Using ship sounding data to reconstruct local sea level changes near Middleton Island, Alaska

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Abstract

The Gulf of Alaska is a data sparse region, leaving sea level reconstructions skewed or nonexistent. These coastlines are particularly vulnerable to large sea level changes and are home to long-term sea level data from historical ship soundings. Using ship sounding data from 1933, 1969 and 1983, reconstructions of local sea level changes near Middleton Island, Alaska were created, which is a technique not attempted prior to this work. By tracking local sea level change over time, we are able to make an impact assessment of sea level change forcings; including the 1964 Magnitude 9.2 Alaska Earthquake. This earthquake resulted in Middleton Island's uplift of 3.05 m, and we aim to differentiate sea level changes caused by this uplift and other processes (Brocher et al., 2014). Using these records in comparison with local and global reconstructions, the processes that contribute to local sea level changes, we attempt to quantify their impacts. In digitizing physical depth soundings from each year and adjusting these reconstructions to a common reference, we have produced sea level change maps between the years 1933-1969 and 1969-1983. Accounting for GMSL changes (Hay et al. 2015), a reconstruction of local sea level changes in the area surrounding Middleton Island was created. Investigating the causes of sea level changes around Middleton Island is crucial, as changes can be attributed to several factors, including the 1964 Earthquake, glacier melt, and glacial isostatic adjustment. We find that there is clear sea level rise south of the island between 1933-1969 by about 10 m, which could be attributed to the Earthquake and/or local tectonic uplift. Middleton Island could be used as a proxy for the impacts that different forcings have on sea level in the Gulf of Alaska if there is more research done surrounding the Island. Our research demonstrates that creating sea level reconstructions from historical shipping records and depth data is workable and important, as it can assist in attaining local sea level trends in the Gulf of Alaska and could be a very useful tool in building sea level data records prior to the technological advancements of the past half century.

I. Project Summary

Our research intends to contribute analysis of the changing climate and local sea levels in the coastal region of the Gulf of Alaska. With a focus on Middleton Island, Alaska; a small island comprised of several uplifted marine terraces, we seek to understand the capacity of past sea level reconstructions to provide a localized representation of sea level changes. We will also consider current local and global sea level forcings and will assess if there is any post seismic deformation around Middleton Island. To do this, we employed historical shipping maps that focus on the area directly surrounding Middleton Island, in order to provide data to reconstruct spatial maps of sea level before and after the 1964 Alaska Earthquake through interpolation over a specified latitudinal and longitudinal areas. The primary goal is to construct spatial maps that track local sea level change in this area during the 20th century. The secondary goal is to differentiate the uplift effects and local sea level changes resulting from the magnitude 9.2 1964 Alaskan Earthquake from uplift and sea level change due to other processes. In our analysis, we identify and try to accurately quantify the sea level changes that can be attributed to specific climatic and non-climatic factors, including uplift, immediate earthquake shock, tectonic deformation, and others.

It is important for our purposes to reemphasize that sea level is not uniform, and therefore global and local sea level projections vary by region depending on geographic location and specific climate mechanisms (Hay et al, 2015). A close study of sea level change around Middleton Island can allow for a better portrayal of how we can expect sea level to change in the exact area as well as nearby coastal locations of Southern Alaska near the Aleutian Trench. We look to prove that the physical shipping maps digitized by the National Oceanic and Atmospheric Administration (NOAA) are accurate representations of sea level. If we are successful in reconstruction, we can employ the spatial maps to compare the sea level change reconstructions for Middleton Island to those of Southern Alaska and the world, doing so in order to differentiate the effects of post-seismic deformation and other climatic and non-climatic factors on local sea level around Middleton Island. If significant, we can begin to explore what factors that impact sea level are specific to our region of study which will be beneficial for research into future trends in the area.

II. Research Framework and Problem

Research Context and Considerations for Southern Alaska

Understanding local sea level changes around different coastal areas across the world is essential, as knowledge of current and future trends can assist in protecting the welfare of communities and industries along coastlines. In Southern Alaska, an understanding of the various factors that affect sea level near the coast is crucial, as it can aid in providing guidelines for preparation against damages and changes caused by local sea level change and tectonic movements (Li et al., 2018).

Currently, Alaska finds itself in a peculiar situation with regard to climate change and local sea level change. As climate change continues to warm the planet, this results in the melting of glaciers, causing rates of uplift in Alaska that are actually higher than local sea level rise (Freymueller, 2010). When a glacier is in the process of being removed/ has been removed from the earth's crust, the crust rebounds upwards in the absence of glacial weight in a process called Glacial Isostatic Adjustment, or GIA. (NOAA, *GIA*, 2018). The rapid thinning of ice and glaciers in the mountains of Southern Alaska and Canada has led to increased rates of GIA, which in part affect coastal uplift rates (Larsen et al., 2004). Tectonics also contribute to local variations in sea level, as different locations in Southern Alaska experience differing levels of subsidence or uplift due to Alaska complex tectonic environment (Freymueller, 2010; Larsen et al., 2015). Subsidence and uplift also occur around the Gulf of Alaska at the continental and oceanic plate boundary, with uplift occurring in the continental region as a result of plate convergence, and the oceanic portion of the crust subsiding into the earth (USGS, 2017). West of Prince William Sound near Kodiak Island, observable in Figure 1, subsidence occurs as the result of the Pacific Plate subsiding under the North American plate (Cohen & Freymueller, 2003). Prince William Sound and Middleton Island are uplifting in part due to regional tectonics and will be discussed even further in the section on the tectonics and uplift in Southern Alaska (Cohen & Freymueller, 2003; Plafker & Rubin, 1997). These differing movements in Southern Alaska create in Prince William Sound gradual tectonic subsidence. This combined with global sea level rise produces a quickly rising local sea level. In Southeast Alaska however, GIA results in uplift that exceeds relative sea level rise (Freymueller, 2010). These factors, coupled with other oceanic, climatic and seismic effects, like climate change and the geophysical changes resulting from the 1964 Great Alaska Earthquake, all interact to affect local sea level in the proximity of Middleton Island and in Prince William Sound.

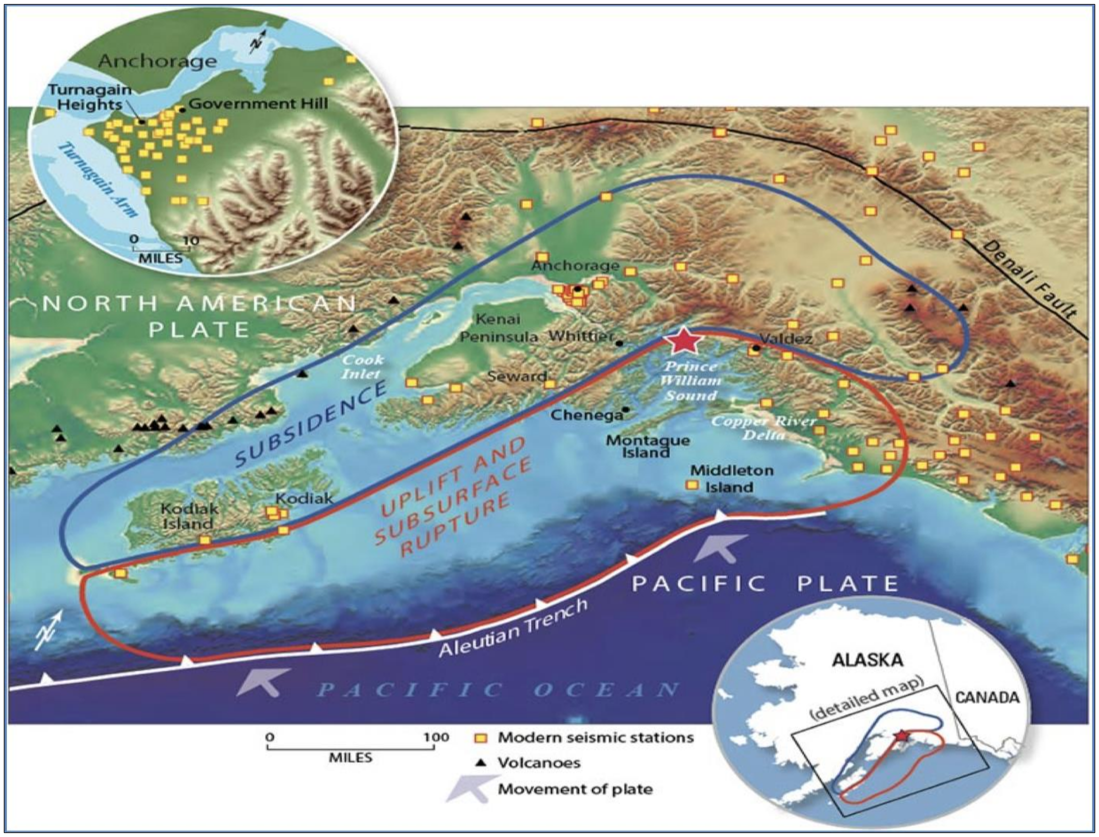


Figure 1: Areas of subsidence and uplift in Southern Alaska. Prince William Sound experiences tectonic subsidence. Combined with rising sea level, this produces higher than average local sea level rise. Middleton Island experiences one of the world's highest uplift rates (Cohen & Freymueller., 2003; Freymueller, 2010).

Terrestrial Warming, Glacier Melt, and Global Isostatic Adjustment

Over the 20th and 21st centuries, mainland Alaska has experienced rapid icefield and glacier melt in the Southern Alaskan mountains. Driving this melt was a significant increase in terrestrial temperatures, which over the last six decades have on average risen 1.67 degrees Celsius with some areas reaching nearly 3.5 degrees of warming; both of which are significantly more than average atmospheric and global temperatures (ACRC & GIUAF, 2017). The American Geophysical Union stated in 2015 that “Alaska’s melting glaciers are adding enough water to the Earth’s oceans to cover the state of Alaska with a 1-foot thick layer of water every seven years” (Larsen et al., 2015). This extreme melting is also recognized by GPS surveys, where in 2004 the American Geophysical Union stated that the majority of Southern Alaska was uplifting at a rate faster than 10 mm/ yr^{-1}, with several other sites uplifting at 25 mm/yr^{-1} (Larsen et al., 2004).

This loss in continental ice mass results in a large mass transfer away from the continent through GIA, as the continent's gravitational pull decreases. GIA is characterized by the rebound of the continental crust to cause uplift, but it also leads to the movement of ocean water away from coastal areas as coastal ice melts, as the water is no longer gravitationally attracted to the massive ice sheets (Kopp et al. 2015). Uplift, combined with shrinking gravitational pull towards ice sheets, results in falling local sea levels in Southern Alaska even as global average sea level rises. Although Alaska has warmed to a higher extent, we assume that these uplift rates have stayed constant or have increased in the past 14 years, as uplift will not accelerate rapidly (Taylor et al., 2017).

Tectonics of Southern Alaska and Middleton Island, Uplift History of Middleton Island, and Implications for Sea Level

Middleton Island is a small (8 km by 2 km) island located on the southern edge of the continental shelf, off the coast of south-central Alaska located near the northern Gulf of Alaska (Prescott & Lisowski, 1977). Middleton Island was uplifted over 3 m during the 1964 Earthquake, and further studies and dating of the island show that the terraces the island consists of were all formed during Earthquakes with similar characteristics as that of the 1964 Earthquake (Brocher et al., 2014). These events had approximate uplifting heights of 7 m, 8 m, 6 m, 9 m, 7.5 m, and 3.5 m (1964) respectively, and occurred at roughly 4,300, 3,800, 3,100, 2,390, and 1,350 years ago, with 1964 the most recent (Plafker & Rubin, 1997). In addition to discussing the formation of Middleton Island, Plafker and Rubin's 1997 study mentions that although nearly 4 meters of uplift occurred during the 1964 Alaska Earthquake, half of the accumulated strain of the plate may not have yet been released. This is assuming that the constant 1.05 cm/yr uplift has been constant for the past 4,000 years (Plafker & Rubin, 1997). Conversely, there is also the less likely circumstance that this rate has not slowed over the past 4,000 years, then most of the accumulated strain in the Gulf of Alaska has been released, and another massive earthquake may not be overdue/ impending for another few thousand years (Plafker & Rubin, 1997).

Although currently uninhabited, studying the factors that cause Middleton Island's local sea level to change is important, as the island can be used as a proxy for the effects that increased rates of uplift and thermal expansion may have on other coastal regions. Sea level rise is affected by both ice melt adding water to the ocean and the thermal expansion of the water as heat is absorbed by the ocean (NOAA, *Sea Level Rise*, 2018). Affected by glacier melt, GIA, and thermal expansions, Alaska will need predictions on how all of these factors interact, as they will dictate how local communities will react and prepare in the short and long term.

The Great 1964 Alaska earthquake had massive economic and environmental effects on the coastal communities of Southern Alaska. It caused significant uplift on Middleton Island and in specific areas around the Southern Coast of Alaska, which in addition to GIA and gradual subsidence in Prince William Sound, has remained a factor in dictating local sea level for several decades, lessening the extent to which thermal expansion has encroached on populated coastal areas (Brocher et al., 2014). Additionally, Middleton Island has one of the highest rates of average uplift in the world at slightly more than 1.05 cm/yr (Plafker & Rubin, 1997). This uplift generally results in lowered relative sea level in these areas, with exceptions in Prince William Sound, as tectonic subsidence in the area and the rising local sea levels in the Sound result in high rates of local rise (Freymueller, 2010; Brocher et al., 2014; Figure 1).

The tectonically-induced changes Middleton Island experiences are essential to understand, as they relate to the 1964 Earthquake, and can be used to predict how relative sea level changes due to uplift, and how it and coastal areas might be altered with another Earthquake occurring in the region. Southern Alaska possesses thinning glaciers near a tectonically active boundary, factors that may combine to increase tectonic strain rates and the rate at which earthquakes occur. While GIA, uplift and subsidence are caused by tectonic movements, massive land ice loss in Southern Alaska may be aggravating and accelerating GIA. Sauber et al. (2004) states "we found an increase in the number of earthquakes ($M_L \geq 2.5$) and seismic rate associated with ice thinning and a decrease in the number of earthquakes and seismic rate associated with ice thickening". Additionally, rapid ice wastage may be linked to smaller seismic events but may also be related to seasonal change and not indicative of causing major tectonic movement. This relationship, in addition to GIA, uplift and subsidence, can also contribute to how infrastructure may be changed to resist and rebound against the effects of tectonic events, climate change, varying local sea level changes, and earthquakes as ice leaves terrestrial Alaska.

III. Data

The Gulf of Alaska is a fairly data-sparse region, mainly due to lack of resources, which has left sea level reconstructions skewed or nonexistent in an area that is especially vulnerable to local sea level change (Gullufsen, 2018). Due to both the 1964 earthquake and the direct impacts of GIA and thermal expansion, it is increasingly important that a more nuanced view of how local sea level is changing around Alaska. In looking into what the possible sources of sea level data were, we can consider information gathered prior to satellite imaging, far enough in the past even to reconstruct what the area looked like pre-earthquake. The Gulf of Alaska has historically been a place where shipping routes have passed and is an area of heavy arctic tourism (Arctic Council, 2009). These shipping routes continued into the 1900s, leaving in their wake a collection of maps that depict sea level data through ship soundings. In nautical terms, ship soundings (or depth soundings) are simply the way of determining how much water is beneath a ship's keel and the bottom of the ocean. Until the development of widespread sonar technology in the mid-1900s this was done with fathometers. Before acoustic technology came around in the early 1900s, this was done manually with weights, wires and rope, and as different technologies developed, they were often used side by side to eliminate error. Clearly increasing in their effectiveness and accuracy over time, they became more reliable ways to create charts and maps for use by other mariners to increase efficiency of routes and for increased knowledge of areas they operated in for commerce or even for recreational uses.

For the purposes of our research, we have found three shipping maps from three distinct time periods and we hope that our analysis will contribute meaningful information regarding sea level in a data scarce region. We hope to also illustrate a new way of reconstructing sea level through depth soundings that has not been done before. With charts from 1933, 1969, and 1983 we hope to make spatial map reconstructions of what the sea level patterns were prior to the earthquake, immediately after, and are now (Sobieralski et al., 1933; Watkins, 1969; NOAA Nautical Charts, 1983). If successful, we will shed light on the vulnerabilities of the Gulf regarding sea level rise and what they can expect by taking a closer look at more region-specific data.

IV. Methods

In order to perform analysis on historical and present sea level data surrounding Middleton Island, we are working with the sounding depths from old shipping maps (Figure 2), recorded in fathoms. A fathom is a unit of length measurement that has historically been used to measure ocean depth and is equivalent to 1.82 meters (m) in SI units (Encyclopedia Britannica). For our purposes, we have digitized the historical data from 1933 and 1969 and 1983 from fathoms to meters for uniform data comparison and cohesiveness with present sea level data. The 1933 historical data spans the longitudinal area [146.7°W, 146°W] and latitudinal area [59.3°N - 59.7°N]. This range will be used to create the spatial maps from 1969 and 1983 as well.

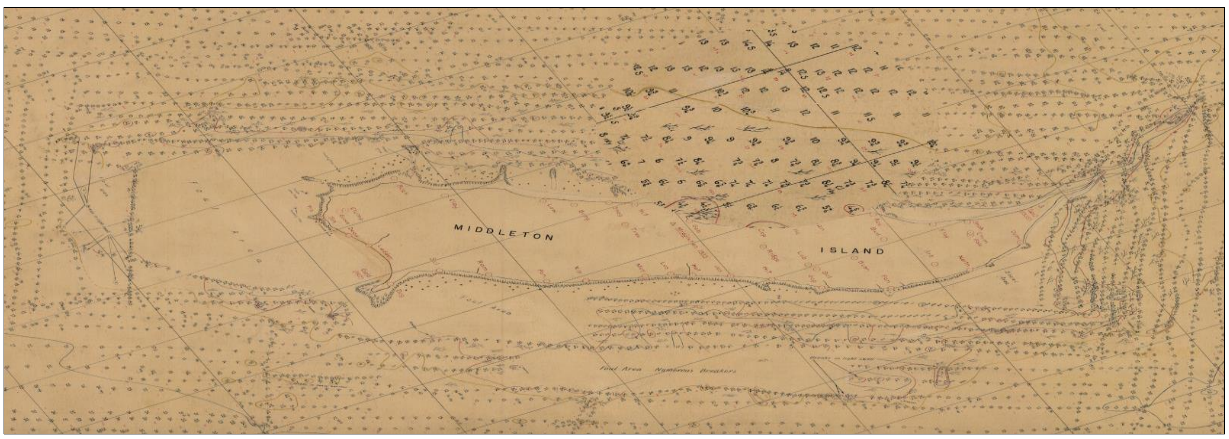


Figure 2: Original 1933 ship sounding map, a select range, and zoom lens to show detail. The ship soundings numbers shown here are in fathoms which have been converted to meters for spatial maps (Sobieralski et al., 1933).

The 1933 data map is the limiting dataset in the scope of our research because it covers the smallest geographical area. Each of the three years gives a general idea of sea level before the earthquake, sea level directly after, and sea level in the 1980s. The most recent sounding depths are from 1983, providing a good window to analyze possible post-seismic deformation from the Earthquake in 1964. The only access to this data is in the physical map form, so in order to perform the comparison and calculations of our analysis we digitized this present depth data into the same format of data points corresponding to our specific range of latitude and longitudes so we can create a model in the same way we do for the historical data.

For the 1933 and 1969 maps we had to convert the depths from fathoms to meters and used natural interpolation to reconstruct sea level over a spatially uniform grid. In order to digitize the 1983 map, we used a code within Mat Lab called Map Click (Pers. Comm. Dr.

Evans, 2018). In this program, we were able to click on each depth on a PDF of the map and record the respective depth, we did this across the map recording each depth directly around Middleton Island and the surrounding area. In order to apply these depths to the geographical area we used control points, where we gathered known latitude and longitude monuments, clicked their respective locations on the map and inputted the respective coordinates. The control points are shown in Table 1. This made it possible to perform the same interpolation scheme as the 1933 and 1969 maps and reconstruct the sea level depth for 1983.

Table 1. Control Points used in Map Click for 1983 map.

Landmark Name	**Latitude**	**Longitude**
Day Harbor	59.9°N	149.1°W
Northern Tip of Montague	60.3°N	147.1°W
Port Nelle Juan	60.5°N	148.1°W
Southeast Hawkins Island	60.4°N	146.3°W
Pinnacle Rock	59.7°N	144.3°W
Northern Tip Kanak Island	60.1°N	144.4°W
Northwestern Point Middleton Island	59.4°N	146.3°W
Wessels Reef	59.7°N	146.1°W

To create spatial maps, we interpolated the sea level depth data over an array of evenly spaced latitude and longitudes within our given area range. To move forward with a confident reconstruction of sea level, we experimented with different types of interpolation, then compared the interpolated values to those found on the physical maps. The 1933 and 1969 maps were closest to actual depths using linear and natural interpolation. It is important to note that as linear interpolation is a more basic method to interpolate data over a grid, so it may present some limitations, therefore we decided to use the natural interpolation scheme for all three maps. Additionally, a focus on the small area of Middleton Island and its surrounding waters may lead to interpolation error as well due to small number of recordings in a small area. In an effort to minimize error in interpolation, we tested multiple interpolations schemes for the 1983 map; cubic, nearest neighbor and natural interpolation methods. However, because there is ample space between recordings on the original map, the smaller scope of our study area caused some error in the 1983 reconstruction, however the outlying depths remained constant over most interpolation methods.

The 1933 data is in reference to the Latouche tide gauge, with the mean lower low water (MLLW) reading at 1.19 m, taken between July and August 1933 (Sobieralski et al., 1933). The 1969 data is also referenced to the Latouche Tide Gauge during the same months in 1969. The 1983 map of the Gulf of Alaska uses the North American Datum of 1983, which is compiled of multiple datum's in the region, including Latouche. The Latouche tide gauge is used across all time periods for mapping, and has the most historic data in the region. Therefore, using the progression of MLLW, Mean Sea Level (MSL) and Mean Higher High Water (MHHW) and Latouche tidal ranges through time, we created a uniform reference datum from which sea level changes can be tracked on the same scale. 1933,1969, and 1983 have data for MLLW, MSL and MHHW between July and August with time referenced to the 135W Meridian. To create a baseline for MLLW values, we looked at the changes of MLLW at Latouche tide gauge between each set of years, 1933-1969 and 1969-1983.

The Latouche tide gauge has data from the three specific years, with MLLW reading 1.19 m, 0.702 m and 0.762 m for 1933, 1969 and 1983 respectively. We decided to keep the 1933 reference as the constant, and adjust the 1969 and 1983 reconstructions accordingly. The adjustment for the 1969 reconstruction is done by subtracting the difference of 0.488 m from the depth grid to account for MLLW difference between 1933-1969. Similarly, the 1983 depth data values are adjusted by subtracting 0.428 m from each value to account for the change in MLLW from 1933-1983 and achieve the reconstructions from 1969 and 1983 on the same datum as 1933.

Establishing this common reference plane based around Latouche allowed us to compile the sea level difference between the three years, which allows for comparison of the remaining differences, and to attribute them to other changes such as GIA, uplift, average global sea level rise, local sea level rise/fall. With reconstructions of the three different time periods referenced to the same datum, we can perform an analysis of how sea level has changed in the area. The calculation is more straightforward, given that we ensured uniformity over the entire area and size of interpolated grid area, as well as amongst the data in terms of reference to 1933 MLLW baseline. The calculation will be an average of the depth changes over the entire area of study for each year.

In order to adjust for spatially uniform changes due to GMSL we adjusted for the difference between global sea level depths in each year (Hay et al., 2015; Dangendorf et al., 2018). Between 1933-1969 and 1969-1983 we subtracted 0.047 m and 0.017 m respectively, from the changes in depth. The remaining changes can be discussed in context to various forcing that are happening locally in the area. Using Plafker and Rubin (1997), and other research in the area (see discussion) we can discuss how uplift of the North American plate could be contributing to the remaining sea level changes that we find in our area of study. Through our analysis, we look to understand if Middleton Island could be used as a proxy for understanding climatic and non-climatic forcing's in the Gulf of Alaska.

V. Results

The ship sounding maps from 1933 and 1969, as well as the digitized map from 1983 were interpolated onto spatially uniform girds as spatial reconstructions with reference to their respective tide datum's (Figure 3-5). Representing sea level surrounding Middleton Island, these initial results qualitatively show that from 1933 to 1969, the southwestern tip of Middleton Island appears to deepen and the western bank of Middleton decreases in depth, possibly indicating uplift from the 1964 Earthquake. In addition, between 1969 and 1983 the encroachment of depths >300 m toward the southeastern edge may be due to interpolation error, as depth readings in the area for 1983 (referenced to the 1983 Tidal Datum) are spaced out in the small area around Middleton Island, leading to the clear jagged yellow spacing (Figure 5). The depth of the water column directly surrounding the island looks to have decreased between 1933 and 1983. While these are helpful initial results to get an idea of the changes happening around Middleton island, it is important to recall that each reconstruction is with reference to different tide gauges, meaning we are not yet seeing changes across a uniform plane of reference.

Figure 6 includes the spatial reconstruction of each year with 1969 and 1983 to reference the Latouche tide gauge from 1933. These reconstructions allow for the quantitative analysis that is carried out in Fig. 9-13. There is not much difference visually from the reconstructions seen in Figure 3-5 to the reconstructions seen in Figure 6, and the observations of changes throughout the water column from each year are relatively the same as our initial qualitative results (Fig. 3-5), only now we are able to move forward and examine the differences in the 36-year time frame between 1933-1969 and the 14-year period between 1969-1983 (Fig 9-13).

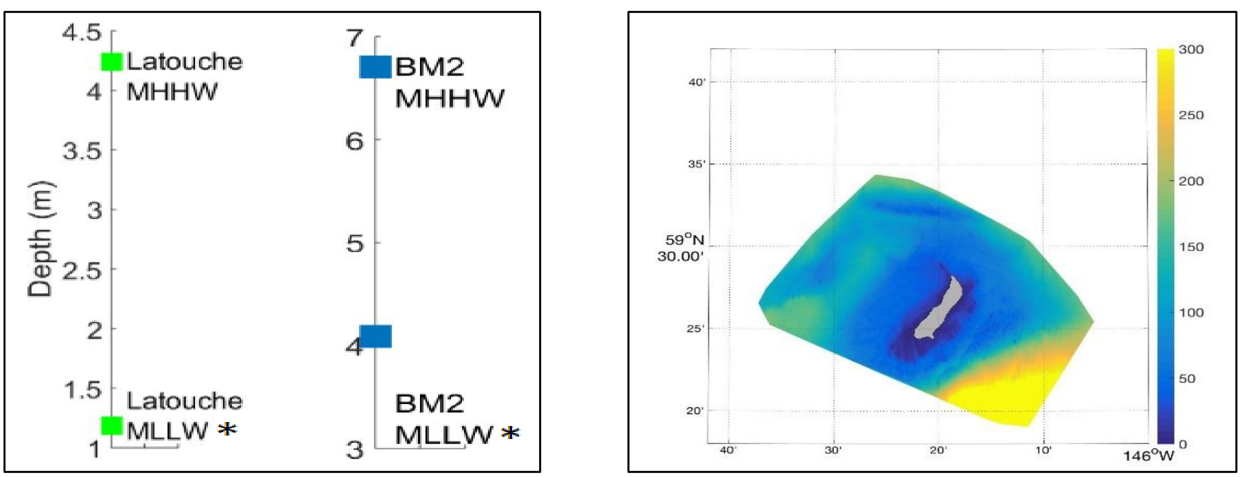


Figure 3: Interpolated sea level field in 1933, m. Referenced to Latouche and Benchmark 2 MLLW in 1933, as indicated by *. Grey Land Mass is Middleton Island.

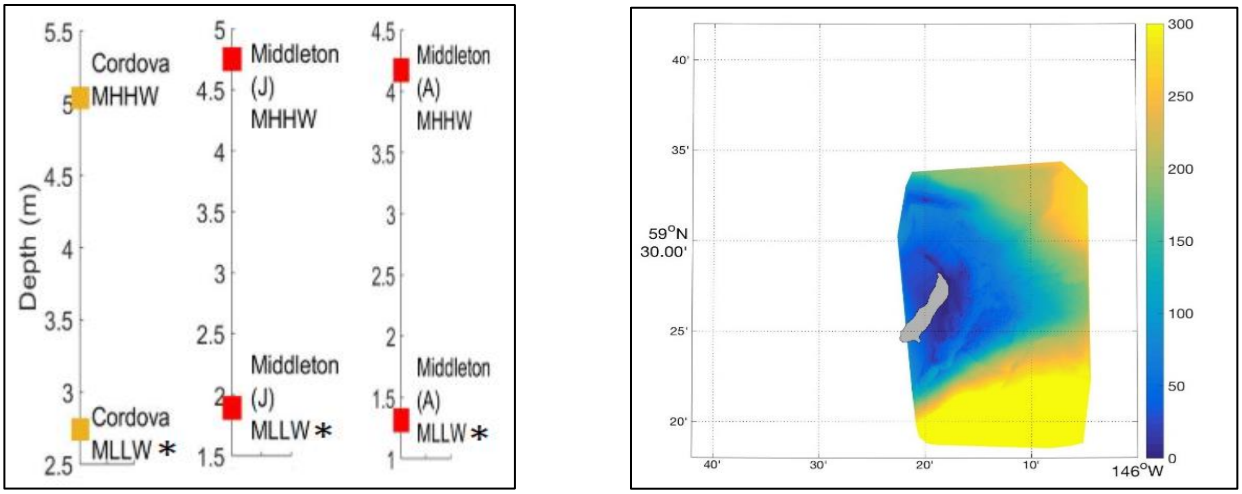


Figure 4: Interpolated sea level field in 1969, m. Referenced to MLLW at Cordova, and Middleton Island (Middleton July and August are Middleton (J) and (A) respectively, indicated by *. Grey Land Mass is Middleton Island.

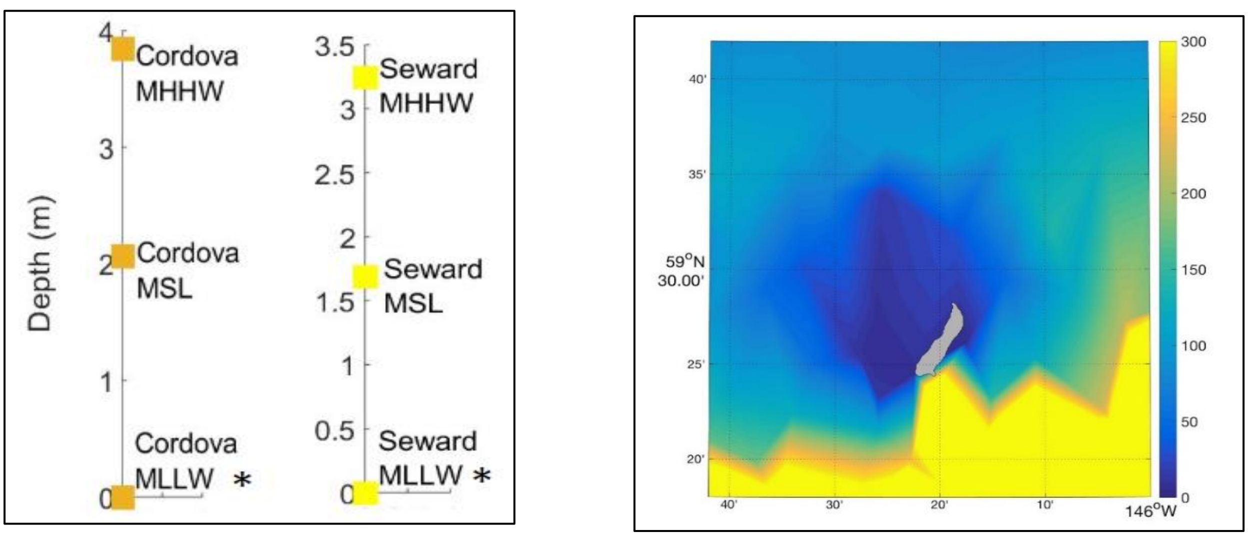
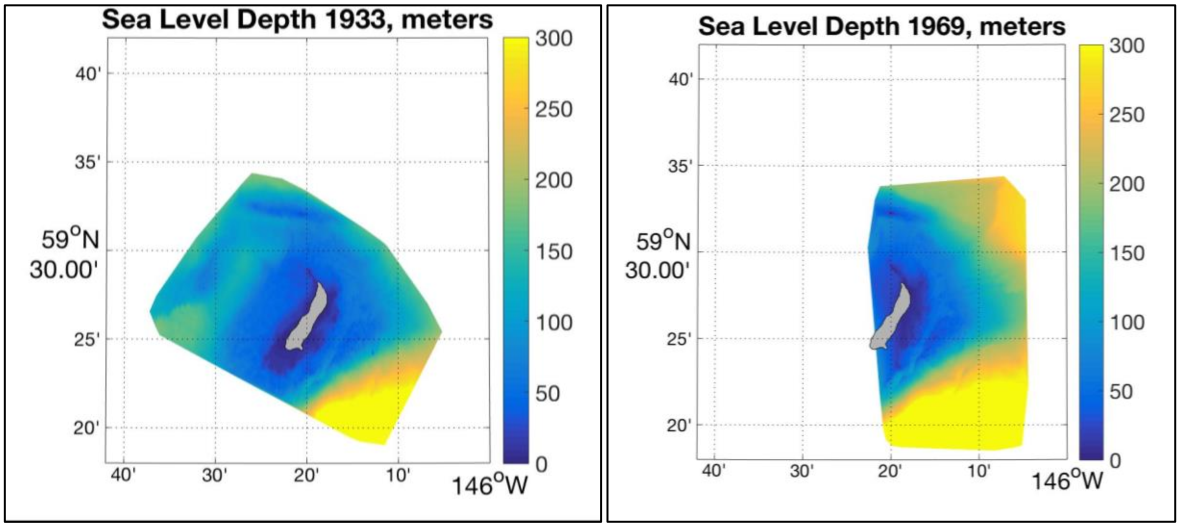


Figure 5: Interpolated sea level field in 1983, m. Referenced to MLLW at Cordova and Seward Tide Gauges, indicated by *. Grey Land Mass is Middleton Island. This 1983 Map is the issue with the clearest interpolation error.



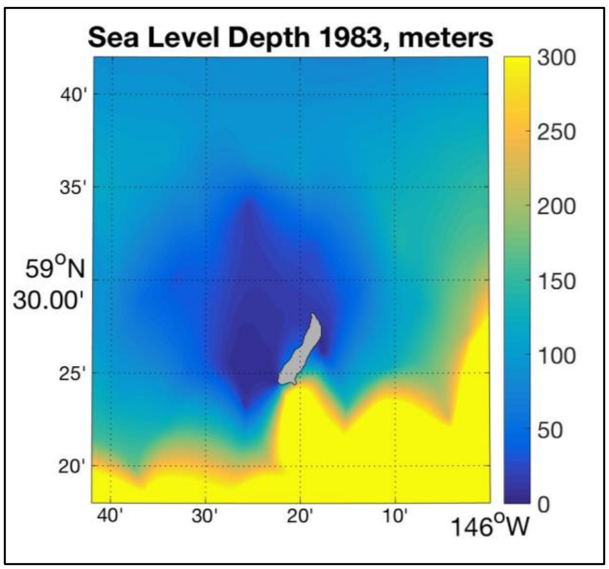


Figure 6: Sea level depth reconstructions for each study year, 1933, 1969, 1983, in meters, with each map in reference to Latouche tide gauge recordings of MLLW in 1933. Middleton Island is the gray land mass in the center of each.

The error in the 1983 map is shown by the sharp changes within the saturated area south of the island. Figure 7 and Figure 8 display a spatial visual of the actual "map-click" data points obtained through physically digitizing the map, these figures illustrate the spacing between data points (Fig. 6) which could explain why we are seeing such a saturated area with sharp changes in sea level depth to the South of Middleton Island.

In order to obtain the closest reconstruction of sea level changes due to local forcing's we adjusted for the GMSL using the GMSL data from Hay et al. (2015). Figure 9-11 are illustrating the changes between the years 1933-1969 (Fig. 9), 1969-1983 (Fig. 10) and 1933-1983 (Fig. 11). In all three intervals, there is a positive difference directly surrounding Middleton Island and the change in depths mostly decreases to negative as one moves outward from the Island (Fig. 9-11). However, in Figure 10 and 11 that involve the 1983 depth data it is clear that there is some error as we would not expect a sea level change greater than +/- 20 m; however as the saturation indicates, our results make it hard to discern a reliable trend since there are likely many outliers.

In an effort to see a clearer localized trend of sea level changes from 1969-1983 and over the whole-time span, 1933-1983, we eliminated outlying sea level change values based on the assumption that any change greater than +/- 20 m were unrealistic. Figure 12 and Figure 13 show the changes over the 17-year span, and the 50-year span respectively, with a more realistic range of changes shown from -10 m to 10 m. Although it is difficult to say if there is a clear fingerprint of sea level change there is a gradient of positive change that gradually decreases moving North (Fig. 12, Fig. 13).

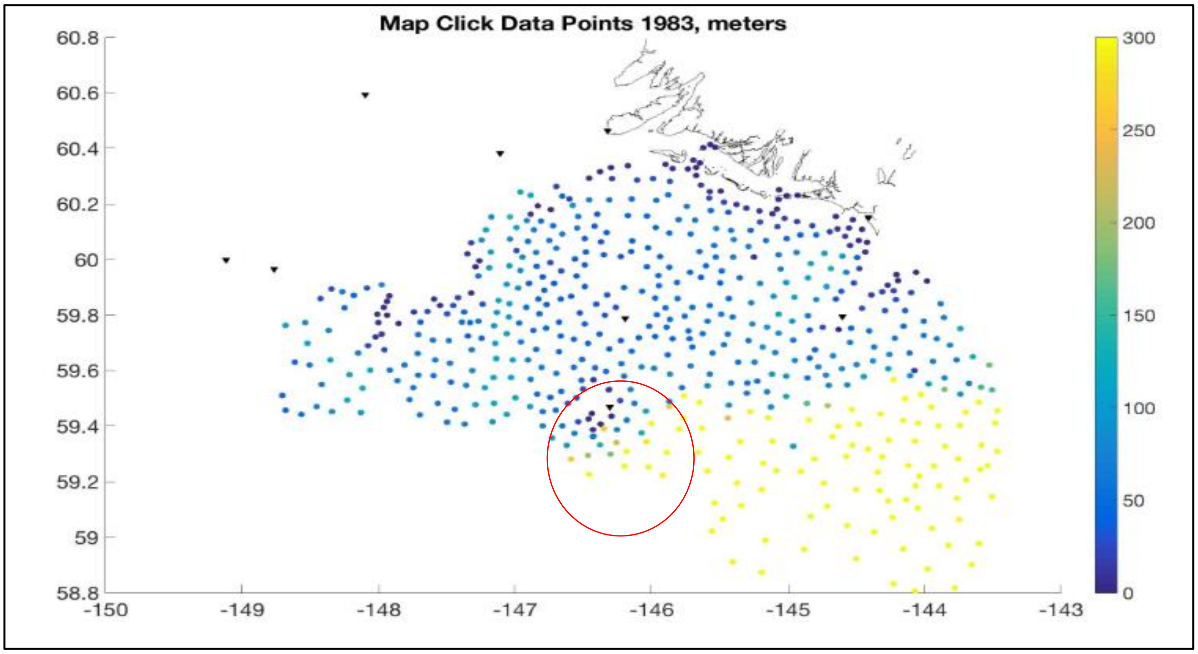


Figure 7: Original digitized data points for 1983 depths, m. Evidenced here is the spacing and depth discrepancies near Middleton Island. The area of our results surrounding Middleton Island is evidenced in red and focused on in Figure 6. Triangle points are the control points (Table 1) used to lay the depth to a geographical space.

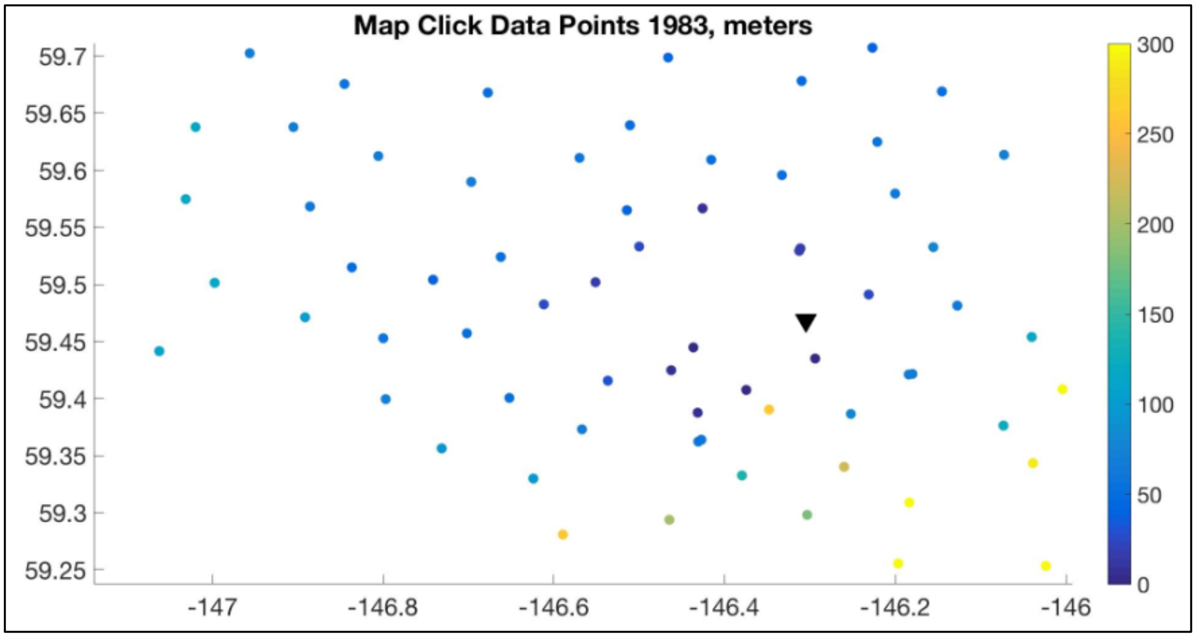


Figure 8: Focus area of Middleton Island, identical to the latitude longitude areas in gridded reconstructions (Fig. 1-4), these digitized points are zoomed in to show the depths, m, within the red circle in Figure 5.

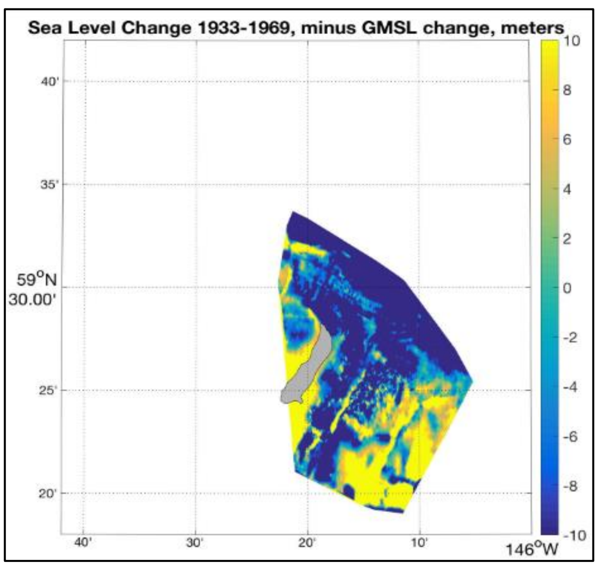


Figure 9: Sea level changes, m, around Middleton Island between 1933-1969. GMSL rise of 47.07 mm accounted for using Hay et al. (2015).

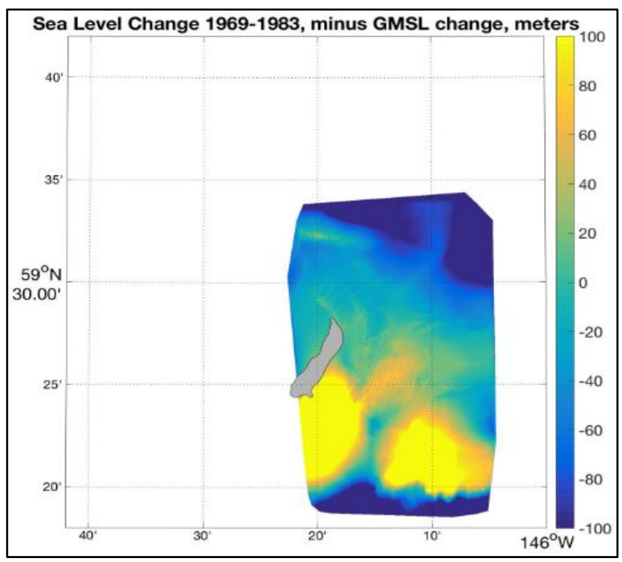


Figure 10: Sea level changes, m, around Middleton Island between 1969-1983. GMSL rise of 17.29 mm accounted for using Hay et al. (2015).

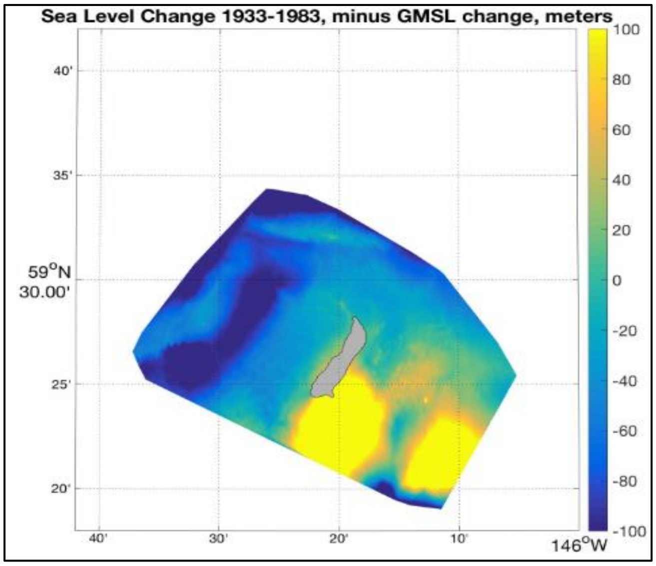


Figure 11: Tracked sea level change, m around Middleton Island, 1933-1983. GMSL rise of 64.36 mm accounted for using Hay et al. (2015).

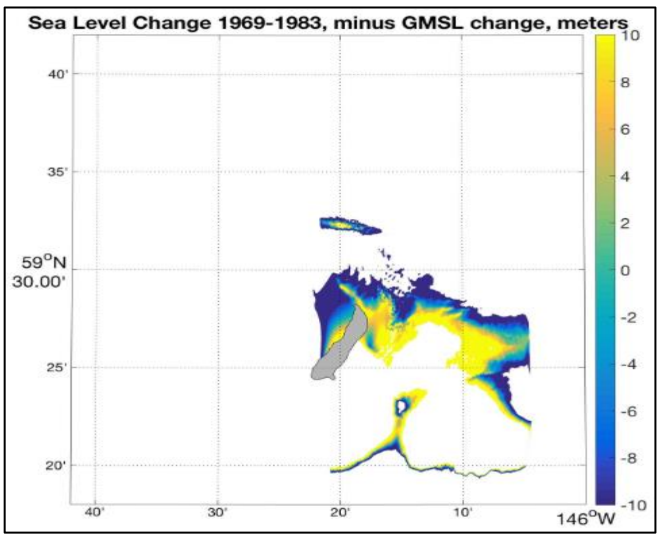


Figure 12: Local sea level change, m, around Middleton Island, 1969-1983. GMSL rise accounted for. Depths greater or less than +/- 20 m eliminated.

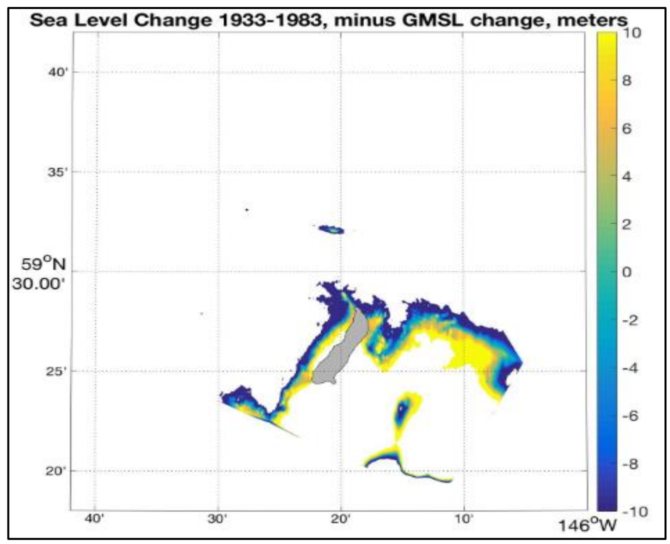


Figure 13: Local sea level change m, around Middleton Island, 1933-1983. GMSL rise accounted for. Depths greater or less than +/- 20 m eliminated.

Overall, results demonstrate that there are sea level changes happening surrounding Middleton Island, between the order of -10 m and 10 m between our time intervals. Although the changes involving the 1983 data result in a large number of sharp shifts in depth due to interpolation there is still evidence of change happening locally in the area after GMSL has been accounted for with those depths removed (Fig 12, Fig 13). These changes could be caused by a number of local forcings, such as GIA, tectonics, and post seismic effects from the 1964 Earthquake (See *Discussion*).

VI. Discussion

Middleton Island, consisting only of uplifted marine terraces, has experienced an average uplift rate of approximately 1.05 cm/yr in the 4,300 years since the island emerged (Plafker & Rubin, 1997). This annual rate continued until 1964 when the 9.4 magnitude Earthquake released tectonic stress across the region. Plafker and Rubin (1997) show that there was a near instantaneous uplift of 3.5 m at and around Middleton Island due to the earthquake, and in the interval following the Earthquake the uplift rate actually decreased to 0.6 cm/yr. This average uplift rate is among the highest documented rates of tectonic uplift in the world and is therefore likely to have contributed to some of the sea level changes illustrated in our results (Fig. 9-13). A consequence of this unique and active tectonic environment in our area of study is that we cannot assume constant uplift rates over long periods of time and uniform areas (Plafker & Rubin, 1997). Because this uplift rate is inclusive of tectonic forcing's as well as glacial isostatic adjustment (GIA) we could not appropriately account for it in Figures 9-13.

Glacial Isostatic Adjustment (GIA), is another forcing in the region, but affects separate areas of the Gulf of Alaska differently (Freymueller et al., 2011). Observed changes in the eastern portion of the Gulf of Alaska range from 10 to 30 millimeters of uplift per year (Freymueller et al., 2011). This range of uplift from GIA makes it difficult to differentiate the difference in local sea level change at Middleton Island, and although a 1 mm change per year may be occurring at Middleton Island, a confident GIA rate is not easily assigned to Middleton Island in order to be used as a proxy on the coast of the Gulf of Alaska (Savage et al., 2014; Freymueller et al., 2000). Plafker & Savage (1991) attribute a range of rise of sea level due to GIA to be between -1 mm/yr. and 1 mm/yr. which would correlate to a contribution from GIA of sea level changes seen between 1933-1969 between -36 and 36 mm and an additional -17 to 17 mm of change between 1969-1983. We cannot confidently assume a uniform GIA rate for this time period, as varied rates have been found across in the region; evidenced in the differing values found in Freymueller et al., (2000). Research done by Kopp et al. (2015) discusses the regional variances in GIA, finding pointing out there is not concrete value for the Alaska region as different locations are responding to melt at varying rates, but also conclude -1 – ~3.5 mm/yr of relative sea level (RSL) change due to GIA. In order to specify changes to illustrate local sea level trends in the area, future studies should attempt to find a uniform GIA adjustment over our time and space intervals or come up with a way to appropriately average and acknowledge the varying reports of GIA rates in the region.

Furthermore, there is an absence of a short-term exponential relaxation following the 1964 Earthquake, meaning uplift at the time of the earthquake as discussed in (Plafker & Rubin, 1997) should be expected, with sea level returning to its previously established trend (Savage & Plafker, 1991). While we cannot discern the pre-earthquake trend produced in our first interval period (Figure 6, 1933-1969), it is possible that some of change seen in later years can be attributed to relaxation and a return to the sea levels identified by Savage and Plafker (1991). Uplift would cause sea level to drop in the area around Middleton Island, and the saturated rise seen around the island in Figures 9-13 could indicate a returning to previous sea level height. However, because of the likely interpolation error and an overall lack of sufficient sea level data, no hard conclusions can be drawn.

Results of attempting to find local sea level change by subtracting the spatially uniform GMSL rate were not conclusive, especially as interpolation error resulted in significant sharp changes in sea level (Fig. 10., Fig. 11), and areas that did not enable analyzation illustrated in the non-values from the depth changes that were adjusted to exclude unrealistic values (Fig. 12, Fig. 13). Interpolation error likely explains these discrepancies as illustrated in the spacing between depth data points shown in Figure 8. Due to the increased spacing between all of the points in Figure 8 and the lack of depth measurements at all in the bottom right corner it is safe to assume that the natural interpolation method likely assigned depth values that were not accurately depicting what was happening in our area. This likely skewed the pictures of both sea level depths in 1983 and the changes we see over the 17-year span 1969-1983 and the 50-year span of 1933-1983. Future research could improve on the data set used for the most recent available map, either through a stronger more robust interpolation method or perhaps an entirely different year that has more data across the area.

From Figure 9, the significant drop in local sea level surrounding Middleton Island shows clearly the effects of a declining sea level in the Gulf of Alaska. With GMSL removed, the 1933 to 1969 depth change map depicts local sea decreasing up to nearly 10 m, which could be contributed to the 1964 Earthquake or other tectonic forcing's in the area. Alaska is unique, because uplift rates are so large that uncertainties within the umbrella of forcing which contribute to uplift are not as important (Savage & Plafker, 1991). At Cordova tide gauge, sea levels appear to indicate a steady rate between 1974-1988, and a rate which is so high that they predict the deformation from the earthquake could be recovered in less than 200 years (Savage & Plafker, 1991). Savage et al. (2014) suggest that there is a contribution of post seismic deformation to the long-term uplift impacts surrounding Middleton Island, stating that the Earthquake's recorded uplift impact is only about half of the differential of uplift that had accumulated in the area in past successive uplift events. This would indicate that there is more uplift to be expected and thus warrants further research into how uplift trends are developing in the region.

VII. Conclusion

While we cannot make robust conclusions on the sea level trends in our area of study, it is nonetheless important to discuss its usefulness. We have demonstrated here that it is possible to take historical ship sounding maps and translate them into spatial reconstructions of sea level (Fig 3-5). This is something that could prove to be useful for many other areas that are data lacking and/or are looking to discover longer term trends from older historical maps. Furthermore, it is important that this region of Alaska has attention brought to it because there are unique trends that cannot be well captured in global averages or by describing the entire Gulf of Alaska. Middleton Island in particular could be used as a proxy for different points of study within the Gulf of Alaska as the various forcings present at Middleton Island could mimic effects and changes on the coast or even inland. Further study of the Gulf of Alaska is essential moving forward, as historically glaciated areas continue to melt as a result of climate change, and understanding the complex mechanisms present in the Gulf of Alaska can help in preparation for tectonic events and large sea level changes.

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