AN ABSTRACT OF THE THESIS OF

Lucy F. Romeo for the degree of Master of Science in Geography presented on June 10, 2014

Title: Spatial Distribution and the Probability of Occurrence of Beluga Whales (*Delphinapterus leucas*) in Alaskan Arctic

Abstract approved:

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The known distribution of beluga whales ranges from sub-Arctic to Arctic waters where they migrate in pods in response to environmental factors such as the presence of sea ice and prey. This study uses bivariate and multivariate analysis techniques to measure how environmental covariates are associated with the spatial-temporal distribution of beluga whales. Exploratory data analysis was used to determine the relationship among environmental covariates: bathymetry, slope, sea surface temperature, and distance to sea ice. Spatial analyses were used to determine the probability of occurrence of beluga whales in the northeastern Chukchi and southwestern Beaufort seas, based on each environmental covariate for the autumn months of the two study periods, from 2000 to 2006 and from 2008 to 2012. Findings from this study suggest that correlations exist between SST and distance to sea ice, and depth and distance to sea ice, and that beluga whales may prefer areas of relatively steep slope and associated increasing depth along the continental slope. Probability of occurrence maps were created for September and October for each year, based on beluga whale preference and avoidance for each environmental covariate. Areas of preference, or high probability of occurrence, had more beluga whale sightings than expected. And areas of avoidance, or low probability of occurrence, had less beluga whale sightings than expected. Model validation included randomly dividing observational data from September of 2011 into a training (70%) and testing (30%) dataset, then creating a probability of occurrence model based on the training dataset and comparing the results to the locations of the testing dataset. Outputs from the analyses can help guide studies of

beluga environmental covariate preferences and the possible influences on their occurrence. Better understanding of the spatial distribution of beluga whales can provide a tool for better management practices. Improved practices in management and conservation of habitat for beluga whales will impact indigenous communities who rely on marine mammals as cultural and consumable resources.

Spatial Distribution and the Probability of Occurrence of Beluga Whales (*Delphinapterus leucas*) in Alaskan Arctic

by
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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Lucy F. Romeo, Author

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1. INTRODUCTION

1.1 MOTIVATION

The beluga whale (*Delphinapterus leucas*) is a small to moderate-sized marine mammal, ranging from 4 to 6 meters in length, whose global geographic range extends from arctic to subarctic waters (Shirihai and Jarrett 2006). Belugas migrate northward as sea ice recedes in the Arctic, where they breed and raise young in the spring, and migrate south as sea ice expands again in the fall. Beluga whales forage and feed throughout the year. The global population of beluga whales is estimated to exceed 150,000 based on estimates from the late 1990s to early 2000s (Angliss and Outlaw 2005, 2007; Lowry and Frost 1999; Frost et al. 1993; Hammill et al. 2004, 2005; Richard 1991; Innes et al. 2002, Heide-Jørgensen and Acquarone 2002; Gjertz and Wiig 1994; Kovacs and Lydersen 2006; Boltunov and Belikov 2002).

Five geographically, genetically, and behaviorally distinct stocks of beluga whales surround Alaska: the Beaufort Sea, Bristol Bay, Cook Inlet, Eastern Bering Sea, and Eastern Chukchi Sea (Dizon et al. 1992; Frost and Lowry, 1990; Richard et al. 2001; O'Corry-Crowe et al. 1997, 2002, 2010). The Cook Inlet stock is classified as endangered, and the Beaufort Sea, Bristol Bay, Eastern Bering Sea, and Eastern Chukchi Sea stocks are considered threatened (Allen et al. 2010). The beluga whale population in the Eastern Chukchi Sea was estimated at 1,200–3,700 individuals in year 2012 (Frost et al. 1993, Allen and Angliss 2012), and the Beaufort Sea population was estimated at 20,000–40,000 individuals in 1992 (Harwood et al. 1996, Allen and Angliss 2012). Upper estimates are based on corrections using radio telemetry data to account for belugas not visible at the surface (Frost and Lowry 1995) and newborns and yearlings that are not visible due to size and color (Brodie 1971).

Beluga whales are ecologically and culturally significant. Belugas are the most gregarious cetacean in the Arctic and can greatly influence prey populations (Quakenbush (in press)). Belugas are also a cultural resource for indigenous groups, who subsistence hunt belugas and other marine mammals (Hassol 2004). Stocks surrounding the northern slope of Alaska are subsistence hunted by Iñupiat communities located along the coast (Suydam 2013). All stocks, except the Cook Inlet stock, are harvested for subsistence by coastal indigenous people and the harvests are sustainable (Allen and Angliss 2011). The Beaufort Sea stock is harvested in Canada during the summer and most of the Alaska harvest of the Beaufort Sea stock occurs during the spring and fall migration (Quakenbush (in press)).

Although the populations of the Eastern Chukchi Sea and Beaufort Sea stocks are not considered to be declining, a study by Krasnova and colleagues (2012) found belugas and other whale species avoid to human activity, including shipping and oil drilling. Therefore, increased human activity in the Chukchi and Beaufort seas off the coast of Alaska, associated with oil development and ecotourism and shipping traffic, might affect the distribution and size of beluga whale stocks (Minerals Management Service 2009; Short et al. 2011).

This research investigates the relationships among the environmental covariates used in this study, including depth, slope, sea surface temperature, and distance to sea ice. How the aforementioned environmental covariates relate to the distribution of beluga whales in the fall months in the Chukchi and Beaufort seas surrounding the north slope of Alaska. And lastly, where is the highest probability of occurrence for beluga whales and how can the results relate to marine conservation management.

1.2 LIFE HISTORY OF BELUGA WHALES

Migratory stocks of beluga whales, including the Eastern Chukchi Sea, Beaufort Sea, Bristol Bay, and Eastern Bering Sea, move along sea ice, estuaries, and river mouths in gregarious pods, stratified by age, sex, and reproductive status (Figure 1)(Frost and Lowry, 1990; Reid et al. 2003). The Cook Inlet stock remains in the Cook Inlet throughout the year (Allen and Angliss 2012). Beluga whales practice natal homing, annually returning to the same reproductive grounds where they were born, which influences migratory patterns of some stocks (O'Corry-Crow et al. 1997).

Beluga whales have a highly plastic diet and are both benthic and pelagic feeders (Seaman et al. 1982; Doan and Douglas 1953; Sergeant 1973; Kleinenberg et al. 1964; Tomlin 1967; Lono and Oynes 1961). Distributions of beluga whales are related to prey aggregations associated with the Alaska Coastal Current and upwelling (Hansen et al. 1999).

Belugas typically mate between February and March. Gestation lasts 12 to 14.5 months, and whales give birth to one calf. Females reproduce every three years (O'Corry-

Crowe, 2002; Shirihai and Jarrett 2006). Females become sexually mature around 8 years of age, and fertility decreases at approximately 25 years. Life expectancy is approximately 30 years (Suydam 2000; Burns and Seaman 1983).

Predators of beluga whales include killer whales (*Orcinus orca*), polar bears (*Ursus maritimus*), and humans. Predator avoidance leads to geographic segregation of habitat use by sex and reproductive status (O'Corry-Crowe et al. 1997). Immature belugas and reproductive females with calves will remain near land or ice, and in shallow waters, where predation is less likely, while adult males and young belugas will venture into ice-covered areas with deeper water, exposing themselves to predation and potential entrapment of sea ice (Loseto et al. 2006; Main et al. 1996).

1.3 PAST STUDIES ON HABITAT OF BELUGA WHALES

The known distribution of beluga whales extends from sub-Arctic to Arctic waters where they migrate in pods following environmental predictors, including sea ice and prey (Heide-Jorgensen et al. 2009; Reid et al. 2003; Newson et al. 2008). Though not all beluga stocks are migratory, the Bering and Chukchi seas provide critical habitat throughout the year, and the Beaufort Sea is only used in the summer to fall months (Frost and Lowry 1990).

Beluga whale habitat is partitioned by sex and reproductive status (Loseto et al. 2006), based on the forage selection hypothesis that whale forage frequency and forage quality varies with energy requirements (Clutton-Brock et al. 1982; Conradt 1988). Females with calves and immature males prefer shallow habitat near land, which provides protection for the offspring, such as areas along the coast in the Chukchi Sea. Large adult males prefer ice-covered areas with deeper water, as the ice provides feeding resources. Young belugas, leaving the maternal groups, explore productive regions, including areas with deeper waters, which have been associated with prey species including Arctic cod (Loseto et al. 2006).

Multiple environmental factors including human activity, tidal oscillations, currents, upwelling, sea ice, and prey are associated with beluga whale distributions. Spatial dynamics of beluga whales in the White Sea from 1999 to 2009 were found to depend on time of day, tidal regime, state of the sea, and air temperature (Krasnova et al. 2012). In a detailed study of an annual aggregation of approximately 100 individuals following ice breakup at the end of May, Krasnova and colleagues (2012) found that during the summer months, females remained sedentary, living in well-defined areas, while the males migrated: individual distributions followed tidal oscillations and prey. Beluga whales, bowhead whales (*Balaena mysticetus*), and narwhals (*Monodon monoceros*) were less abundant in areas affected by human activity, such as ecotourism and ship traffic (Krasnova et al. 2012). The distribution of beluga whales is related to the resulting aggregation of prey species, which has been attributed to areas of upwelling and the Alaska Coastal Current (Hansen et al. 1999).

Beluga whale distributions are associated with environmental covariates of depth, slope, sea surface temperature, and distance to sea ice. Beluga whales use areas ranging in bathymetry, from shallow to deep areas, depending on pod structure and season (Goetz et al. 2007; Loseto et al. 2006; Moore et al. 2000; Moore et al. 1997; Barber et al. 2001). Belugas prefer continental slope habitat during summer and fall months due to productivity of the area (Stafford et al. 2013). Belugas were found in areas of slope >0.5°, including areas along the continental ridge and areas of potential upwelling (Stirling et al. 1977). Belugas are associated with upwelling associated with salt and heat fluxes (Pickart et al. 2013; Mountain et al. 1976), which produce prey aggregations (Asselin et al. 2011; Ashjian et al. 2009). There is evidence of upwelling along the continental shelf in the Beaufort Sea (Aagaard et al. 1981; Overland and Pease 1982). Sea ice provides protection from predators and productivity to beluga whales as they migrate along the edge (Loseto et al. 2006; Reid et al. 2003; Heide-Jorgensen 2010).

Beluga whales have flexible dietary preferences, which may increase their resilience to environmental change (Luque et al. 2009). From 1993 to 2003, body length and survivorship of beluga whales in the eastern Beaufort Sea did not change despite changes in prey, including Arctic cod, squid, octopus, decapod crustaceans, mollusks, and annelid worms (Reid et al. 2003; Krasnova et al. 2012). Apparently, whales modified their diets without compromising growth or survival, perhaps through intensified diving activities in specific areas where prey was available throughout the migration cycle. On the other hand, beluga whales may be sensitive to climate change, because the foraging ecology of beluga whales is closely linked with the ice edge and the associated productivity, associated with phytoplankton, which leads to a greater abundance of prey including Arctic cod (Newson et al. 2008). In addition, whales may be sensitive to changes in human activity (Hovelsrud et al. 2008).

Goetz and colleagues (2007) showed that beluga distributions were not related to bathymetry and distance to freshwater, but were related to distance to mudflats in Cook Inlet, Alaska. Ezer (2008) correlated beluga whale movement to temperature, salinity, currents, and ice cover.

1.4 OPPORTUNITY FOR RESEARCH

The availability of a large, previously unexamined spatial dataset on beluga whales (Halpin et al. 2009; seamap.env.duke.edu; LaBrecque et al. 2009) provided an opportunity to test hypotheses about environmental factors influencing beluga whale distributions. The dataset contains occurrence records of beluga observations in the southwestern Beaufort Sea since 1979, and the northeastern Chukchi Sea since 2008 (Clarke et al. 2011). Although these data have been analyzed to examine distributions of various cetaceans including bowhead whales, gray whales (*Eschrichtius robustus*), and belugas (Moore 2000; Moore et al. 2000; Clarke et al. 2011a, 2011b, 2011c, 2011d, 2012; Givens et al. 2014), no work has been done to determine habitat associations with the beluga whale data.

1.5 RESEARCH QUESTIONS

1. What are the correlations among the environmental covariates of depth, slope, sea surface temperature, and distance to sea ice within the Chukchi Sea and Beaufort Sea study areas from 2000 to 2012?
2. How are environmental covariates related to the distribution of beluga whales?
3. Where is the greatest probability of occurrence for beluga whales and how is it related to marine conservation management?

The ultimate goal is to determine the potential habitat of beluga whales during the months of September and October in the Chukchi and Beaufort seas surrounding the northern coast of Alaska. The most accurate results might then be used by resource managers to plan resource extraction activities and to measure the potential impacts of climate change.

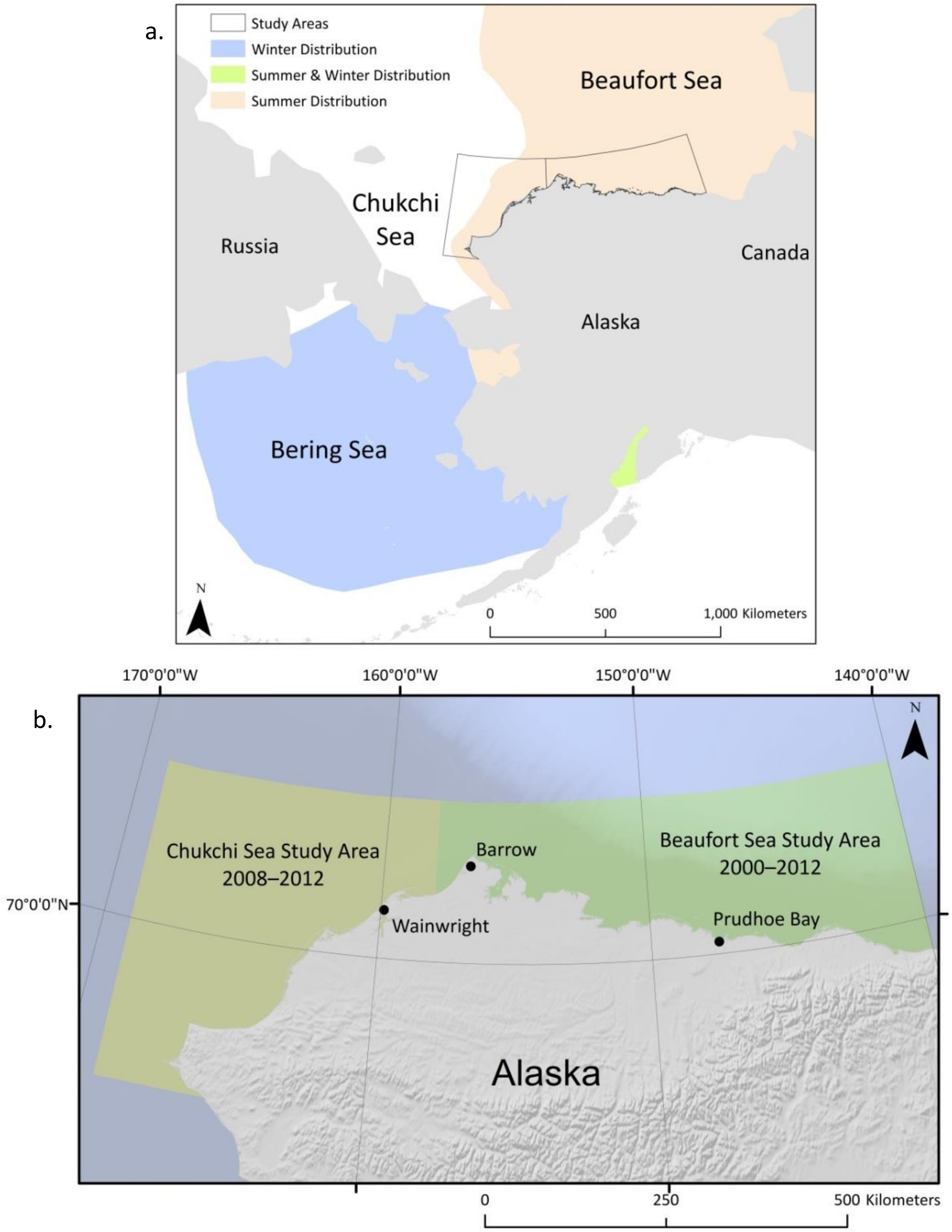


Figure 1: (a) Distribution on beluga stocks surrounding Alaska. (b) Study area extents.

2. METHODS

2.1 STUDY AREAS

From 2000 to 2007, observations of beluga whale occurrence were collected in the southwestern Beaufort Sea, ranging from 140°W to 157°W, and up to 72°N (Figure 1) (Clarke et al. 2011). From 2008 to 2013, the study area expanded west to 169°W and south to 68°N, to encompass the eastern Chukchi Sea (Figure 1) (Ferguson and Clarke 2013). The Beaufort Sea study area consists of 124,659 km^2. In 2008 the area observed was increased to 245,814 km^2, encompassing a portion of the Chukchi Sea.

2.2 DATA SOURCES

Data from the National Marine Mammal Laboratory (NMML) were acquired through the Ocean Biological Information System's Spatial Ecological Analysis of Megavertebrate Populations database (Halpin et al. 2009; seamap.env.duke.edu; NMML 2011). Environmental data including bathymetry, sea surface temperature (SST), and distance to sea ice were acquired through the National Oceanic and Atmospheric Administration's (NOAA) International Bathymetry Chart of the Arctic Ocean, Advanced Very High Resolution Radiometer, Global High-Resolution Sea Surface Temperature Pilot Project, and the National Snow and Ice Data Center (Jakobsson et al. 2012; NOAA/NESDIS/OSDPD/SSD 2013; Casey et al. 2010).

2.2.1 BELUGA OBSERVATION DATA

Data on beluga whale locations were acquired through the Ocean Biological Information System's Spatial Ecological Analysis of Megavertebrate Populations database (Halpin et al. 2009; seamap.env.duke.edu; LaBrecque et al. 2009). The dataset contains occurrence records of belugas in the Beaufort and Chukchi seas since 1979 following a protocol established in 1982 (Clarke et al. 2011). This dataset has been managed by the NMML since 2008 (NMML 2011).

The Bureau of Ocean and Energy Management (BOEM), formerly the Minerals Management Service, then the Bureau of Ocean and Energy Management, Regulation and

Enforcement funded the Bowhead Whale Aerial Survey Project (BWASP) (Clarke et al. 2011). The original purpose of BWASP was to document the distribution of bowhead whales (*Balaena mysticetus)* during the fall migration. Throughout the survey, presence data were also collected for other species, resulting in the development of a long-term database of marine mammal observations in the Beaufort, Chukchi, and Bering seas (Clarke et al. 2011, 2013).

Data were collected in the Beaufort Sea from 2000 to 2007 and data collection was expanded to encompass the Chukchi Sea from 2008 to 2012 (Figure 2, 3, 4). Whale sightings were acquired using aerial line-transect surveys during the ice-free months of September and October (Figure 5). Offshore drilling and resource exploration activities and subsistence hunting off the coast of northern Alaska also occurred in the study area during the study period. Survey track lines within the study areas were selected based on sea state, which limit visibility, and therefore were not random. Attempts were made to evenly distribute transect lines spatially across the region (Halpin et al. 2009; NMML 2011; Clarke et al. 2011, 2013).

Sea state conditions (wind speed and wave height) affect detection probability (Ferguson and Clarke 2013; Clarke et al. 2011, 2013; Teilmann 2003). Sea state conditions are classified by weather conditions, wind speed, and wave height, and sea states ranging from 0 to 3 are considered to have less associated environmental uncertainty than sea states >4 (Gunnlaugsson et al. 1988; Teilmann 2003). Over 80% of the observations (n = 861) were collected during sea states of <3 (Figure 6). Sea states were observed and recorded at each whale sighting (Figure 7, 8).

Aerial surveys extending to the northern Chukchi Sea were also conducted by the NMML, using the same protocol as previous surveys, over the period 2008 to 2013, as part of the Chukchi Offshore Monitoring in Drilling Area (COMIDA) marine mammal aerial survey project. The goals of COMIDA were to measure the distribution and relative abundance of species in the Chukchi Sea Planning Area from June to October (Clarke et al. 2011, 2013).

A total of 1025 observations points were used in the study, approximately 96% (n = 985) of which were in the Beaufort Sea and 4% (n = 40) were in the Chukchi Sea. This study used observations for September to October only, because they were available for all years, 2000-2012 (Clarke et al. 2010) (Figure 6, 7, 8). Moreover, 2007 was a record year in the recession of sea ice and increasing SST (Stroeve et al. 2008; (Schiermeier 2007; Serreze et al. 2007), based on the mean monthly SST and distances to sea ice (Table 1), observations from 2007 were omitted from analyses, therefore the 15 observations from 2007 were omitted from the study.

2.2.2 ENVIRONMENTAL DATA AND DERIVED VARIABLES

Environmental data include (1) bathymetry and slope at 500m^2 resolution, (2) sea ice extent at a 1 and 4km^2 resolution, and (3) sea surface temperature at 1 and 4.7km^2 resolution (Jakobsson et al. 2012; NOAA/NESDIS/OSDPD/SSD, 2013; Casey et al. 2010).

Bathymetric data were acquired through the National Oceanic Atmospheric Administration's (NOAA) International Bathymetry Chart of the Arctic Ocean. The topographic dataset was compiled from multibeam and single beam data with a horizontal datum of World Geographic 1984 (Jakobsson et al. 2012). Bathymetry was then given a projected coordinate system, which was measureable in meters.

Slope was derived from the bathymetric dataset using the slope tool in ArcGIS 10.1. The slope tool identifies the rate of maximum change in elevation from each cell within the bathymetry raster surface to the adjacent and neighboring cells. Slope is calculated using average maximum techniques (Burrough and McDonell 1998).

For 2000 to 2010, monthly average SST was acquired from NOAA's Advanced Very High Resolution Radiometer at a 4km resolution (NOAA/NESDIS/OSDPD/SSD 2013). From 2010 to 2012, ultra-high resolution SST data (produced by the Regional Ocean Modeling System group using datasets from the Global High-Resolution Sea Surface Temperature Pilot Project) were acquired through NOAAs OceanWatch catalog (Donlon et al. 2007). The 1km data were reformatted from Network Common Data Form (NetCDF) to Tagged Image File Format (TIFF)for ease of processing, then averaged by month. Raster calculator was used to calculate all SST data to degrees Celsius for consistency (ArcGIS 10.1). The resulting spatial resolution of SST data from 2000 to 2010 is 4km^2, and 1km^2 for data from 2010 to 2012.

Distance to sea ice was derived from sea ice extent data produced by the Interactive Multisensor Snow and Ice Mapping System (IMS) acquired through the National Snow and

Ice Data Center's (NSIDC) File Transfer Protocol (FTP) website. Daily sea ice data acquired from 2000 to 2006 have a spatial resolution of $24km^2$ and were in American Standard Code for Information Interchange (ASCII) format. Data from 2006 to 2012 have a spatial resolution of $4km^2$ and were in GeoTIFF format (National Ice Data Center 2008).

A Python (2.7) script was developed to search for data in the NSIDC FTP site, download daily sea ice data matching each observation date, and process the data into a usable format. Data were reclassified as land, sea, or sea ice. Portions of the raster representing sea ice and sea were created as individual layers. Distance to sea ice was calculated for each cell classified as "sea" by least cost distance analysis to the nearest cell classified as sea ice (Greenberg et al. 2011).

2.3 DATA ANALYSIS

Geographic Information Systems (GIS) was used to spatially analyze observation and environmental data. Techniques included kernel density analysis and raster analysis. Utilized fields within the dataset included coordinates and the date in Greenwich Mean Time (GMT) format. Fields including pod size and age were tested for correlation with environmental covariates. There were a high number of single belugas observed and a high number of "No Data" values for age, therefore these fields were not used in the analyses of this dataset. This study only considered the presence or absence of whales at observation, not abundance.

There are clusters of beluga whale occurrences within the western Beaufort Sea study area. Kernel density was used to spatially analyze the density of whale sightings using a search radius of approximately 30km (ArcGIS 10.1). Kernel density calculates the magnitude per kilometer squared, based on the observation point input layer. A kernel smoothing function is applied to fit a surface to each of the points. The search radius was based on the latitudinal range of the study areas point extent, which is approximately 300km, which was then divided by 10 for visualization purposes.

Ordination analysis, also known as gradient analysis, is a multivariate statistical technique used in exploratory data analysis. Here, ordination analysis was used in the process of examining which environmental variables influence a species distribution (Praca et al. 2008). Three techniques were used to better visualize and analyze the potential multivariate relationships of the environmental data values and how they might influence the distribution of belugas: scatterplots, PCA, and histograms. Difference histograms were then created from the histograms, representing the probability of occurrence for beluga whales.

2.3.1. MATCHING OBSERVATIONS TO ENVIRONMENTAL COVARIATES IN TIME AND SPACE

A series of Python (2.7) scripts were written to modify the spatial resolution of the environmental rasters to a single resolution, using the Resample Tool (ArcGIS 10B.1). Raster data from 2000 to 2009 (except 2007) were resampled to 4km^2 resolution, and rasters from 2010 to 2012 were resampled to 1km^2 resolution. The resampled raster data were extracted to their respective study areas, using Extract by Mask (ArcGIS 10.1). Environmental raster data from 2000 to 2006 were overlaid on the Beaufort Sea study area; environmental rasters with data from 2008 to 2012 were overlaid on the Beaufort and Chukchi Sea study areas. As an additional input to the Extract by Mask tool, output rasters were aligned cell-by-cell using a constant raster with a matching resolution and extent through the Snap Raster input (ArcGIS 10.1). Resulting raster data ranged in spatial resolution from 4km^2 to 1km^2.

Distance to sea ice (km) and SST (°C) values were matched to beluga whale data for each month and year of the study (September and October of all years 2000–2012, except 2007). The date field in the observational data table was read through a Python (2.7) script and a new field was created giving that observation's year and month (YYYYMM). This new field, headed YearMonth, was used to match each beluga sighting with the associated SST and distance to sea ice raster. A Python (2.7) script searched the YearMonth field in the observational data table, identified records with matching YearMonth values, and matched each record with the associated environmental raster of interest. The Extract Values to Points function (ArcGIS 10.1) was then used to append the environmental values of interest to previously selected points as an additional field.

A total of 63 beluga whale location points out of 1025 (6.1%) lacked one or more environmental covariate values. Missing environmental covariate values were due to null portions of environmental covariate rasters, typically associated with SST. Of these, 56 data points were obtained during the 2000 to 2012 survey period, and 7 were obtained during the

2008 to 2012 study period. These data points were omitted from the bivariate and multivariate analyses.

2.3.2 RANDOM POINTS: THE "NULL" DATASETS

For scatterplots and PCA, observational data were formatted into comma separated value (CSV) files containing the whale presence observations date in “YearMonth” format, and corresponding environmental covariates for that location.

To assess habitat characteristics objectively, a "null" dataset of random points was created for each month and year of the study. Null datasets contained the same number of points as the associated observed dataset per study period. Using a randomization tool in ArcGIS 10.1, points were randomly selected within the study areas. Then environmental values were obtained for each point in the null dataset. Completed datasets were then stratified into the two study periods and by the months September and October, resulting in two datasets for both the null and observational data: September and October of 2000 to 2006, and September and October of 2008 to 2012.

The null dataset was used to represent the total habitat within the study area that could be occupied by whales. Comparisons were made between the distributions of the observed data versus a null dataset. The null dataset was used to assess the bivariate and multivariate influences on a randomly distributed dataset versus the observed dataset.

2.3.3 BIVARIATE CORRELATIONS AMONG ENVIRONMENTAL COVARIATES: TWO TIME PERIODS, RANDOM VS. OBSERVED POINTS

Scatterplots were created for both the null and observed datasets, for each of the study periods using R (3.0.3). The scatterplots were used to assess bivariate correlations among the environmental variables: SST, distance to sea ice, slope, and bathymetry. Distance to sea ice data values were log-transformed to better evaluate the high values.

Resulting scatterplots were visually examined to detect differences in bivariate correlation among the null and observation datasets, and over the two study periods to identify potential environmental influences on the distribution of belugas. Bivariate correlations were compared between the study periods to identify possible changes in relationships of environmental variables to beluga locations.

2.3.4 MULTIVARIATE ANALYSIS: TWO TIME PERIODS, RANDOM VS. OBSERVED POINTS

Principal Component Analysis (PCA) was used to better understand what environmental variables are associated with observations of whales in the observed dataset versus the null dataset. Multivariate ordination such as PCA reduces the dimensionality of the data, which consists of interrelated environmental variables, while retaining relationships among observations that covary in the dataset. PCA transforms the data into a new set of variables, called Principal Components (PCs). PCs are uncorrelated and ordered into first (PC1), second (PC2), third (PC3), and fourth (PC4) so that the PC1 and PC2 retain the most variation present in the original variables (Legendre and Legendre 1998; Jolliffe 2002; McCune and Grace 2002).

Results of PCA indicate which variables seem to explain the variation within the dataset (Jolliffe 2002; McCune and Grace 2002; Hirzel et al. 2002). A set of PCA were conducted for both the random and observed datasets. This enabled a comparison of correlations among environmental variables in a randomly distributed dataset with the observed beluga whale presence data. This analysis was conducted on the both the random and observed datasets for the 2000 to 2006 and 2008 to 2012 study periods.

PCA was performed using R (3.0.3). Inputs for PCA included CSV files containing records for each observation and null data point and its spatiotemporally-associated environmental values. The datasets were then broken into the two time periods (2000–06 and 2008–12). From the four resulting CSV files, all environmental values at the null and observation points were input into PCA as dimensions.

All of the environmental covariates were standardized by subtracting the mean value from each environmental value associated to an observational or null record, then dividing this difference by the standard deviation for those environmental values. Standardization sets the centroid of the variable to 0 and the standard deviation to 1. Standardization was required because all environmental variables were measured in different units (bathymetry (m), slope (degrees), distance to sea ice (km), and SST (°C)).

In outputs from the R (3.0.3) graphs resulting from PCA are usually plotted in two dimensions wth x and y axes. The x-axis represents the first Principal Component (PC1), and the y-axis represents the second Principal Component (PC2), and in some cases a third component (PC3). Environmental variables strongly correlated with PC1 and PC2 explain the majority of variation within the dataset. Environmental variables correlated with PC1 explain the greatest amount of variance in the input datasets, while those correlated to PC2 explain the second greatest amount of variance. Environmental variables contributing to each PC are displayed as vectors, or red arrows, in each of the PCA outputs. Each vector represents one environmental variable and one dimension. Standardized environmental variable values increase along the vectors. Positive correlation among the environmental variables is indicated when the angle among the vectors approaches 0°. Negative correlation among the environmental variables is indicated when the angle among the vectors approaches 180°. No correlation among the environmental variables is indicated when the angle among the vectors is close to 90°.

Null and observational records are shown as index numbers within each PCA graph. Each index is placed into n-dimensional space based on associated environmental variable values. In addition to the PCA graphs, R (3.0.3) outputs include loadings data, which give the proportion of variation explained by each of the PCs, and which environmental variables contribute to each of the PCs. Loadings are defined as the weight by which each standardized original variable values would be multiplied by to get the component scores (Shaw 2003).

2.3.5 HISTOGRAMS AND DIFFERENCE HISTOGRAMS

Histograms were created to compare the frequency of environmental values at beluga whale observation points to all possible environmental values within the study areas. For each environmental variable, four histograms were created (September and October of two study periods). Histograms were also used to show the frequency of observations at environment values by year for September and October. Bins for the histograms were based on the resolution of the data and defined to produce more-or-less equal numbers of observations among bins. Histograms were expressed as percentages of the total observations.

Observational data were stratified by month and year then organized into separate Excel (2010) files by environmental variable. A series of Python (2.7) codes were used to read out all non-null cell values for all environmental rasters into lists. In Excel, the lists of environmental values were binned based on the resolution and relevance of the environmental data. These bins were uniformly used throughout the remainder of the analyses. The Excel Data Management Histogram tool calculated the number of occurrences by bin. Because there were more cells in the environmental rasters than the number of observations, both were scaled to a percentage (out of 100%) by dividing the frequency per bin by the total number of cells with values, then multiplying by 100 to calculate a percentage.

For each of the environmental variables two types of histograms were created. First, an overlapping histogram was created, which compared the percentages of all possible environmental variable values within the study area to the percentages of environmental variable values at the observed locations. These histograms were made by month, and for each of the two study periods. Calculated percentages associated with these histograms were then used for modeling analysis. Second, the total numbers of observations were plotted against the same predefined bins for each of the environmental variables.

2.3.6 DIFFERENCE HISTOGRAMS AND MAP VISUALIZATIONS

Difference histograms were created from the overlapping histograms by subtracting the frequency of environmental variable values from the frequency of observed beluga whale observations within each bin. The resulting difference value per bin reflects the probability of occurrence based on the environmental covariates used and the locations of the beluga whale occurrences.

The difference values, bin parameters, and associated values for each of the environmental covariates were then appended to CSV files based on the month and time period. This resulted in four CSV files representing environmental covariates from September of 2000 to 2006, September of 2008 to 2012, October of 2000 to 2006, and October of 2008 to 2012.

Resulting CSV files were then used to classify each cell value from each environmental covariate raster based on the aforementioned bins. The classified cell values were then given the same difference values as in the difference histograms. Positive values indicate potential preference, 0 values give no preference, and negative values show a potential avoidance. The resulting reclassified rasters showed the probability of occurrence of beluga whales for each environmental covariate based on observations from that month and time period.

Maps depicting the probability of occurrence of beluga whales were derived from environmental covariate rasters classified based on the difference histograms. Topographic environmental covariates of bathymetry and slope are constant overtime. Monthly probability maps were made for the temporally dynamic environmental covariates of SST and distance to sea ice. Red areas indicate high probability, yellow to green areas indicate moderate probability, and light to dark blue indicate low probability. No data values are shown as white.

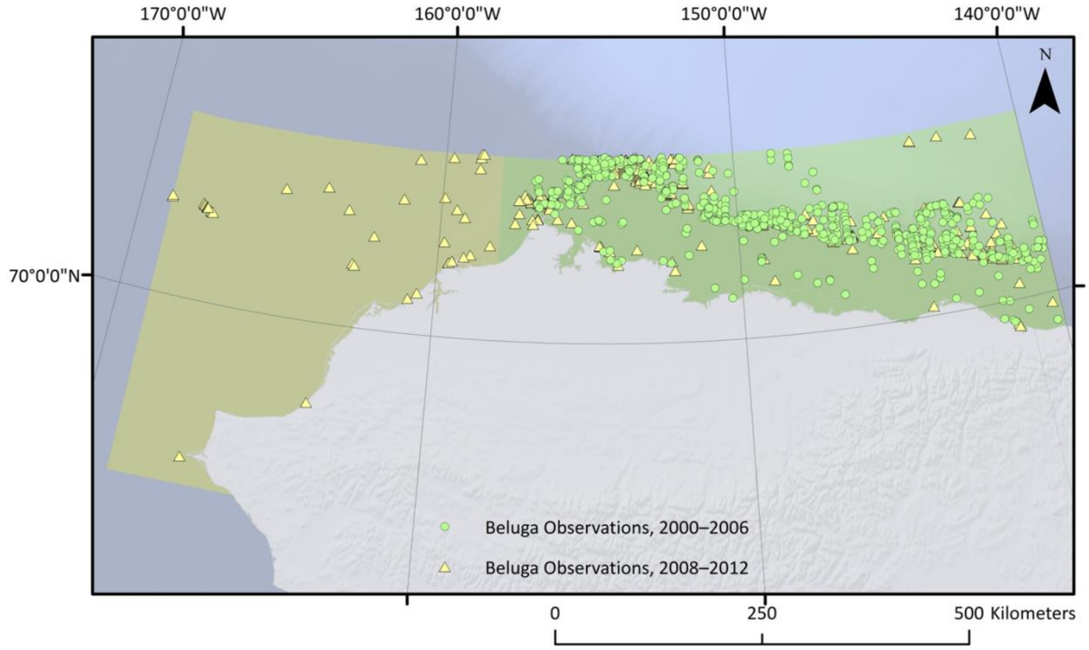


Figure 2: Observation data from both time periods and study areas.

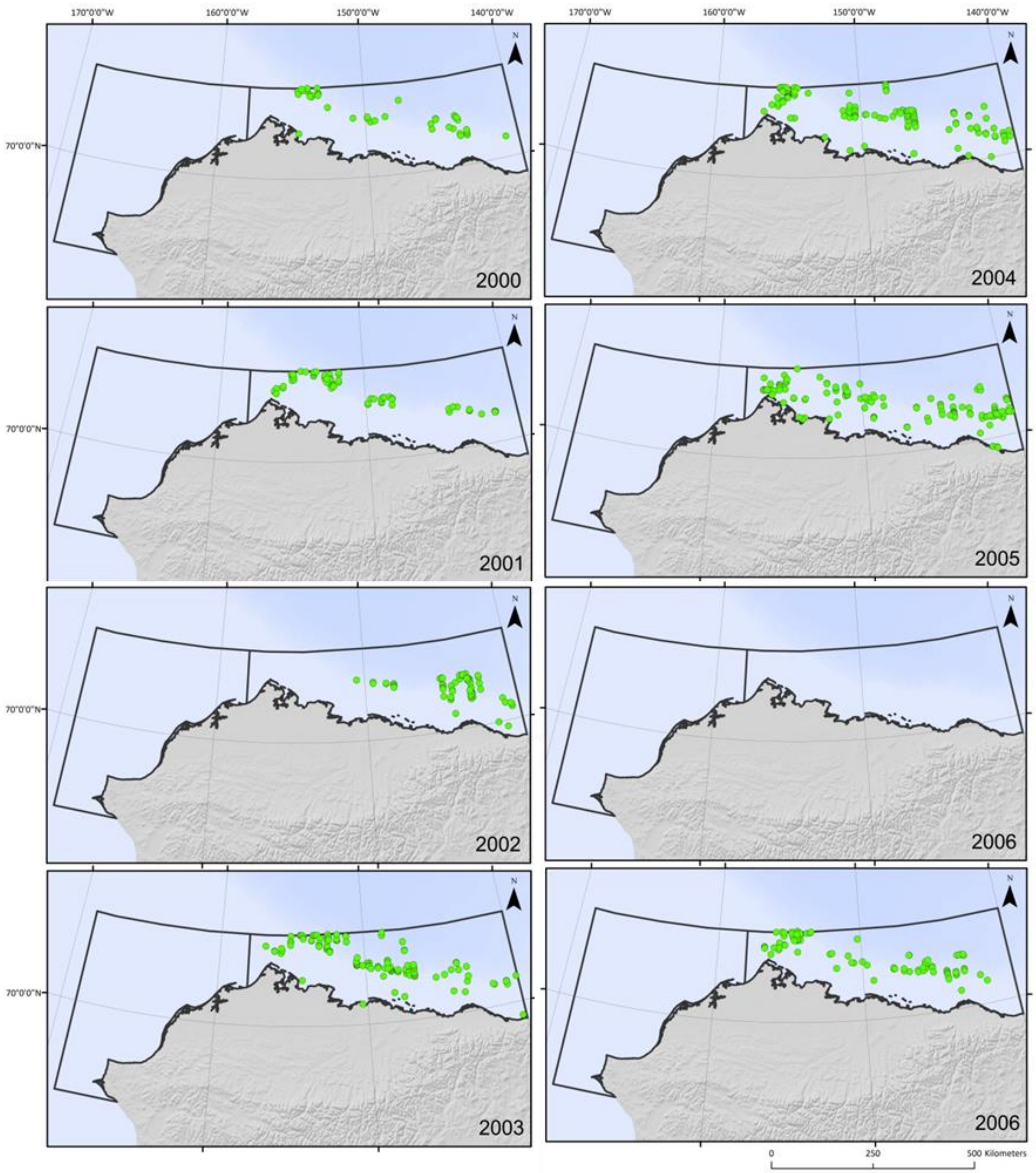


Figure 3: Annual whale sightings from 2000 to 2006.

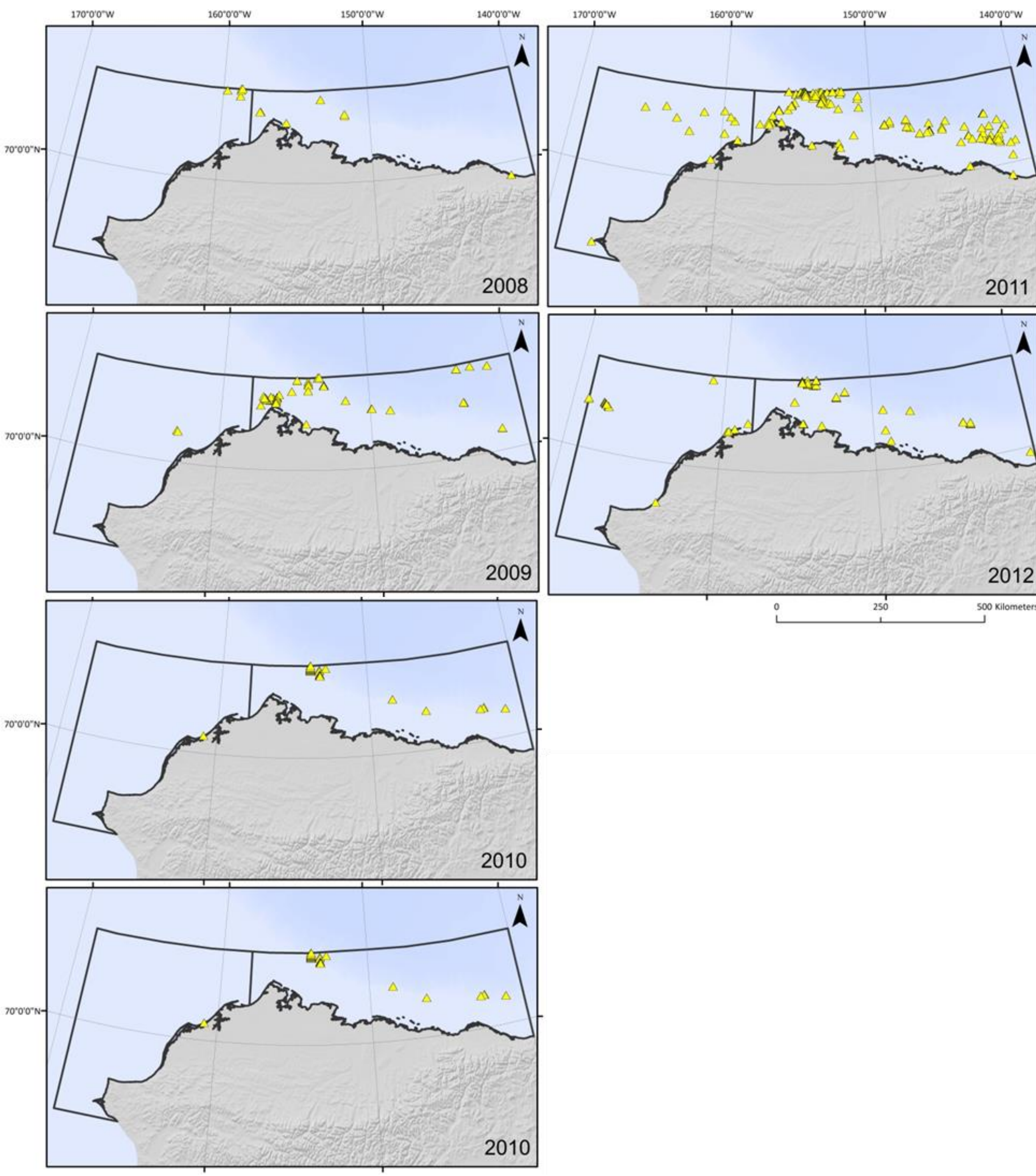


Figure 4: Annual whale sightings from 2008 to 2012.

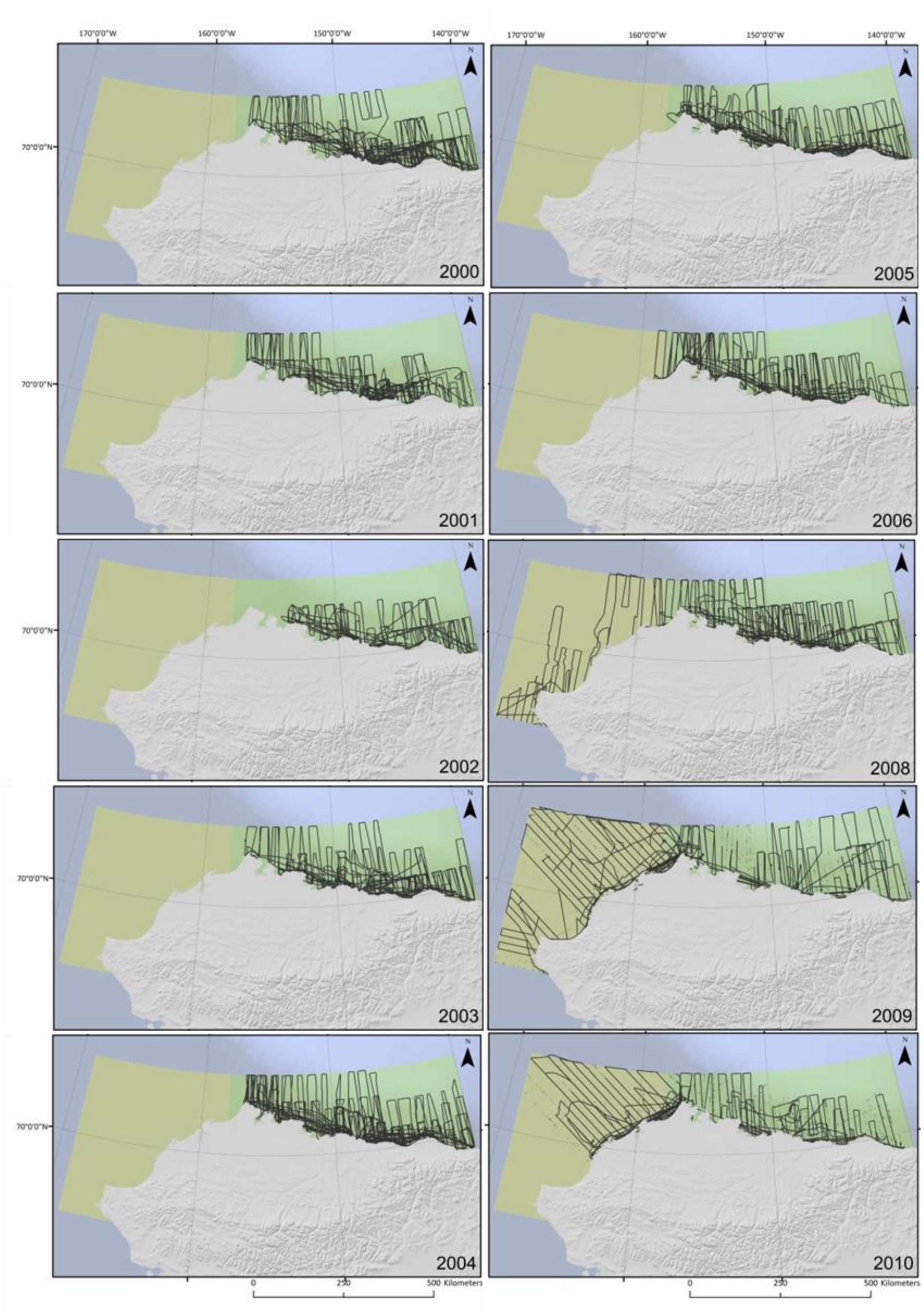


Figure 5: Intensity of aerial surveys from 2000 to 2006 and 2008 to 2010.

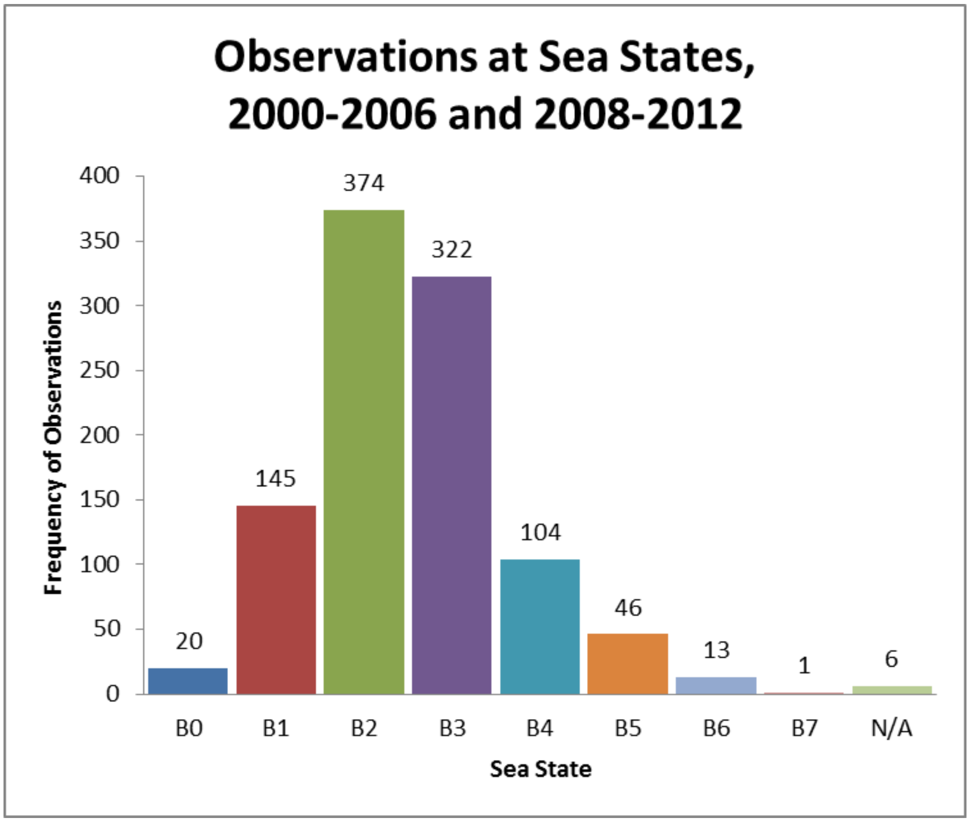


Figure 6: Counts of beluga whale observations by sea state.

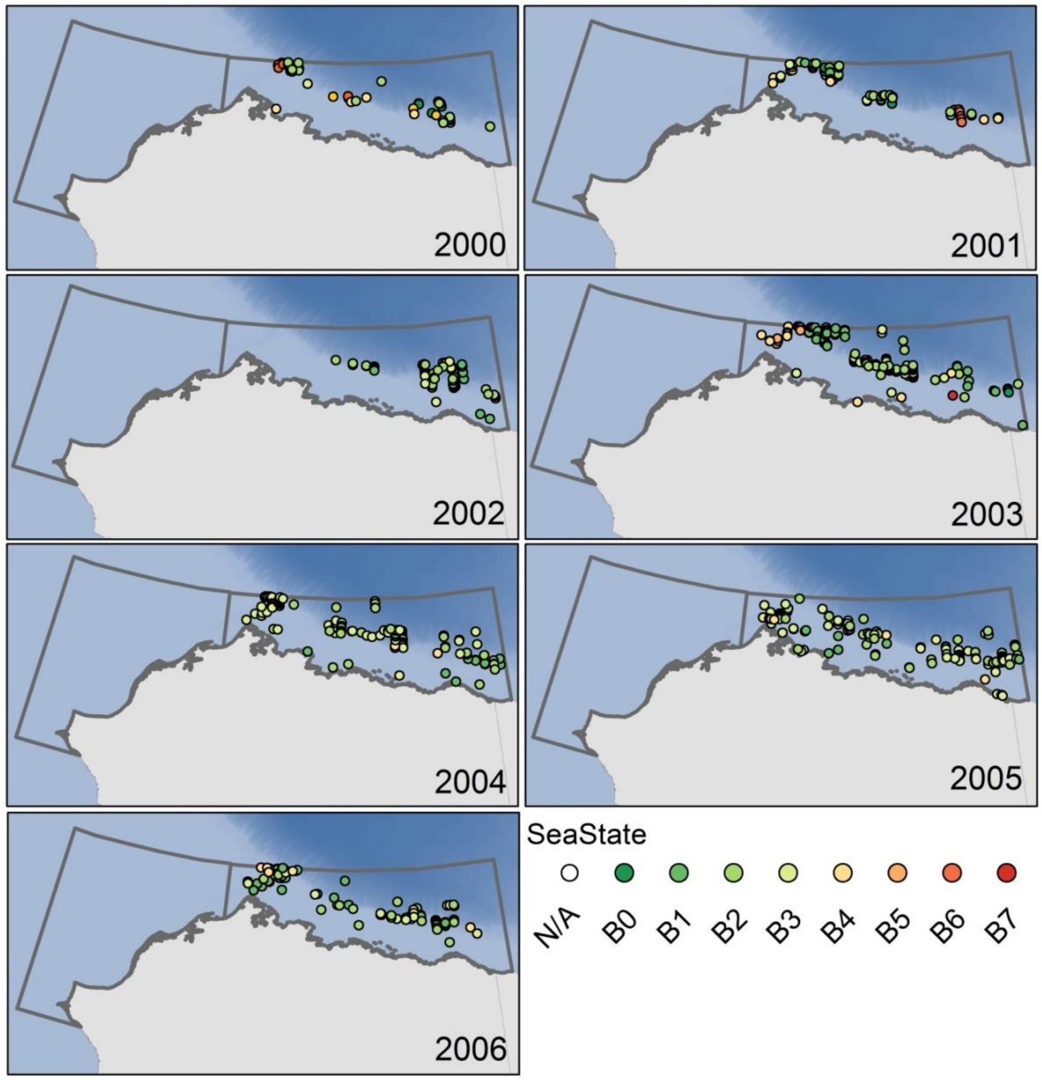


Figure 7: Observations classified by sea state for 2000 to 2006.

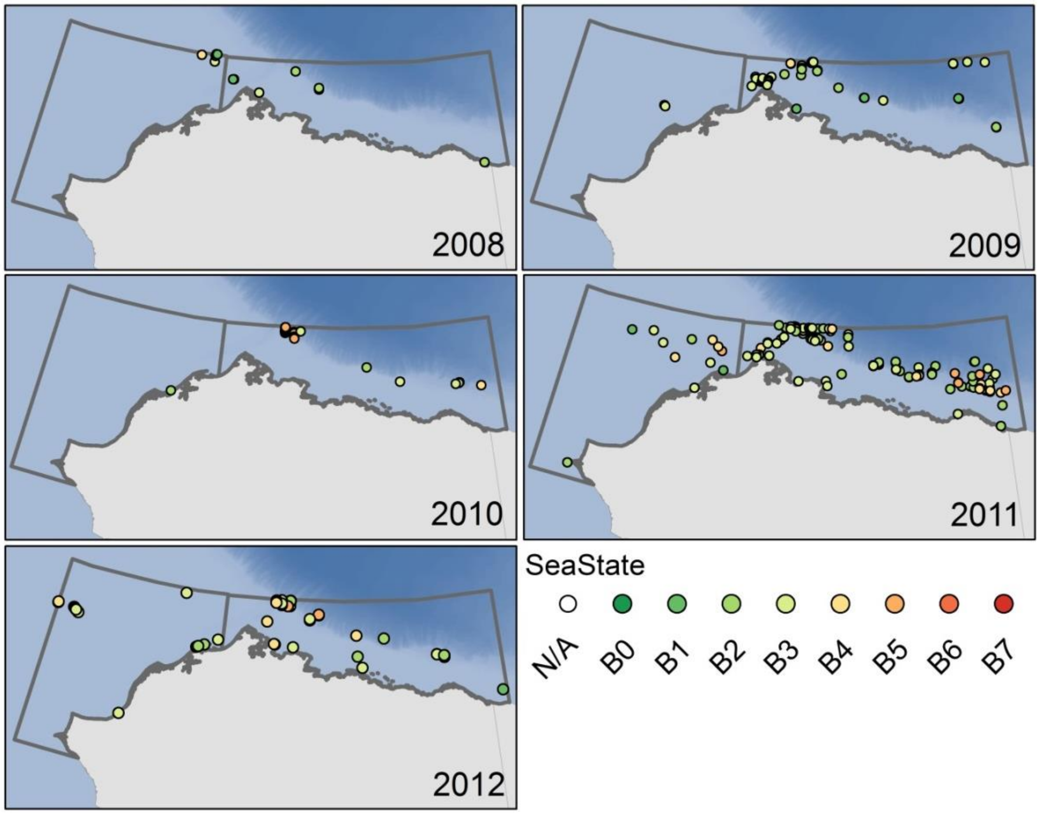


Figure 8: Observations classified by sea state for 2008 to 2008.

3. RESULTS

3.1 DATA EXPLORATION

The number of observations of beluga whales varied by year, with the highest numbers of observations occurring during September and October of 2011 (n= 186), 2003 (n = 143), 2005 (n = 127), and 2004 (n = 121) (Figure 9). Years with low observation counts include 2008 (n = 12), 2007 (n = 15), and 2010 (n = 35) (Figure 9). Belugas were more abundant during years with increased counts. Years with higher counts had more influence on the histograms and surface outputs.

The total length of survey track line per year was compared with the observation count per year from 2000 to 2006 and 2008 to 2010 to determine if there was any correlation between survey intensity and the number of belugas observed (Figure 10). There was weak negative correlation between the two variables (r = -0.04), which means that the survey intensity did not affect the number of whales observed.

Beluga whale distributions are most highly concentrated (>25%) between 71ºN and 72ºN latitude, and between 152ºW to 155ºW longitude (Figure 11). Distributions are moderately concentrated (25%-5%) between 70ºN and 72ºN latitude and between 141ºW and 150ºW longitude, and around 72°N and 160°W. Low concentrations (<5%) occurred in the majority of the Chukchi Sea study area and south of 70ºN in the Beaufort Sea study area.

Mean distance to sea ice was highest in 2002, 2007, and 2011, and lowest in 2001, 2006, and 2008 (Table 1, Figure 12). Mean SST was highest in 2007, 2010, and 2004, and lowest in 2000, 2006, and 2008 (Table 1, Figure 12). The high mean distance to sea ice in 2007, might be correlated with high mean SST. In addition, the low mean distance to sea ice in 2008, might be correlated with the low mean SST (Table 1, Figure 12).

3.2 BIVARIATE CORRELATIONS

For 2000 to 2006, correlations among environmental variables associated with beluga observation points differed from those at randomly selected points (Table 2, Figure 13). For the randomly selected points in the null dataset, depth was negatively related to distance to sea ice (r = -0.40); all other pairs of environmental variables were uncorrelated.

For beluga occurrence points, no pairs of environmental variables were correlated (Table 2.3). Relationships of environmental variables in 2008 to 2012 were similar to those from 2000 to 2006, SST was significantly positively related to distance to sea ice for both random points and beluga observation points in the time period from 2008 to 2012 ($r = 0.42$ and 0.35) (Table 2, Figure 14).

3.3 MULTIVARIATE ANALYSIS

The first two axes, PC1 and PC2 from the 2000 to 2006 random dataset explain approximately 65% of the variation in the data (Figure 15, Table 3). The first axis, PC1, which explained 40.3% of the variation, was related to depth, slope, and distance to sea ice, whereas PC2, which explained 24.9% of the variation, was related to SST (Table 3). In the 2000 to 2006 observational dataset, PC1 and PC2 explain approximately 57% of the variation in the dataset (Figure 16, Table 4). The first axis, PC1, which explained 30.9% of the variation, was related to distance to sea ice, slope and depth (Table 4). The second axis, PC2, which explained 26.2% of the variation, was related to SST and slope -0.484 (Table 4).

The first two axes, PC1 and PC2 from the 2008 to 2012 randomly selected null dataset explain approximately 71% of the variation in the data (Figure 17, Table 5). The first axis, PC1, which explained 38.4% of the variation, was related to distance to sea ice and depth, and PC2, which explained 32.4% of the variation was related to SST, slope, and depth (Table 5). In the 2008 to 2012 observational dataset, PC1 and PC2 explain approximately 63% of the variation in the dataset (Figure 18, Table 6). The first axis, PC1, which explained 33.3% of the variation, was related to distance to sea ice and SST (Table 6). The second axis, PC2, which explained 30% of the variation, was related to slope and depth (Table 6).

Table 7 shows which environmental variables explained the most amount of variance in the distribution for PC1 and PC2 of the random and observed datasets for both study periods. Depth explained the most variation in the random and observed datasets from 2000-2006, and slope and distance to sea ice explained the second greatest amount of variation. Distance to sea ice explained the most variation in the random and observed datasets from 2008-2012, and bathymetry and SST explained the second greatest amount of variation.

3.4 HISTOGRAMS: DEPTH, SLOPE, SST, AND DISTANCE TO SEA ICE

In September and October in both periods (2000–06 and 2008–12), 82.4% of beluga whales were observed in cells at 90–2500m depth; very few observations occur at depths <90m (Figure 19). Most of the study area is shallow depths (51.3% is 30–50m), but in all four study periods, beluga whales were more frequent than expected (77.1%) at 90–1500m (or 2500m) (Figure 20).

In September and October in both periods (2000-06 and 2008-12), beluga whales were observed in cells with slopes of 0.3° to 6.0°, and very few occurred in areas with slopes greater than 9.0° (Figure 21). However, 55% of the study area has a slope of less than 0.05°, and less than 5% of the study area has slope values ranging from 0.3° to 1.0°, or between 5.0° to 15.0° (Figure 22). During September for both study periods, and October for 2000 to 2006, beluga whales were more frequent in areas with moderate slope ranging from 2° to 8° (75%), In contrast, in October of 2008 to 2012 beluga whales were more frequent in areas with <1° slope (Figure 22).

Beluga whales were observed in areas with differing SST values for September and October of both periods (2000–06 and 2008–12). Eighty-three percent of beluga whales were observed in areas with SST from 0°C -4°C in September of 2000 to 2006 and from 1.5°C–4°C during September of 2008 to 2012 (38.0%) of beluga whale sightings occurring in areas with SST of 0°C (Figure 23). In October of 2000 to 2006, and between -1°C and 2.25°C during October of 2008 to 2012 (Figure 23). However, 99.2% of the study area has a SST between -1°C and 10°C during September and between -1.5°C and 5°C during October for both periods (2000–06 and 2008–12)(Figure 24). Beluga whales were more frequent in areas with SST between 0°C to 4°C during September and between -1.5°C to 2°C during October for both periods (2000–06 and 2008–12)(Figure 24).

Beluga whales were observed in areas with differing distances to sea ice during September and October of both periods (2000–06 and 2008–12). Twenty-five percent of beluga whales were observed in cells with distances to sea ice ranging from 0km to 500km in September and October of 2000 to 2006, and 7.1% were between 0km to 900km in September and October of 2008 to 2012 (Figure 25). During September and October of 2000 to 2006, 95.7% of the study area has distances to sea ice from 0km to 600km, and from 0km to 800km during September and October of 2008 to 2012 (Figure 26). During September and October of 2000 to 2006, belugas were most frequent 53.3% at distances from 100km to 400km, and during September and October of 2008 to 2012, 81.7% of belugas were 50–700km from sea ice (Figure 26).

3.5 DIFFERENCE HISTOGRAMS

In all four study periods, beluga whale observations were correlated positively with areas ranging from 90–500m depths, and negatively correlated with areas of shallow water ranging from 20–50m depths (Figure 27). Whales appear to avoid flat areas with slope <0.2° and prefer areas from 2°–8° slope in all four study periods (Figure 28). In September of both periods, whale observations were most common in areas with SST ranging from -0.25°–3°C and much less frequent in areas >4°C (Figure 29). In October of both periods, whales preferred areas with SST <1°C, and avoided areas of SST >1.5°C (Figure 29). In September of 2000 to 2006, beluga whales preferred areas that were 100–400km away from sea ice and avoided areas that were <100km from sea ice. In September of 2008 to 2012, beluga whales preferred areas that were around 300 km away from sea ice, and avoided distances >400 km (Figure 30). In October of 2000 to 2006, beluga whales preferred areas that were 10–50km and around 300km away from sea ice, and avoided areas that were 100–200km and >300km away from sea ice (Figure 30). During October of 2008 to 2012, beluga whales preferred areas that were 10–150km and 700km away from sea ice, and avoided areas that were 200–400km away from sea ice (Figure 30).

3.6 MAP VISUALIZATION OF PROBABILITY OF OCCURRENCE

Environmental covariate data from September and October of 2000 to 2006, and 2008 to 2012 were used to model probability of occurrence. The highest probability of occurrence for beluga whales during September and October of 2000 to 2006(red areas of figures) is in areas with low to moderate depths and relatively steep slope in the northeast portion of the Beaufort Sea study area, along the continental shelf and low in areas with flat slope on the continental shelf and the deep areas north of the continental shelf (Figure 31).

Figures 32 to 38 illustrate the potential probability of occurrence based on the environmental covariates used in the study region. In 2000, probability of occurrence based on SST is highest in the eastern portion of the study area around 145°W and 155°W, and probability of occurrence based on distance to sea ice is highest between 68°N and 70°N, extending northward to 155°W (Figure 32). Probability of occurrence based on SST in 2001 is highest in is highest east of 150°W, along the coast and around 155°W, and probability of occurrence based on distance to sea ice is highest in the southeast (Figure 33). In 2002, probability of occurrence based on SST is highest in areas surrounding 71°N and 150°W , and probability of occurrence based on distance to sea ice was highest around 150°W (Figure 34). Probability of occurrence based on SST in 2003 is highest in areas ranging from 71°N to 72°N and around 158°W, and probability of occurrence based on distance to sea ice is highest between 145°W and 155°W, and to the west (Figure 35). In 2004, probability of occurrence based on SST is highest in the western areas along the coast, areas around 71°N and 148°W, and in the eastern portion of the study area, and probability of occurrence based on distance to sea ice is highest in the western portion of the study area (Figure 36). Probability of occurrence in 2005 based on SST is scattered throughout the study area and highest in the east in October, and probability of occurrence based on distance to sea ice is highest between around 71°N and 72°N (Figure 37). In 2006, probability of occurrence based on SST was randomly distributed in September and in high in the majority of the study area in October, and probability of occurrence based on distance to sea ice was high in the southeast corner of the study area in September and extended west in October (Figure 38).

Probability of occurrence for beluga whales during September and October of 2008 to 2012 was high in areas with shallow depths along the coast and in deep areas past the continental shelf in the northeast portion of the Beaufort Sea study area (Figure 39). Probability of occurrence was also high to moderate in areas with moderate to high slope, especially along the edge of the continental shelf (Figure 39).

In 2008, probability of occurrence based on SST is highest along the coast and along 163°W, and probability of occurrence based on distance to sea ice was highest around 150°W and in the eastern portion of the study area (Figure 40). Probability of occurrence in 2009 based on SST is highest in coastal areas between 155°W and 140°W, in the north between 168°W to 155°W, and along the coast from 163°W to 145°W, and probability of occurrence based on distance to sea ice was highest west of 155 (Figure 41). In 2010, probability of occurrence based on SST is highest along the coast around 155°Wand north of 71°N, between 150°W and 140°W, and probability of occurrence based on distance to sea ice was highest to the east of 157°W (Figure 42). Probability of occurrence in 2011 based on SST was highest around 71°N from 150°W to 140°W in September and between 155°W and 150°W in October, and probability of occurrence based on distance to sea ice was highest between 140°W and 150°W and in the southwest portion of the study area (Figure 43). In 2012, probability of occurrence based on SST was highest in the north, to the east of 150°W, along 71°N west of 160°W, and along the coast from 155°W to 143°W, and probability of occurrence based on distance to sea ice was highest in the northwest portion of the study area (Figure 44).

Table 1: Statistics for SST and distances to sea ice for (a) September and (b) October from 2000–2012.

a.	Sea Surface Temperature (ºC)			Distance to Sea Ice (km)		
Year	Minimum	Maximum	Mean	Minimum	Maximum	Mean
2000	-0.7	7.8	2.5	0.7	3277.9	158.6
2001	-0.9	7.5	3.1	0.0	3204.1	143.4
2002	-1.1	7.7	3.3	109.6	3651.9	506.6
2003	-1.7	7.7	2.4	33.3	3531.8	431.9
2004	-0.6	10.3	4.4	4.7	3526.1	404.4
2005	-1.2	9.7	3.7	8.2	3227.7	283.1
2006	-1.4	8.9	2.9	0.0	1240.7	73.4
2007	-0.8	11.6	5.2	43.0	1658.1	408.2
2008	-0.8	6.9	2.6	40.1	1676.2	404.2
2009	-1.3	8.9	3.4	0.0	1452.2	306.6
2010	-0.6	10.3	4.8	1.7	1504.1	321.6
2011	0.3	7.4	4.2	67.6	1727.7	452.1
2012	-0.7	9.0	2.9	180.0	1956.5	517.2

b.	Sea Surface Temperature (ºC)			Distance to Sea Ice (km)		
Year	Minimum	Maximum	Mean	Minimum	Maximum	Mean
2000	-1.7	4.5	0.3	0.0	3179.0	130.8
2001	-1.7	4.9	0.5	0.0	3080.9	69.0
2002	-1.7	5.6	1.2	37.9	3443.7	428.5
2003	-1.7	5.5	1.1	0.0	3527.8	417.2
2004	-1.7	6.5	1.0	0.0	3406.8	381.2
2005	-1.7	6.6	1.5	6.2	3211.0	241.8
2006	-1.7	6.6	0.5	51.5	1452.6	211.7
2007	-1.7	8.0	2.3	22.4	1640.0	495.1
2008	-1.7	4.7	0.1	0.0	976.8	40.8
2009	-1.7	4.1	1.0	0.0	475.7	133.9
2010	-2.0	5.5	1.0	0.0	483.2	130.3
2011	-1.8	3.3	0.8	14.5	1486.1	379.6
2012	-1.2	2.9	0.9	142.5	1416.0	357.3

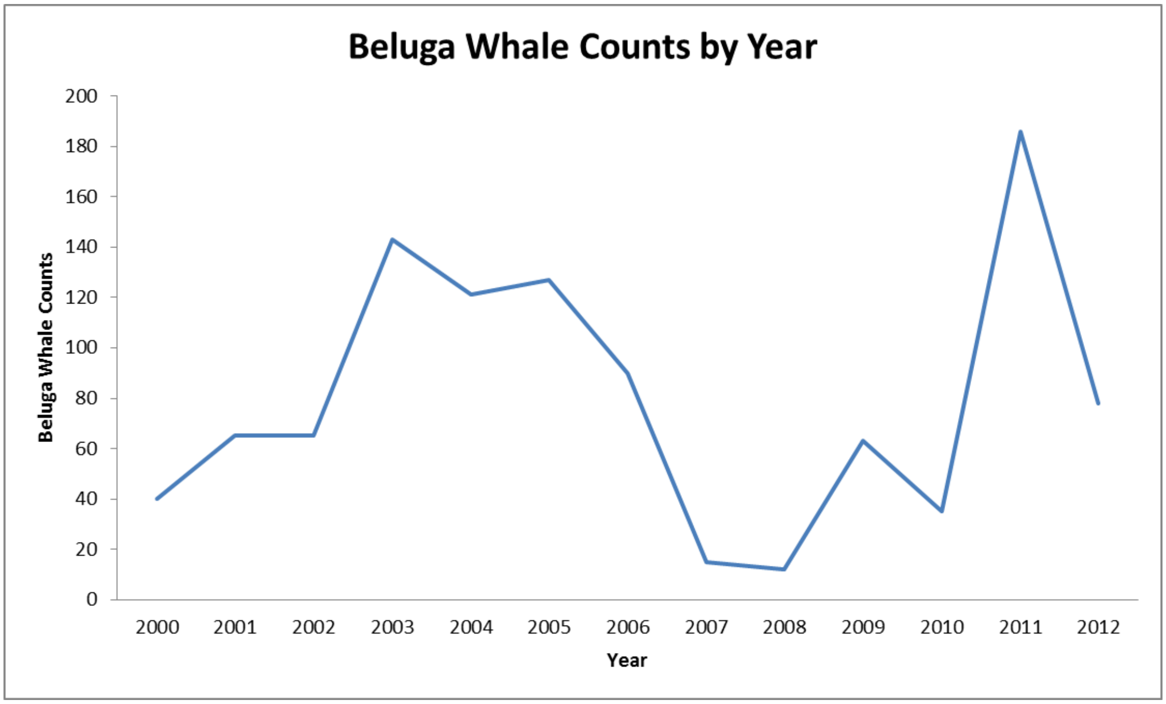


Figure 9: Counts of beluga whale observations per year.

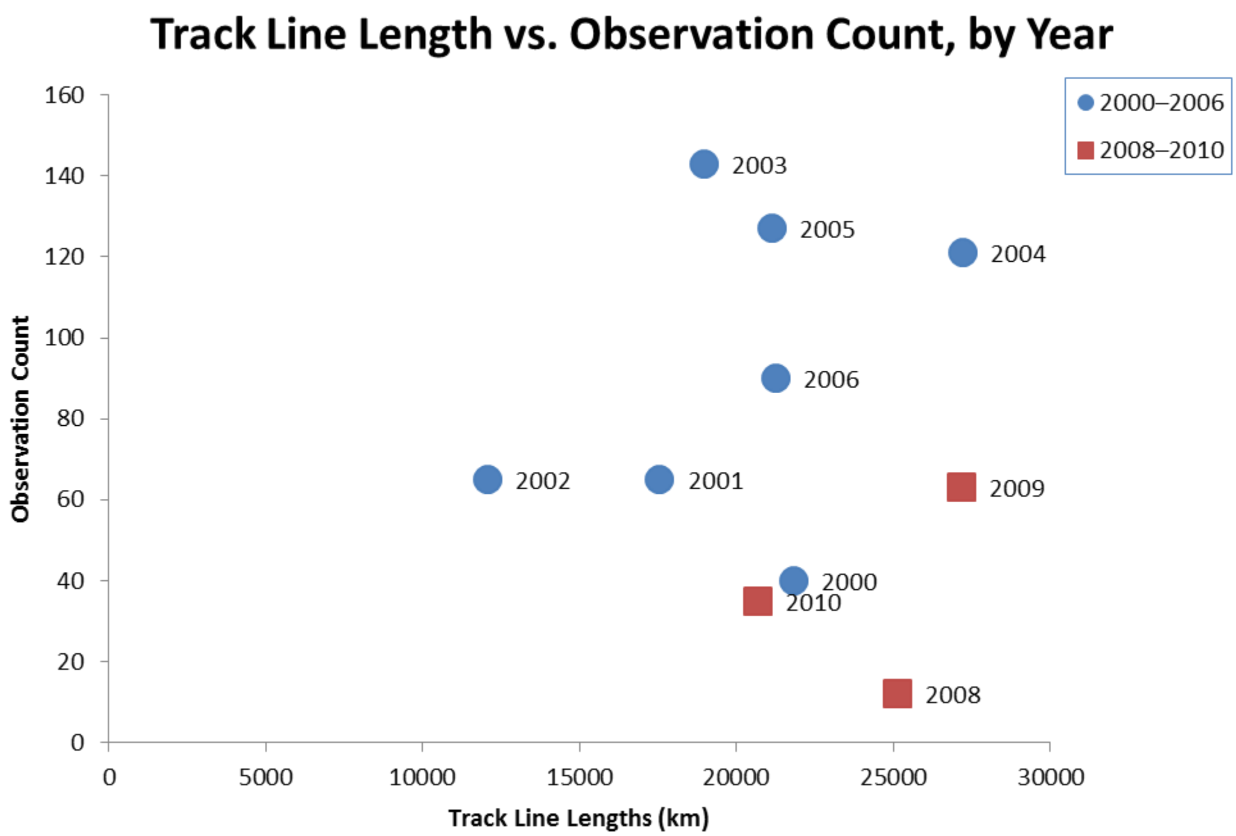


Figure 10: Correlation between line lengths and observation count.

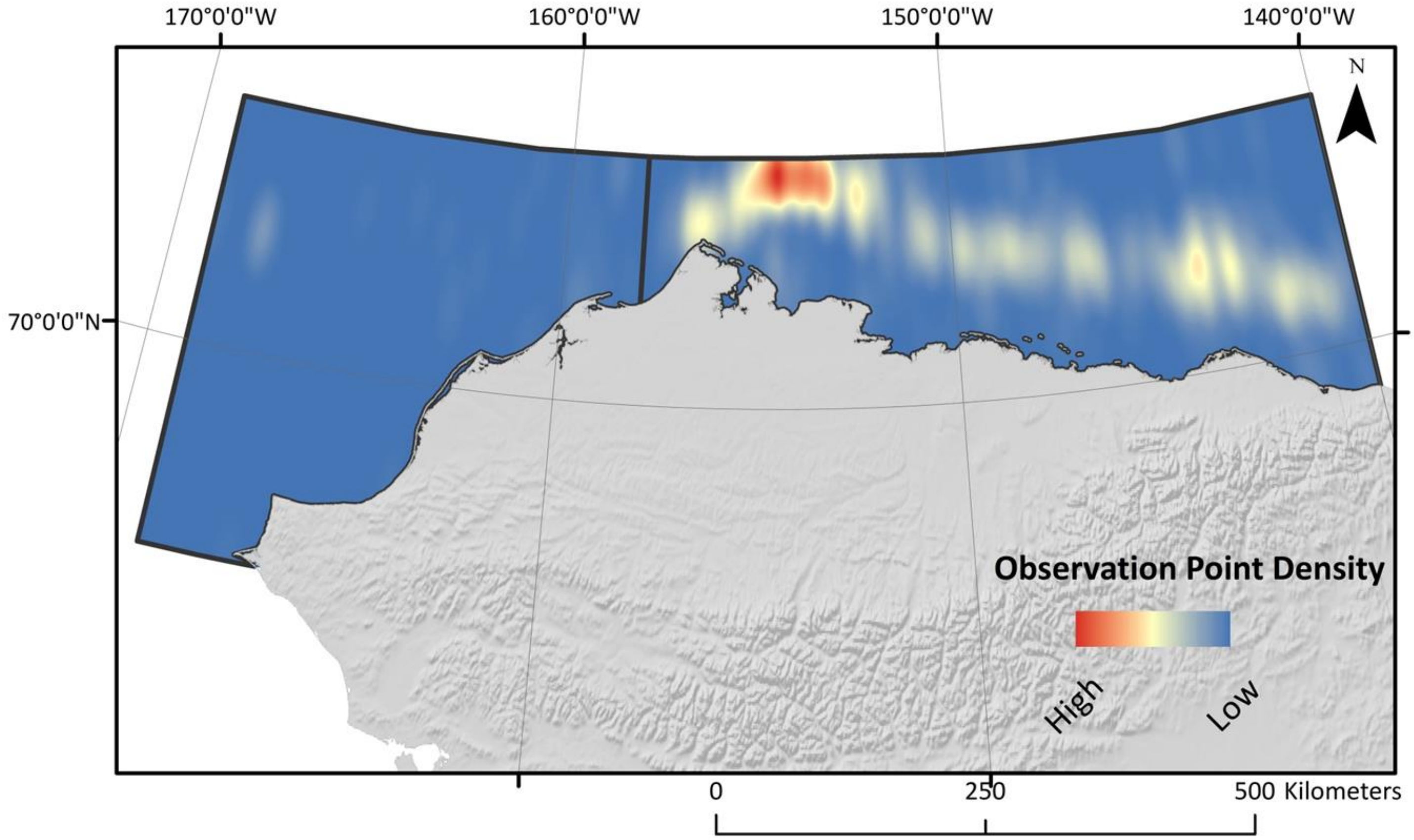
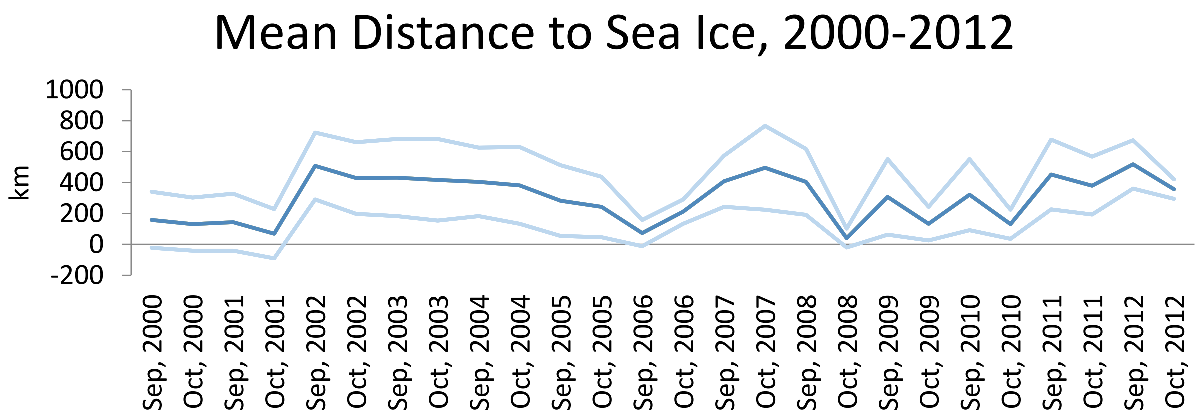


Figure 11: Results of density analysis of observation points.



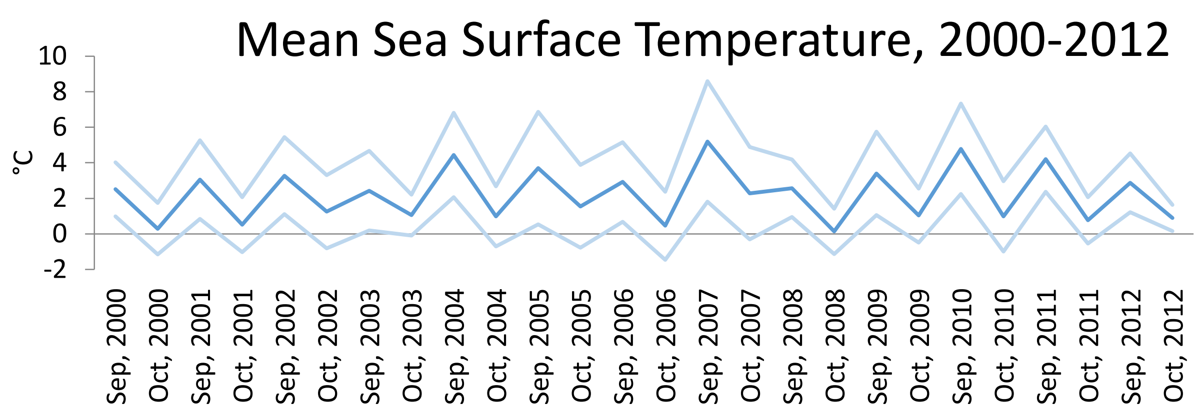


Figure 12: Temporal trends of mean distance to sea ice and sea surface temperature.

a. Environmental Values at Random Points, 2000-2006

b. Environmental Values at Observation Points, 2000-2006

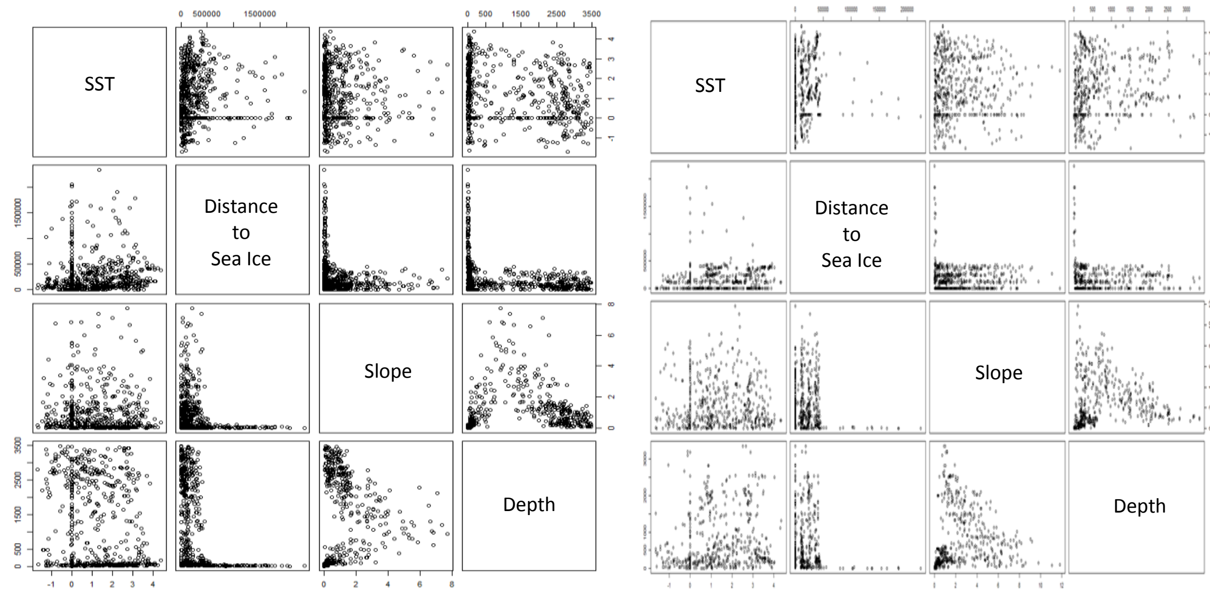


Figure 13: Bivariate correlation at random points (a) and values of environmental variables at observation points (b) from 2000 to 2006.

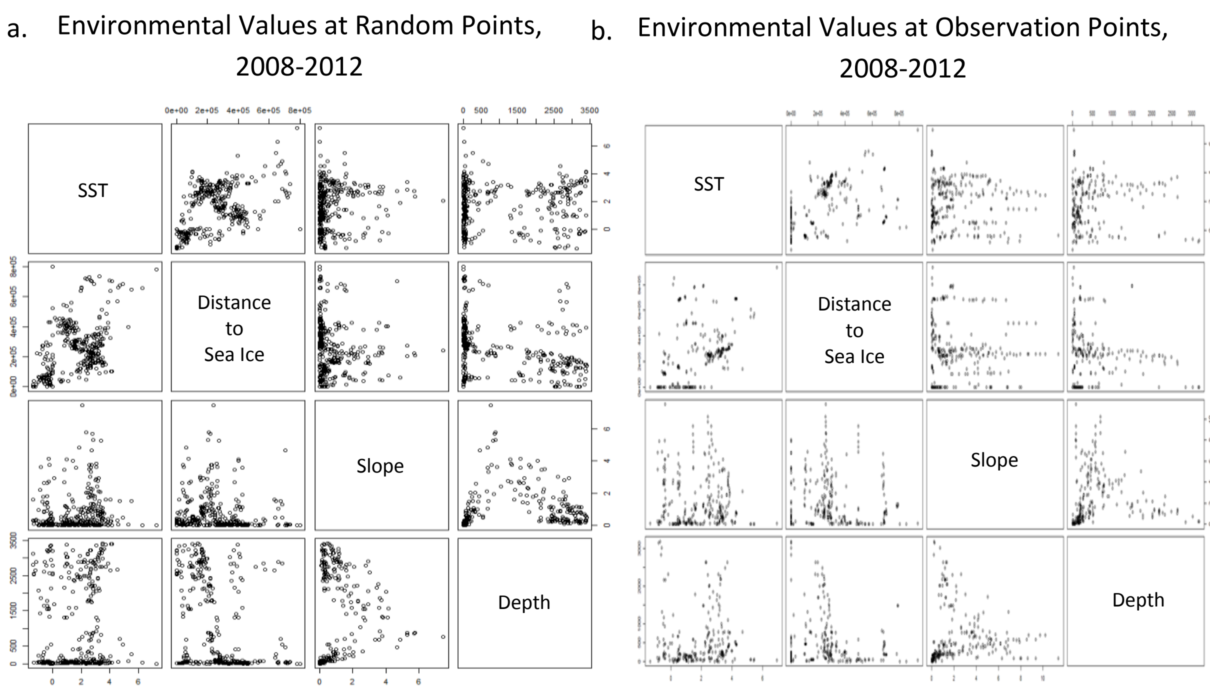


Figure 14: Bivariate correlation at random points (a) and values of environmental variables at observation points (b) from 2008 to 2012.

Table 2: Correlation coefficients for scatterplots from Figure 2.4 and 2.5.

	Random, 2000-2006	Observed, 2000-2006	Random, 2008-2012	Observed, 2008-2012
Depth vs. Slope	0.22	0.08	0.24	0.021
Depth vs. SST	-0.16	0.12	0.099	0.052
Depth vs. Distance to Sea Ice	-0.4	-0.14	-0.35	-0.12
Slope vs. SST	-0.033	-0.016	0.12	-0.0075
Slope vs. Distance to Sea Ice	-0.24	-0.1	-0.11	-0.011
SST vs. Distance to Sea Ice	0.04	0.00013	0.42	0.35

Environmental Values at Random Points,
2000-2006

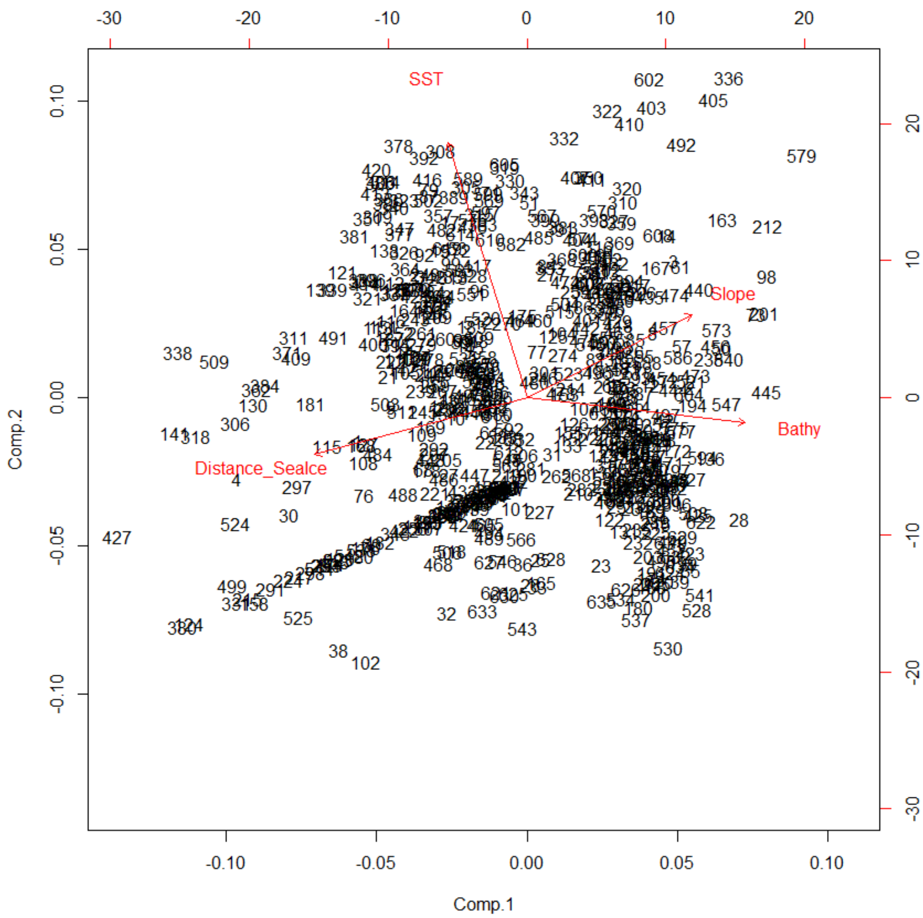


Figure 15: PCA graph displaying the distribution of variance at random points from 2000 to 2006.

Table 3: (a) Results from PCA of random dataset from 2000 to 2006, and (b) loadings from PCA of random dataset from 2000 to 2006.

a.	**Random, 2000–06**	**PC1**	**PC2**	**PC3**	**PC4**
	Standard Deviation	1.27	0.10	0.90	0.76
	Proportion of Variance	0.40	0.25	0.02	0.14
	Cumulative Variance	0.40	0.64	0.86	1.00

b.	**Random, 2000–06**	**PC1**	**PC2**	**PC3**	**PC4**
	SST	-0.22	0.93	-0.22	0.21
	Distance to Sea Ice	-0.60	-0.21	0.38	0.68
	Slope	0.46	0.30	0.83	NA
	Bathymetry	0.61	NA	-0.34	0.71

Environmental Values at Observation Points,
2000-2006

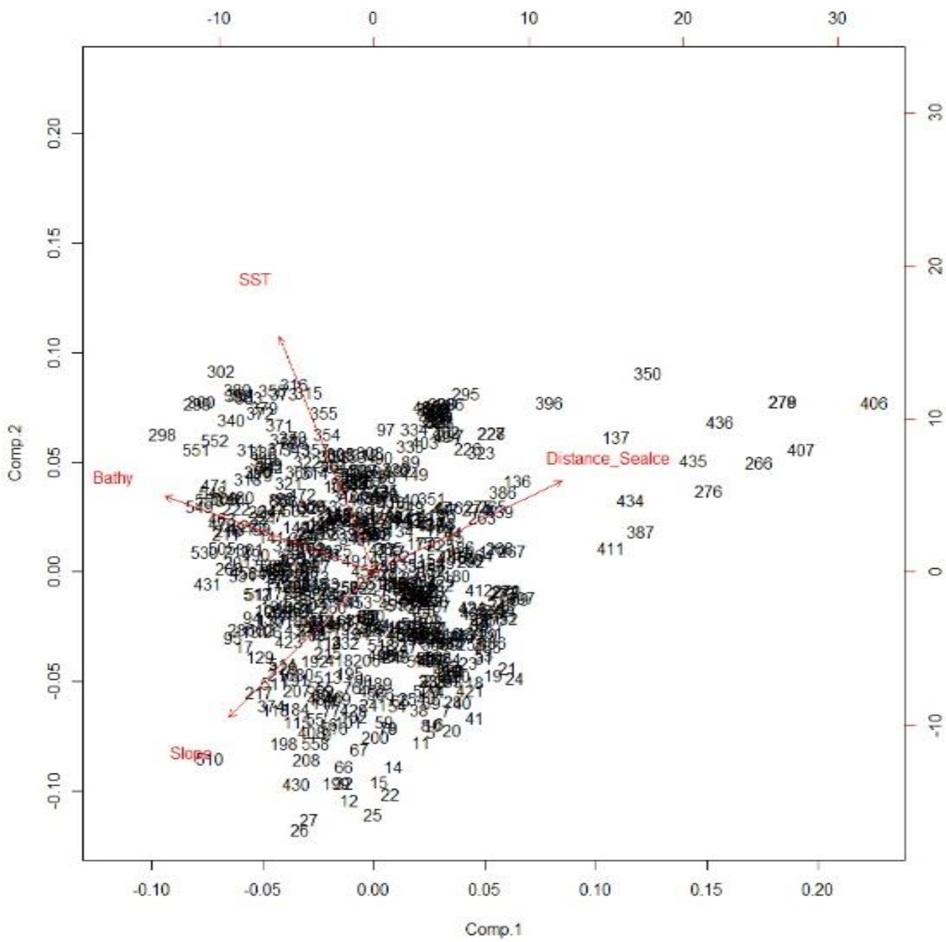


Figure 16: PCA graph displaying the distribution of variance at beluga observations from 2000 to 2006.

Table 4: (a) Results from PCA of observed dataset from 2000 to 2006, and (b) loadings from PCA of observed dataset from 2000 to 2006.

a.	**Observed, 2000–06**	**PC1**	**PC2**	**PC3**	**PC4**
	Standard Deviation	1.11	1.02	0.95	0.90
	Proportion of Variance	0.31	0.26	0.22	0.20
	Cumulative Variance	0.31	0.57	0.80	1.00

b.	**Observed, 2000–06**	**PC1**	**PC2**	**PC3**	**PC4**
	SST	-0.23	0.78	-0.29	0.47
	Distance to Sea Ice	0.57	0.30	-0.57	-0.51
	Slope	-0.44	-0.48	-0.75	NA
	Bathymetry	-0.63	NA	0.15	-0.72

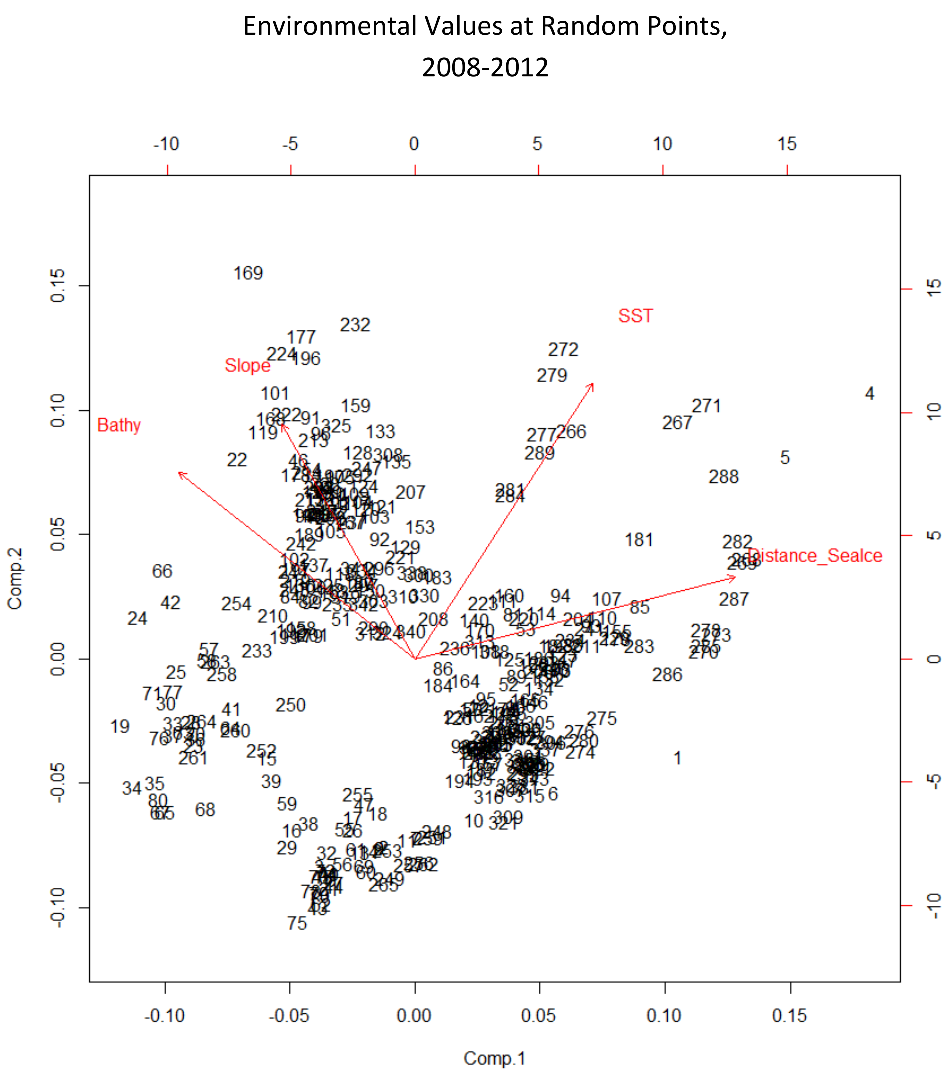


Figure 17: PCA graph displaying the distribution of variance at random points from 2008 to 2012.

Table 5: (a) Results from PCA of random dataset from 2008 to 2012, and (b) loadings from PCA of random dataset from 2008 to 2012.

a.	**Random, 2008–12**	**PC1**	**PC2**	**PC3**	**PC4**
	Standard Deviation	1.24	1.14	0.88	0.63
	Proportion of Variance	0.38	0.32	0.20	0.10
	Cumulative Variance	0.38	0.71	0.90	1.00

b.	**Random, 2008–12**	**PC1**	**PC2**	**PC3**	**PC4**
	SST	0.39	0.66	0.30	0.56
	Distance to Sea Ice	0.70	0.20	NA	-0.68
	Slope	-0.29	0.57	-0.77	NA
	Bathymetry	-0.52	0.45	0.56	-0.47

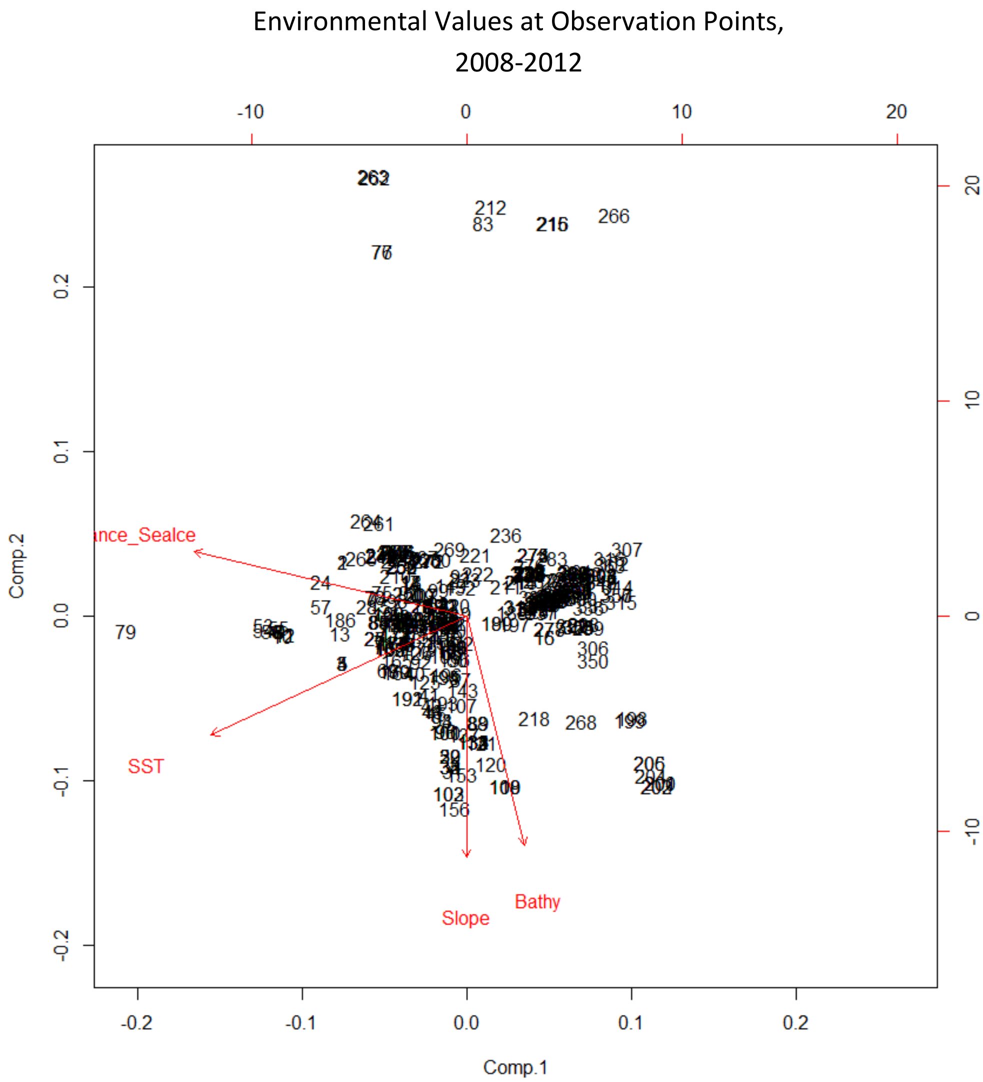


Figure 18. PCA graph displaying the distribution of variance at beluga observations from 2008 to 2012.

Table 6: (a) Results from PCA of observed dataset from 2008 to 2012, and (b) loadings from PCA of observed dataset from 2008 to 2012.

a.	**Observed, 2008–12**	**PC1**	**PC2**	**PC3**	**PC4**
	Standard Deviation	1.24	1.14	0.88	0.63
	Proportion of Variance	0.38	0.32	0.20	0.10
	Cumulative Variance	0.38	0.71	0.90	1.00

b.	**Observed, 2008–12**	**PC1**	**PC2**	**PC3**	**PC4**
	SST	0.39	0.66	0.30	0.56
	Distance to Sea Ice	0.70	0.20	NA	-0.68
	Slope	-0.29	0.57	-0.77	NA
	Bathymetry	-0.52	0.45	0.56	-0.47

Table 7: Environmental covariates with the highest loading values for PC1 and PC2 for the random and observed dataset for both study periods.

	PC1 Highest Loading	PC1 Second Highest Loading	PC2 Highest Loading	PC2 Second Highest Loading
Random, 2000-2006	Bathymetry	Slope	SST	Slope
Observed, 2000-2006	Bathymetry	Distance to Sea Ice	SST	Slope
Random, 2008-2012	Distance to Sea Ice	Bathymetry	SST	Slope
Observed, 2008-2012	Distance to Sea Ice	SST	Slope	Bathymetry

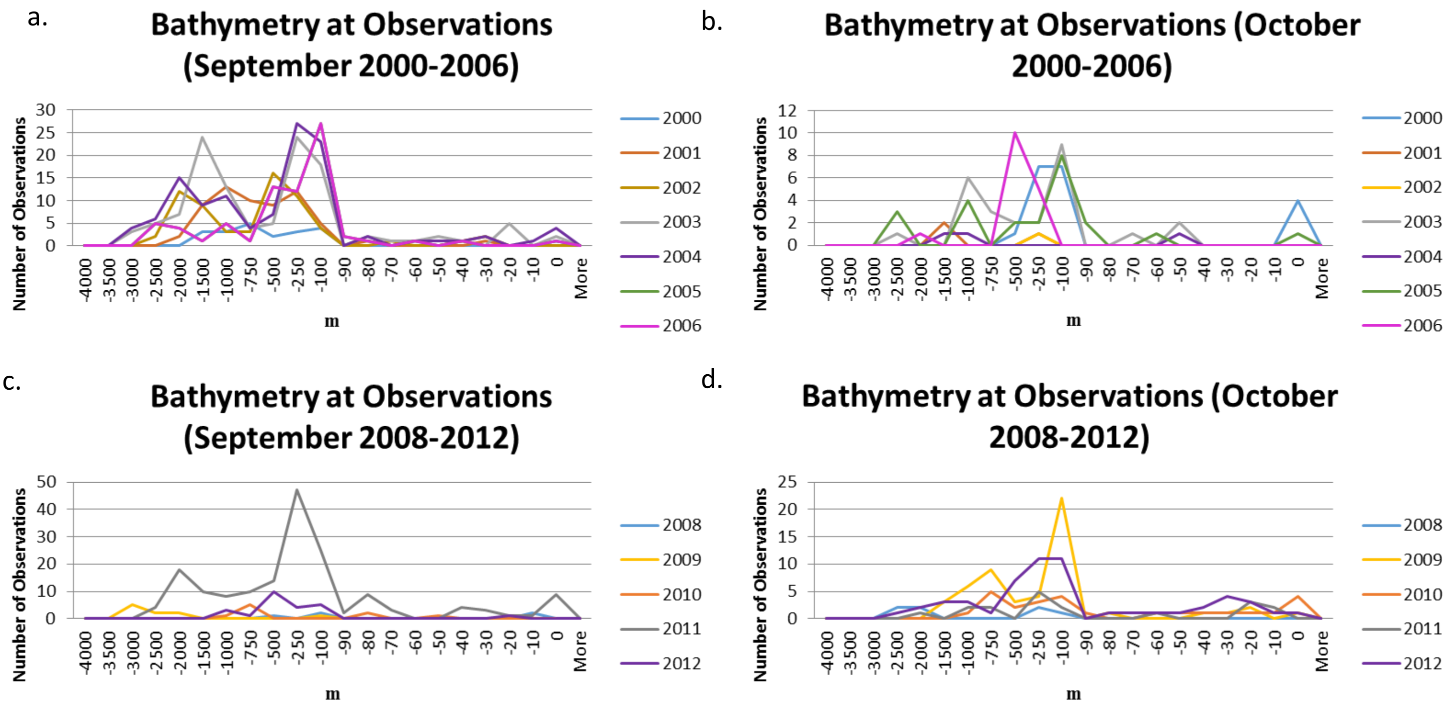


Figure 19: Histograms showing depth values at observations for (a) September, 2000-2006, (b) October, 2000-2006, (c) September, 2008-2012, and (d) October 2008-2012.

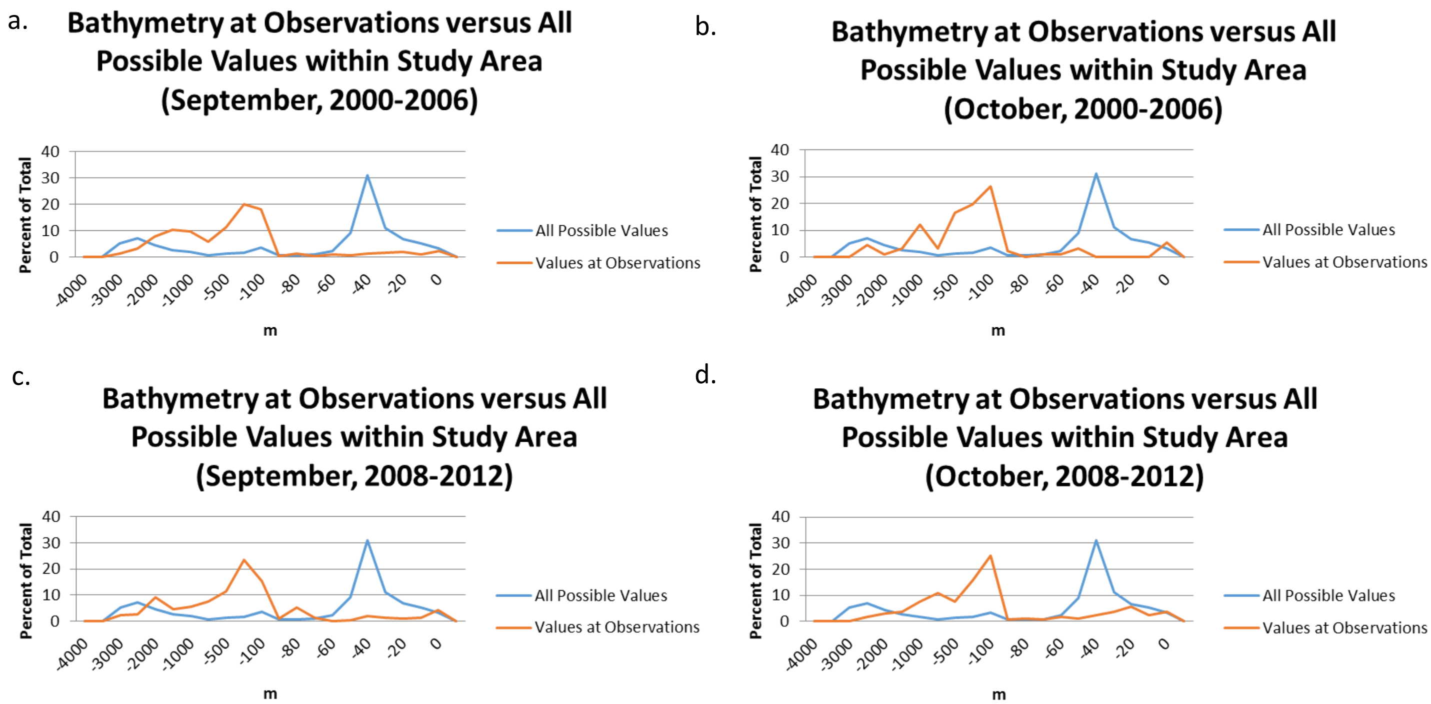


Figure 20: Histograms showing all possible depth values within study area versus depth values at observations for (a) September, 2000-2006, (b) October, 2000-2006, (c) September, 2008-2012, and (d) October 2008-2012.

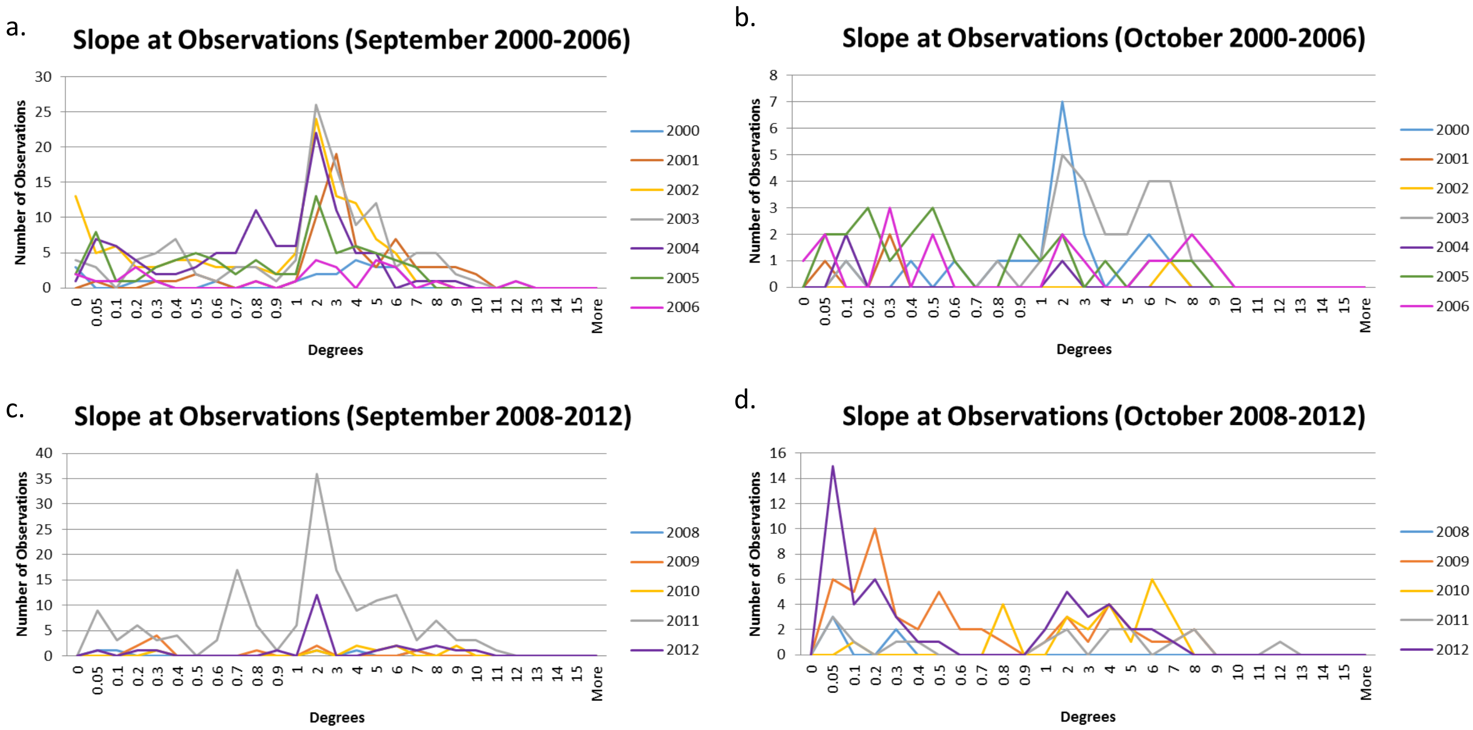


Figure 21: Histograms showing slope values at observations for (a) September, 2000-2006, (b) October, 2000-2006, (c) September, 2008-2012, and (d) October 2008-2012.

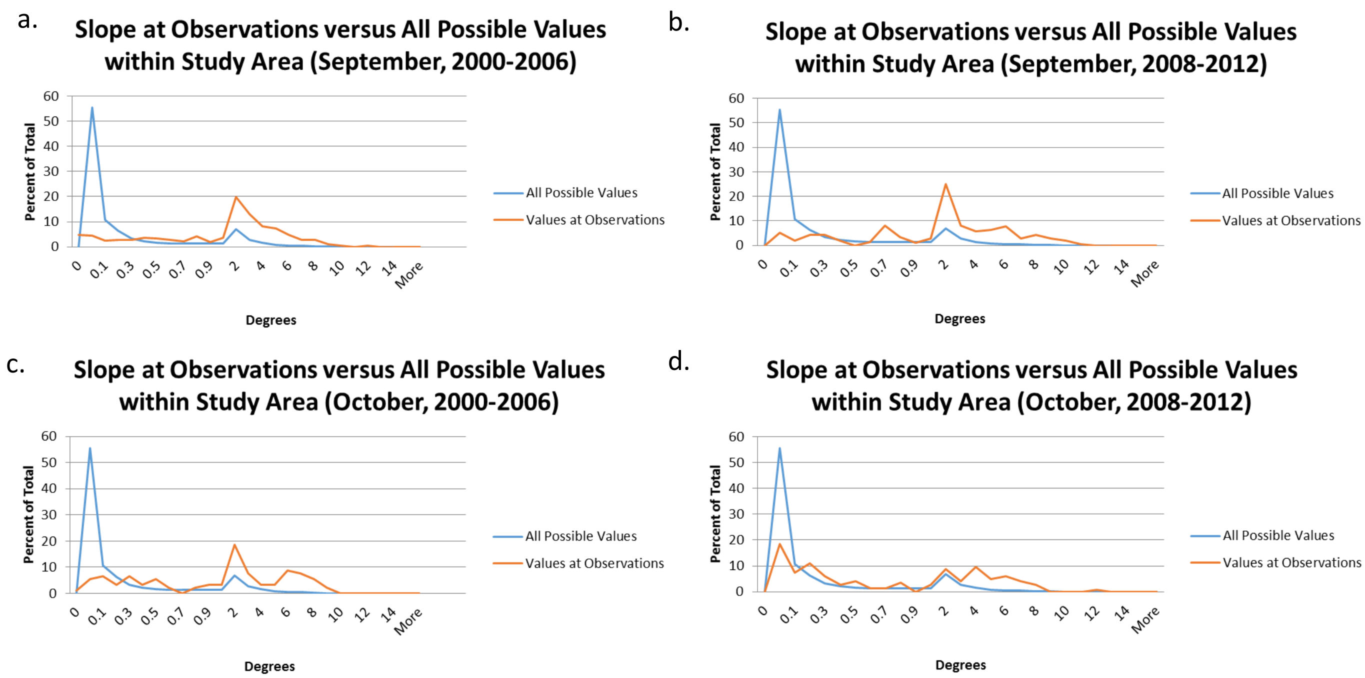


Figure 22: Histograms showing all possible slope values within study area versus slope values at observations for (a) September, 2000-2006, (b) October, 2000-2006, (c) September, 2008-2012, and (d) October 2008-2012.

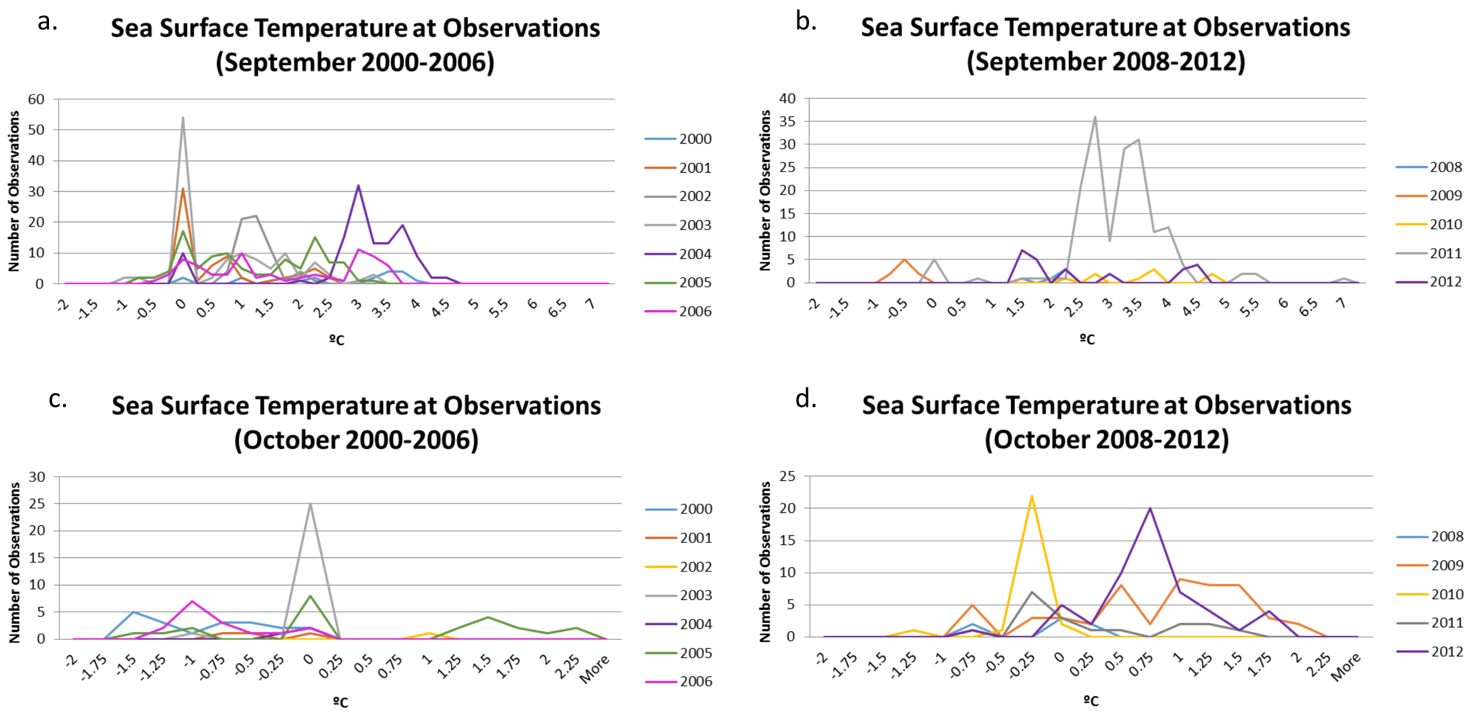


Figure 23: Histograms showing SST values at observations for (a) September, 2000-2006, (b) October, 2000-2006, (c) September, 2008-2012, and (d) October 2008-2012.

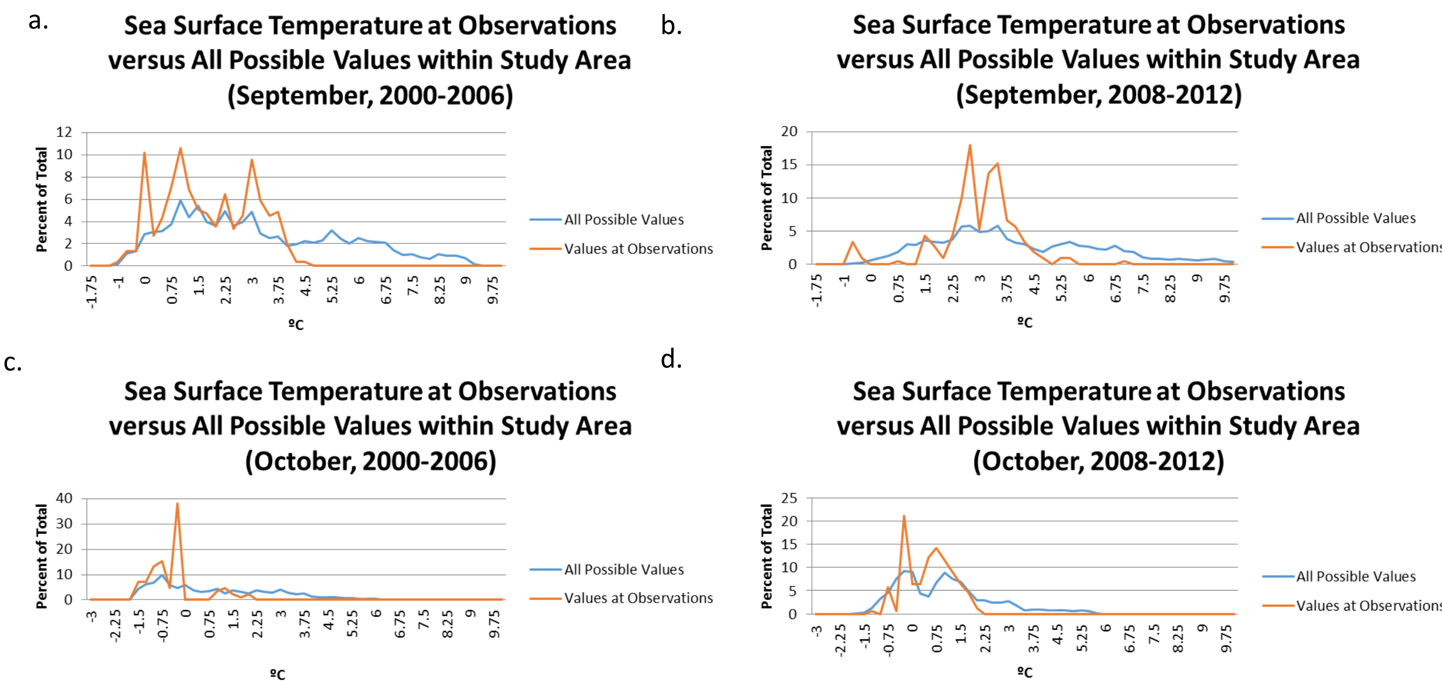


Figure 24: Histograms showing all possible SST values within study area versus SST values at observations for (a) September, 2000-2006, (b) October, 2000-2006, (c) September, 2008-2012, and (d) October 2008-2012.

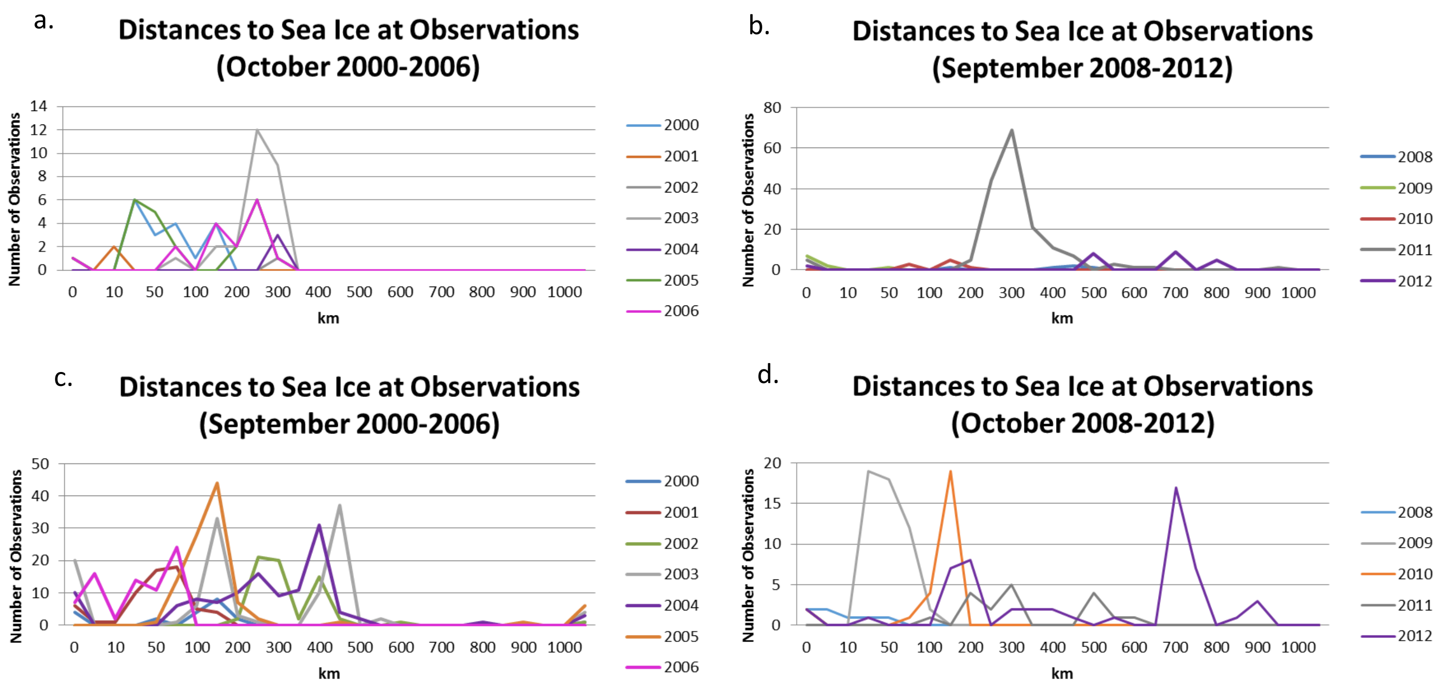


Figure 25: Histograms showing distances to sea ice values at observations for (a) September, 2000-2006, (b) October, 2000-2006, (c) September, 2008-2012, and (d) October 2008-2012.

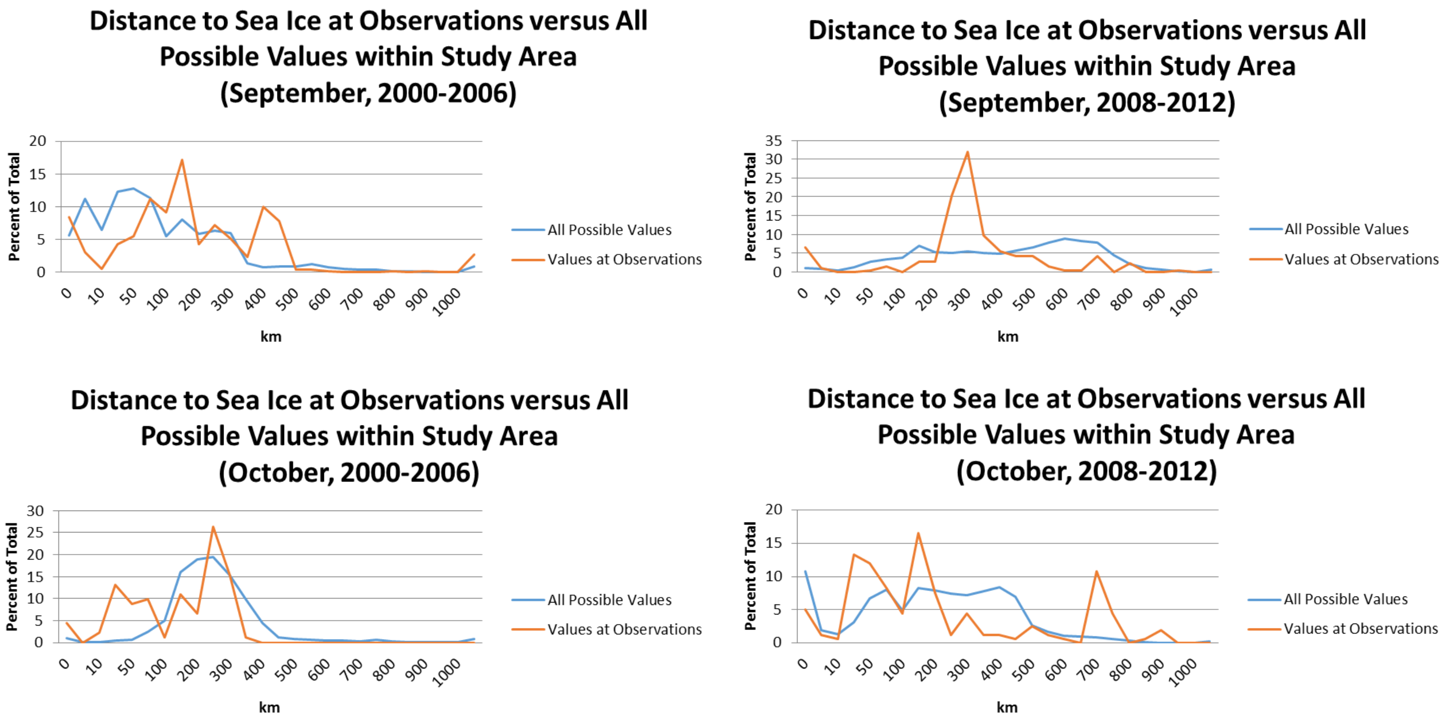


Figure 26: Histograms showing all possible distances to sea ice within study area versus distances to sea ice at observations for (a) September, 2000-2006, (b) October, 2000-2006, (c) September, 2008-2012, and (d) October 2008-2012.

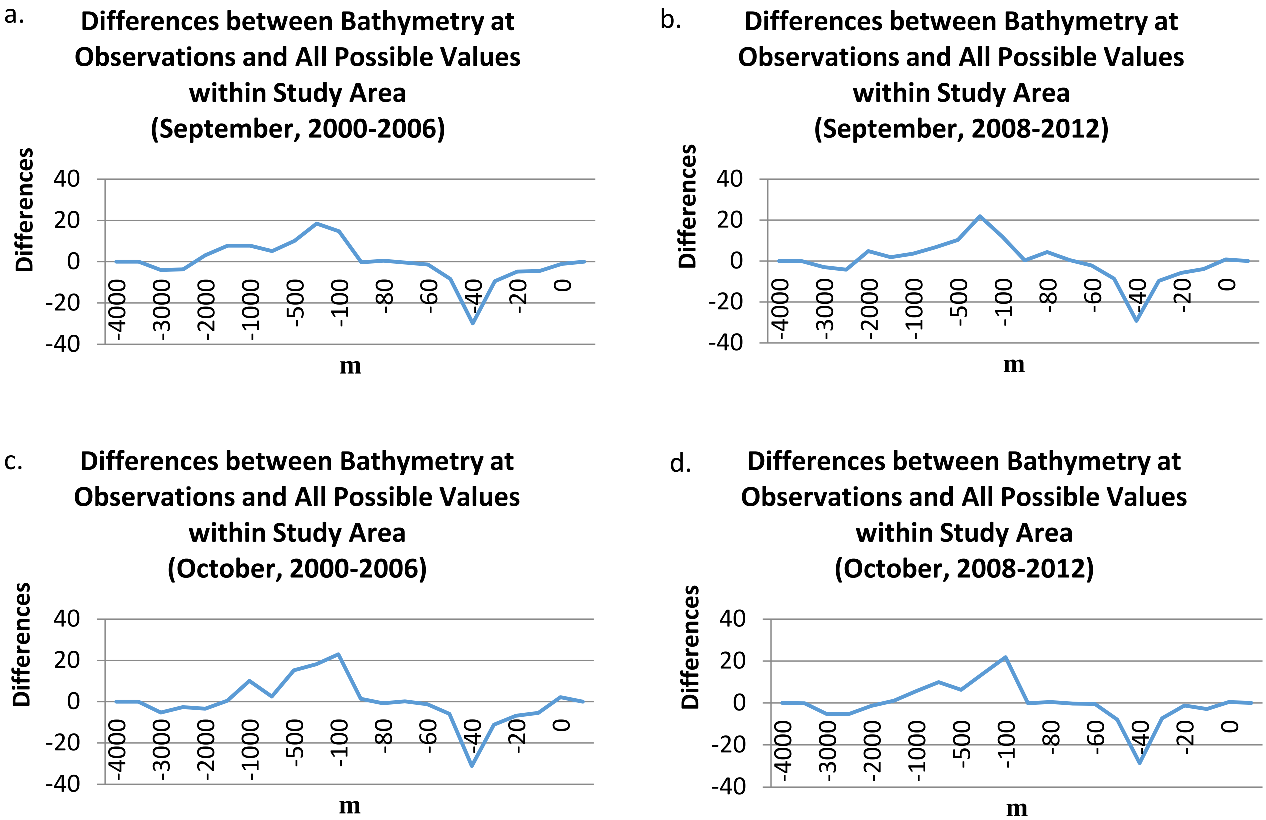


Figure 27: Histograms displaying resulting differences for depths at observations from (a) September of 2000 to 2006, (b) September of 2008 to 2012, (c) October of 2000 to 2006, and (d) October of 2008 to 2012.

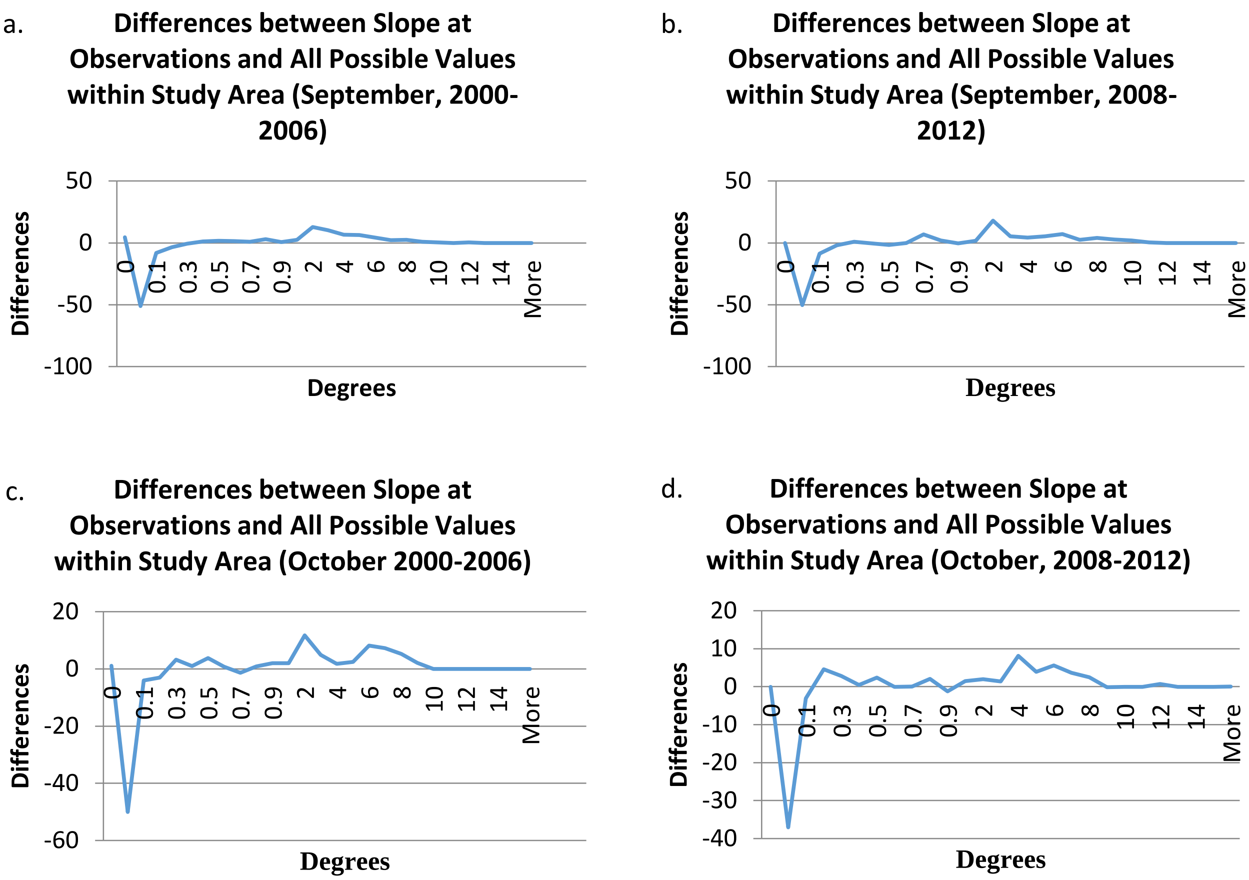


Figure 28: Histograms displaying resulting differences for slope at observations from (a) September of 2000 to 2006, (b) September of 2008 to 2012, (c) October of 2000 to 2006, and (d) October of 2008 to 2012.

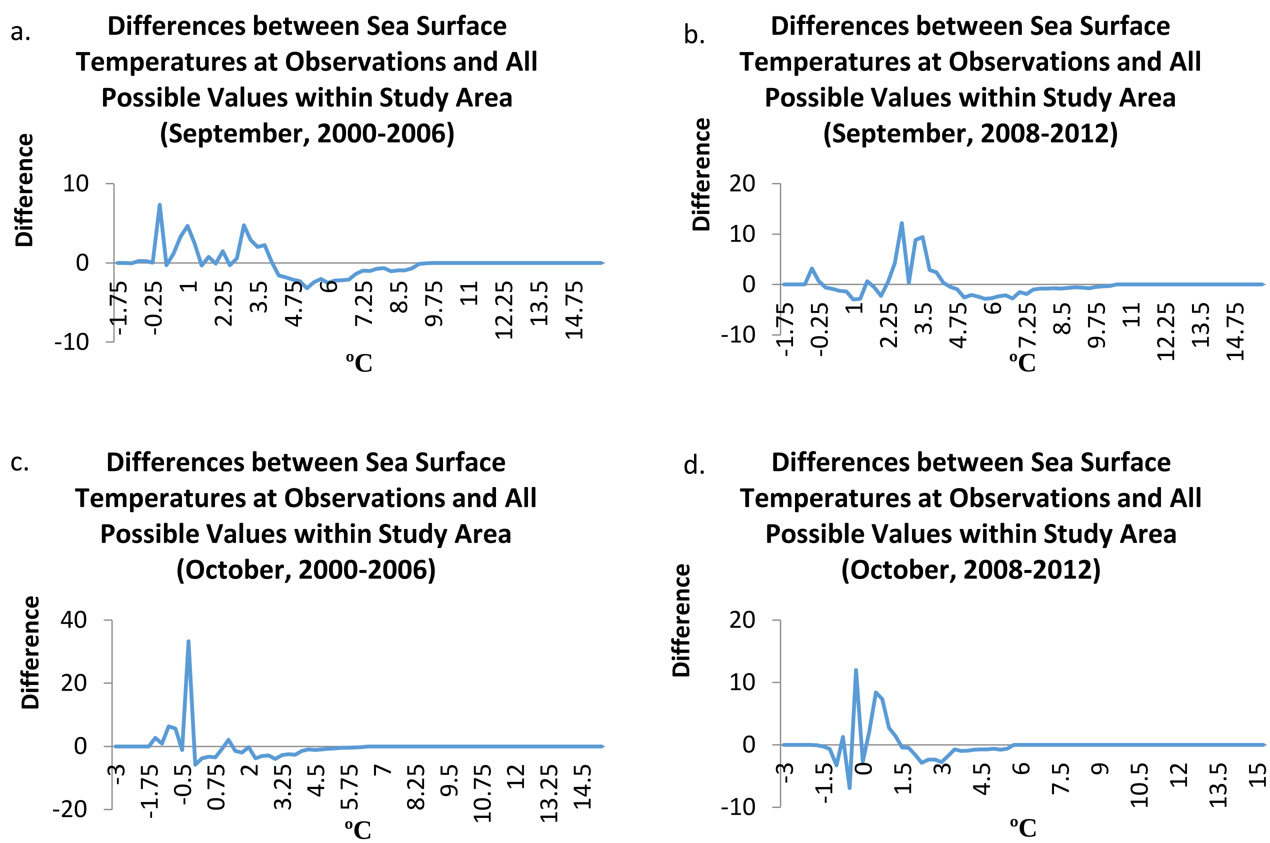


Figure 29: Histograms displaying resulting differences for SST at observations from (a) September of 2000 to 2006, (b) September of 2008 to 2012, (c) October of 2000 to 2006, and (d) October of 2008 to 2012.

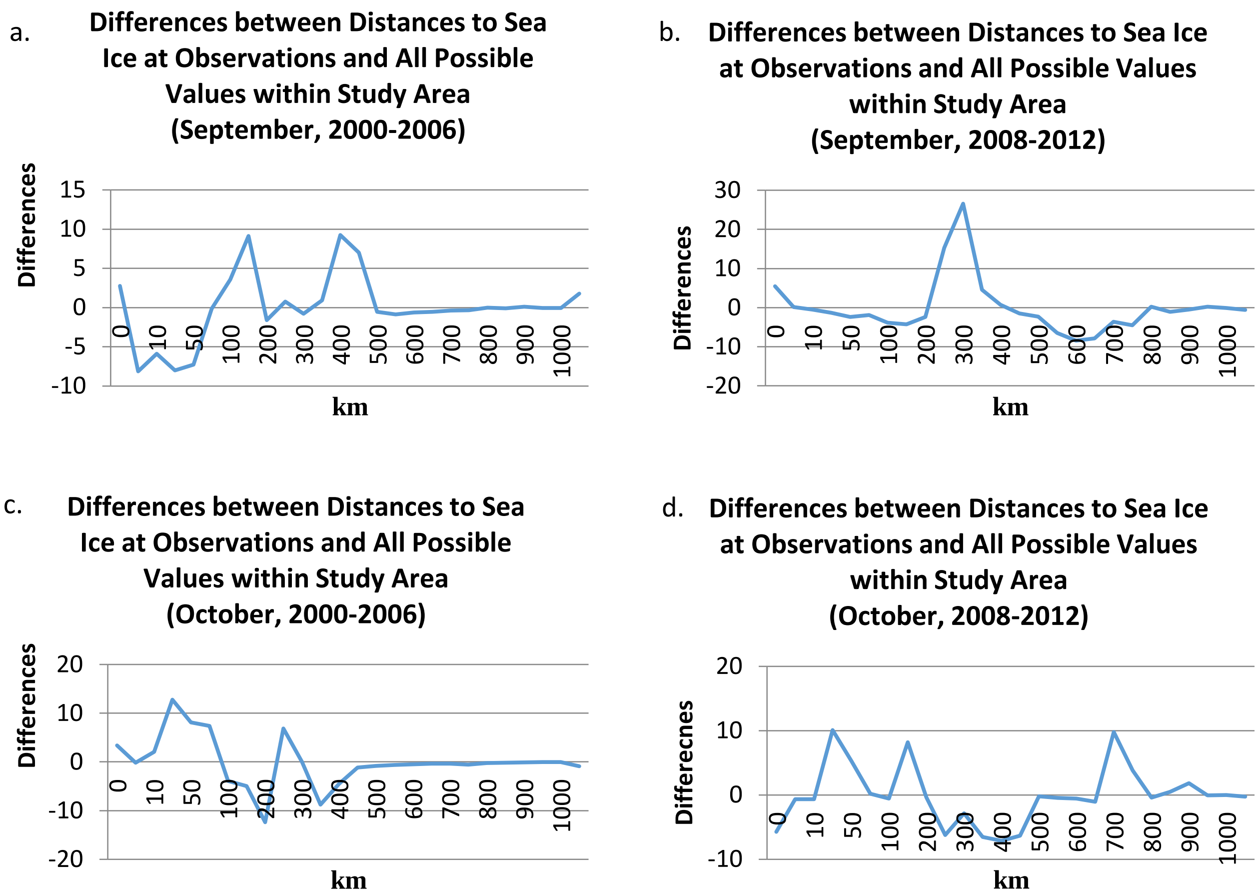


Figure 30: Histograms displaying resulting differences for distance to sea ice at observations from (a) September of 2000 to 2006, (b) September of 2008 to 2012, (c) October of 2000 to 2006, and (d) October of 2008 to 2012.

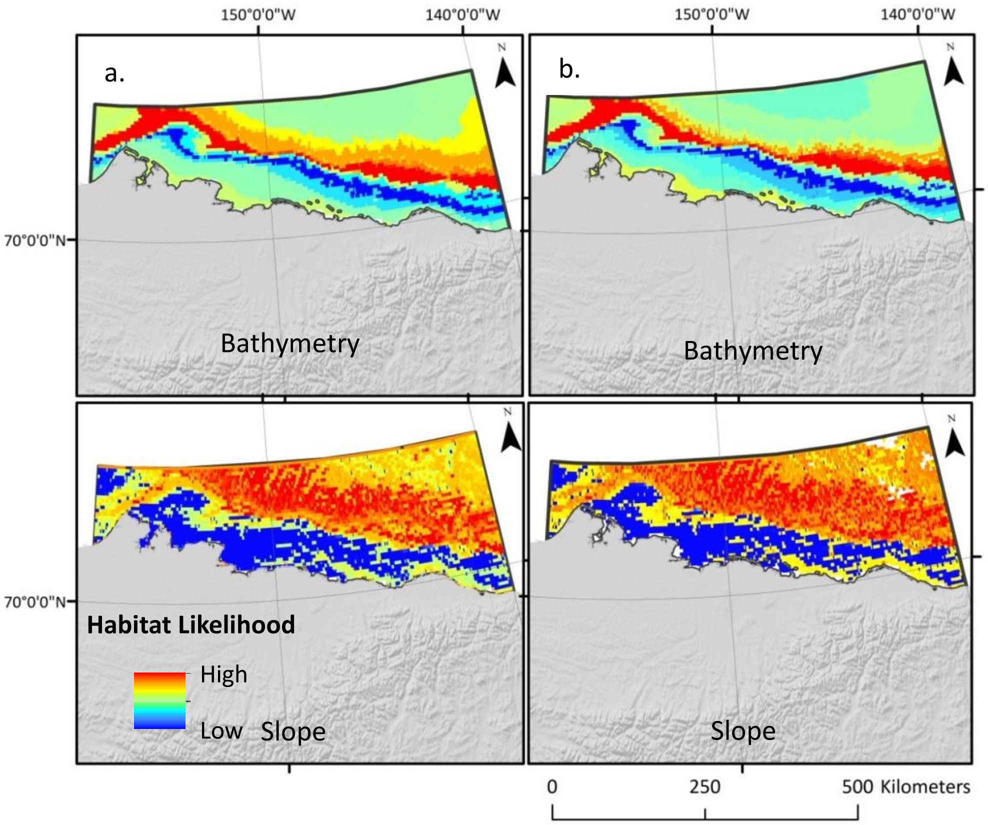


Figure 31: Maps depicting the probability of occurrence for bathymetry and slope for (a) September and (b) October of 2000 to 2006.

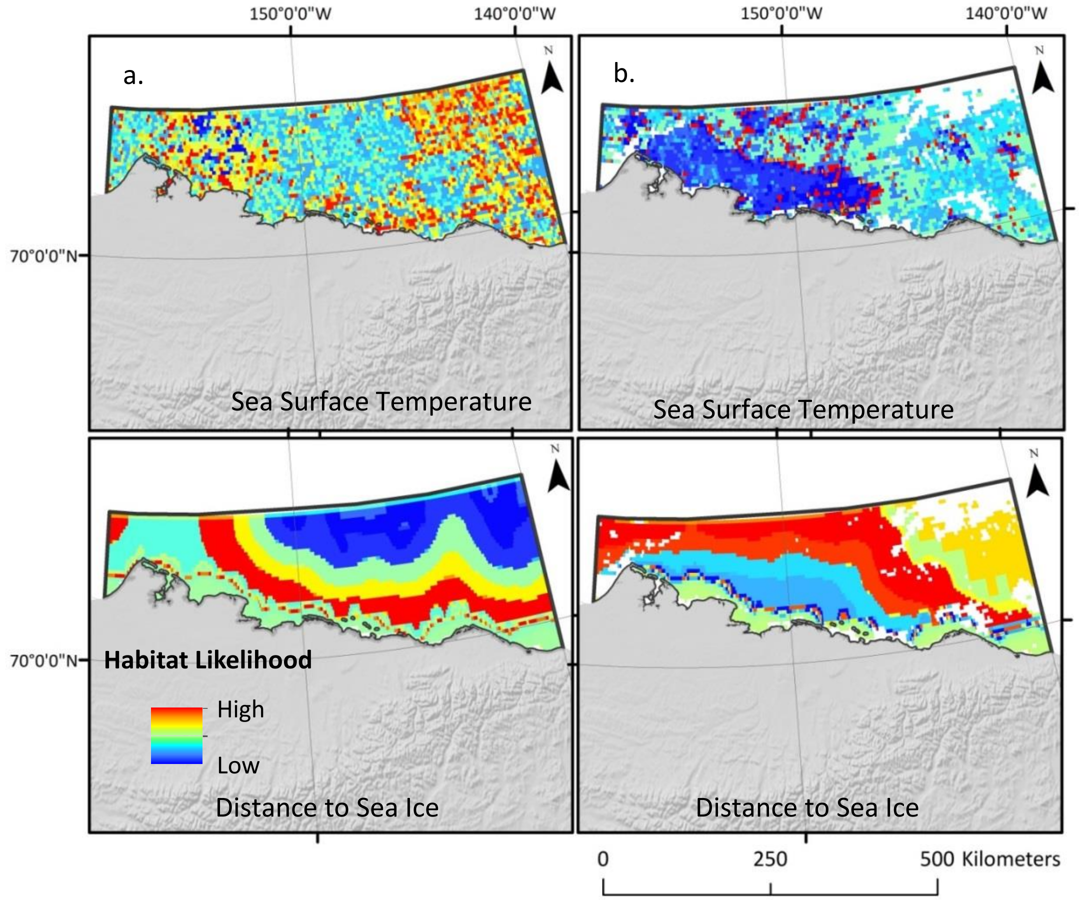


Figure 32: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2000.

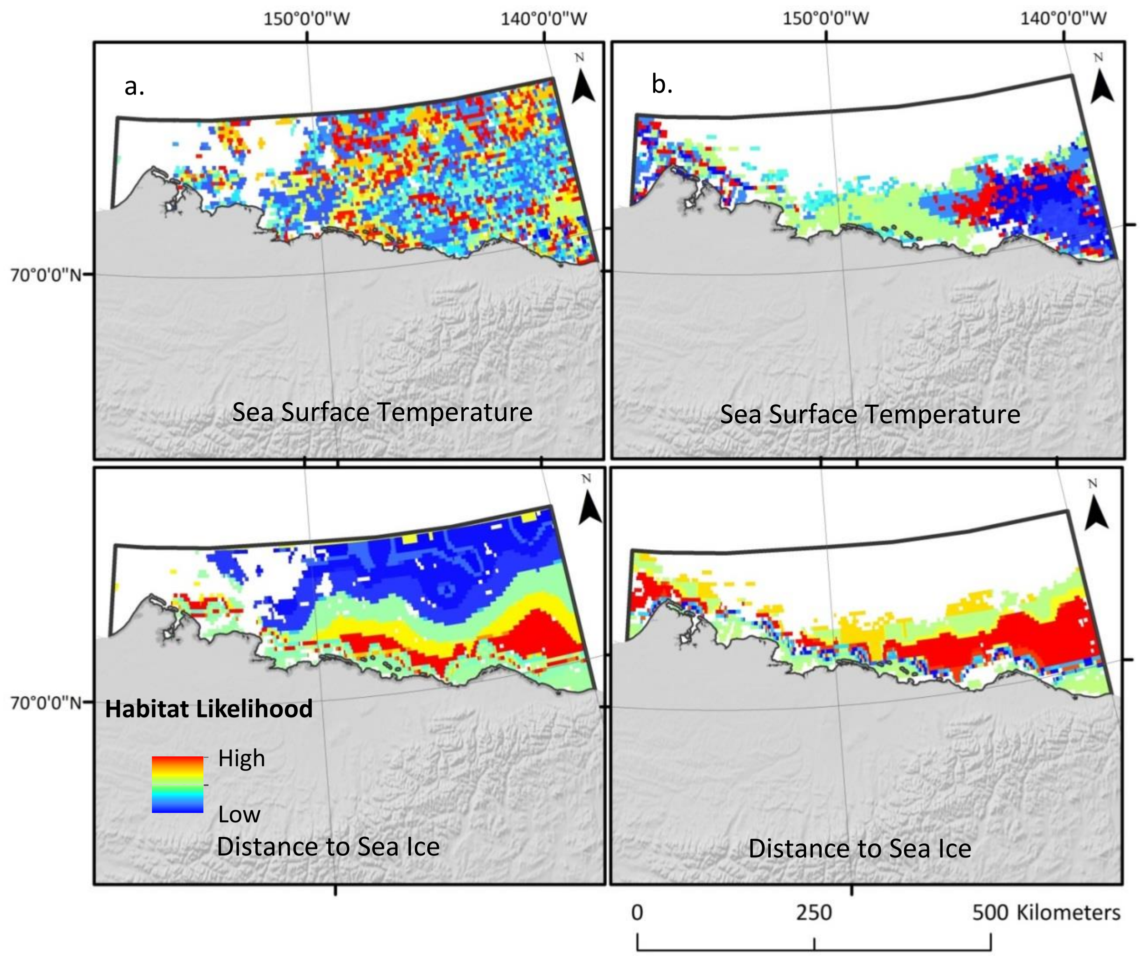


Figure 33: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2001.

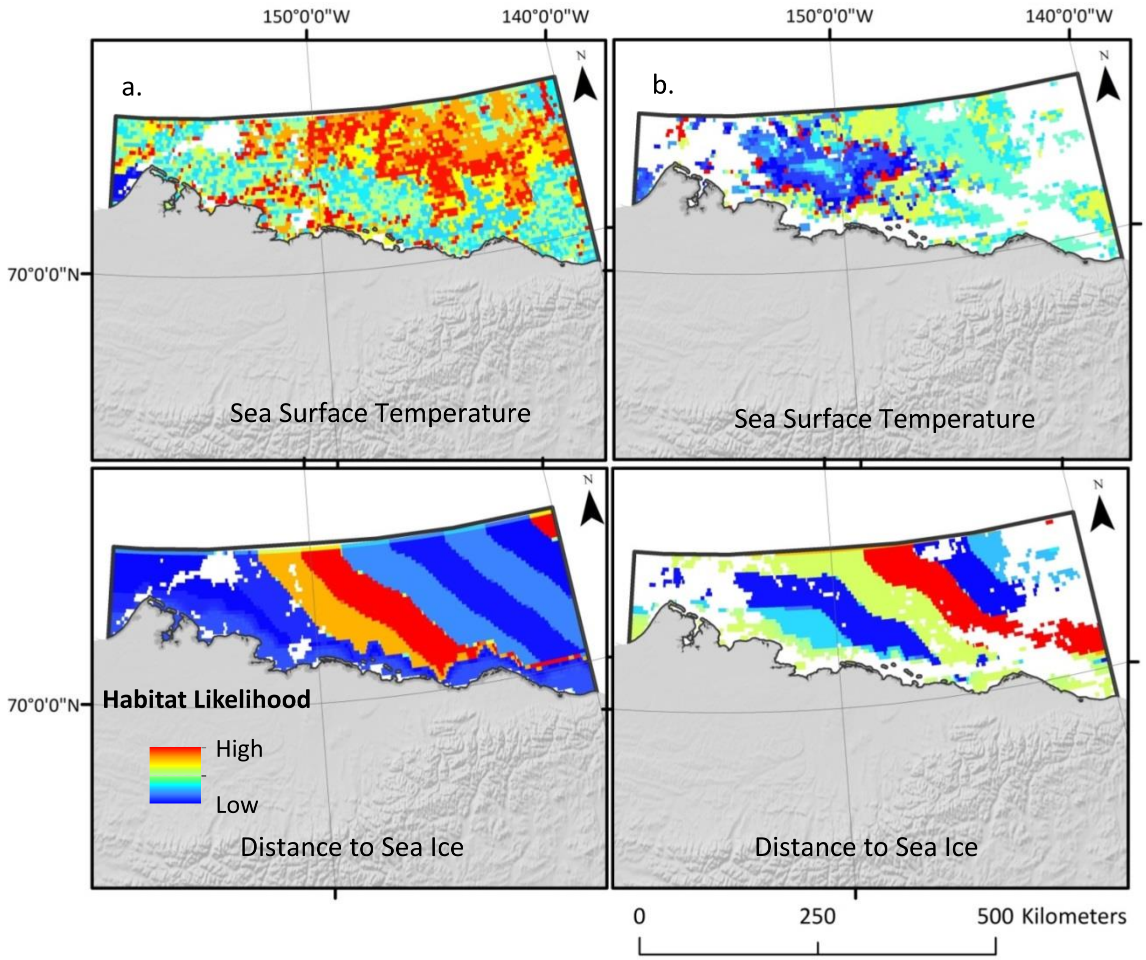


Figure 34: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2002.

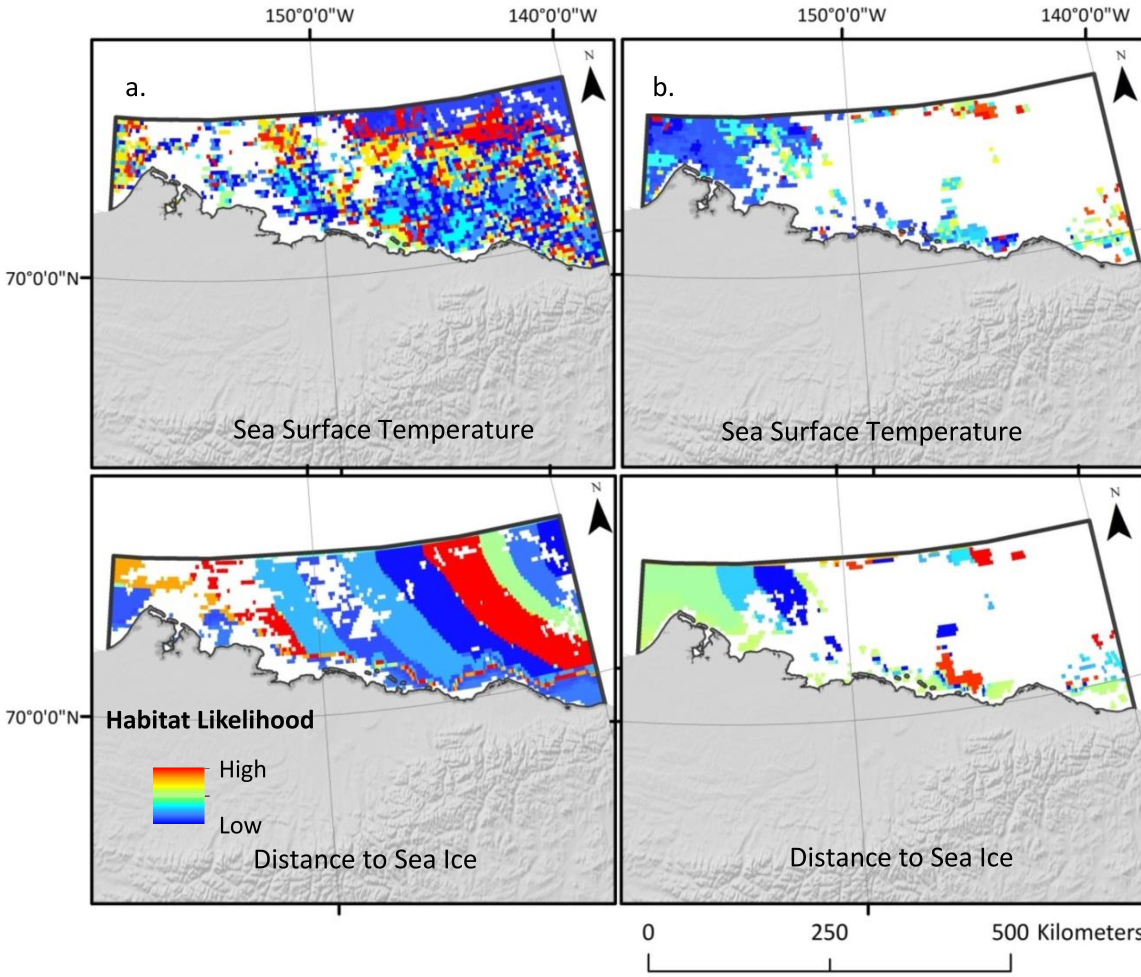


Figure 35: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2003.

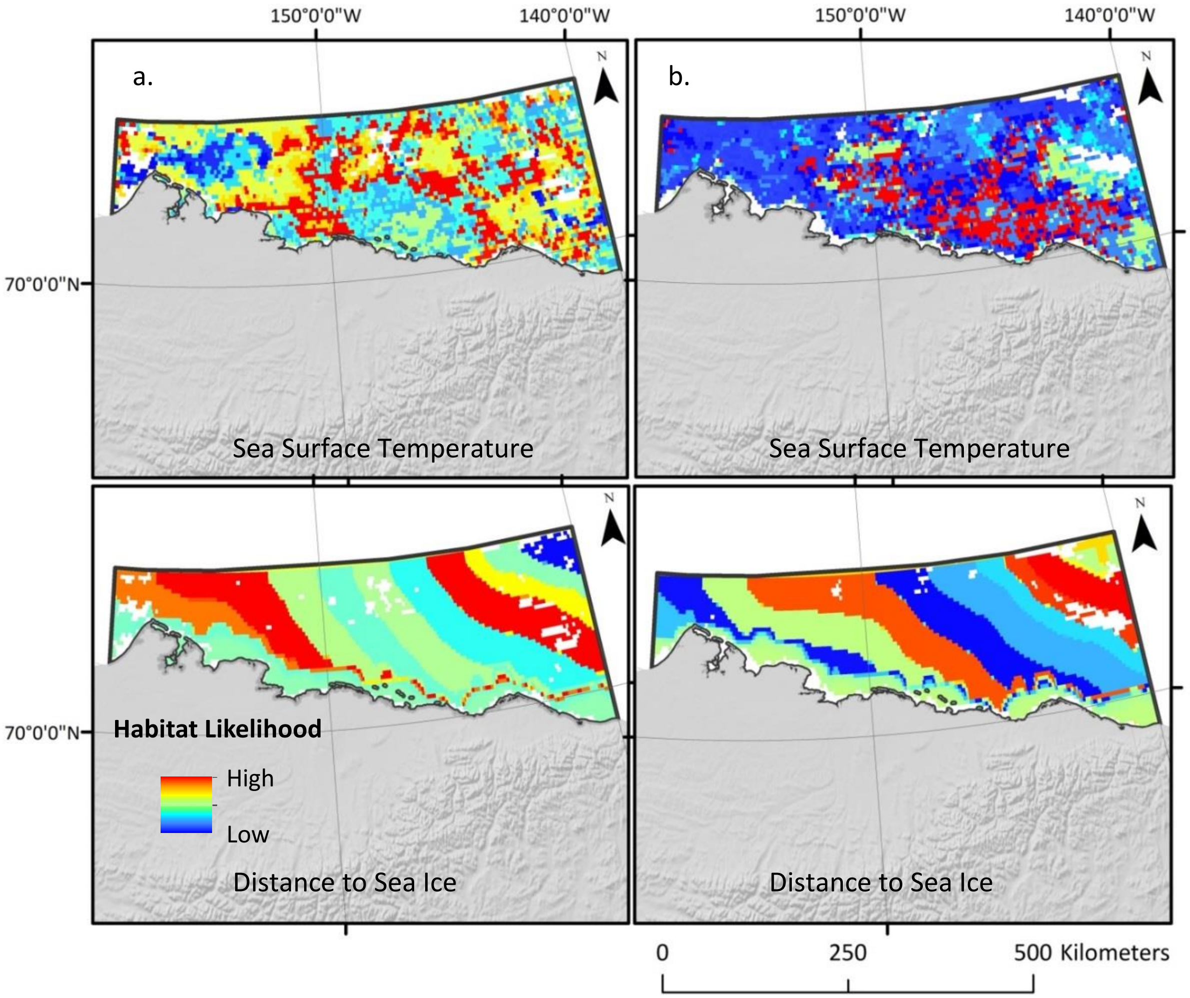


Figure 36: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2004.

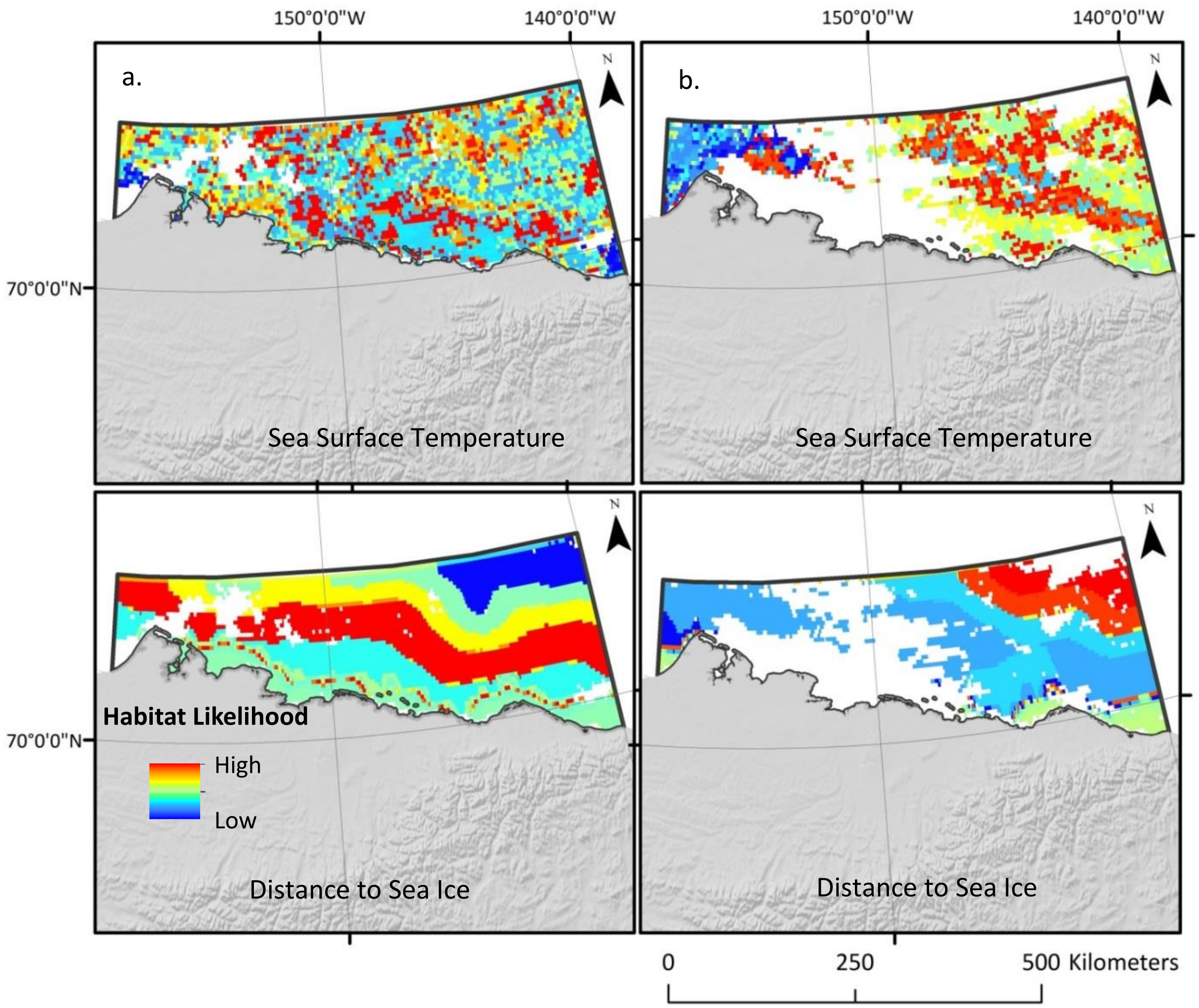


Figure 37: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2005.

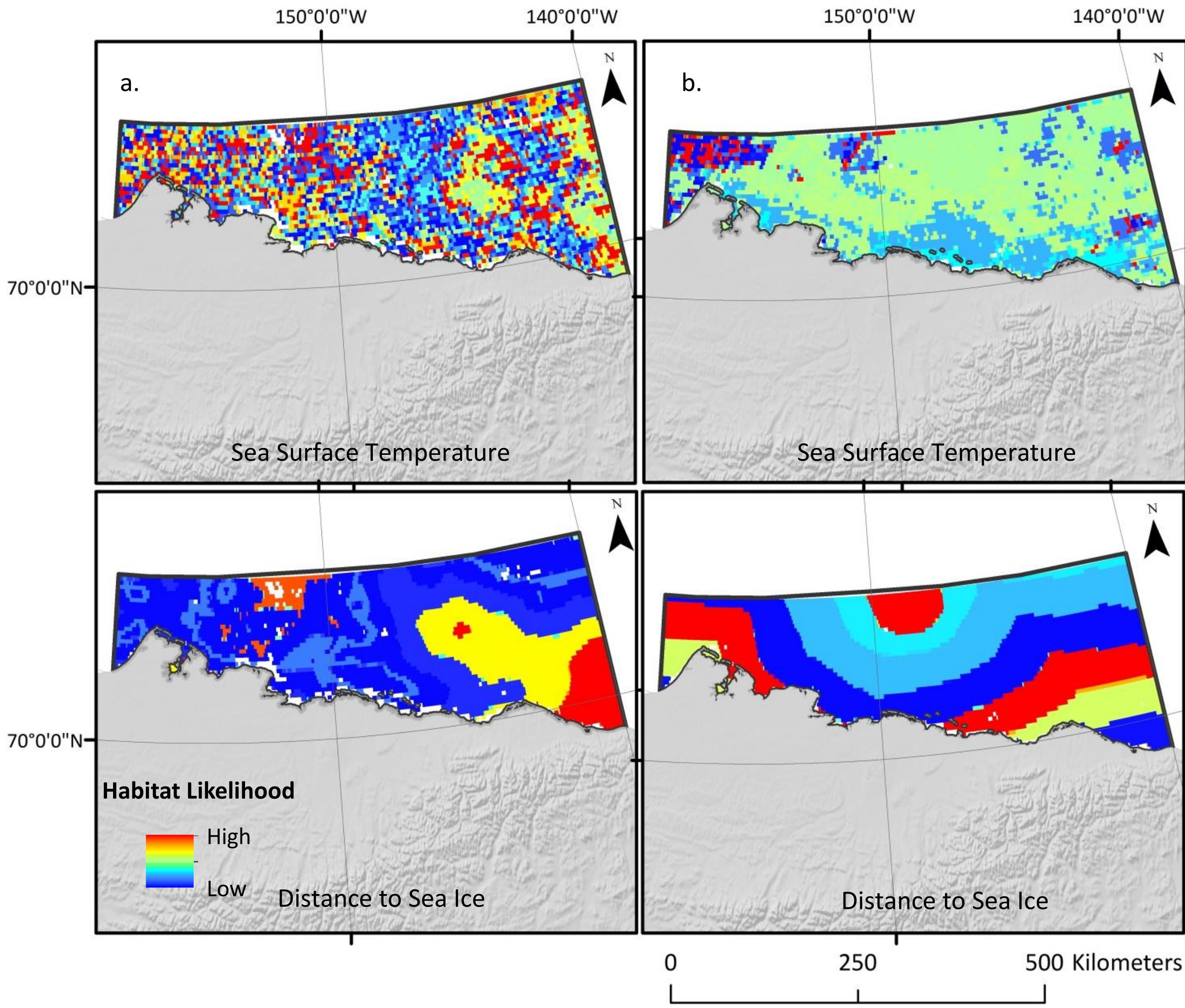


Figure 38: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2006.

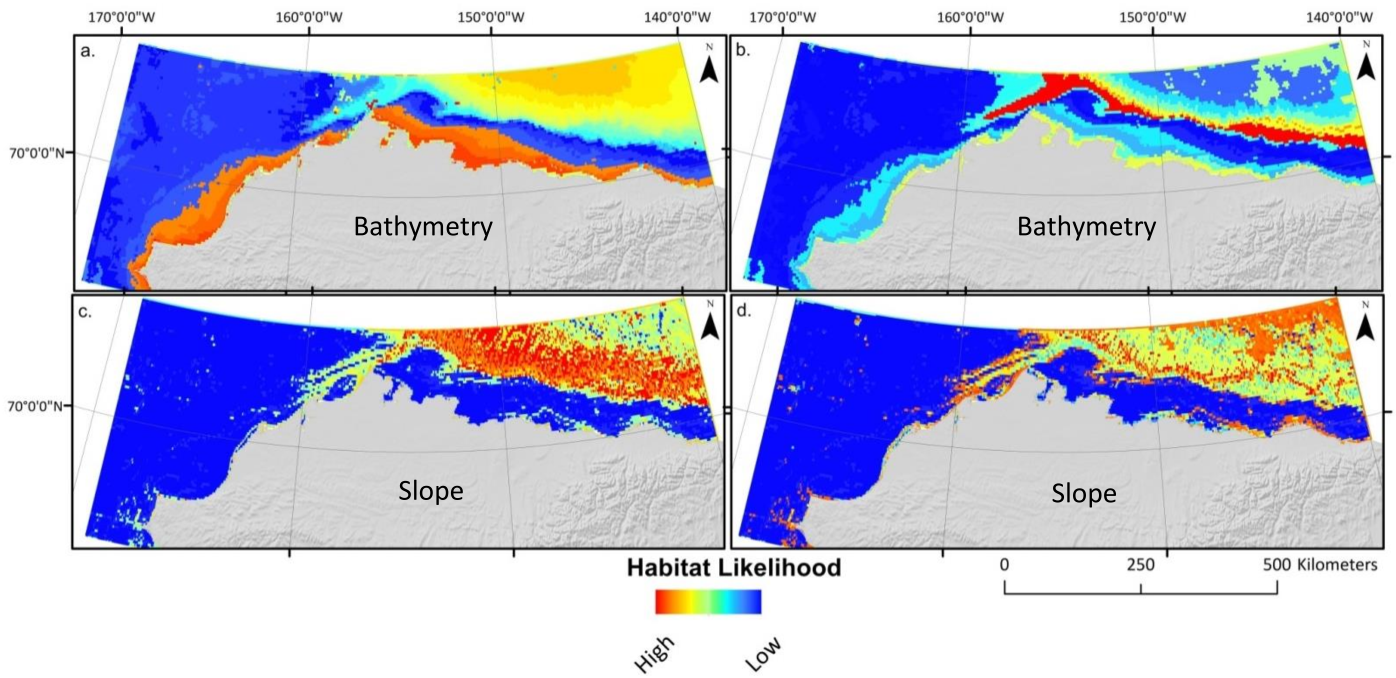


Figure 39: Maps depicting the probability of occurrence for bathymetry and slope for (a) September and (b) October of 2008 to 2012.

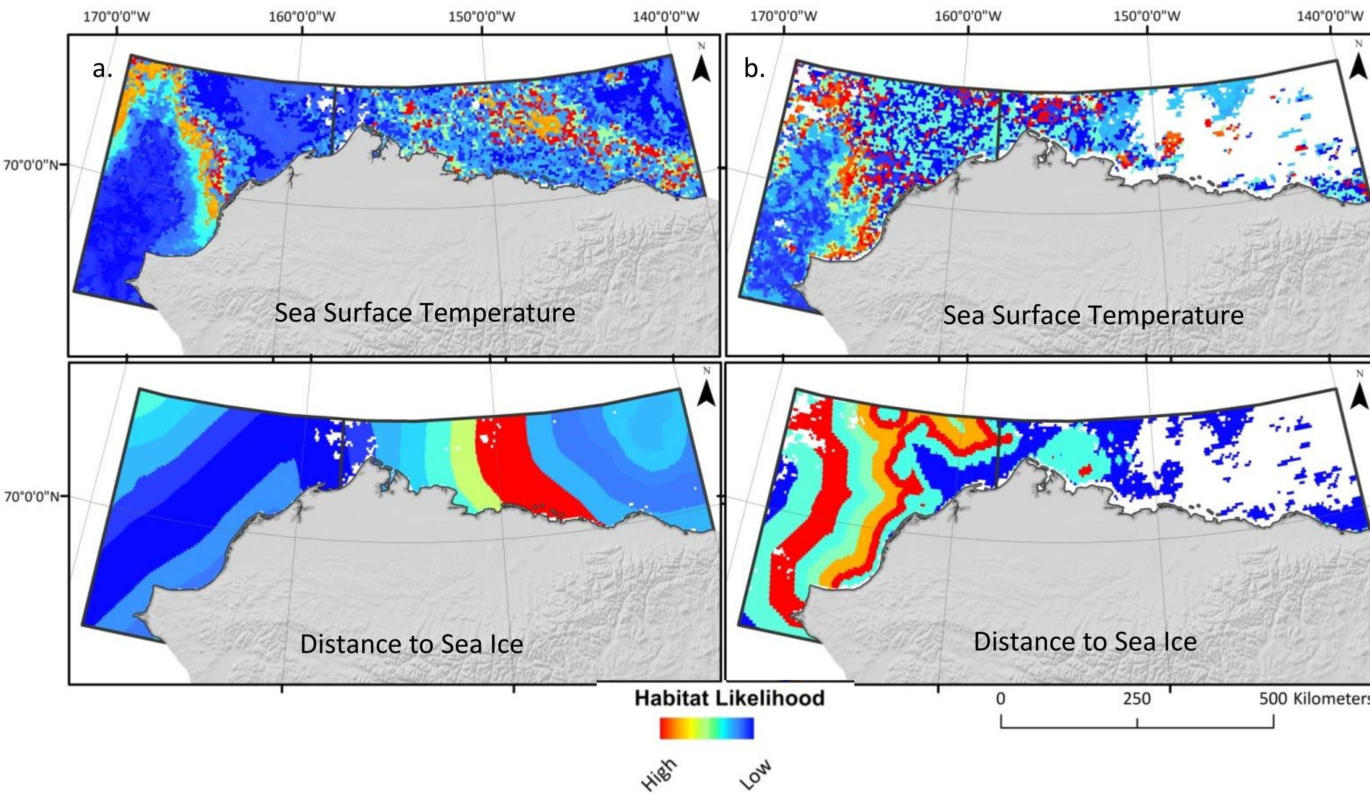


Figure 40: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2008.

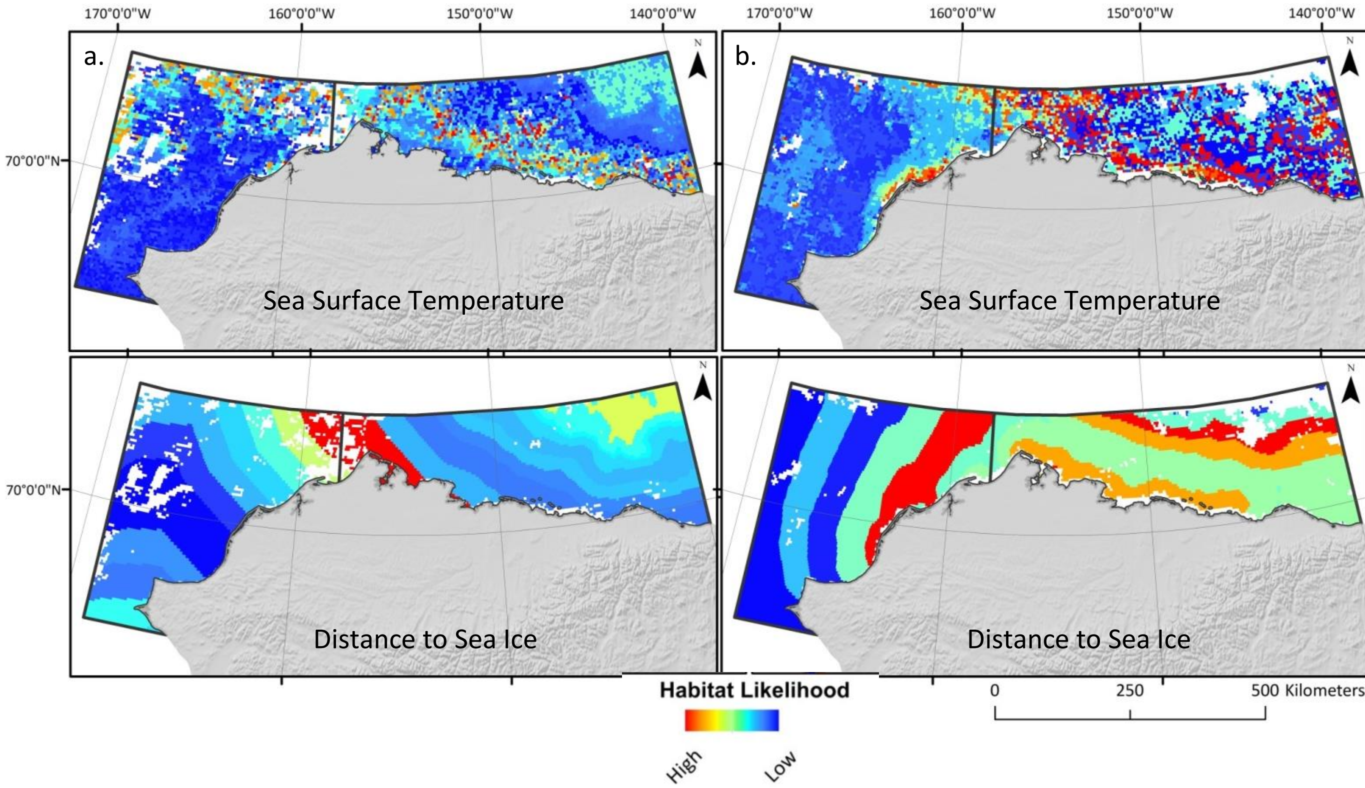


Figure 41: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2009.

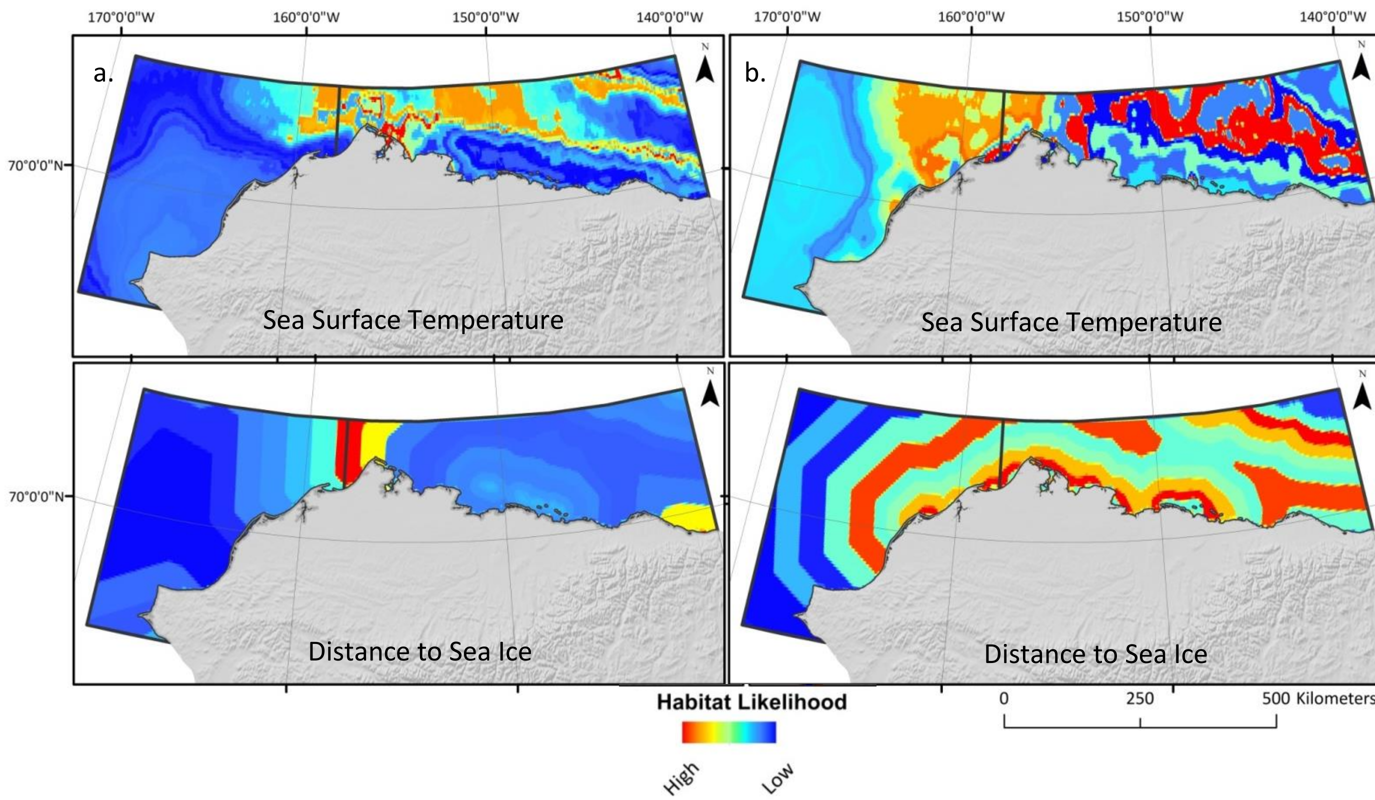


Figure 42: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2010.

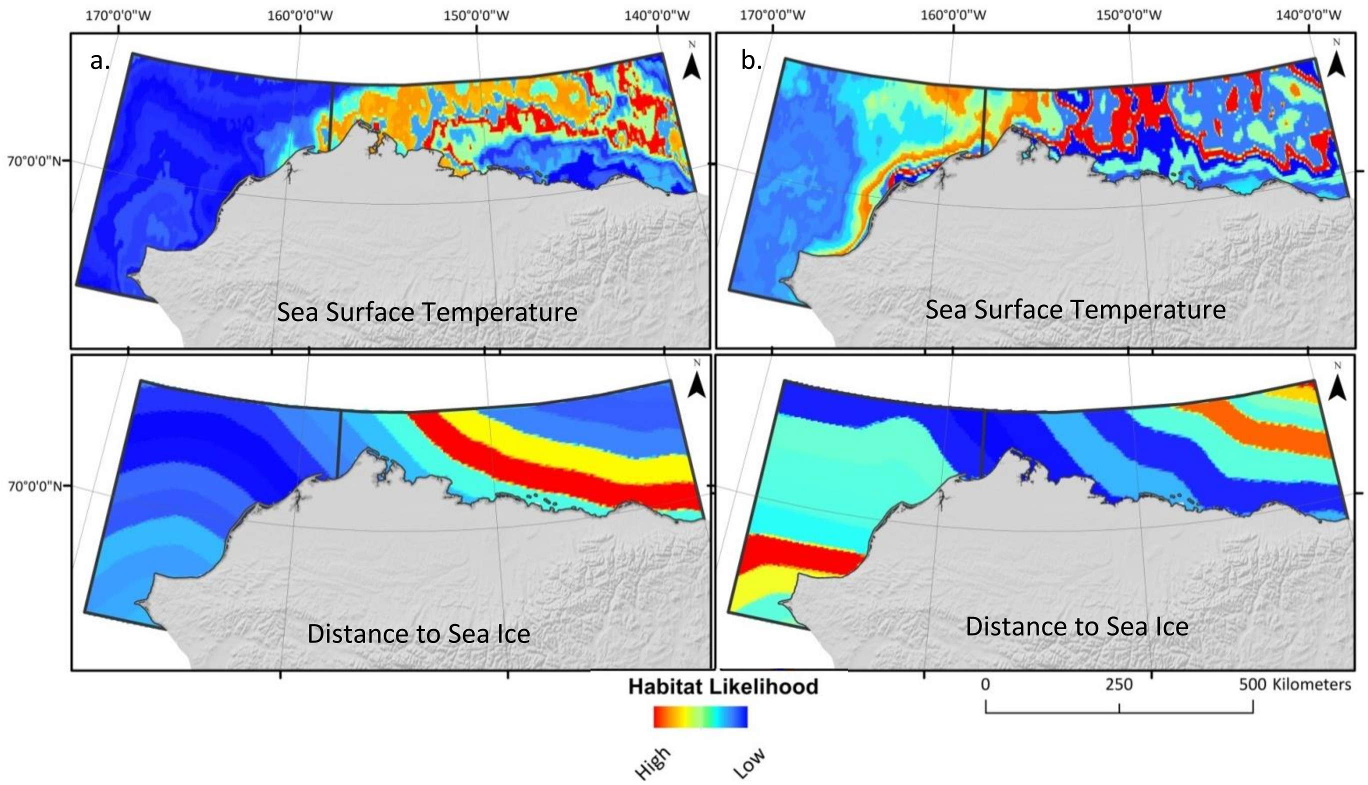


Figure 43: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2011.

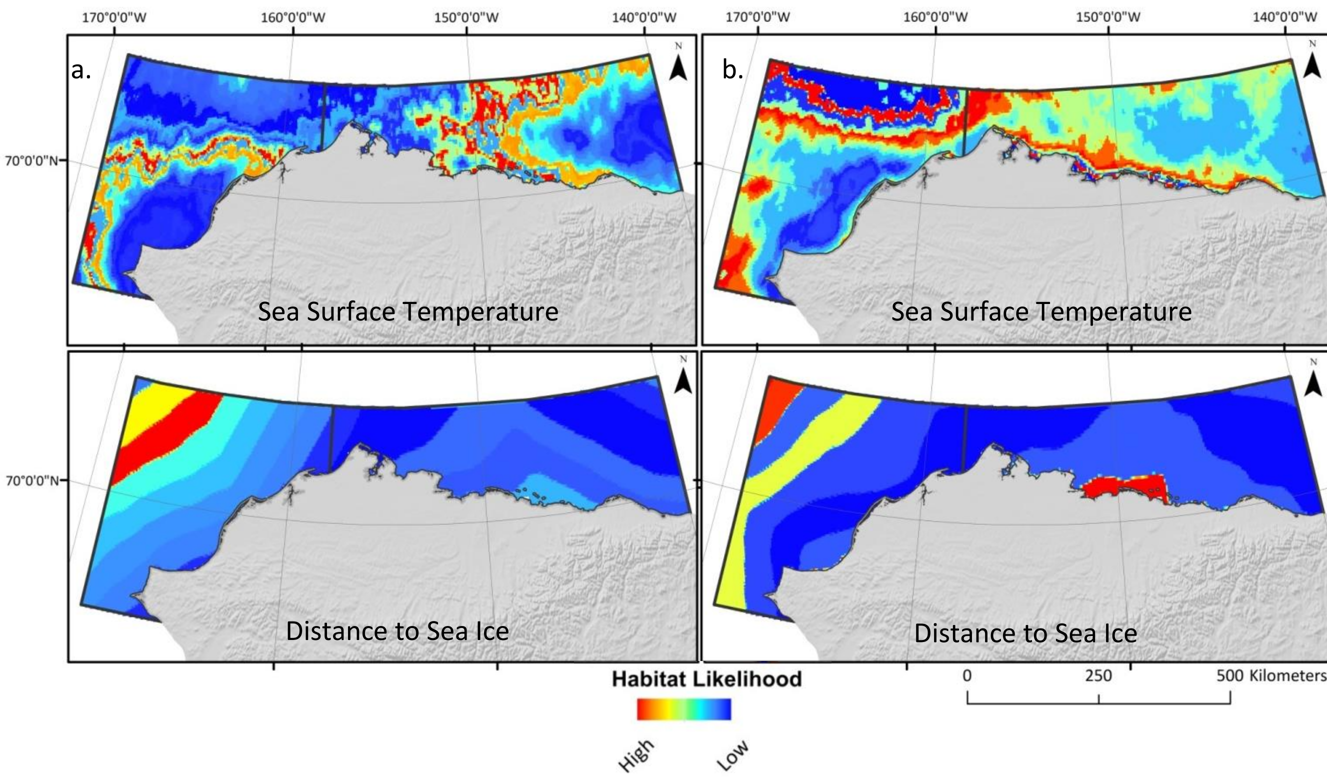


Figure 44: Maps depicting the probability of occurrence for sea surface temperature and distance to sea ice for (a) September and (b) October of 2012.

4. DISCUSSION

4.1 HABITAT

Probability of occurrence for beluga whales follows G. Evelyn Hutchinson's ecological niche theory (1961), which states that within a set space and using environmental variables, spatial dynamics of a species can be modeled. Based on the species, certain environmental factors influence where species can survive. The ecological background defines which environmental gradients relate to the habitat beluga whales and determines environmental parameters. From these parameters, distinct habitats can be modeled (Vandermeer 1972).

Habitat associations between environmental covariates and the observed belugas were analyzed for bivariate and multivariate correlation. Based on results from the habitat associations, output surfaces have been developed for each environmental covariate: sea surface temperature (SST), distance to sea ice, bathymetry, and slope. Modeling of ecological phenomena provides insight to the relationships within the complex system. Output surfaces might produce patterns that can better explain a species relationship with the environment (Franklin, 2009).

Throughout the study periods, beluga whales were consistently associated with topographic covariates, preferring relatively deep areas with high slope. Results of this study are consistent with previous studies of beluga whale habitat (Goetz et al. 2007; Loseto et al. 2006; Moore et al. 2000; Moore et al. 1997; Barber et al. 2001), which show that belugas prefer areas of varied bathymetry depending on pod structure and season. Females and their young, and immature males, prefer shallow areas along the coast, and adult males prefer deeper areas (Loseto et al. 2006). In addition, this study confirmed previous studies (Stafford et al. 2012; Stirling et al. 1977), which show belugas prefer areas with relatively steep slope.

In the summer and fall months belugas migrate northward. During this time, belugas are believed to be feeding, molting, and calving (Quakenbush (in press); Hansen et al. 1999; Frost and Lowry 1990). During this time, and depending on pod structure, belugas might be seeking productive areas for feeding opportunities, such as along sea ice and in areas of upwelling. If molting, beluga whales might seek areas with higher water temperatures, which would allow them to save energy or molt more rapidly (Boily 1995).

Observed beluga whale preference for deep areas with relatively steep slopes might indicate that they are seeking areas with higher productivity which attract prey species, including areas of upwelling (Stafford et al. 2013; Stirling et al. 1977; Aagaard et al. 1981; Overland and Pease, 1982). Productivity might also be indicated by distance to sea ice, due to aggregations of prey along the ice edge, including Arctic cod (Loseto et al. 2006; Reid et al. 2003) and SST, which might be related to upwelling (Pickart et al. 2013; Mountain et al. 1976). Beluga whale preference for areas with SST between 0°–4°C might also indicate areas that provide better habitat for molting (Boily 1995).

4.2 UNCERTAINTY

Potential errors in the collection of the datasets include miscounting or missing whales at the water surface. Environmental covariates used in the analysis ranged in spatial resolution from 500m^2 to 4km^2, and distance to sea ice raster resolution were interpolated to 1km^2. A principal source of error in the probability of occurrence modeling is over fitting the models to the data, resulting in the modeling of the data rather than the natural phenomena (Franklin, 2009). Beluga sighting data from September of 2011 were divided into a training (70%) and testing (30%) dataset (Figure 45). The same modeling process was applied to each dataset, resulting in slightly differing probability of occurrence maps (Figure 46). The resulting habitat maps were then compared, by measuring how results from the test dataset deviated from results based on the training dataset; the greatest differences between the datasets are shown in the bathymetry and distance to sea ice maps (Figure 47).

Environment covariate raster data for SST did not cover the entire study area for all months and years, resulting in gaps in the probability of occurrence map outputs. In addition, distance to sea ice rasters were interpolated, using bilinear interpolation in ArcGIS (10.1) to finer spatial resolutions (24km^2 to 4km^2 for raster data from 2000 to 2010, and 4km^2 to 1km^2 for raster data from 2010 to 2012).

Environmental covariates including upwelling, chlorophyll, and salinity might provide a better understanding of beluga habitat associations in relation to prey. However, available upwelling data was at a spatial resolution of 25km^2 and was only available for 2010 to present, and chlorophyll data did not cover the entire study area (Walton et al. 1998; AQUA/MODIS).

4.3 SPATIAL AND TEMPORAL CHANGES

Annual variation of beluga whale counts relates to the percent of sea ice in the study area and SST values present within the study area. Percent of sea ice was highest during 2008 (24.7%) and 2001 (17.4%), and beluga counts were low in both years (Figures 9, 48). Beluga counts were high in years in which no sea ice was detected in the study area (2005 and 2011) (Figure 9, 48).

Annual variation of beluga counts might relate to the percent of study area with SST values between 0°–4°C during September of 2000 to 2012 (Figure 49). Over 40% of the study area had SST values from 0°–4°C. September of 2005 had the most areas with temperature values varying from 0°–4°C (69.6%), and a high number of observations, meaning that beluga whales might prefer increased temperature variation. September of 2008 had the least amount of variation in SST from 0°–4°C (32.4%), and was also a year with low observation counts (Figure 9, 49).

Variation of beluga counts in October from 2000 to 2012 might also relate to the percent of the study area with SST values from 0°–2°C (Figure 50). The highest amount of the study areas with SST values between 0°–2°C occurred in October of 2003 (45.6%) and 2010 (39.5%), but whale counts were high in 2003 and low in 2010 (Figure 9, 50). The least amount of area with SST values from 0°–2°C occurred in October of 2006 (90.5%) and 2007 (91.4%), 2006 had a relatively high number of counts and 2007 had a low number of counts (Figure 9, 50).

4.4 BELUGA WHALE CONSERVATION AND MANAGEMENT

During September and October, the Eastern Chukchi and Beaufort Sea stocks of beluga whales seem to prefer areas with moderate to deep depths and increased slope. Environmental covariates including SST and distance to sea ice produce are too variable to detect notable patterns; this variation might be attributed to the fine resolution of the SST and sea ice extent used. In addition, results from this study demonstrate that there is no strong correlation between distance to sea ice or SST and the distribution of beluga whales. Topographic covariates (bathymetry and slope) appear to have a much stronger correlation to the distribution of beluga whales in the northeast Chukchi and southwest Beaufort seas, especially in areas with notable topographic changes including areas with steep slope. Marine management should therefore consider topographic covariates (depth and slope) when designing plans that related to the conservation of habitat for beluga whales off the north coast of Alaska, including Marine Protected Areas (MPAs).

MPAs are areas of interest within which human activity is regulated to conserve species habitat (Wilkinson et al. 2009; GSGislason and Associates Ltd. 2003). There are no MPAs within the Chukchi and Beaufort seas study areas; however, there are Canadian MPAs surrounding the study areas in Shallow Bay in Mackenzie Bay, around Kendall Island, and in Kugmallit Bay (GSGislason and Associates Ltd. 2003). Subsistence hunting, commercial fisheries, oil and gas, mining, shipping, and tourism industry activities are regulated within these areas to protect critical beluga habitat (GSGislason and Associates Ltd. 2003).

4.5 BROADER IMPACTS

Results from this study contribute to ecological understanding of the complex Arctic environment in relation to beluga whales, which are the most gregarious cetaceans in the Arctic and have a great impact in prey populations (Quakenbush (in press)). Beluga whales are a cultural and consumable resource of subsistence hunting indigenous communities along the coast of Alaska. Whale hunting is a key element of traditional ecological knowledge, which is threatened by industrial development (Hassol 2004; Allen and Angliss, 2011). Increased resource extraction activities in the Arctic, including oil drilling, might lead to oil-spills that could result in environmental, economic, and social consequences, including the habitat loss of marine species (Minerals Management Service 2009; Short et al. 2011).

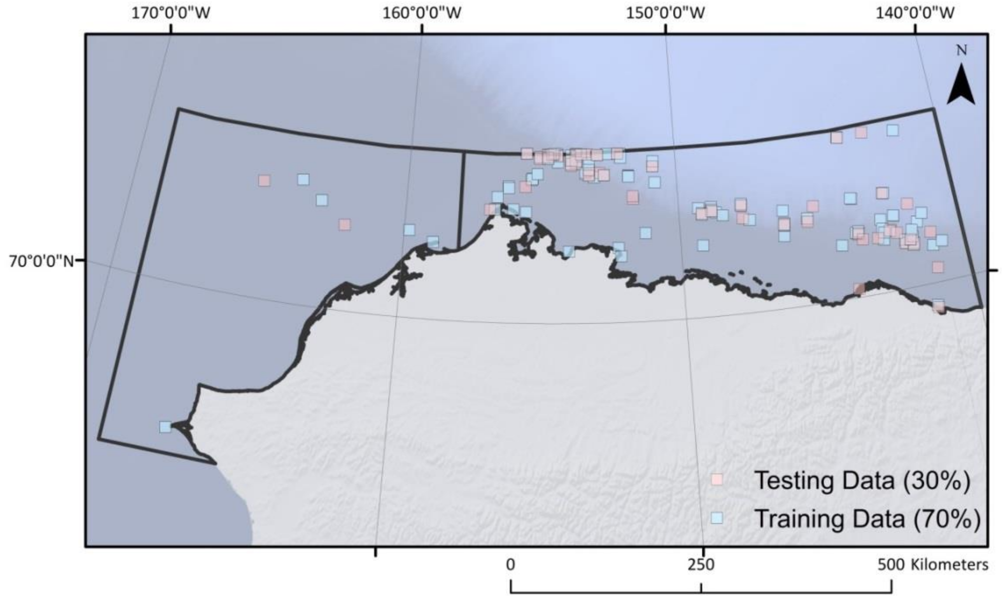


Figure 45: Training and testing datasets used for model validation.

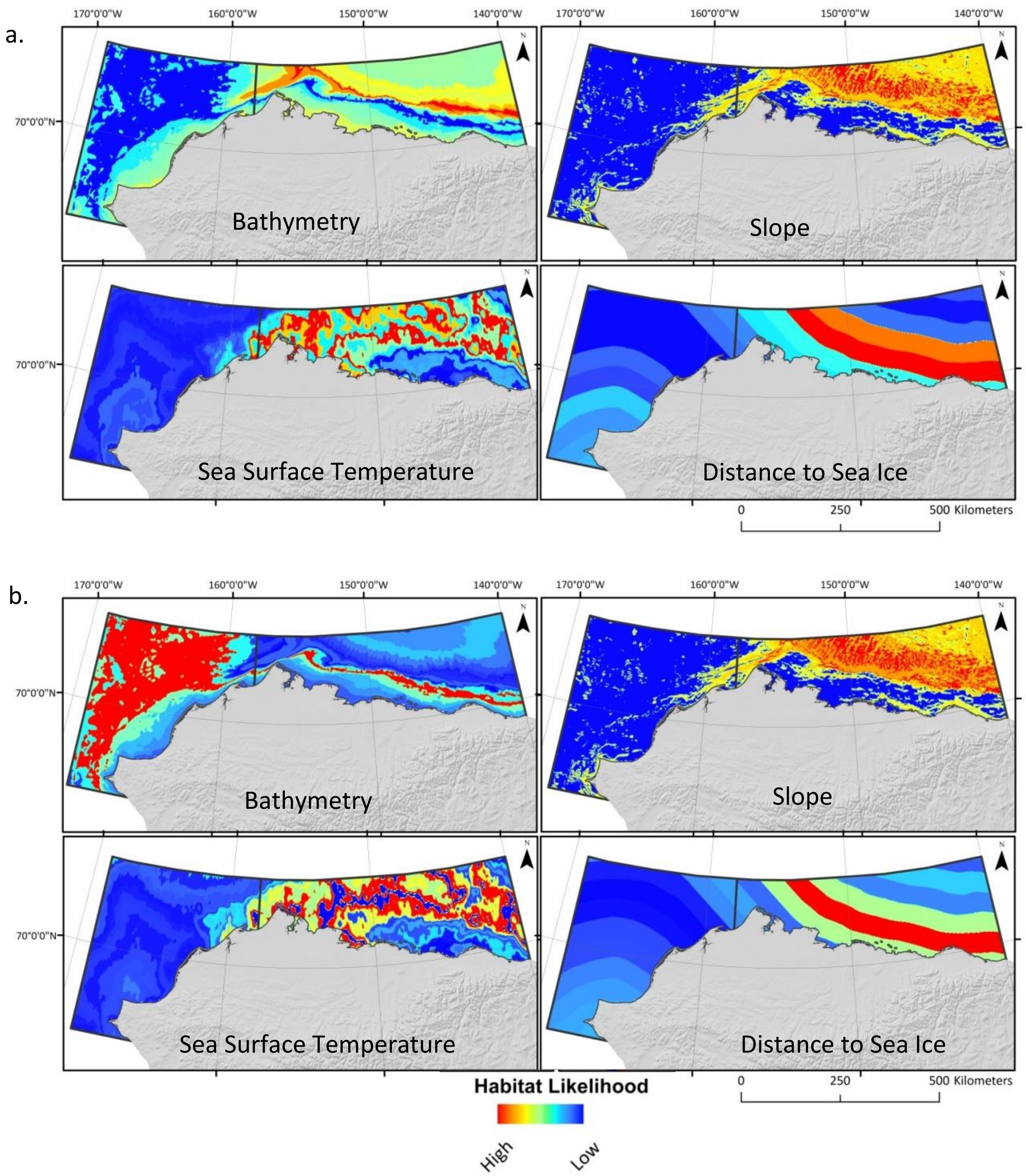


Figure 46: Probability of occurrence maps for each environmental covariate, based on the (a) training and (b) testing datasets for September of 2011.

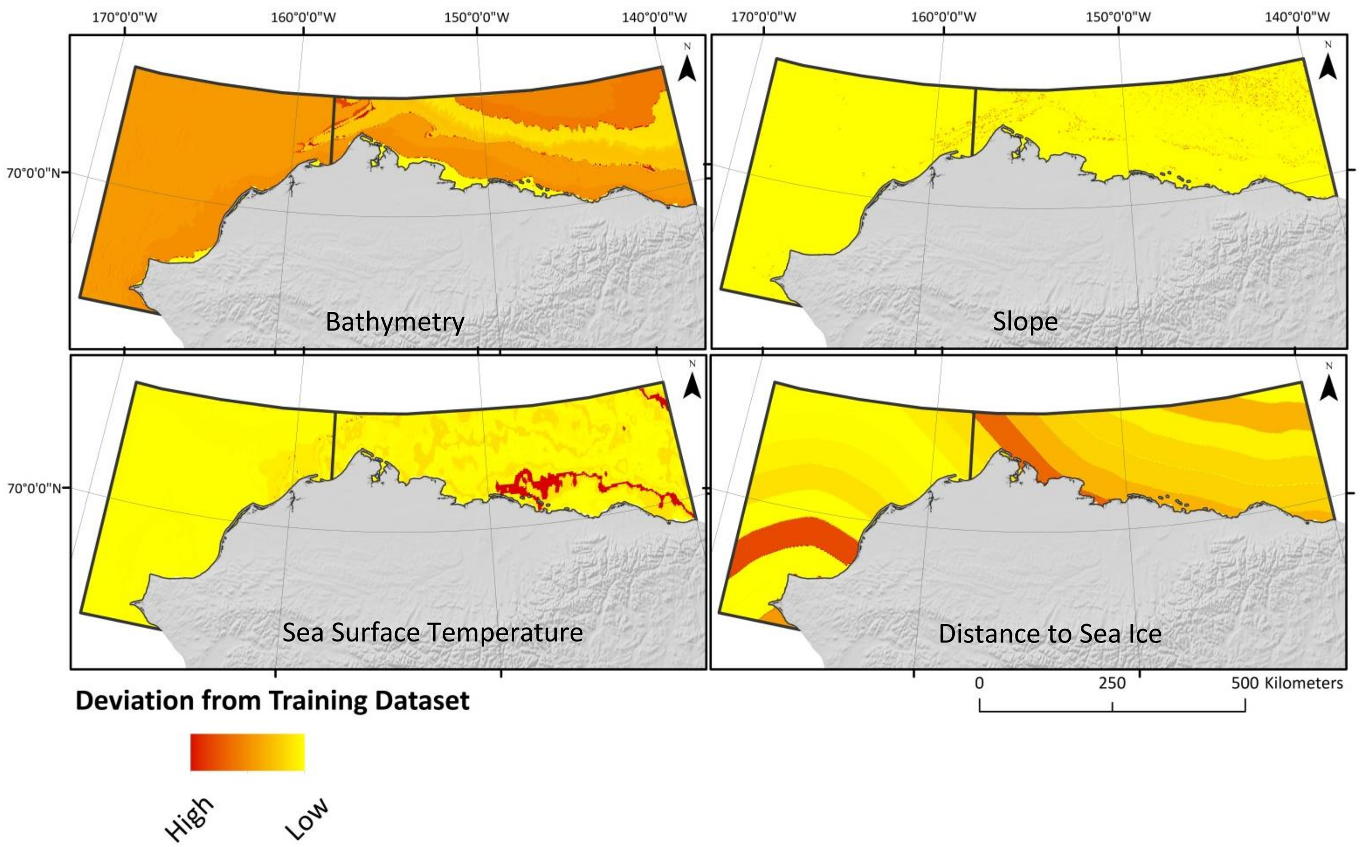


Figure 47: Maps showing the deviation of the probability of occurrence per environmental covariate of the testing dataset from the training dataset, based on data from September of 2011.

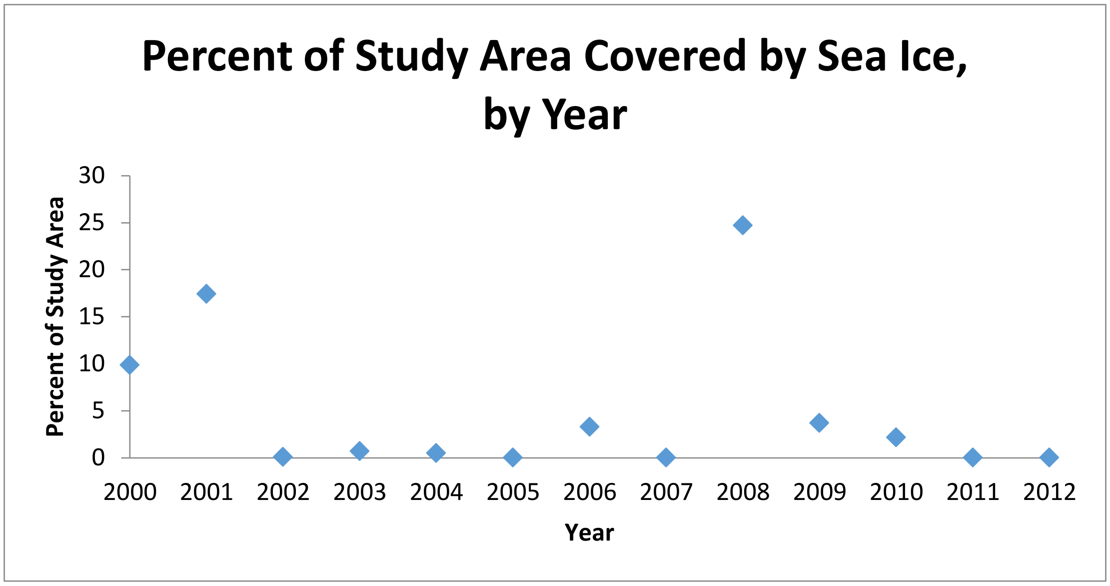


Figure 48: Percent of study area covered by sea ice from 2000–2012.

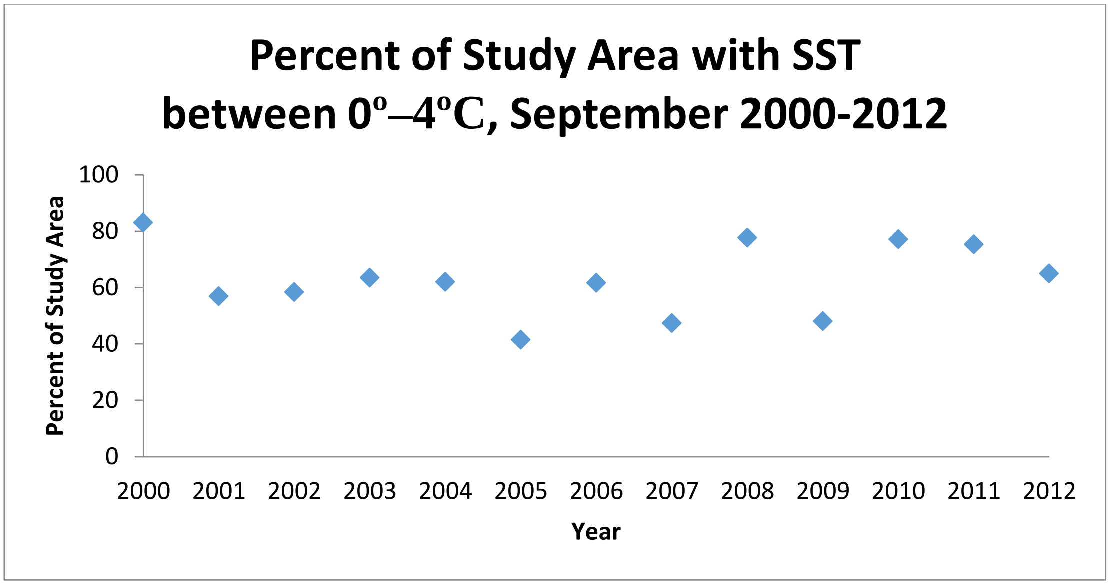


Figure 49: Percent of study area with SST value between 0º–4ºC during September of 2000–2012.

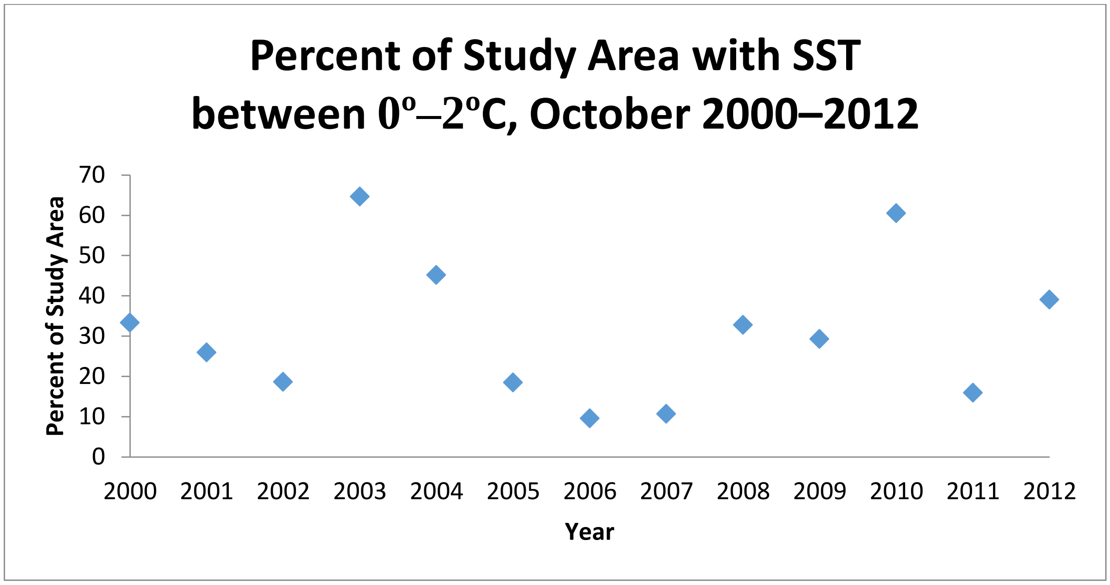


Figure 50: Percent of study area with SST value between 0º–2ºC during October of 2000–2012.

5. CONCLUSION

This research sought to answer three main questions: (1) What are the correlations among the environmental covariates of depth, slope, sea surface temperature, and distance to sea ice within the Chukchi and Beaufort sea study areas from 2000 to 2012, (2) How are these environmental covariates related to the distribution of beluga whales, and (3) Where are areas of high probability of occurrence for beluga whales and how might the results relate to marine conservation management?

Findings suggest that correlations exist between depth and distance to sea ice (2000–06), SST and distance to sea ice (2008–12), and that depth (2000–06) and distance to sea ice (2008–12) explain the most amount of environmental variation within the study area.

Beluga whales show a preference for areas with depths from 90 to 500m, avoiding shallow (20 to 50m) areas along the continental shelf. In addition, belugas avoided flat areas (slope <0.2º), and preferred areas with steeper slope (2° to 8°). Beluga whales preferred areas with SST ranging from -0.25°–3°C in September and areas <1°C in October. From 2000 to 2006, belugas preferred areas 100–400km away from sea ice in September, and 10–50km in October. From 2008 to 2012 beluga whales preferred areas around 300km away from sea ice in September, and 10–150km in October.

This study contributed to understanding of how the habitat of beluga whales is associated with environmental factors. SST and distance to sea ice covariates were too variable to be related to beluga habitat therefore it was uncertain how these factors influence beluga whale habitat. More importantly, the habitat associations between belugas and the environmental covariates of bathymetry and slope historically show preference for areas of relatively steep slope and associated increasing depth along the edge of the continental shelf during the fall in the Chukchi and Beaufort seas. The consistent preference for the continental shelf edge provides a relatively static based line for where marine protected areas might best conserve the potential habitat of the Eastern Chukchi and Beaufort sea stocks beluga whales during the fall months.

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