levels.[28] However, stressors such as warming temperatures reduce coral reef resilience and their ability to vertically accrete.[28] Without the ability of corals to keep up with rising sea levels, atolls have the potential to become drowned.

The future of atolls is going to be a complex problem. Sea-level rise itself is likely to be a major problem due to many atoll islands averaging 2-3 meters in elevation. As shown with Midway compared to Oahu, an increase in half a meter of sea level rise made a major change in inundation versus a small change in the larger and higher island. This is going to make it even more important to improve climate models to be able to measure the smallest changes. This would also make the implementation of major storm events in adaptation planning important to consider and study since a small rise would yield much higher flooding on a low-lying coral atoll.

Conclusion

Climate change is happening and its affects are being felt around the world. One of the major impacts of climate change for coral atolls is sea-level rise. Atoll islands are especially vulnerable to changes in sea level due to their low-lying nature, which is restricted by the ability of waves to pile up sediments. As sea-level rises and temperatures increase, it is uncertain whether coral reefs will be able to keep up or if they will be outpaced. Inundation of atoll islands is highly probable and increases with rising sea levels. Inundation and flooding is likely to be further exacerbated by major storm events whose storm surges could further flood the islands. It is important to study the major processes and events that are interconnected and will affect the future of atoll islands.

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Appendix

The script was created on collaboration with Dr. Patrick Applegate, Dr. Greg Garner, and Dr. Klaus Keller.

Appendix 1. This is a script for plotting figures of the progression of sea-level rise scenarios of 0.5-1.5 m for Midway Island. This can be changed to read in other digital elevation models.

```
#Reads in a DEM (probably for an island threatened by sea-level
 rise) and shows progression of inundation #from 0.5-1.5 meters of
 sea-level rise

# Change the working directory.  Your directory should contain the
# unzipped data set.
setwd('C:/Documents/Midway_Atoll_v2_DEM_4373')

# Uncomment the following line to read in the data.
data = read.table('midway_1_3s_v2.asc', skip = 6)

#Change this script so that it automatically converts
# the values in the data file, which are in meters above Mean High
 Water,
# to meters above mean sea level.
#
 http://tidesandcurrents.noaa.gov/datums.html?units=1&epoch=0&id=161
 9910&name=Sand+Island%2C+Midway+Islands&state=
#MHW = 1.152, MSL = 1.020

# Set some values.
is_name = 'Midway'         # name of island
MHW2MSL = 0.132            # convert from mean height water to mean sea
```

```
 level
dem_res = 10         # m; horizontal resolution of the DEM
sl_rise = seq(0.5, 2, by = 0.5)

#convert MHW to MSL
data = data - MHW2MSL

# Define the latitude and longitude grid for the DEM.
# See xml file accompanied with the data.
lat <- seq(28.09, 28.42, l=3565)
lon <- seq(-177.57, -177.16, l=4429)

# Rotate the matrix so that it has the correct orientation.  Uses
 code
# from http://stackoverflow.com/questions/16496210/rotate-a-matrix-
 in-r
rot_data = as.matrix(t(data[nrow(data): 1, ]))

# Find the extent, in the x and y directions, of the land above sea
 level.
which_land = which(rot_data > 0, arr.ind = TRUE)
min_x = min(which_land[, 2])
max_x = max(which_land[, 2])
min_y = min(which_land[, 1])
max_y = max(which_land[, 1])

# Subset the data set so that it defines the smallest rectangle that
 includes
# all points above sea level.
sub_data = rot_data[seq(min_y, max_y, by = 1), seq(min_x, max_x, by
 = 1)]

# Subset the latitudes and longitudes to match the subset of data
# above.  Note that the data have been rotated, so the latitudes
# should span the x-range and longitudes span the y-range
sub_lat <- lat[min_x:max_x]
sub_lon <- lon[min_y:max_y]

# How many grid cells are there in the x and y directions?
n_x = length(sub_data[, 1])
n_y = length(sub_data[1, ])

# Create x and y vectors for plotting.
grid_x = seq(0.5* dem_res, by = dem_res, length.out = n_x)
grid_y = seq(0.5* dem_res, by = dem_res, length.out = n_y)
```

```
# Create the ocean color ramp palette
my.blues <- colorRampPalette(colors = c("darkblue", "lightblue"))

# Create the vector of colors for...
# ...plotting
plot.cols <- c(my.blues(100), terrain.colors(100))

# ...colorbar
bar.cols <- c(my.blues(100), terrain.colors(400))

# Define the custom breaks for plotting the ocean
# and the terrain
# Ocean = [-30, 0], Land = (0, 12]
plot.breaks <- c(seq(-30,0,l=100), seq(0,12,l=102)[-1])

# Plot the results.
# Load 'fields' library
library(fields)


# Rasterized version of plot
png("midway_slr_plot.png", w=4250, h=3500, res=500)


#No SLR
par(fig=c(0,0.5,0.575,1), mar=c(4,4,2,1)+0.1)
temp.data <- sub_data
temp.data[temp.data < -30] <- -30
image(x=sub_lon, y=sub_lat, z=temp.data, col=plot.cols,
 breaks=plot.breaks,
      main = "No SLR", xlab="Longitude [deg E]", ylab="Latitude [deg
 N]")

#0.5 M SLR

par(fig=c(0.5,1,0.575,1), mar=c(4,4,2,1)+0.1, new=T)
temp.data <- sub_data - 0.5
temp.data[temp.data < -30] <- -30
image(x=sub_lon, y=sub_lat, z=temp.data, col=plot.cols,
 breaks=plot.breaks,
      main = "0.5 Meter SLR", xlab="Longitude [deg E]",
 ylab="Latitude [deg N]")

#1 M SLR

par(fig=c(0,0.5,0.15,0.575), mar=c(4,4,2,1)+0.1, new=T)
```

```
temp.data <- sub_data - 1.0
temp.data[temp.data < -30] <- -30
image(x=sub_lon, y=sub_lat, z=temp.data, col=plot.cols,
 breaks=plot.breaks,
      main = "1.0 Meter SLR", xlab="Longitude [deg E]",
 ylab="Latitude [deg N]")

#1.5 M SLR
par(fig=c(0.5,1,0.15,0.575), mar=c(4,4,2,1)+0.1, new=T)
temp.data <- sub_data - 1.5
temp.data[temp.data < -30] <- -30
image(x=sub_lon, y=sub_lat, z=temp.data, col=plot.cols,
 breaks=plot.breaks, main = "1.5 Meter SLR", xlab="Longitude [deg
 E]", ylab="Latitude [deg N]")


# Put the legend at the bottom of the multi-panel figure
par(fig=c(0,1,0,1), new=T)
image.plot(zlim=c(0,5), legend.only=T,
           col=bar.cols, legend.shrink = 0.75,
           legend.width = 0.8, horizontal = TRUE,
           axis.args=list(at=seq(0,5,l=6), labels=c("< -30 m", "0
 m", "3 m", "6
m", "9 m", "12 m")))

dev.off()
```

Appendix 2. This is a script for sea-level rise scenarios of 0.5-2, plotting a cumulative density function of Midway, and making a table of the results. This can be changed to read in other digital elevation models.

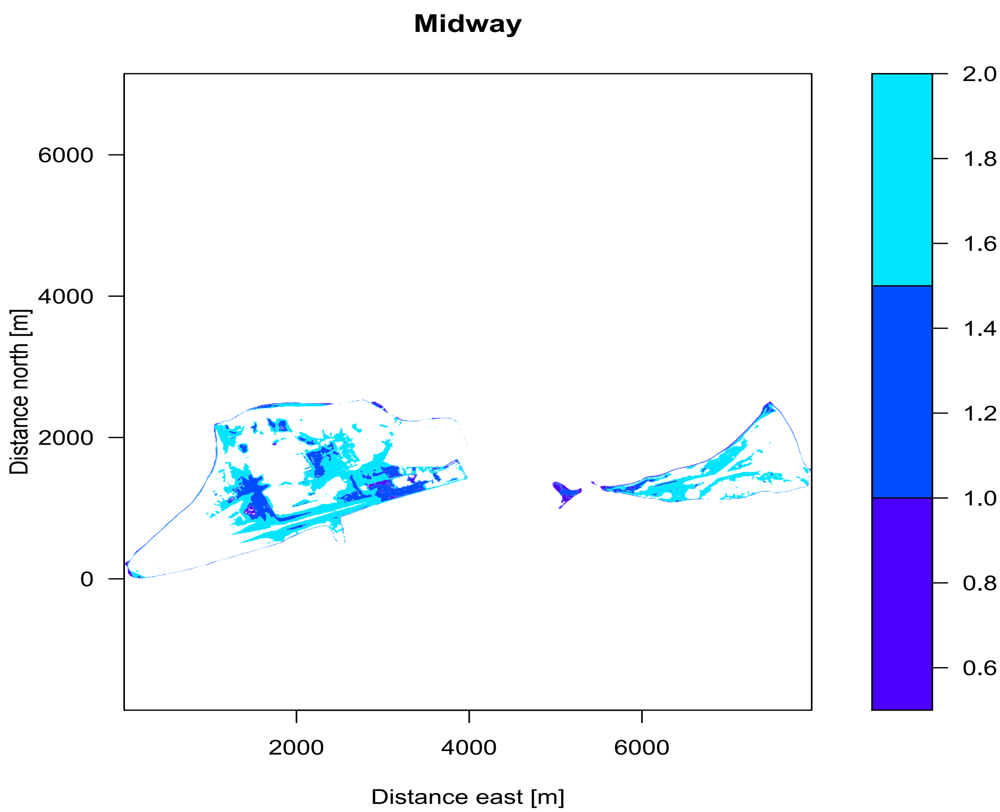
```
# Reads in a DEM (probably for an island threatened by sea level
 rise),
# calculates the area that will be covered by different amounts of
# sea level rise, makes a table of the results, and plots the CDF.

#Change this script so that it automatically converts
# the values in the data file, which are in meters above Mean High
 Water,
# to meters above mean sea level.
#
 http://tidesandcurrents.noaa.gov/datums.html?units=1&epoch=0&id=161
```

```
 9910&name=Sand+Island%2C+Midway+Islands&state=
#MHW = 1.152, MSL = 1.020

# Mise en place.
# Clear variables and figures.
rm(list = ls())
graphics.off()

# Change the working directory.  Your directory should contain the
# unzipped data set.
setwd('C:/Documents/Midway_Atoll_v2_DEM_4373')

# Set some values.
is_name = 'Midway'       # name of island
MHW2MSL = 0.132
dem_res = 10          # m; horizontal resolution of the DEM
sl_rise = seq(0.5, 2, by = 0.5)
                      # m of sea level rise

# Read in the data.  You may need to change the file name to get
 this script
# to work.
# data = read.table('Midway_Atoll_DEM_1107/midway_atoll_1_3s.asc',
 skip = 6) # v1 -- wrong
data = read.table('midway_1_3s_v2.asc', skip = 6) # v2

#convert MHW to MSL
data = data - MHW2MSL

# Rotate the matrix so that it has the correct orientation.  Uses
 code
# from http://stackoverflow.com/questions/16496210/rotate-a-matrix-
 in-r
rot90_data = as.matrix(t(data[nrow(data): 1, ]))

# Find the extent, in the x and y directions, of the land above sea
 level.
which_land = which(rot90_data > 0, arr.ind = TRUE)
min_x = min(which_land[, 2])
max_x = max(which_land[, 2])
min_y = min(which_land[, 1])
max_y = max(which_land[, 1])

# Subset the data set so that it defines the smallest rectangle that
 includes
# all points above sea level.  Also set all water-covered points to
```

```
 NAs.
sub_data = rot90_data[seq(min_y, max_y, by = 1), seq(min_x, max_x,
 by = 1)]
sub_data[sub_data < 0] = NA

# How many grid cells are there in the x and y directions?
n_x = length(sub_data[, 1])
n_y = length(sub_data[1, ])

# Create x and y vectors for plotting.
grid_x = seq(0.5* dem_res, by = dem_res, length.out = n_x)
grid_y = seq(0.5* dem_res, by = dem_res, length.out = n_y)

# Identify the fraction of the total island area covered by water
 for the
# different values in sl_rise.
elev_ecdf = ecdf(sub_data)
frac_cover = elev_ecdf(sl_rise)

# Estimate the total island area (remember to compare this estimate
 to
# Wikipedia or some other source as a check).
tot_area = dem_res^2* sum(sub_data > 0, na.rm = TRUE)

# Calculate the area covered by various amounts of sea level rise.
area_cover = tot_area* frac_cover

# Print off a table relating sea level rise to the fraction of the
# island covered and the area covered.
out_table = matrix(cbind(sl_rise, frac_cover, area_cover), byrow =
 FALSE, nrow = length(sl_rise), ncol = 3, dimnames = list(NULL,
 c('Sea level rise [m]', 'Fraction of area covered', 'Area covered
 [m^2]')))
print(out_table)

# Save the table to a file.
table_file = sprintf('%s_table.txt', is_name)
write.csv(out_table, table_file, row.names = FALSE)


# Plot the results.
fig_file = sprintf('%s_figures.pdf', is_name)
pdf(fig_file)

# par(pty = 's')
plot.ecdf(sub_data, xlab = 'Height above Mean Sea Level [m]', ylab =
```

```
 'Cumulative density', main = is_name, xlim = range(sub_data, na.rm
 = TRUE))
segments(x0 = sl_rise, x1 = sl_rise, y0 = rep(0, length(sl_rise)),
 y1 = frac_cover, lty = 2)
segments(x0 = sl_rise, x1 = rep(0, length(sl_rise)), y0 =
 frac_cover, y1 = frac_cover, lty = 2)
dev.off()
```

Appendix 3. Inundation of Midway with 0.5 -2 m of projected sea-level rise. The different shades of purple to aqua represent the areas that would be covered for differing amounts of sea level rise.



Appendix 4. Inundation of Oahu with 0.5 to 2 meters of projected sea-level rise. The different shades of purple to aqua represent areas that would be covered for differing amounts of sea level rise.