Improving Sea Level Projections in Northern Alaska: The Vital Role of Permafrost Melt-Induced Land Subsidence

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Abstract

Modern day climate change is exacerbating sea level change both locally and globally. The magnitudes of these changes are dependent on numerous global and regional factors that make it difficult to accurately project local sea level into the future. In Alaska, there are many processes contributing to sea level changes along the coast. In particular, there is substantial vertical land movement, in the form of uplift and subsidence, due to the isostatic adjustment of the land once burdened by ice sheets. In Northern Alaska, there is an additional source of land motion that occurs because the flat, tundra landscape is underlain by ~100-300m of permafrost. This permafrost is currently melting and the area is experiencing land subsidence because of it. This study refines sea level projections along northern Alaska by accounting for this extra climate signal. The addition of permafrost-melt induced isotropic land subsidence in projections for the northern coast of Alaska results in sea level rise estimates at the end of the century that double previously published projections. These improved Alaska projections will be vital for the coastal communities, especially in coming decades, in order to minimize losses of coastal property and infrastructure.

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1. Introduction

A major aspect of modern day climate change is the rapid amount of sea level change that is occurring all over the world, at varied rates. Sea level change can be caused by a great deal of different factors, therefore making it difficult to project into the future. By studying regional effects of land surface changes, we can better understand what the regional effects of sea level rise will be, which is a vital need for local coastal communities.

In Alaska, there are many dynamic processes of land movement occurring along the coast and by honing in on one specific region of the state, we can work to create more accurate sea level rise projections in that region. This paper works to understand the different dynamic processes of land movement that are affecting the northern region of Alaska. The Alaskan North Slope is the tundra region of the state located to the north of the Brooks Range along the coast of the Arctic Ocean. Only the surface layer of tundra landscape thaws each season, while most of the soil along the North Slope is permanently frozen as permafrost year-round. The Northern Slope of Alaska is an area that is already experiencing sea level rise, however, current local sea level rise projections due not completely account for the regional effects of land movement. Along the North Slope, there is isotropic land subsidence occurring due to melting permafrost. This land subsidence can be added as a new component of land movement that alters sea level projections in the region. This paper links the in-situ land surface observations with the tide gauge data and allows for altered projections of sea level rise along the Northern Slope of Alaska.

2. Background

To gain a better understanding of sea level projections along the North Slope of Alaska, a background understanding of the processes that induce sea level change in Alaska first have to be understood. In southern Alaska, massive glaciers occupy the mountainous region and their growth and melt effect sea level change in that region and globally. In north and west Alaska, the flat tundra landscape does not contain massive glaciers, but does contain ice beneath the surface within the permafrost. While sea level changes in southern Alaska may be more well understood with the current melting of glaciers, the permafrost melt in north and west Alaska is major factor contributing to sea level change in those regions. Globally, sea level change occurs due to two main processes: thermal expansion of the ocean and the addition of melt water from land-based ice sheets and glaciers. On a regional and local scale, sea level change, and the uncertainty associated with that change, are a result of numerous processes. In Alaska, one of the main contributions to sea level change is glacial isostatic adjustment. A new factor that is considered in this study is the land subsidence induced by permafrost melt. By revising estimates of these two processes, improvements can be made for projections of future sea level rise along the North Slope of Alaska.

2.1. Climate Projections for Alaska

Average annual temperatures in Alaska have increased by 1.7°C since 1949 and climate models predict continued rapid warming in northern latitudes in subsequent years. If we continue our current carbon emissions path, by mid-century Alaska's average temperature will likely increase by 2.2°C to -13.3°C and by the end of the century, Alaskan temperatures will likely rise by 4.21°C to -8.89°C (Bloomberg et al. 2014). The bulk of this warming is expected to occur in the winter months, which would significantly decrease the number of extremely cold days that Alaska experiences. It is expected that with our current emissions path, freezing days in Alaska will decrease by 30% to 50% by the end of this century, not boding well for glacier growth in the winter months (Bloomberg et al. 2014).

In southern Alaska, there is a large concern about continued melting of the massive Alaskan mountain glaciers, where major mountain uplift is occurring. Collision between the Pacific Ocean plate and the North American continental plate along the Aleutian megathrust and Yakautat microplate creates a massive south Alaska subduction zone which leads to active mountain building close to the coast, with the highest coastal mountain reaching over 5400 meters above sea level (Barlow et al. 2011).

The majority of Alaskan mountain glaciers have lost mass since the Little Ice Age (LIA), with nearly every glacier that descends below an elevation of about 1500 meters currently thinning and/or retreating. It is estimated that the mountains around the Gulf of Alaska contain up to 90,000 km^2 of glacier area, which include the largest glaciers in the world outside of Antarctica and Greenland (Meier & Dyurgerov, 2002). Changes in their mass contribute significantly to both global and local sea-level change. Massive glacier mass loss in southeast Alaska and northwest British Columbia (BC) have caused increasing rates of global average sea level rise. Many glaciers in this region are particularly sensitive to climate change, as they have large areas of ice at low elevations, susceptible to small changes in atmospheric temperatures. The net average rate of ice loss in this region is estimated to be 16.7 ± 4.4 km^3/yr, which is equivalent to a global sea-level rise contribution of 0.04 ± 0.01 mm/yr (Larsen et al. 2007). Another study of Alaskan glaciers by Radic and Hock (2011) predicts that the melting of Alaska glaciers may add a further 26 ± 0.007 mm of sea-level rise by 2100.

Both the advance and retreat of mountain glaciers and tectonic crustal deformation along the Alaskan coast drive local and regional sea-level changes. While there are massive glaciers in southern Alaska, the North Slope is characterized by its flat, tundra landscape which is not as affected by glacier melt as it is by the subsurface permafrost melt.

2.2. Drivers of Sea Level Change

Sea level change is of great interest to researchers for two main reasons. Firstly, the changes in the rate of sea-level rise are closely related to changes in the Earth's climate. Secondly, sea level change has very important socioeconomic consequences for populations around the globe living near sea level. Therefore, it is important to determine the current rate of both global and regional sea level change to understand if the rate is accelerating, to identify the causes of these changes, and to make better projections for the future.

Coastal areas around the world are mostly located on coastal plains composed of unconsolidated or loosely consolidated sediments, rather than lithified bedrock. These coastal sediments compact under their own weight as the pressure of overlying sediments leads to a reduction in pore space. Anthropogenic withdrawal of water and hydrocarbons can accelerate this rate of sediment compaction, causing increased rates of subsidence coinciding with periods of peak extraction (Kopp et al. 2015).

The Intergovernmental Panel on Climate Change (IPCC) provides climate predictions assembled by a group of international scientists from a collection of different climate observations and climate model predictions. However, while the IPCC can provide these global projections and estimations of historical sea level change, regional sea level can be much harder to quantify. Observations on a local level become much more sparse and local processes can exacerbate or hide the global sea level rise signal. Local processes are also often poorly understood and poorly modeled, which makes it difficult to quantify and provide relevant information for local communities.

Sea level is defined as the vertical position of the ocean surface (the geoid) relative to the solid surface. There are two main types of global sea-level change, “steric” and “barystatic.” Steric sea level represents the changes in ocean volume which result from temperature and salinity variations. Changes in temperature are called “thermosteric,” or thermal expansion, while changes in salinity are called “halosteric.” Conversely, barystatic sea level change represents water mass that is added to or removed from the oceans as a result of water mass exchange between the oceans and other surface water reservoirs such as ice sheets, glaciers, land water reservoirs, and the atmosphere (Cazenave & Nerem, 2004). Global sea level rise is caused mainly by ocean expansion due to warming and by ocean mass increase due to the melting of glaciers and ice sheets on land. This type of sea level rise is called the relative sea level (RSL). The RSL is the difference in elevation between the sea-surface height (SSH) and the height of the solid-Earth surface. While the difference between these two measures of sea level can be small in the global mean, local differences between the RSL and SSH can be quite significant (Kopp et al. 2015).

RSL changes arise from one of three types of effects: vertical land motion (VLM), changes in the height of the geoid, and change in the height of the sea surface relative to the geoid (Kopp et al. 2015). The first effect is vertical land motion (VLM), which can be measured directly by using global positioning systems (GPS) receivers. VLM arises from a range of sources, including tectonics, soft-sediment compaction (from either the weight of overburden or by the withdrawal of groundwater or hydrocarbons), and deformation associated with ice-ocean mass transfer. This ice-ocean mass transfer is generally separated into two components: glacial-isostatic adjustment (GIA) and the elastic response to recent mass flux in glaciers and grounded ice sheets. GIA is defined as the ongoing viscoelastic response of the Earth to the deglaciation of the large ice sheets that were present during the last ice age (Kopp et al. 2015). Both of these components drive perturbations in SSH and the geoid.

The rise of RSL poses an enormous risk to communities, ecosystems and economies from the inundation of coastal communities and by increasing both the frequency and magnitude of coastal flooding. Both RSL and socioeconomic exposure varies with location, therefore, failure to account for the differences between local RSL change and global-mean sea-level (GMSL) change can lead to the incorrect estimation of the magnitude of RSL rise in a specific region or town. Agencies and stakeholders responsible for quantifying flood hazards in their area require accurate RSL projections for risk assessments and decision-making.

There are two types of observational techniques employed to measure sea level directly to understand sea level changes. The first are tide gauge measurements, which record RSL changes and can go back over 200 years, and the second are satellite altimeter measurements, which observe near-global SSH changes and are available since the early 1990s. Tide gauge measurements are the main data set used to determine the historical rate of sea level change over the last 50 to 100 years and they provide excellent measurements of local relative sea level change.

The two main issues with tide gauges are that they have poor spatial distribution, being located only on the continental margins and ocean islands, and secondly, they are attached to the land, which can move vertically and can thus create an apparent sea level change that is unrelated to climatic variations. However, by selecting tide gauges away from tectonically active areas and making corrections for the vertical motion of the Earth's crust since the last deglaciation (postglacial rebound) using models, one can obtain a more accurate understanding of relative sea level change. One major driver of sea level change in Alaska is the glacial isostatic adjustment due to the melting of major glaciers that covered large areas of North America during the last ice age.

2.3. Glacial Isostatic Adjustment

One major aspect of regional sea level change, especially in northern latitudes, is glacial isostatic adjustment (GIA). During an ice age glaciation event, as the ice sheet grows, the crust below the ice sheet subsides and the crust at the periphery of the ice sheet bulges out, in what is called a periphery bulge. Peripheral bulges are formed because as an ice sheet depressed the land surface below it, the earth material underneath is displaced. As a result, the earth material moves out radially from under the ice sheet, producing bulges along the periphery of the ice sheets, uplifting the surrounding area. This pattern is then reversed during the deglaciation: the crust below the melting ice sheet begins to rebound while the peripheral bulges subside, leveling out the land area once morphed by the massive ice sheet. This multi-millennial, viscoelastic response of the land due to the redistribution of ice and ocean loads can cause large changes in RSL.

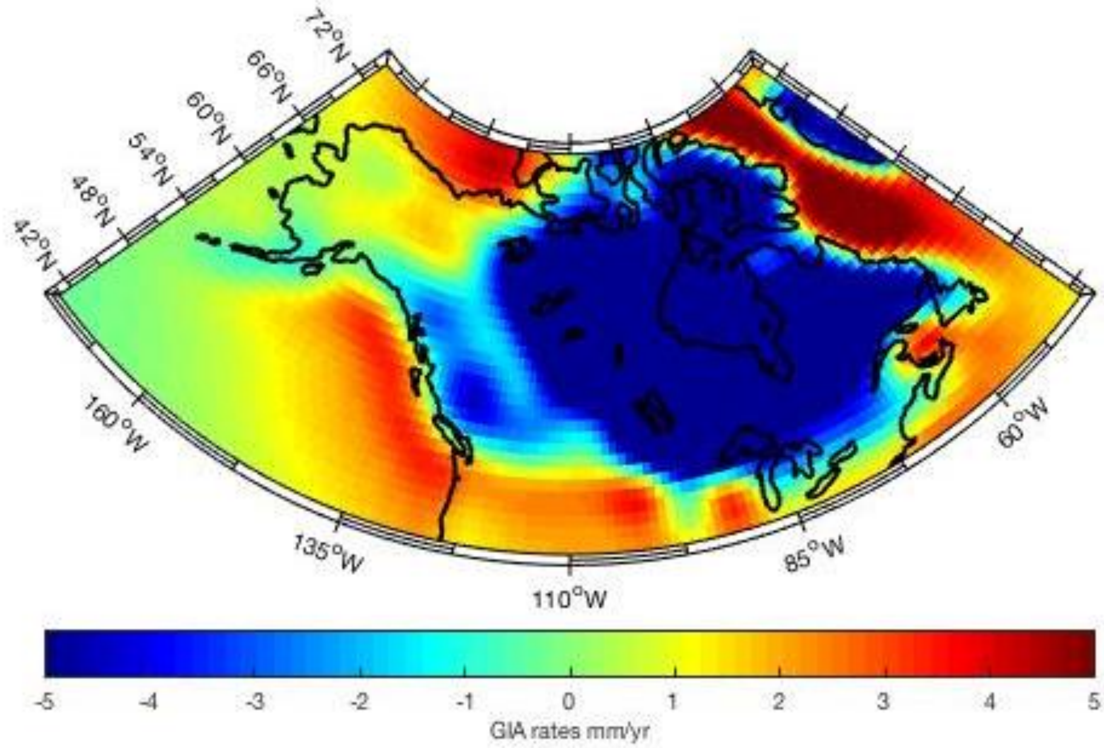


*Figure 1: current rates of sea level change (mm/yr) due to GIA in Canada and Alaska computed using the ICE-5G ice model (Peltier, 2004), with prescribed lithosphere thickness of 72 km, an upper mantle viscosity of 0.5*1021 Pa s and a lower mantle viscosity of* $5*10^{21}$ *Pa s*

In near-field regions where massive ice sheets once inhabited, such as Hudson Bay in Canada, the GIA-induced RSL changes are dominated by post-glacial uplift. As you can see in Figure 1, the large deep blue body over the Hudson Bay indicates an area of rebound of 20 mm/yr where the former Laurentide ice sheet was at its thickest. This area is subject to RSL falls of ~20 mm/yr while sites around the periphery are experiencing GIA-driven RSL rises of 1-3 mm/year. This sea-level rise is driven by ongoing peripheral bulge subsidence.

Conversely, in the “far field” of the Late Pleistocene ice sheets, the changes in sea surface height tend to dominate the GIA sea-level signal. In low-latitude tropical ocean regions, a RSL fall occurs during the deglacial and interglacial stages of the ice age cycle due to a process known as "ocean syphoning." Ocean syphoning is when water migrates away from equatorial ocean basins to fill the space formally occupied by the forebulges at the periphery of previously glaciated regions (Kopp et al. 2015). Since the start of the current interglacial period, ocean syphoning has contributed up to ~3 m of relatively uniform RSL fall in these tropical regions, observed by exposed corals or notches in the coastline, indicating ancient ocean shorelines (Pirazzoli & Shemann, 1996). While this ocean syphoning often occurs in the interior regions of ocean basins, "continental levering" is a GIA process that occurs closer to continental margins. This levering is the crustal tilt downward towards offshore and upwards towards the continents in response to the loading of meltwater in the ocean during the deglaciation. Therefore, sites that are located toward a continental interior will show elevated rates of sea level fall and sites located closer to the ocean will exhibit lower rates of sea level fall (Mitrovica & Milne, 2002).

In this study, estimates of present day sea level changes due to GIA are computed with the ICE-5G ice model (Peltier, 2004) assuming that the Earth is spherically symmetric with a 1D profile that is characterized by an average lithospheric thickness, average upper mantle viscosity, and average lower mantle viscosity. Variations in the lithospheric thickness and mantle viscosities are used to generate 161 different GIA models that result in different local uplift and subsidence rates. The range of GIA predictions for a single location can be used to gain an understanding of potential uncertainties in both historical and future sea level changes.

There is a lot of variability in GIA-induced land movement around Alaska, particularly in the southeastern region where uplift is occurring at rapid rates mainly from the contributions of post-little ice age and present day ice melting (Larsen et al., 2005). Uplift rates in southeastern

Alaska range between 0.3 to 35 mm/yr and the uplift rates originating from the Laurentide ice sheet after the last glacial maximum are less than 2 mm/yr (Tanaka et al., 2014). Figure 2 is a map of sea level change in Alaska caused by GIA, where the GIA estimate is computed assuming a lithosphere thickness of 72 km, and that the viscosity of the upper mantle is $0.5*10^{21}$ Pa s and that the viscosity of the lower mantle is $5*10^{21}$ Pa s. The blue areas in southeastern Alaska were formerly covered by large ice sheets and are now experiencing an uplift (sea level fall) while the red and orange portions, particularly along the North Slope of Alaska, indicate areas of relative sea level rise due to the subsidence of the peripheral bulge. Notably, the location of the peripheral bulge will change when the Earth model is varied, therefore changing GIA-induced sea level change estimates to vary dependent on the model.

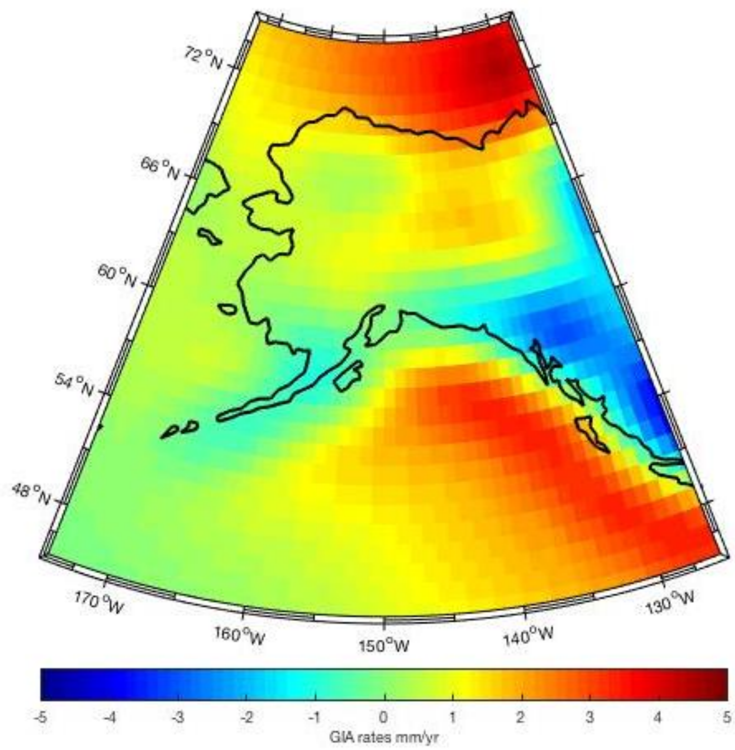


*Figure 2: Sea level changes due to GIA in Alaska computed using the ICE-5G ice model (Peltier, 2004), with prescribed lithosphere thickness of 72 km, an upper mantle viscosity of 0.5*1021 Pa s and a lower mantle viscosity of $5*10^{21}$ Pa s.*

2.4. Permafrost-Induced Subsidence

While the GIA signal in different parts of Alaska is fairly well constrained, permafrost melt in Alaska, especially along the North Slope has not been well constrained or modeled. Better understanding the regional effects of permafrost melt in Alaska is therefore an important area of study.

Permafrost is defined as the soil that is at or below 0°C for at least two consecutive years. A terrain underlain by permafrost exhibits different layers at differing depths. The surface ground layer is called the active layer and this ground section thaws each summer and completely refreezes each winter (Liu et al., 2012). The active layer thickness (ALT) is an important area of study because the ALT influences plant rooting depths, hydrological processes, and the quantity of soil organic matter exposed to above-freezing seasonal temperatures (Schuur et al. 2008). Under the active layer is the transition zone, an ice-rich layer separating the active layer from the more stable permafrost below. A conceptual model of the active layer, the transition layer, and the permafrost layer can be seen in Figure 3. Permafrost soils contain a variety of visible ice inclusions including ice wedges, segregated ice and pore ice. Ice wedges are massive wedge-shaped and foliated ice bodies, segregated ice is

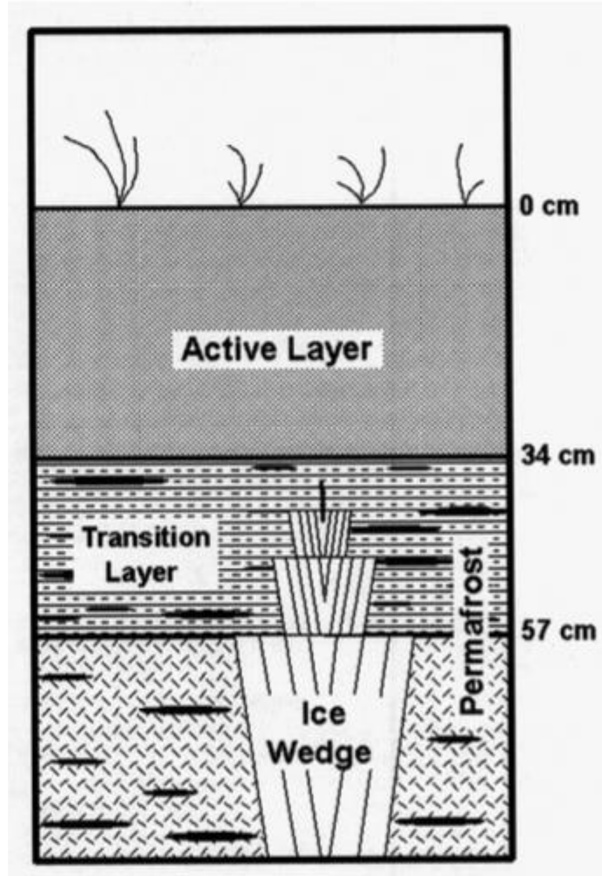


Figure 3: Bockheim and Hinkel (2005) three-component conceptual model of arctic soil layers

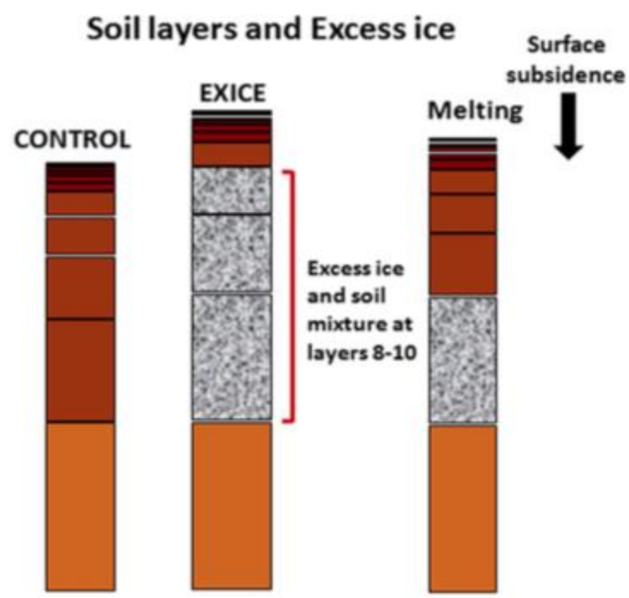


Figure 4: Lee et al. (2014) excess ice schematic highlighting the permafrost-melt induced surface subsidence

strictly large ice pieces found in layers or lenses throughout the permafrost layers, and pore ice can be found as small, interstitial crystals. Ground ice, which can occupy up to 80% of the permafrost soil volume (Brown et al. 1998), can have profound effects on surface topography and surface subsidence when it melts. Figure 4 is a schematic of the surface subsidence due to excess ice formation and melting.

Permafrost temperature, thickness, and geographic continuity are largely controlled by the surface energy balance and thus very strongly with latitude (Schuur et al. 2008). There are three main distinctions of permafrost coverage: the continuous, discontinuous, and sporadic permafrost zones. The continuous permafrost zone of the Northern Hemisphere is where the mean annual soil temperature is below -5° C and the influence of terrain is not sufficient to thaw permafrost (Schuur et al. 2008). The permafrost thickness in the continuous zone ranges between 350 and 650 m (Yershov, 1998). Further south in the discontinuous zone, the regional temperature is not low enough to maintain permafrost everywhere; therefore, the patterns of permafrost distribution are determined by local factors such as topography, hydrology, vegetation, snow cover and subsurface material properties (Schuur et al. 2008). In the discontinuous zone, permafrost depths typically range from less than 1 m to 50 m (Yershov 1998).

Figure 5 from Brown et al. (1998) shows the latitudinal zonation of permafrost, highlighting the different types of permafrost through the Arctic. In the state of Alaska, 80% of the area is underlain by permafrost. Of that area, 32% is underlain by continuous permafrost, 31% by discontinuous permafrost, 8% by sporadic permafrost, and 10% by isolated permafrost (Jorgenson et al., 2010). Permafrost does not respond directly to air temperature change due to its thermal interaction with ecosystem characteristics such as topography, surface water, ground water, soil properties, vegetation, and snow (Jorgenson et al., 2010).

Figure 5: Brown et al. (1998) map of permafrost extent and type throughout the Arctic

There have already been observations showing a decrease in the area covered by permafrost as well as an increase in the active layer thickness (ALT). The active layer plays a critical role in the ecology of permafrost regions by limiting the depth of most biological and hydrological activity in the substrate. By increasing the thickness of the active layer, there are increases in microbial activity, release of CO_2 and CH_4, and loss of substrate-bearing strength (Streletskiy et al., 2012).

Within the realm of permafrost melt, particular attention has been focused on uneven land surface subsidence, called “thermokarst terrain.” This type of uneven terrain occurs at local ranges when large ice lenses melt from the soil layers, causing irregular thaw-induced pits, mounds, bodies of standing water, hillslope mass movements, and other collapse structures. Thermokarst terrain is caused by differential subsidence accompanying thaw of ice-rich permafrost. Its development is often caused by discrete, geographically constrained disturbance of vegetative cover or hydrological patterns. This type of localized land subsidence is irregular and difficult to predict on long time-scales; however, these depressions do exist in areas of ice-rich permafrost where thaw settlement of 1 to 2 m has been observed (Osterkamp 2007).

There is also a more spatially-consistent land subsidence phenomenon called “isotropic thaw subsidence” coined by Shiklomanov et al. (2013). Isotropic thaw subsidence refers to slow, widespread, relatively homogeneous, and low-magnitude thaw-induced lowering of the land surface while the more extreme thermokarst terrain comes from more geographically restricted, irregular and relatively large-magnitude subsidence. Results from Shiklomanov et al (2012) indicate that the entire natural landscape underlain by ice-rich permafrost is slowly subsiding in response to warming of the atmosphere. This isotropic land subsidence is both slow (decimeters/decade) and more uniform relative to the thermokarst features. Since this isotropic subsidence involves the consolidation of the soil column, it may not be apparent to those solely measuring active layer thickness which explains the apparent stability of ALT in areas underlain by ice-rich materials. In order to understand the subsidence along the North Slope, in-situ studies of the land must be used.

There are two main techniques to study permafrost-induced land subsidence. One way to measure subsidence is to use differential GPS technology (dGPS). High resolution dGPS technology allows for the observation of the vertical position of the ground surface at the vegetation/organic soil layer interface. This technology often employs several dGPS observation points per each observation site. For example, Shiklomanov et al. (2013) used 32 observation points arranged in four groups, with horizontal separations between sampling points of 1, 3, 10 and 30 meters. The bifurcation of the site distances provides eight sampling points at each primary station. The varied horizontal separation distances allow for the relative changes in elevation position to be calculated as differences in mean site elevation between subsequent years. These land surface dGPS measurements were accompanied by ALT measurements collected by using a calibrated, 1 cm diameter steel rod to probe to the point of refusal, interpreted as the ice-bonded base of the active layer (Shiklomanov et al 2013).

A second way to study isotropic land subsidence in Alaska is by using interferometric synthetic aperture radar (InSAR) to monitor surface deformation in permafrost areas. InSAR is a remote sensing technique with high spatial resolution which is widely used to measure surface deformation over large areas. In a study conducted by Liu et al. (2010), InSAR was used to find both seasonal and long-term trends in surface subsidence near Prudhoe Bay on the North Slope of Alaska. InSAR has the ability to remotely sense millimeter to centimeter surface deformation over a 100-km-wide swath of land with spatial resolution of 10s of meters or better. By measuring the phase difference between two synthetic aperture radar (SAR) images taken at different times, InSAR constructs interferograms of the ground surface displacement of a region during the time interval of the SAR images. An interferogram is a way to generate maps of surface deformation by using the differences in the phase of the waves returning to a satellite (Liu et al. 2010). Both of these land surface observational techniques are useful in understanding the regional land subsidence along the North Slope, and their results are often quite similar. In this study, I use a combination of their observations to assess subsidence in this region.

On the Alaskan North Slope, climate conditions are highly marine-influenced, characterized by cool summers, relatively warm and long (8-month) winters, and low precipitation **(**Zhang et al., 1996**)**. A large portion of the Northern Slope is a flat and low-elevation terrain underlain by alluvial and marine deposits with high organic and silt content. This land also has large amounts of ground ice along with shallow thermokarst ponds scattered across the area (Liu et al 2010). Seasonal thawing and seasonal land subsidence is caused mainly by thaw settlement in the active layer. On the North Slope of Alaska, the maximum thaw depth usually occurs in September and reaches from 30 to 70 cm (Romanovsky and Osterkamp, 1997). From this range, the magnitude of seasonal thaw settlement can be relatively easily calculated using known soil porosity percentage and assuming a frozen active layer saturated with ice before thawing.

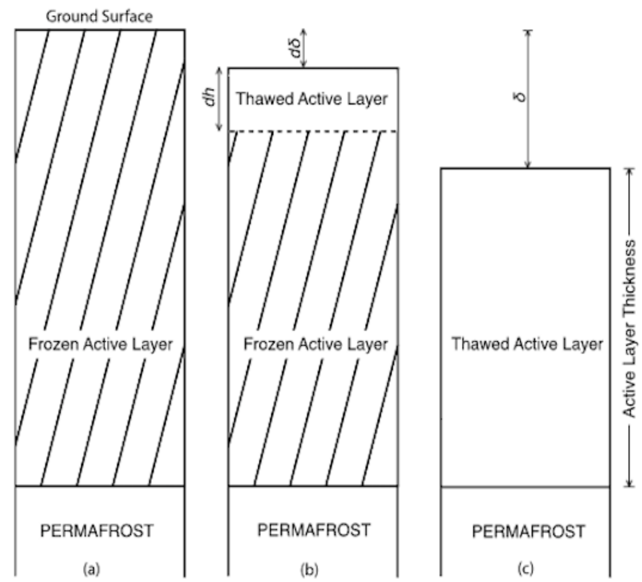


Figure 2: Liu et al. (2012) schematic diagram of active layer states throughout a thaw season.

During the thawing season, surface subsidence occurs as the ice in the active layer melts into liquid water, resulting in a volume decrease (Figure 6). When transforming back from water to ice in the freezing season, the volume expansion causes frost heave, the inverse process of thaw settlement. This type of seasonal land subsidence that occurs due to the change in temperature throughout a yearly cycle is considered the seasonal subsidence, while long term land subsidence due to a warming climate is called the secular subsidence. Generally, the surface undergoes similar amounts of seasonal subsidence and uplift during the annual thaw-freeze cycle. This thaw settlement caused by volume contraction is 12-28 mm within one thawing season. While this analytic estimate matches InSAR-measured seasonal subsidence (Liu et al. 2010), the observed secular subsidence is unlikely due to thaw settlement of the active layer. Even if there were a small secular increase of ALT on the North Slope, it would have contributed only slightly to the observed secular trend in surface subsidence. Instead, the secular isotropic surface subsidence is likely due to thawing of ice-rich permafrost directly beneath the active layer. If there is enough heat to transfer through the active layer and transition layer into the underlying permafrost, the ice-rich permafrost will thaw and ground ice will melt into liquid water. This meltwater drains into lowlands, river channels, and thaw lakes, which results in surface subsidence over areas that are underlain by ice-rich permafrost (Liu et al. 2010). This new idea of ice-rich permafrost thaw near the permafrost table offers an explanation as to why the InSAR-measured secular subsidence occurs while ground-based measurements of ALT reveal negligible trends despite an observed increase in permafrost temperature over time (Osterkamp et al. 2007).

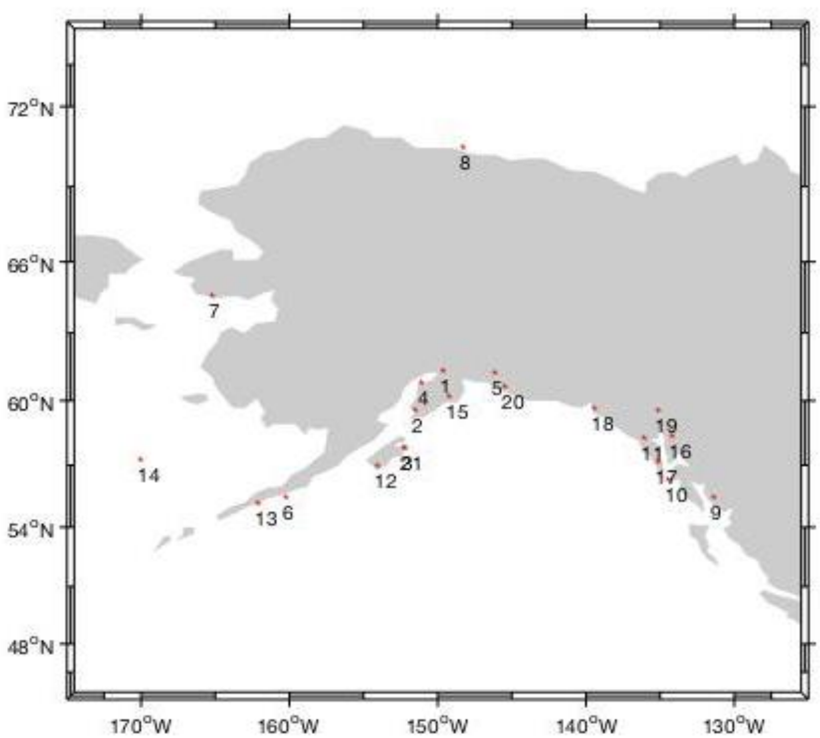
Widespread permafrost degradation in Alaska could result in profound effects on biological, biogeochemical, hydrologic, and landscape processes, on the flux of greenhouse gases, and on human infrastructures in the Arctic (White et al. 2007). Additionally, widespread land subsidence along the Northern Slope of Alaska will lead to a sea level rise in the region, causing many issues to coastal communities and habitats. Permafrost melt-induced land subsidence is therefore an important area of study that will better refine local sea level change projections. This contribution to sea level change is dependent on the longevity and magnitude of global warming, therefore, it cannot be considered part of a background local rate of sea level change as it will likely accelerate with accelerated carbon emission projections.

For the North Slope of Alaska, there is uncertainty associated with historical (background) rates of sea level changes associated with GIA and local vertical motion as well as the uncertainty associated with the rate of land subsidence due to permafrost melt. While the background rate, which is a combination of GIA and other on-going local effects, are assumed to be constant over time, the land subsidence due to permafrost melt will be dependent on the amount of warming that is projected to occur. Although past permafrost melt-induced land subsidence may be partially accounted for in background rates of sea level change, improved projections of this component of sea level change are necessary to make better regional projections of sea level rise along the North Slope of Alaska.

3. Results and Discussion

3.1. Historical Sea Level Change

The goal of this study is to refine the historical background rate of local sea level and to add in projections for the additional factor of permafrost-melt induced sea level rise along the North Slope of Alaska. To understand the background rates of sea level change in Alaska, it is necessary to look at sea level changes over time. Tide gauge data for Alaska are provided by the Permanent Service for Mean Sea Level (PSMSL). The PSMSL was established in 1933 and its primary function is to collect, publish, analyze and interpret sea level data from the global network of tide gauges (Holgate et al., 2013; PSML, 2017). The locations of the 21 tide gauges located in Alaska are shown in Figure 7. Additional information about the length of the individual tide gauge dataset can be found in Appendix 5.1. It is clear from Figure 7 that the



1	Anchorage
2	Seldovia
3	St. Paul's Harbor, Kodiak
4	Nikiski
5	Valdez
6	Sand Point, Popof Island
7	Nome, Alaska
8	**Prudhoe Bay, Alaska**
9	Ketchikan
10	Port Alexander
11	Elfin Cove, Port Althorp
12	Alitak, Lazy Bay
13	King Cove, Deer Passage
14	Village Cove, St. Paul Island
15	Seward
16	Juneau
17	Sitka
18	Yakutat
19	Skagway
20	Cordova
21	Kodiak Island, Women's Bay

Figure 7: PSMSL tide gauge locations in Alaska

majority of tide gauges are located along the southern coast of Alaska, with only one site located along the North Slope (Prudhoe Bay). The tide gauge with the longest dataset is the Ketchikan tide gauge (site #9), dating back to 1920, while the newest tide gauge site is in Nome, Alaska (site #7) and it started collecting data in 1995. The Prudhoe Bay tide gauge site, which is the focus of this study, began recording sea level in 1992**.** Tide gauge time series for Seldovia,

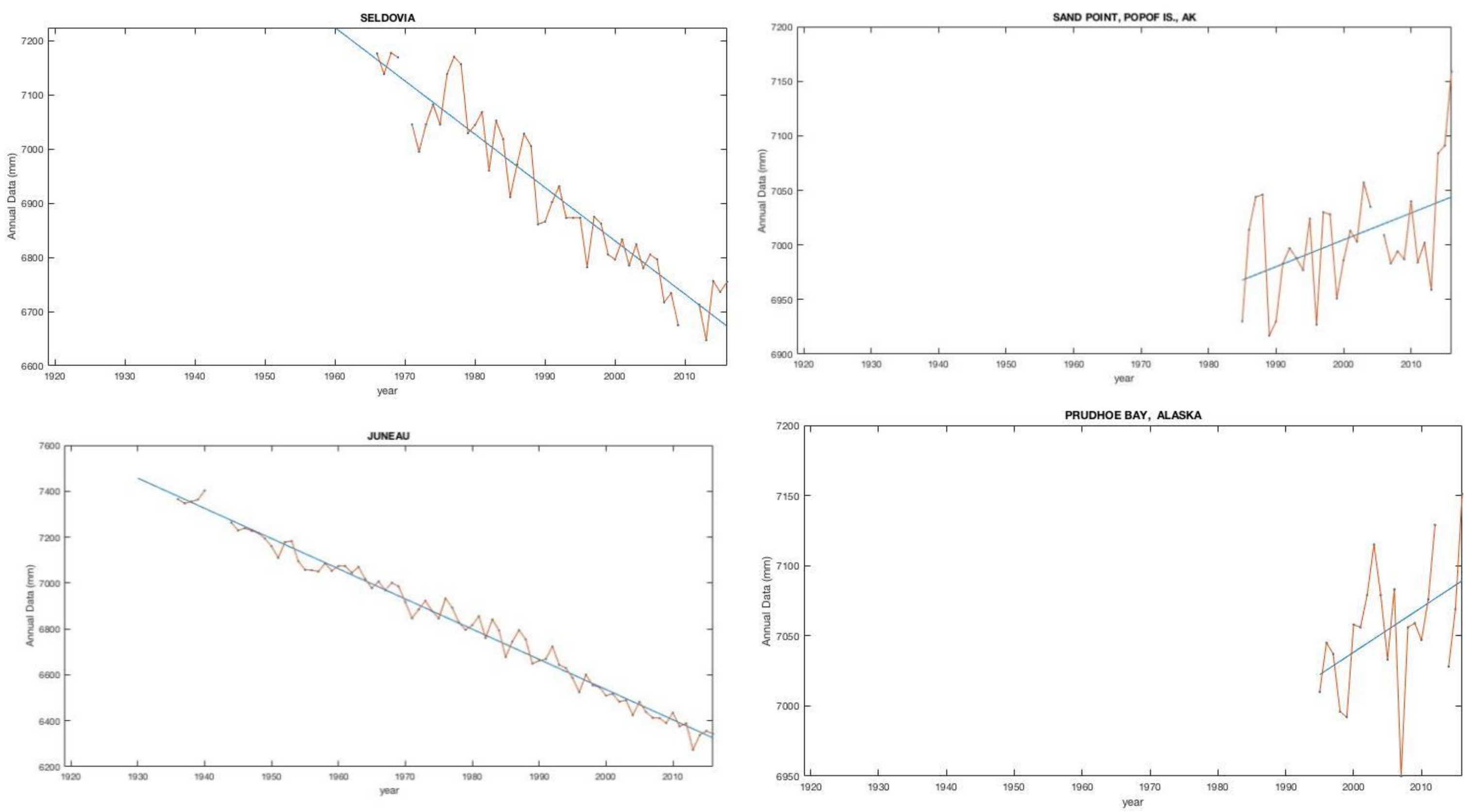


Figure 8: Tide gauge data (orange line) overlaid with lines of best fit (blue line) from the Alaska sites Seldovia (gauge #2), Sand Point (#6), Juneau (#16) and Prudhoe Bay (#8)

Sand Point, Juneau, and Prudhoe Bay are shown in Figure 8. The long-term sea level changes are quite variable and are dependent on the location of the tide gauge due to strong regional affects such as GIA and glacier melt. For example, in southeastern Alaska (where Seldovia and Juneau are) there is a large rebound occurring because that area was once burdened by massive ice sheets, which have since melted. However, at Sand Point, GIA rates average around

0 mm/yr indicating an area that may be at the hinge point between uplift and subsidence. Additionally, Prudhoe Bay, which is located along the peripheral bulge along the North Slope, shows land subsidence rates higher than any other tide gauge site in Alaska.

For each tide gauge site in Alaska, both linear and quadratic best fit lines were computed and the linear slope as well as the fit parameters for the quadratic can be found in Appendix 5.2. The linear rates for sea level change at the tide gauge sites in Alaska are shown in Figure 9.

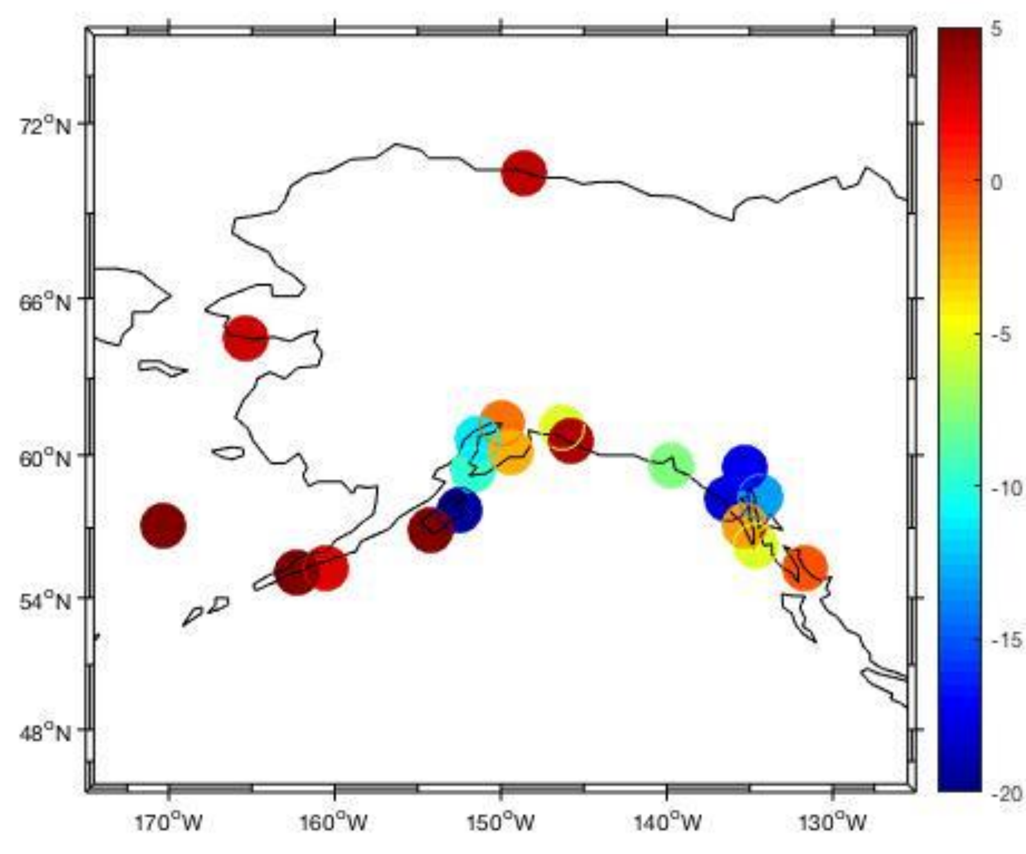


Figure 9: Linear rates of sea level change in Alaska, in mm/year

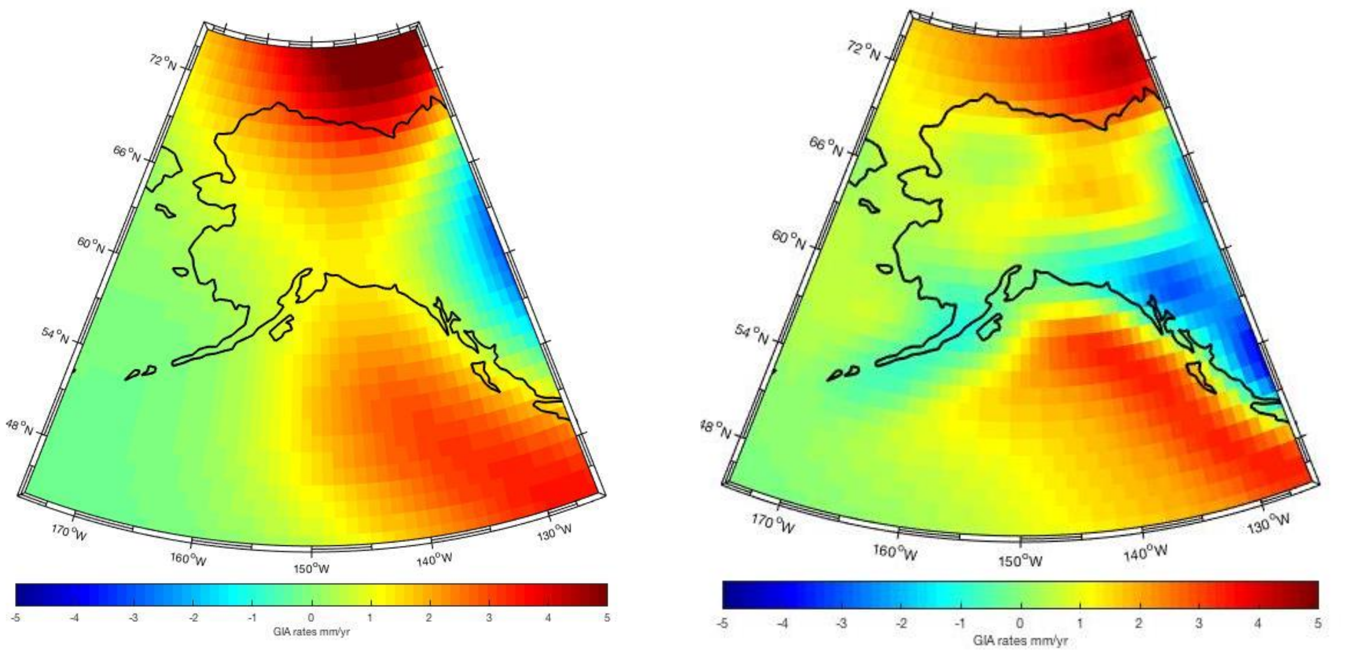


Figure 10: Sea level changes due to GIA in Alaska, left figure uses (global_150p3100) a lithosphere thickness of 150 km, an upper mantle viscosity of $0.3*10^{21}$ and a lower mantle viscosity of $1*10^{23}$ Pa s. The GIA map on right uses a lithosphere thickness of 72 km, a viscosity of upper mantle of $0.5*10^{21}$ Pa s and a viscosity of the lower mantle of $5*10^{21}$ Pa s

Along north and west Alaska, sea level has been increasing over time, while in south and southeastern Alaska about half of the sites have been experiencing a sea level fall. The fall in sea level exhibited in these regions is dominated by GIA. As seen in the maps of present day rates of sea level change due to GIA (Figure 10), there is rebound occurring in southeast Alaska due to the unburdening from the Laurentide Ice Sheet, while most other sites in Alaska in the north and west situated in the location of the former peripheral bulge and those areas are experiences subsidence due to GIA. In locations such as Juneau and Skagway, a study by Larsen et al. (2003) found that present uplift is 13.6 ± 1.0 and 17.1 ± 1.0 mm/yr respectively, which would explain why these areas in southeastern Alaska are experiencing high levels of apparent sea level fall. Figure 5 shows the range of GIA values from the 161 models at the 21 different tide gauge sites in Alaska. The variability in the different GIA models comes from changes in the

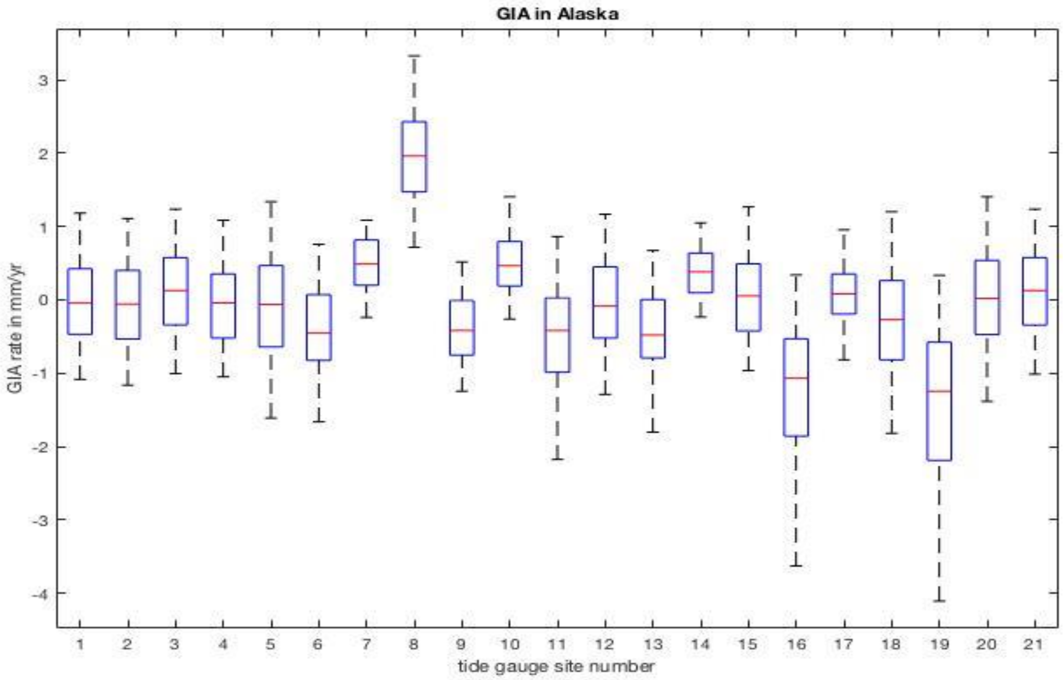


Figure 11: Boxplot of variability in GIA rates among 161 different models, note Prudhoe Bay (tide gauge site 8). The central rectangle spans the first quartile to the third quartile, and the red segment inside the rectangle shows the median value for each site. The "whiskers" above and below the box show the locations of the minimum and maximum data values.

lithosphere thickness, the viscosity of the upper mantle, and the viscosity of the lower mantle. However, there is a large range of GIA values for different locations in Alaska. This variability is due to both the movement of the peripheral bulge and the location of the region of uplift for different GIA models. In Figure 8 left frame, the peripheral bulge extends into the interior of Alaska in the and the uplift is confined to the very eastern edge of Alaska. This leaves room for high variability in GIA-induced sea level change at locations along the southern coast of Alaska (e.g., site 19: Skagway). For Prudhoe Bay, however, the average sea level rise due to GIA is 2 ± 0.59 mm/yr, indicating that GIA is causing sea level to rise at that location regardless of which GIA model is used.

To further understand historical estimates of local sea level in Alaska, I first extracted the estimated background rates of sea level change from the Kopp et al. (2014) dataset of sea level at tide gauge sites. The Kopp et al. (2014) background rates for the tide gauge locations around Alaska are plotted in Figure 12**.**

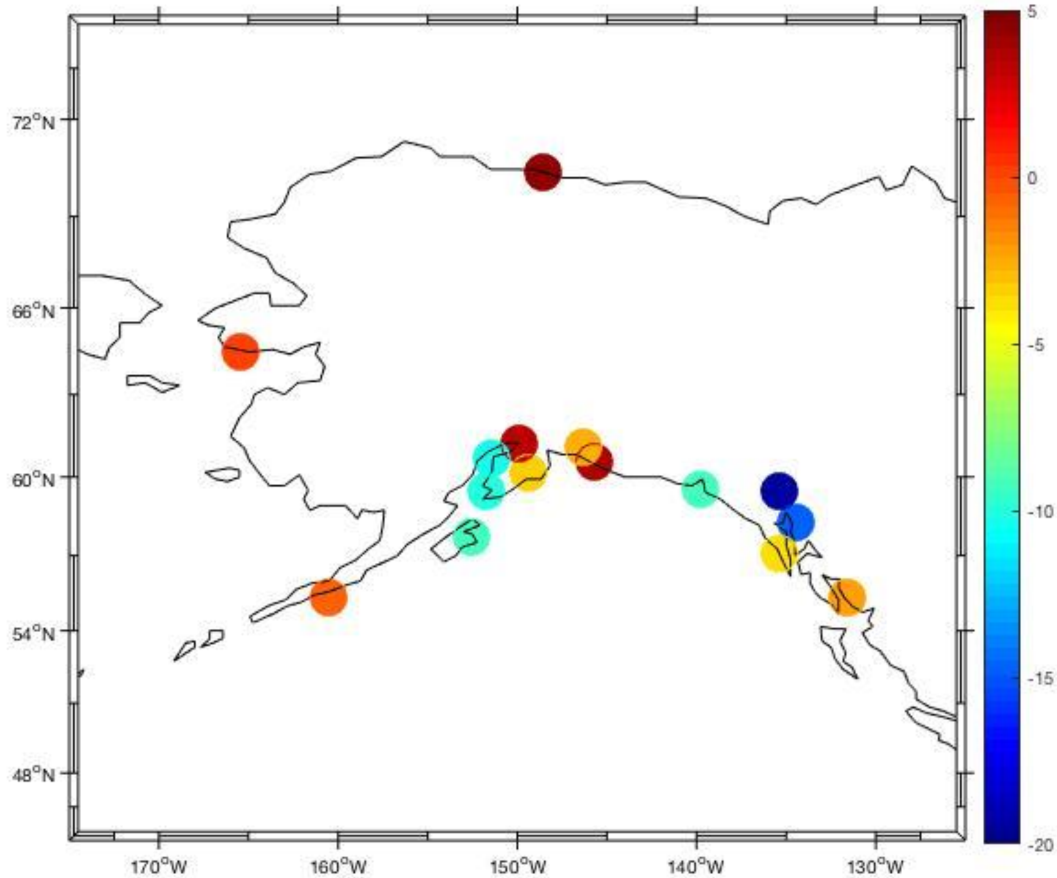


Figure 12: Kopp et al. (2014) estimates for background rates of sea level change (mm/yr)

There is a large difference in the background rates around Alaska, ranging from -19.300 mm/yr in Skagway (southeastern Alaska) to 4.400 mm/yr in Prudhoe Bay on the North Slope.

The background rates of sea level change incorporate the local GIA signals and are an estimate of the on-going sea level changes that would be occurring in the absence of thermal expansion and modern ice sheet and glacier melt. Subtracting out the Kopp et al. (2014) background rates from the computed linear trends at the tide gauge site should therefore leave only sea level changes due to the present day climatic affects. That is, the sum of the different components of local sea level change should equal the observed trend at the tide gauge site. If the background signal is underestimated, it may be an indication that there is an unaccounted for background sea level signal that needs to be understand and incorporated into sea level change projections for the future.

At Prudhoe Bay, I computed the linear trend over 1992 - 2015 to be 3.2 mm/yr and Kopp et al. (2014) estimated a background rate of 4.40 ± 4.21 mm/yr. The difference between these two rates is -1.2 ± 4.2 mm/yr. This suggests that either the background rate has been over estimated or that the combination of thermal expansion and glacier melt may be causing sea level to fall in Prudhoe Bay over the last ~20 years. Assessing the latter hypothesis is difficult because modern estimates of local sea level changes due to thermal expansion and present-day mass loss are difficult to obtain for Prudhoe Bay since satellite altimeters have poor coverage of these northern latitudes. Instead I will focus on determining whether or not the background rate is appropriate for this region.

From the 161 GIA models, it is clear that GIA is producing a sea level rise of 2 ± 0.59 mm/yr at Prudhoe Bay, an amount that agrees with the Kopp et al. (2014) rate within their large uncertainty range that spans values of 0.19 to 8.61 mm/yr. Differences between the Kopp et al. (2014) background rate and the GIA prediction may be a result of historical land subsidence from permafrost melt at the Prudhoe Bay site. In a study by Streletskiy et al. (2016), permafrost-induced land subsidence was measured along the coast of the North Slope. The observed subsidence due to permafrost melt was 0 mm/yr over 1962 to 2003. Additionally, a study using InSAR by Liu et al. (2010) found that land subsidence from 1992 to 2000 was only 1-

4 mm/yr along the North Slope. A summary of the observed (in-situ) land subsidence along the coast of the Alaskan North Slope is in Table 1, with a description of the type of measurement tool used. As is apparent in the dGPS studies, permafrost-melt induced land subsidence has been increasing from the base rate of 0 mm/yr to 10 mm/yr in recent years. This leads me to conclude that the permafrost subsidence is not fully incorporated into the Kopp et al. (2014) background rate because the ~4 mm/yr background rate cannot include both the GIA signal and this increasing rate of permafrost land subsidence.

Table 1: Computed long term subsidence from ground observations along the North Slope coast of Alaska.

Author	Location	Measurement tool	Start year	End year	Observed Ground Subsidence
Streletskiy et al. 2016	Barrow, Alaska	dGPS	1962	2003	0 mm/yr
Liu et al 2010	North Slope	InSAR	1992	2000	1-4 mm/yr
Streletskiy et al. 2016	Barrow, Alaska	dGPS	2003	2015	4 - 10 mm/year
Shiklomanov et al. 2013	West Dock, Prudhoe Bay oilfield	dGPS	2001	2012	7.5 mm/yr
Shiklomanov et al. 2013	Sagwon 1, Arctic Foothills	dGPS	2001	2012	15.83 mm/yr
Streletskiy et al. 2016 (updates Shiklomanov)	West Dock, Prudhoe Bay oilfield	dGPS	2001	2015	10 mm/yr

It is clear that the tide gauge dataset at Prudhoe Bay shows a rate of sea level change that appeared lower than expected given the additional vertical land motion associated with historical permafrost melt. Why is this the case? Permafrost melt is occurring in regions characterized by Arctic tundra soil; however, the NOAA-run tide gauge is situated on a piling for a Seawater Treatment Plant (STP) operated by British Petroleum (NOAA.gov). This indicates that the tide gauge is not actually on the tundra landscape of the North Slope but a man-made piling that is experiencing different vertical land motion than the North Slope landscape. This is likely why the permafrost land subsidence signal is not apparent on the tide gauge data; that is, to accurately depict what is occurring along the North Slope, the tide gauge should be situated on a tundra landscape soil rather than a cement piling that is not subsiding at the same rates. Therefore, projections of sea level rise for North Slope region around Prudhoe Bay need to include permafrost-induced land subsidence as an additional sea level rise factor.

3.2. Sea Level Projections

Climate projections for both Alaska and the globe are made for different future climate scenarios or representative concentration pathways (RCPs). An RCP is a greenhouse gas concentration trajectory created by the IPCC for its fifth Assessment Report (AR5) in 2014. The four pathways are used for climate modeling and research and the RCPs are called: RCP2.6, RCP4.5, RCP6, and RCP8.5, named after the possible range of radiative forcing values in the year 2100, relative to the pre-industrial values. The number (2.6 – 8.5) indicates the radiative forcing in W/m^2. By 2100, there is an expected global warming increase projection of 1.0 ±0.7 °C under RCP 2.6 while under RCP 8.5 a warming of 3.7±1.1 °C is expected to occur (IPCC AR5). These RCP scenarios are then used to make projections of sea level through the 21st century.

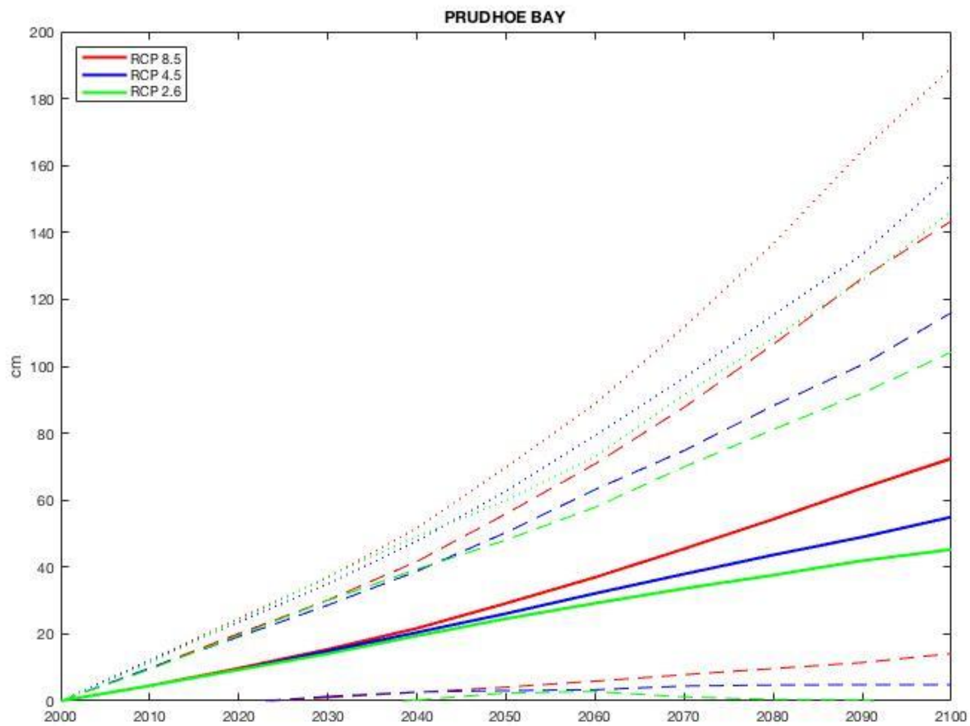


Figure 13: Sea level projections at Prudhoe Bay for RCP2.6, RCP4.5, and RCP8.5 (modified from Kopp et al., 2014).

Sea level projections at Prudhoe Bay up until 2100 can be seen in Figure 13 **(**Kopp et al., 2014). In these projections, there is a projected sea level rise between 44 and 75 cm, dependent on the RCP scenario. Figure 14 shows the sources of variance in projections of absolute sea level change (left) and in fractional terms (right) for Prudhoe Bay under the three climate scenarios, RCP2.6, RCP4.5, and RCP8.5. The main source of variance at Prudhoe Bay comes from uncertainty in the ocean processes (thermal expansion and changes in ocean circulation), accounting for about 60% of the total variance. Notably, the second largest portion of the variance is the background rate, accounting for about 40% of the total variance. In addition, the fraction of the uncertainty associated with the background rate is nearly constant over time and across RCP scenarios. While both the ocean processes and background rate account for the vast majority of the variance at the tide gauge site, it is important to remember

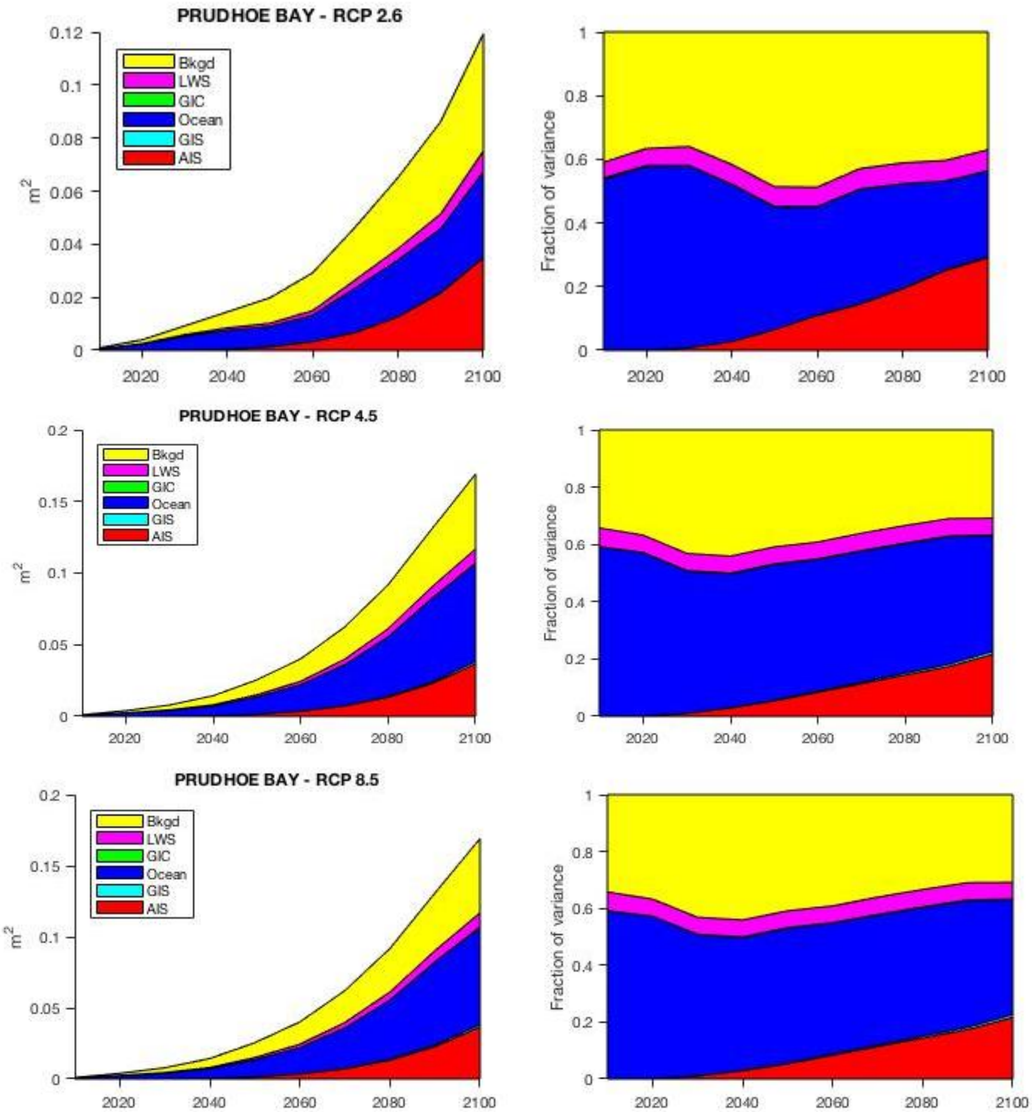


Figure 14: Uncertainty distribution for projections of sea level at the Prudhoe Bay, AK tide gauge site (modified from Kopp et al., 2014).

that the background rate is not fully accounting for the permafrost melt-induced subsidence. Thus, by accounting for this additional component of sea level change, which is both a historical/background signal as well as a future climatic signal, it may be possible to decrease some of the uncertainty in the projections. The first step in accounting for the permafrost component of sea level rise in the Prudhoe Bay region is to incorporate the permafrost melt-induced isotropic land subsidence in to the projections.

To project land subsidence along the North Slope, I used rates produced both by in-situ land subsidence measurements from Shiklomanov et al. (2013) and Streletskiy et al. (2016) while also using land subsidence projections as result of excess ice melt in permafrost by Lee et al. (2014). Prudhoe Bay, as well as Barrow, are coastal towns along the North Slope of Alaska. Barrow is 329.6 km west of Prudhoe Bay, also on the Beaufort Sea. While there is only tide gauge data available for Prudhoe Bay, the sea level rise projections there can also be used for the coastal town of Barrow because it exhibits similar land subsidence and GIA signals, as is observed in the spatial GIA maps in Figure 10. Both Barrow and Prudhoe Bay are characterized by a relatively flat surface with poorly developed vegetation. The underlying soils of these North Slope locations mainly consist of alluvial and marine deposits which have high organic and silt content, as well as large amounts of ground ice (Liu et al. 2012). Both sites have very similar soil horizons, therefore, sea level change projections with Prudhoe Bay data can be made for Barrow as well.

Along the North Slope of Alaska under Representative Concentration Pathway (RCP) 8.5, Lee et al. (2014) projects a total subsidence of 0.48 m. This projection incorporates a simple representation of excess ice within the permafrost soil column into the Community Land Model to investigate how excess ice will affect projected permafrost thaw. By obtaining datasets on the excess ice from the Circum-Arctic Map of Permafrost and Ground-Ice Conditions and by using projections of surface temperature changes in 2100, Lee et al. (2014) produced spatial maps of projected permafrost induced surface subsidence in the Arctic. Using this study, I project a linear path of land subsidence from 2000 to 2100 and added that additional land movement to the Kopp et al. (2014) sea level projection.

Figure 15 shows the edited RCP8.5 projection of sea level rise at tundra sites near Prudhoe Bay with the additional land subsidence projection by Lee et al. (2014) incorporated. Projection are made only the RCP8.5 scenario because it represents an upper bound on permafrost induced subsidence.

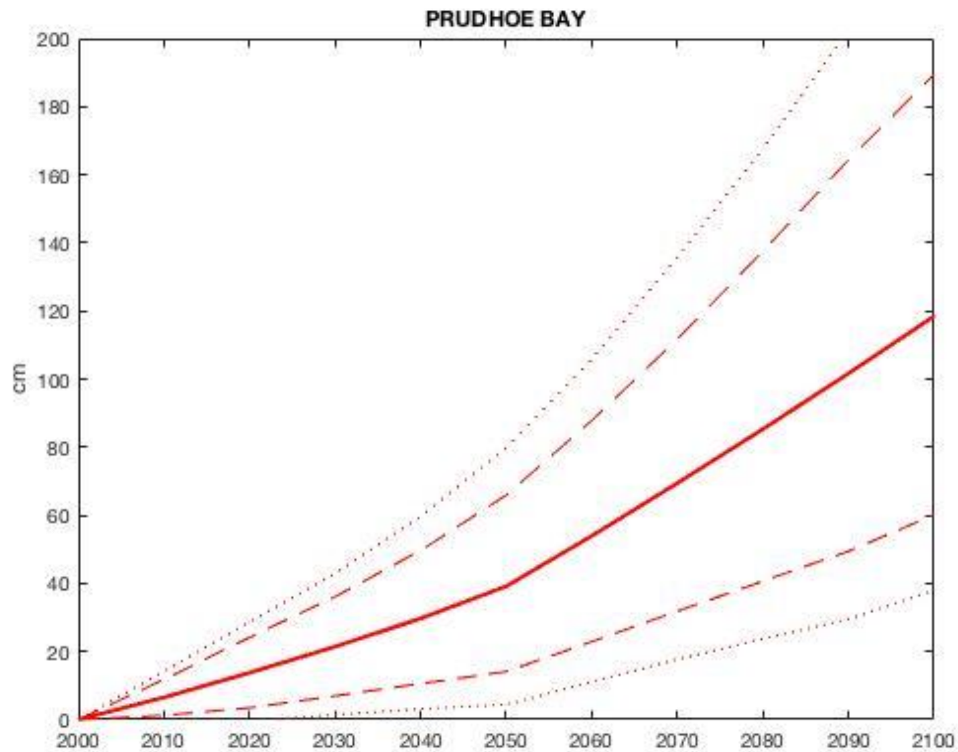


Figure 15: Edited sea level change at Prudhoe Bay using Lee et al. 2014 excess ice land subsidence projections under RCP8.5

From the in-situ dGPS data from Shiklomanov et al. (2013) and Streletskiy et al. (2016), I derived an additional scenario for land subsidence along the North Slope. Shiklomanov (2013) reported 7.5 mm/yr of land subsidence between the years of 2001 and 2012. Streletskiy et al. (2016) also studied the Prudhoe Bay area and revised Shiklomanov's (2013) land subsidence to 10 mm/yr of land subsidence due to permafrost melt from the years of 2001 to 2015. Therefore, I project an additional 10 mm/yr of land subsidence going forward over the 21st century. Figure 16 shows an edited projection of Kopp's sea level with the addition of both

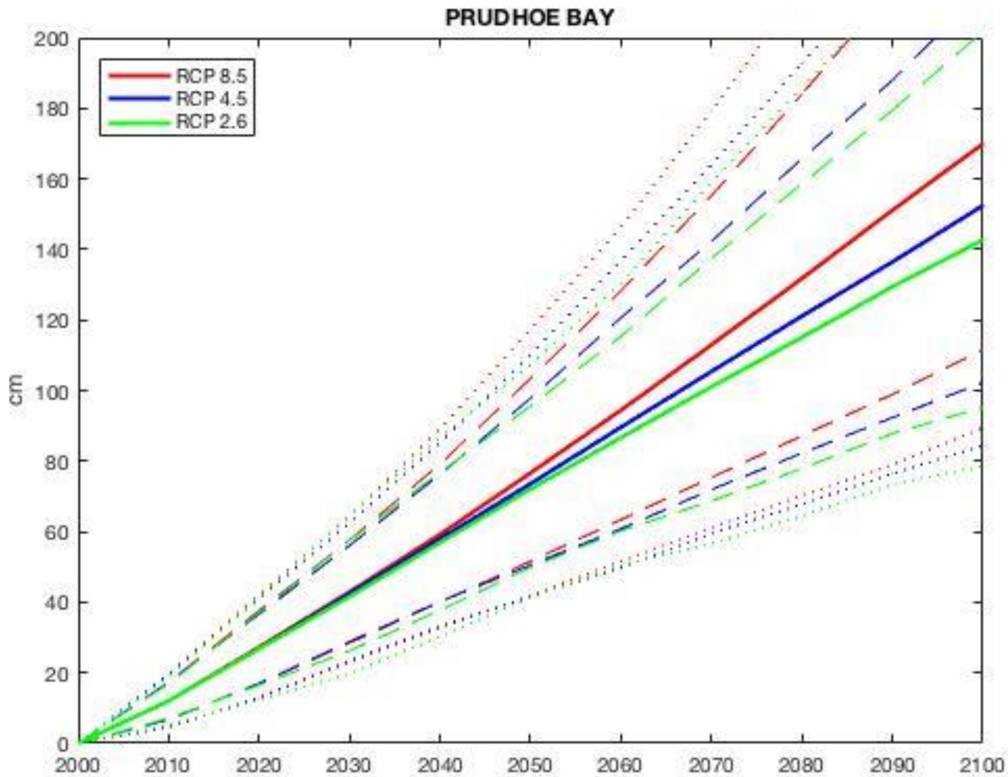


Figure 16: Edited sea level projection with the addition of land subsidence data from Shiklomanov et al. (2013) and Streletskiy et al. (2016)

Shiklomanov (2013) and Streletskiy's (2016) land subsidence observations. It is probable that this projection path is a conservative estimate because there was an apparent acceleration of land subsidence between the years of 2012 and 2015 from 7.5 mm/yr to 10 mm/yr and there is no evidence to suggest that subsidence rates will slow down in coming years. It is likely that this rate may accelerate even more, but no current projections provide the exact rate of land subsidence expected by 2100. The 10 mm/yr prediction is therefore the current best estimate.

Comparison of the projections presented in Figure 13 with the new updated projections of Figures 15 and 16 makes it clear that with the addition of permafrost-melt induced isotropic land subsidence, it is probable that projected sea level rise will double from the Kopp et al. (2014) projection by 2100 in areas surrounding Prudhoe Bay.

4. Conclusion

Alaska is heavily coastal, with 84% of Alaskans living on coastal counties and 86% of the state's GDP coming from these coastal counties (Bloomberg et al. 2014). The ability to effectively and accurately project sea level changes for coming decades could greatly impact these coastal communities and minimize large-scale losses of coastal property and infrastructure.

One of the most difficult factors in assessing climate change and sea-level rise is understanding both the global and regional effects. While the global sea level signal can be well understood, many different regional processes cause ambiguity in local sea level signals. As seen in Alaska, there is a great deal of variability that can occur regionally, even across one state. While the southeastern part of Alaska is experiencing a relative sea level fall, the north and west parts of Alaska are experiencing a sea level rise. Most of this regional variability can be contributed to background rates of sea level change, which is a combination of GIA and other background local effects. By refining the background rate and adding in a climate-driven process like permafrost melt, future projections can be better constrained and more accurate.

Current projections of sea level rise in Prudhoe Bay suggest that there will be a sea level rise of 40 to 70 cm by 2100, however, with the additional component of isotropic land subsidence due to permafrost melt, sea level could rise by 1.2 to 1.7 meters by the end of the 21st century. This extra meter of sea level rise has serious implications for these coastal communities and further studies are necessary to better constrain the uncertainty. In addition, uncertainties associated with future permafrost induced subsidence have not been formally characterized in this study. Incorporating these uncertainties into sea level rise projections will be an important in future work on refining local projection in Alaska and other high latitude regions.

It is important to note that there are some additional limitations to this study. Two main issues with the tide gauge dataset from the North Slope of Alaska are the limited number of available records and short length of the available dataset at Prudhoe Bay. For example, there are 18 tide gauge sites along south and southeastern Alaska that have been recording sea level changes for decades, while there is only one tide gauge on western Alaska and one along the North Slope of Alaska.

To better constrain the effects of climate change on the tundra landscape of the North Slope and improve local projections, monitoring of sea level and local vertical land motion in this area should increase. Furthermore, while I can say with some confidence that the land subsidence effects occurring at Prudhoe Bay should be the same all along the North Slope, further studies of the northern tundra region of Alaska should be conducted to understand this area better. Additionally, to really improve projections along northern Alaska, the projections should take into account a wider range of both global and regional effects; this study mainly focused on refining the contribution from GIA in the background rate of sea level rise, while adding in the additional permafrost-induced subsidence. To further refine this projection, adding in the current melting of Alaskan and Arctic glaciers should be considered, along with other global and regional drivers of sea level change.

For this study, I focused on the long-term regional effects of GIA and permafrost melt that alter sea level in Alaska. While adding in this additional factor of permafrost melt does almost double the projections for sea level rise, it is important to understand that this study does assume a modest projection of permafrost subsidence. The rate of land subsidence that was observed on land in North Slope has been accelerating in recent years, and there is no data to suggest that the rate will decrease. By assuming no acceleration in the rate of permafrost melt, this makes the projection a conservative one. Further studies understanding how increasing temperatures directly correlate with permafrost subsidence would be useful in constraining land subsidence measurements.

Another important area of study along the North Slope is the more noticeable, more extreme coastal erosion process that is occurring. Because the permafrost is melting below the surface, the cliffs of soil containing permafrost along the coast are being undercut by strong waves and are cleaving off at high rates. This process, along with the thermokarst terrain associated with permafrost melt, will wreak havoc for these local communities.

This study aimed to refine the sea level projections along the North Slope of Alaska. By adding in the additional component of permafrost-melt induced isotropic land subsidence, the sea level rise projections increase by approximately 1 m. Since this new component of land movement has before now not been added into projections for the North Slope, it is probable that sea level rise will pose more of an issue for the northern coastal towns, their nearshore infrastructure, and ecosystems. While the climate signal of permafrost melt has been marginally more well studied on land, further studies along the coast of Alaska are important to understand the interaction between coastlines and permafrost melt. Improving technology and developing new ways to monitor the relative sea level changes in these far-flung regions will be vital for these northern communities as global climate continues to rise.

5. Appendix

5.1. Tide gauge site information

This table shows the length of time that each tide gauge dataset from PSMSL provides. While the first year of recording data varies, all 20 of the tide gauges have data up until 2015. The different colors represent different regions of Alaska. Red font represents south-central Alaska, green represents southeastern Alaska, black represents the west coast of Alaska and the purple for Prudhoe Bay represents the northern coast of Alaska.

Site number	Site location	Time period of tide gauge data		Years of Record
1	Anchorage	2015	1960	**55**
2	Seldovia	2015	1960	**55**
4	Nikiski	2015	1996	**19**
15	Seward	2015	1960	**55**
5	Valdez	2015	1970	**45**
20	Cordova	2015	1965	**50**
9	Ketchikan	2015	1920	**95**
16	Juneau	2015	1930	**85**
17	Sitka	2015	1935	**80**
19	Skagway	2015	1940	**75**
6	Sand Point	2015	1983	**32**
7	Nome	2015	1995	**20**
8	**Prudhoe Bay**	**2015**	**1992**	**23**

5.2. Tide gauge linear and quadratic rates of sea level change

This table shows the degree-1 polynomial (linear rate) and quadratic equation fitted for the tide gauge site datasets. A linear best fit line was fit to each tide gauge time series, and the slope of that line is provided below. Negative values indicate a sea level fall, while positive values indicate a sea level rise over time. For the quadratic, the a, b, and c values are given in the table below and are related to sea level change with the equation: $SL = at^2 + bt + c$, where t = time, given in years. The degree-1 polynomial most appropriately fits all the tide gauge sites except for Valdez and Cordova. The quadratic equation for Valdez and Cordova more accurately fits the regional sea level trends occurring at those two locations.

Site number	**Site location**	**Linear rate (mm/yr)**	**Quadratic fit**			
			a	**b**	**c**	**Acceleration (mm/yr^2)**
1	Anchorage	-1.1068	-0.0211	82.8952	-74299.82	-0.0422
2	Seldovia	-9.8373	0.0304	-130.8415	146952.40	0.0608
4	Nikiski	-11.1572	-0.0236	82.9481	-64864.12	-0.0471
15	Seward	-2.5833	-0.0516	202.7568	-192062.20	-0.1032
5	Valdez	-5.4543	-0.2285	906.7351	-892446.02	-0.4570
20	Cordova	3.5350	-0.1833	733.7102	-727002.28	-0.3666
9	Ketchikan	-0.3139	-0.0089	34.8115	-26866.57	-0.0179
16	Juneau	-13.1537	-0.0169	53.5760	-33103.23	-0.0338
17	Sitka	-2.3088	-0.0058	20.5877	-11062.28	-0.0116
19	Skagway	-17.6247	-0.0528	191.5128	-165227.04	-0.1056
6	Sand Point	2.4587	0.1688	-672.8798	677598.71	0.3376
7	Nome	2.6784	0.4712	-1887.2927	1896803.03	0.9424
8	**Prudhoe Bay**	**3.1879**	**0.0600**	**-237.5353**	**242036.20**	**0.1200**

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