THE SEASONAL DYNAMICS OF COASTAL ARCTIC LAGOONS IN NORTHWEST ALASKA

By

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Abstract

Lagoons are zones of habitat transitions between freshwater and marine ecosystems, providing safe and productive feeding habitats for whitefishes in Northwest Alaska, important to subsistence users in the region. However, many important lagoon processes are not understood. Therefore, the goal of this thesis was to gain a baseline understanding of two important seasonal processes of lagoons in Northwest Alaska. First, I attempted to identify environmental processes correlated with Arctic lagoon breaching for three indicator lagoons that represent a range of environmental characteristics using generalized linear models (GLM) in an information theoretic approach and model averaging. Second, I developed a habitat suitability (HS) model to identify the range of physical conditions that whitefishes may experience if overwintering under ice of these lagoons during the Arctic winter, for the same three lagoons. The GLM model suggested that lagoon breaching day of year was slightly negatively related to day of year of river break-up, but other unconditional confidence intervals for the covariate parameters overlapped zero indicating considerable uncertainty in these estimates. Further data collection and monitoring in the region is needed to improve and verify lagoon breaching modelling results. The HS model indicated that lagoons have reduced suitability as whitefish habitat in winter due to loss of habitat due to the presence of bottomfast ice and a reduction of liquid water quality due to cold temperatures, high salinities and low dissolved oxygen levels. Importantly, small lagoons without freshwater inputs were potential sinks for fish populations. The results from this research will help the National Park Service and the Native Village of Kotzebue in a joint effort to understand and manage these important habitats that are critical for subsistence fisheries as the Arctic faces an uncertain future with climate change, oil spill threats, and increased coastal development.

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Introduction

Coastal lagoons are dynamic transition zones between freshwater and marine ecosystems (Mouillot et al. 2007; Dürr et al. 2011), characterized by relatively shallow waters, incomplete isolation from the ocean by barriers of sand or gravel, and high physicochemical variability (Barnes 1980; Kjerfve 1994). Approximately 13% of the coastline worldwide is composed of coastal lagoons (Isla and Bujalesky 2008), with higher concentrations found in certain regions (e.g. Australia, South Africa, Arctic Beringia). Lagoons resulted from a combination of sea level rise during the Holocene (last 150,000 years), which significantly flooded many low-lying areas, and constructive waves that built barriers of sand and gravel. These processes enclosed the water between land and the gravel/sand barrier, thus creating lagoons (Barnes 1980). The geomorphology of a region determines the configuration and extent of coastal lagoons and typically, coastlines that are straight and steep do not have lagoons. The prevailing sediments in a region affect barrier formation and coastlines that are predominantly composed of sands, gravels, or shale are ideal for the formation of barriers (Bird 1994). Once formed, lagoons are modified by erosion and deposition caused by wave action (Bird 1994).

Coastal lagoons are connected to the marine environment via channels that are either always, never, or periodically open (Kraus et al. 2008). Open lagoons have a high degree of connectivity to the ocean, but are largely separated from the ocean by barrier island systems. These lagoons exhibit characteristics that are very similar to the marine environment and typically are the largest in area. Periodically open lagoons have at least one connection to the marine environment that is open at irregular intervals. They exhibit patterns of barrier breaching, with breaching defined as a new opening in the barrier separating lagoon from ocean (Kraus et al. 2002). Barrier breaching can be initiated from the ocean or lagoon side. Breaching initiated from the ocean side is a product of sustained high water levels and high waves, typically associated with storm surges, whereas breaching from the lagoon side can occur through overflow or seepage due to large differences in water elevation between the lagoon and the ocean (Kraus et al. 2002; Kraus et al. 2008). Breaching in periodically open lagoons can be a seasonal process driven by local climates that induce barrier breaching and closing conditions at regular intervals throughout the year.

The lagoon connectivity regimes dictate abiotic conditions (e.g. water quality, salinity) and thus the species assemblages present (Kraus et al. 2002; Petry et al. 2016; Haynes et al. 2017). Further, breaching events that lead to connectivity are key to the overall functionality and health of lagoon systems (Stretch and Parkinson 2006). Such events influence water quality by flushing stagnant water out of the system, as well as biodiversity by allowing aquatic organisms to migrate in and out of lagoon habitats (Kraus et al. 2008). Periodically open lagoons experience large variations in their physical characteristics at a seasonal and/or annual scale, especially in salinity which can range from almost fresh to hypersaline. This variability greatly affects the biotic community present in the lagoons, potentially changing the food web drastically from year to year (Haynes et al. 2017).

The coastline of the southeastern Chukchi Sea is heavily comprised of always and periodically open coastal lagoons, with approximately 37% of the Alaskan Arctic coastline north of the Bering Strait comprised of lagoon habitat (Haynes et al. 2017). Lagoon habitat plays a key role in aquatic ecosystems in the Arctic, acting as an intermediary between fresh and marine conditions and thus supporting a host of both freshwater and marine species. In the southern Chukchi Sea, lagoons typically breach in the spring during snow melt and ice break-up that raise water levels in the closed lagoons until a breaching event occurs. Lagoons later close during the summer months when berms across the breach are rebuilt by constructive waves and longshore (i.e. parallel to the shoreline) sediment transport (Reynolds 2012; Ranasinghe et al. 2013). During the ice-free season, when they are connected to the marine environment, Arctic lagoons are highly productive, well-mixed brackish water bodies during the ice-free season (Dunton et al. 2012). The epibenthic fauna flourish in the mixed brackish water, providing rich feeding grounds for Arctic fishes, migratory birds, marine mammals as well as critical resources for local subsistence hunters and fishermen in the lagoons (Dunton et al. 2012). Many of these species rely on the regular opening of seasonal lagoons, entering these habitats during the brief summer to maximize feeding opportunities.

The most significant research on coastal Arctic lagoons has been focused in the Northern Chukchi and Beaufort seas region, between Kivalina and Kaktovik (Wilimovsky and Wolfe 1966; Johnson et al. 2010; Thedinga et al. 2010; Dunton et al. 2012) . The spatial and temporal dynamics of coastal fish assemblages in lagoons in this region have been documented relatively well (e.g., Jarvela and Thornsteinson 1999; Thedinga et al. 2010). The major fish species caught within lagoons in these studies were coregonines and sculpins. Further, these studies all found that there was significant variability in seasonal physical conditions and species abundances within lagoons. Researchers also noted that the species composition of fishes in this area is relatively unchanged for the past 25 years (Johnson et al. 2010).

Whitefishes are important lagoon-rearing subsistence resources in Arctic Alaska. Whitefishes are in the salmonid family, along with grayling, trout, char and salmon. There are eight species of whitefishes in Alaska: *Prosopium cylindraceum,* Round Whitefish; *Prosopium coulteri*, Pygmy Whitefish; *Coregonus nasus*, Broad Whitefish; *Coregonus pidschian*, Humpback Whitefish; *Coregonus sardinella*, Least Cisco; *Coregonus laurettae,* Bering Cisco;

Coregonus autumnalis, Arctic Cisco; *Stenodus leucichthys*, Sheefish (Mecklenburg et al. 2002). In northwest Alaska, whitefishes are one of the most reliable subsistence resources for communities, comprising ~18% of subsistence harvests (by average edible weight) from 1964–2007 (Magdanz et al. 2010). Whitefishes (*Coregonus* spp.) are currently not subject to any formal management regulations at local, state, or federal levels.

Whitefishes can have several life history strategies: anadromous, amphidromous, lacustrine and riverine (Reist and Bond 1988). Anadromous and amphidromous whitefishes typically rear as young in ponds, sloughs and coastal lagoons until they reach a certain size and begin to migrate between freshwater and marine systems to maximize feeding opportunities. Once they reach maturity, whitefishes migrate up rivers to spawn, typically beginning their upriver migration in early summer and spawning in gravelly reaches in the fall (Alt 1979). Many whitefishes occupy lagoons during some time in their lives, particularly during the summer when lagoons have an open connection to the ocean. During this time, traditional ecological knowledge (TEK) holders have stated that “fish go to lagoons to grow,” referring in particular to whitefishes (A. Whiting, Kotzebue IRA, personal communication). In anticipation of the lagoon closing in the fall when freshwater input decreases, fishes generally move out of the lagoon systems. However, in some cases after the lagoons close, large concentrations of whitefishes are found at the outlets of the lagoons (Georgette and Loon 1993). The lagoons then act as giant fish traps, with fishes getting trapped within the closed lagoons at the onset of winter. At this time, subsistence users dig a trench in the gravel at the lagoon outlet, allowing water to flow down the trench into a pool. The fishes attempt to escape the lagoons by swimming down the trench and into the pool, where they are harvested easily (Uhl and Uhl 1977). Fishes remaining in these systems must overwinter there, and thus lagoons also support overwintering whitefish populations that sustain important local subsistence fisheries (C. Harris, subsistence fisherman, personal communication).

As a result of many fishes being trapped in small, isolated areas, winter in lagoons is a potential bottleneck for fish survival (Huusko et al. 2007). The heavy ice cover that occurs in Arctic aquatic systems poses unique challenges to aquatic life. In the winter, ice thickness can reach up to 2 m in Arctic freshwater systems, limiting the availability of liquid water for fish populations and industrial water needs (Jeffries et al. 1994; West et al. 1992). Areas that continue to have liquid water throughout the winter are limited across the landscape and can experience conditions that further impact fish survival, including hypoxia, hypersalinity and extremely cold water temperatures in brackish estuarine and lagoon habitats.

With the onset of climate change and increased anthropogenic stress, citizens from the Native Village of Kotzebue in Northwest Alaska have expressed concerns about the health and persistence of these important lagoon habitats and their resident fish populations, which support a subsistence fishery unique to the region (Alex Whiting, *personal communication*). The paucity of information about these systems is of concern as a current understanding of lagoon processes is necessary to evaluate potential impacts of future conditions. Specifically, little is known about breaching processes, which is important for whitefishes in the region, and plays a key role in subsistence fishing activities. Changes in the periodicity of lagoon breaching will affect the abiotic conditions and availability of habitats for important subsistence fisheries resources, like whitefishes. Further, because relatively little is understood about basic fisheries information (e.g., harvest numbers) and ecological characteristics of fishes targeted in Arctic coastal subsistence fisheries, it is important to understand habitats necessary for their survival.

The following work has been designed and informed with the help of TEK provided by local residents which has guided the formation of hypotheses about regional lagoon processes. Despite the ecological importance of Arctic lagoons, there is a lack of scientific understanding of lagoon processes and habitat due to their remote nature, inaccessibility, and relative distance from inhabited areas in the Alaskan Arctic. These challenges necessitate the exploration of alternative methods to gain important baseline information about lagoons. Satellite imagery has great utility for studying remote areas that are challenging to physically sample. It provided methods to explore lagoon breaching and winter dynamics. I used multispectral imagery to provide historical dates of lagoon breaching and interferometric synthetic aperture radar imagery (InSAR) during the winter to identify potential overwinter habitat for whitefishes in the lagoons.

The following thesis aims to address the knowledge gaps regarding coastal Arctic lagoons as whitefish habitat in two standalone chapters. Chapter 1 describes an important process, spring lagoon breaching, which influences physical lagoon dynamics and the availability of lagoons as whitefish habitat. Understanding the processes behind lagoon breaching will allow us to determine if the effects of climate change will affect the timing and frequency of breaching. Chapter 2 describes the habitat suitability of lagoons for overwintering whitefishes, which is currently unknown. InSAR coupled with point measurements taken during a field campaign were used to create a Habitat Suitability (HS) model to further identify the quantity and quality of overwinter habitat in the lagoons for whitefishes. The HS model aims to determine the spatial distribution of viable overwinter habitat for whitefishes across the coastal Arctic landscape. By doing so, we move towards a better understanding of the importance of coastal lagoons for overwintering migratory fishes and illuminate a key period of the life history for a culturally important group of fishes. The overarching goal of this work is to understand the current conditions in these areas which ultimately may provide information needed to protect these pivotal locations and support managers of the critical subsistence fisheries.

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Chapter 1 : Environmental processes correlated with seasonal Arctic lagoon breaching[1]

Abstract

In the Arctic, lagoons are periodically connected to the marine environment through breaching events. This key process controls the connection between fluvial and marine environments important for a wide variety of fish, bird and marine mammal species. To understand key processes related to breaching, we examined three lagoons by identifying correlations between breach date and environmental data using a generalized linear model (glm) information theoretic approach. Breaching dates were identified using Landsat series multispectral imagery, as there were no direct observations of lagoon breaching in this remote region. Model covariates included metrics for air temperature, snowfall, river break-up, and sea ice concentration, all hypothesized to have an effect on the date of lagoon breaching. Using model averaging, our model suggested that lagoons breach later during years of earlier river break-up. The glm model proved to be a useful framework for examining the environmental correlations with lagoon breaching and could easily be updated in the future with improved environmental data series to improve identification of correlations. This tool is useful for several management applications, such as understanding and mitigating potential oil and gas spills that may occur with the expected increases in hydrocarbon exploration.

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[1] Tibbles M, JA Falke, A Prakash, MD Robards, AC Seitz. 2018. Environmental processes correlated with seasonal Arctic lagoon breaching. Prepared for submission to Estuaries and Coasts.

Introduction

Lagoons and estuaries are zones of habitat transitions between freshwater and marine ecosystems (Mouillot et al. 2007; Dürr et al. 2011). Lagoons are defined as shallow coastal water bodies that are typically oriented shore-parallel, separated from the ocean by barriers, and connected at least intermittently to the ocean by one or more inlets (Bird 1994; Kjerfve 1994). There is increasing recognition of the essential ecosystem services provided by lagoons such as shoreline protection, water quality improvement, and habitat for fishes and other subsistence resources (Levin et al. 2001; Mouillot et al. 2007). As a result, lagoons are recognized at a global scale for their contribution to fisheries and aquaculture (Mee 1978), and their high economic value (de Groot et al. 2012). The economic importance of coastal lagoons in many cases has led to exploitation of, and high anthropogenic stress on, these ecosystems, decreasing their ability to deliver essential ecosystem services (Costanza et al. 1997; Mouillot et al. 2007).

Coastal lagoons worldwide are connected to the marine environment via channels and are classified as either permanently, never, or periodically open (Kraus et al. 2008). In microtidal regions (areas with relatively small tides), the connection between ocean and lagoon is typically periodically open, with the connection commonly closing, separating the fluvial and marine environments (Ranasinghe et al. 2013; McSweeney et al. 2017). Relatively large tides tend to keep connections between the lagoons and ocean open year-round. These systems have been referred to by a range of regionally used terms, such as Temporary Open/Closed Estuaries (TOCEs), Intermittently Closed/Open Lakes and Lagoons (ICOLLs), bar-built estuaries, seasonally open estuaries, and periodically open lagoons (Hodgkin and Lenanton 1981; Stretch and Parkinson 2006; Haines and Thom 2007; Kraus et al. 2008; Tagliapietra et al. 2009; McSweeney et al. 2017). The many terms describing these ecosystems point to the dynamic nature of lagoons and their connections to the ocean. Here, this lagoon type will be referred to as periodically open.

Patterns of lagoon connectivity are driven by processes that lead to barrier breaching with breaching defined as a new opening in a landmass that allows water to flow between two previously separated water bodies (Kraus et al. 2002). Barrier breaching processes can be initiated from the ocean or lagoon side. Breaching initiated from the ocean side is a product of sustained high water levels and large waves, frequently associated with storm surges (Kraus et al. 2002). Breaching initiated from within the lagoon occurs through overtopping or seepage due to significant differences in water elevation, or head, between the lagoon and ocean (Kraus et al. 2008). Breaching can be a seasonal process driven by local climates that induce barrier breaching conditions at regular intervals throughout the year, such as spring snowmelt at high latitudes.

Breaching events lead to significant, rapid variations in the physico-chemical environment of lagoons, which in turn affect biotic communities and are important to the overall functionality and health of lagoon systems (Stretch and Parkinson 2006). Further, breaching events can lead to rapid changes in water level and quality, fast currents, and scouring of significant quantities of accumulated sediments from the lagoons, thereby playing an important physical role in these systems (Stretch and Parkinson 2006). In heavily populated areas, barrier breaching can have severe consequences, including loss of human life, infrastructure damage, and loss of protected areas (Kraus 2003). Due to the negative impacts of breaching in populated areas, there has been interest in creating models to predict barrier breaching. Of the relatively few models created, the majority are for tropical and temperate systems and focus on sediment transport and flow equations to predict barrier breaching conditions (Kraus 2003; Kraus and Hayashi 2005; Ranasinghe et al. 2013; Elsayed and Oumeraci 2016). These models focus on the physical conditions that lead to breaching events, rather than the environmental processes correlated with the timing of lagoon breaching, because breaching events in lagoons in tropical and temperate environments do not occur at any particular time of the year, unlike Arctic systems.

Arctic Beringia is a microtidal region (Kowalik and Proshutinsky 1994), and as such, the coastline is heavily comprised of periodically open coastal lagoons (Haynes et al. 2017). Lagoon habitat plays a key role in aquatic ecosystems in the Arctic, acting as an intermediate between fresh and marine conditions and thus supporting a host of both freshwater and marine species. During the ice-free season, periodically open lagoons are connected to the marine environment, which can create a highly productive, well-mixed brackish water body (Dunton et al. 2012). Epibenthic fauna (e.g. mysids, amphipods) flourish in lagoons, providing rich feeding grounds for Arctic fishes, migratory birds, and marine mammals, all of which are critical resources for local subsistence hunters and fishermen (Dunton et al. 2012). Many migratory species rely on the regular seasonal opening of periodically open lagoons, entering these habitats during the brief summer to maximize feeding opportunities.

Arctic lagoon ecosystems are uniquely vulnerable to climate change and other acute anthropogenic impacts, and as such are listed as areas of major concern (Alaska Clean Seas 1999). Lagoons are susceptible to changes in coastline dynamics; the forecasted increase in sea level coupled with rises in storm action and coastal erosion may result in increased lagoon barrier breaching (Jones et al. 2009), and lead to significant changes in the physical characteristics of lagoon habitats, and thus the species assemblages present (Haines and Thom 2007; Jones et al. 2009; Ranasinghe et al. 2013). Additionally, increased industrial development in the Arctic has led to more shipping traffic through the Bering and Chukchi seas (Ellis and

Brigham 2009), increasing the threat of oil spills in Northwest Alaska, which may affect lagoons that are open to the ocean. Because lagoons are areas of concern, it is increasingly important to have a baseline understanding of their physical processes against which to make future comparisons as climate change and increased anthropogenic pressure endanger these ecosystems.

Despite the ecological importance of Arctic lagoons, there is a paucity of understanding of the processes governing lagoon breaching in the Alaskan Arctic due to their remote nature, inaccessibility, and relative distance from inhabited areas. Additionally, the Arctic is data-sparse and variables that have previously been used to predict model breaching, such as sediment transport and flow, are unavailable. Finally, the processes driving barrier breaching may be significantly different than in non-Arctic regions due to unique dynamics of the region such as eight-month-long winters and heavy seasonal ice cover. It is thought that periodically open Arctic lagoons breach in the spring from high water levels resulting from snow melt and ice break-up (Reynolds 2012; Robert Schaeffer, *personal communication*); however, this has not been confirmed for Arctic lagoons through rigorous analysis. The causes of berms rebuilding and closing the lagoons also are yet to be explored. It is thought that in Northwest Alaska, this process occurs through constructive waves created in westerly fall storms (Alex Whiting, *personal communication*). For these reasons, it has become critical to create a tool to observe, understand, and predict lagoon barrier breaching, especially in the Arctic.

Here we report on a tool created to investigate the processes driving the seasonal breaching of coastal Arctic lagoons. We hypothesized that lagoon breaching would be related to air temperature, precipitation, and river discharge. The objectives of this study were to 1) determine the historical dates of breaching for three lagoons in Northwest Alaska using satellite imagery, and 2) use breaching dates as a response variable in a model relating environmental parameters to barrier breaching events to identify which physical processes influence spring Arctic lagoon barrier breaching. These objectives aim to take the first necessary steps towards understanding processes leading to barrier breaching in coastal Arctic lagoons.

Methods

We used a generalized linear model (glm) using climate, sea ice, and remote sensing data to explore the processes behind lagoon breaching in Northwest Alaska. We first used Landsat series satellite imagery to identify lagoon breaching dates in the late spring and summer for three lagoons. We then collated environmental data for climate and sea ice and created several metrics from these data to use as covariates in the glm. Using an information-theoretic approach and model averaging, we identified relationships between the covariates and the timing of lagoon breaching.

Study area

The study area was located in Northwest Alaska in Cape Krusenstern National Monument (Figure 1.1). The 2670 km^2 monument is located approximately 70 km north of the Arctic Circle (center point 67°26'N 163°32'W) and is characterized by tundra habitat and coastal lagoons. Kotzebue's 30-year average air temperatures in January and July are -19°C and 13°C, respectively (Reynolds 2012). The coast abuts the Chukchi Sea and has seven lagoons, three of which are examined in this study: Aukulak, Krusenstern and Kotlik lagoons (Figure 1.1). Each lagoon has one connection to the marine environment, and one or more significant freshwater inputs (Aukulak, n = 1; Krusenstern, n = 4; Kotlik, n = 4). Aukulak and Krusenstern lagoons connect to Kotzebue Sound whereas Kotlik Lagoon connects to the Chukchi Sea.

Remote sensing of lagoon breaching

Landsat imagery for the study area was acquired from the USGS EarthExplorer portal. Landsat missions 4, 5, 7, and 8 were used to provide imagery for 2000–2013. Landsat 8 ETM+ imagery was used for dates after 2013, when the mission began. Landsat 5 TM imagery was preferentially used over Landsat 7 ETM+ imagery after 2003 because of the Scan Line Correction (SLC) fail for the Landsat 7 ETM+ sensor in 2003 (USGS 2016). Here, the red, green, blue and near infrared (NIR) spectral bands were used (30 m spatial resolution), and the panchromatic band which was only collected by Landsat missions 7 and 8 (15 m spatial resolution). Scenes covering the study area were downloaded for the months April through July for the 13 year period.

The Landsat imagery was analyzed in ERDAS Imagine software (Hexagon AB 2016). Before analysis, images were checked for quality, including cloud cover, striping (from the SLC fail), and haze. Scenes in which one, two or all the lagoons were visible were selected for further processing. With each Landsat image that passed the quality considerations, a layer stack was made with the bands of 30 m resolution. The Normalized Difference Water Ratio (NDWI) was applied to the stacked image to enhance water features and interpretation. McFeeters (1996) describes the NDWI as NDWI = (Green – NIR) / (Green + NIR) where the Green and NIR are the reflectances of the green and near-infrared bands, respectively. This index takes advantage of the low correlation between the Green and NIR bands to enhance water features, giving them a positive pixel value in comparison to the vegetation and soil features (McFeeters 1996). The NDWI image (30 m resolution), stacked image (30 m resolution) and the panchromatic band (15 m resolution) were compared at the areas of breaching to determine the connectivity of Krusenstern, Aukulak and Kotlik lagoons to the ocean. Images where the degree of connectivity was not discernable were then pan-sharpened using the projective resolution merge, which merges the stacked image with the panchromatic band to increase the spatial resolution of the image while keeping the spectral information (Landsat series 7 and 8 only). The date ranges in which the lagoons opened and closed were estimated from the imagery by determining the dates of the two images in which the lagoons changed from closed to open. These data were recorded and to midpoint between the two dates was used as the day of year of lagoon breaching.

Model predictors and data

Lagoon

Lagoon was included as a factor covariate in the glm. Wherever possible, lagoon-specific environmental data were included. When lagoon-specific dates were not available, proxies from adjacent areas were used. For Aukulak and Krusenstern lagoons, data from Kotzebue (35 km southeast) were used, whereas for Kotlik Lagoon, data from Kivalina (43 km north) were used.

Sum of cumulative degree days above freezing (cdd.sum)

A temperature metric was calculated as the sum of the cumulative air temperature degrees greater than 0°C for each day. This was chosen as a predictor for the model, as we hypothesized that snow and ice melt contribute to high water conditions within the lagoon, leading to breaching. Daily weather data for Kotzebue and Kivalina from 2000 – 2013 were downloaded from the National Climactic Data Center (NCDC) Climate Data Online portal (https://www.ncdc.noaa.gov/cdo-web/). The Kotzebue weather station is located at the Kotzebue Ralph Wein Memorial Airport (66.86667°N, -162.63333°W) and the Kivalina weather station is located at the Kivalina Airport (67.73167°N, -164.54833°W). Each dataset included daily summary information for air temperature and precipitation. Mean temperature (°C) was recorded in Kotzebue, however, for Kivalina mean temperature data were missing so it was calculated as the mean of the daily minimum and maximum temperatures. For each day from January to May for 2000 – 2013, the degree day was calculated as the mean recorded temperature minus 0°C. If the temperature was ≤ 0°C, it was given a value of 0. Finally, the sum of these values from January to May for each year was calculated.

Day of year of thaw (doy.thaw)

Day of year of thaw was another air temperature metric calculated from NCDC climate data. This metric corresponded to the day of year when the mean air temperature exceeded freezing point (0°C) for at least three consecutive days. This was chosen as an alternative predictor to CDD.sum, as the day of thaw likely also relates to local melt and thaw conditions.

Total winter snowfall (snowfall)

Total winter snowfall was included as a predictor in the model, with the assumption that total amount of snowfall acts as a proxy for precipitation during winter. The Kotzebue dataset included precipitation data as both precipitation and snowfall; the Kivalina dataset only provided precipitation. Therefore, snowfall data from Kotzebue, calculated as the sum of all snowfall that occurred from November to April for each year, was used for each lagoon.

Wulik River break-up day of year (*wul.brup)*

River break-up was included as a predictor as we hypothesized that date of river break-up may reflect the interaction between air temperature, snow accumulation and snow melt for each spring. Daily discharge (m^3/s) data from the Wulik River for 2000 – 2013 were downloaded from the USGS National Water Information System. The Wulik River was chosen as a representative river for the lagoon watersheds due to its proximity to the lagoons and its relatively smaller drainage area (1826 mi^2) as compared to other available datasets (e.g. Kobuk River, 9480 mi^2). From these data, a metric of river break-up date was calculated as the day of year when daily discharge exceeded 2.8 m^3/s. This value was selected to represent Wulik River break-up date after an examination of baseflow values for each year. Minimum baseflow values ranged from 0.08 – 0.88 m^3/s, and increased rapidly over a week to flows in the thousands. The minimum flow in rivers is reached in late winter in this system, and increasing flows signal the beginning of spring melt and river break-up (Hamilton and Moore 1996).

June sea ice concentration (june.ice)

The metric for sea ice concentration was included as a predictor, as we hypothesized that sea ice concentrations would reflect the harshness of the winter and temperature and break-up processes. Sea ice concentration data were downloaded from National Snow and Ice Data Center (NSIDC) Gridded Monthly Sea Ice Extent and Concentration, 1850 Onward, Version 1 data set. This data set provides sea ice concentration data over a grid of 0.25 degree x 0.25 degree on the 15th of each month from 1880 – 2013. Sea ice concentration was reported as a percent coverage for each pixel of ocean in the data set. We used data for the pixel closest to Aukulak and Krusenstern lagoons, and for the pixel closest to Kotlik Lagoon. After a cursory examination of the sea ice concentration data for these two pixels, June 15th sea ice concentration was chosen as a predictor in the model, due to June having the largest variation in sea ice concentration, showing the greatest amount of contrast.

Data analysis

Our approach included lagoon breach day of year (discrete value, 1 – 365) as the response variable, and the main effects were cdd.sum, wul.brup, doy.thaw, snowfall, june.ice and lagoon. The quality of these data for modeling purposes was assessed following the methods reported in Zuur et al. (2010). The response variable had an approximately normal distribution. No significant outliers were detected, and although there was a small amount of heterogeneity in the variance between lagoons as identified in a boxplot of the response by lagoon, this was assumed to be a minor issue owing to the small sample size. The variance inflation factor was $<$ 2.5 for all covariates, indicating no multicollinearity.

To discern the relative importance of the environmental factors that contribute to the breach date, and owing to the discrete nature of the response (day of year), a glm with a Poisson distribution and identity link was applied. Twelve candidate models were included in the model set. These models were formulated to include all single-covariate models, several covariate combinations that reflected our hypotheses, and a global model that included all covariates. We used an information-theoretic approach to select the best model predicting lagoon breach day of year given the environmental parameter data (Burnham and Anderson 2002). The top model was selected based on Akaike's information criterion corrected for small sample size (AIC_c); models with the lowest AIC_c and highest Akaike model weight (w_t) were considered top models. We averaged parameter estimates over models with $\mathrm{AIC_c}\ w_t > 0.05$ to address model uncertainty. Models were constructed in Program R (R Core Team 2017) and analysis was done using the Multi-Model Inference package *MuMIn* (Barton 2015).

Results

Remote sensing of lagoon breaching

A total of 62 Landsat scenes were analyzed, including 24 Landsat 5 scenes, 33 Landsat 7 SLC-off scenes, and five Landsat 8 scenes. Of these scenes, the panchromatic band (15 m resolution) was available for 38, and classification was only possible from 12 of these scenes, due to the lack of definition. The NDWI was calculated for 27 scenes and used for classification in each of these instances. The pan-sharpened true color composite was only necessary for the classification of one scene. There were two years in the time series, 2004 and 2013, in which opening dates could not be discerned due to heavy cloud cover for the opening time period.

During most time periods, the panchromatic images were most useful for classifying lagoons as open or closed. The 30 m resolution of the stacked and NDWI image was frequently inadequate for the classification of the lagoons because the mouth of the lagoons were only several pixels wide which lead to higher classification uncertainty. In contrast, during the spring period of break-up and snowmelt, the panchromatic images became difficult to interpret because the snow and ice cover made distinguishing between areas of ice and land challenging. The true color composites were then most useful for classifying the lagoons because they showed a clearer difference between ice, water and vegetation on land despite the coarser resolution. The NDWI index was not useful in this case either, as both ice and water have positive values. Finally, the NDWI indices showed the contrast between land and water more distinctly than the panchromatic and true color images and were useful when the classification was ambiguous during periods of open water. When the true color composite, panchromatic image and NDWI index had ambiguous interpretations, the pan-sharpened true color composite reduced ambiguity and provided an interpretable image in most cases, allowing for the classification of the lagoon as either open or closed.

Lagoon breaching analysis

Open.dat for the three lagoons ranged from day 127 – 165 (SD, 9.6 days), wul.brup ranged from 120 – 146 (SD, 6. 6 days), and doy.thaw ranged from 110 – 153 (SD, 13.2 days). Snowfall from November to April totals were 32.2 – 106.4 mm with a mean of 73.6 mm (SD, 21.3 mm), and june.ice ranged from 0 – 100%, with a mean of 61% (SD, 41.3%). There were no obvious trends in the predictor values throughout the time period (Figure 1.2).

Model selection results of lagoon breach day of year identified seven top models (AIC$_c$ w_t > 0.05) that included a combination of all five environmental predictors: cdd.sum, doy.thaw, snowfall, wul.brup and june.ice. There was underdispersion (phi = 0.49) in the glm model, indicating that there was less variability in the data than expected, likely due to the small sample size. The highest ranked model for day of lagoon breaching represented 23% of the weight of candidate models (w_i= 0.23; Table 1.2) and indicated that the date of river break-up had a negative effect on date of lagoon breaching (Figure 1.4). Seven other models appeared in the confidence model set ($w_i > 0.05$), and model-averaged estimates further suggested that the date of river break-up was the most influential predictor, as determined by the relative variable importance. Parameter estimates for snowfall and june.ice were negative, whereas estimates for doy.thaw and cdd.sum were positive. However, unconditional 90% confidence intervals for all covariates except wul.brup overlapped zero, indicating considerable uncertainty in these estimates (Table 1.3).

Discussion

Our study exploring the environmental processes behind Arctic coastal lagoon breaching delivers a novel approach for understanding this process that is critical for many fish, bird and marine mammal species, as well as humans. We found that lagoon breach day of year for the three lagoons was slightly negatively related to day of year of river break-up (Figure 1.4). The other environmental covariates were quite variable and the direction of the effects was uncertain, failing to explain variability in lagoon breaching date. We have outlined a tool to examine lagoon breaching timing; however, more monitoring and data are necessary before it can identify the processes correlated with breaching event timing.

The model findings contradicted our hypothesis of a positive relationship between lagoon breach date and river break-up. We hypothesized a positive relationship because spring break-up causes a peak in discharge in Arctic streams and rivers (Hamilton and Moore 1996) that may create significant differences in water elevation between the lagoon and ocean (Kraus et al. 2008). However, the breaching model identified a negative correlation between river break-up date and breaching events, predicting that lagoons breach later in years with earlier river break-up. Because this is an unintuitive relationship, the finding suggests that the model is failing to capture the processes underlying spring lagoon breaching correctly, the data quality is not sufficient for correct model performance, or there is an unintuitive dynamic that we do not understand.

The model may be failing to capture the processes underlying spring lagoon breaching correctly because it relies solely on one simple correlation, when in reality, many of the processes involved in spring break-up are complicated and can have interacting effects. Therefore, it is possible that our simple hypothesis is not capturing important environmental processes involved in breaching. Further, the glm modeling approach may not be flexible enough to identify complex relationships in the data (Zuur et al. 2007).

An alternative explanation for why the model may be failing to capture the processes underlying spring lagoon breaching correctly is that the data quality are not sufficient for correct model performance. The environmental data behind the covariates in the model that had no relationship with the response were likely measured at inadequate spatial and temporal resolutions and were unable to capture the complexity of breaching processes. Northwest Alaska is a relatively understudied region, with little information available on the local hydrology, especially for coastal lagoons (Haynes et al. 2017). Processes correlated with breaching events likely depend on local hydrology and lagoon size. It is difficult to know how river inputs would affect lagoons with varying watershed areas, though smaller lagoons with larger watersheds would likely be more responsive to runoff and discharge during spring break-up. Additional environmental parameters may need to be included in the modeling framework to capture the mechanisms involved. However, parameters such as sediment transport and longshore flow, included in prior lagoon breaching models (Kraus and Hayashi 2005; Elsayed and Oumeraci 2016), might be inappropriate for the Arctic because of the unique regional dynamics. Many of the model covariates were summaries of extended environmental datasets. For each environmental parameter, several different methods of summarization were explored before a final decision was made. It is possible that different summary methods may have been more appropriate and lead to improved results. For example, summarizing day of river break-up as the date where the river baseflow is exceeded may not be the appropriate discharge metric for the modeling approach.

The environmental data behind model covariates with no relationship to the response were likely measured at inadequate spatial and temporal resolutions and thus unable to capture the complexity of breaching processes. Specifically, most of the covariates (e.g. cdd.sum, wul.brup, snowfall, and doy.thaw) had regional values that were used for all three lagoons, instead of unique values for each lagoon. Weather stations were located in villages in the region and often did not record the same data types, making it difficult to use unique values for the lagoon covariates. Further, the temporal resolution of the satellite imagery inhibited the identification of exact dates of lagoon breaching, leading to up to 14 days of error in the estimates for the response variable. The temporal resolution was further deteriorated by the weather patterns of the region; heavy cloud cover frequently impeded the identification of lagoon breaching further increasing the error margin. The medium spatial resolution of the satellite imagery likely also lead to interpretation errors for the smaller lagoons. Further, 13 years of data is a relatively short time series for understanding complex phenomena such as lagoon breaching and may be at the root of the weak predictive power of the model.

Finally, it is possible that our methods for summarizing the environmental data did not capture the processes or variability that underpin lagoon breaching. It is possible that there is an unintuitive dynamic that we have not explored, due to a lack of basic understanding of the processes at play. There also may be an indirect relationship between breaching and break-up that our summary methods were unable to capture.

Overall, we speculate that the data-poor nature of this modeling attempt identified a false correlation, though there are likely many sources of error in our approach that contributed to the spurious result. Most importantly, the issues associated with identifying lagoon breaching dates accurately are likely a significant source of error to the model. This error is compounded by the lack of localized climate information, which thus fails to capture more localized weather phenomenon.

To improve the model, we recommend further monitoring and data collection in the region. The lagoons are all located in Northwest Alaska, but this region extends over a large geographic area and different areas of the coast frequently experience dissimilar conditions. Installing more weather stations across the coast would allow us to capture small-scale weather patterns and more accurately assess both the cumulative degree days greater than 0°C as well as the day of thaw for each lagoon. Weather stations would also allow us to determine the amount of snowfall that occurs at each lagoon. Snowfall is especially variable in this coastal region, as high winds frequently shift the snowpack and lead to a patchy, uneven distribution of snow across the landscape (Liston and Sturm 2002). It is possible to observe snow depth across the landscape with satellite imagery (Brown et al. 2010; Callaghan et al. 2011), though current datasets have a very coarse spatial resolution and can be quite inaccurate along the coast. Rapid advances in satellite technology may make this technique for identifying total winter snowfall possible in the near future, increasing the spatial resolution at which we can collect this information. For river break-up, more river gauging stations would provide us with better hydrologic data for the lagoons. Creeks flowing into the lagoons are generally much smaller than the rivers currently with gauge stations, and thus existing gauging stations might not be representative of the smaller creeks. Additionally, it would be ideal to have camera stations set up at the lagoon mouths to record the date of breaching with more accuracy. Landsat imagery was frequently inadequate for precisely identifying date of breach for the lagoons due to insufficient spatial and temporal resolutions. There are newer satellites (e.g. Planetscope, Rapideye, Sentinel 2) that have higher spatial and temporal resolutions but would still be hindered by cloud cover as they collect data in the visible spectrum. Camera stations would provide the best data, as cloud cover would not be an issue, and they would allow real-time monitoring of lagoon breaching. Finally, a longer time-series would also help to identify potential trends and correlations in the data set.

After tuning the model in the future, it will have several immediate applications, including providing a mechanism to understand potential changes in the Arctic as a result of climate change. In the future, several important changes are expected, including warmer air and water temperatures, as well as changes to the precipitation regime (Reist et al. 2006; Wrona et al.

2016). These changes will lead to earlier ocean and river ice break up dates, which are already being observed in the Arctic where a five to six day advance per century has already been noted in Alaska and the Yukon Territories (White et al. 2007; Janowicz 2010). Future predicted climate parameters can be input into the model to determine their effect on the timing of lagoon breaching.

Additionally, information about lagoon breaching in the Arctic will lead to a better understanding of how environmental changes will impact coastal ecological communities, including humans, as well as mitigating oil and gas spills. This may impact the ability of lagoon habitats to continue to provide nursery grounds and feeding areas for species targeted by local subsistence users. Breaching also has several important social considerations for coastal communities in the area. Beaches in the summer time are a highway for travel to and from villages and important subsistence resources (*personal observation*). Breached lagoons cut off travel routes, leading to longer and more dangerous travel conditions. An understanding of the conditions that cause breaching to occur may prevent human travel accidents due to unexpected lagoon breaching. Further, open lagoons are more vulnerable to potential oil spills and would likely be permanently damaged by the entrainment of oil in sensitive wetland and lagoon habitats (Alaska Clean Seas 1999). The ability to predict day of breach would be critical for understanding where resources should be allocated for the best protection and mitigation during such an event.

Our research approach demonstrates a method for monitoring remote areas in the Arctic and identifies areas for improvement and additional data collection. Specifically, satellite imagery provides breaching dates when direct, on-the-ground observations are not available. Further, the model can provide information about processes that affect ecological and social aspects of Arctic life likely to be influenced by climate change. Critical breaching processes are likely to be affected by climate change, leading to cascading effects on the wide variety of fish, bird and marine mammal species and subsistence users that rely on these ecosystems. The modeling framework can be updated when more data become available to further understand Arctic lagoon breaching and inform management considerations.

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Table 1.1 Summary of the environmental parameters for the Arctic lagoon breach model. Uniqueness indicates whether the data were unique for each lagoon or a common value used for all three lagoons

Data source	Uniqueness	Description	Abbreviation	Example or units
N/A	Unique	Lagoon	lagoon	Aukulak (AK)
NCDC	Same for all 3	Sum of cumulative degree days greater than freezing January-May	cdd.sum	°F
NCDC	Same for all 3	Day of year where three consecutive days are above freezing	doy.thaw	Day of year (1 – 365)
NCDC	Same for all 3	Total winter snowfall	snowfall	mm
USGS NWIS	Same for all 3	Day of year of Wulik River break-up	wul.brup	Day of year (1 – 365)
NSIDC	Unique	June concentration of sea ice	june.ice	%

Note: Abbreviations are as follows. National Climate Data Center (NCDC); United States Geological Survey National Water Information System (USGS NWIS); National Snow and Ice Data Center (NSIDC).

Table 1.2 Summary of model selection statistics for lagoon breach models.

Model names	*df*	*AICc*	Δ *AICc*	w_t	*LL*
wul.brup	2	261.32	0.00	0.23	-128.47
snowfall	2	261.95	0.63	0.17	-128.79
june.ice + wul.brup + doy.thaw	4	262.03	0.71	0.16	-126.35
cdd.sum + snowfall	3	263.42	2.10	0.08	-128.32
june.ice + wul.brup	3	263.70	2.38	0.07	-128.46
cddo.sum	2	263.83	2.51	0.07	-129.73
doy.thaw	2	264.00	2.68	0.06	-129.81
doy.thaw + snowfall	3	264.10	2.78	0.06	-128.66
june.ice	2	264.31	2.99	0.05	-129.97
june.ice + cdd.sum	3	265.98	4.66	0.02	-129.60
june.ice + wul.brup + cdd.sum	4	266.11	4.78	0.02	-128.39
Full	8	272.93	11.61	0.00	-125.70

Note: Abbreviations are as follows: df = degrees of freedom; ΔAICc = difference in the corrected Akaike information criterion value for a particular model compared with the top-ranking model; w_t = AICc weight; LL = log-likelihood.

Table 1.3 Model-averaged parameter estimates and lower and upper unconditional 90% confidence limits (CLs) for covariates predicting lagoon breach day of year.

Parameter	Estimate	Lower CL	Upper CL
(Intercept)	184.487	100.249	268.725
wul.brup	-0.694	-1.375	-0.012
snowfall	-0.155	-0.320	0.010
june.ice	-0.033	-0.136	0.069
doy.thaw	0.342	-0.079	0.764
cdd.sum	0.007	-0.007	0.021

Table 1.4 Summary information on indicator lagoon breaching from satellite imagery.

	Range of breaching day of year	Range of error for breaching day of year
Aukulak	128–165	7–48
Krusenstern	127–164	7–48
Kotlik	128–156	2–40

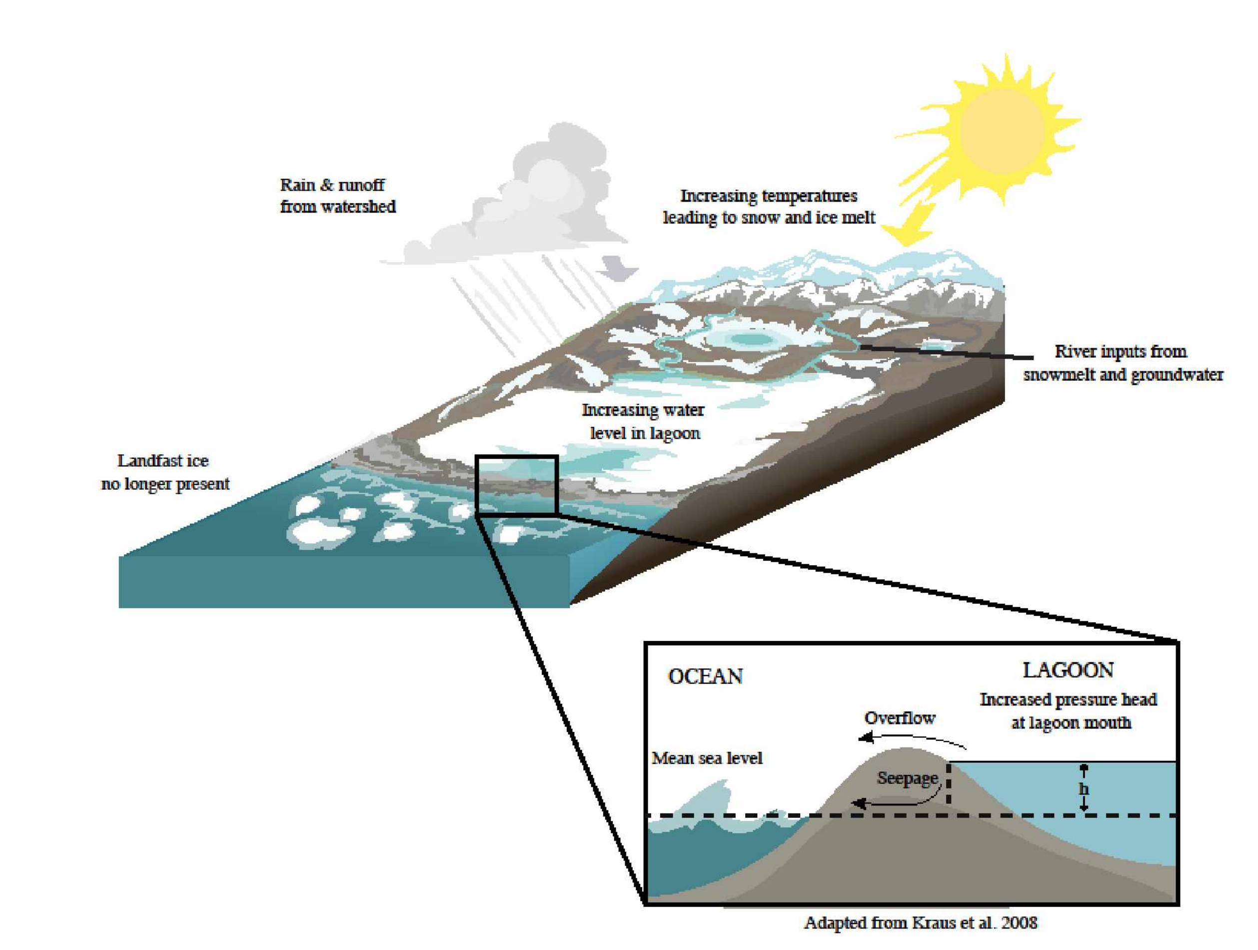

Figure 1.1 Depiction of the hypothesized environmental processes correlated with spring lagoon breaching in Northwest Alaska, both at the watershed scale and specifically at the mouth of the lagoon (adapted from Kraus et al. 2008).

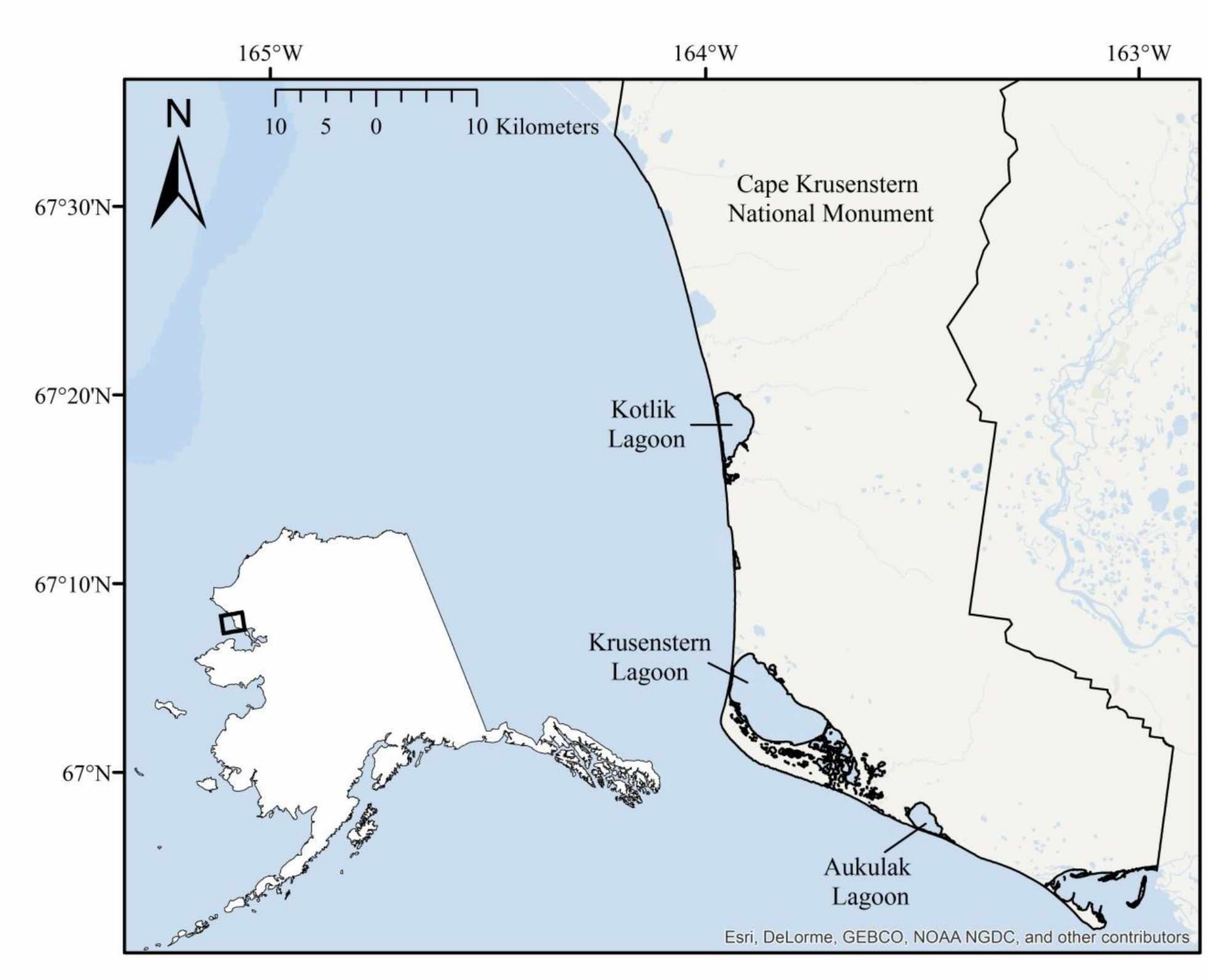

Figure 1.2 Study area and lagoons located in Cape Krusenstern National Monument, Northwest Alaska.

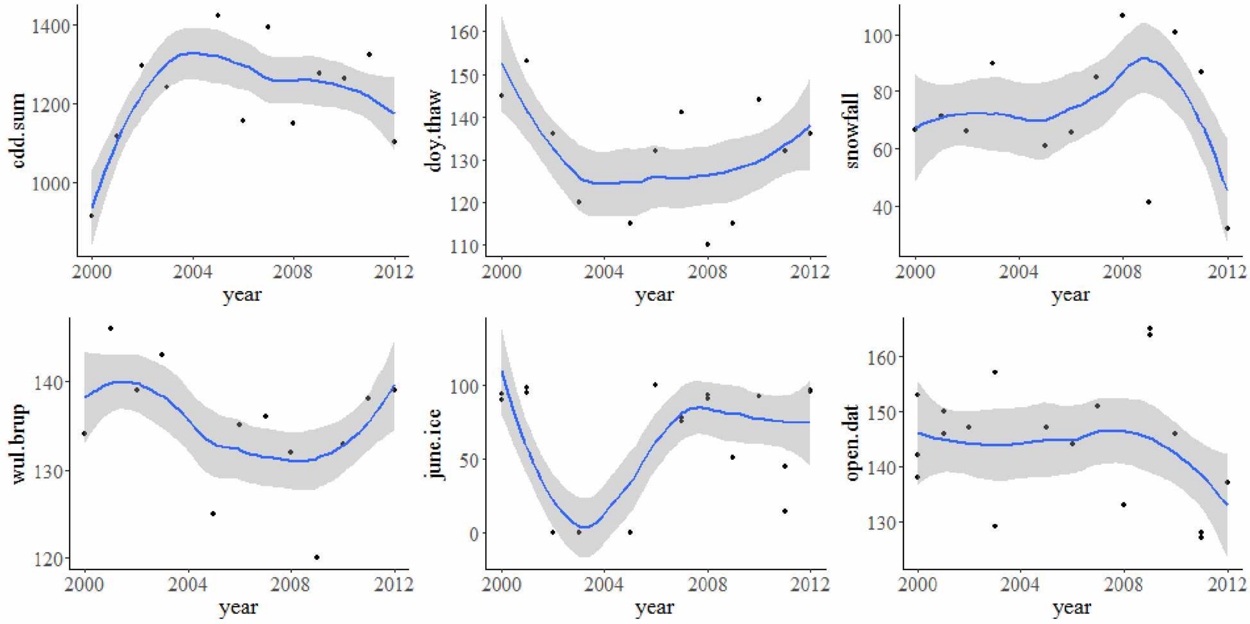

Figure 1.3 Relationships between the environmental covariates included in the generalized linear model and the response with respect to year. Observed data for each environmental metric included in the analysis are represented by black points. A loess smoother is superimposed (blue line) with a 95% confidence interval (shaded grey region) to help identify any trends over time. Abbreviations for the covariates are as follows: sum of cumulative degree days above freezing (cdd.sum), day of year of thaw (doy.thaw), total winter snowfall (snowfall), Wulik River break-up day of year (wul.brup), June sea ice concentration (june.ice), and lagoon breaching date (open.dat).

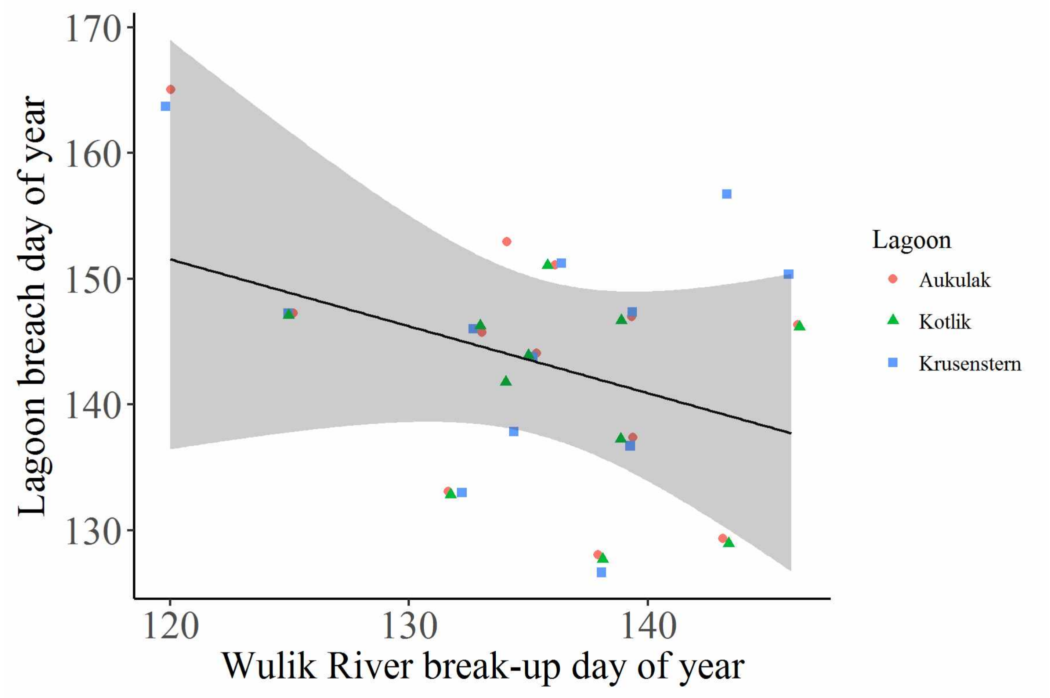

Figure 1.4 Relationship between lagoon breach day of year and Wulik River break-up date. Observed data for breaching days are indicated by points, color- and shape-coded by lagoon. The black line indicates the predicted relationship and the shaded gray area indicates the 90% confidence interval for the predicted values.

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Appendix 1

Table 1.5. Table of the satellite images used, their processing and classification (open or closed) for the three lagoons, Aukulak (AK), Krusenstern (KR), and Kotlik (KO). Question marks indicate uncertainty in the classification of the lagoon as either open (o) or closed (c), resulting from either cloud cover, striping, or insufficient spatial resolution.

Image Name	Satellite	Sensor	Date	Cloud Cover (%)	Processing	AK	KR	KO
LC80820132013244LGN00	Landsat 8	OLI, TIRS	9/1/2013	5.4	ndwi	c	c	o
LC80810132013237LGN00	Landsat 8	OLI, TIRS	8/25/2013	15.72	ndwi	c	c	c
LE70800132013190EDC00	Landsat 7	ETM SLC-off	7/9/2013	14	ndwi	?	o	?
LC80810132013173LGN00	Landsat 8	OLI, TIRS	6/22/2013	20.39	ndwi	c	o	o
LC80820132013164LGN00	Landsat 8	OLI, TIRS	6/13/2013	10.99	ndwi	o	o	o
LC80800132013150LGN00	Landsat 8	OLI, TIRS	5/30/2013	8.94	ndwi, TCC sharpened	o	c	o
LE70810132013149EDC00	Landsat 7	ETM SLC-off	5/29/2013	16	ndwi	o	c	o
LE70810132012259EDC00	Landsat 7	ETM SLC-off	9/15/2012	40	ndwi	?	?	c
LE70800132012204EDC00	Landsat 7	ETM SLC-off	7/22/2012	0	ndwi	c	?	o
LE70820132012170EDC00	Landsat 7	ETM SLC-off	6/18/2012	0	ndwi	c	?	o
LE70810132012147EDC00	Landsat 7	ETM SLC-off	5/26/2012	4	ndwi	c	c	c
LT50800132011273GLC00	Landsat 5	TM	9/30/2011	33		c	c	c
LT50810132011168GLC00	Landsat 5	TM	6/17/2011	13		o	o	o
LT50800132011161GLC00	Landsat 5	TM	6/10/2011	37		o	o	o
LE70810132011144EDC00	Landsat 7	ETM SLC-off	5/24/2011	14	ndwi	c	c	o
LT50820132011143GLC00	Landsat 5	TM	5/23/2011	28		c	c	c
LE70800132010262EDC00	Landsat 7	ETM SLC-off	9/19/2010	0	ndwi	c	c	?
LT50810132010261GLC00	Landsat 5	TM	9/18/2010	12		c	c	c
LE70810132010253EDC00	Landsat 7	ETM SLC-off	9/10/2010	14		c	?	c
LE70810132010205EDC00	Landsat 7	ETM SLC-off	7/24/2010	20	ndwi	c	c	c
LT50800132010190GLC00	Landsat 5	TM	7/9/2010	0		c	c	c
LE70810132010189EDC00	Landsat 7	ETM SLC-off	7/8/2010	0	ndwi	c	o	c
LT50810132010181MGR01	Landsat 5	TM	6/30/2010	0	ndwi	o	o	c
LT50800132010174GLC00	Landsat 5	TM	6/23/2010	15		o	o	c
LE70820132010164EDC00	Landsat 7	ETM SLC-off	6/13/2010	29		?	?	c
LT50800132010158GLC00	Landsat 5	TM	6/7/2010	2		o	o	c
LT50810132010149GLC00	Landsat 5	TM	5/29/2010	1		o	o	c
LE70820132010148EDC00	Landsat 7	ETM SLC-off	5/28/2010	1		o	o	c

Table 1.5 continued

LE70810132009250EDC01	Landsat 7	ETM SLC-off	9/7/2009	34	ndwi	?	?	c
LE70820132009225EDC00	Landsat 7	ETM SLC-off	8/13/2009	25		c	c	?
LE70810132009202EDC01	Landsat 7	ETM SLC-off	7/21/2009	38	ndwi	c	?	c
LT50810132009194GLC00	Landsat 5	TM	7/13/2009	4	ndwi	c	c	c
LT50810132009194GLC00	Landsat 5	TM	7/13/2009	4		c	c	c
LT50800132009171GLC00	Landsat 5	TM	6/20/2009	21	ndwi	o	o	o
LE70800132009163EDC00	Landsat 7	ETM SLC-off	6/12/2009	1	ndwi	o	o	o
LT50800132009155GLC00	Landsat 5	TM	6/4/2009	4		o	o	o
LT50810132009146GLC01	Landsat 5	TM	5/26/2009	18		c	c	c
LT50810132008256GLC00	Landsat 5	TM	9/12/2008	3		c	c	c
LE70810132008248EDC00	Landsat 7	ETM SLC-off	9/4/2008	16	ndwi	c	?	c
LE70800132008241EDC00	Landsat 7	ETM SLC-off	8/28/2008	12	ndwi	c	o	c
LT50800132008233GLC00	Landsat 5	TM	8/20/2008	1		o	o	c
LE70810132008232EDC00	Landsat 7	ETM SLC-off	8/19/2008	1	ndwi	o	o	c
LE70800132008209EDC00	Landsat 7	ETM SLC-off	7/27/2008	8	ndwi	o	?	?
LT50800132008185GLC00	Landsat 5	TM	7/3/2008	8		o	o	o
LT50800132008153GLC00	Landsat 5	TM	6/1/2008	17		o	o	o
LE70820132008143EDC00	Landsat 7	ETM SLC-off	5/22/2008	2		?	?	?
LE70820132007236EDC00	Landsat 7	ETM SLC-off	8/24/2007	30		c	?	?
LT50800132007230GLC00	Landsat 5	TM	8/18/2007	5		o	o	c
LE70810132007229EDC00	Landsat 7	ETM SLC-off	8/17/2007	3	ndwi	o	o	o
LE70800132007206EDC00	Landsat 7	ETM SLC-off	7/25/2007	23	ndwi	o	o	c
LT50820132007196MGR00	Landsat 5	TM	7/15/2007	18		o	o	?
LE70820132007188EDC00	Landsat 7	ETM SLC-off	7/7/2007	7		o	o	?
LE70820132007140EDC00	Landsat 7	ETM SLC-off	5/20/2007	1		?	c	c
LT50800132006243GLC00	Landsat 5	TM	8/31/2006	2		c	c	c
LE70810132006242EDC00	Landsat 7	ETM SLC-off	8/30/2006	4		c	c	c
LE70800132006187EDC00	Landsat 7	ETM SLC-off	7/6/2006	28		o	o	o
LE70820132006185EDC00	Landsat 7	ETM SLC-off	7/4/2006	6		o	?	o
LE70810132006178EDC00	Landsat 7	ETM SLC-off	6/27/2006	41		o	o	o
LT50820132006177GLC01	Landsat 5	TM	6/26/2006	42		o	o	o
LE70810132006162EDC00	Landsat 7	ETM SLC-off	6/11/2006	39		o	o	o
LT50820132006161GLC00	Landsat 5	TM	6/10/2006	47		o	o	o
LE70820132006153EDC00	Landsat 7	ETM SLC-off	6/2/2006	25		?	?	o
LT50800132005272GLC00	Landsat 5	TM	9/29/2005	1		c	o	o
LT50810132005247GLC01	Landsat 5	TM	9/4/2005	4		c	c	c

Table 1.5 continued

LT50820132005238GLC00	Landsat 5	TM	8/26/2005	33		c	c	c
LT50800132005208GLC00	Landsat 5	TM	7/27/2005	11		c	c	c
LE70800132005184EDC00	Landsat 7	ETM SLC-off	7/3/2005	5		o	o	o
LE70800132005168EDC00	Landsat 7	ETM SLC-off	6/17/2005	9		o	o	o
LE70820132005166EDC00	Landsat 7	ETM SLC-off	6/15/2005	3		o	o	o
LT50820132005158GLC00	Landsat 5	TM	6/7/2005	60		o	o	o
LE70810132005143EDC00	Landsat 7	ETM SLC-off	5/23/2005	19		o	o	o
LE70800132005136EDC00	Landsat 7	ETM SLC-off	5/16/2005	9		o	o	?
LE70820132005134EDC00	Landsat 7	EMT+ SLC-on	5/14/2005	56		?	o	?
LE70800132005120EDC00	Landsat 7	EMT+ SLC-on	4/30/2005	11		c	c	c
LE70810132004237EDC01	Landsat 7	ETM SLC-off	8/24/2004	1		c	c	c
LE70820132004180EDC01	Landsat 7	ETM SLC-off	6/28/2004	0		c	?	c
LE70810132004157EDC01	Landsat 7	ETM SLC-off	6/5/2004	1		o	o	o
LE70800132004150EDC01	Landsat 7	ETM SLC-off	5/29/2004	7		o	o	o
LE70810132004125EDC02	Landsat 7	EMT+ SLC-on	5/4/2004	34		c	c	c
LE70810132003266EDC01	Landsat 7	EMT+ SLC-on	9/23/2003	0		c	?	c
LE70810132003218EDC02	Landsat 7	ETM SLC-off	8/6/2003	4		c	c	c
LE70810132003202EDC01	Landsat 7	ETM SLC-off	7/21/2003	36		c	c	c
LE70820132003145EDC00	Landsat 7	EMT+ SLC-on	5/25/2003	61		?	?	?
LE70810132003122EDC00	Landsat 7	EMT+ SLC-on	5/2/2003	0		c	c	c
LE70810132002231PFS00	Landsat 7	EMT+ SLC-on	8/19/2002	26		c	c	c
LE70800132002224PFS00	Landsat 7	EMT+ SLC-on	8/12/2002	26	pan-sharpened	o	o	c
LE70810132002215AGS01	Landsat 7	EMT+ SLC-on	8/3/2002	0		o	c	c
LE70800132002208AGS00	Landsat 7	EMT+ SLC-on	7/27/2002	2		o	o	c
LE70810132002199AGS00	Landsat 7	EMT+ SLC-on	7/18/2002	0		o	c	c
LE70800132002176AGS00	Landsat 7	EMT+ SLC-on	6/25/2002	0		o	o	o
LE70810132002167AGS00	Landsat 7	EMT+ SLC-on	6/16/2002	0		o	o	o
LE70820132002158PFS00	Landsat 7	EMT+ SLC-on	6/7/2002	3		o	o	o
LE70800132002144PFS00	Landsat 7	EMT+ SLC-on	5/24/2002	5		o	o	o
LE70820132002142AGS00	Landsat 7	EMT+ SLC-on	5/22/2002	0		o	o	o
LC80820132016141LGN01	Landsat 7	EMT+ SLC-on	5/15/2002	0		c	c	c
LE70810132001260PFS00	Landsat 7	EMT+ SLC-on	9/17/2001	41		?	?	c
LE70820132001235AGS00	Landsat 7	EMT+ SLC-on	8/23/2001	14		c	c	o
LE70810132001228AGS00	Landsat 7	EMT+ SLC-on	8/16/2001	18		c	c	?
LE70820132001203AGS02	Landsat 7	EMT+ SLC-on	7/22/2001	41		c	o	o
LE70820132001187AGS00	Landsat 7	EMT+ SLC-on	7/6/2001			c	o	o

Table 1.5 continued

LE70800132001173AGS00	Landsat 7	EMT+ SLC-on	6/22/2001	3	c	o	o
LE70800132001157PFS00	Landsat 7	EMT+ SLC-on	6/6/2001	5	c	o	o
LE70820132001155PFS00	Landsat 7	EMT+ SLC-on	6/4/2001	0	c	c	c
LE70810132001148AGS00	Landsat 7	EMT+ SLC-on	5/28/2001	6	c	c	c
LE70810132000258AGS00	Landsat 7	EMT+ SLC-on	9/14/2000	44	c	c	c
LE70800132000203AGS01	Landsat 7	EMT+ SLC-on	7/21/2000	8	c	o	o
LE70820132000201AGS00	Landsat 7	EMT+ SLC-on	7/19/2000	29	c	o	o
LE70820132000201AGS00	Landsat 7	EMT+ SLC-on	7/19/2000	29	c	o	c
LE70810132000194AGS00	Landsat 7	EMT+ SLC-on	7/12/2000	7	?	?	o
LE70820132000185AGS00	Landsat 7	EMT+ SLC-on	7/3/2000	11	?	?	o
LE70820132000185AGS00	Landsat 7	EMT+ SLC-on	7/3/2000	11	?	?	o
LE70800132000171AGS01	Landsat 7	EMT+ SLC-on	6/19/2000	33	c	o	o
LE70810132000162EDC00	Landsat 7	EMT+ SLC-on	6/10/2000	68	?	?	o
LE70800132000155AGS00	Landsat 7	EMT+ SLC-on	6/3/2000	16	?	?	o
LE70800132000139AGS00	Landsat 7	EMT+ SLC-on	5/18/2000	17	c	c	c

Note: Abbreviations are as follows: Operational Land Manager (OLI), Thermal Infrared Sensor (TIRS), Enhanced Thematic Mapper + (ETM+), Scan Line Correction off (SLC-off), Thematic Mapper (TM), Normalized Difference Water Index (NDWI), True Color Composite (TCC).

Chapter 2 : An InSAR habitat suitability model to identify overwinter conditions for coregonine whitefishes in Arctic lagoons[1]

Abstract

Lagoons provide critical habitats for many fishes, including whitefishes, which are a mainstay in many subsistence fisheries of Arctic Alaska rural communities. Despite their importance, little is known about the overwintering habits of whitefishes in Arctic Alaska due to the challenges associated with sampling during winter. We developed a habitat suitability (HS) model to understand the potential range of physical conditions that whitefishes experience during the Arctic winter, using three indicator lagoons that represent a range of environmental characteristics. The HS model was built using a three-step approach. First, interferometric synthetic aperture radar (InSAR) remote sensing identified areas of floating and bottomfast ice. Second, through in-field groundtruthing, we confirmed the a) presence, and b) quality of liquid water (water depth, temperature, and dissolved oxygen) beneath the ice cover. Third, we assessed the suitability of that liquid water as habitat for whitefishes, based on published literature and expert interpretation of water quality parameters. InSAR determined that 0, 65.4, and 88.2 % of the three lagoons were composed of floating ice, corresponding with areas of liquid water beneath a layer of ice. The HS model indicated that all three lagoons had reduced suitability as whitefish habitat in winter as compared to summer due to loss of habitat from the presence of bottomfast ice and a reduction of liquid water quality due to cold temperatures, high salinities and low dissolved oxygen levels. However, only the shallowest lagoon had lethal conditions and zero suitability as whitefish habitat. The methods outlined here provide a simple,

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[1] Tibbles, M., J.A. Falke, A.R. Mahoney, M. Robards, A. C. Seitz. 2018. An InSAR Habitat Suitability model for identifying overwinter conditions for coregonine whitefishes in Arctic lagoons. https://doi.org/10.1002/tafs.10111.

cost-effective method to identify habitats that consistently provide critical winter habitat and integrate remote sensing in a HS model framework.

Introduction

Zones of habitat transitions between freshwater and marine ecosystems, such as lagoons and estuaries, are important for many diadromous fishes during different stages of their life history (Dürr et al. 2011). Lagoons are shallow coastal water bodies typically oriented shore-parallel, separated from the ocean by barriers, and connected at least intermittently to the ocean by one or more inlets (Bird 1994; Kjerfve 1994). There is widespread and increasing recognition globally of the essential ecosystem services lagoons provide such as shoreline protection, water quality improvement, and habitat for fishes and other subsistence resources (Levin et al. 2001; Mouillot et al. 2007). Further, they contribute to fisheries and aquaculture (Mee 1978), and have high economic value (de Groot et al. 2012).

Over a third of the Alaskan Arctic coastline north of the Bering Strait is comprised of permanently and periodically open coastal lagoons (Haynes et al. 2017). Lagoons in Northwest Alaska typically form an open connection to the ocean in the spring during snow melt and ice break-up that raise water levels in the closed lagoons until a breaching event occurs. They later close during the summer months when berms across the breach are rebuilt by constructive waves and longshore sediment transport (Barnes 1980; Reynolds 2012). During the ice-free season, when they are connected to the marine environment, Arctic lagoons are highly productive, well-mixed brackish water bodies (Dunton et al. 2012), providing rich feeding grounds for Arctic fishes, migratory birds, and marine mammals, which are critical resources for subsistence hunters and fishermen (Dunton et al. 2012).

In Northwest Alaska, whitefishes (*Coregonus* spp.), part of the salmonid family (Helfman et al. 2009), are a reliable subsistence resource for indigenous residents and comprised ~18% of subsistence harvests from 1964–2007 (Magdanz et al. 2010). Many whitefishes occupy lagoons during some period of their lives, particularly during the summer when lagoons in this region have an open connection to the ocean. During this time, Traditional Ecological Knowledge holders have stated that "fish go to lagoons to grow," referring in particular to whitefishes that feed and spawn in lagoons (A. Whiting, Kotzebue IRA, personal communication). Large concentrations of whitefishes can be found within the lagoons in the fall when the lagoons are closed (Georgette and Loon 1993), and these remaining whitefishes must overwinter in these systems (C. Harris, subsistence fisherman, personal communication).

Winter is a challenging period for fishes, and small areas of the landscape can have a disproportionate impact on the persistence and productivity of fish populations (Cunjak 1996; Reynolds 1997). Therefore, understanding fish habitat, particularly during winter, is important in high-latitude regions. In the Arctic, suitable fish habitat relies primarily on the presence of liquid water, which exists in lagoons with summer liquid water depths >2 m. In these cases, liquid water remains beneath ice cover that can reach up to 2 m in thickness by spring, whereas shallower water bodies experience a total loss of fish habitat where ice becomes bottomfast (Craig 1984; Jeffries et al. 1996). Additionally, for the remaining liquid water to be suitable fish habitat, conditions must not become anoxic, extremely cold and/or hypersaline (Cunjak 1996).

There is a paucity of basic ecological information about overwintering whitefishes in the Arctic, and their habitats are frequently not understood. Fish habitat can be studied by using in situ measurements of abiotic conditions, which provide discontinuous, yet accurate, information about specific point locations. Remote sensing is an alternative for augmenting in situ sampling that is limited due to the challenges of sampling in cold temperatures and heavy ice cover associated with Arctic winters (Brown et al. 2010). For example, identification of bottomfast and floating ice for understanding potential fish overwintering habitat has been accomplished using an analysis of synthetic aperture radar (SAR) backscatter magnitude (Brown et al. 2010). However, this SAR technique is only effective in freshwater systems where the dielectric contrast between the ice and liquid water allows for the differentiation of bottomfast and floating ice (Jeffries et al. 1994; Eicken et al. 2005; Grunblatt and Atwood 2014; Mahoney et al. 2016). An emerging technique that may be effective in brackish lagoons is interferometric synthetic aperture radar (InSAR). This is a signal processing technique that can be used to measure surface motion by analyzing the phase differences between two synthetic aperture radar (SAR) scenes acquired from coherent (i.e. correlated) viewing geometries (Bamler and Hartl 1998; Moreira et al. 2013). InSAR techniques have been previously used to identify areas of bottomfast and floating ice in estuarine areas as well as for the identification of landfast ice in the Beaufort Sea (Meyer et al. 2011; Yue et al. 2013; Dammann et al. 2016). However, this is a relatively new application of InSAR technology which has not yet been used to understand fish habitat.

In situ and remotely sensed measurements can be combined in habitat suitability (HS) models to provide more comprehensive and continuous information about fish habitat and investigate relationships between fishes and their environment (Ahmadi-Nedushan et al. 2006). HS models frequently inform management decisions about the conservation of habitats important for the survival, growth, and spawning of species, especially in data-poor environments such as the Arctic (Store and Jokimäki 2003; Gillenwater et al. 2006; Vincenzi et al. 2006; Bidlack et al. 2014). Further, they provide insights into the potential conditions that fishes may face in areas and times that are impossible to comprehensively sample and are a useful first step towards understanding critical fish habitats.

Here, we develop a HS model using an emerging InSAR technique and in situ measurements of abiotic conditions to explore the potential range of physical conditions that a culturally and ecologically important group of fishes face during the Arctic winter in lagoons, using three indicator lagoons that represent a range of characteristics found in Northwestern Alaska lagoons. Our research goal was to understand the quality and quantity of overwintering habitat for whitefishes in coastal Arctic lagoons. Our specific objectives were to 1) identify areas of liquid water in lagoons in late winter using an InSAR technique, 2) determine the abiotic conditions beneath the ice during this period, and 3) build an HS model informed by InSAR and field data in a GIS framework. By examining the spatial distribution and habitat factors contributing to viable overwinter habitat for whitefishes in the Arctic landscape, we move towards a better understanding of the importance of coastal lagoons for overwintering migratory fishes and illuminate a key period of the overwintering life history for a culturally important group of fishes.

Methods

We followed a three-stage approach to model the habitat suitability of lagoons as overwintering habitat for whitefishes. First, several pairs of SAR images were acquired to create interferograms, which were used to map areas of bottomfast and floating ice in three lagoons that were chosen to represent the range of conditions found across the coast. To understand the conditions of liquid water beneath the floating ice, we measured water depth, dissolved oxygen, and temperature beneath floating ice in the lagoons during field sampling in March, 2017. Third, parameter values from InSAR and field data were transformed using non-linear parameter-specific suitability functions to a Suitability Index ranging from 0 to 1. The geometric mean of these values was then taken to determine the overall habitat suitability in the lagoons.

Study area

The study area is located in Northwest Alaska in Cape Krusenstern National Monument (Figure 2.1). The 2670 km^2 monument is located near the village of Kotzebue approximately 70 km north of the Arctic Circle (center point 67°26’N 163°32’W) and is characterized by tundra habitat and coastal lagoons. Kotzebue’s 30-year average air temperature in January and July are -19°C and 13°C respectively (Reynolds 2012). The coast abuts the Chukchi Sea and has seven lagoons, three of which were examined in this study: Aukulak, Krusenstern and Kotlik lagoons (Figure 2.1). These three lagoons were chosen because they encompass a range of physical characteristics observed across lagoons during the summer months, more specifically, a breadth of summer water depths, salinities and degrees of freshwater inputs (Table 2.1). Aukulak Lagoon is the smallest in area and the shallowest lagoon, with no deep channels in the body of the lagoon. The salinity of the lagoon is highly dependent on the length of time of its connection to the ocean, and thus can exhibit large variations. In years when it does not become connected to the ocean, Aukulak Lagoon is fresh; when the connection to the ocean is open, it is brackish. Krusenstern Lagoon is the largest lagoon by area, and has the greatest mean summer depth. Krusenstern connects to the marine environment via the Tukruk River at a location approximately 25 km downstream from the main lagoon body. Due to the distance between the lagoon and the connection with the marine environment, it is a relatively fresh lagoon. Kotlik Lagoon has an intermediate area and summer depth, with a shallower mean summer depth than Krusenstern Lagoon, but has deep channels at the mouth of a creek entering the lagoon. Its salinity also depends on the connection to the ocean; however, Kotlik Lagoon regularly connects to the ocean and is generally brackish. Several small creeks flow into Krusenstern and Kotlik lagoons, whereas Aukulak Lagoon has very little significant freshwater input. Despite the breadth of knowledge on summer conditions, little is known about winter conditions. The lagoons provide habitat for to up to 10 taxonomic families and 20 fish species during the summer months (Haynes et al. 2017), including several species of whitefishes: Humpback Whitefish *Coregonus pidschian*; Bering Cisco *C. laurettae*; Least Cisco *C. sardinella*; and Inconnu *Stenodus leucicthyes*, all of which are important for local food security of the neighboring, largely indigenous communities.

Developing InSAR techniques for identifying pools of liquid water beneath floating ice

This study utilized C-band Sentinel-1 Synthetic Aperture Radar (SAR) images acquired by the Sentinel-1B platform, operated by the European Space Agency. SAR provides high-resolution imagery regardless of weather conditions. The interferometric wide (IW) beam mode images, with a spatial resolution of 5 m x 20 m and a 12-day repeat cycle at 67° latitude, were used to create interferograms (subsequently described). Three IW Sentinel-1 SAR image pairs (images taken 12 days apart) from March 2017, when ice cover is at a maximum (Duguay and Lafleur 2003), were chosen to create interferograms using the online engine HYP3 (Hogenson et al. 2016). HYP3 uses GAMMA algorithms to create the differential InSAR products (Hogenson et al. 2016).

InSAR techniques measure surface motion by analyzing the phase differences between two synthetic aperture radar (SAR) scenes acquired from coherent (i.e. correlated) viewing geometries. Coherence describes the degree of correlation between two SAR images; areas with low signal noise and minimal temporal decorrelation should have high coherence (Moreira et al. 2013). Sources of temporal decorrelation on sea ice and lagoon ice include excessive movement or other changes such as flooding or melting. An interferogram is created by measuring the interferometric phase (ϕ) differences between two images acquired at different times and can be used to determine displacement that occurred during the imaging period (Moreira et al. 2013; Dammann et al. 2016). The particular value of ϕ at a given pixel is not meaningful on its own, but variation of ϕ between pixels indicates a topographic slope or that one pixel has moved relative to the other. That is, if adjacent pixels have the same value of ϕ then they are at the same elevation and experienced the same amount of elevation change. The use of InSAR to measure the displacement of ice is limited to cases in which net horizontal motion between image acquisitions is less than half the width of a resolution cell (i.e. pixel). If ice motion exceeds this limit then coherence between the two images is lost and the interferometric result is not meaningful. Thus, the use of InSAR over sea ice is primarily limited to areas of otherwise stationary landfast ice (Dammert et al. 1998; Morris et al. 1999; Meyer et al. 2011). In lagoons, floating ice will be subject to motion due to thermal expansion and contraction and vertical changes in water level that are detectable using InSAR techniques (Dammann et al. 2016; Dammann et al. 2017). Bottomfast ice will not be subject to vertical motion and will exhibit an interferometric signature very similar to the surrounding land area. InSAR techniques can delineate areas of floating ice within the lagoons, identifying areas that contain liquid water that may represent potential overwintering habitat.

On this basis, we used the interferogram with the best coherence to infer areas of bottomfast and floating ice in the lagoons, which was created using SAR images acquired March 16 and 18, 2017. Bottomfast ice was defined as areas of ice inside of the shoreline that exhibited less than 1.5 cm of vertical movement compared to the surrounding land. The 1.5 cm threshold was chosen as it represents our best inference about the amount of movement that could be exhibited by bottomfast ice through expansion and contraction processes, as well as ice growth and doming that may occur in the 12-day temporal acquisition period. For the Sentinel-1 viewing geometry, this equates to 1.7 radians, as calculated using equation 34 from Moreira et al. (2013). Regions of ice with a phase difference from the surrounding land of greater than 1.7 radians were considered to be floating. A profile of the ϕ was drawn across the lagoons in the interferogram (Figure 2.2). From the profile, we identified the phase values associated with land and bottomfast ice, and identified the boundary that corresponded with ice that exhibited greater than 1.5 cm of movement, indicating the transition from bottomfast to floating ice. Regions of floating ice indicated that 1.5 cm or more of liquid water were available beneath the ice. These areas were used as starting points for identifying areas which potentially could be habitable by fishes.

Field sampling

Field sampling was conducted in lagoons in March 2017 (Figure 2.1). Seven dual-purpose sampling and groundtruthing locations in each of the three lagoons were chosen based on previous work conducted in these lagoons to provide continuity with those datasets (Reynolds 2012; Robards 2014). These sampling locations encompass a range of habitats found in the lagoons, ranging from sampling near freshwater inputs to sampling near the marine edge. The maps of floating and bottomfast ice created using InSAR also were used to inform sample design to sample areas delineated as bottomfast and floating ice.

At each of the seven sampling locations, an ice auger was used to drill one hole through the ice. The ice thickness and the depth of liquid water below the ice (hereafter referred to as "water depth") were measured with an ice thickness measuring gage (m) at each location. Physicochemical parameters, including temperature (°C), dissolved oxygen (mg/L), salinity (ppt), and pH, were measured beneath the ice using a YSI multiparameter sonde.

HS model formulation in a GIS framework

We built an HS model to understand the potential range of conditions that whitefishes overwintering in lagoons might experience. Input variables in HS models are habitat features that if modified would affect the capability of the habitat to support the basic species requirements (US Fish & Wildlife Service 1980; Vincenzi et al. 2006). Therefore, for this study, we chose water depth (m), temperature (°C), and dissolved oxygen (mg/L) as the parameters to model winter habitat suitability in the lagoons. Salinity was not included in the model after preliminary examination for collinearity showed that temperature covaried with salinity (Pearson's $r = 0.95$), and we have a greater understanding of the thermal tolerances of salmonids than salinity tolerances.

Point measurements of water depth, temperature, and oxygen were interpolated using a simple kriging approach in ArcMap (version 10.4; Environmental Systems Research Institute, Redmond, California) to produce spatially continuous estimates of each parameter for each lagoon. The kriged layers were converted to raster format with a pixel size of 500 m^2. After kriging was performed for the water depth parameter, areas with bottomfast ice (as determined using InSAR) were assigned a water depth of 0 m.

Each parameter was transformed to a Suitability Index (SI) value on a scale from 0 (unsuitable habitat) to 1 (most suitable habitat), using a non-linear parameter-specific suitability function (Figure 2.3). The suitability functions related the abiotic parameters to their suitability for whitefish survival. The functions were constructed based on a literature review of ideal, marginal, and lethal abiotic characteristic values for Arctic salmonids as well as the authors' expert opinion (Table 2.2; Store & Kangas 2001). The literature review included other salmonid species when information on Arctic coregonines was lacking. The coregonine whitefish species found in the lagoons were pooled to create one set of suitability functions because of the paucity of information available for the individual coregonine species, under the assumption that coregonine whitefishes in these systems have similar biological tolerances to abiotic characteristics.

The SI values for each parameter were then aggregated to produce a metric representing the overall habitat suitability (HS) for a given location within a lagoon by taking the unweighted geometric mean of the parameter-specific SI values:

$$HS = \left(\prod_{i=1}^{n} SI_i\right)^{1/n} \tag{2.1}$$

where SI_i is the SI value for each parameter in the model, and n is the number of parameters in the model. An unweighted geometric mean was used as each parameter was assumed to have the same magnitude of effect for whitefish survival, and because if the value of one parameter was unsuitable for whitefishes, the habitat would also be unsuitable. We interpreted all non-zero HS values to be suitable habitats under the assumption that we cannot know the true minimum suitability threshold for whitefish survival, and which habitat suitability values whitefishes would inhabit, without extensive laboratory experiments. Therefore, it was assumed that whitefish would potentially inhabit all habitat suitability values > 0, and that there was a linear gradation in habitat suitability from 0 to 1. Within the range of suitable habitat, we defined HS < 0.3 as poor, 0.3 – 0.7 as marginal, and > 0.7 as good habitat. The final HS values were mapped to demarcate the spatial distribution and quality of whitefish overwintering habitat in the lagoons.

Finally, we calculated an area-based overall suitability metric, hereafter referred to as HS_A, by dividing the area of a lagoon with HS > 0 by the total surface area of the lagoon,

$$HS_A = \frac{Surface\ area_{HS>0}}{Surface\ area_{total}} \times 100 \quad (2.2)$$

where $Surface\ area_{HS>0}$ is the surface area of the lagoon corresponding to HS values greater than 0, and $Surface\ area_{total}$ is the total surface area of the lagoon. The resulting number corresponds to the area remaining as suitable habitat for whitefishes during winter.

Results

Developing InSAR techniques for identifying pools of liquid water beneath floating ice

The interferogram (Figure 2.4) constructed from images taken in late March 2017 had the highest coherence and approximately represents the maximum ice thickness and bottomfast ice extent for the winter (Duguay and Lafleur 2003). At this time, bottomfast ice was found along the shores of the lagoons where summer depths were less than approximately 1 m. This was expected, as ice thicknesses in this region are typically 1.5 m by the end of winter (Alex Whiting, *personal communication*), indicating there is approximately 1.35 m of ice draft. Aukulak Lagoon had the greatest inferred percentage of bottomfast ice (100%; Table 2.3), indicating that 0% of the lagoon had available liquid water of any appreciable depth beneath the ice. In contrast, 65.4% of Krusenstern Lagoon and 88.2% of Kotlik Lagoon were composed of areas of floating ice, respectively. Bottomfast ice was inferred around the shores of the lagoons and in shallow areas, whereas floating ice was inferred in the center of the lagoons.

Field sampling

Bottomfast ice was found in four of the seven sampling sites at Aukulak Lagoon. InSAR predicted a lack of water for all sites, and thus only produced a correct prediction for four of seven sites. Of the three sites with liquid water, they had a mean water depth of 0.2 m (SD, 0.04

m; Table 2.1). The water beneath the ice was hypersaline (52.70 ± 0.27 ppt) and had sub-freezing temperatures (-3.41 ± 0.09°C) and was hypoxic (1.85 ± 0.42 mg/L).

Liquid water was found in all six sampling sites at Krusenstern Lagoon. The seventh site was not sampled due to technical difficulties due to cold temperatures in the field. InSAR correctly identified the presence of liquid water for six of the seven sites. Beneath the ice, there was a mean water depth of 1.2 m (SD, 0.45 m) across the lagoon. The water beneath the ice had low salinities (6.65 ± 1.07 ppt), moderately cold temperatures (-0.54 ± 0.08°C) and low levels of dissolved oxygen (4.33 ± 1.02 mg/L).

Liquid water was found at six of the seven sampling sites at Kotlik Lagoon. InSAR correctly identified the presence of liquid water or bottomfast ice for six of the sample locations, and incorrectly predicted bottomfast ice at one sample location where 1.14 m of liquid water was found. Kotlik Lagoon had a mean water depth of 0.86 m (SD, 0.39 m), with moderate salinities (12.73 ± 6.95 ppt), cold temperatures (-0.73 ± 0.73°C) and moderate dissolved oxygen levels (5.55 ± 1.68 mg/L). The salinity varied greatly within Kotlik Lagoon, from 0.53 ppt near freshwater inflows to 17.92 ppt in the center of the lagoon. Dissolved oxygen levels were highest near the outlets of creeks entering the frozen lagoons. At the confluence of a small creek entering Kotlik Lagoon, dissolved oxygen levels were 7.43 mg/L.

HS model

Our HS model suggested Aukulak Lagoon had no suitable fish habitat (Figure 2.5) with HS_A = 0%, because of extensive bottomfast ice, high salinity and low dissolved oxygen levels where liquid water occurred. The HS_A of Krusenstern and Kotlik lagoons were 65.4% and 34.2% respectively. Bottomfast ice was found in the nearshore and shallow areas of each lagoon. Where liquid water remained, the habitat was considered poor with mean HS values of 0.21 and 0.18 for

Krusenstern and Kotlik respectively. There was some variation in the HS values of liquid water beneath the floating ice due to variations in temperature and dissolved oxygen with HS values ranging between 0 and 0.58 (Table 2.3).

Discussion

Our HS model informed by InSAR provided a starting point for understanding potential conditions whitefishes may experience in lagoons in Northwest Alaska. This approach is valuable due to the challenges associated with sampling these remote locations during winter. The InSAR technique was able to identify broad areas of liquid water in lagoons and expands our ability to identify potential overwintering areas, especially in brackish lagoon and estuarine regions that provide critical fish habitat across the coast. Overall, we found that all representative lagoons had reduced suitability as whitefish habitat in the winter compared to the summer. However, we determined that where liquid water was present, the quality of lagoon habitat generally decreased with decreases in both lagoon depth and the volume of freshwater input.

Suitability partially depended on the presence of bottomfast ice, which in turn is related to an interaction between ice thickness and overall depth of the lagoon. In general, areas in lagoons with overall summer depths less than or equal to the ice draft exhibited less than 1.5 cm of vertical movement and were characterized as bottomfast ice. As such, in relatively shallow lagoons, the ice occupies a greater proportion of the overall water depth, leaving less remaining liquid water. In deeper lagoons, such as Krusenstern and Kotlik, a greater proportion of liquid water remained beneath the ice. Habitat was unsuitable when ice reached the bottom of the lagoon and precluded liquid water, which commonly occurred near shore. Shallow lagoon systems were more likely to exhibit areas of unsuitable habitat that could lead to winterkill events.

Suitability also partially depended on quality of liquid water, which ranged from marginal to lethal for whitefish survival. Poor suitability of liquid water was related to cold temperatures, low dissolved oxygen, and high salinities. As ice forms in the lagoons, salt is excluded from the ice crystals leading to brine rejection, increasing the salinity of the water directly below the ice layer (Petrich and Eicken 2010). Because of the finite volume of water in the lagoons, the salinity of water beneath the ice increases with the ice thickness, and becomes saltier than the ocean (~35 ppt; Millero et al. 2008), also known as hypersaline. Hypersalinity depresses the freezing point of liquid water, leading to extremely cold water that can reach temperatures well below that of marine waters. For example, the small amount of liquid water between the ground and ice interface in Aukulak Lagoon became hypersaline, leading to temperatures of -3.5°C. Because the temperature was well below the freezing point of blood plasma for salmonids, which is approximately -0.7°C (King et al. 1989), the lagoon during this time was completely unsuitable for whitefishes. Hypersaline and very cold water were also observed beneath the ice in Aukulak in April 2003 when salinities reached 62.1 ppt, but they were not seen in April 2004 (Reynolds 2012), indicative of the dynamic nature of the water quality conditions in these lagoons.

Additionally, inflow of creek water appears to be one of the main drivers of habitat suitability in Arctic lagoons. Areas of freshwater inflow from small creeks may provide respite for fishes from cold, saline conditions in the lagoons. In March, any flow in the creeks is supplied by groundwater as the air temperatures are well below freezing. Groundwater is generally warmer than surrounding waters and it also can be exposed to the atmosphere in areas without ice (i.e., leads in creeks) when acting as baseflow in creeks, increasing dissolved oxygen levels (Cunjak 1996; Bradford et al. 2001). As the relatively warm and oxygenated water flows from the creek into the lagoon, the area of inflow may offer refugia from the colder, oxygen-depleted waters of the lagoon. Furthermore, several areas in this region, typically in creeks, are known for their springs that keep water open all winter (Robert Schaeffer, subsistence fisherman, *personal communication*). In our study, dissolved oxygen levels at the mouth of a creek entering Kotlik Lagoon were well within the range of suitable levels of dissolved oxygen for salmonids. Additionally, this area had the lowest salinity and highest temperature; therefore, this area of the lagoon was the most suitable as whitefish habitat according to our model. In contrast, Aukulak Lagoon has no significant inflow from a creek, and no suitable habitat during winter, perhaps due to the lack of freshwater inflow.

Winter habitat in shallow lagoons without freshwater inflow such as Aukulak Lagoon may be ephemerally suitable among years, and suggests these systems may be ecological traps for some whitefish populations during some years (Schlaepfer et al. 2002). In contrast, deeper lagoons had intermediate salinities well within the range of suitability for whitefishes. As such, these deeper lagoons with freshwater inflow may consistently provide suitable winter habitat for whitefish populations. Therefore, lagoons with significant freshwater inputs can better support overwintering whitefish populations due to the presence of more suitable habitat characteristics.

We further demonstrated the utility of using an emerging application of InSAR techniques to inform habitat suitability models. InSAR techniques have been used previously to identify areas of bottomfast and floating ice in estuarine areas, however, these techniques have not been used in conjunction with HS modelling. InSAR was relatively accurate here, identifying points of floating and bottomfast ice 80% (16/20) correctly, with 90% accuracy at predicting floating ice and 67% accuracy at predicting bottomfast ice. Several of the incorrect bottomfast ice InSAR predictions were located in Aukulak Lagoon, where 0.2 m of water was found beneath the ice.

This approaches the InSAR detection threshold, which may be the cause of the inaccurate predictions. Although more groundtruthing is needed to further determine the accuracy of this technique, it promises to be increasingly effective with the advances in SAR imagery and the introduction of new satellites with higher temporal and spatial resolutions that allow for images with high temporal coherence. The effectiveness of InSAR proved useful input for HS models in nearshore, estuarine and lagoon areas in the Arctic.

Overall, the HS model was a useful tool for understanding basic habitat information across the Northwest Alaskan coast in locations that are remote and logistically challenging to sample for poorly understood taxa. Furthermore, the HS model provides a platform for researchers and managers to monitor changes in the distribution and quality of habitat available for whitefishes during the critical life history period of winter. It would be relatively simple and cost-effective to implement future HS modeling for lagoon whitefishes across the Alaskan Arctic coast where physical and fisheries data are available. The model could be improved through the inclusion of more parameters, like turbidity or substrate. Previous HS models have included these parameters (Brown et al. 2010); however, we lacked any even baseline information on how whitefish distribution and abundance would be influenced by these parameters. One notable aspect of the model that could be improved is its reliance on expert opinion for understanding suitability of specific environmental conditions. This reliance resulted from the paucity of published information on responses of Arctic coregonines to gradients in environmental conditions. The lack of biological data to support the model also leads to an unknown level of uncertainty in the model. This could be addressed by completing a sensitivity analysis by modifying the suitability functions and determining the relative impact on HS and HS_A. However, as whitefishes are environmental generalists (Brown et al. 2012) and have been found surviving across a wide gradient of environmental conditions, the functions derived here likely encompass the appropriate range of conditions in which whitefishes can survive, even without having suitability values derived from rigorous research. More intensive fish and environmental sampling will help describe the relationship between habitat characteristics and suitability, lending credence to the model predictions.

This study provided important information on potential winter habitat conditions faced by whitefishes in lagoons in Northwest Alaska. The modeling approach provides managers with a tool to tentatively identify lagoons that provide consistent overwinter habitat and serve to maintain fish populations, as opposed to lagoons that are only ephemerally suitable and cannot support fish populations year-round. As such, the approach used in this study could be used to rank or categorize the importance of lagoons, if needed, during times of limited resources for local communities. Finally, this technique is transferable to other geographic areas and could be used to understand winter lagoon habitats across the entire Arctic coast.

Acknowledgments

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Table 2.1 Surface area, mean depth, typical salinity, and ocean connection type for three southern Chukchi Sea lagoons in the summer months (information from Reynolds (2012), Robards (2014), and Haynes et al. (2017)), and mean ice and water quality parameters and standard deviations (SD) identified during winter sampling.

Parameter	Aukulak	Krusenstern	Kotlik
Area (km^2)	9	56	24
Mean summer depth (m)	1.4	2.4	2.1
Physical Tendency	Brackish	Fresh	Brackish
Connection	Intermittently Open	Seasonally-Closed	Intermittently Open
Ice thickness (m (SD))	1.25 (0.04)	1.47 (0.43)	1.31 (0.13)
Water depth (m (SD))	0.2 (0.04)	1.2 (0.45)	0.89 (0.39)
Temperature (°C (SD))	-3.41 (0.09)	-0.54 (0.08)	-0.73 (0.73)
Dissolved oxygen (mg/L (SD))	1.85 (0.42)	4.33 (1.02)	5.55 (1.68)
Salinity (ppt (SD))	52.70 (0.27)	6.65 (1.07)	12.73 (6.95)
pH (SD)	7.73 (0.11)	8.15 (0.10)	7.90 (0.64)

[a] Based on average lagoon salinity: <11 ppt fresh; >11 - <30 ppt brackish; >30 ppt marine

Table 2.2 References used to construct the non-linear parameter-specific suitability functions, and the species from which the values are derived respectively. Expert opinion was provided by: Dr. Andrew Seitz, Dr. Martin Robards, and Marguerite Tibbles.

Parameter	References	Species
Winter water depth	Expert opinion	NA
Dissolved oxygen	Doudoroff and Shumway (1970); Davis (1975); Czerkies et al. (2001); expert opinion	*Coregonus nasus*; *Salvelinus alpinus*; *C. lavaretus*, *C.albula*; NA
Temperature	Edsall et al. (1970); Edsall and Rottiers (1976); Fechhelm et al. (1993); Lyytikäinen et al. (1997); Elliott and Elliott (2010); expert opinion	*Coregonus hoyi*; *C. clupeaformis*; *C. autumnalis*; *Salvelinus alpinus*; *S. alpinus*; NA

Table 2.3 Floating ice percentage and area-based overall suitability metric (% suitable) of the lagoons as winter habitat as inferred using InSAR and the habitat suitability (HS) raster statistics for each lagoon. Pixels indicates the number of pixels represented by the HS map for each lagoon. Abbreviations are as follows: minimum value (min), maximum value (max), standard deviation (SD).

Parameter	Aukulak	Krusenstern	Kotlik
Floating ice (%)	0	65.4	88.2
HS_A	0	65.4	34.2
HS mean (SD)	0 (0)	0.21 (0.16)	0.18 (0.25)
HS min	0	0	0
HS max	0	0.35	0.58
Pixels	44	209	104

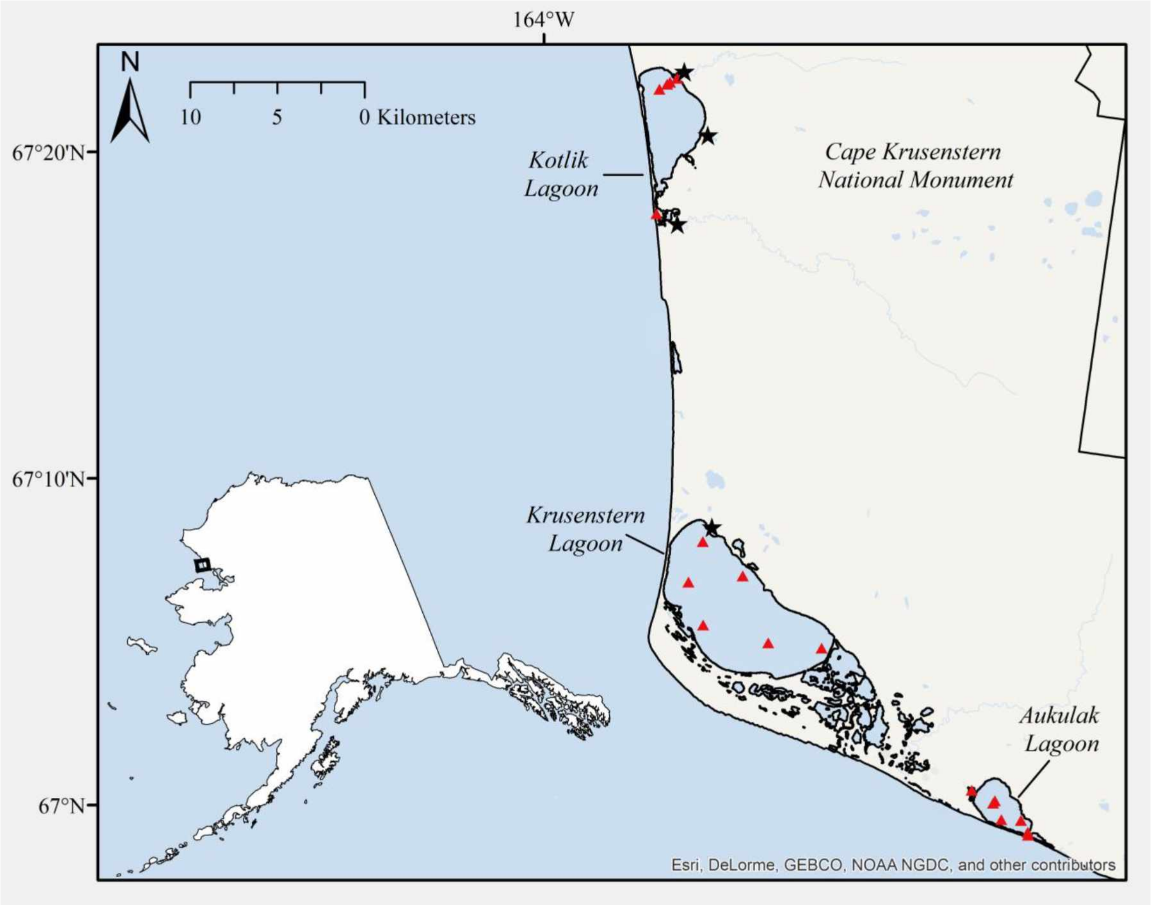
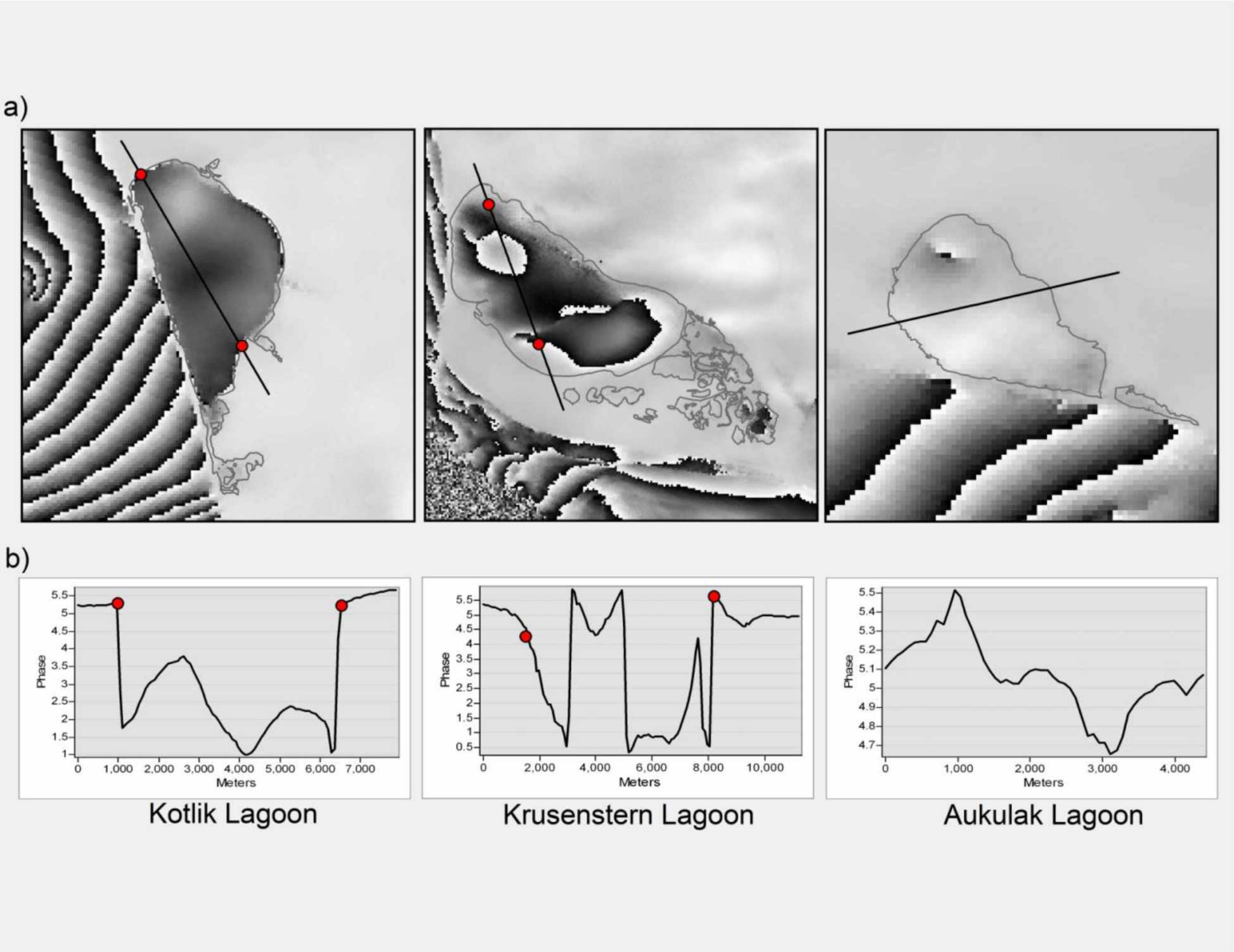


Figure 2.1 Study area in Cape Krusenstern National Monument, Alaska. Red triangles indicate sample locations and black stars indicate creek inflows.



Kotlik Lagoon

Krusenstern Lagoon

Aukulak Lagoon

Figure 2.2 A) Wrapped phase interferograms for the three lagoons located in Cape Krusenstern National Monument, Alaska, with a black line indicating the path of the B) interferometric synthetic aperture radar phase profiles, where red dots indicate the boundary between bottomfast and floating ice across the profiles of the lagoons.

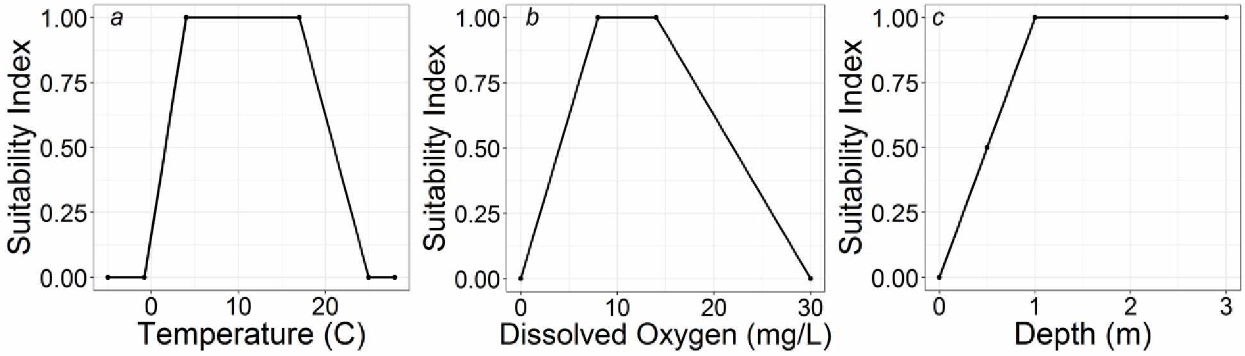


Figure 2.3 Non-linear parameter-specific suitability functions for the habitat characteristics: a) temperature; b) dissolved oxygen; c) liquid water depth. Each function describes the suitability of the range of abiotic conditions as habitat for whitefishes in the study area.

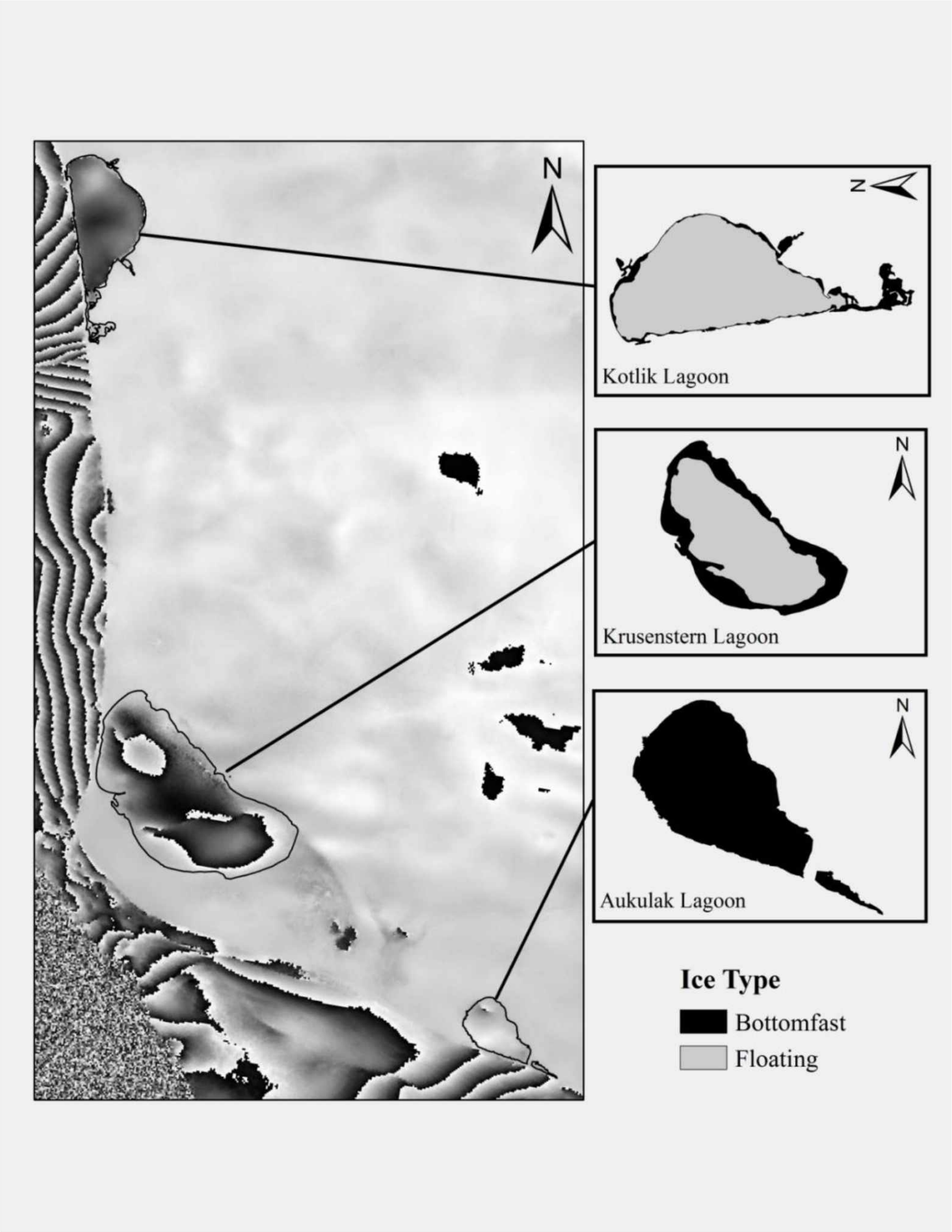


Figure 2.4 Left: the wrapped phase of the interferogram constructed from Sentinel 1 interferometric wide beam satellite imagery using images taken March 16 and March 28, 2017, with the lagoons outlined in black. Right: bottomfast and floating ice types mapped from the interferogram for the lagoons. Floating ice indicates lagoon areas that have liquid water available beneath the ice cover.

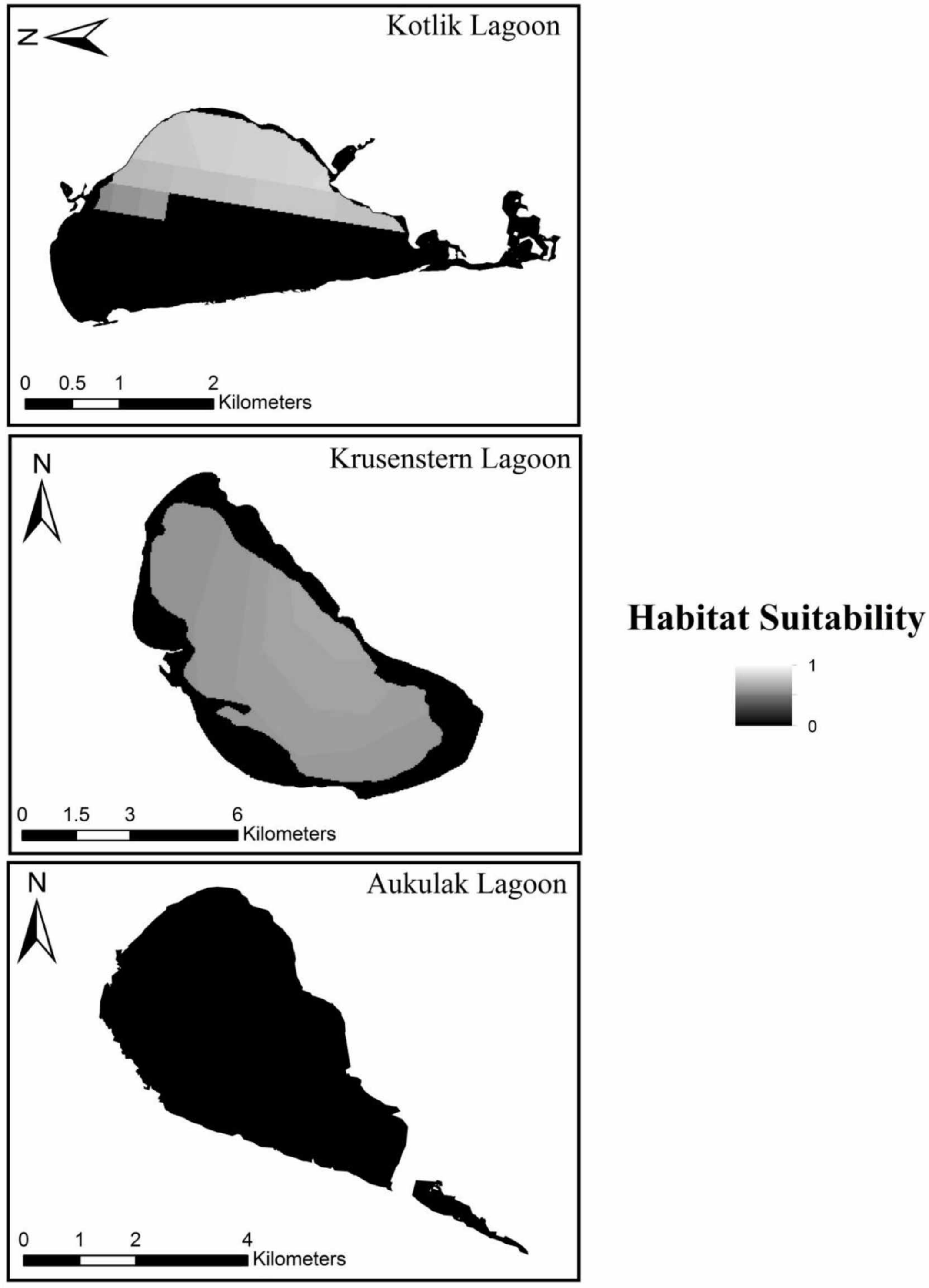


Figure 2.5 Habitat suitability maps delineating the range of suitable overwintering habitat for each lagoon.

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Conclusion

This study contributed to our understanding of seasonal coastal Arctic lagoon dynamics. In Chapter 1, I created a modeling framework to explore the processes behind seasonal lagoon breaching for three indicator lagoons in Northwest Alaska. Using a generalized linear model (glm), an information theoretic approach, and model averaging, I identified a negative correlation between the date of river break-up and date of lagoon breaching (earlier river break-up leads to earlier lagoon breaching). This was the highest ranked model for day of lagoon breaching, representing 23% of the weight of candidate models. Seven other models appeared in the confidence model set, and model-averaged estimates further suggested that the date of river break-up was the most influential predictor. I concluded that the glm model proved to be a useful framework for examining correlations among environmental conditions and lagoon breaching. To increase the model's utility in the future, it could easily be updated with the advent of higher temporal and spatial resolution environmental covariate data. Overall, the study provided baseline information on a critical process that affects both biological and social aspects of life in coastal Arctic Alaska.

In chapter 2, I developed a habitat suitability (HS) model to understand the physical conditions that whitefishes may experience during the Arctic winter, using three indicator lagoons that represented a wide range of environmental characteristics found in northwestern Alaskan lagoons. The HS model indicated that all three indicator lagoons had reduced suitability as whitefish habitat in winter compared to summer. This was due to loss of habitat from the presence of bottomfast ice and a reduction of liquid water quality due to cold temperatures, high salinities and low dissolved oxygen levels. The largest lagoon, which had the greatest degree of freshwater input, provided the greatest area of overwintering habitat while the shallowest lagoon with little to no freshwater input had lethal conditions and no suitability as overwintering whitefish habitat. The methods outlined provided a simple, cost-effective method to allow stakeholders to identify lagoons that consistently provide critical winter fish habitat that are widely used for subsistence activities, as the Arctic faces an uncertain future with climate change, risks of oil spills, and increased coastal development.

Overall, these studies allowed me to explore dynamic seasonal lagoon processes, during both spring and winter, increasing our baseline understanding of important lagoon systems that lack basic information. Breaching has not been studied in Arctic lagoons; therefore, this study provides a new understanding of this process that has critical biological and social implications. The data included in the model highlighted the extreme variability that this region encounters, namely in climatic parameters, and how they influence regional processes. The HS model provided a glimpse into under-ice dynamics in the lagoons, which also highlighted the variability in possible lagoon conditions. Conditions beneath the ice spanned the range from lethal to sub-optimal for supporting overwintering whitefish populations. These insights into seasonal processes in Arctic lagoons highlight the variability of lagoon ecosystems. This has implications for fishes and other fauna relying on lagoons as nursery and feeding grounds, and points to the adaptability of these species. Whitefishes in particular, which rely heavily on lagoons in their life histories, must be able to adapt to different conditions in lagoons every year to be able to exploit these productive habitats.

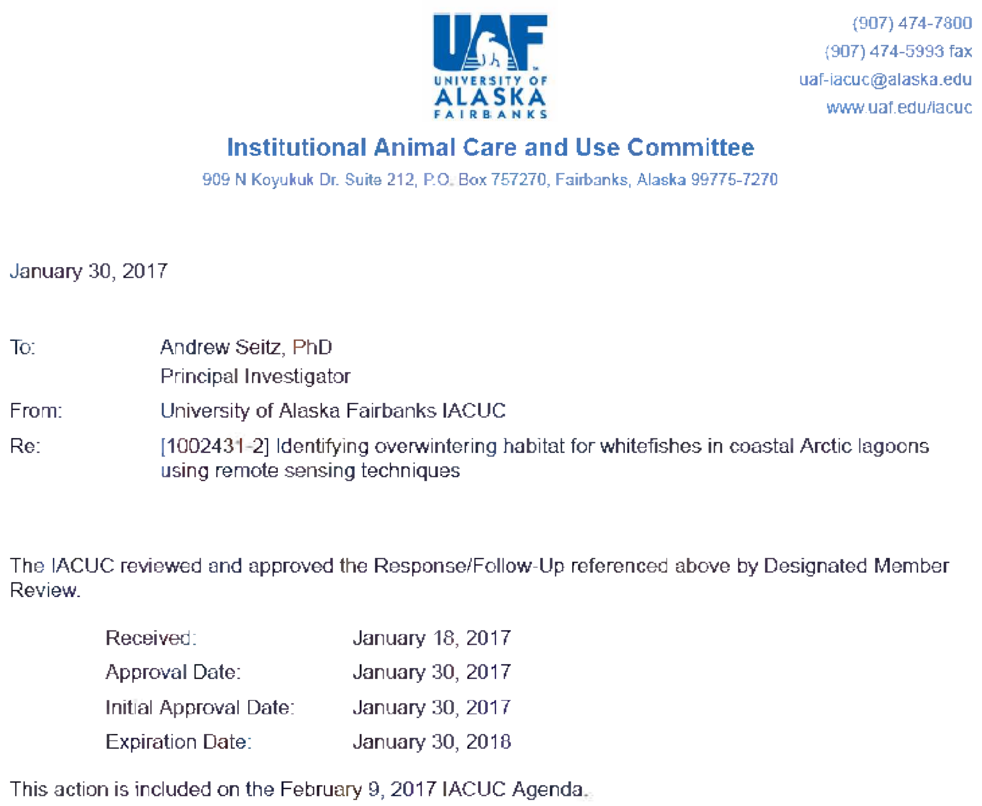
Both chapters of this thesis aimed to create tools to further understand lagoon ecosystems. These tools can be easily updated with the advent of additional data, to further our understanding of these systems. This is important, as there is currently no formal management of whitefishes in the region due to a lack of baseline information on whitefish biology, life history, and habitat use. As the Arctic is threatened with a future of climate change, there is increasing concern and interest in managing critical subsistence resources, like whitefishes. The analytical tools developed in this thesis will provide critical information on whitefish habitat for future management considerations in the region. Both the glm and HS model are widely applicable to coastal regions in Northwest Alaska as well as throughout the entire Arctic coast where lagoons occur and could serve the many communities found in this region. These tools can help identify lagoons that consistently provide available habitat for whitefish persistence in the region, which is a step forwards towards the benchmark understanding necessary for management considerations.

Critical to both chapters was the use of satellite imagery to help observe phenomena in remote and challenging to sample regions of the Arctic. This work attempted to make real world links between remote sensing and meaningful ecological processes at a fine scale. The groundtruthing of satellite imagery is necessary to be able to connect remotely sensed data with on the ground processes. By groundtruthing imagery collected, I was able to incorporate remotely sensed data into analyses, increasing the scope of the project.

There were several key limitations that affected both the glm and HS models. The general paucity of available data in the region limited the scope and focus of both models. The glm lagoon breaching model may have performed better and found stronger and more intuitive correlations between the covariates and response if unique, localized values were available for each covariate. Further, the temporal resolution of the satellite imagery prevented the identification of exact dates of lagoon breaching, leading to an unknown level of error in the estimates for the response variable. The temporal resolution was further deteriorated by the weather patterns of the region where heavy cloud cover frequently impeded the identification of lagoon breaching. Finally, a relatively short time series was available for understanding complex phenomena such as lagoon breaching and may be at the root of the weak predictive power of the model. A longer time series may help determine if other covariates are correlated with lagoon breach timing. The HS model could be improved through the inclusion of more parameters, like turbidity or substrate type. Previous HS models have included these parameters (Brown et al. 2010); however, we lacked baseline information on how whitefish distribution and abundance would be influenced by these parameters. One notable aspect of the HS model that could be improved is its reliance on expert opinion for understanding suitability of specific environmental conditions. This reliance resulted from the paucity of published information on responses of Arctic coregonines to gradients in environmental conditions. More intensive fish and environmental sampling will help describe the relationship between habitat characteristics and suitability, lending credence to the HS model predictions.

The combination of environmental variability and the dynamic nature of the lagoons points to the importance of long-term monitoring and research for these ecosystems. Isolated studies will fail to appreciate the range of possible conditions as well as the processes underpinning the importance of lagoon systems for fishes in the region. The National Park Service Vital Signs Monitoring Program for lagoons located in both Cape Krusenstern National Monument and Bering Land Bridge National Preserve is a great first step towards collecting a long-term data set in this region, and the Beaufort Sea Lagoon Long-Term Ecological Research (LTER) project will provide valuable insight into Alaska’s North Slope lagoons. These long-term monitoring and research projects will provide a greater understanding of these ecosystems that are widely used for subsistence as the Arctic faces an uncertain future with climate change and increased oil and gas exploration.

Appendix 2



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Institutional Animal Care and Use Committee
909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

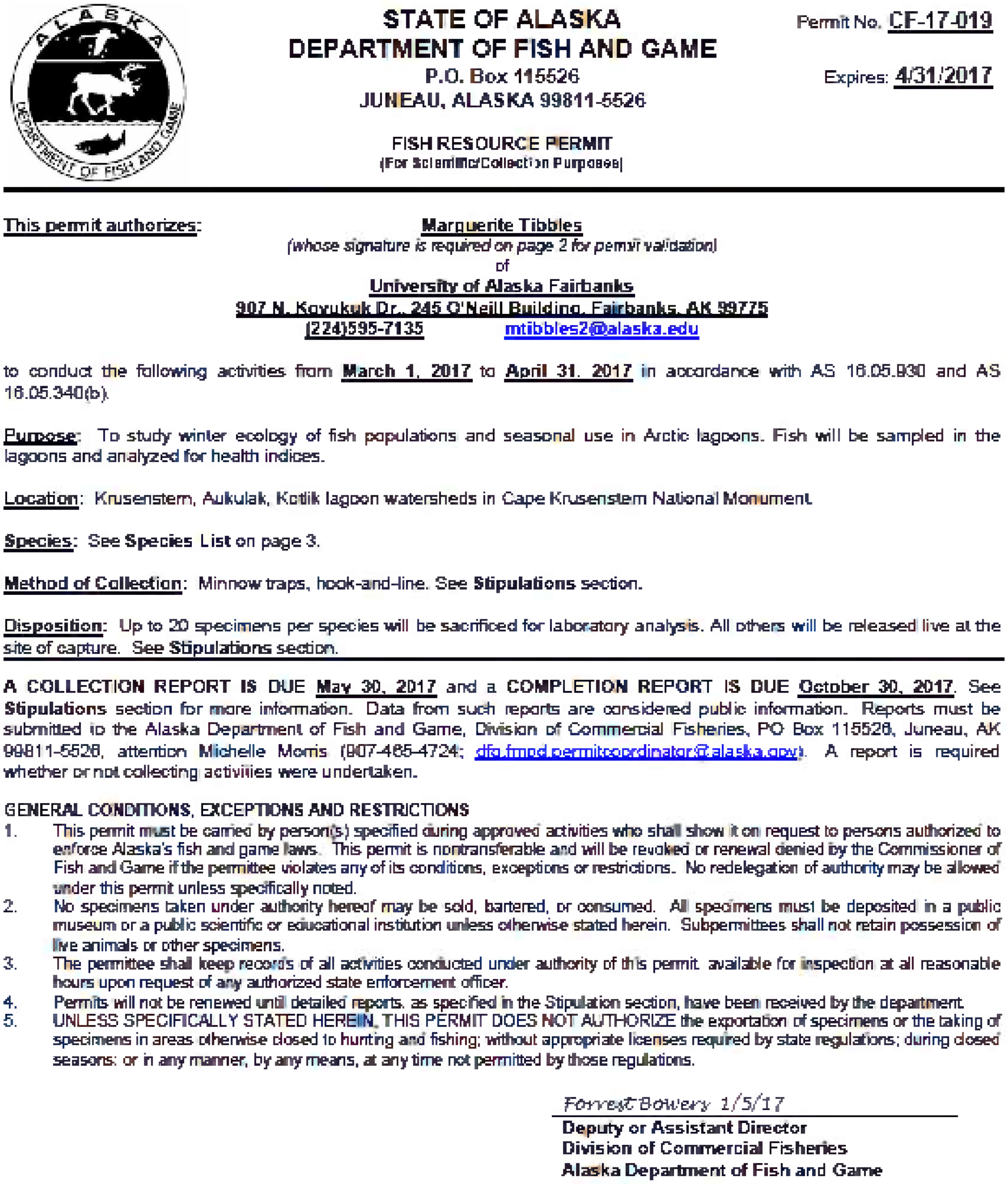
January 30, 2017

To: Andrew Seitz, PhD
Principal Investigator
From: University of Alaska Fairbanks IACUC
Re: [1002431-2] Identifying overwintering habitat for whitefishes in coastal Arctic lagoons using remote sensing techniques

The IACUC reviewed and approved the Response/Follow-Up referenced above by Designated Member Review.

Received:	January 18, 2017
Approval Date:	January 30, 2017
Initial Approval Date:	January 30, 2017
Expiration Date:	January 30, 2018

This action is included on the February 9, 2017 IACUC Agenda.



STATE OF ALASKA
DEPARTMENT OF FISH AND GAME
P.O. Box 115526
JUNEAU, ALASKA 99811-5526

Permit No. CF-17-019

Expires: 4/31/2017

FISH RESOURCE PERMIT
(For Scientific/Collection Purposes)

This permit authorizes:

Marguerite Tibbles
(whose signature is required on page 2 for permit validation)
of
University of Alaska Fairbanks
907 N. Koyukuk Dr., 245 O'Neill Building, Fairbanks, AK 99775
(224)595-7135 mtibbles2@alaska.edu

to conduct the following activities from **March 1, 2017** to **April 31, 2017** in accordance with AS 16.05.930 and AS 16.05.340(b).

Purpose: To study winter ecology of fish populations and seasonal use in Arctic lagoons. Fish will be sampled in the lagoons and analyzed for health indices.

Location: Krusenstern, Aukulak, Kotlik lagoon watersheds in Cape Krusenstern National Monument.

Species: See **Species List** on page 3.

Method of Collection: Minnow traps, hook-and-line. See **Stipulations** section.

Disposition: Up to 20 specimens per species will be sacrificed for laboratory analysis. All others will be released live at the site of capture. See **Stipulations** section.

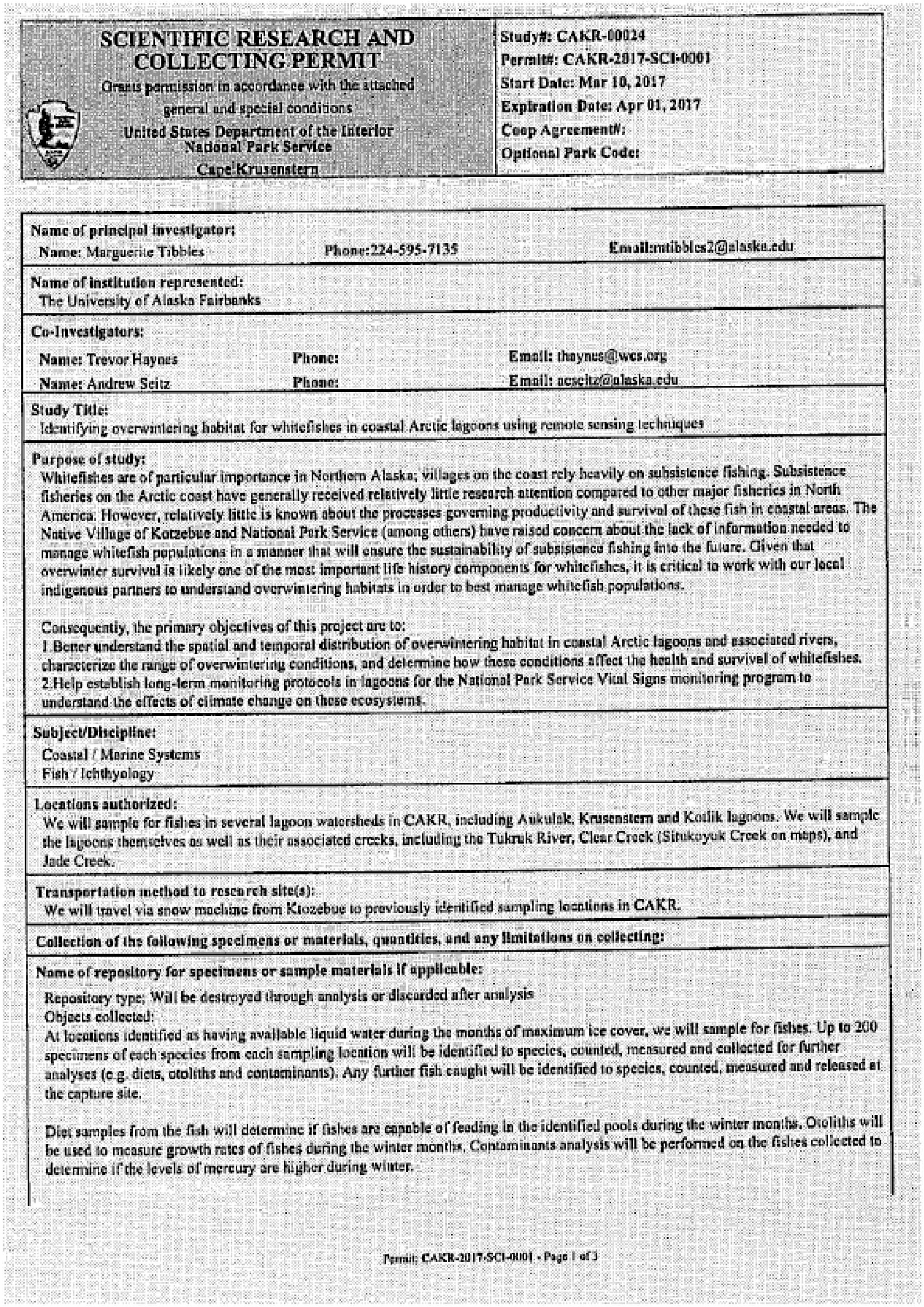
A COLLECTION REPORT IS DUE May 30, 2017 and a **COMPLETION REPORT IS DUE** October 30, 2017. See **Stipulations** section for more information. Data from such reports are considered public information. Reports must be submitted to the Alaska Department of Fish and Game, Division of Commercial Fisheries, PO Box 115526, Juneau, AK 99811-5526, attention Michelle Morris (907-465-4724; dfg.fmpd.permitcoordinator@alaska.gov). A report is required whether or not collecting activities were undertaken.

GENERAL CONDITIONS, EXCEPTIONS AND RESTRICTIONS

1. This permit must be carried by person(s) specified during approved activities who shall show it on request to persons authorized to enforce Alaska's fish and game laws. This permit is nontransferable and will be revoked or renewal denied by the Commissioner of Fish and Game if the permittee violates any of its conditions, exceptions or restrictions. No redelegation of authority may be allowed under this permit unless specifically noted.
2. No specimens taken under authority hereof may be sold, bartered, or consumed. All specimens must be deposited in a public museum or a public scientific or educational institution unless otherwise stated herein. Subpermittees shall not retain possession of live animals or other specimens.
3. The permittee shall keep records of all activities conducted under authority of this permit available for inspection at all reasonable hours upon request of any authorized state enforcement officer.
4. Permits will not be renewed until detailed reports, as specified in the Stipulation section, have been received by the department.
5. UNLESS SPECIFICALLY STATED HEREIN, THIS PERMIT DOES NOT AUTHORIZE the exportation of specimens or the taking of specimens in areas otherwise closed to hunting and fishing; without appropriate licenses required by state regulations; during closed seasons; or in any manner, by any means, at any time not permitted by those regulations.

Forrest Bowers 1/5/17

Deputy or Assistant Director
Division of Commercial Fisheries
Alaska Department of Fish and Game



SCIENTIFIC RESEARCH AND COLLECTING PERMIT

Grants permission in accordance with the attached general and special conditions

United States Department of the Interior
National Park Service
Cape Krusenstern

Study#: CAKR-00024
Permit#: CAKR-2017-SCI-0001
Start Date: Mar 10, 2017
Expiration Date: Apr 01, 2017
Coop Agreement#:
Optional Park Code:

Name of principal investigator:
Name: Marguerite Tibbles Phone:224-595-7135 Email:mtibbles2@alaska.edu

Name of institution represented:
The University of Alaska Fairbanks

Co-Investigators:
Name: Trevor Haynes Phone: Email: thaynes@wcs.org
Name: Andrew Seitz Phone: Email: acseitz@alaska.edu

Study Title:
Identifying overwintering habitat for whitefishes in coastal Arctic lagoons using remote sensing techniques

Purpose of study:

Whitefishes are of particular importance in Northern Alaska; villages on the coast rely heavily on subsistence fishing. Subsistence fisheries on the Arctic coast have generally received relatively little research attention compared to other major fisheries in North America. However, relatively little is known about the processes governing productivity and survival of these fish in coastal areas. The Native Village of Kotzebue and National Park Service (among others) have raised concern about the lack of information needed to manage whitefish populations in a manner that will ensure the sustainability of subsistence fishing into the future. Given that overwinter survival is likely one of the most important life history components for whitefishes, it is critical to work with our local indigenous partners to understand overwintering habitats in order to best manage whitefish populations.

Consequently, the primary objectives of this project are to:
1.Better understand the spatial and temporal distribution of overwintering habitat in coastal Arctic lagoons and associated rivers, characterize the range of overwintering conditions, and determine how these conditions affect the health and survival of whitefishes.
2.Help establish long-term monitoring protocols in lagoons for the National Park Service Vital Signs monitoring program to understand the effects of climate change on these ecosystems.

Subject/Discipline:
Coastal / Marine Systems
Fish / Ichthyology

Locations authorized:
We will sample for fishes in several lagoon watersheds in CAKR, including Aukulak, Krusenstern and Kotlik lagoons. We will sample the lagoons themselves as well as their associated creeks, including the Tukruk River, Clear Creek (Situkoyuk Creek on maps), and Jade Creek.

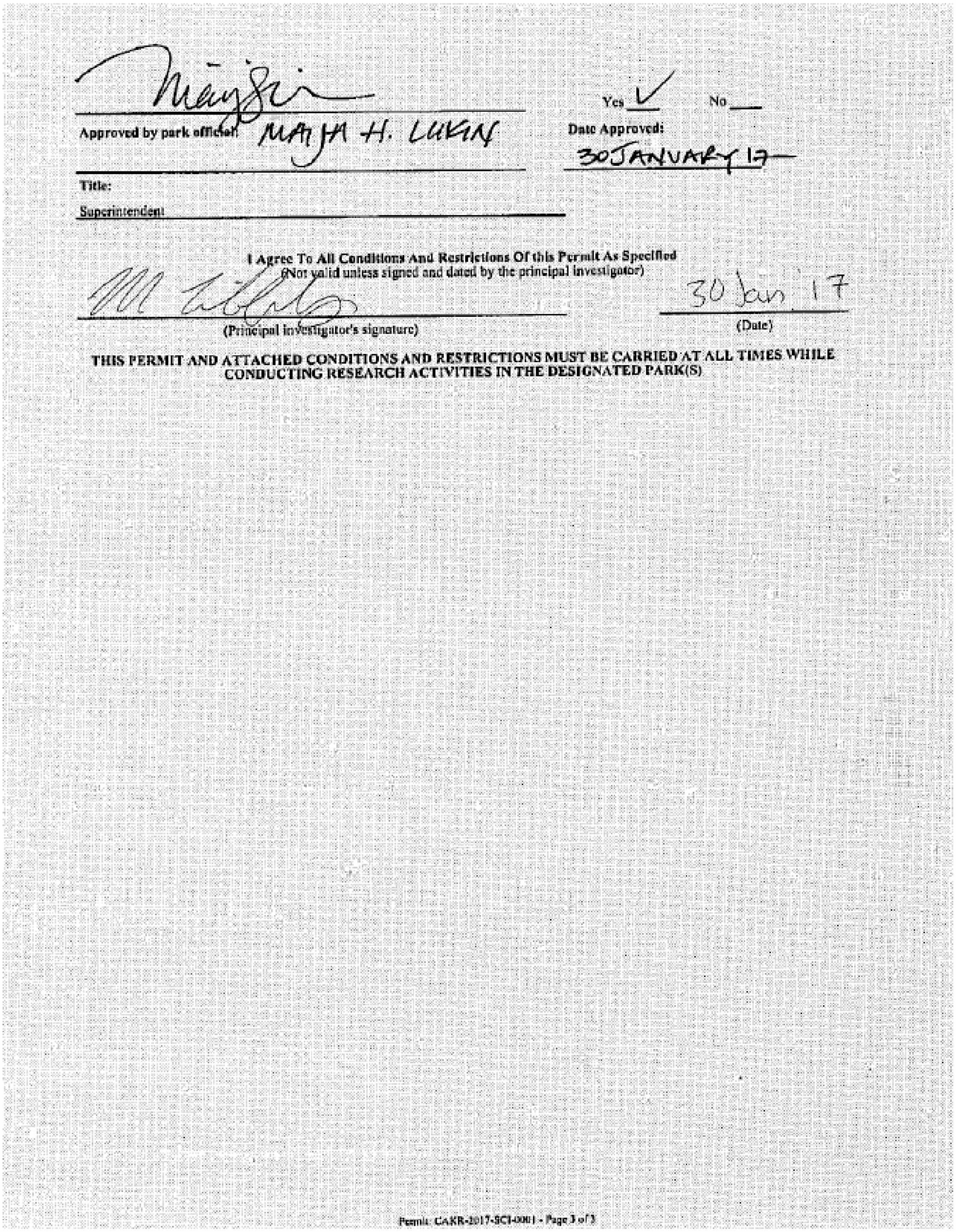
Transportation method to research site(s):
We will travel via snow machine from Ktozebue to previously identified sampling locations in CAKR.

Collection of the following specimens or materials, quantities, and any limitations on collecting:

Name of repository for specimens or sample materials if applicable:

Repository type; Will be destroyed through analysis or discarded after analysis
Objects collected:
At locations identified as having available liquid water during the months of maximum ice cover, we will sample for fishes. Up to 200 specimens of each species from each sampling location will be identified to species, counted, measured and collected for further analyses (e.g. diets, otoliths and contaminants). Any further fish caught will be identified to species, counted, measured and released at the capture site.

Diet samples from the fish will determine if fishes are capable of feeding in the identified pools during the winter months. Otoliths will be used to measure growth rates of fishes during the winter months. Contaminants analysis will be performed on the fishes collected to determine if the levels of mercury are higher during winter.



Yes [✓ No]

Approved by park official: MAIJA H. LUKIN

Date Approved: 30 JANUARY 17

Title:

Superintendent

I Agree To All Conditions And Restrictions Of this Permit As Specified
(Not valid unless signed and dated by the principal investigator)

(Principal investigator's signature)

30 Jan 17
(Date)

THIS PERMIT AND ATTACHED CONDITIONS AND RESTRICTIONS MUST BE CARRIED AT ALL TIMES WHILE CONDUCTING RESEARCH ACTIVITIES IN THE DESIGNATED PARK(S)

Permit: CAKR-2017-SCI-0001 - Page 3 of 3