GEOMETRIC AND THERMAL CONSTRAINTS ON THE TIMING OF ALAKSAN TIDEWATER GLACIER RETREAT

by

LUCY WAGHORN

A THESIS

Presented to the Department of Earth Sciences
and the Robert D. Clark Honors College
in partial fulfillment of the requirements for the degree of
Bachelor of Science

May 2022

An Abstract of the Thesis of

Lucy Waghorn for the degree of Bachelor of Science
in the Department of Earth Science to be taken June 2022

Title: Geometric and Thermal Constraints on the Timing of Alaskan Tidewater Glacier Retreat

Approved: *Dave Sutherland, Ph.D.*
Primary Thesis Advisor

Glaciers around the world are retreating at increasing rates, prompting concerns over sea level rise and the future of the cryosphere. In southern Alaska, some have retreated while their neighbors have advanced, indicating that local atmospheric conditions are not the only influence on glacier retreat. One possible factor is the interaction of ocean water with the glacier at the terminus. However, fjord geometry can alter the ocean water that interacts with the terminus, and the interaction of fjord geometry and ocean temperature anomalies has not been investigated in Alaska thus far. To investigate the interaction of fjord geometry and glacier retreat, we used bathymetry, air temperature (AT), sea surface temperature (SST), and terminus position data. Here we show that high SST anomalies may enhance glacial retreat in fjords with shallow sills. During a high SST anomaly, some glaciers in shallow-silled fjords retreated rapidly from a point of relative stability. It is possible that shallow sills influence fjord water circulation where only the warmest part of the water column can enter the near terminus region, potentially leading to enhanced glacier retreat after high SST anomalies. Many glaciers also showed enhanced retreat in the two years after a high AT anomaly. Though other factors can also contribute, understanding the processes and interactions that lead to glacier retreat is becoming increasingly important as climate change alters the atmosphere and environment.

Acknowledgements

I would like to thank Professor Dave Sutherland and PhD Candidate Alex Hager for their guidance on this project, I have enjoyed the opportunity to explore the world of ocean and ice interactions in my time as an undergraduate. Alex's help cannot be overestimated, thank you for the unwavering support and guidance. I would also like to thank Professor Samantha Hopkins for being my CHC representative in this process. I am also extremely grateful for my friends and family that have helped me along the way, listening to the process and helping me think aloud through the challenging aspects of this project. I have very much appreciated the University of Oregon's Geology Club and all its wonderful members for being an enriching community that has kept me engaged with the geological sciences and with my peers in the department.

I'd like to acknowledge the financial assistance of the Presidential Undergraduate Research Scholars program as well as the Ocean and Ice Lab, Earth Sciences Department, and the University of Oregon.

Table of Contents

Introduction 1

Research Question 7

Methods 8

Study Area 9

Data Collection 11

Bathymetry 11

Terminus Positions 14

Sea Surface Temperature and Air Temperature 15

Data Organization and Analysis 16

Selecting Representative Glaciers 16

Defining A Retreat Event 17

Defining Sill Depths 18

Results 20

Sill Distribution 20

Glacial Retreats by Subregion 21

Archipelago 24

Glacial Retreat by Sill Depth 25

Temperature Anomalies 26

Sea Surface Temperature and Glacier Retreat 27

Retreats During SST Anomalies by Region 28

Retreats During SST Anomalies by Sill Depth 30

Air Temperature and Glacier Retreat 31

Retreats During AT Anomalies by Region 31

Retreats During AT Anomalies by Sill Depth 34

Discussion 36

Conclusion 42

Bibliography 43

List of Figures

Figure 1: Fjord Water Circulation	5
Figure 2: Study Area	9
Figure 3: Columbia Glacier thalweg transect.	13
Figure 4: Length Change for South Sawyer and LeConte Glaciers	15
Figure 5: Sill Depths at LeConte Glacier	19
Figure 6: Number of Retreats per Year	21
Figure 7: KPWS Length Changes	23
Figure 8: Archipelago Relative Length Changes	25
Figure 9. Sea Surface Temperature and Air Temperature Anomalies	27
Figure 10: Retreat events plotted with SST anomalies	30
Figure 11: Retreat events plotted with AT anomalies	34

List of Tables

Table 1: Retreat Data 21

Table 2: SST anomalies and Sill Depths. 31

Table 3: AT anomalies and Sill Depths. Expressed in percentage of retreats of total. 35

Introduction

Understanding tidewater glacier retreat is becoming increasingly important because they have a large influence on global sea level rise (Gardner et al., 2013). A number of glaciers in southeast Alaska have experienced short lived yet significant retreats that neighboring glaciers have not experienced. These retreats are not consistent temporally or geographically, but some have occurred after summers that have had anomalously high sea surface temperatures (SST) (McNabb & Hock, 2014). Reasons for these retreats are poorly constrained as this is an emerging area of research, with studies published as recently as 2018 and 2020 starting to understand these mechanisms (Catania et al., 2018; Eidam et al., 2020). One direction of study is the interactions between ocean water and ice at the ice-ocean boundary at the terminus of tidewater glaciers. One gap in the knowledge is understanding how geometric constraints, such as shallow sills in glacial fjords, impact water circulation near the glacier terminus and the repercussions for subsurface melt of the glacier.

Current research is largely aimed at understanding the global ice mass budget in order to be better able to understand the impacts of melting ice on global sea level rise. Melt from glaciers that are not part of the Greenland Ice Sheet (GIS) and the Antarctic Ice Sheet (AIS) contribute a disproportionately large amount to global sea levels. Though comprising a smaller quantity of ice, melt quantities from non-Greenland or Antarctic Ice Sheet glaciers were found to be comparable to melt quantities from the GIS and AIS (Gardner et al., 2013). The group of glaciers outside of the GIS and AIS is largely composed of land-terminating mountain glaciers and marine-terminating tidewater glaciers. There has been a large quantity of research conducted about air temperature and its impacts on mountain glacier surface mass balance, as air temperature is one of the only ways to influence land-terminating glaciers. Applying some of this knowledge to tidewater glaciers will help us understand the controls on tidewater glacier retreat.

A large number of the tidewater glaciers that are melting and are distinct from the GIS and AIS are found in Alaska. Some of these glaciers experience retreats that are not linear through time and are instead observed to be in a stepwise fashion (McNabb & Hock, 2014). Reasons for these step retreats are unknown but it is theorized that transported sediment or changes in ocean temperature are triggers to the phenomenon (Brinkerhoff et al., 2017; McNabb & Hock, 2014). Glacier terminus positions change over time and are influenced by a number of different factors, both environmental and physical (Fahrner et al., 2021; McNabb & Hock, 2014). The rate of retreat is different for each glacier due to a number of factors including cross-sectional area and ice thickness (McNabb et al., 2015). Changes in glacier length can be described by the following equation where dL/dt is the change in length over time, U_{ice} is mass entering from up the glacier, and $U_{ablation}$ is mass loss at the terminus from melt and calving.

$$\frac{dL}{dt} = U_{ice} - U_{ablation} \tag{1}$$

There are many different influences on tidewater glacier melt, including ice and ocean interactions at the terminus, and the melt that leaves the glacier in the subglacial discharge plume (Brinkerhoff et al., 2017; Catania et al., 2018; Eidam et al., 2020; Matthews, 1981; McNabb & Hock, 2014). Understanding and quantifying the subsurface melt of the world’s tidewater glaciers is important because the melt may trigger a change in ice dynamics, potentially resulting in a retreat or significant contributions to global sea level rise (Gardner et al, 2013).

As glaciers flow, they scour the bedrock beneath them resulting in a channel. This sediment is then deposited by the glacier at its furthest reach, the terminus. Large deposits can accumulate at the terminus when the glacier remains at a relatively constant length (Winkler & Matthews, 2010). These terminus deposits are known as "terminal moraines" when on land or as "sills" when submerged. These sills or moraines are only visible as the glacier retreats and exposes them. The landform is not a product of the retreat but can only be seen once the glacier has moved back. Depending largely on the length of time that the glacier was at a stable length, sills can range in height from less than 10 meters below sea level to many hundreds of meters below sea level. They are relatively narrow deposits that cross fjords perpendicularly to the direction of water flow and have an influence on the circulation of the water that is in contact with it (Hager et al., 2022).

Some tidewater glacier termini move in a pattern known as the tidewater glacier cycle, which is characterized by fast retreat, long stable periods, and slow advances (Meier and Post, 1987; Post et at al., 2011). In this scenario, the terminus can rapidly retreat from a stable position through an area of low stability then slow its retreat as it gets "pinned" in another area of high stability - such as a constriction in the fjord or shallow section like a sill (Amundson, 2016; McNabb & Hock, 2014).

Many tidewater glaciers in southern Alaska have experienced rapid and short-lived retreats after a period of high summer SST anomalies (McNabb & Hock, 2014). These retreats are called "step change retreats" and have been identified as an area of future study, especially in relation to the observed high SST anomalies (McNabb & Hock, 2014). One proposed mechanism for step change retreats is that an ice-sediment feedback loop creates cyclic glacial advance and retreat patterns, meaning that as the glacier deposits sediment it is then impacted by that dropped sediment (Brinkerhoff et al., 2017).

Near-terminus water circulation also has impacts on the melt rate of tidewater glaciers (Hager et al., 2022; Matthews, 1981; Slater et al., 2017). There are two main driving factors of near-terminus circulation: the presence of a subglacial discharge plume, and fjord geometry (Figure 1a) (Carroll et al., 2017; Hager et al., 2022; Matthews, 1981; Slater et al., 2015; Slater et al., 2017). Fjord geometry, such as the presence of sills and depth of the grounding line of the glacier (the deepest part of the terminus), changes the flow of water through the fjord (Carroll et al., 2017; Matthews, 1981). The ratio of sill depth to grounding line depth is a primary control on the renewal of water near the terminus of a tidewater glacier (Carroll et al., 2017).

Ocean water is stratified by both temperature and salinity. At cooler temperatures salinity is a driver of density, resulting in some systems, such as Greenlandic fjords or near Antarctica, having their warmest conditions at depth. Other systems, such as in Alaska, are different. In the Alaskan summer, ocean water entering the fjord is warmer toward the surface and cooler at depth (Hager et al., 2022). Due to this stratification, the presence of a sill, or lack thereof, may also impact water circulation (Figure 1b) (Merrifield et al., 2018).

a

b

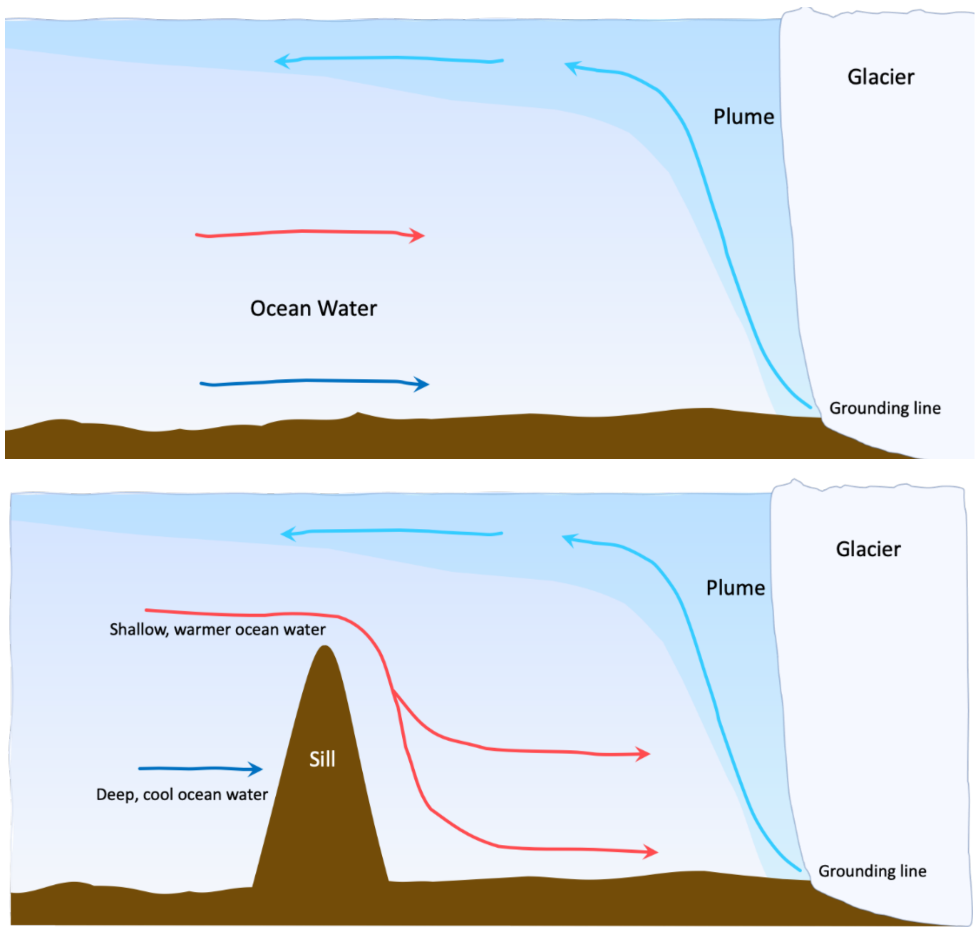


Figure 1: Fjord Water Circulation

(a) Water circulation in a fjord with no sill present. The subglacial discharge plume rises buoyantly and entrains ocean water into the near terminus region. (b) Water circulation in a fjord with a sill. The subglacial discharge plume entrains ocean water but only the top of the water column travels over the sill into the near terminus region.

Another summertime impact on water circulation is the presence of a subglacial discharge plume (Carroll et al., 2017; Hager et al., 2022; Slater et al., 2015). In summer there is significantly more melt occurring along the surface of the glacier that is then channeled to the terminus where it rises up the face of the terminus and drives fjord water circulation (Hager et al., 2022). The plume rises to the surface of the fjord because it is composed of fresh water and is more buoyant than saltwater. As it does so, it pulls in ocean water from outside the fjord near the glacier terminus (Figure 1a) (Carroll et al., 2015; Slater et al., 2015).

This plume has the potential to undercut the terminus and create an overhanging geometry. The undercutting process does not have a large impact on ice melting but glaciers that are already undercut have larger melt rates due to their greater surface area (Slater et al., 2017). The degree to which subglacial melt contributes to terminus melt is not entirely quantified, but it has been found that melt is increased when subglacial discharge occurs in many smaller channels rather than one larger one (Slater et al., 2017). The differences in the spatial distribution of melting have different magnitude impacts on fjord water circulation, as water circulation is largely driven by the subglacial discharge plume (Hager et al., 2022).

Fjord geometry and subglacial topography have also been found to have an impact on glacial retreat (Brinkerhoff et al., 2017; Catania et al., 2018; Eidam et al., 2020). A previous study characterized the retreats of 15 tidewater glaciers in Greenland and found that there is a relationship between the topography under a glacier and its retreat rate. This relationship is such that glaciers will retreat rapidly through wide over-deepened areas. The retreats through such areas are heightened when the bed has a slope that trends downhill from the terminus away from the ocean, also known as a retrograde slope (Amundson & Carroll, 2018; Catania et al., 2018). In Alaska, the Columbia Glacier has exhibited this behavior since 1952, when it started to retreat rapidly through a deepened area. The glacier then then sat pinned at a constriction between 2000 to 2004, dramatically slowing the retreat rate for these years (McNabb & Hock, 2014).

Glaciers are also able to create pinning locations by the sediments they carry (Brinkerhoff et al., 2017; Eidam et al., 2020). The growth of a new moraine at the terminus of the glacier may delay glacier retreat by providing stability at the terminus (Eidam et al., 2020). Dynamic combinations of geometry of the fjord floor and walls are evidence that the atmosphere isn't the only factor driving glacial melt and it is highly likely that the fjord geometry and ocean have some impact (Catania et al., 2018; McNabb & Hock, 2014.

Research Question

This project aims to address the question: does sea surface temperature control glacier terminus retreat in Alaska? To do this, we look at sea surface temperature and fjord geometry to see if there is a connection between shallow sills within the fjord and anomalously high sea surface temperatures with tidewater glacier step retreat events. We also investigate another mechanism that may have an impact: anomalously high air temperature. This is because SST analogies may not be the only driver and the interaction of anomalously high air temperatures with tidewater glaciers may have an impact on the timing of Alaskan tidewater glacier retreat. This study combines fjord geometry, sea surface temperature, and air temperature with terminus position data. Through the combination of these data, we aim to provide a possible contributing factor for the non-uniform retreats of Alaskan tidewater glaciers.

Methods

To start out, geometric features were compared across two subregions, KPWS and Archipelago. These included the distribution of sills and sill depths in the 17 fjords. The majority of sills were less than 100 meters deep, with some as shallow as 2 meters. Glacial retreats were then assessed at the subregional level. Retreats were then assessed by sill depth, to see if there is a connection between shallow-silled fjords and enhanced glacier retreat, and then by temperature anomalies to get an understanding of the atmosphere's impact on glacier retreat. Both SST and AT anomalies were broken into categories by subregion and sill depth.

Study Area

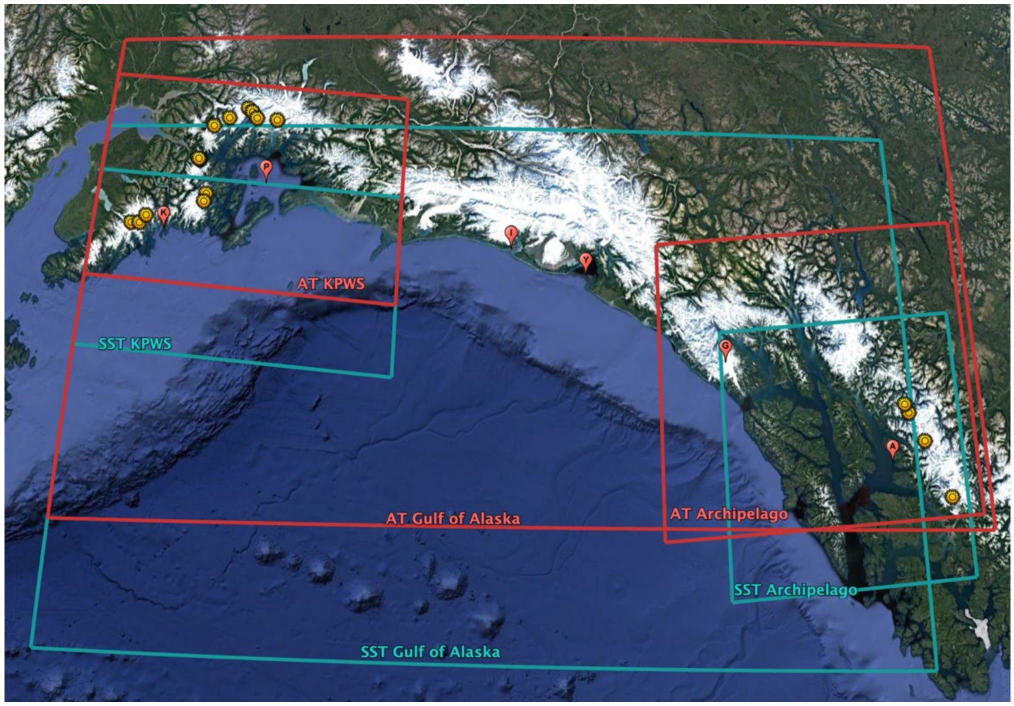


Figure 2: Study Area

Google Earth image of southern Alaska with the included tidewater glaciers marked by yellow stars. Pins with letters inside indicate studied areas (K: Kenai Peninsula, P: Prince William Sound, A: Archipelago) or places mentioned as potential future study sites (I: Icy Bay, Y: Yakutat Bay, G: Glacier Bay). Blue boxes show where SST data were taken from and red boxes show where AT data were taken from.

The mountainous state of Alaska is home to many glaciers, both alpine and tidewater terminating. The southern coast of Alaska is home to 59 glaciers, 50 of which terminate into tidewater (McNabb & Hock, 2014). This study focuses on a subgroup of the 50 tidewater glaciers in the region.

We investigated 17 Alaska tidewater glaciers divided into two regions in the southern and southeastern portion of the state (Figure 2). There were six possible areas of interest: Kenai Peninsula, Prince William Sound, Icy Bay, Yakutat Bay, Glacier Bay, and the Archipelago. These are labelled on the map above. Of these six potential areas, we studied three: Kenai Peninsula, Prince William Sound, and the Archipelago. We grouped Kenai Peninsula and Prince William Sound into a subregion to get our final two subregions: KPWS and the Archipelago. We studied these areas in particular because we had both terminus position and bathymetry data for them which made it viable to investigate these areas.

The glaciers studied range in area from tens of square kilometers (Beloit Glacier, 22.93 km^2) to hundreds of square kilometers (Columbia Glacier, 943.68 km^2). Glacier lengths vary over the time series, with a minimum length of 8.8 km (Holgate Glacier in 1980) to a maximum of 66.9 km (Columbia Glacier in 1975) (McNabb & Hock, 2014).

The fjords these glaciers terminate into were of varying length, ranging from 4.38 km to 50.8 km with an average fjord length of 21.4 km from glacier terminus to where the fjord joined either the Pacific Ocean or other main channel or body of water.

The area was divided into two subregions, Prince William Sound (PWS) and Kenai Peninsula to the north, and the Archipelago to the southeast (Figure 2). Dividing the two subregions was necessary because there are approximately four degrees latitude between them. We also compared results to the whole Gulf of Alaska in order to explore the systems as a whole. These regions are shown on Figure 2 above.

Prince William Sound is a large sound on the south coast of Alaska that opens to the Pacific Ocean. The PWS region has 13 tidewater glaciers in total, though we focus on 10 of those systems here. One notable glacier within PWS is Columbia Glacier, which has seen a dramatic retreat since 1957 (McNabb & Hock, 2014). Also in this subregion, the Kenai Peninsula contains the westernmost glaciers investigated. It is a

200+ km long peninsula in southern Alaska with 11 tidewater glaciers, three of which were included in the study (McNabb & Hock, 2014). The glaciers here terminate in fjords that have direct contact with the Pacific Ocean. Due to the proximity with PWS (resulting in the two regions having very similar climates) and the small sample size, the two areas were combined into one called KPWS. The other subregion, the Archipelago, contains the most southerly and most eastern glaciers examined here. Of the 14 tidewater glaciers in SE Alaska, we focus on four specific systems (McNabb & Hock, 2014). One notable glacier in this area is LeConte Glacier, which is the southernmost tidewater glacier in the Northern Hemisphere (McNabb & Hock, 2014). These systems help provide an understanding of how southern tidewater glaciers are reacting to the changing climate.

Data Collection

Bathymetry

Fjord bathymetry data were from a combination of single beam and multibeam echosounder surveys compiled by the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (National Centers for Environmental Information, 2021). The data were gridded at resolutions between 5 and 20 meters. Bathymetry data for LeConte Bay were gathered during August 2016 by a multibeam echosounder survey at a resolution of 5 meters. Data gaps for LeConte Bay were interpolated using two 20-meter resolution fathometer surveys conducted during August 1999 and September 2000 (Eidam et al., 2020).

The calculation of thalweg transects was estimated by selecting a geographic region encompassing a specified fjord, then manually tracing the deepest part of each fjord in order to create a thalweg profile (Figure 3a). The thalweg sections provided geometric information including the fjord length, depth, and sill location(s), with an example bathymetry and thalweg transect for Columbia Glacier shown in Figure 3. This figure shows the fjord transect with the glacier on the left and ocean to the right. There are two sills highlighted, one much shallower than the other. The glacier terminus can be seen on the left side of the profile as a rapid shallowing-out of a 400 m deep area. Many fjords contain multiple sills, such as this one, which show up clearly on the thalweg transect. Across-fjord profiles were obtained at each sill to determine sill depth and fjord width. In fjords with multiple sills, sills were labeled numerically with increasing values indicating distance away from the glacier terminus and toward the ocean.

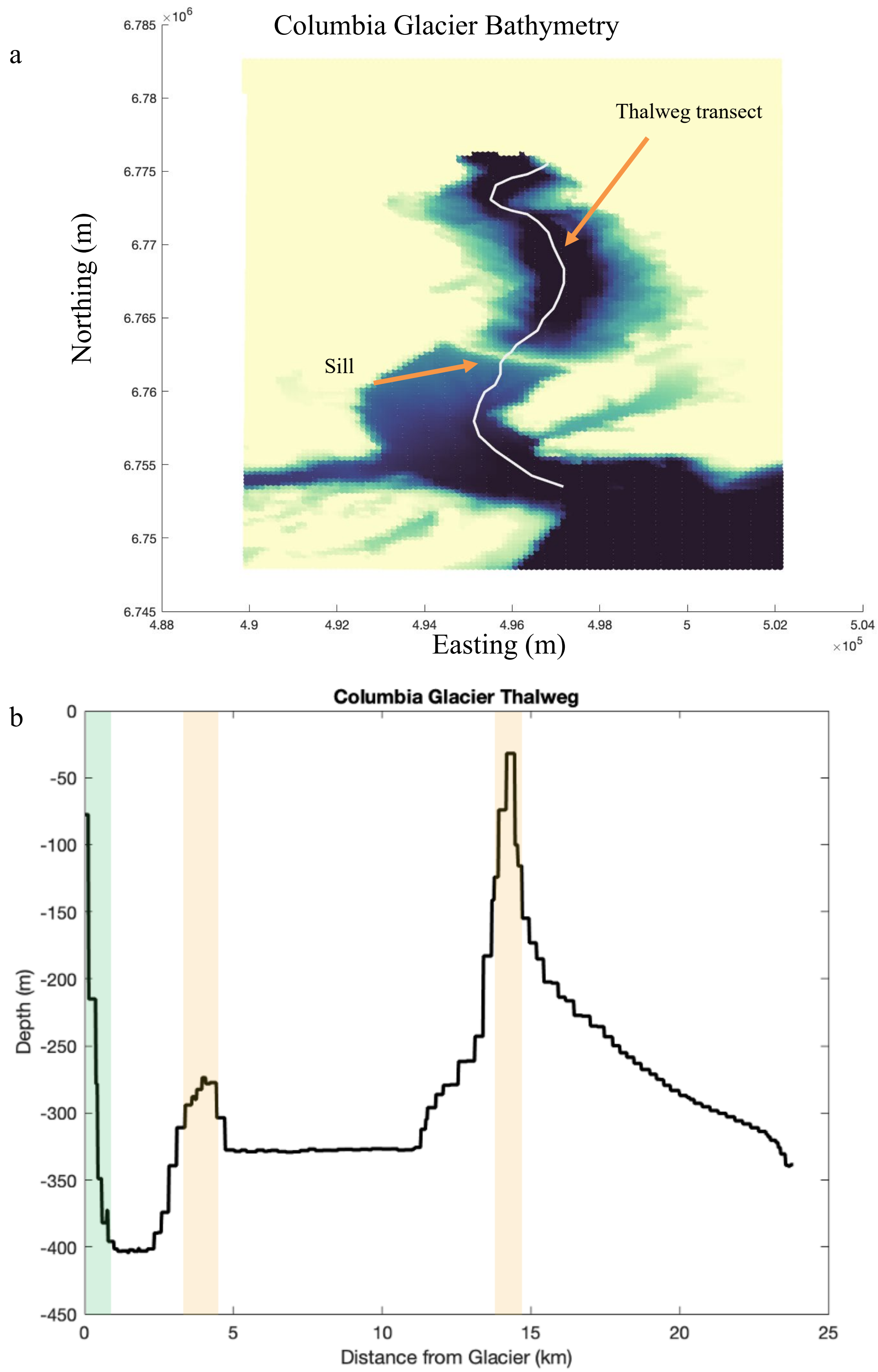


Figure 3: Columbia Glacier thalweg transect.

a) Bathymetry for section of Prince William Sound that Columbia Glacier terminates into with thalweg line in white, darker colors indicate greater depths below sea level. b) Fjord depth profile along the thalweg in front of Columbia Glacier with sills highlighted in orange. The two sills in this fjord sit at approximately 50 m and 275 m below sea level. Some thalweg profiles show a rapid rise in topography near the glacier, which is actually the face of the terminus, highlighted in green. The ocean is on the right and the glacier flows from left to right. On the y-axis, 0 m shows the sea surface with other elevations taken from that reference.

Terminus Positions

Terminus position data were sourced from McNabb and Hock (2014), who calculated terminus positions for 50 Alaska tidewater glaciers from 1948 to 2012. For years prior to 1972, terminus positions were assembled from manually digitized U.S. Geologic Survey topographic maps. For years after 1972, images from the National Aeronautics and Space Administration and United States Geological Survey's joint Landsat program were compiled and used to find terminus positions (McNabb & Hock, 2014). These data were organized into plots of total length change and relative length change for each glacier. We show two examples of relative length change in Figure 4, one for South Sawyer Glacier and the other for LeConte Glacier. Relative length change was taken with respect to the earliest measurement for each glacier which was 1948 ± 1 year. Using the relative change in length for each glacier meant that it was easier to compare between glaciers because we were able to look at the distance the terminus had retreated rather than the length change of the glacier as a whole.

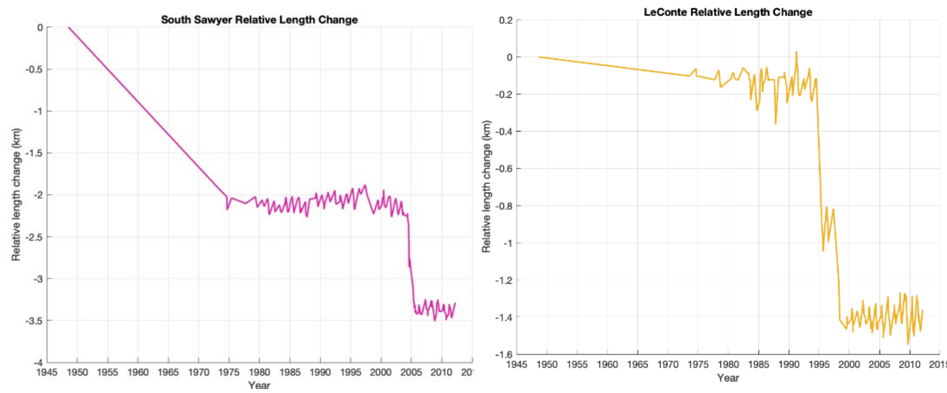


Figure 4: Length Change for South Sawyer and LeConte Glaciers

Relative length change (km) for South Sawyer (left) and LeConte (right) glaciers from 1948 to 2012. Step change retreat events can be seen for South Sawyer in the mid 2000s and LeConte in the mid 1990s. The y-axes differ for each glacier, with 0 km representing the glacier terminus position at the earliest measured date. Data were sparse before approximately 1970, which is why the retreat between the initial date and then is a straight line.

Sea Surface Temperature and Air Temperature

Sea surface temperature (SST) and air temperature (AT) data were downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF). Specifically, the data came from the ECMWF Reanalysis v5 (ERA5) which is produced by the Copernicus Climate Change Service, a section of the ECMWF. ERA5 provides climate information in a 30 km grid updated hourly. It uses a combination of historical and gathered data (both satellite and in-situ) as inputs for the ECMWF's climate model (Copernicus Climate Change Service, 2022).

The ERA5 dataset begins in 1979, which we used as the start of the observed time period, and we extend our study until 2012, the last year of available terminus positions from McNabb and Hock (2014).

Sea surface and air temperatures were each averaged over one year in order to remove seasonal variations. The removal of seasonal variations was necessary because we were looking at interannual and longer-term trends, not the difference between summer and winter temperatures and behaviors. Temperature anomalies were calculated by subtracting the mean annual temperature from 1979-2012 from the annual mean temperature for each year. Significant anomalies were then defined as temperature anomalies greater than 0.25ºC from the mean of the study period.

Temperature data were specified for three regions: the Gulf of Alaska, Kenai Peninsula/Prince William Sound, and the Archipelago regions (Figure 2), resulting in three separate time series. To count glacier retreat events within each subregion, retreat events were compared to SST and AT anomalies for their subregion. We also compared SST and AT anomalies across all regions in the Gulf of Alaska, for which we used SST and AT averaged over the entire gulf.

Data Organization and Analysis

Selecting Representative Glaciers

In total, we used 17 of the 50 glaciers with terminus positions in McNabb and Hock (2014). We selected these glaciers because they fit two criteria: (i) remained tidewater glaciers for the entire study period and (ii) had adequate and available bathymetry data.

A number of glaciers in the region had retreated onto land during the study period which, because there would no longer be any interaction with the ocean, resulted in their elimination from analysis here. Other glaciers were omitted due to a lack of adequate bathymetry data. This included the region near Glacier Bay as well as Icy Bay and Yakutat Bay (Figure 2).

Defining A Retreat Event

Glacier retreat events were defined by the following equation in which dL is the length change of the glacier, μ is the mean length change, N is the number of standard deviations, and σ is the standard deviation of length change.

$$dL < -(\mu + N\sigma) \tag{2}$$

This equation describes the process in which we defined a glacier retreat first by calculating the mean and standard deviation of annual glacier length change for each glacier over the entire time series. This provided an understanding of the natural variability and seasonal fluctuations in terminus position for each glacier. Then, if the retreat was greater than a specified number of standard deviations, the behavior was considered to be "outside of normal" and recorded as a retreat event. Consecutive retreat years were counted as one coherent retreat by only recording the first year of retreat. Example retreat events can be seen in Figure 4 where South Sawyer Glacier has a relatively constant length from 1975 to 2003. The glacier then retreated 1 km rapidly in 2003 before restabilizing once more. This process can also be seen in the same figure for LeConte Glacier but with a brief period of stability from 1995-1997.

The number of standard deviations away from the mean varied depending on the glacier in question but was between 1 and 2. Though not constant, this variability is not unexpected due to the natural variability between glaciers. Retreat events were manually crosschecked to verify the success of this method. There was at least one occasion where this method provided a less than ideal result but those were few and overall this method provided accurate dates for step retreats for the given glaciers. It was more reliable and repeatable than finding retreats by eye or by our other attempted methods. Despite this method being the best we tried, it would have been preferable to have one standard deviation value for all glaciers.

Defining Sill Depths

Fjords were categorized into groups by sill depth, since we expect sills to influence fjord circulation and the amount of heat that is available to melt the glacier front. Sills were divided into three depth categories: shallow (0-10 m), intermediate (10-100 m), and deep (>100 m). An example fjord profile showing multiple sills is LeConte Bay (Figure 5), which shows the three sill depth categories used. Many fjords had multiple sills at varying depths, such as in Figure 5, which meant that we had to decide which value to use as our representative sill depth for the system. The shallowest sill depth was chosen because we were looking at the passage of the external water column over sills and considered the shallowest sill to be the greatest constricting factor in water passage through the fjord.

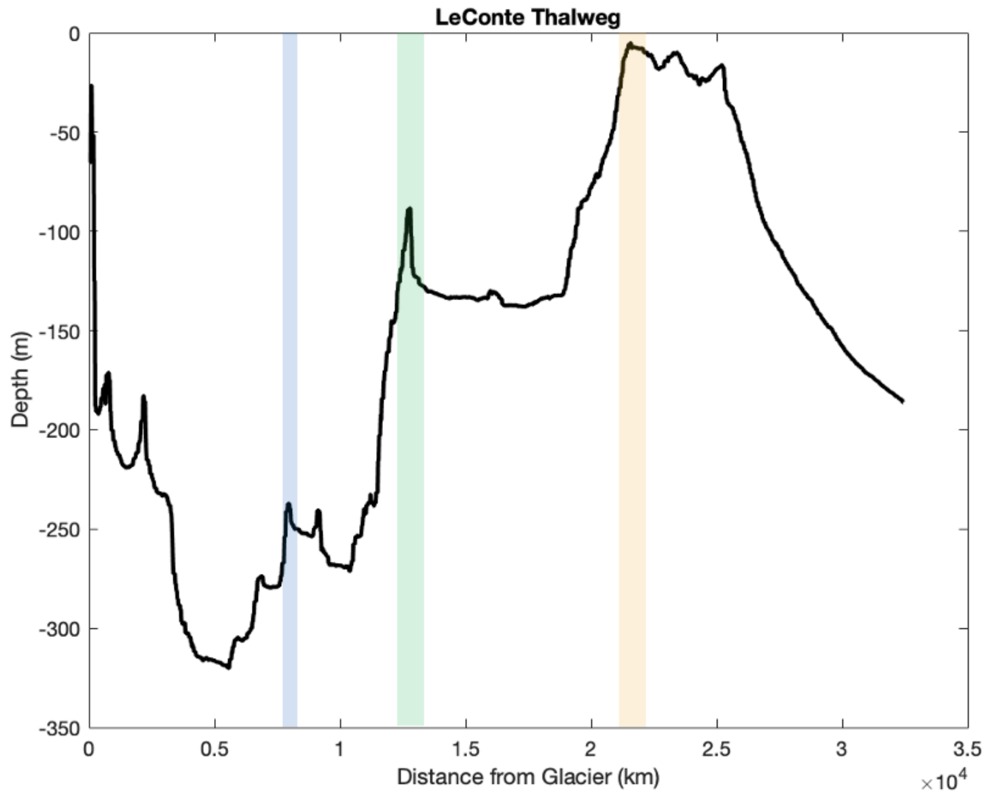


Figure 5: Sill Depths at LeConte Glacier

This thalweg shows the three sill depths, shallow (0-10 m) in orange, intermediate (10-100 m) in green, and deep (>100m) in blue. The glacier is on the left and ocean to the right. Flow of LeConte is left to right.

Results

Sill Distribution

Many fjords in the Gulf of Alaska contain sills that are relics of previous glacial extent. Sill depths vary across the region from 2 meters to 120 meters below sea level. In the study area there are five shallow-silled fjords, 10 fjords with intermediate sills, and two deep-silled fjords (Table 1). The KPWS subregion contained 13 glaciers terminating in fjords with varying geometry. Of the 13 glaciers in this subregion, four terminated in fjords with shallow sills. The remaining nine terminated in fjords with intermediate sills. The Archipelago subregion contained four of the 17 glaciers. Of these four, one (LeConte Glacier) terminated in a fjord with a shallow sill, one (Sawyer Glacier) terminated in a fjord with an intermediate sill, and two (Dawes and South Sawyer Glaciers) terminated in fjords with deep sills (Table 1).

Glacial Retreats by Subregion

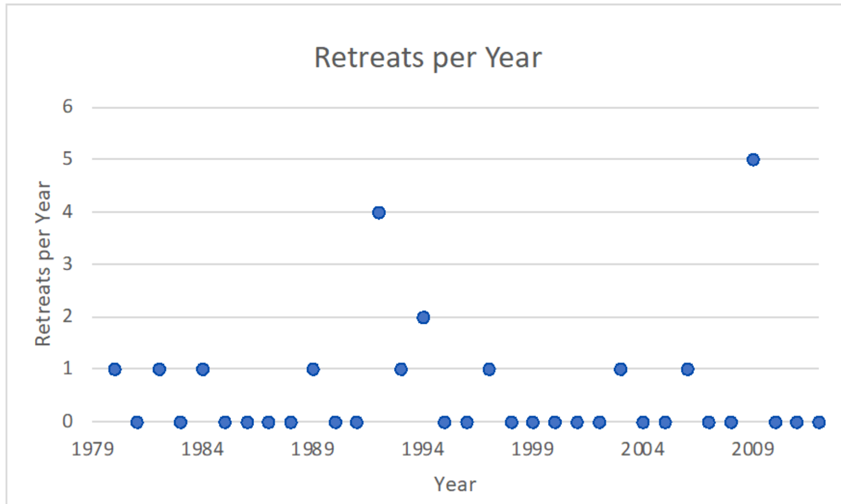


Figure 6: Number of Retreats per Year

Cumulative number of retreat events per year for the study period.

Glacier	Subregion	Number of sills	Deepest Fjord Depth	Shallowest Sill (m)	Sill Depth Category	Retreat Date(s) 1979-2012
Beloit	PWS	3	-134	-1.6	Shallow	1984
Blackstone	PWS	1	-134	-4.5	Shallow	n/a
Chenega	PWS	1	-336.6	-40.4	Intermediate	1976, 2009
Columbia	PWS	2	-404	-32	Intermediate	1993, 2009
Harvard	PWS	1	-232	-42.7	Intermediate	1992
Meares	PWS	1	-335.6	-8.2	Shallow	n/a
Tiger	PWS	1	-149	-36.1	Intermediate	n/a
Yale	PWS	2	-232	-34.2	Intermediate	1977
Surprise	PWS	3	-131	-19	Intermediate	n/a
Barry	PWS	1	-113.8	-17.5	Intermediate	2009
Aialik	KP	2	-293	-10.4	Intermediate	1982, 1992
Holgate	KP	4	-293	-6.3	Shallow	1976, 1992, 2009
Northwestern	KP	2	-304.8	-10.9	Intermediate	1994
Dawes	Archipelago	1	-329.2	-118.9	Deep	1980, 1989
LeConte	Archipelago	3	-320.1	-5.1	Shallow	1994, 1997
Sawyer	Archipelago	1	-175	-30.1	Intermediate	1992, 2006, 2009
South Sawyer	Archipelago	1	-209.1	-114.1	Deep	2003

Table 1: Retreat Data

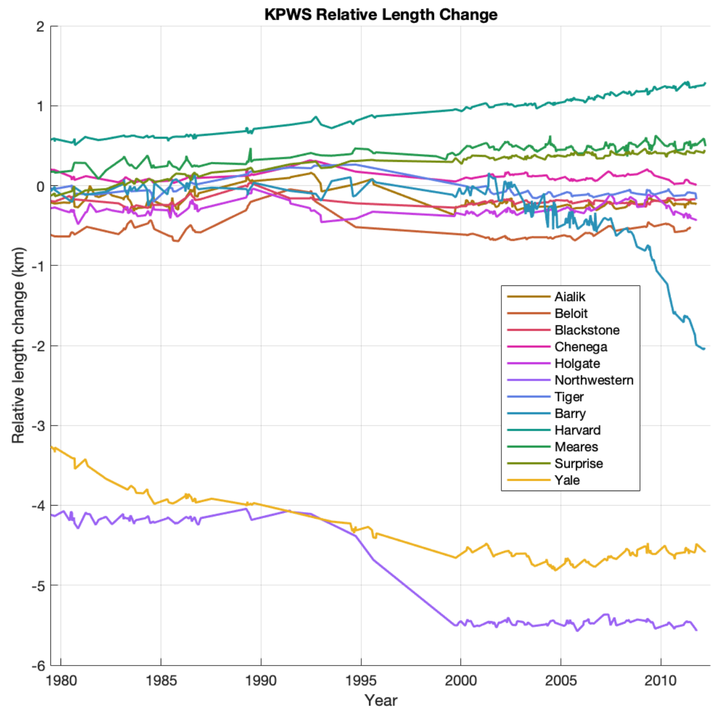
Location, number of sills, deepest fjord depth, depth of the shallowest sill in the fjord, classification as shallow/intermediate/deep, and retreat year(s) between 1979 and 2012 for the systems studied.

During the time period 1979 to 2012, 13 of the 17 glaciers studied retreated with a total of 19 distinct retreat events (Table 1). Notably, in 2009, a total of 5 glaciers experienced retreat events, which was the highest number of retreat events recorded in one year. The year containing the second highest number of retreat events was 1992

(Figure 6). The majority of glaciers experienced two retreat events, with a range of 0-3 per system (Table 1).

In the KPWS subregion, 10 glaciers retreated, and three glaciers advanced during the time period (Figure 7a). Glacier retreats varied from 170 meters (Blackstone Glacier) to 20,110 meters (Columbia Glacier) (Figure 7b). Three glaciers advanced with a maximum advance of 1290 meters (Harvard Glacier) and a minimum advance of 4 meters (Chenega Glacier). Four glaciers in this subregion did not experience stepwise retreat events while nine experienced either one or more events. Found, but not shown here, was that there was no correlation between net length change or sill depth and the occurrence of one or more retreat events.

a



b

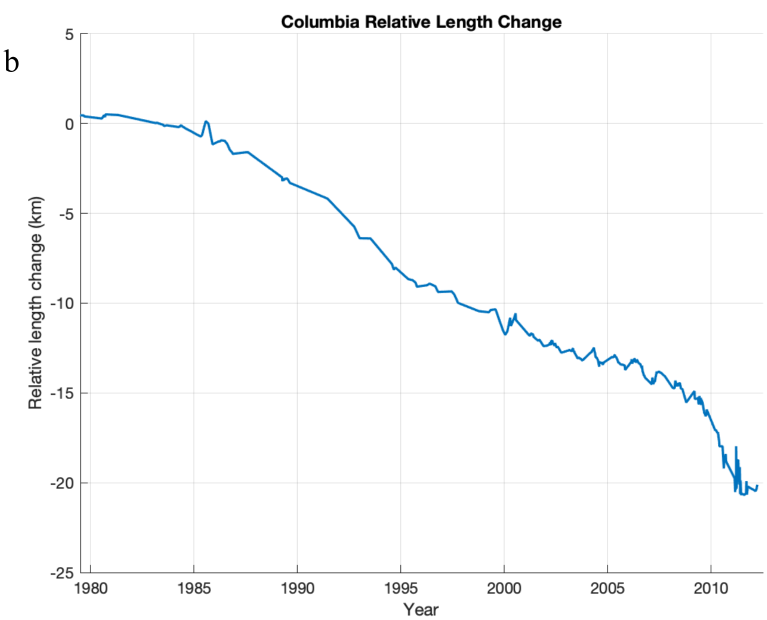


Figure 7: KPWS Length Changes

(a) Relative length change (km) for KPWS glaciers from 1979 to 2012 with 0 length fixed to 1948. (b) Same as in a, but for the Columbia Glacier relative length change (km). The dramatic retreat of this glacier required an expanded y-axis scale. We did not classify this retreat as a step change retreat but did classify the years 1993 and 2009 as having step retreats. The retreat events were found by our method described earlier. Using this method, we were able to find either the 1993 and 2009 step retreats or neither of them, at a standard deviation of 1.7. It would have been preferable to be able to exclude the 1993 result and describe the 2009 result as a relatively weak step retreat, especially in comparison to some other events such as for South Sawyer (Figure 8), but with our method we were unable to achieve this distinction.

Archipelago

All glaciers in the Archipelago subregion retreated. The maximum retreat distance was 4350 meters (Dawes Glacier), and the minimum retreat distance was 1360 meters (LeConte Glacier). All glaciers in this subregion experienced at least one retreat event (Figure 8).

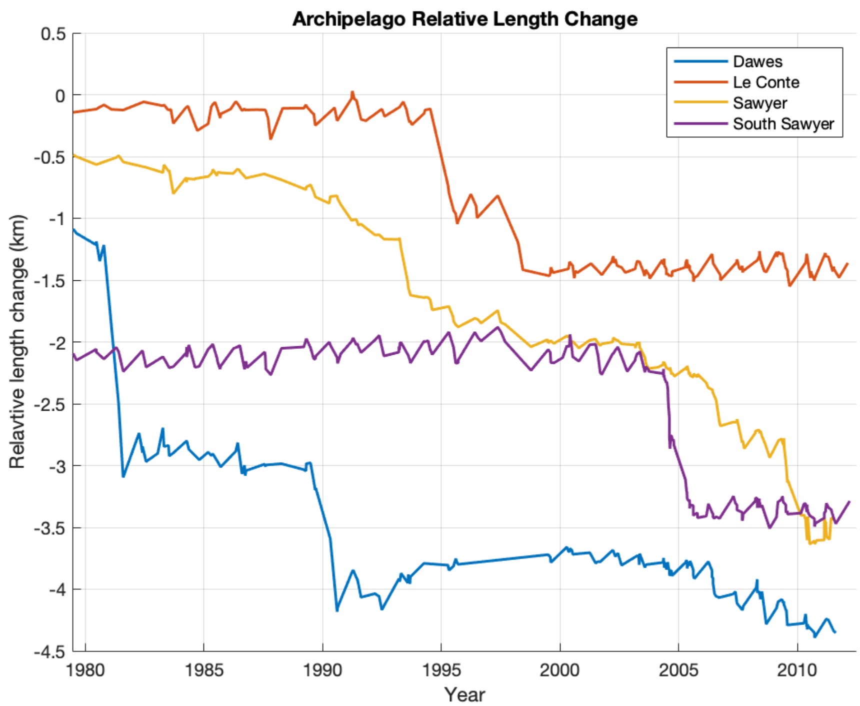


Figure 8: Archipelago Relative Length Changes

The relative length changes for the Archipelago subregion from 1979 to 2012. Distances taken with respect to 0 in 1948. Step retreat events can be seen in 1980 and 1989 for Dawes Glacier, 1994 and 1997 for LeConte Glacier, 1992, 2006, and 2009 for Sawyer Glacier, and in 2003 for South Sawyer Glacier.

Glacial Retreat by Sill Depth

The 17 glaciers cumulatively experienced 19 retreat events. Across the three depth categories, the majority of retreat events occurred in fjords with intermediate sills. 13 of the 17 glaciers retreated during the study period and four advanced. Both of the two glaciers that terminated in fjords with deep sills retreated during this time. Dawes Glacier and South Sawyer Glacier make up this category and retreated approximately 3.5 and 1.5 km respectively in the study period. There was a total of three retreat events between these two glaciers which can be seen in Figure 8. Shown in blue (Dawes

Glacier) and purple (South Sawyer Glacier) in Figure 8, retreat events are clear, beginning in 1980, 1989, and 2003. Five glaciers terminated in fjords with shallow sills. Three of these glaciers experienced step retreats within the time period while two glaciers did not. There were five total retreat events for glaciers with shallow sills. The two glaciers in this category that did not retreat were Blackstone and Meares Glaciers, both of which showed erratic behavior but not step retreats (Figure 7a). Ten glaciers terminated in fjords with intermediate sill depths. Of these ten glaciers, seven experienced retreat events during the time period for a total of 11 retreat events. The three that did not experience step retreat events were Yale Glacier, which retreated fairly consistently for the entire time, Surprise Glacier, which advanced, and Tiger Glacier, which rapidly advanced approximately 300 m in the 1990s then retreated approximately that distance in the early 2000s. The behavior of these three glaciers can be seen in Figure 7a which depicts the relative length change for glaciers in the KPWS subregion.

Temperature Anomalies

Temperature anomalies varied for both subregions over the study period of 1979-2012. SST anomalies varied from -1ºC to +1.1ºC for the KPWS subregion and from -0.75ºC to slightly over +1ºC for the Archipelago subregion (Figure 9). AT anomalies tended to be greater in magnitude, ranging from -2.6ºC to +2.4ºC for the KPWS subregion and from -3.1ºC to +2.5ºC for the Archipelago subregion (Figure 9).

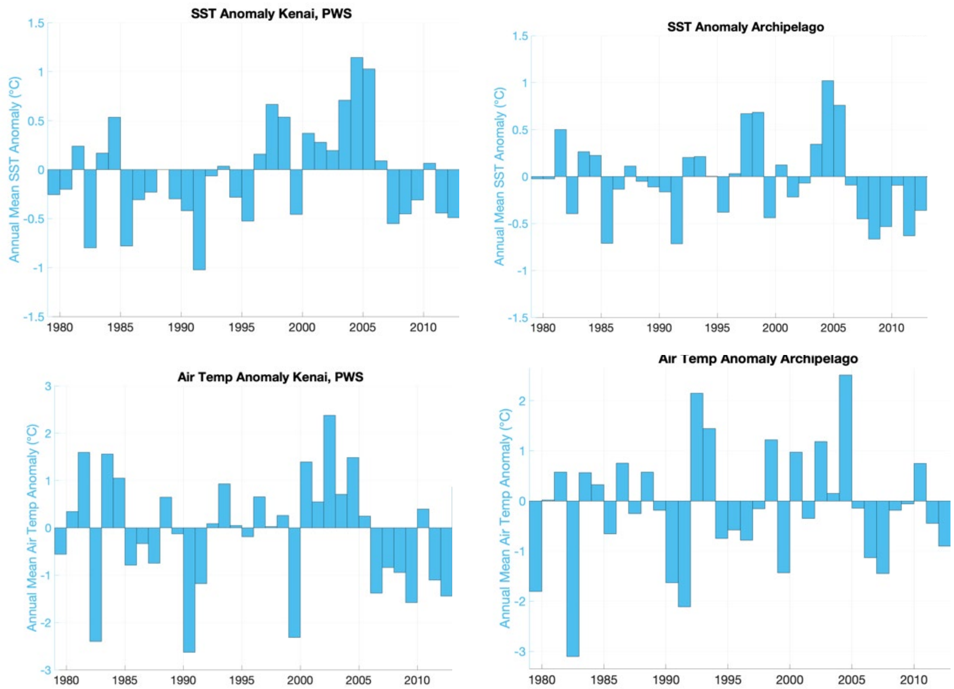


Figure 9. Sea Surface Temperature and Air Temperature Anomalies

Y-axes differ between SST and AT.

Top: Annual SST anomalies for KPWS and Archipelago subregions 1979-2012.

Bottom: Annual AT anomalies for KPWS and Archipelago subregions 1979-2012.

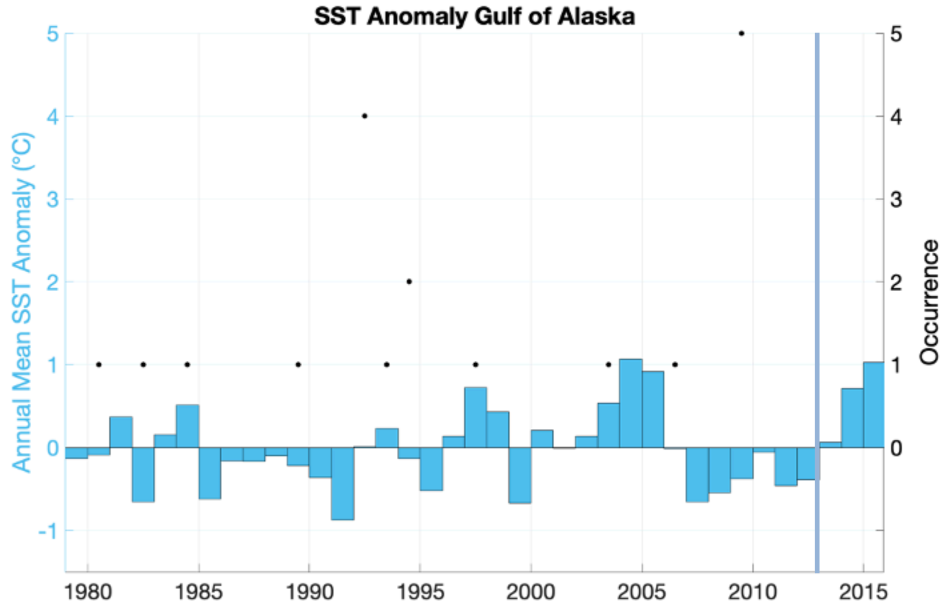
Sea Surface Temperature and Glacier Retreat

Through the entrainment of warmer water over a sill, high SST anomalies may impact glacial melt at the terminus and retreat. The Gulf of Alaska experienced seven above average sea surface temperature anomalies between 1979 and 2012. The highest anomaly was greater than 1ºC above average, in 2004. Across the Gulf of Alaska, 3 retreat events (16%) were experienced during SST anomalies and 5 (26%) occurred within two years after (Figure 10a).

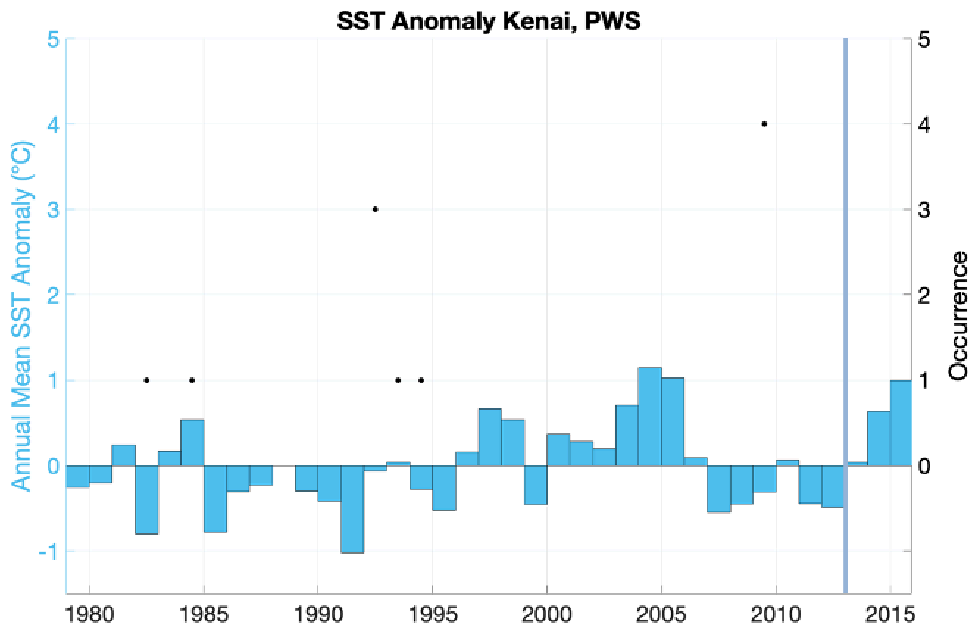
Retreats During SST Anomalies by Region

Of the 13 glaciers in the KPWS subregion, one (9%) retreat event occurred during the same year as an SST anomaly. There were no retreat events one year or two years after and including an anomalous year (Figure 10b). In the Archipelago subregion, two (25%) glaciers retreat events occurred in the year of an SST anomaly and three (38%) retreats occurred within one year of an SST anomaly with no increase two years after an anomaly (Figure 10c).

a


SST Anomaly Gulf of Alaska
Annual Mean SST Anomaly (°C)
Occurrence
5
4
3
2
1
0
-1
1980
1985
1990
1995
2000
2005
2010
2015

b


SST Anomaly Kenai, PWS
Annual Mean SST Anomaly (°C)
Occurrence
5
4
3
2
1
0
-1
1980
1985
1990
1995
2000
2005
2010
2015

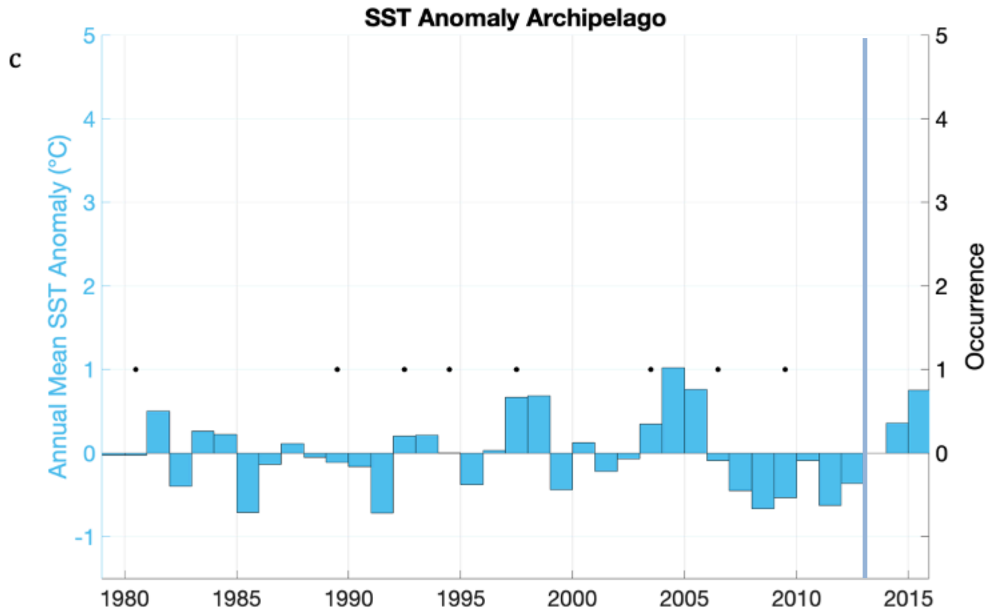


Figure 10: Retreat events plotted with SST anomalies

SST anomalies are in blue with retreat event occurrence in various colors on right axis shown in black dots denoting number of glaciers that experienced a retreat event in the given year. (a) shows this for the Gulf of Alaska, (b) for KPWS subregion, and (c) for the Archipelago subregion. Vertical lines denote end of study period (2012).

Retreats During SST Anomalies by Sill Depth

Two out of five (40%) retreats in shallow-silled fjords occurred within the same year as an SST anomaly. There were no further retreats within one or two years of an SST anomaly. No glaciers with intermediate sills retreated in the same year as an SST anomaly. This increased to 1 (9.1%) retreat within one year of an anomaly and did not change within two years. One third of retreats (1 retreat) in deep-silled fjords occurred in the same year as an SST anomaly with no further retreats occurring within the year after or two years after a temperature anomaly (Table 2).

Sill Depth	Retreats during SST anomaly	Retreats within 1 year of SST anomaly	Retreats within 2 years of SST anomaly
All Glaciers	16%	26%	26%
0-10 meters	40%	40%	40%
10-100 meters	0.00%	9.10%	9.10%
100+ meters	33.30%	33.30%	33.30%

Table 2: SST anomalies and Sill Depths.

Sill depth, percent of retreats during an SST anomaly, percent of retreats within one and two years of an anomaly. Expressed in percentage of retreats of total.

Air Temperature and Glacier Retreat

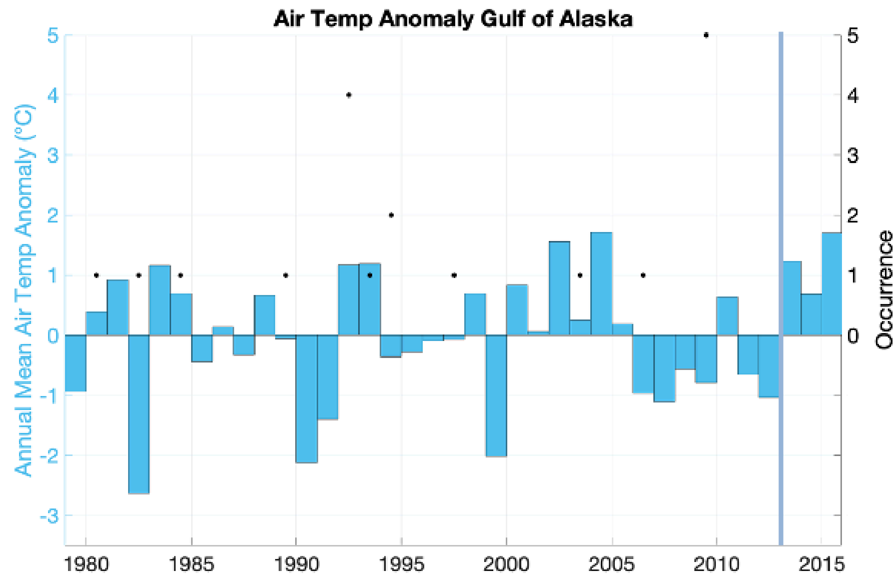
Air temperature interacts with a glacier at the surface and may increase melt along the length of the glacier. Increases in air temperature can affect the surface mass balance of the glacier, resulting in thinning if not compensated for by additional accumulation. Increases may also increase surface melt that can lead to higher subglacial discharge at the glacier terminus. Increased subglacial discharge increases the temperature and salinity of the near terminus region which can impact water circulation. There were 13 positive air temperature anomalies in the Gulf of Alaska over the course of the study period. The highest anomaly was 1.7ºC above average in 2004. Of the 19 retreat events, eight (42%) occurred during anomalous years. A further four occurred during the year after an AT anomaly, increasing the percentage of retreats to 63% (12 retreats) within one year (Table 3). Within two years of an AT anomaly, an additional one glacier retreated leading to a total of 13 retreat events (68% of retreats) occurring within two years of an AT anomaly (Figure 11a).

Retreats During AT Anomalies by Region

In the KPWS subregion, two (18%) retreats occurred during a year with an AT anomaly and four (36%) retreats occurred within that year and the year after (Figure

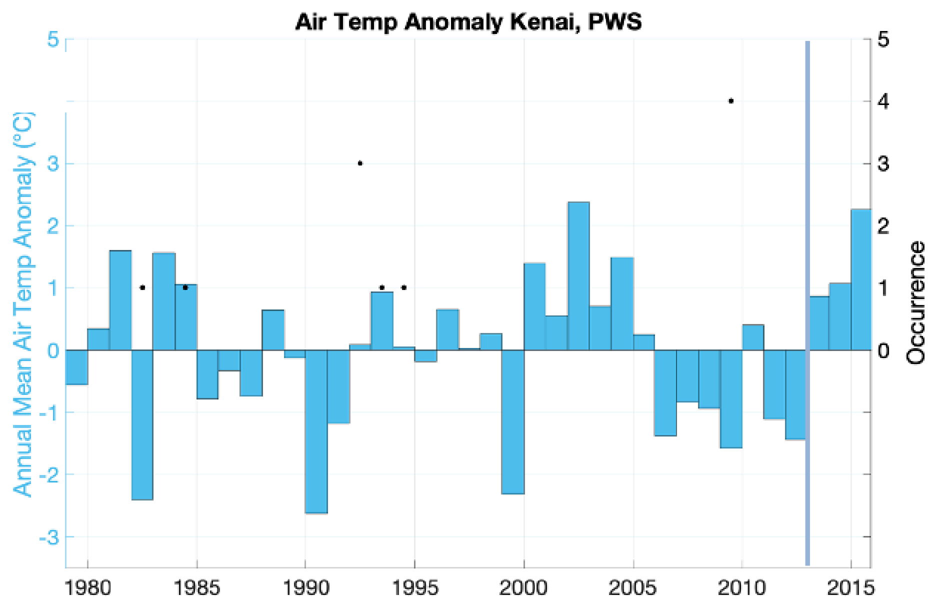
11b, Table 3). In the Archipelago subregion, two (25%) retreats occurred within the same year as an AT anomaly. Four retreats (36%) occurred within the same year and the following year, and six (75%) of retreats occurred up to two years after an AT anomaly (Figure 11c, Table 3).

a



Air Temp Anomaly Gulf of Alaska
Annual Mean Air Temp Anomaly (°C)
Occurrence
5
4
3
2
1
0
-1
-2
-3
1980
1985
1990
1995
2000
2005
2010
2015

b



Air Temp Anomaly Kenai, PWS
Annual Mean Air Temp Anomaly (°C)
Occurrence
5
4
3
2
1
0
-1
-2
-3
1980
1985
1990
1995
2000
2005
2010
2015

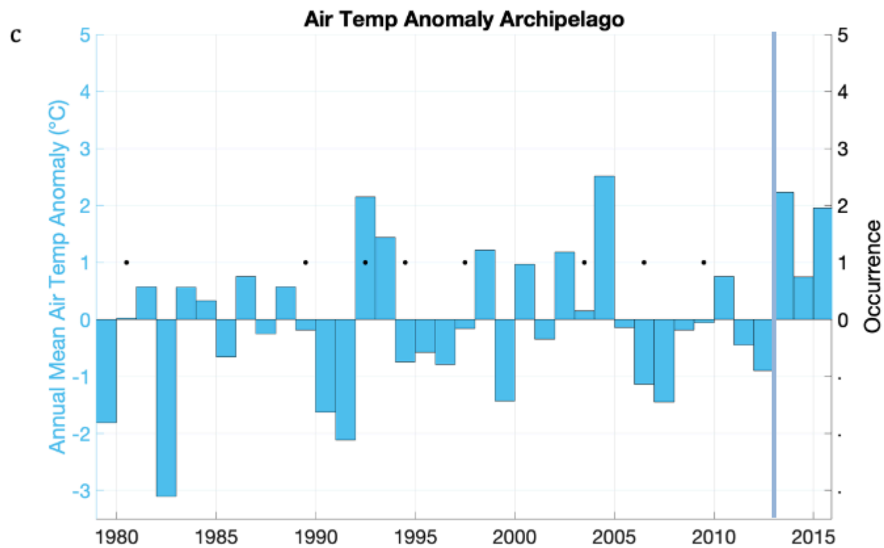


Figure 11: Retreat events plotted with AT anomalies

AT anomalies are in blue with retreat event occurrence in various colors denoting number of glaciers that experienced a retreat event in the given year. (a) shows this for the Gulf of Alaska, (b) for KPWS subregion, and (c) for the Archipelago subregion. Vertical blue lines denote end of study period (2012).

Retreats During AT Anomalies by Sill Depth

Table 3 shows that in shallow-silled fjords, one (20%) glacier retreat occurred within the same year as an AT anomaly. Two (40%) retreats occurred within the anomalous year and during the following two. In fjords with intermediate sills, two (18.2%) retreats occurred during an anomalous year. Four (36.4%) retreats occurred within the same year and the year after an AT anomaly, and five (45.5%) retreats occurred up to two years after an anomaly. Deep-silled fjords experienced no retreats within the same year as an AT anomaly. This rose to two (66.7%) retreats occurring within the year after an anomaly and there were no retreats in the second year after an AT anomaly (Table 3).

Sill Depth	Retreats during AT anomaly	Retreats within 1 year of AT anomaly	Retreats within 2 years of AT anomaly
All Glaciers	42%	63%	68%
0-10 meters	20%	40%	40%
10-100 meters	18.20%	36.40%	45.50%
100+ meters	0%	66.70%	66.70%

Table 3: AT anomalies and Sill Depths. Expressed in percentage of retreats of total.

Discussion

Tidewater glacier retreat in Alaska is non-uniform over time and geography, making it difficult to accurately quantify the total melt of the systems and their contribution to global sea level rise (Eidam et al., 2020; McNabb & Hock, 2014**)**. To try continue to understand what these driving factors are, we investigated the interaction of tidewater glacier retreat with the environment. Specifically, how fjord geometry and SST anomalies interact to impact water temperature at the terminus of marine terminating glaciers. We also investigated how AT anomalies impact the start of step retreat events for tidewater glaciers. Many other factors can impact the timing of tidewater glacier retreat, notably including the tidewater glacier cycle (Meier and Post, 1987; Post et at al., 2011). In these cases, the retreats are possibly unrelated to environmental forcings. By comparing the data we have with each other, we can suggest that SST anomalies may have an impact on the timing of retreat of tidewater glaciers that terminate in fjords with shallow sills.

Glacier retreat during years of anomalously high SST may be impacted by sill depth in the fjord. A higher percentage of retreats occurred in the same year as a high SST anomaly in fjords with shallow sills than in fjords with intermediate or deep sills (40% of retreat events in shallow-silled fjords compared to 0% in intermediate and 33% in deep-silled fjords). This higher percentage of retreats may indicate that when the sill impacts water circulation during a high SST anomaly, glacier termini are impacted. The water column in Alaska is stratified with warmer water near the surface and cooler water at greater depths (Hager et al., 2022). Only permitting the topmost part of the water column into the near terminus region would raise the temperature of the rest of the water in the near terminus region. This higher temperature could result in an increased rate of melt of the face of the terminus and possibly prompt a retreat from a point of relative stability in years of anomalously high SST (McNabb & Hock, 2014). There were only five glaciers with shallow sills; however, so it may be valuable to compare with a higher number of shallow-silled fjords. The low percentage of glacial retreats from intermediate-silled fjords indicates that it is possible that shallow sills enhance glacier retreat by changing water circulation in the fjord.

The number of retreats that occurred within a high SST anomaly and within the two years after were approximately the same. This indicates that SST only has an impact in the same year as the anomalously high temperature. The effects of SST only act at the terminus, where the water touches the glacier. This means that, as SST changes year to year, the interactions of ice and ocean with each other are also on a year to year timescale, unlike AT which interacts with more of the glacier.

Though SSTs corresponded with the trigger of some retreat events, they did not account for all, indicating that there must be other influences on tidewater glacier retreat. A possible other influence is AT. The percentage of retreat events within the following two years after an AT anomaly tended to increase, particularly in the first year following the anomaly. Higher AT anomalies may lead to enhanced melting along the length of the glacier. Higher quantities of melt may contribute to liquid water running between the base of the glacier and the ground. This has been shown to increase the speed at which the glacier travels and could be linked to enhanced retreat (Alexander et al., 2013). Increased melt could have impacts lasting longer than one year which would explain the occurrence of increased retreat events within two years after an AT anomaly. This may also mean that AT has a larger impact on glacier retreat than SST, which has been observed in Greenland (Fahrner et al., 2021). In Alaska, the impacts appear to be particularly strong in the first year after a high AT anomaly.

Air temperatures tended to have a greater impact on glacier retreats in the Archipelago subregion than in KPWS. This may have been due to the nature of the anomalies, the Archipelago subregion had three anomalies greater than two degrees Celsius whereas KPWS had two anomalies greater than two degrees. The Archipelago subregion is further south than KPWS by ~4 degrees. The subregion may already be warmer and closer to 0°C, so an anomaly of 1-2 degrees may have a greater impact for the Archipelago. KPWS on the other hand may not be as impacted by a 1-2°C anomaly because 1-2°C from a lower initial starting point does not take the area as close to the melting point.

Through the entrainment of the topmost part of the water column, shallow sills alter the temperature regime at the terminus of a tidewater glacier (Hager et al., 2022). In years of anomalously high SST, the fjord geometry and water circulation may result in these anomalously warm ocean waters reaching the terminus region, potentially triggering the step retreat of the glacier. Thus, it seems that SST anomalies have some forcing on the timing of Alaskan tidewater glacier retreat for glaciers terminating in fjords with shallow sills. However, SST anomalies do not account for the triggering of all step retreats, leading us to believe that other factors, including AT anomalies, have an impact as well.

Limitations

One limitation of this study is the sample size. In order to get representative glaciers, many that data exist for had to be removed for various reasons, such as no available bathymetry or that the glacier ceased being a tidewater glacier during the study period. The included glaciers cover a large area, but there are gaps in geographic coverage and distribution such as the region of the Southeastern Alaskan coast between the two subregions where Icy Bay, Yakutat Bay, and Glacier Bay are. From Figure 2, one can see how these three locations would help fill in the void between the two studied subregions.

Another limitation is that air temperature and sea surface temperature co-vary but were treated as independent variables. This may mean that patterns between the two unintentionally confounded some aspects of the interpretation. Because air and ocean meet at a boundary, heat can be transferred from one to the other. A large difference between SST and AT may drive thermal transport between the two, resulting in SSTs influenced by ATs and vice versa. This could possibly lead to confusion in the results in which it is not clear which temperature factor was the initial controller of a glacial retreat.

In this study, we used SST to represent the temperature for the topmost layer of the ocean. SST is not indicative of the whole water column temperature, and it is unclear to what depth our values of temperature remain accurate. This gap could be remedied by having a better understanding of the relationship of SST to temperature at depth.

There were also features of glaciers that were out of the scope of this study but may contribute to glacier retreat. One such factor is the amount of debris on the surface of the glacier. Higher quantities of debris lower the albedo (reflection of solar radiation from a surface back into space) by changing the color of the surface from white or near white to darker, rockier colors. The darker surface would absorb more solar radiation which would heat the glacier more than if the radiation was reflected (Ming et al., 2015).

Another feature not included is glacier size. Glacial retreat rates vary for each glacier for a number of reasons including cross-sectional area and ice thickness. These features contribute to the rate of mass loss or gain, particularly through the rate of frontal ablation. Generally, thicker glaciers will have a larger cross-sectional area at the terminus than a thinner glacier, meaning they have larger calving fronts and tend to move faster than smaller, thinner glaciers (McNabb et al., 2015).

Future Directions

A next step for this project would be to include more regions with tidewater glaciers, such as Glacier Bay, Yakutat Bay, and Icy Bay as these locations would help fill the geographical gap between the KPWS and Archipelago subregions (Figure 2). Another aspect to include in future work would be to include a higher number of shallow-silled fjords. This may have been possible with the inclusion of Glacier Bay or other regions in the initial study.

Increasing the sample size would also help eliminate problems relating to glacier-to-glacier variation. Variables such as size, thickness, or albedo could have smaller impacts with a larger number of glaciers. The average value for each category would be more representative or applicable by lowering the impact of outlier variables.

Another aspect to include in future work is the statistical comparison of retreat magnitude to SST, AT, and sill depth. This could provide a statistical backing to findings from this research. Unfortunately, it was out of the scope of the study in terms of resources and time.

Further enhancing the scope of this study, it would be valuable to compare SST to the temperature at depth in the ocean. Comparing these would create a more holistic understanding of the water column which would enrich the understanding of how water circulation occurs in silled fjords and how it interacts with glacier termini. As well as understanding more about the water column, another approach to consider would be to study the sills in more depth. Deciding upon what constitutes a "shallow" sill or an "intermediate" sill could change the results and by understanding the temperature stratification of the water column better, one would be able to create these depth distinctions more accurately.

Another valuable aspect to consider would be investigating the relationship between SST and AT. Out of the scope of this study, looking at the connection between these two driving variables would allow for a better understanding of how step retreats are triggered in tidewater glacier systems.

Conclusion

We aimed to find contributing factors to glacial retreat by comparing glacial retreat event timing to the geometry of the fjords they terminate in and to sea surface and air temperature anomalies. This study indicates that there may be a relationship between fjord geometry and glacier retreat. In fjords with shallow sills, some glaciers retreated rapidly from a point of stability after a year with anomalously high SSTs. This may be due to the entrainment of only the topmost, warmest section of the water column into the near-terminus region. This may explain why some glaciers (such as Yale and Harvard Glaciers) have experienced different retreat activity to their neighbors when exposed to the same atmospheric impacts (McNabb & Hock, 2014).

Air temperatures tend to have a larger impact on glacier retreat than sea surface temperatures. ATs also seem to have a longer-range over time impact than SSTs, with more glaciers retreating in the two years after an anomalously high AT year than in the year of the AT anomaly.

The process of quantifying ice loss is ongoing, but by studying the relationships of fjord geometry to SST anomalies, as well as studying AT anomalies, and the impacts on the timing of retreats, we can help to understand the contribution of non-ice sheet ice loss into the world's oceans. The retreat of glaciers has been accelerated by climate change, and as these glaciers melt, they eventually release their ice as water into the ocean, adding to sea level rise. By understanding more about glacial retreat, we can improve the estimates of glacial contributions to sea level rise.

Bibliography

Alexander, D., Davies, T., & Shulmeister, J. (2013). Basal melting beneath a fast-flowing temperate tidewater glacier. *Annals of Glaciology, 54*(63), 265-271. doi:10.3189/2013AoG63A259

Amundson, J. M. (2016). A mass-flux perspective of the tidewater glacier cycle. *Journal of Glaciology, 62*(231), 82-93. https://doi.org/10.1017/jog.2016.14

Amundson, J. M., & Carroll, D. (2018). Effect of topography on subglacial discharge and submarine melting during tidewater glacier retreat. *Journal of Geophysical Research: Earth Surface, 123,* 66-79. https://doi.org/10.1002/2017JF004376

Brinkerhoff, D., Truffer, M. & Aschwanden, A. (2017), Sediment transport drives tidewater glacier periodicity. *Nature Communications, 8*(90). https://doi.org/10.1038/s41467-017-00095-5

Carroll, D., Sutherland, D. A., Shroyer, E. L., Nash, J. D., Catania, G. A., & Stearns, L. A. (2015). Modeling Turbulent Subglacial Meltwater Plumes: Implications for Fjord-Scale Buoyancy-Driven Circulation, *Journal of Physical Oceanography*, *45*(8), 2169-2185. https://doi.org/10.1175/JPO-D-15-0033.1

Carroll, D., Sutherland, D. A., Shroyer, E. L., Nash, J. D., Catania, G. A., & Stearns, L. A. (2017). Subglacial discharge-driven renewal of tidewater glacier fjords. *Journal of Geophysical Research: Oceans*, *122*(8), 6611– 6629. doi:10.1002/2017JC012962

Catania, G. A., Stearns, L. A., Sutherland, D. A., Fried, M. J., Bartholomaus, T. C., Morlighem, M., Shroyer, E., & Nash, J. (2018). Geometric controls on tidewater glacier retreat in central western Greenland. *Journal of Geophysical Research: Earth Surface*, *123*(8), 2024– 2038. https://doi.org/10.1029/2017JF004499

Copernicus Climate Change Service. (n.d.). *ECMWF Reanalysis v5 (ERA5)* [Data set]. European Centre for Medium-Range Weather Forecasts. Retrieved January 4, 2022. https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

Eidam, E. F., Sutherland, D. A., Duncan, D., Kienholz, C., Amundson, J. M., & Motyka, R. J. (2020). Morainal bank evolution and impact on terminus dynamics during a tidewater glacier still stand. *Journal of Geophysical Research: Earth Surface*, *125*(11), 2169-9003. https://doi.org/10.1029/2019JF005359

Fahrner D., Lea J. M., Brough S., Mair D. W. F., Abermann J. (2021). Linear response of the Greenland ice sheet's tidewater glacier terminus positions to climate. *Journal of Glaciology 67*(262), 193–203. https://doi.org/ 10.1017/jog.2021.13

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, M. J., Hagen, J. O., Van Den Broeke, M. R., & Paul, F. (2013). A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009. *Science, 340,* 852-857. https://doi.org/10.1126/science.1234532

Hager, A. O., Sutherland, D. A., Amundson, J. M., Jackson, R. H., Kienholz, C., Motyka, R. J., & Nash, J. D. (2022). Subglacial discharge reflux and buoyancy forcing drive seasonality in a silled glacial fjord. *Journal of Geophysical Research: Oceans*, *127*, e2021JC018355. https://doi.org/10.1029/2021JC018355

Ming, J., Wang, Y., Du, Z., Zhang, T., Guo, W., Xiao, C., Xiaobin, X., Ding, M., Zhang, D., & Yang, W. (2015). Widespread albedo decreasing and induced melting of Himalayan snow and ice in the early 21st century. *PLoS One, 10(6)*: e0126235. doi: 10.1371/journal.pone.0126235

Matthews, J.B. (1981). The seasonal circulation of Glacier Bay, Alaska fjord system. *Estuarine, Coastal and Shelf Science, 12*(6), 679-700. https://doi.org/10.1016/S0302-3524(81)80065-5

Meier, M. F., and Post, A. (1987). Fast tidewater glaciers, *Journal of Geophysical Research: Solid Earth*, 92(B9), 9051– 9058. doi:10.1029/JB092iB09p09051.

National Centers for Environmental Information. (n.d.). [Bathymetry Data of the Gulf of Alaska]. Retrieved June 4, 2021, from https://www.ncei.noaa.gov/maps/bathymetry/

McNabb, R. W., & Hock, R. (2014). Earth Surface Variations in Alaska tidewater glacier frontal ablation. *Journal of Geophysical Research: Earth Surface*, *119*(2), 153–167. https://doi.org/10.1002/2013JF002915

McNabb, R. W., Hock, R., & Huss, M. (2015). Variations in Alaska tidewater glacier frontal ablation, 1985–2013. *Journal of Geophysical Research: Earth Surface*, *120*, 120– 136. https://doi.org/10.1002/2014JF003276

Merrifield, S., Otero, M.P., & Terrill, E.J. (2018). Observations of Shelf Exchange and High-Frequency Variability in an Alaskan Fjord. *Journal of Geophysical Research: Oceans, 123*(7), 2169-9275. https://doi.org/10.1029/2018JC013931

Post, A., O'Neel, S., Motyka, R. J., and Streveler, G. (2011). A complex relationship between calving glaciers and climate, *Eos Trans. AGU*, 92(37), 305. https://doi.org/10.1029/2011EO370001

Slater, D. A., Nienow, P. W., Cowton, T. R., Goldberg, D. N., & Sole, A. J. (2015). Effect of near-terminus subglacial hydrology on tidewater glacier submarine melt rates. *Geophysical Research Letters*, 42(8), 2861– 2868. https://doi.org/10.1002/2014GL062494

Slater, D. A., Nienow, P. W., Goldberg, D. N., Cowton, T. R., & Sole, A. J. (2017), A model for tidewater glacier undercutting by submarine melting. *Geophysical Research Letters*, *44*(5), 2360– 2368. https://doi.org/10.1002/2016GL072374

Winkle, S., & Matthews, J. A. (2010). Observations on terminal moraine-ridge formation during recent advances of southern Norwegian glaciers. *Geomorphology*, *116*(1-2), 87-106. https://doi.org/10.1016/j.geomorph.2009.10.011